

Speed Control of DC Motor Using Interval Type-2 Fuzzy Logic Controller

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Abstract: Direct current (DC) motors are considerably utilized in many implementations requiring speed and position controls. The simplicity of DC motor speed control is also the main reason for its widespread use. Recently, with rapid developments in power electronics, microprocessors and semiconductor materials, many control structures are designed for DC motors. In this study, the speed control of the DC motor is carried out using Matlab/Simulink package program. Type-2 Fuzzy Logic controller (T2FLC) that has efficient performance in modelling uncertainties is proposed for DC motor speed control. The classical Proportional+Integral (PI) controller and T2FLC are connected to the speed control unit of DC motor. Simulation studies have also been realized under several operating conditions such as tracking reference speeds and load changes. According to the obtained simulation results, it has been observed that T2FLC has better results than the classical PI controller in operating conditions.

Keywords: DC Motors, PI Controller, Robust Control, Type-2 Fuzzy Logic Controller

1. Introduction

Direct current (DC) motors are known as electric machines that convert direct current energy into mechanical energy. The speeds of DC motor with superior control such as easy controllability and high performance can be set within wide limits. The main reason why DC motors find wide application area is that it is easy to control according to alternating current (AC) motors. Compared to AC motor drives, DC motor drive circuits are both simple and inexpensive. The simple implementation of the drive design has brought the DC motor drivers to the fore in adjustable speed applications. Since the speed characteristics of the DC motors are very good, they are frequently used in industrial applications where speed and position control is required, such as electric trains, winding machines, winches and robot arms. DC engines have certain disadvantages, such as maintenance requirements with certain periods due to the brush-commutator contact and inability to use in all environments [1-4].

With advances in motor technology and power electronics, the torque produced for per volume in motor has increased and the brush-commutator maintenance problems have been minimized with the advance of permanent magnet technology. Thus, the application areas of the direct current motors have expanded even further. In addition to the driver circuit used in the control of speed and position of DC motors, the importance of the controller is quite high. Since DC motor speed changes depending on the load, closed loop control is preferred in the speed control of the DC motors instead of open loop control in constant speed applications [5-7].

It is necessary to feedback the motor speed in a closed loop speed control. The speed information measured from the motor is applied to a controller and the voltage required for the motor is calculated. This voltage is then applied to the motor with the help of the driver circuit.

The conventional controllers (PI and PID) are used because of the simplicity of the position and speed controls of DC motors. It is

important for the system to determine the proportional (P), integral (I) and derivative (D) parameters of PID controllers. The Ziegler-Nichols method [8], which is a classical method, is frequently used to determine these gain parameters. However, there are some problems, such as determining the maximum gain value for the given control system or finding the oscillation period in this method.

Intelligent controllers are frequently used in many areas and provide very good results. These controllers have special calculation features for solving specific problems. The fuzzy logic controller (FLC) proposed by L. Zadeh in 1965 has been widely used in recent years [9]. Fuzzy logic is described as a set of rules, which can be used to describe the action of complex systems that cannot be defined mathematically. FLC is based on the transfer of verbal expressions mathematically into the computer environment with the experience of the expert. For these reasons, FLC has attracted great interest in numerous fields such as production technique, decision-making, nonlinear approach, data analysis, modern information technology, pattern recognition. Recently, one of the most remarkable research topics is the Type-2 Fuzzy Logic controller (T2FLC) structure. L. Zadeh first introduced this structure in 1975 [10]. In these years, researchers and scientists have not shown sufficient interest because of the difficulty of implementing this controller structure. Because T2FLCs have better modeling of uncertainties than type-1 FLCs (T1FLCs) and have better results in complex systems, many studies have been done on this topic. In addition, T2FLC ensures robust and adaptive structure for high performance control against system uncertainties and parameter changes [11-15].

Recently, many controller structures have been proposed for position and speed controls of DC motor. Ref [16] presents self-constructing wavelet neural network for controlling of DC motor. In Ref [17], fuzzy logic controller is used for control of DC motor speed. Simulation studies are realized in Matlab/Simulink environment. The proposed controller is also compared with PID controller at constant speed. Ref [18] proposes fuzzy-PID controller for brushless DC motors. Fuzzy-PID controller is

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compared with PID controller in terms of overshoot, undershoot, peak and settling times. Ref [19] presents the speed control system based on bacterial foraging algorithm for a DC motor. Simulation studies for proposed system have been realized in Matlab/Simulink. In Ref [20], Proportional-Derivative and Integral (PD-I) type fuzzy-neural network controllers are designed for brushless DC motor drives. Experimental studies have been carried out on the proposed controller structure. In addition, the behavior of controller structures are investigated against nonlinear loads and parameter variations of the motor. In this paper, it is aimed to realize the speed control of DC motor using T2FLC, which has a durable structure. A simulation model is designed to show the behavior of both controllers in Matlab/Simulink. DC motor speed is controlled using T2FLC and PI controller. In order to indicate dynamic performance of T2FLC, three operation conditions are considered. The results of T2FLC for these conditions are presented and compared with traditional PI controller. This paper is organized as follows: Section 2 presents the mathematical model of DC motor. In Section 3, the structure of T2FLC controller is given. Simulation results are given in Section 4. Section 5 contains conclusions.

2. Mathematical Model of DC Motor

It is known that DC motors are electrical machines that convert electrical energy into mechanical energy. According to Faraday's law, an electric motor can operate as both a motor and a generator when the necessary conditions are met [21-23]. DC motor can be modeled with the structure given in Fig. 1.

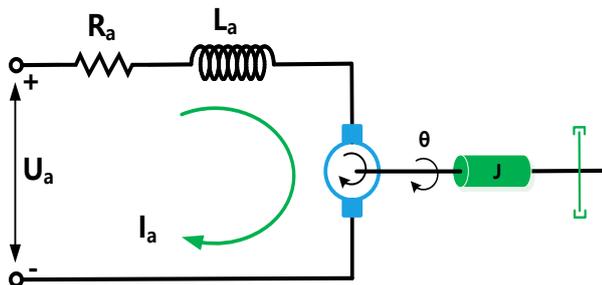


Fig. 1. DC motor equivalent circuit

As seen from the Fig.1, the armature circuit consists of the resistor (R_a), the inductor (L_a) and the back electromotive force (U_b). U_a is input voltage. As shown in Equation 1, the moment (T_m) is proportional to the armature current (I_a) and the torque constant (K_i).

$$T_m = K_m \phi I_a(t) \quad (1)$$

Where, ϕ is air-gap flux. The back electromotive force (U_b) is related to the angular velocity and is given in (2)-(3).

$$U_b = K_m \phi \omega_m \quad (2)$$

$$U_b = K_b \frac{d\theta_m(t)}{dt} = K_b \omega_m(t) \quad (3)$$

According to the DC motor equivalent circuit given in Fig. 1, the following equations can be explained as:

$$\frac{dI_a}{dt} = \frac{1}{L_a} U_a(t) - \frac{1}{L_a} U_b(t) - \frac{R_a}{L_a} I_a(t) \quad (4)$$

$$\frac{d^2\theta_m(t)}{dt^2} = \frac{1}{J_a} T_m(t) - \frac{B_m}{J_m} \frac{d\theta_m(t)}{dt} \quad (5)$$

Where, T_m and J_m are motor torque and inertia, respectively. The transfer function between the angular position of the motor and the input voltage can be represented by the following equation.

$$\frac{\theta_m(s)}{U_a(s)} = \frac{K_i}{L_a J_m s^3 + (R_a J_m + B_m L_a) s^2 + (K_i K_b + R_a B_m) s} \quad (6)$$

Where, K_i is torque constant, and B_m is viscous friction of coefficient. The DC motor model can be constructed as a state space model and can be expressed by the following equations.

$$\dot{x} = Ax + Bu \quad (7)$$

$$\dot{y} = Cx + Du \quad (8)$$

$$\begin{bmatrix} \dot{I}_a \\ \dot{\omega} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} & 0 \\ \frac{K_i}{J_m} & -\frac{B_m}{J_m} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_a \\ \omega_m \\ \theta_m \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \\ 0 \end{bmatrix} U_b \quad (9)$$

$$\omega_m = [0 \quad 1 \quad 0] \begin{bmatrix} I_a \\ \omega_m \\ \theta_m \end{bmatrix} \quad (10)$$

Where, ω_m is rotor angular velocity and θ_m is angular position of the rotor.

3. Structure of T2FLC

T2FLC can be considered as an extension of T1FLC. Therefore, the both controller structures are similar. The first significant difference between these controller structures is defuzzification stage. Membership functions are classified as type-1 and type-2, because defuzzification process is performed with membership functions and they differ structurally from each other. One of the most important features that separates T2FLC from T1FLC is the type reduction process [12-15, 24-25]. Type-1 and type-2 triangular membership functions are also shown in Fig. 2. Type-1 membership function can be expressed as follows:

$$B = (x, \mu_B(x)) / \forall x \in X \quad (11)$$

Where, $\mu_B(x)$ which represents the membership level of variable x related to B set is between 0 and 1. The uncertainty cannot be expressed because there is a membership level between 0 and 1 for each variable x . If the membership level of a variable is not fully known and can not be determined, the use of the type-2 membership function is required.

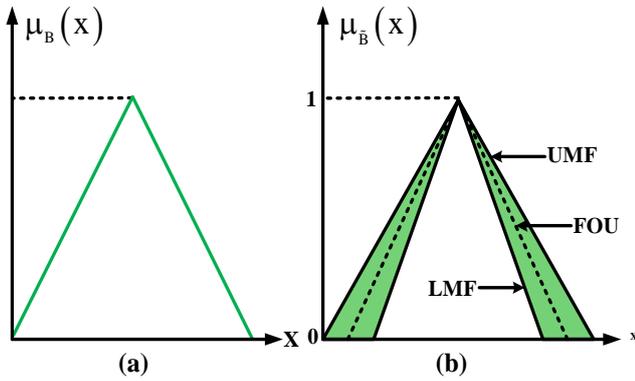


Fig. 2. Triangular membership functions a) T1FLC b) T2FLC

The type-2 fuzzy set given in Fig. 2(b) can be expressed by \tilde{B} and can be explained by the following equations.

$$\tilde{B} = \{ (x, u, (\mu_{\tilde{B}}(x, u))) / \forall x \in X, \forall u \in J_x^u \subseteq [0, 1] \} \quad (12)$$

$$\tilde{B} = \int_{x=X} \int_{u \in J_x} \mu_{\tilde{B}}(x, u) / (x, u) J_x \subseteq [0, 1] \quad (13)$$

Here, X is the domain of the 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, $\mu_{\tilde{B}}(x, u)$ is the secondary membership function [24-25].

$$\tilde{B} = \int_{x=X} \int_{u \in J_x} 1 / (\mu_{\tilde{B}}(x, u)) J_x \subseteq [0, 1] \quad (14)$$

Where, $J_x \subseteq [0, 1]$ and \int indicates the union over all admissible x and u . After defuzzification process, the combination of all secondary sets can be expressed as follows:

$$\tilde{B} = \int_{x \in X} \left[\int_{u \in J_x} f_x(u) / u \right] / x J_x \subseteq [0, 1] \quad (15)$$

The defuzzified type-1 membership functions do not have a uniform geometric shape. A limited area with a uniform geometrical shape named the footprint of uncertainty (FOU) is created in order to better express the membership functions. The following equation can be given for FOU.

$$FOU(\tilde{B}) = \bigcup_{x \in X} J_x \quad (16)$$

The structure of the T2FLC is similar to the T1FLC. The type reducer is the most important difference in T2FLC structure. Figure 3 shows the structure of T2FLC. The fuzzifier, the input unit of T2FLC, is a process of converting a corresponding linguistic variable depending on the appropriate membership function of any sharp value. The inference mechanism is a simulation of the human decision making process. Type-reduction can be expressed as the process of finding the center of gravity of the output membership functions created for the system to be controlled [24-25].

In this study, triangular membership functions are preferred and are given in Fig. 4. In addition, rules in Table 1 are established for T2FLC structure. Two inputs and one output are selected for designed T2FLC. The error of speed (e) and change in speed (Δe) are determined as:

$$e(k) = \omega^*(k) - \omega(k) \quad (17)$$

$$\Delta e = e(k) - e(k-1)$$

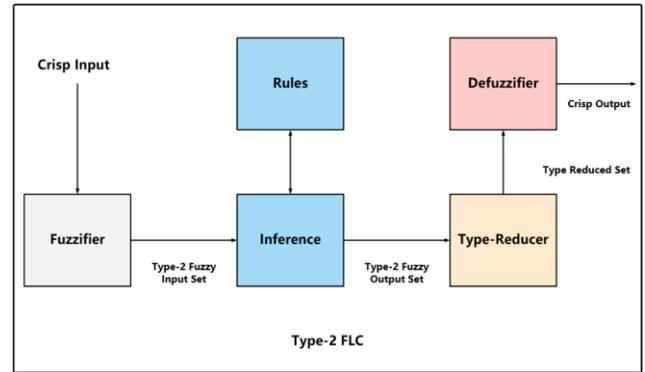


Fig. 3. Block diagram of T2FLC

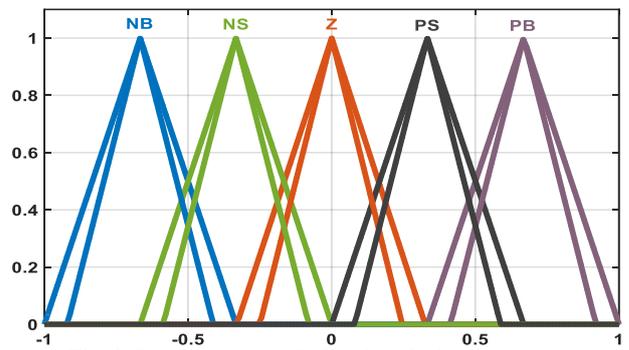


Fig. 4. Triangle membership functions for inputs and output

Table 1. Rule Table

| $e \backslash \Delta e$ | N_{Big} | N_{Small} | Z | P_{Small} | P_{Big} |
|-------------------------|-----------|-------------|-------------|-------------|-------------|
| N_{Big} | N_{Big} | N_{Big} | N_{Big} | N_S | Z |
| N_{Small} | N_{Big} | N_{Small} | N_{Small} | Z | P_{Small} |
| Z | N_{Big} | N_S | Z | P_{Small} | P_{Big} |
| P_{Small} | N_S | Z | P_{Small} | P_{Small} | P_{Big} |
| P_{Big} | Z | P_{Small} | P_{Big} | P_{Big} | P_{Big} |

In defuzzification process of T2FLC, the inputs and output variables are transformed into symbolic expressions. Linguistic variables of T2FLC are Negative Big (N_{Big}), Positive Big (P_{Big}), Zero (Z), Negative Small (N_{Small}), Positive Small (P_{Small}).

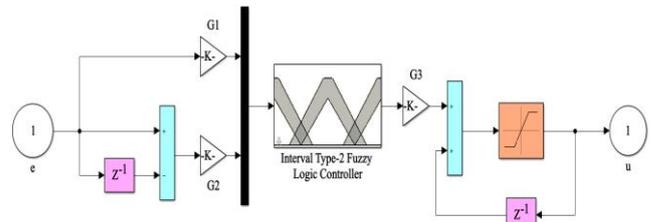


Fig. 5. Matlab/Simulink Model of T2FLC

Matlab/Simulink model of T2FLC used in speed control is shown in Fig. 5. An anti-windup integrator is connected to the output of the controller so that its tracking capability is provided. In addition, gains G_1 , G_2 and G_3 are connected to scale inputs and output.

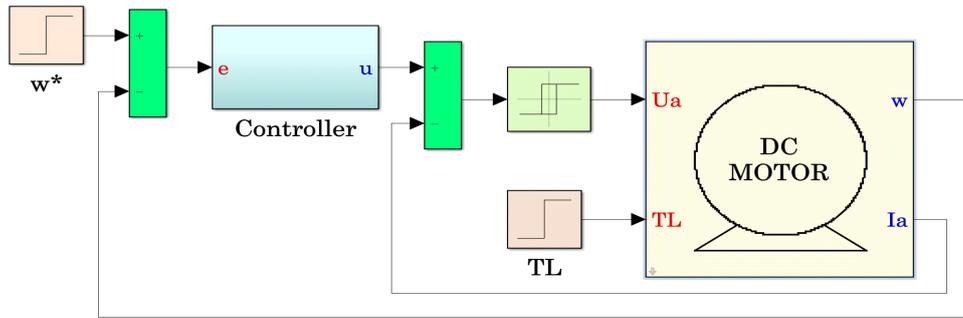


Fig. 6. Matlab/Simulink model of DC motor

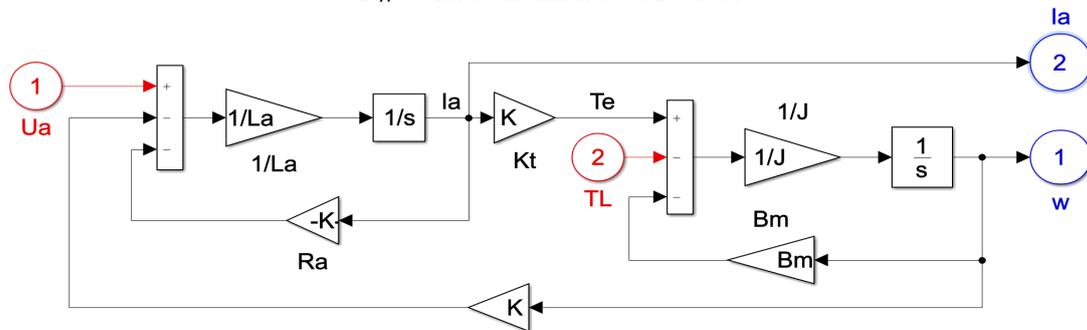


Fig. 7. Inner block of DC motor

4. Simulation Studies

A simulation model of DC motor is built by using Matlab/Simulink software. The simulation parameters of DC motor are summarized in Table 2.

Table 2. DC motor parameters used in simulation study

| Symbol | Value |
|---|-----------------|
| Armature resistance (R_a) | 2 Ω |
| Armature inductance (L_a) | 0.0054 |
| Moment of inertia (J_m) | 1.5e-4 Kg m^2 |
| Frictional torque coefficient (B_m) | 1e-3 Nms/rad |
| Electromechanical coupling coefficient | 0.1 N.m/A |

Matlab/Simulink model of DC motor is given in Fig. 6. In addition, the internal structure of the DC motor block is shown in Fig. 7. In this designed system, PI controller and T2FLC are applied to the speed control unit of DC motor under the same conditions. The control signals obtained from the output of the controllers are applied to the DC motor block. To evaluate dynamic performance of DC motor based on proposed controller, simulation studies have been performed under three operation conditions. These operation conditions are given as follows:

Case-1: In this case, reference speed is set to a constant value of 200 rad/s. In this way, transient and steady state performances of T2FLC based DC motor is assessed for this case.

Case-2: The reference speed of DC motor has been changed and the reference-tracking performances of the controllers have been investigated in this case.

Case-3: A step load is applied to the DC motor. The performances of controllers are investigated against disturbances in this case.

The performances of both controllers are evaluated in terms of overshoot and settling time. The simulation results obtained from case-1 are presented in Fig. 8. DC motor is started at $t=0$ s and reference speed of DC motor is adjusted to 200 rad/s. The speed responses of controllers are given in Figs. 8 (a) and (b). T2FLC follows quickly the reference speed value without overshoot whereas PI controller tracks the reference speed value with overshoot. The settling times of T2FNN and PI controller are 20 and 27 ms, respectively. Both controllers have not steady state error for this case. In addition, the performances of both controllers in this case are presented in the Table 3.

Table 3. The performances of both controllers in case-1

| Controller | Rise Time | Settling Time | Overshoot |
|------------|-----------|---------------|-----------|
| PI | 14.171 ms | 27 ms | 3.65% |
| T2FLC | 14.032 ms | 20 ms | 0% |

The simulation results obtained from case-2 are indicated in Fig. 9. The reference speed of DC motor is changed 200 to 250 rad/s at $t=0.05$ s. As it is seen from Fig. 9(a), controllers follow the reference speed without steady state error. In reference and step speed values, the PI controller's speed responses are increased to 207.3 and 256.7 rad/s, respectively. The speed of the proposed controller is not exceed the reference values. For 200 to 250 rad/s speed change, the settling times of T2FNN and PI controller are 8.2 and 15 ms, respectively. As seen from the Fig. 9 (b), the reference speed has been reduced from 200 to -250 rad/s in order to indicate the four-quadrant operation behavior of the DC motor. As shown in Fig. 9, T2FLC has better performance than PI controller in terms of overshoot and settling time. The performances of both controllers in case-2 are presented in the Table 4.

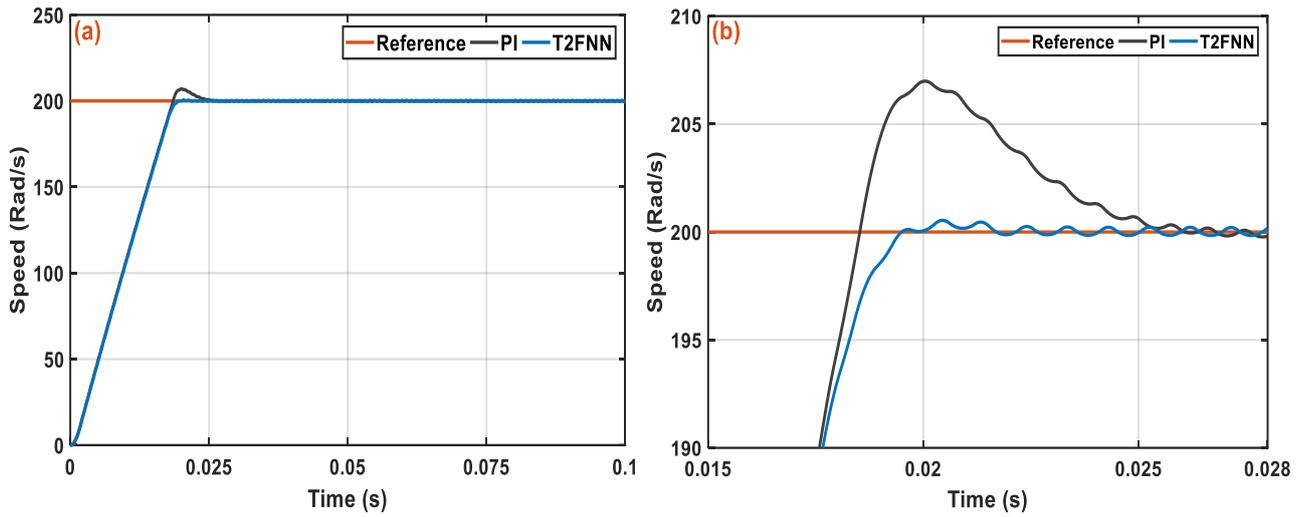


Fig. 8. Speed responses obtained from case-1

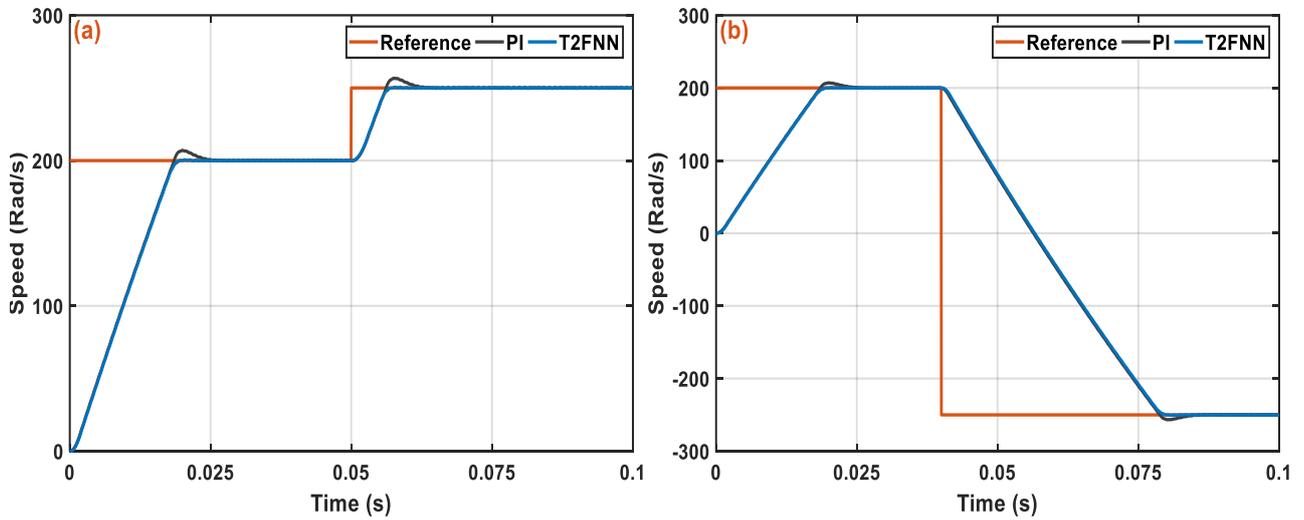


Fig. 9. Speed responses obtained from case-2

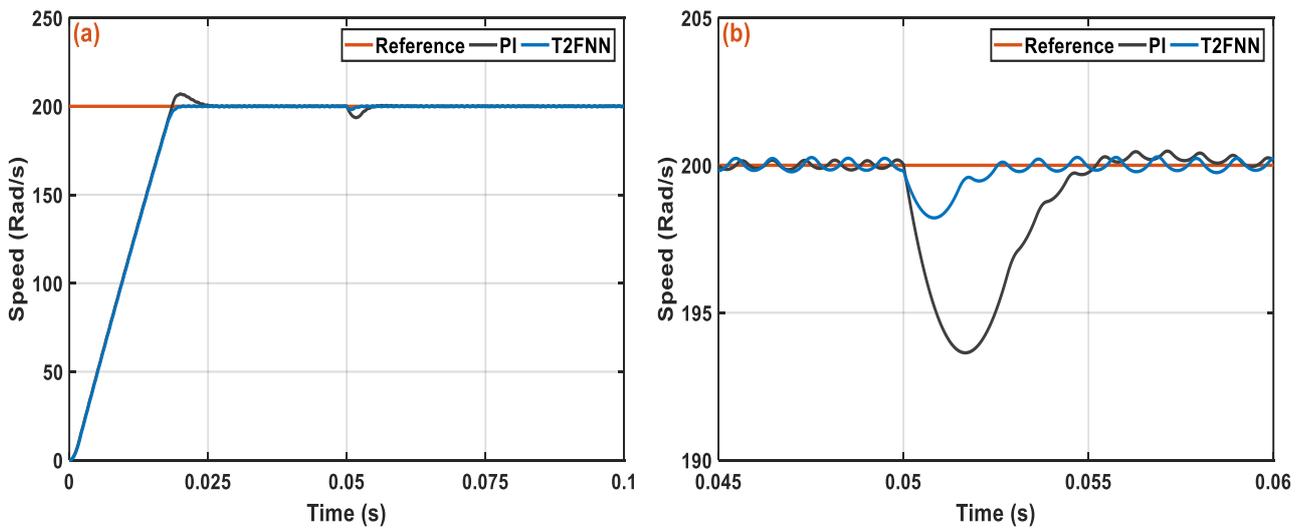


Fig. 10. Speed responses obtained from case-3

Table 4. The performances of both controllers in case-2

| Controller | Settling Time | Overshoot | |
|------------|---------------|------------|-------------|
| Fig 9(a) | PI | 27↔15 ms | 3.65%↔2.68% |
| | T2FLC | 20↔8.2 ms | 0%↔0% |
| Fig 9(b) | PI | 27↔36.1 ms | 3.65%↔4.45% |
| | T2FLC | 20↔28.2 ms | 0%↔0% |

The simulation results obtained from case-3 are given in Figs. 10 (a) and (b). DC motor is initially unloaded and the step speed of 200 rad/s is applied to the speed unit of the DC motor for 0.1 s. In this case, a step load change in speed of DC motor is applied at t=0.05 s. As can be seen in Figures, the speed responses of PI controller and T2FLC based DC motor are dropped to 193.5 and 198.2 rad/s. The PI controller follows the reference speed after 11.4 ms while the T2FLC tracks the reference after 2 ms. The performances of both controllers in case-3 are given in the Table 5.

Table 5. The performances of both controllers in case-3

| Controller | Settling Time | Undershoot |
|------------|---------------|------------|
| PI | 11.4 ms | 3.25% |
| T2FLC | 2 ms | 0.9% |

5. Conclusion

The speed and position controls of DC motors are an important issue and numerous studies are being done on this subject. In this study, T2FLC is proposed for controlling the speed of DC motor. A model is developed in the Matlab/Simulink environment to verify the performance of T2FLC. The developed model is tested under many operation conditions. The dynamic performance of DC motor is evaluated for these conditions. In order to demonstrate the performance of the PD-T2FNN controller, the speed response obtained from T2FLC is compared with PI controller. According to simulation studies, DC motor based on proposed controller structure has better performance in all reference speeds and load change.

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