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EFFICIENT SPEED CONTROL OF THYRISTOR FED DC MOTOR DRIVE USING INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER

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Abstract

The speed variation in DC motor drive is still a challenging issue, and hence various control strategies have been developed for the DC motor speed control. One of the important techniques is the utilization of Thyristor fed DC motor drive (TFDCMD). Although, the TFDCMD provides stable speed characteristics, but the practical applications demand more precise speed control. Hence, this drive also utilizes additional controllers such as PI, PID and fuzzy controller to achieve precise speed for practical applications. This paper presents a novel Interval Type-2 Fuzzy Logic Controller (IT2FLC) for the efficient speed control of the TFDCMD. The speed control performance of the proposed IT2FLC has been carried out on the MATLAB/Simulink platform and compared with the state-of-the-art controllers. The obtained simulation results clearly validates that the proposed IT2FLC controller outperforms and provide better speed control efficiency for the DC motor as compared to the popular controllers.

1. Introduction

DC motor is basically an electric machine that performs conversion of direct current in the mechanical rotation. It is very popular in the industrial applications due to its low cost, simple control structure and broad variety of speed and torque characteristics [1]. There are numerous techniques available in the literature for the speed control of DC drives such as armature voltage based control, field based control, and armature resistance based control techniques [2]-[3].

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Usually, the armature voltage based control technique is extensively utilized to control the speed variations in the DC drives. In this technique, a controlled rectifier or chopper is employed. However, due to the involvement of power electronics elements, this technique shows a nonlinear speed torque characteristics, which is undesirable for the control performance [4]. Currently, advanced speed control techniques for the DC motor drives are available which comprise Thyristor fed DC drive along with the feedback control design. In such speed control schemes additional controllers are used in the feedback loop in order to improve the speed control ability of the Thyristor fed DC motor drives.

The most cost effective controllers are the conventional controllers such as Proportional (P), Integral (I), and Derivative (D) or well-known combinations PI, PD, and PID controller. The PID is a popular controller and hence a commonly used technique for so many non-linear control system applications [5]. However, the PID controller still has some problems such as the unwanted overshoot, slow speed of operation due to the abrupt change in the load torque, and high sensitivity to the gains of the controller K_P, K_I and K_D parameters. The recent techniques for speed control of DC motor employed Fuzzy Logic Controller (FLC) [7]-[8], which provides better speed control performance than the previous controllers. However, the control ability of the FLC controller also sticks between the choices for the number of membership functions (MFs). Less number of MFs provides poor control, whereas higher number of MFs leads to good control performance but comes with a higher computational burden. Therefore, this paper presents a novel Interval Type-2 Fuzzy Logic Controller (IT2FLC) to provide better speed control efficiency for the DC motor drive with less complexity as compared to the existing PI, PID and Type-1 fuzzy controllers. The rest of the paper is structured as follows. Section 2, presents brief description of the modeling of thyristor fed separately excited DC motor drive. Section 3, presents the basic mathematical formulation of interval type-2 fuzzy logic. Next, Section 4 presents speed control simulation study of thyristor fed separately excited DC motor drive along with the development details of the proposed Interval Type-2 Fuzzy Logic Controller (IT2FLC). Finally, the simulation results and discussions are presented in Section 5, which is followed by conclusions of the present work in Section 6.

2. Modeling of Thyristor Fed Separately Excited DC Motor Drive

In order to properly analyze the torque and speed characteristics of the separately excited DC motor, its dynamic and steady-state mathematical modeling is the most essential part. Initially at the broad sense, the mathematical model of a separately excited DC motor can be simply configured in the form of armature and field circuit as shown in Fig. 1, in which e_a is the applied terminal voltage. R_a, L_a, R_f and L_f are the resistance and inductance of the armature circuit and field circuit respectively, e_b is the generated back electromotive force (emf) and T_m is the electromagnetic torque [9].

As depicted in Figure 1, the torque in the separately excited DC motor is produced as a result of interaction between field flux and current in armature conductors, hence the resultant torque can be given by [9],

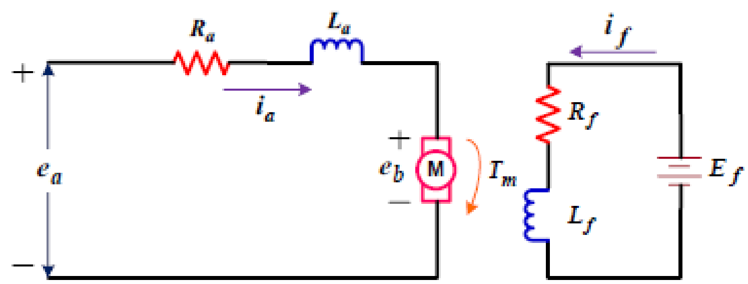

Figure 1. Equivalent circuit of a separately excited DC motor.

$$T_m = K_t \phi i_a \tag{1}$$

Where, K_t is a constant term that depends on the motor geometry and windings, $\emptyset$ is the flux per pole induced by the field winding. The final equation of the speed of DC is then given by,

$$\omega = \frac{E_a}{K_t \phi} - \frac{T_m}{(K_t \phi)^2} R_a \tag{2}$$

Equation (2) clearly reveals that, the speed of a separately excited DC motor can be effectively controlled by varying one of the three motor parameters namely E_a, R_a, and ϕ Consequently, there are three techniques for the speed control of DC motor namely: (i) Armature voltage control (E_a) (ii) Armature resistance control (R_a) and (iii) Flux control (ϕ) Speed control of DC motor using armature resistance technique employs addition of an external resistor and hence it is not popular because of the large energy losses due to external resistance. The next Armature voltage control technique is quite popular and generally utilized for required speed of motor up to the rated or base speed. Flux control technique is normally used for the requirements of speed beyond the rated motor speed but utilization of this method leads to the drawback of reduction in maximum torque capability of the motor [4].

Hence, this paper mainly focuses on the armature voltage control method for DC motor speed control. In this technique, the input voltage e_a, which is applied across the armature is varied while keeping the field voltage constant. One of the simplest configuration of armature voltage control technique is the utilization of controlled rectifiers widely known as Thyristor fed DC motor drive, which has four main configurations viz. (i) Single phase half wave converter drive, (ii) Single phase semi converter drive, (iii) Single phase full converter drive, and (iv) Single phase dual converter drive. Among the four thyristor fed DC motor drives, the most significant and widely used configuration is the single phase full converter drive. However, in the practical applications, the thyristor fed drives also shows nonlinear speed torque characteristics due to the involvement of thyristors, which is undesirable for the practical control applications [4]. To compensate this limitation advanced speed control techniques for DC motor drives are available in the literature which comprises thyristor fed DC drive along with the feedback control loop. A simple illustration of advanced thyristor fed DC drive with additional PI controller is shown in Figure 2.

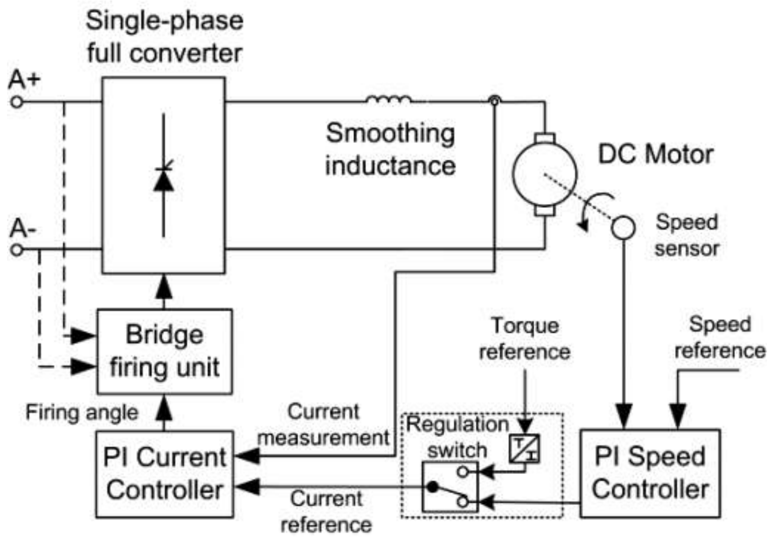

Figure 2. Thyristor fed DC motor drive with additional PI controllers.

In Figure 2, two additional PI controllers for the separate speed and current control are placed in the feedback loop in order to improve the speed control ability of the thyristor fed DC motor drives.

3. Interval Type-2 Fuzzy Logic

Type-2 Fuzzy Logic (T2FL) is simply an extension of Type-1 fuzzy logic (T1FL) [10]. Consequently, the structures of both controllers are very much similar. The first major difference in the structure of these two controllers is defuzzification stage. Another important difference between T2FL and T1FL lies in the Membership functions (MFs). In a T2FL the MFs contain footprint of uncertainty (FOU), which basically represents the blurring effect of a type-1 MF, and is entirely expressed by its two bounding functions (Figure 3 (a) and (b)), a lower MF (LMF) and an upper MF (UMF), both of which are simply type-1 fuzzy sets. Another important aspect that separate T2FLC from the T1FLC is the type reduction process [11-15]. A Type-1 fuzzy set can be simply defined as in (3).

$$A = (x, \mu_A(x)) \text{ for all }) \; x \in X \tag{3}$$

Where, $\mu_A(x)$ represents the membership level of variable x related to type-1 fuzzy set A is between 0 and 1.

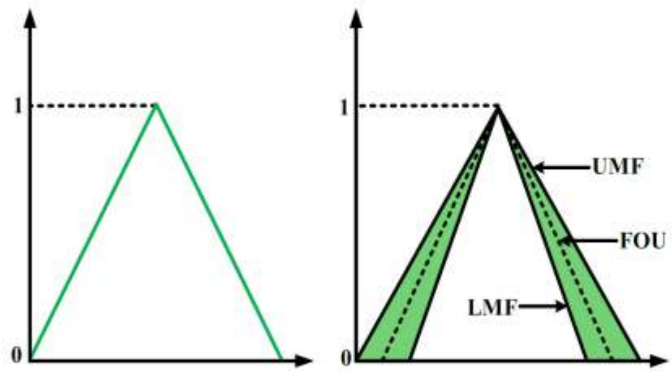

Figure 3. Triangular membership functions (a) T1FLC (b) T2FLC.

The T2FL fuzzy set $\widetilde{A}$ whose MF is shown in Figure 3(b) can be expressed by the following equations.

$$\widetilde{A} = (x, u, \mu_A(x, u)), \forall x \in X, \forall u \in J_x^u \subset [0, 1] \quad (4)$$

$$\widetilde{A} = \int_{x \in X} \int_{u \in J_x} \mu_{\widetilde{A}}(x, u)/(x, u), J_x^u \subseteq [0, 1]$$

Here, X is the domain of input variable, x is the value of the input variable, u is the primary grade of a type-2 fuzzy set and J_x is the primary membership of a type-2 fuzzy set, $\mu_{\widetilde{A}}(x, u) = 1,$ is the secondary membership function [15].

$$\widetilde{A} = \int_{x \in X} \int_{u \in J_x} 1/\mu_{\widetilde{A}}(x, u), J_x^u \subseteq [0, 1] \quad (6)$$

Where, $J_x^u \subseteq [0, 1]$ and ∬ indicates the union over all admissible x and u. When all the $\mu_{\widetilde{A}}(x, u) = 1,$ then T2FL set $\widetilde{A}$ becomes an Interval Type-2 Fuzzy Logic Set (IT2FLS).

After the defuzzification process, the combination of all the secondary sets can be expressed as follows:

$$\widetilde{A} \int_{x \in X} \left[\int_{u \in J} f_x / u \right] / J_x^u \subseteq [0, 1] \quad (7)$$

The defuzzified type-1 MF do not comprise a uniform geometric shape. Hence, in T2FL a narrow area with uniform geometrical shape known as FOU is created to better express the MFs. The equation for FOU can be given by,

$$FOU(\widetilde{A}) = \bigcup_{x \in X} J_x \tag{8}$$

The basic structure of the IT2FL inference system is similar to that of the T1FL. Figure 4 shows the structure of IT2FL inference system. The most important difference is the type reducer available in IT2FL structure [15].

4. Speed Control Simulation of Thyristor fed Separately Excited DC Motor Drive

This section first presents the simulation of thyristor fed separately excited DC motor drive in single phase full converter configuration with important controllers namely PI, PID and Type-1 Fuzzy Logic Controller (T1FLC). The next part of this section presents the development of the proposed IT2FLC controller for the efficient speed control of thyristor fed separately excited DC motor drive.

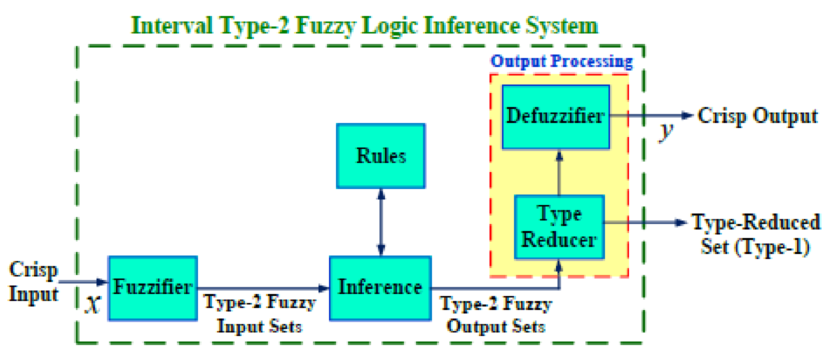

Figure 4. Interval Type-2 Fuzzy Logic Inference System.

Now, starting from the simulation modeling part, a simulation model for the thyristor fed separately excited DC motor drive in the single phase full converter configuration has been developed with two PI controllers in the feedback loop based on the model shown in Figure 2 in MATLAB Simulink software platform version 2020 (a), which is shown in Figure 5. The developed simulation model is a two-quadrant single-phase convertor/rectifier drive for a 5 HP DC motor, where the motor is excited separately by a constant 150 V DC voltage source for field windings. The armature voltage is supplied by a single-phase rectifier which is controlled by two separate PI controllers. The thyristor based rectifier is connected to a 220 V AC 50 Hz voltage supply via a linear transformer for the voltage boosts up to a sufficient value. Other parameters related to the simulation model shown in Fig. 5 are given in Appendix 1.

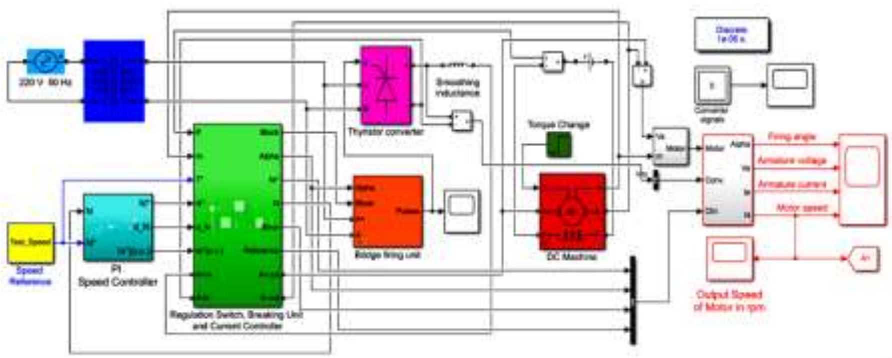

Figure 5. Simulation model of thyristor fed separately excited DC motor drive with PI controller.

In the developed simulation model shown in Figure 5, the simulated control structure for the PI speed controller is shown in Figure 6, in which the reference speed N^* and the actual speed of the motor N are used as input to the controller, that provides controlled value of the armature current to be fed to the motor. The value of PI controller gain parameters K_P and K_I are given in Table 1.

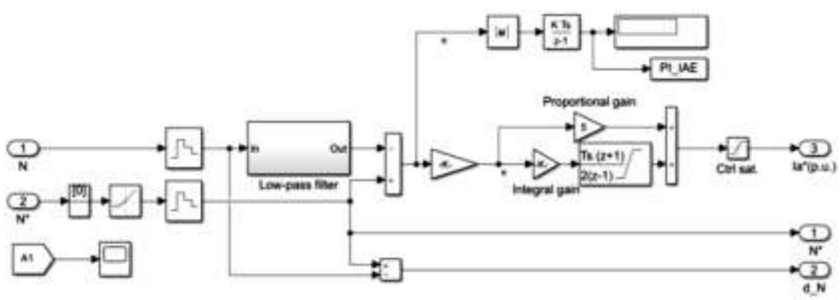

Figure 6. Simulated PI speed controller structure.

The same model of thyristor fed separately excited DC motor drive is also implemented with the PID controller, whose gain parameters K_P, K_I and K_D are also given in Table 1. Next, in order to analyze the DC motor speed control performance of the Type-1 Fuzzy Logic Controller (T1FLC) a type-1 Fuzzy inference System (FIS) named as "VST_Third_Type1.fis" is developed and used in place of PI speed controller in the simulation model shown in Figure 5. In the control structure of developed T1FLC speed controller as shown in Figure 7, the error signal (Error) between reference speed N^* and the actual speed of the motor N and the derivative of error signal ChangeError (ChangeError) are used as the inputs to the T1FLC speed controller, that generates controlled value of the armature current to be fed to the motor.

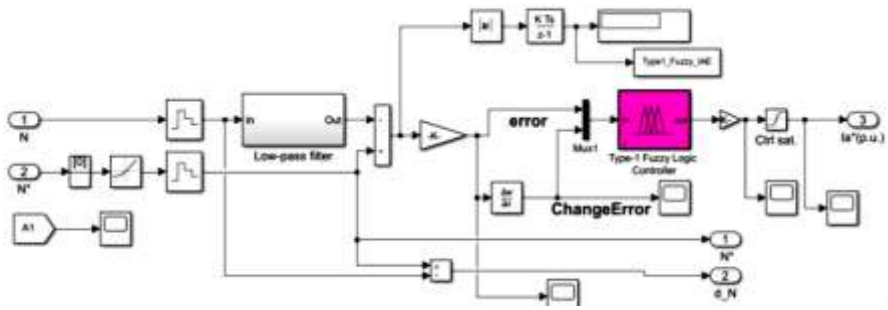

Figure 7. Simulated T1FLC speed controller structure.

Table 1. PI and PID Controllers Parameter Values.

Controller	K_P	K_I	K_p
PI	5	160	NA
PID	10	160	0.1

The detailed plots of all the membership functions used in the input and output variables of the developed T1FLC "VST_Third_Type1.fis" are shown from Figure 8 and Figure 9.

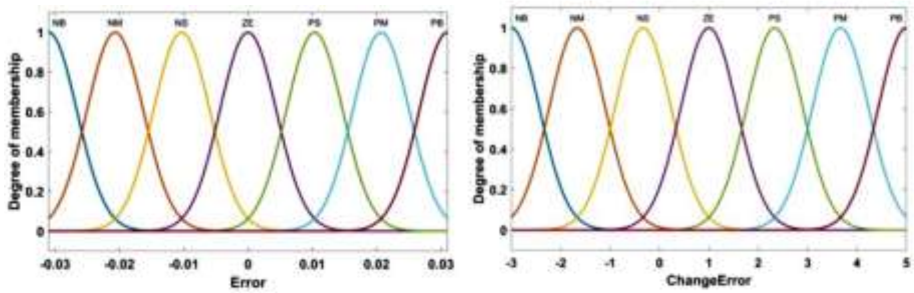

Figure 8. Membership function plots of the input variables of developed T1FLC speed controller ("VST_Third_Type1.fis"): (a) "Error" and (b) "ChangeError".

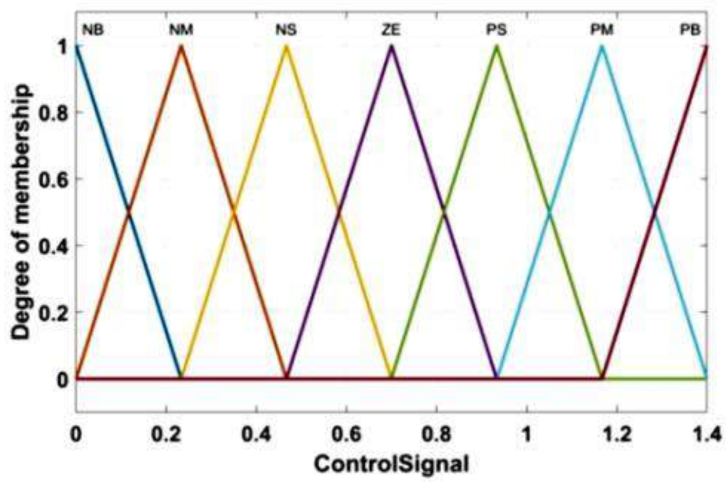

Figure 9. Membership function plots of the output variable "ControlSignal" of T1FLC speed controller (VST_Third_Type1.fis).

During the rule base and membership function designing of the proposed IT2FLC speed controller ("VST_First_Type2.fis"), the short forms of Linguistic variables used are same as that of the used in the designing of T1FLC speed controller. Further, the rule base designed for the proposed IT2FLC speed controller ("VST_First_Type2.fis") module is given in Table 3.

Table 2. Rule Base of Proposed T1FLC Controller.

ChangeError → / ↓ Error	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

4.1. Development of the proposed of the proposed Interval Type-2 Fuzzy Logic Controller (IT2FLC) for the efficient speed control of thyristor fed separately excited DC motor drive.

This subsection presents the detailed description of the development process and the structure of the proposed Interval Type-2 Fuzzy Logic Controller (IT2FLC) for the efficient speed control of thyristor fed separately excited DC motor drive. Similar to the design structure of T1FLC, the proposed IT2FLC speed controller comprises two inputs namely “Error” and “ControlSignal” and one output named as “ControlSignal”. The first input “Error” is the difference between reference speed N^* and the actual speed of the motor N and the derivative of “Error” signal is the second input “ChangeError” of the proposed IT2FLC speed controller. The output variable of the proposed IT2FLC speed controller named as “ControlSignal” is the controlled value of the armature current to be fed to the motor. Each of the inputs “Error” and “ChangeError” and the output variable “ControlSignal” of the proposed IT2FLC speed controller consist only five membership functions (MFs) for the fuzzification and output generation process respectively. Hence, the rule base of the proposed IT2FLC speed controller contains only 25 rules, whereas, the T1FLC speed controller contains 49 rules. Therefore, the proposed IT2FLC speed controller offers about 49% less complexity as compare to the T1FLC speed controller. The detailed description about the Structure of the Proposed IT2FLC speed controller is shown in Figure 10.

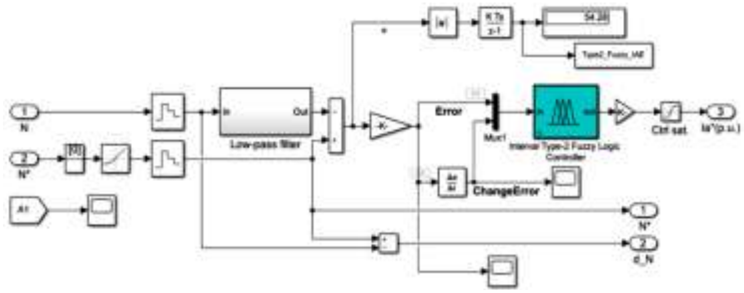

Figure 10. Structure of the Proposed IT2FLC speed controller.

The plots of all the membership functions used in the input and output variables for the "VST_First_Type2.fis" are shown from Figure 11 to Figure 12.

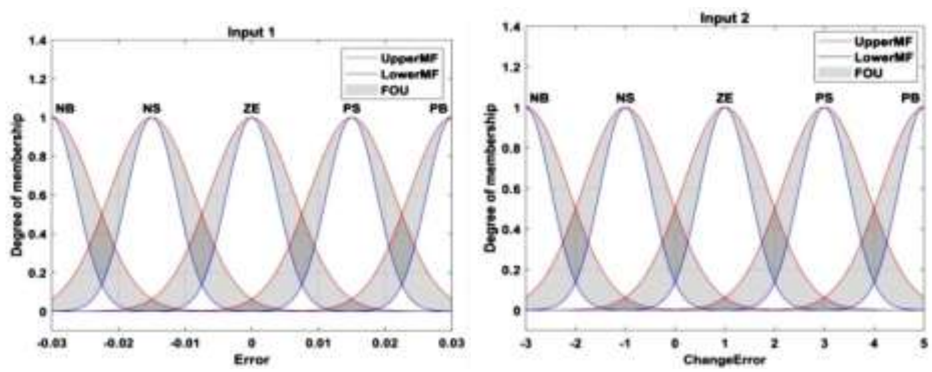

Figure 11. Membership function plots of the input variables of proposed IT2FLC speed controller ("VST_First_Type2.fis"): (a) "Error" and (b) "ChangeError".

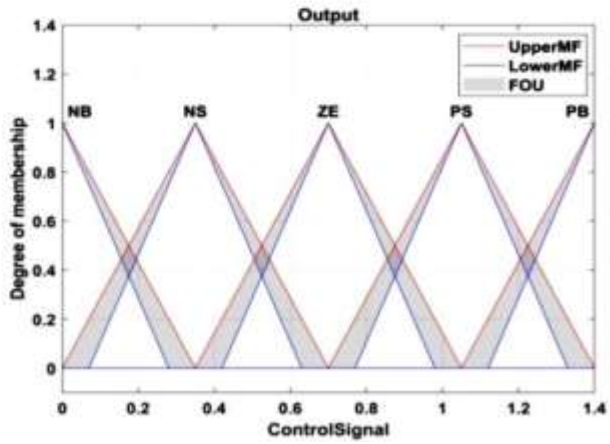

Figure 12. Membership function plots of the output variable "ControlSignal" of the proposed IT2FLC speed controller ("VST_First_Type2.fis").

During the rule base and membership function designing of the proposed IT2FLC speed controller ("VST_First_Type2.fis"), the short forms of Linguistic variables used are same as that of the used in the designing of T1FLC speed controller. Further, the rule base designed for the proposed IT2FLC speed controller ("VST_First_Type2.fis") module is given in Table 3.

Table 3. Rule Base of Proposed IT2FLC Controller.

ChangeError → / ↓ Error	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

Finally, the simulation model of thyristor fed separately excited DC motor drive with the proposed Interval Type-2 Fuzzy Logic Controller (IT2FLC) has been developed by replacing the PI speed controller in the simulation model shown in Figure 5 by the proposed IT2FLC controller.

5. Results and Discussions

This section presents extensive speed control performance evaluation and comparison of the proposed interval type-2 fuzzy logic controller (IT2FLC) for the thyristor fed DC motor drive against the popular and state-of-the-art controllers such as PI, PID and type-1 fuzzy logic controller (T1FLC). In order to obtain the practical speed control performance of all the controllers, their respective simulation models have been run for a time span of 00 sec to 06 sec for the three different reference speeds of 1000 rpm, 1200 rpm, and 1400 rpm with a constant reference torque value of 10 Nm. Meanwhile, to get the clear parametric analysis for the speed control characteristics of the tested controllers, a detailed step response study has been performed to analyze the key factors such as undershoot, overshoot and settling time of the resultant speeds. In addition to this, in order to reach to a strong conclusive remark about the speed control efficiency of the tested controllers, a well established and important parameter known as Integral of Absolute Error (IAE) is also calculated in this work. After the complete simulation of all the models, the resultant speed control performances for the PI, PID, type-1 fuzzy logic controller (T1FLC) and the proposed interval type-2 fuzzy logic controller (IT2FLC) at the reference speeds of 1000 rpm, 1200 rpm, and 1400 rpm are shown from Figure 13 to Figure 15 respectively.

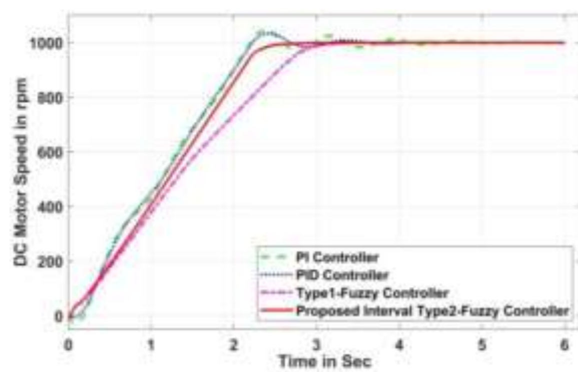

Figure 13. Speed control response of PI, PID, T1FLC and proposed IT2FLC controller at reference 1000 rpm speed.

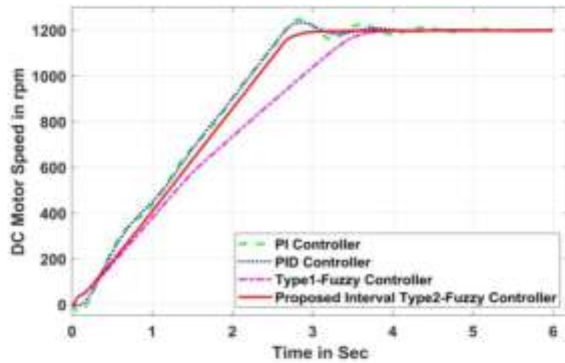

Figure 14. Speed control response of PI, PID, T1FLC and proposed IT2FLC controller at 1200 rpm reference speed.

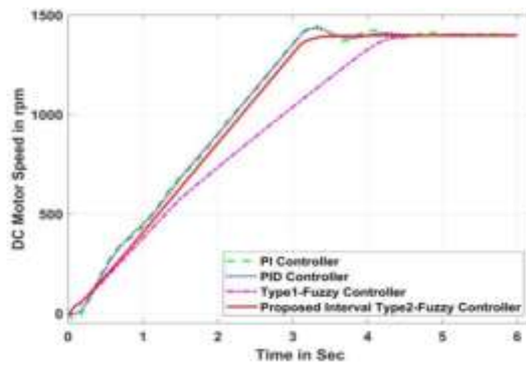

Figure 15. Speed control response of PI, PID, T1FLC and proposed IT2FLC controller at 1400 rpm reference speed.

From the speed control responses of the test controllers as shown from Figure 13 to Figure 15, it is clearly evident that the proposed IT2FLC controller delivers significantly better speed control for the thyristor fed DC motor drive for all the test speeds of 1000 rpm, 1200 rpm, and 1400 rpm as compared to the PI, PID and T1FLC controllers. It also visible from the above speed response curves that the proposed IT2FLC controller offers fast settling to the target speed with very less deviation between target and actual speed in the steady state part. The comparative transient and steady state analysis parameters: settling time, overshoot and undershoot that are calculated from the resultant speed response covers are given in Table 4. The resultant value of Integral of Absolute Error (IAE), which is an important error indicator in the settling state are tabulated in Table 5.

Table 4. Comparison of resultant settling time, overshoot and undershoot parameters.

S. No.	Parameter	Test Speed	PI Controller	PID Controller	Type-1 Fuzzy Logic Controller (T1FLC)	Proposed Interval Type-2 Fuzzy Logic Controller (IT2FLC)
1	Settling Time	1000	4.21	3.58	3.084	2.48
2	1200	4.61	4.01	3.67	2.89	2.89
3	1400	5.01	4.52	4.42	3.42	3.42
4	Overshoot (in %)	1000	4.6315	3.4372	0.0175	0.0158
5	1200	3.8632	2.8388	0.0129	0.0127	0.0127
6	1400	3.428	2.4086	0.0079	0.0075	0.0075
7	Undershoot (in %)	1000	2.6756	0.5104	0.4985	0.4983
8	1200	2.2258	0.4253	0.4158	0.4155	0.4155
9	1400	1.9156	0.3645	0.3566	0.3561	0.3561

From Table 4, it is clearly evident that the proposed IT2FLC controller requires lowest settling time to reach the final reference or test speed and also offers very less percentage of overshoot and undershoots in the transient state as compared to the popular PI, PID and T1FLC controllers.

Table 5. Comparison of Resultant Integral of Absolute Error (IAE) parameter.

S. No.	Parameter	Test Speed	PI Controller	PID Controller	Type-1 Fuzzy Logic Controller (T1FLC)	Proposed Interval Type-2 Fuzzy Logic Controller (IT2FLC)
1	IAE	1000	78.4492	49.9373	37.7425	24.4237
2	1200	80.3044	49.6432	59.6534	30.411	30.411
3	1400	76.4966	49.7841	88.2768	36.2864	36.2864

From Table 5, we can see that the value of IAE parameter is lowest for the proposed IT2FLC controller as compared to the PI, PID and T1FLC controllers for all the test speed conditions. Therefore, the proposed IT2FLC controller delivers highest efficiency in the speed control of motor via keeping the error between target and actual speed in the steady state part.

6. Conclusions

In this paper, a novel interval type-2 fuzzy logic controller (IT2FLC) has been proposed and successfully developed for the efficient speed control of thyristor fed separately excited DC motor drive. The speed control performance of the proposed IT2FLC controller has been carried out on the MATLAB/Simulink platform version 2020 (a), and extensively compared with the state-of-the-art controllers over the different test speeds. The obtained simulation results clearly validates that the proposed IT2FLC controller outperforms and provide better speed control efficiency for the thyristor fed separately excited DC motor drive as compared to the popular controllers PI, PID and type-1 fuzzy controller (T1FLC). It is also validated that the proposed interval type-2 fuzzy logic controller (IT2FLC) offers about 49 % less complexity as compared to the recent type-1 fuzzy controllers (T1FLC).

Appendix 1. DC Motor Simulation Parameters.

Armature Resistance (R_a)	0.78 Ω
Armature Inductance (L_a)	0.016 H
Field Resistance (R_f)	150
Field Inductance (L_f)	112.5 H
Field-armature mutual inductance (L_{af})	1.234 H
Total inertia (J)	0.25 Kg.m^2

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