Omar T. Mahmood
Department of Electrical Technologies, Mosul Technical Institute, Northern Technical University, Iraq.
omar.talal@ntu.edu.iq
omar_taee2002@yahoo.com

Received on: 12/7/2017
Accepted on: 23/11/2017

Speed Reference Tracking for Separately Excited DC Motor Based ANFIS and Hysteresis Current Control Techniques

Abstract- *In this work, a closed loop control system has designed to control the speed of separately excited direct current motor (SEDCM) using Fuzzy (Mamdani and Sugeno) and an Adaptive Neuro - Fuzzy techniques (ANFIS). The action of these control techniques is to produce the reference armature current that has fed to the hysterics current controller (HCC) that produces the required gating signal to a Buck chopper .Different load conditions has been applied to the motor to obtain many mode of operation, the speed held constant at the required references values using both fuzzy (Mamdani-type and Sugeno-type) and ANFIS techniques. The results has collected and compered with a classical PID controller using MATLAB/Simulink. Step response for the speed has drawn and the control parameters for this response have evaluated. According to the results, the Mamdani fuzzy controller technique is better than as compared with the other controllers. There are many applications for this plant such as production process that need to fill or Packaging any product or used in the autopilot channels. The new goal for this proposed system is to get robust speed controllers that track the speed at any mode of operation using three artificial intelligent techniques.*

Keywords- *Speed Control, Fuzzy Logic, ANFIS, SEDCM.*

How to cite this article: O.T. Mahmood, "Speed Reference Tracking for Separately Excited DC Motor Based Fuzzy ANFIS and Hysteresis Current Control Techniques," *Engineering and Technology Journal*, Vol. 36, Part A, No. 6, pp. 680-690, 2018.

1. Introduction

Direct current machines has a widely used in many industrial applications such as motive applications, rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills, excavators and cranes. Fractional horsepower DC motors are widely used as servomotors for positioning and tracking [1]. So that it is very important to design a suitable controller to adjust the speed of the motor according to the required reference speed demands by the user. Many control strategies used for speed adjustment of DC motors such as PI, PID, fuzzy, and ANFIS. In [1] the researchers designed a speed controller of DC motor using PID controllers but uses the bioinspired optimization technique of Artificial Bee Colony Optimization (ABC) to select the parameters of the controller. Fuzzy Neural Model Reference controller has used in [2] to control the speed of SEDCM, the results obtained presented a good performance and robust response in load variations, this work uses Fuzzy Neural Model Reference controller and MRAC method, while our present work uses fuzzy and ANFIS techniques to implement the speed control for the DC motor. To select the parameters of the PID controllers, Elsrogy et al. in [3] used genetic algorithm (GA) and Adaptive Neuro-Fuzzy Inference System (ANFIS) for controlling the speed of DC motor. A Comparison study has presented in [4] between fuzzy and ANFIS controllers that control the speed of SEDCM, the results indicate that ANFIS is better than fuzzy controller. Based on Sensorless Technique a fuzzy controller has designed in [5] to control the speed of brushless motor using matlab Simulink, the results compared with PI controller. The importance of a fuzzy logic controller over conventional PID method presented in [6] the result shows that the fuzzy logic approach has better performance. Proportional integral (PI), proportional integral derivative (PID) and Ziegler- Nichols method controller has used in [7] to control the speed of SEDCM, the results declared that the final method has an advantages as compared with the other methods. In [8] Premkumar and Manikandan demonstrate the performance of BLDC motor using classic PI controller, fuzzy tuned PID controller and fuzzy variable structure controller and, the results reveal that the ANFIS controller outperforms other controllers in all aspects. The Researchers in [9] proposed an improved adaptive fuzzy PID controller to control the speed of BLDCM and compare the results obtained with a classical PID controller. Hussain et al, designed an ANFIS controller to control knee joint during sit to stand movement through electrical stimuli to

https://doi.org/10.30684/etj.36.6A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

quadriceps muscles, the results shows that the proposed controller reduced the deviations between desired trajectory and actual knee movement to ±5˚ [10].

In this paper, proposed fuzzy logic and ANFIS controllers has designed to track the variable reference speed of SEDCM, using HCC as a gating signal generator for the chopper circuit. i.e. there are two control loops, one used to produce the armature reference current using the speed error and that fed to the three controllers and the second loop receives this reference current and compare it with the actual armature current of the motor to produce the gating signals for the chopper circuit using HCC. The results obtained has compared with a results of a classical PID controller. Step response parameters has evaluated for all the above control techniques. At first, the system operates for PID controller and the speed response has been obtained and then fuzzy controller has been designed by selecting the fuzzy memberships and rules and finally, the system has been trained and checked to obtain the optimum memberships and rules using ANFIS controller in the matlab GUI for ANFIS editor.

2. SEDCM Fundamentals and DC Drive Circuit

I. DC Motor

Many methods to control the speed of DC motors can achieve, which are, armature control and field control methods. In the first method, we change the applied voltage to the armature with a constant applied voltage to the field windings. Most popular method is the armature voltage control, which has two advantages, the first one is to retain maximum torque capability, and the second one is to allow the variation of speed below rated value, so that we use this method in our proposed system. The second method achieved by changing the applied voltage to the field windings. However, this method has two main disadvantages, the first one is that we cannot control the speed below the normal value, and the second one is that the maximum speed cannot obtained easily by this method. The below Figure 1 represent the equivalent circuit for the SEDCM which is used in our proposed system [11-12].

The characteristic equations (electrical and mechanical) of the DC motor are: [11]

$$\frac{di_a}{d_t} = \frac{1}{L_a}\,(V_a - R_a i_a - E)$$

(1)

$$\frac{di_f}{d_t} = \frac{1}{L_f}\,(V_f - R_f i_f)$$

(2)

$$\frac{d_\omega}{d_t} = \frac{1}{J}\,(T_e - T_L - B\omega)$$

(3)

(i_a) is the armature current, (R_a) is the armature resistance and (L_a) is the armature inductor. (V_a) Is the applied voltage to the motor, (i_f) is the field current, (V_f) is the field applied voltage,(R_f) and (L_f) are the field resistance and inductor respectively (E) is the back EMF. (T_e) is the development electrical torque, (T_L) is the load torque. (B) is the viscous friction coefficient. (J) is the moment of inertial and (ω) is the machine angular speed. As it is clear from figure (1), the armature circuit comprised of armature inductor in series with armature resistance and emf source (E) which is proportional to the DC motor speed as below:

$$E = K_E \omega$$

(4)

$$K_E = L_{af}\, I_f$$

(5)

$$T_e = K_T\, I_a$$

(6)

Where, K_E is the voltage constant, L_{af} is the field-armature mutual inductance and K_T is the constant of torque.

From equations (1) and (4), the dynamic steady state equations of the motor speed can write as:

$$V_a - R_a i_a = E$$

(7)

$$\omega = \frac{V_a - R_a i_a}{K_E}$$

(8)

II. Chopper fed-DC motor drive and HCC II. Chopper fed-DC motor drive and HCC

From equations (7) and (8), the control of the motor speed can be done by changing the applied armature voltage V_a,and this can easily achieved by pulse width modulation (PWM) method applied using a single MOSFET which is called a Buck chopper circuit and it is seen in Figure (2 a). The chopper is a voltage step-down connection is required to convert the fixed voltage into a variable-voltage / variable-current source for the speed control of the DC motor drive [2].

The simple PWM scheme shown in figure (2 b), where T is the signal period, td is the pulse-width, and V_m is the signal amplitude. The average applied voltage to the armature circuit from the chopper is:

$$V_{ag} = \frac{1}{T}\int_0^T \int V(t)dt \; = \frac{td}{T}V_m = K_1 V_m \qquad (9)$$

K_1 : is the duty cycle.

It is obvious from equation 9 that the DC component of V_{ag} is proportional to the PWM of the signal or with K_1 of the signal, since the period is fixed. The DC chopper is supplying a train of unidirectional voltage pulses to the armature of the DC motor. If td is varied keeping T constant, the resultant voltage wave represents a form of pulse width modulation will vary according to the duty cycle value [13].

The design procedures for this chopper is done using equations 10 and 11 below to evaluate the value of the inductance L and capacitance C at (1000 Hz) frequency and 0.5 duty cycle D [13].

$$L = \frac{(1-D)R}{2f} \qquad (10)$$

$$C = \frac{(1-D)V_a}{V_{in}L\,f^2} \qquad (11)$$

V_s represents the applied voltage to the chopper.

HCC simply implemented by comparing the reference current that produced from the first control loop with the actual armature motor current with a fixed hysteresis band. The output from this controller is the gating voltage for the chopper switch V_s.

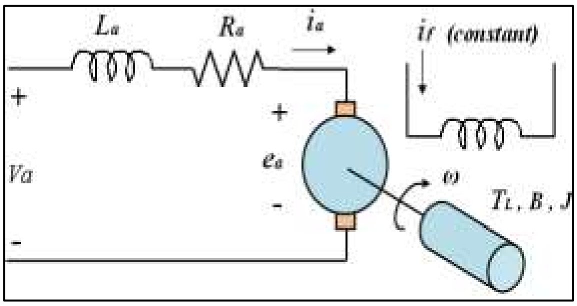
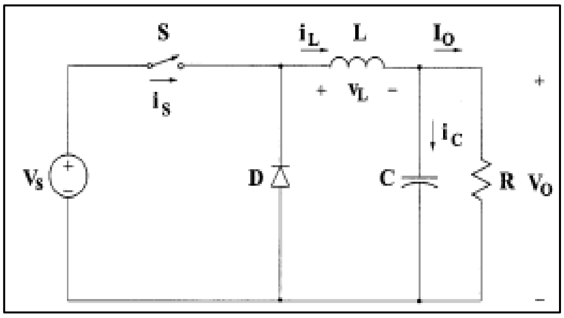
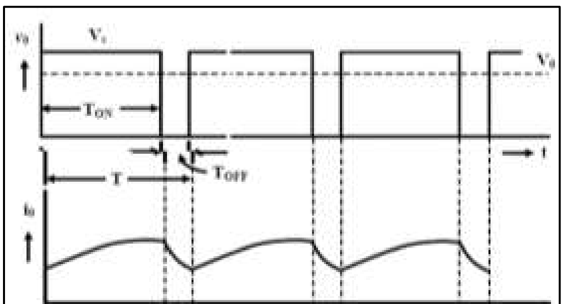
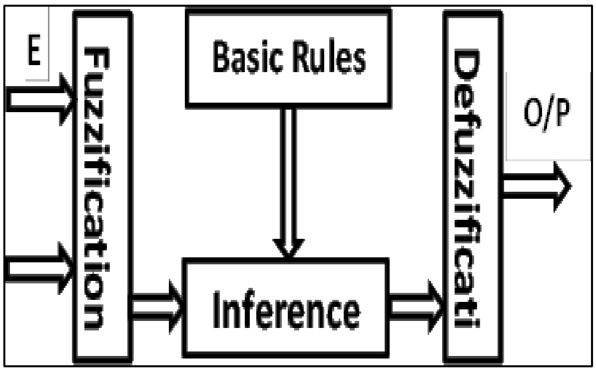


Figure 1: SEDCM equivalent circuit



A





B

Figure 2: (a) Buck converter (b) PWM

Figure 3: Fuzzy logic structure

3. Fuzzy Controllers

Fuzzy control is a method of intelligent technique that tries to emulate human actions by using a complex fuzzy logic and elements of artificial intelligence (simplified deduction principles). The word "fuzzy" used here to describe terms that are either not well known or not clear enough, or their closer specification depends on subjectivity, estimation, and even the intuition of the person who is describing these terms [14]. The input to the fuzzy system is the motor speed error E and rate change of the error CE. The general basis of fuzzy logic control is as shown in Figure 3; it consists of three principal components [13]:

I. Fuzzification

This component is used to conditioning the values of the input data into suitable values for the fuzzy inference system in a form of certain membership functions. The error and change of error signals has been fed to saturation and gain blocks to be fit with the fuzzy inference block (FIS). Them, then they will gather and fed to the FIS block in matlab as an inference system shown in Figure 4. The linguistic labels in our proposed fuzzy Mamdani Sugeno system are:

- For the input variables E (error) and CE (change of error), they are Negative (N), zero (ZE), and positive (P).
- For the OUT (output), they are positive small (PS), positive medium (PM) and positive large (PL).
- In ANFIS controller, the OUT variable have N1 …N8 (for negative), P1 …P7 (for positive).

Membership functions for inputs and output of Mamdani and Sugeno controllers for our proposed system has been chosen after many trials and using the best membership shape that will give the best performance, it is shown in Figure 5 below.

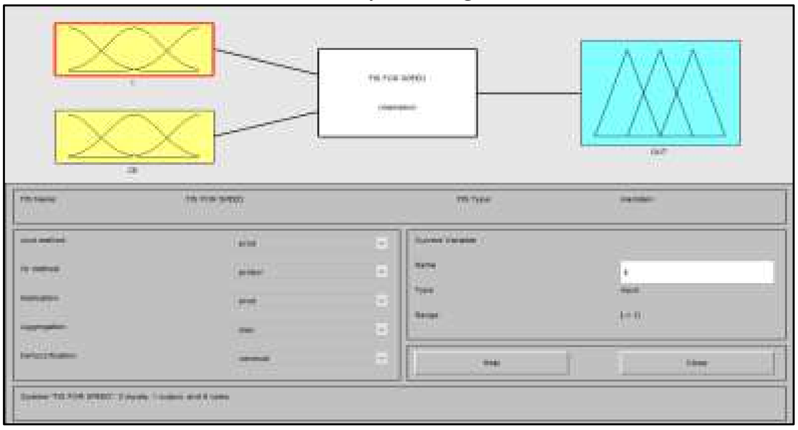
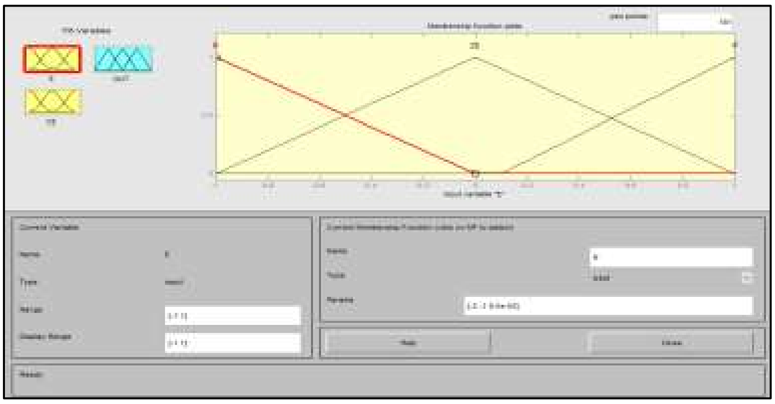
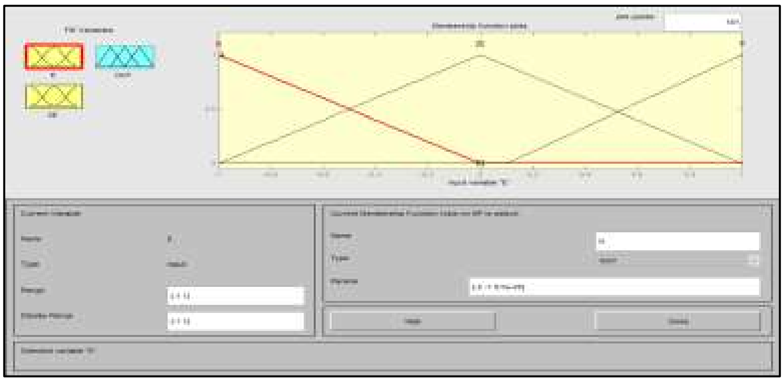


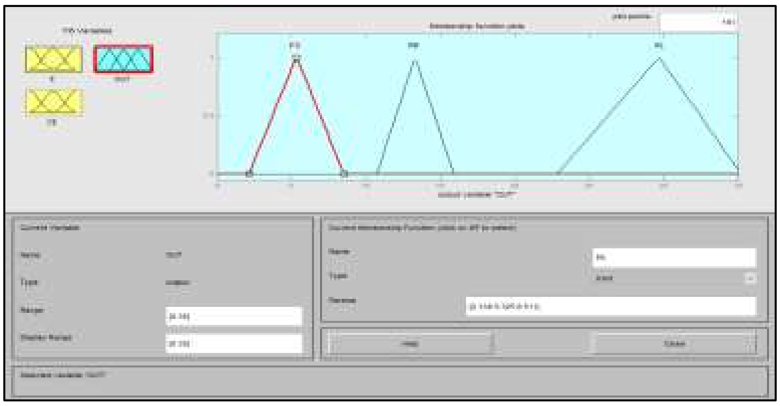
Figure 4: Fuzzy logic inference system for the proposed system



(a): Membership function for the input CE



(b): Membership function for the input E



(c): Membership function for OUT in Mamdani controller

(d): Membership function for OUT in Sugeno controller

Figure 5: membership function for Mamdani and Sugeno fuzzy controllers

II. Rules

It is the brain of the fuzzy system, it combines all the inputs with all the outputs to generate suitable logic formulas that make the required decision to solve the system issue, the simple form of a rule is:

If E is P and CE is N then OUT is PS (12)

Rules for Mamdani and Sugeno control systems for the proposed system shown in and Table 1 below, while Table 2 shows the effective rules for ANFIS controller. These rules has been chosen according to complex procedures that uses the error and change of error signals for all the operation period of the system to produces the wanted output for the fuzzy system.

Table 1: Effective rules for Mamdani controller

OUTPUT		E		
		N	ZE	P
CE	N	PS	PS	PL
	ZE	PS	-	PL
	P	-	-	PL

Table 2: Effective rules for ANFIS controller

OUTPUT		E			
		N	ZE	PS	PL
CE	N	N1	P1	P3	N8
	ZE	N2	P2	P4	P5
	PS	N3	N5	N6	P6
	PL	N4	ZE	N7	P7

III. Defuzzification

In this step, the final actual results that called crisp. There are numerous defuzzification methods, but the most common one used is the center of gravity, center of area, modified center of area. The membership of the output linguistic variables simply converted to numerical values [14].

4. Adaptive Nero-Fuzzy Controllers

It is a type of artificial neural system based on Sugeno fuzzy control system. It is combining the best advantages of neural and fuzzy technique and tries to beat the deficiency that may appear if they used alone [15]. The procedure of working with ANFIS GUI has the below steps:

1) Loading Data: This will load our previously saved data from .dat extension file. After loading the data, ANFIS editor will be displayed as shown in Figure 6-a. This data obtained from the speed response of the PID and Mamdani fuzzy controller that has saved in the Matlab workspace and it has reloaded to train and test the ANFIS controller. We made many training and testing trials until we obtain the best performance for this controller.

2) Generate FIS: FIS model generated by using any one of the following techniques.

a) Grid partition: in this step, the data has generated via grid portioning.

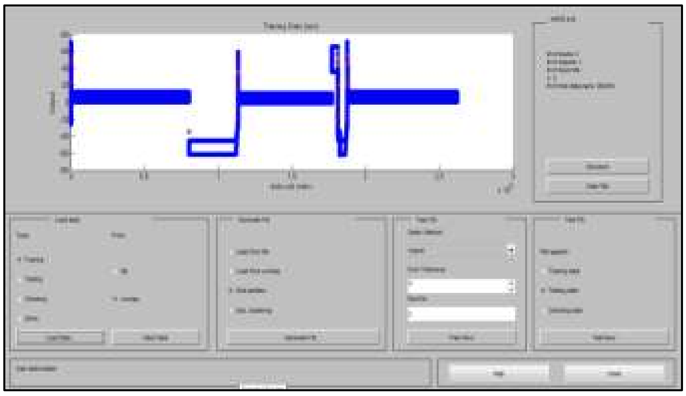
b) Sub clustering: It generates data by analysing the number of clusters in the given set of data. ANFIS structure can be observed clicking option of "Structure" as shown in Figure 8.

3) Training and validation of FIS: in this step, the FIS model generated, repeats itself until and unless required number of epoch is reached and goal of training error is attained .This is shown in Figure 6-a.

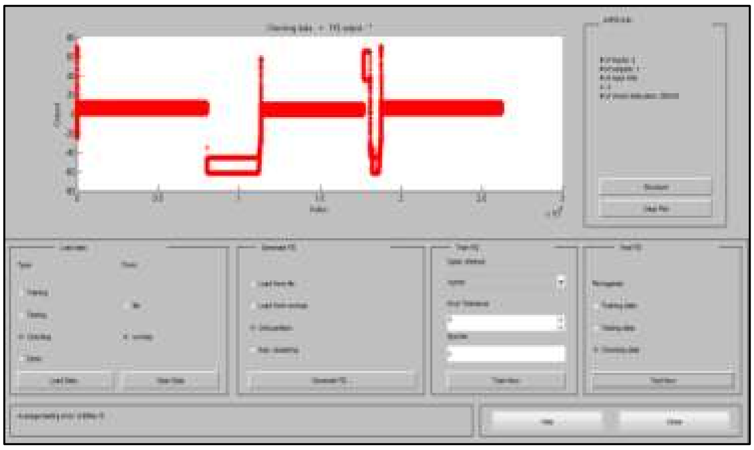
4) Testing of the FIS carried out by clicking "Test now". "Test now" shows the value of "Average testing error". This is shown in Figure 6-b.

After many training trails, the results for the specified inputs and output data is a new membership function for the output (OUT) , and new membership functions for the input variables E and CE with new parameters, it is shown in Figure (7) (a, b, and c) respectively.

Figure (8) below shows the structure of the ANFIS controller for the proposed system that automatically created after the many training procedures by the ANFIS GUI inference system.



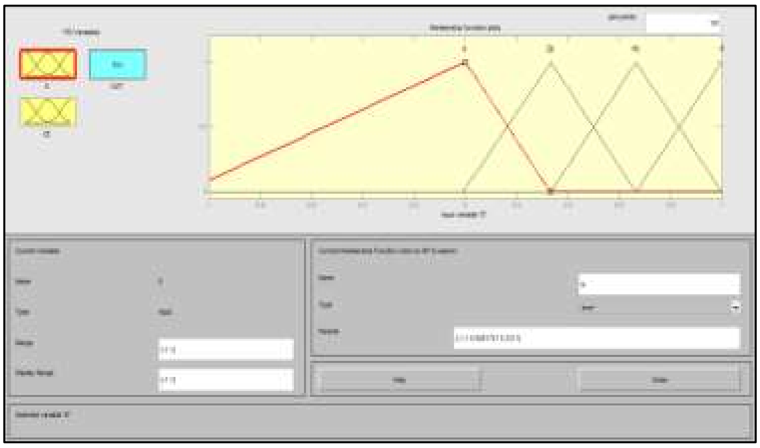
(a): Training data



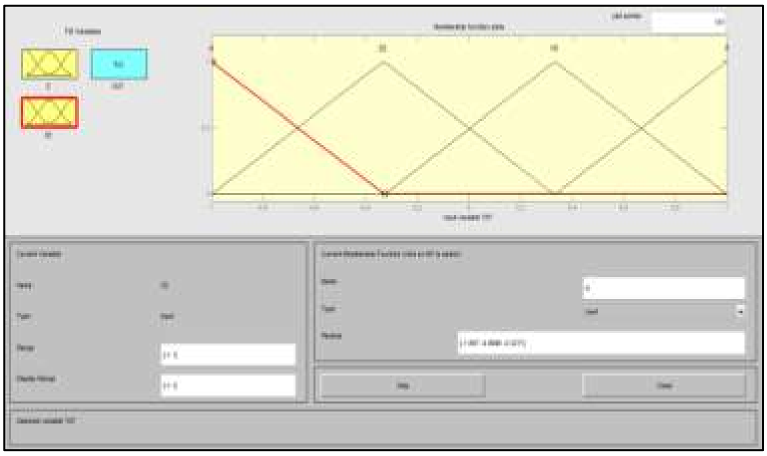
(b): Checking data

Figure 6: Training and checking data for the ANFIS controller

(a): Membership function for variable OUT in ANFIS controller



(b): Membership function for variable E in ANFIS controller



(c): Membership function for variable CE in ANFIS controller

Figure 7: membership functions for the ANFIS controller

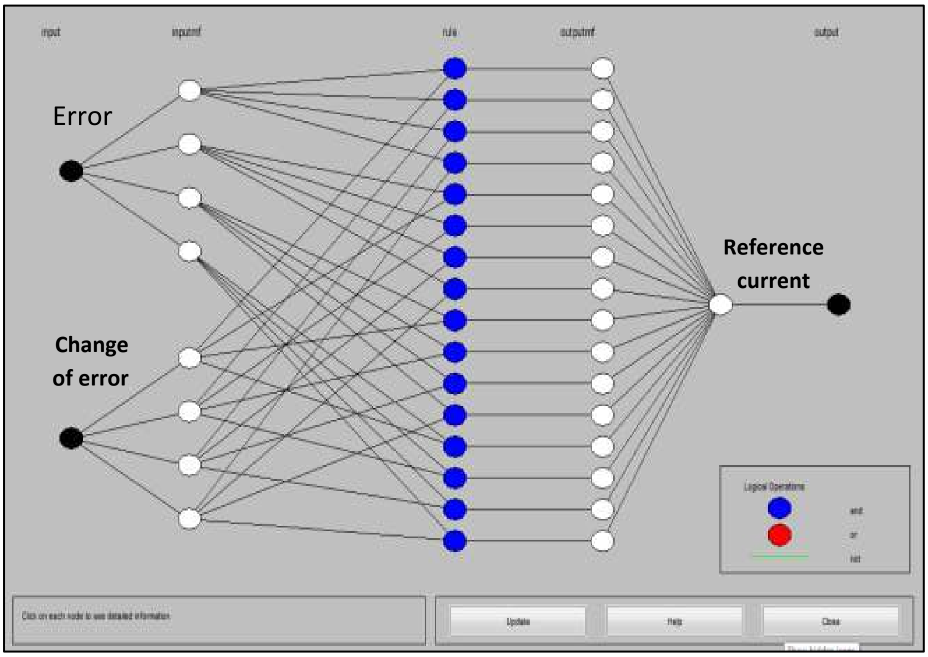
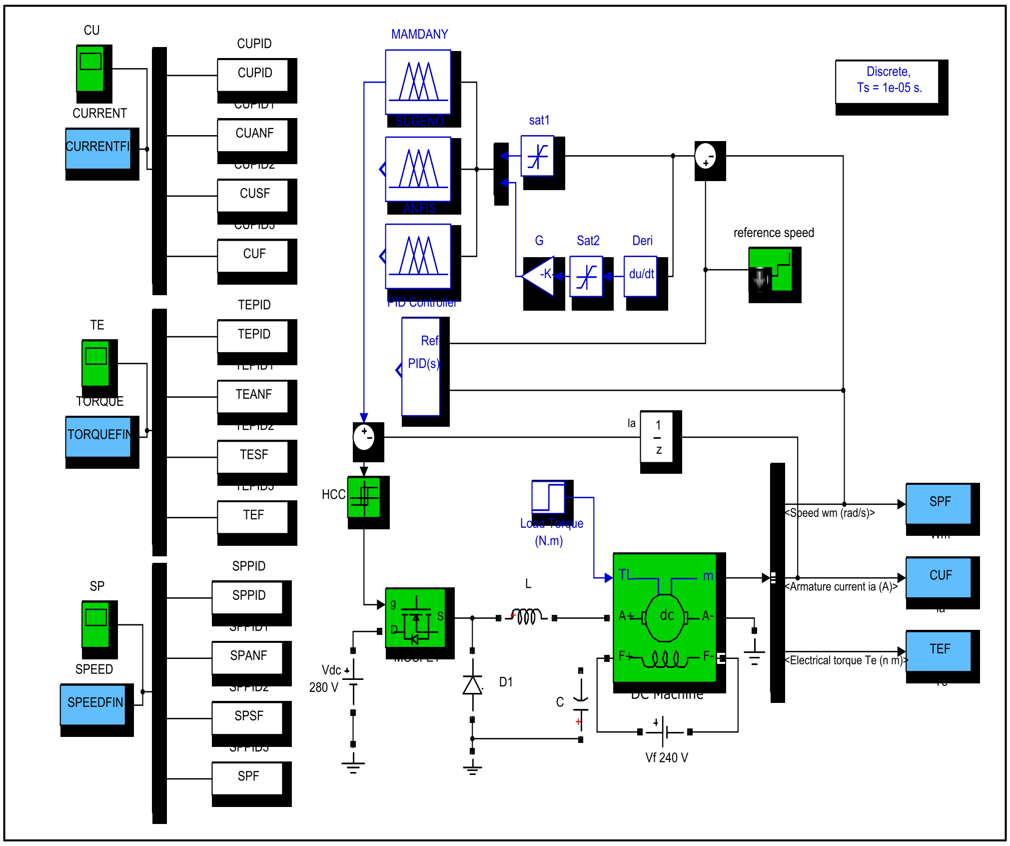


Figure 8: Structure of the ANFIS controller for the proposed system

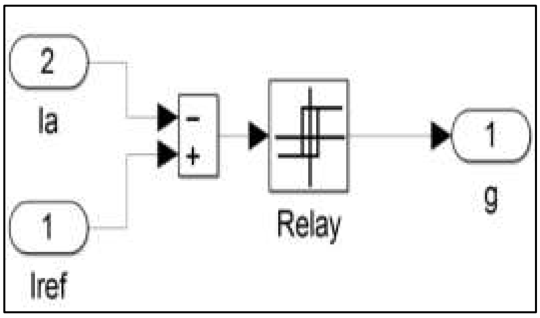
5. Simulation Work

The Simulink model for the proposed control system is shown in Figure (9- a). This model is consists of a SEDCM (5 horsepower, separately excited 240 DC volt,280 DC voltage for the armature, 0.5 Ω armature resistance,240 Ω field resistance ,total inertia (J) equal to 0.05 ⟦ Kg.m⟧ ^2,and 0.02 N.m.s as a viscous friction coefficient). We have two control loops; the first one receives the motor speed-reading and compares it with the reference speeds (generated by the timer block). This error and its rate change is modified and then fed to the controllers: mamdani fuzzy (MFUZZY), Sugeno fuzzy (SFUZZY) and Nero-fuzzy controller (ANFIS). These controllers generate the required reference armature current according to the speed deviation in the second control loop, which is HCC as shown in Figure (9- b). Then, this reference current is compared with the actual armature current of the motor and the error is directed to relay that has a (+ 0.5 and -0.5) as a switch on and switch off points respectively that stands for hysteresis band for the HCC. The output of HCC is simply the gating signal for the buck chopper switch (MOSFET) as a PWM technique. The simulation has repeated for all the four types of controller. Speed, armature current and electrical torque for all modes of operations has measured using the measurement output from the DC motor model and using three scopes with the help of to workspace and from workspace blocks.

In our work, there are five modes of operation; the first one (at t=0) when the speed reference is at 0 rad/sec and increased to 100 rad/sec. The second mode (at t= 1 sec.), when the speed reference increased to 120 rad/sec, the third mode (at t= 2 sec.), when the speed reference increased to 140 rad/sec., the fourth mode (at t= 3 sec.), when the speed reference increased to 160 rad/sec, in all these mode the load torque is held constant (5 N.m). The firth mode (at t= 4 sec.), when the load torque increased to 25 N.m at the final speed reference.



(a): Matlab Simulink model for the SEDCM speed controllers



(b): Hysteresis Current controller

Figure 9: Matlab Simulink model for the proposed system

6. Results and Calculations

Response for the motor speed, armature current and electrical torque for the various modes of operations and controllers has shown in Figures 10, 11 and 12 respectively. After zooming the current and torque plots in the first portion of Figures 11 and 12, we can see that there are none discontinues behavior for the current and torque in PID and Mamdani fuzzy controllers. However, there is a small discontinues action (pulse) in the Sugeno fuzzy controller and finally, the greatest discontinuous action is noted using ANFIS controller. Also, it is clear that the armature current and motor load torque has a highest pulsated value (about 65 amps and 75 N.m respectively) in the case that uses ANFIS controller, while in the other controllers these values is about 30 amp and 40 N.m respectively. We use figure 10 and the below transient response equation of a second order system to extract and calculate the step response parameters which are: rise time (T_r), time to peak overshoot (T_p), settling time (T_s), maximum percentage overshoot (M_p), undershoot, natural frequency (ω_n), and damping ratio (ζ), the required equations are: [16]

Time to peak overshoot:

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \quad (11)$$

Settling time

$$T_s = \frac{4}{\omega_n\zeta} \quad \text{for 5\% criteria} \quad (12)$$

Maximum percentage overshoot

$$M_p = e^{-\pi\zeta/\sqrt{1-\zeta^2}} \quad (13)$$

$$e(t) = r(t) - c(t) \quad (14)$$

The results of the calculations at 120 rad/sec speed and at 25 N.m torque illustrated in Table 3 and 4 respectively.

Table 3: step response parameters at 120 rad/sec. speed

Controller type	T_r (sec)	T_p (sec)	T_s at 5% criteria (sec)	Percentage overshoot M_p%	Undershoot	Steady state error	ω_n	ζ
PID	0.156	0.245	0.325	4.88	none	1.5	17.77	0.692
Fuzzy (Mamdani)	0.128	0.163	0.153	1.095	none	0.12	32.48	0.7049
Fuzzy (Sugeno)	0.0877	0.115	0.105	1.258	Yes	0.12	46.877	0.812
ANFIS	0.06	0.091	0.081	1.4	none	0.11	60.25	0.819

Table 4: step response parameters when the load torque increased to 25 N.m

Controller type	T_r (sec)	T_p (sec)	T_s at 5% criteria (sec)	Undershoot
PID	0.314	0.05	0.0314	Yes

Fuzzy (Mamdani)	0.12	0.0044	0.012	Yes
Fuzzy (Sugeno)	0.12	.0044٠	0.012	Yes
ANFIS	0.0143	0.0044	0.0143	Yes

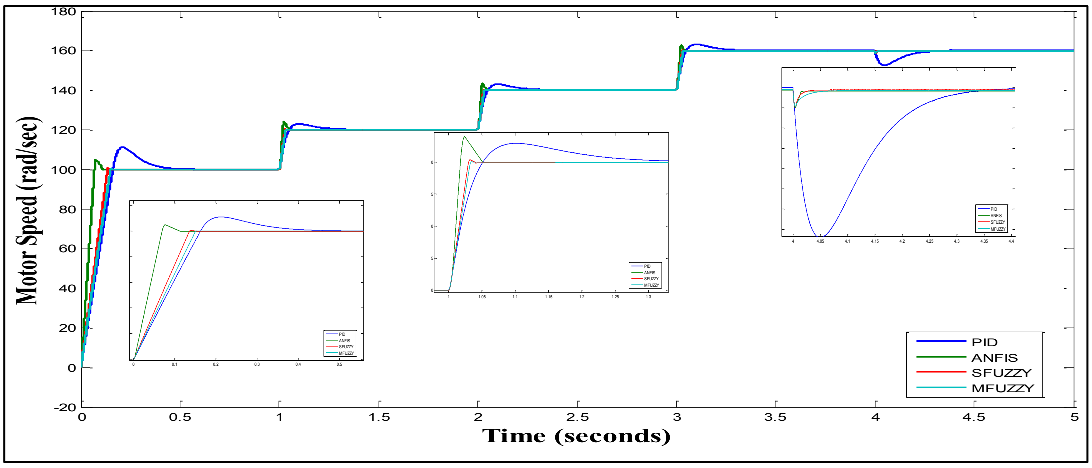


Figure 10: Speed for the SEDCM various controllers

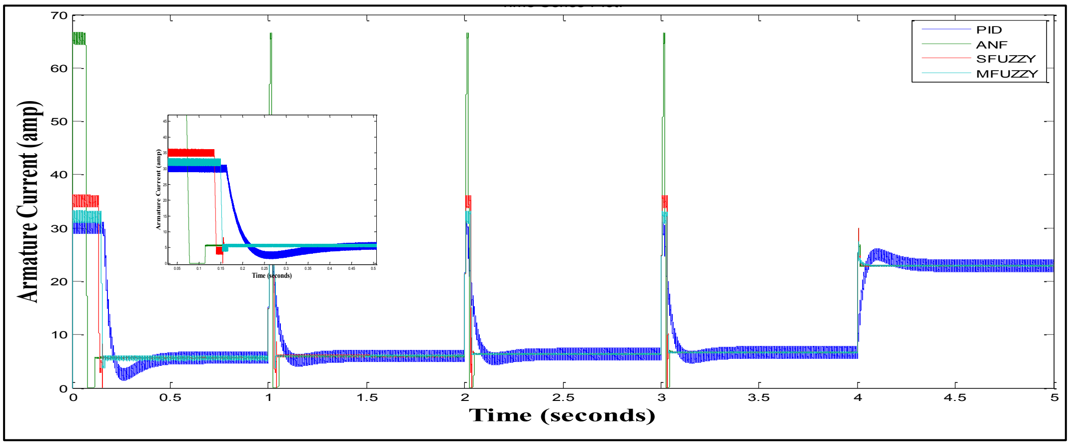


Figure 11: Armature current fr the SEDCM using various controllers

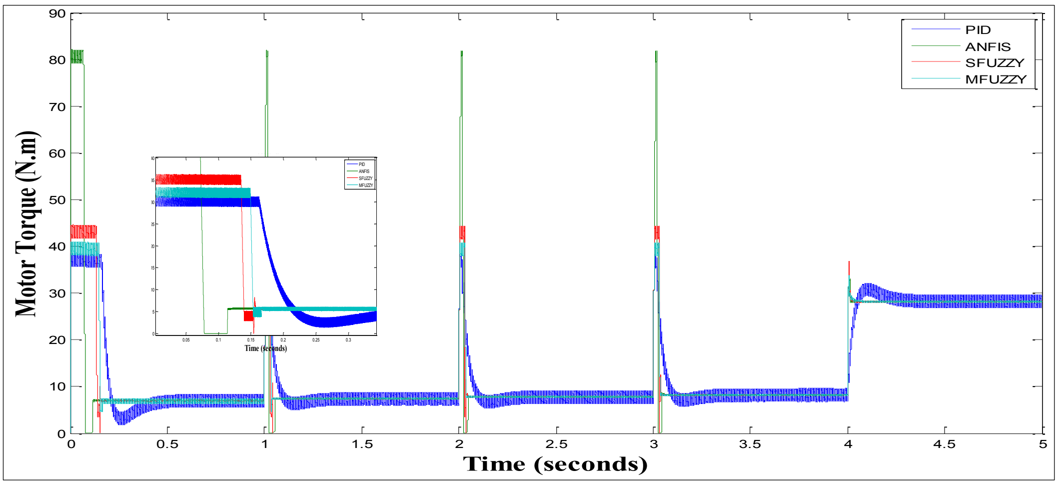


Figure 12: Electrical torque for the SEDCM using various controllers

7. Conclusion

As it is clear from the calculations, the optimal design has made using Mamdani fuzzy controller. This is because of the armature current and torque current of the motor does not have any discontinues work region as it seen clearly in Figures 11 and 12, while the ANFIS and Sugeno controllers have a small discontinuity in the values of the current and torque. The reason behind this is the selection of the rules, memberships shape and values.

The first four modes of operation have nearly the same response, so we will discuss the first and the fourth modes only. For mode one and with the help of the calculated results in table 3, we can see the ANFIS controller has a minimum rise time ,time to peak overshoot , settling time and steady state error. Sugeno controller in this mode have the better performance after the ANFIS controller but it is the only controller that have undershoot , Mamdani will came in the third place ,while the PID controller has the maximum values for all these control parameters. However, if we consider the percentage overshoot we see that the Mamdani controller has the minimum value as compared with the other controllers. Best natural frequency (ω_n), and damping ratio (ζ) is obtained using Mamdani fuzzy controller (32.48 rad/sec and 0.7049).

When the load torque becomes 25 N.m , and if we consider the parameters in table 4 and figure 10, we see that all the controllers has undershoot but the PID controller has the maximum value and ANFIS has the minimum one. ANFIS controller also have the minimum rise time, time to peak overshoot and settling time. Therefore, we can conclude that Mamdani fuzzy controller is the best controller that can used to track the reference speed for SEDCM as compared with the others.

References

[1] A.K. Mishra, V.K. Tiwari, R. Kumar, "Speed control of dc motor using artificial bee colony optimization technique," IEEE International Conference on Control, Automation, Robotics and Embedded Systems (CARE 2013), Jabalpur, 2013.

[2] W.I. Hameed, K.A. Mohamad, "speed control of separately excited dc motor using fuzzy neural model reference controller," International *Journal of Instrumentation and Control Systems (IJICS)*, Vol.2, No.4, pp.27-39, October 2012.

[3] W.M. Elsrogy, M.A. Fkirin, M.A. Moustafa Hassan, "Speed Control of DC Motor Using PID Controller Based on Artificial Intelligence Techniques," IEEE Control, Decision and Information Technologies (CoDIT), International Conference, Hammamet pp.196-201, 2013.

[4] A. Jilani, S. Murawwat, S.O. Jilani , "Controlling Speed of DC Motor with Fuzzy Controller in Comparison with ANFIS Controller," *Intelligent Control and Automation journal*, vol.6, No.1,pp. 64-74,February, 2015.

[5] J. Sriram, K. Sureshkumar, "Speed Control of BLDC Motor Using Fuzzy Logic Controller Based on Sensorless Technique," IEEE International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE), Coimbatore, 2014.

[6] R. Kushwah, S. Wadhwani, "Speed Control of Separately Excited DC Motor Using Fuzzy Logic Controller," *International Journal of Engineering Trends Technology (IJETT)* – Vol.4, No. 6, pp.2518-2523, June 2013.

[7] U. Kumar, D. Dohare, "Separately Excited DC Motor Speed control of using various Tuning Conventional Controllers," *International Research Journal of Engineering and Technology (IRJET),* Vol. 02, No.8, pp.496-499, November 2015.

[8] K. Premkumar, B.V.Manikandan, "Adaptive Neuro-Fuzzy Inference System based speed controller for brushless DC motor," *ELSEVIR Neurocomputing journal*, Vol.138, pp.260 -270, August 2014.

[9] R. Kandiban, R. Arulmozhiyal, "Speed Control of BLDC Motor Using Adaptive Fuzzy PID Controller," International conference on Modeling, Optimization and Computing , ELSEVIR Procedia Engineering , pp. 306-313, Tamil Nadu 2012.

[10] R. Hussain, R. Massoud, M. Al-Mawaldi, "ANFIS-PID Control FES-Supported Sit-to-Stand in Paraplegics: (Simulation Study)," *Journal of Biomedical Science and Engineering,* Vol. 7, No. 4, pp. 208-217, 2014.

[11] G.A. Adepoju, I.A. Adeyemi, O.S. Oni, "Application of Fuzzy Logic to the Speed Control of DC Motor," *International Journal of Engineering Trends and Technology (IJETT),* Vol. 15,No. 5 pp.215-219, September 2014.

[12] M.F. Algreer, Y.R. Kuraz, "Design Fuzzy Self Tuning of PID Controller for Chopper-Fed DC Motor Drive," *Al-Rafidain Engineering journal*, Vol. 16, No.2. pp. 54- 66, 2008.

[13] B.A. Omar, A.Y. Haikal, F.F. Areed, "An Adaptive Neuro-Fuzzy Speed Controller for a separately excited DC Motor," *International Journal of Computer Applications*, VOL.39, No. 9, pp.29-37, February 2012.

[14] Z. Kovaˇci´c, S. Bogdan, "Fuzzy Controller Design Theory and Applications," Taylor & Francis Group, LLC, 1st ed Boca Raton, 2006.

[15] W.N. Abed, "Speed Control of DC Motor Using Adaptive Neuro Fuzzy Controller," *journal of scientific and engineering research,* Vol. 2, No.1, pp.16-21, March 2015.

[16] R.C. Dorf, R.H. Bishop, "Modern Control Systems", Pearson Prentice Hall, eleventh ed, New Jersey,2008.

https://doi.org/10.30684/etj.36.6A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

Author biography

O.T. Mahmood

Born in Mosul/Iraq (1972). Earned his BSc in Electrical Engineering from University of Technology (1996). MSc degrees in Technical power engineering from Technical Engineering college of Mosul/Northern Technical University / Iraq (2009).Work in Ministry of Higher Education and Scientific research since 2011 as a lecturer in Mosul technical institute, IEEE member.