Type-2 fuzzy logic controller Implementation for tracking control of DC motor

*1Meena Tushir and #2Smriti Srivastava

*1Department of Electrical Engineering
Maharaja Surajmal Institute of Technology, New Delhi, India
#2Department of Instrumentation & Control Engineering
Netaji Subhash Institute of Technology, New Delhi, India
meenatushir@yahoo.com,ssmriti@yahoo.com

***Abstract* - Type-2 fuzzy logic systems have recently been utilized in many control processes due to their ability to model uncertainty. This research article proposes the speed control of a DC Motor (series as well as shunt motor).The novelty of this article lies in the application of a interval type-2 fuzzy logic controller (IT2FLC) in the design of fuzzy controller for the speed control of DC Motor. The entire system has been modeled using MATLAB 7.0/Simulink type-2 toolbox. The performance of the proposed IT2FLC is compared with that of its corresponding conventional type -1 FLC in terms of several performance measures such as rise time, peak overshoot, settling time, integral absolute error (IAE) and integral of time multiplied absolute error (ITAE) and in each case, the proposed scheme shows improved performance over its conventional counterpart. Extensive simulation studies are conducted to compare the response of the given system with the conventional type -1 fuzzy controller to the response given with the proposed IT2FLC scheme.**

***Index Terms*— DC Motor, Fuzzy control, interval Type-2 fuzzy sets**

I. INTRODUCTION

Series and shunt connected motors are used in a variety of applications. They have relatively high torque for their weight, especially when compared to similarly sized permanent magnet motors. Permanent magnet motors are linear while shunt and series motors are non-linear. The non-linearity of the series/shunt-connected motors complicates their use in applications that require automatic speed control. Unfortunately, the non-linear dynamical model of the dc machine poses certain limits on the design of the closed-loop feedback controllers. Major problems in applying a conventional control [1,2] algorithm in a speed controller are the effects of non-linearity in a DC motor. The non-linear characteristics of a DC motor such as saturation and friction could degrade the performance of conventional controllers. In recent years, significant advances in the theory of nonlinear control have been reported, which take fully into account the non-linearities. The main advantage of such approaches is their validity for a wide range of operating conditions.

Emerging intelligent techniques have been developed and extensively used to improve or to replace conventional control technique because these techniques do not require a precise model. One of intelligent technique, fuzzy logic by Zadeh is applied for controller design in many applications. The advantage of fuzzy control methods [3,4,5,6,7,8] is the fact that they are not sensitive to the accuracy of the dynamical model.

With the development of T2 FLSs and their ability to handle uncertainty, utilizing type-2 FLCs (IT2 FLCs) has attracted a lot of interest in recent years. The concept of type-2 fuzzy sets was first introduced by Zadeh as an extension of the concept of well-known ordinary fuzzy sets, type-1 fuzzy sets. A type-2 fuzzy set [9,10] is characterized by a fuzzy membership function i.e. the membership grade for each element is also a fuzzy set in [0,1],unlike a type-1 fuzzy set ,where the membership grade is a crisp number in [0,1].The membership functions of type-2 fuzzy sets are three dimensional and include a footprint of Uncertainty(FOU),which is the new third dimension of type-2 fuzzy sets. The footprint of uncertainty provides an additional degree of freedom to handle uncertainties.

In this paper, the application of type-2 fuzzy logic concepts to the speed control of a simple dc motor is illustrated. The device model is straightforward and the physical implications of speed control are readily perceived. Thus attention is concentrated upon the fuzzy logic aspects of the problem rather than upon the complexities of the model. The outline of the paper is as follows: Section 2 briefly reviews the mathematical model of DC series and shunt motor. Section 3 describes type-2 fuzzy logic systems. Section 4 describes the control design method using the proposed IT2FLC scheme. Section 5 shows the simulation results of our approach. Finally, section 6 concludes the paper.

II. DYNAMIC MODELING OF DC MOTOR

DC Motors are electrical machines that consume DC electrical power and produce mechanical torque. Historically, DC machines are classified according to the connection of the field circuit with respect to the armature circuit. In shunt machines, the field circuit is connected in parallel with the armature circuit while DC series machines have the field circuit in series with armature where both field and armature currents are identical.

2.1 DC Series Motor

DC series motor, with its own characteristics of high starting torque which makes it suitable for high inertia as well as traction systems, has a nonlinear dynamical model. As its name indicates, the field circuit is connected in series with the armature and therefore the armature and field currents are the same. The equivalent circuit of a DC series motor is shown in Figure 1.

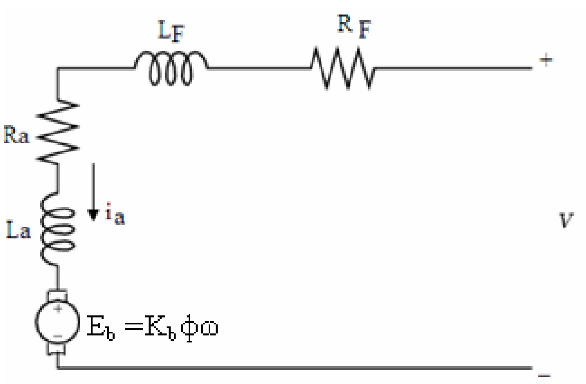

Figure 1. Equivalent Circuit of DC Series Motor

The equation of the armature:

$$(L_a + L_F)\frac{di_a}{dt} = V - (R_a + R_F)i_a = K_b\phi\omega$$

(1)

Where L_F : field winding inductance, L_a : armature winding inductance, i_a :armature current, V : applied terminal voltage, R_a :armature winding resistance, R_F :field winding resistance, K_b : constant depends on the design of the machine, ϕ : flux per pole and ω : rotational speed of the rotor.

The motion equation is:

$$J\frac{d\omega}{dt} = K_t\phi i_a - T_L \tag{2}$$

where K_t =torque constant, J =rotor and load moment of inertia and T_L : load torque.

2.2 DC Shunt Motor

In shunt machine, the field circuit is connected in parallel with the armature circuit. It has the following equivalent circuit (Figure 2).

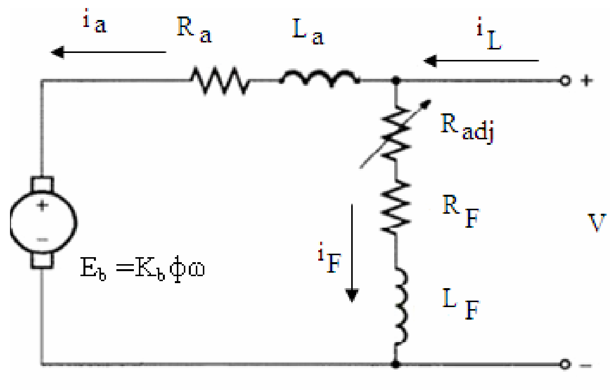

Figure 2. Equivalent Circuit of DC Shunt Motor

The mathematical model of the electromechanical system is as follows:

$$\dot{\theta} = \omega \tag{3}$$

$$J\dot{\omega} = T_m - B\omega - T_L \tag{4}$$

Where

$T_m = K_m\phi i_a$, T_m = Electromagnetic torque

$\phi = K_F i_F$, ϕ = Flux in armature

$i_a = (V - E_A)/R_a$, i_a = Armature current

$E_A = K\phi\omega$, E_A = back emf

T_L = load torque , V = terminal voltage

L_F = field Inductance , J = rotor moment of inertia

L_a = Armature inductance, B = viscous friction co-efficient

θ = Angular position, ω = speed

K_F = Field Constant , K_m = Torque constant

K =Back Emf constant, R_a = armature resistance

III. TYPE-2 FUZZY LOGIC SYSTEMS

An IT2FLS shown in Fig. 3 is also characterized by fuzzy IF-THEN rules, but the membership functions of the ITFLSs are now interval type-2 fuzzy sets (IT2FLSs).From Figure 3 ,it can be seen that the structure of an IT2FLS is very similar to the structure of a T1FLS and the only difference exists in the output processing block. For a T1FLS, the output processing block only contains a defuzzifier, but for an IT2FLS, the output processing block includes a type-reducer, which maps a T2FS into a TIFS and a defuzzifier.

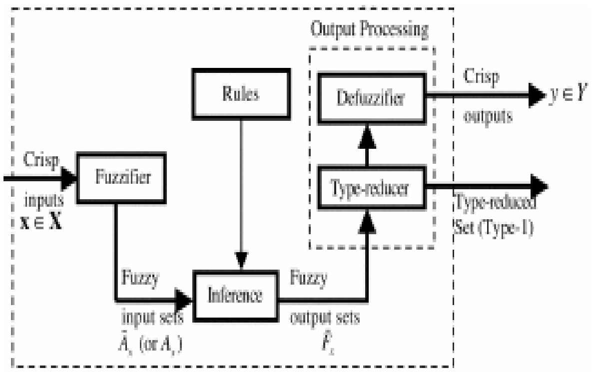

Figure 3. Structure of a type-2 FLS

Assume that there are M rules in the rule base, each of which has the following form

Rule k : IF x_1 is $\tilde{A}_1^k$ and x_2 is $\tilde{A}_2^k$ and …..and x_p is $\tilde{A}_p^k$,THEN y is $\left[\underline{w}^k, \bar{w}^k\right]$.

(6)

Where $k = 1,2,...M$, p is the number of input variables in the antecedent part, $\tilde{A}_i^k$ $(i = 1,2,...p, k = 1,2...M)$ are IT2FLS of the IF-part, and $\underline{w}^k, \bar{w}^k$ are the singleton lower and upper weighting factors of the THEN-part.

Once a crisp input $X = (x_1, x_2, ..., x_p)^T$ is applied to the IT2FLS, through the singleton fuzzifier and the inference process, the firing strength of the k th rule which is an interval type-1 set can be obtained as

$$F^k = [\underline{f}^k, \bar{f}^k]$$

Where

$$\underline{f}^k = \underline{\mu}_{\tilde{A}_1^k}(x_1) * \underline{\mu}_{\tilde{A}_2^k}(x_2) * .... * \underline{\mu}_{\tilde{A}_p^k}(x_p) \qquad (7)$$

$$\bar{f}^k = \bar{\mu}_{\tilde{A}_1^k}(x_1) * \bar{\mu}_{\tilde{A}_2^k}(x_2) * .... * \bar{\mu}_{\tilde{A}_p^k}(x_p) \qquad (8)$$

In which $\underline{\mu}(\,)$ and $\bar{\mu}(\,)$ denote the grades of the lower and upper membership functions of IT2FSs and * denotes minimum or product t-norm.

To generate a crisp output , the outputs of the inference engine should be type reduced and then defuzzified.

IV. CONTROLLER STRUCTURE

Unlike conventional control, which is based on mathematical model of a plant, a FLC usually embeds the intuition and experience of a human operator and sometimes those of designers and researchers. While controlling a plant, a skilled human operator manipulates the process input (i.e. controller output) based on e and Δe with a view of minimizing the error within shortest possible time. The controlled variable of fuzzy controller is u(t).Once the fuzzy controller inputs and outputs are chosen , one must think about the membership functions (MFs) for these input and output variables. In this paper, all membership functions for the conventional fuzzy controller inputs (e and Δe) and the controller output are defined on the common normalized domain [-1 ,1]. We use symmetric triangles (except the two MFs at the extreme ends) with equal base and 50% overlap with neighboring MFs. This is the most natural and unbiased choice for MFs. Here,the seven membership functions are shown in Figure 4.

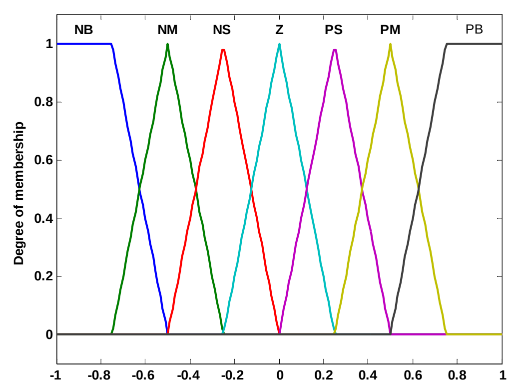

Figure 4. MFs for e , Δe and Δu

NB-Negative Big ,NM-Negative Medium, NS-Negative Small ,ZE-Zero Error, PS-Positive Small, PM-Positive Medium, PB-Positive Big

The next step is to design the rule base. If the number of MFs for inputs is 7 , the corresponding rules are 7^2 =49 (Table 1). By way of the above design process, the actual control input voltage for the main fuzzy controller (In the case of PI-type FLC) can be written as

$$u(k) = u(k-1) + \Delta u(k) \qquad (9)$$

In (9), k is the sampling instant and Δu(k) is the incremental change in controller output.

TABLE I
RULE BASE

Δe_i / e_i	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Membership function in interval type2 fuzzy logic set as an area called Footprint of Uncertainty (FOU) which is limited by two type1 membership function.Those are: Upper membership

Function (UMF) and Lower Membership function (LMF). Interval type2 membership function is shown in Figure 5.

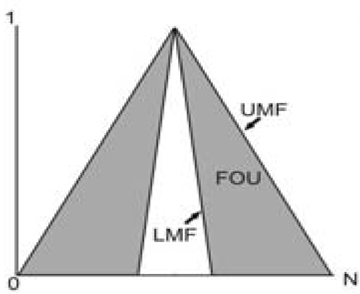

Figure 5. Membership Function Interval Type2 Fuzzy Logic Set

In the design of IT2 FLC, the same configuration as that of type-1FLC is chosen. There are two-input-single-output and each input /output variable has same seven linguistic variables which are defined in figure 6.

Fuzzy Inference system (FIS) which is used in this paper is Mamdani method or used to call Max-Min method. Operation on Interval type-2 fuzzy set is identical with an operation on type-1 fuzzy set. Howerver, on interval type-2 fuzzy system, fuzzy operation is done at two type-1 membership function which limits the FOU, LMF and UMF to produce firing strengths. Operation on interval type-2 fuzzy logic is shown in Figure 7.

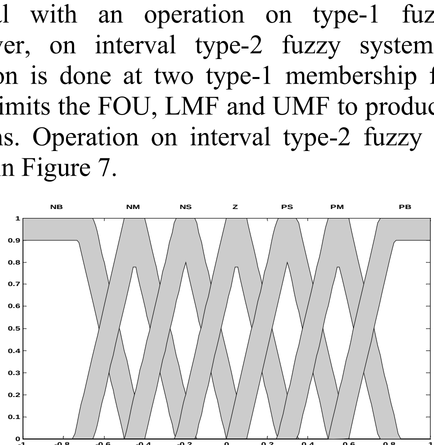

Figure 6. Type-2 membership grades for e,Δe and u

Fuzzy Inference system (FIS) which is used in this paper is Mamdani method or used to call Max-Min method. Operation on Interval type-2 fuzzy set is identical with an operation on type-1 fuzzy set. However, on interval type-2 fuzzy system, fuzzy operation is done at two type-1 membership function which limits the FOU, LMF and UMF to produce firing strengths. Operation on interval type-2 fuzzy logic is shown in Figure 7.

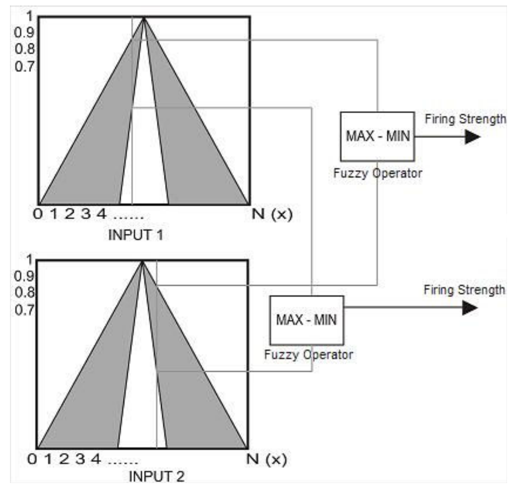

Figure 7. Operation on interval Type-2 membership functions

V. SIMULATION AND ANALYSIS

To examine the feasibility and validity of the proposed controller, we apply the developed IT2FLC for the speed control of DC motor. Before performing the simulations, a type-2 fuzzy inference graphic interface is first designed with MATLAB type-2 toolbox [11] to monitor the controller system dynamically. Two performance criteria were utilized for the comparison: settling time and peak overshoots. The step response plots were obtained with MATLAB 7.0-Simulink software and therefore, settling times and overshoots of the two controllers were compared against each other. In order to compare the feasibilities of these two controllers, two commonly used performance indices : Integral of the absolute error (IAE) and Integral of time multiplied absolute error (ITAE) are adopted to evaluate the tracking performance of these controllers. The two performance indices are defined as:

$$IAE = \sum_{k=1}^{N} |e(k)| \tag{10}$$

$$ITAE = \sum_{k=1}^{N} |e(k)| \times kT \tag{11}$$

Where, $N = T_f / T$, T_f is the final time of the simulation and T is the sampling time.

5.1 Simulation

In this section, we show the simulation results for speed control of DC motor using both the proposed type-2 fuzzy controller and the conventional fuzzy controller. The simulink model for the fuzzy controller for DC motor Speed Control is shown in Figure 8.

To obtain the gain Kp,Ki and Ks,a two step method has been used. These two steps consist of adjusting Kp and Ki in order to normalize input and thus tuning Ks to obtain best results. The values of gain are Kp=0.25,Ki=1,Ks=4.25 for DC Series Motor and Kp=0.5,Ki=1,Ks=2 for DC Shunt Motor.

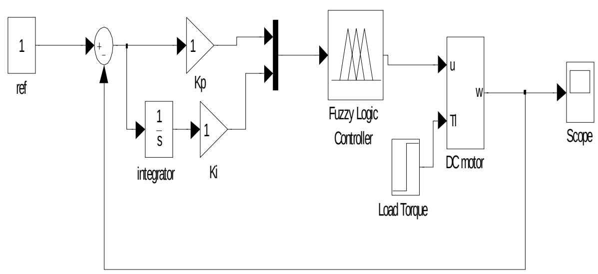

Figure 8. Simulink Model of Fuzzy controller for DC Motor Speed Control

5.2 Experiment Analysis

5.2.1 DC series motor

Simulation experiments under different operation status is carried out based on the fore established model and performance comparison with proposed I2FLC and conventional type-1 fuzzy controller is made. The simulink model for the DC series motor is shown in Figure 9. The parameters used for DC series motor can be taken reference for simulation, as shown in appendix A.

The two curves in Figure 10 are the simulation curves of the rated running state for DC series motor respectively under the control of conventional type-1 fuzzy controller and the proposed type-2 fuzzy controller. For a clear comparison between the conventional fuzzy controller and the proposed clustering based fuzzy controller, several performance measures such as peak overshoot *(%OS)*, settling time, rise time, integral absolute error (IAE) and integral-of-time-multiplied-absolute error (ITAE) are computed as shown in table 2 .

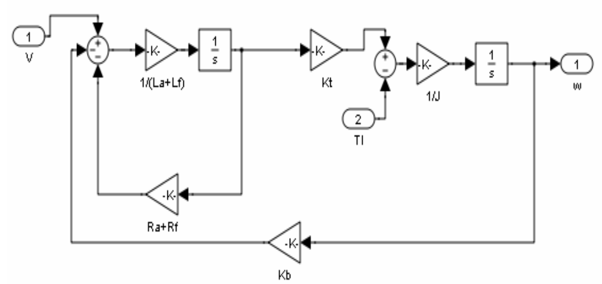

Figure 9. Simulink Model of DC series motor

Using proposed controller, the rise time and settling time improves whereas for other measures, both the controllers give approximately the same performance. However, under load disturbance, the performance of the proposed scheme shows improved results. Figure 11 shows the response of the system with a 40 % load disturbance applied at t=2.5 secs. Table 3 shows the values of peak overshoot, settling time, IAE and ITAE computed under this condition.

After 2.5 seconds, the rated speed of the DC series motor is suddenly increased and then decreased by 20% as shown in Figure 11 and Figure 12.As can be seen, under the condition of given speed changing, the proposed controller compared with conventional fuzzy controller, is able to quickly reach a steady state and has better tracking performance. Table 4 and table 5 shows the values of IATE and IAE under these conditions of speed changing.

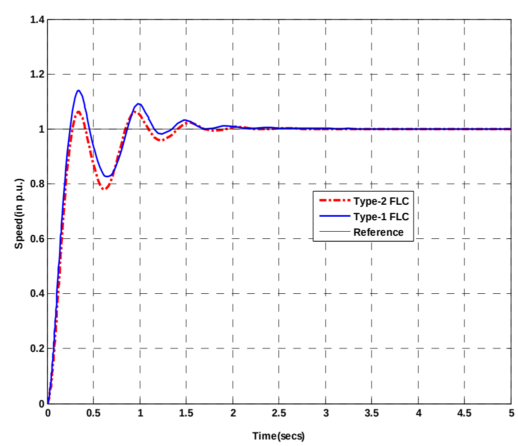

Figure 10. Speed Response of DC series motor without load disturbance

Table 2 : Numerical result of experiment on DC series motor without load disturbance

Controller	%Mp	ts (secs)	ITAE	IAE
Type 1 FLC	11.4	1.58	0.089	0.23
Type 2 FLC	**6**	**1.56**	**0.084**	**0.22**

Table 3 : Numerical result of experiment on DC series motor with load disturbance

Controller	%Mp	ts (secs)	ITAE	IAE
Type 1 FLC	10.7	3.18	0.224	0.27
Type 2 FLC	**8.5**	**3.07**	**0.174**	**0.26**

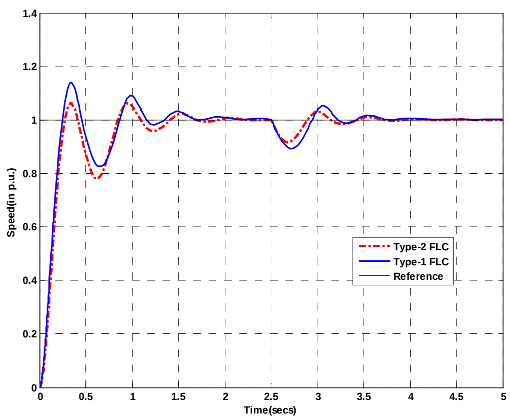

Figure 11. Speed Control of DC series Motor under load disturbance

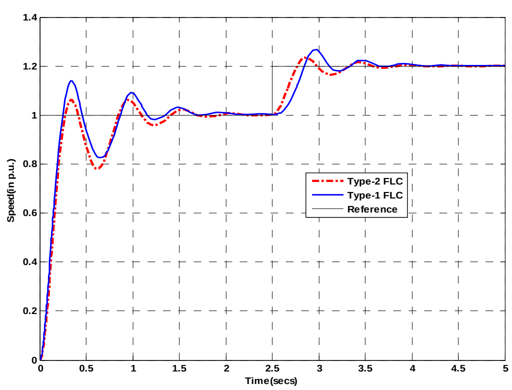

Figure 12. Speed Response of DC series motor with sudden increase in Speed

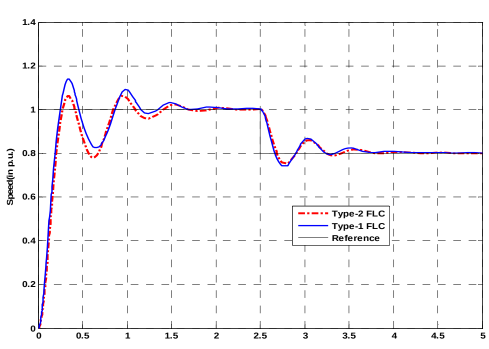

Figure 13. Speed Response of DC series motor with sudden decrease in Speed

Table 4 : Numerical result of experiment on DC series motor with sudden increase in speed

Controller	ITAE	IAE
Type 1 FLC	0.282	0.30
Type 2 FLC	**0.22**	**0.28**

Table 5 : Numerical result of experiment on DC series motor with sudden decrease in speed

Controller	ITAE	IAE
Type 1 FLC	0.241	0.276
Type 2 FLC	**0.223**	**0.27**

5.2.2 DC shunt motor

In this section, DC shunt motor is used in simulation. Figure 14 shows the simulink model of DC shunt motor .The machine parameters are given in appendix A. Figure 15 compares the simulation results of the two controllers when the external load disturbance is zero. The performance of the two controllers is listed in table 6. Observe that type-1 FLC has a noticeable overshoot and a slower convergence to the set point in comparison to IT2 FLC .Clearly, the IT2 FLC has less overshoot. It is easy to see that IT2 FLC has a faster settling time than type-1 FLC. At the time t=6 secs, the external load torque is decreased by a step of 40 %(Figure 16).The system again reaches the steady state after transient period. Table 7 shows the values of peak overshoot, settling time, IAE and ITAE computed under this condition. The illustrated figures verify that a significant improvement has been achieved using the proposed type-2 fuzzy controller.

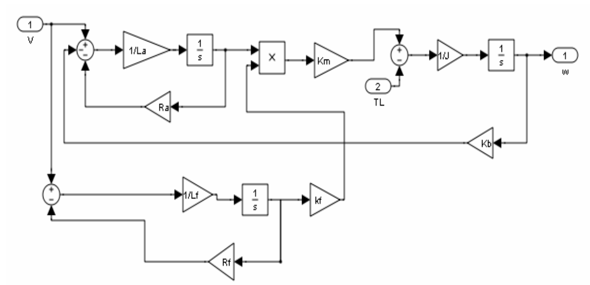

Figure 14. Simulink model of DC Shunt Motor

Initially the motor is operated at the steady state. At the time t=6 secs , an increased step of 20 % of initial set point ω_r occurs and then a decreased step of 20 % of initial set point. As shown in Figure 17 and Figure 18, the rotor speed tracks the new set point after a transient period. Obviously, the external load torque is assumed constant. Table 8 and table 9 shows the values of IATE and IAE under these conditions. Comparisons with the conventional fuzzy controller indicate the improvement achieved.

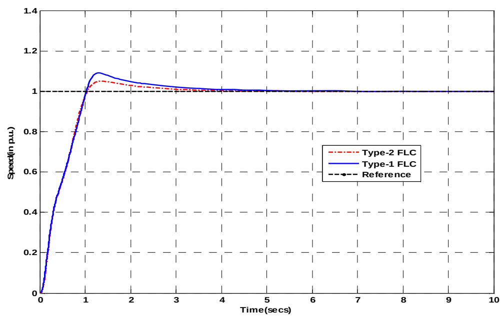

Figure 15. Speed Response of DC shunt motor without load disturbance

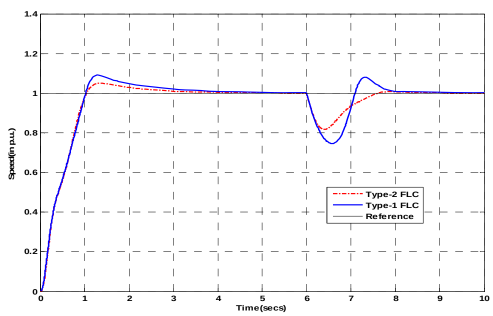

Figure 16. Speed Response of DC shunt motor with load disturbance

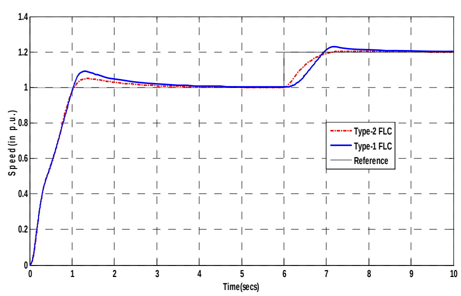

Figure 17 Speed Response of DC shunt motor with sudden increase in Speed

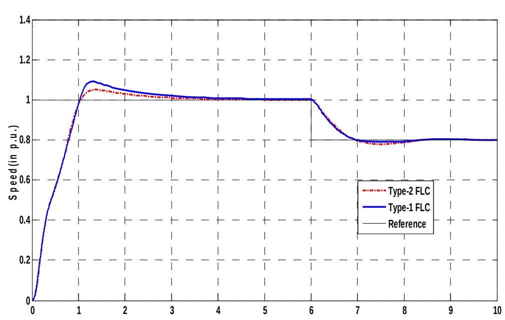

Figure 18 Speed Response of DC shunt motor with sudden decrease in Speed

Table 6 : Numerical result of experiment on DC shunt motor without load disturbance

Controller	%Mp	ts (secs)	ITAE	IAE
Type 1 FLC	9	5	0.4316	0.5883
Type 2 FLC	**5**	**2.3**	**0.2868**	**0.5298**

Table 7: Numerical result of experiment on DC shunt motor with load disturbance

Controller	%Mp	ts (secs)	ITAE	IAE
Type 1 FLC	25.4	7.7	1.90	0.816
Type 2 FLC	**18.3**	**7.4**	**1.28**	**0.679**

Table 8: Numerical result of experiment on DC shunt motor with sudden increase in Speed

Controller	ITAE	IAE
Type 1 FLC	1.411	0.735
Type 2 FLC	**0.878**	**0.622**

Table 9: Numerical result of experiment on DC shunt motor with sudden decrease in Speed

Controller	ITAE	IAE
Type 1 FLC	1.021	0.679
Type 2 FLC	**0.998**	**0.637**

Appendix A:

Dc Series Motor parameters:

L_F =44mH , R_F=0.2 ohms, V =125V, L_a =18mH , R_a =0.24 ohms, J = 0.5kgm^2

K_b=0.55 , Kt=3

Dc Shunt Motor parameters:

La=18 mH , Ra=0.24 ohm , Kt=Km=1000 , J=0.5 kgm^2 ,K_b =0.7 , Lf=10H

R_f=120 ohms , K_f=K_{b1}=0.05

VI. CONCLUSION

In this study, a novel interval type-2 fuzzy controller has been proposed for speed control of DC motors (series as well as shunt). Performance of the proposed IT2FLC was also compared with corresponding conventional FLC's with respect to several indices such as peak overshoot *(%OS)*, settling time, rise time, Integral of absolute error (IAE) and integral-of-time-multiplied absolute error (ITAE) and from the simulation, it shows that the proposed controller can track the reference speed satisfactorily even under load torque disturbances. It can be concluded that proposed control scheme can be successfully applied to the problem of designing a robust control for the non-linear model of DC motor system.

REFERENCES

[1] P. K. Nandam, and P. C. Sen, “A comparative study of proportional-integral (P-I) and integral-proportional (I-P) controllers for dc motor drives,” Int. Jour. of Control, vol. 44, pp. 283-297, 1986.

[2] Liu,Z.Z.,Luo,F.L.,Rashid,M.H., “Non-linear speed controllers for series DC Motor”, *Proceedings of IEEE Int. Conf. on Power Electronics and Drive systems,*vol 1 , pp. 333-338,1999.

[3] S.Saneifard, N.R.Prasad, H.A.Smolleck and J.J.Wakileh, “Fuzzy logic speed control of DC shunt Motor,” in *IEEE Transactions on Education*, Issue 2. vol. 41, pp. 159–164,1998.

[4] Aydemir,S;Sezen,S,Ertunc,H.M, “Fuzzy logic speed control of a DC Motor”, *Proceedings of Int. Conf. on Power Electronics and Motor Control,* vol 2, pp. 190–194,2004.

[5] Hong fu Zhou, “DC Servo system design based on fuzzy control with DSP” *Proceedings of IEEE Int. Conf. on Networking, Sensing and Control,* pp. 190–194,2008.

[6] Muruganandam,M;Madheswaran,M, “Modeling and Simulation of Modified fuzzy Logic Controller for various types of DC Motor Drives” *Proceedings of Int. Conf. on Control, Automation, Communication and Energy Conservation,*pp. 1-6,2009.

[7] S. Yuvarajan, Abdollah Khoei and Kh. Hadidi, “Fuzzy logic DC motor controller with improved performance”, IEEE Transactions on Power Electronics, vol. 11(3), pp 1652-1656,1998.

[8] J. C.Bezdek,’ A convergence theorem for the fuzzy ISODATA clustering algorithms, ‘*IEEE Transaction on Pattern Analysis and Machine Intelligence* (2), pp.1-8,1980.

[9] J.M.Mendel ,”Rule-Based Fuzzy Logic Systems: Introduction and new Directions”, Prentice-Hall, New jersey,2001.

[10] N.N.Karnik,Jerry M.Mendel and Q.Liang, “Type-2 Fuzzy Logic Systems”, *IEEE Transactions on Fuzzy Systems*,Vol.7,pp.643-658,1999.

[11] Castro, J.R., Castillo, O., Melin, P.: An Interval Type-2 Fuzzy Logic Toolbox for Control Applications. In *FUZZ-IEEE*(2007) 1-6.