

Closed loop performance investigation of various controllers based chopper fed DC drive in marine applications

S.Selvaperumal^{*}, P.Nedumal Pugazhenth[#] & A.Amudha¹

Syed Ammal Engineering College, Ramanathapuram, Tamilnadu, India

¹Karpagam University, Coimbatore, Tamilnadu, India

[E.Mail: *perumal.om@gmail.com, # neduaupci@rediffmail.com]

Received 15 March 2015 ; revised 29 May 2015

In this proposed work, the speed of the chopper fed separately excited dc motor can be regulated from below and up to rated speed by using a chopper as a converter. Controller output provides the required gating signal that is used to vary the duty cycle of chopper. Chopper firing circuit receives signal from controller, gives variable voltage to the armature of the motor for achieving desired speed response. For better performance of the DC motor various kind of controller namely Proportional plus Integral (PI), Set point weighting PI, and Fuzzy logic controller are used. Modeling of chopper fed dc motor is done. Complete model of proposed system is simulated using MATLAB (SIMULINK). Finally a comparative study is done between all the controllers.

[**Keywords:** Separately Excited DC Motor, Chopper, PI Controller, Armature Voltage Control, MATLAB].

Introduction

Development of high performance motor drives is very essential in marine applications. A high performance motor drive system should have good dynamic output (speed) command tracking capability. The power supply of a DC motor connects directly to the field of the motor which allows for precise voltage control and it is used in speed control of marine applications. DC drives, because of their, ease of application, simplicity, reliability and favorable cost have long been a backbone of marine applications¹. Comparing with the AC drive systems DC drives have less complexity and also less expensive². DC motor drives are still widely used in many industries such as rolling mills, paper machines, and unwinding and rewinding machines³. DC Motor finds a wide range of applications owing to its ease of operation and exhibits favorable mechanical characteristic⁴. Recently, Induction motors, Brushless DC motors and Synchronous motors have gained widespread use in electric

traction system⁵. Even then, there is a persistent effort towards making them behave like dc motors through innovative design and control techniques. Therefore, DC motors are always a good option for advanced control algorithm because the theory of dc motor speed control is extendable to other types of motors as well. Traditionally rheostatic armature control method was widely used for the speed control of low power dc motors⁶.

Various controllers that can be used in speed control operation are available. In this work three types of controllers are used namely Proportional plus Integral (PI), Set point weighting PI controller and the Fuzzy logic controllers. Proportional plus Integral (PI) is one of the most preferred controllers, which are designed to eliminate the need for continuous operator attention thus provides automatic control to the system⁷. PI controller is robust in terms of speed tracking can be easily designed and implemented according to the choice of the

overall closed-loop transfer function. The proportional and integral gains are tuned by various PI controller tuning methods⁸.

The set-point weighted proportional, integral, and derivative (PID) controller has been shown to be equivalent to an error feedback PID controller. Idea of this controller is set-point value for the proportional action of the PID is multiplying by a constant parameter which is less than one, and this will results in reduction of overshoots⁹. Fuzzy logic control (FLC) is one of the most successful applications of fuzzy set theory, introduced by L.A Zadeh in 1973 and applied (Mamdani 1974) in an attempt to control system¹⁰. Fuzzy logic controllers (FLCs) are increasingly applied to many systems with nonlinearity and uncertainty and it is based on experience of a human operator. While controlling a plant a skilled human operator manipulates the output of the controller based on error and change in error with an aim to reduce the error with a shortest possible time¹¹.

Also the speed control of separately excited dc motor using chopper circuit is presented. A chopper is a static power electronic device that converts constant dc input voltage to a variable dc output voltage. Chopper systems are highly efficient and have smooth control capability and also fast in response¹². Separately excited dc motor finds many applications in marine where precise speed control over wide range is required¹³.

Armature voltage control method is used to vary the speed of separately excited DC motor around the rated speed. The system consists of buck converter type DC–DC power converter or chopper for driving the separately excited DC motor. Performance of the DC drive will be based on the choice of controllers. Output of the motor is compared with the reference and the error signal which is the deviation of the output from the reference is fed to controller which takes necessary action to minimize or quash the deviation. The output from the speed controller is the control voltage E_c that provides required gating signals to vary the duty cycle of the chopper circuit. Chopper output gives the required armature voltage to achieve the desired speed response.

Materials and Methods

Development of mathematical model for chopper fed dc motor

Nomenclature

J	Moment of inertia of the motor (kg m ²)
B	Friction coefficient of the motor (Nm/rad/s)
K _T	Torque constant of the motor (Nm/A)
K _b	Motor back emf constant (V/rad/s)
T _L	load torque applied (Nm)
i _o	Armature current (A);
V _o	Armature voltage applied (V)
R _a	Armature resistance (ohms)
L _a	Armature inductance (mH)
V _s	Supply voltage to chopper (V)
D	Duty cycle
T _s	Switching period(sec)

The simulation and design of the controller was done using equation models of the chopper and motor. The DC motor has been modeled with the modeling (Eqs. 1 and 2).

$$\frac{d^2\theta}{dt^2} = \frac{1}{J} \left[K_T i_o - B \frac{d\theta}{dt} - T_L \right] \tag{1}$$

$$\frac{di_o}{dt} = \frac{1}{L_a} \left[V_o - R_a i_o - K_b \frac{d\theta}{dt} \right] \tag{2}$$

The DC chopper is modeled with a supply voltage of V_s and DC motor as load using (Eqs.3–6). Mode 1 is when the MOSFET switch of the chopper is ON and Mode 2 is when the MOSFET switch of the chopper is OFF.

Mode 1: (Switch ON)

$$V_s = R_a i_a + L_a \frac{di_a}{dt} + K\omega \tag{3}$$

$$K i_a = J \frac{d\omega}{dt} + B\omega + T_L. \tag{4}$$

Mode 2: (Switch OFF)

$$0 = R_a i_a + L_a \frac{di_a}{dt} + K\omega. \tag{5}$$

$$K i_a = J \frac{d\omega}{dt} + B\omega + T_L. \tag{6}$$

The above two states of the converter can be averaged using the fact that the switch is in position 1 for a period of (D × T_s) over the switching period T_s, where D is the duty cycle. The averaged small signal model is formulated by assuming perturbations \bar{v}_s, \bar{d} in the steady state values of supply voltage V_s and the duty cycle D respectively. The small signal model for the

chopper fed DC drive is given by Eqs. (7) and (8).

$$L_a \frac{d\bar{i}_a}{dt} = D\bar{v}_s + V_s \bar{d} - R_a \bar{i}_a - K\bar{\omega}. \quad (7)$$

$$J \frac{d\bar{\omega}}{dt} = K\bar{i}_a - B\bar{\omega} - T_L \quad (8)$$

Considering duty cycle $\bar{d}(s)$ as control signal and speed $\bar{\omega}(s)$ as the output signal, the motor speed transfer function is calculated as

$$\frac{\bar{\omega}(s)}{\bar{d}(s)} = \frac{\bar{\omega}(s)}{\bar{i}_a(s)} \times \frac{\bar{i}_a(s)}{\bar{d}(s)}. \quad (9)$$

From the above equation, the speed gain is given by (Eq.10) assuming the load torque is constant.

$$\frac{\bar{\omega}(s)}{\bar{i}_a(s)} = \frac{K}{Js+B}. \quad (10)$$

Similarly, when the supply voltage is kept constant, the current gain is given by (Eq. 11).

$$\frac{\bar{i}_a(s)}{\bar{d}(s)} = \frac{V_s(Js+B)}{(L_a s + R_a)(Js+B) + K^2} \quad (11)$$

So, the final transfer function of the chopper fed DC motor under the assumed conditions is calculated as in (Eq.12).

$$\frac{\bar{\omega}(s)}{\bar{d}(s)} = \frac{KV_s}{(L_a s + R_a)(Js+B) + K^2} \quad (12)$$

The Specifications of the DC motor are described as follows: DC supply voltage: 110v, Armature resistance [R_a]: 1 Ω , Armature inductance [L_a]: 46mH, Inertia constant [J]: 0.093 Nm/(rad/s²), Damping constant [B]: 0.008 Nm/rad/s, Torque constant [K_t]: 0.55 Nm/A, Back emf constant [K_b]: 0.55 V/(rad/s), Speed: 1500 rpm. Second order of transfer function is,

$$\frac{\bar{\omega}(s)}{\bar{d}(s)} = \frac{KV_s}{(L_a s + R_a)(Js+B) + K^2} \quad (13)$$

The transfer function of the proposed chopper fed separately excited dc motor is,

$$\frac{\bar{\omega}(s)}{\bar{d}(s)} = \frac{60.5}{0.00042s^2 + 0.0930s + 0.3109}$$

Controllers design method and simulation

Various controllers that can be used in speed control operation are available. The controllers used for the proposed chopper fed dc drive are, PI Controller, Set point weighting PI Controller, Fuzzy Logic Controller.

PI Controller. Proportional plus Integral (PI) is the one of the most preferred controller for speed control of dc drive, which are designed to eliminate the need for continuous operator attention thus provide automatic control to the system. They can be easily understood and implemented in practice. PI controller calculation involves two separate constant parameters, Proportional and Integral denoted by P and I. P depends on present error and I on the accumulation of past errors. The proportional term does the job of fast-acting correction which will produce a change in the output as quickly as the error arises. The integral action takes a finite time to act but has the capability to make the steady-state error zero. By tuning these two parameters in PI control algorithm the controller can provide desired action designed for specific process requirement. The PI controller algorithm can be implemented as,

$$output(t) = K_p e(t) + K_i \int_0^t e(t) \quad (14)$$

Where $e(t)$ is error (Reference input – system output)

In this work the proportional and integral gains are tuned by various PI controller tuning methods, also the various performances criteria of the system and the controller are investigated based on those methods. Simulink Model for PI controller based closed loop speed control of chopper fed separately excited DC motor is shown in Fig 1. The speed and error response of the system for a reference input of 1500 rpm is shown in Fig.2 and Fig.3 respectively. The system performance for different reference speed responses are shown in Fig.4

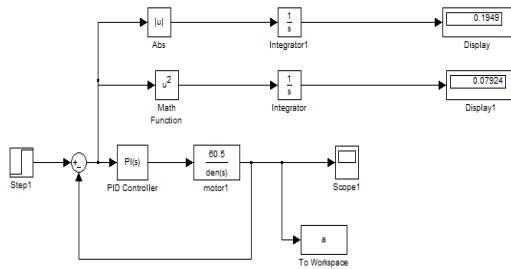


Fig.1 Simulink model of PI controller based Chopper fed DC Drive

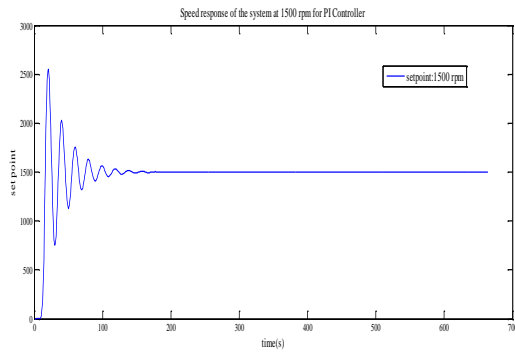


Fig.2 Speed response of the system at 1500 rpm for PI controller

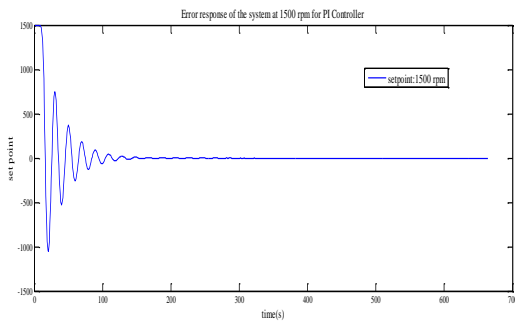


Fig.3 Error response of the system at 1500 rpm for PI controller

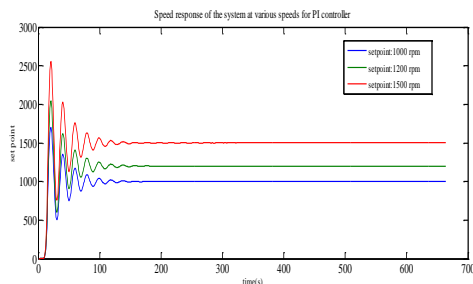


Fig.4 Speed response of the system at various speeds for PI controller

Performance analysis of the system with various controllers

Performances of various controller tuning methods for PI controller are analyzed in

MATLAB. The Controller performance indices analysis of PI controller for various tuning rules for the proposed system is given in (Table I).

Table I

PERFORMANCE ANALYSIS

Tuning method	ISE	IAE
Zhuang and Atherton(1993)	0.05822	0.1401
Murrill(1967)	0.06791	0.1576
Ziegler and Nichols(1942)	0.07924	0.1949
Astrom and Hagglund(1995)	0.1108	0.2727
Chien(1952)	0.1147	0.2862
St. Clair(1997)	0.1258	0.3106

In this analysis the Integral Square Error, Integral Absolute Error is measured. Based on this analysis the Zhuang and Atherton method gives minimum ISE (0.05822) and IAE (0.1401) values. The time domain parameters analysis is given in (Table II). It is found that tuning based on Murrill is outperforming the other methods with better settling time and lesser peak overshoot. Also the Chien method is showing promising improvement in rise time.

Table II

TIME DOMAIN SPECIFICATIONS

Tuning method	Rise time (sec)	Peak time (sec)	Peak Overshoot (%)	Settling time (sec)
Zhuang and Atherton(1993)	0.07	0.14	1.48	1.8
Murrill(1967)	0.12	0.21	1.4	1.6
Ziegler and Nichols(1942)	0.08	0.13	1.61	2.1
Astrom and Hagglund(1995)	0.1	0.15	1.65	3.1
Chien(1952)	0.06	0.15	1.65	3
St. Clair(1997)	0.11	0.19	1.64	3.3

The system response after applying the PI controller for different tuning methods that are used in the performance analysis are shown in Fig. 5(a) and Fig.5 (b)

Set Point Weighted PI Controller.

The PID controller has the following well-known standard form in the time domain

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(\tau) d\tau \quad (15)$$

Where, it is obviously, $K_d = K_p T_d$, and $K_i = \frac{K_p}{T_i}$

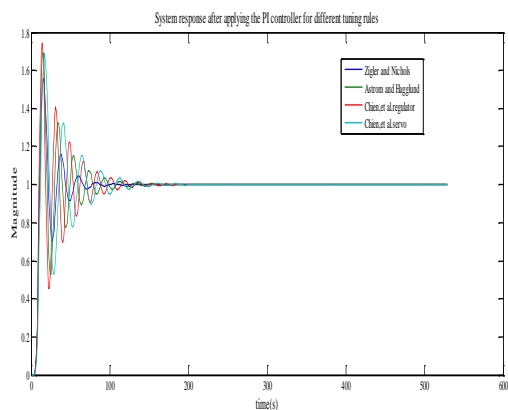


Fig.5 (a) System response after applying the PI controller for different tuning rules

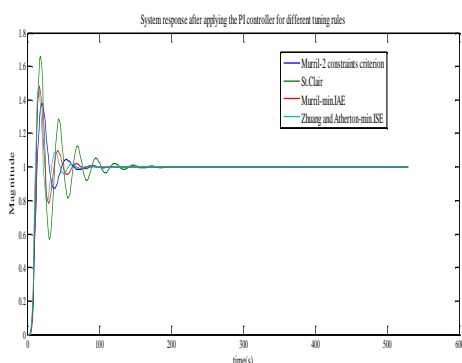


Fig.5 (b) System response after applying the PI controller for different tuning rules

The typical tuning problem consists of selecting the values of these three parameters, and many different methods have been proposed in order to meet different control specifications such as set-point following, load disturbance attenuation, robustness with respect to model uncertainties and rejection of measurement noise. Using the Ziegler–Nichols formula generally results in good load disturbance attenuation but also in a large overshoot and settling time for a step response that might not be acceptable for a number of processes. Increasing the analog gain K_p generally highlights these two aspects.

An effective way to cope with this problem is to weight the set-point for the proportional action by means of a constant $b < 1$ so that we get,

$$u(t) = K_p e_p(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(\tau) d\tau \quad (16)$$

Where, $e_p(t) = by_{sp}(t) - i(t)$.

In this work, set point weighted PI controller is implemented using MATLAB

(SIMULINK). The speed response of the system at 1500 rpm using weighted PI controller is shown in Fig 6. The error minimization of the system by controller is also shown in Fig.7. The output response of the system with weighted PI controller for different set point changes is given in Fig.8

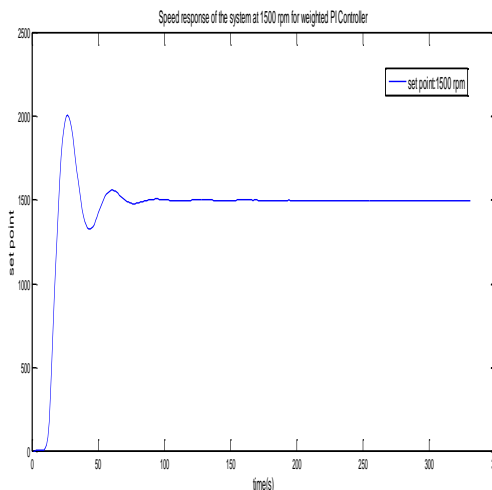


Fig.6 Speed response of the system using set point weighted controller

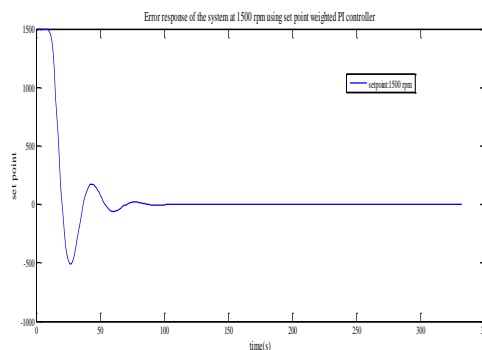


Fig.7 Error response of the system using set point weighted controller

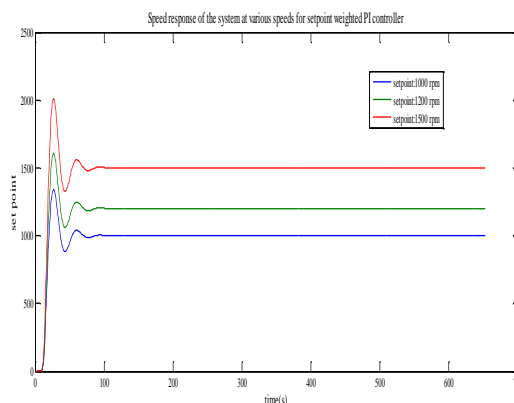


Fig.8 Speed responses of the system at various speeds using set point weighted controller

Fuzzy Logic Controller

Fuzzy logic control is one of the control algorithm based on a linguistic control strategy, which is being derived from expert knowledge into an automatic control strategy. Fuzzy uses only simple mathematical calculation to simulate the expert knowledge. Although it doesn't need any difficult mathematical calculation, it gives good performance in a control system. Thus, it can be one of the best available answers today for a broad class of challenging controls problems. For the speed control of DC motor study, seven linguistic variables for each of the input and output variables are used to describe them. The required algorithm for fuzzy speed control can be summarized as follows.

- The triangular membership functions for input variable speed error (e(k)), change in speed error (ce(k)) and control output (du(k)) i.e. change in firing angle are shown in normalized units. The general considerations in the design of the controller are:
- If both e and ce are zero, then maintain the present control settings i.e. du=0
- If e is not zero but it is approaching to this value at a satisfactory rate, then maintain the present control Settings.
- If e is increasing then change the control signal du depending on the magnitude and sign of e and ce to force e towards zero.
- ce and e are change in speed error and speed error respectively (normalized).
- du is change in firing angle (normalized).

The rules framed for the fuzzy controller is provided in table III.

Table III

RULES FOR FUZZY LOGIC CONTROLLER							
E(k) \ CE(k)	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NM	NM	NS	ZE
NM	NL	NL	NM	NS	NS	ZE	PS
NS	NL	NM	NS	NS	ZE	PS	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	ZE	PS	PS	PM	PL
PM	NS	ZE	PS	PS	PM	PL	PL
PL	ZE	PS	PM	PM	PL	PL	PL

There can be $7 \times 7 = 49$ possible rules in the matrix, where a typical rule reads as IF e = PS and ce = NM then du = NS. Fig.9 shows the surface viewer of the fuzzy logic controller.

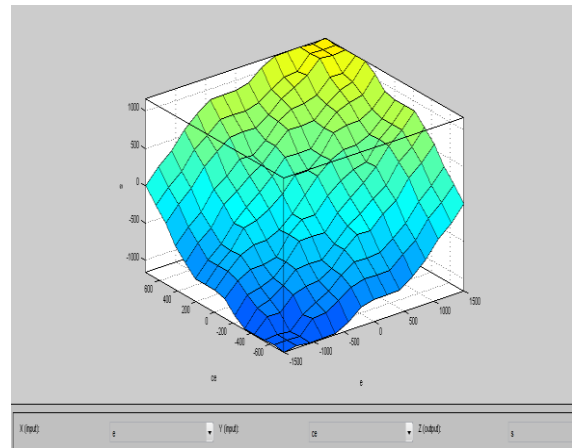


Fig.9 Surface viewer for the fuzzy logic controller

The system response using fuzzy logic controller for a reference input of 1500 rpm is shown in Fig.10. The error minimization response of the system is shown in Fig.11. The response of the system for various reference speeds is given in Fig.12.

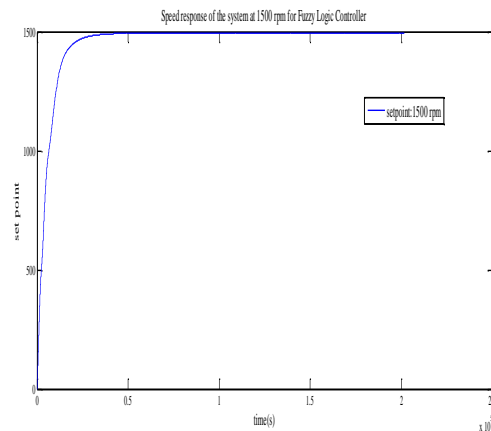


Fig.10 Speed response of the system at 1500 rpm for fuzzy logic controller

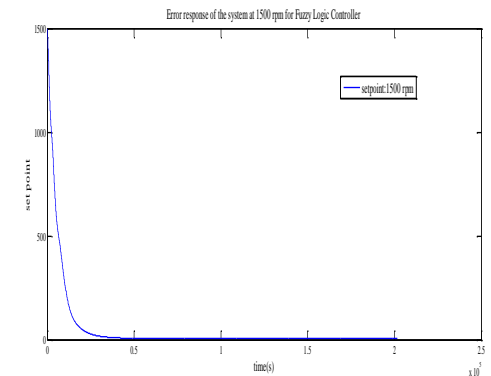


Fig.11 Error response of the system at 1500 rpm for fuzzy logic controller

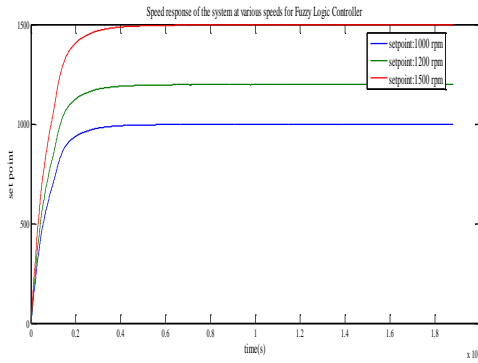


Fig.12 Speed response of the system at various speeds for fuzzy logic controller

Results and Discussion

The output response of the system for a reference speed of 1000 rpm with PI, Set point weighted PI and Fuzzy logic controller is provided in Fig. 13 and the time domain specification analysis is provided in Table IV.

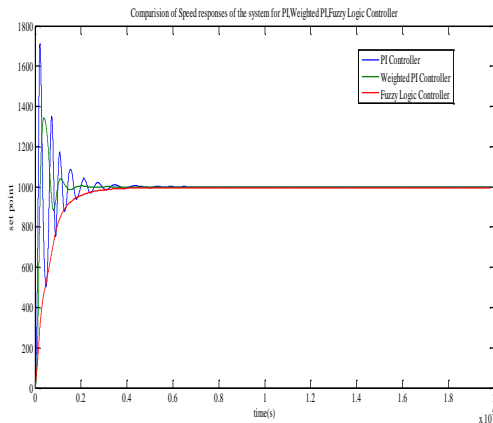


Fig.13 Comparison of speed responses for PI, Set point weighted PI, Fuzzy logic controller response for a set point speed of 1000 rpm.

Table IV

COMPARISON BETWEEN PI, SET POINT WEIGHTED PI, FUZZY LOGIC CONTROLLERS

S . N o	Controller Used	Rise Time (Tr) (sec)	Settling Time (Ts) (sec)	Peak Overshoot (Mp) (%)	Transient Behavior
1	PI Controller	0.08	4.2	66.6	Oscillatory
2	Set Point Weighted PI controller	0.16	1.62	33.3	Less Oscillation
3	Fuzzy Logic Controller	2.18	2.45	0	Smooth

weighted PI controller the settling time and amount of overshoot is minimized in set point weighted PI controller also it results less amount of oscillation. From, the comparative study, it is found that the Fuzzy logic controller provides the better results for the proposed system among the type of controllers considered in this work.

Conclusion

The speed of chopper fed separately excited dc motor has been successfully controlled by using PI, Set point weighted PI controller, and Fuzzy logic controller. Initially Mathematical model of chopper fed separately excited dc motor is derived. Then, the proposed model is simulated in MATLAB using three types of controllers. A comparison has been done between the performances of PI, Set point weighted PI controller and fuzzy controller for dc motor control by setting the reference speed to 1000 rpm. It is clear from the results that the fuzzy logic controller performs in a better way than the other conventional controllers with no overshoot and oscillations which could improve the performance especially the life time and efficiency of the motor considered in this work.

Acknowledgement

Authors are grateful to Dr. Chinna Durai Abudullah, Correspondent, Syed Ammal Engineering College, Ramanathapuram for providing facilities and encouragement to carry out the above research work.

References

1. Rishabh Abhinav, Jaya Masand, PiyushVidyarthi, GunjaKumari, NehaGupta, Separately excited dc motor speed control using chopper, *International Journal of Scientific & Engineering Research* Volume 4, Issue 1, January-2013, ISSN 2229-5518
2. C.U. Ogbuka, Performance characteristics of Controlled separately excited dc motor, *Pacific Journal of Science and Technology*, 10(1), 67-74.
3. ZuoZong Liu, Fang Lin Luo, Muhammad H. Rashid, Speed Nonlinear Control of DC Motor Drive With Field Weakening, *IEEE Transactions on Industry Applications*, Vol. 39, No. 2, March/April 2003.
4. V.Thebinaa, A.Ezhilarasi, M.Subhashini, M.Ramaswamy, Speed Regulation of Dc Drive Using Variable Structure Controller *International Journal of Engineering Research & Technology (IJERT)*, Vol. 2 Issue 5, May – 2013, ISSN: 2278-0181
5. Ronald S. Rebeiro M. NasirUddin, Performance Analysis of an FLC- Based Online Adaptation of Both Hysteresis and PI Controllers for IPMSM

- Drive , *IEEE Transactions on Industry Applications*, Vol 48.No.1, January/February 2012.
6. Moleykutty George., Speed Control of Separately Excited DC motor, *American Journal of Applied Sciences*, 5(3), 227-233, 2008
 7. Ya-Gang Wang, Hui-He Shao, Optimal tuning for PI controller, *Research Institute of Automation, Shanghai Jiao Tong University, Shanghai 200030, Automatica* 36 (2000) 147-152
 8. Aidan O'Dwyer, A Summary of PI and PID Controller Tuning Rules for Processes with Time Delay. Part 1: PI Controller Tuning Rules, *Proceedings of PID '00:IFAC Workshop on Digital Control*, pp. 175,180, Terrassa, Spain, April 4-7,2000
 9. Antonio Visioli, Fuzzy Logic Based Set-Point Weight Tuning of PID Controllers, *IEEE Transactions On Systems, Man, And Cybernetics—Part A: Systems And Humans*, Vol. 29, No. 6, November 1999
 10. Jaydeep Chakravorty, Ruchika Sharma, Fuzzy Logic Based Method of Speed Control of DC Motor, *International Journal of Emerging Technology and Advanced Engineering*, ISSN 2250-2459, Volume 3, Issue 4, April 2013.
 11. Seema Chopra, R. Mitra , Vijay Kumar, Auto Tuning of Fuzzy PI Type Controller Using Fuzzy Logic, *International Journal of Computational Cognition*, Vol. 6, NO. 1, March, 2008
 12. Nazanin Afrasiabi, Mohammadreza Hairi Yazdi, DC Motor Control Using Chopper, *Global Journal of Science, Engineering and Technology* (ISSN: 2322-2441) Issue 8, 2013, pp. 67-73
 13. N. Senthil Kumar,V. Sadasivam, H.M.AsanSukriya, S. Balakrishnan, Design of low cost universal artificial neuron controller for chopper fed embedded DC drives, *Applied Soft Computing*,8 (2008) 1637–1642