ANFIS based IMC PID Controller for Permanent Magnet DC Motor

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Abstract: Permanent Magnet Direct Current (PMDC) motors are widely used in industrial application and PID controllers are usually applied to improve performance characteristics of PMDC motor. There are different methods for setting up PID parameters that one of them has been called Internal Model Control (IMC) which is used λ parameter to modify performance characteristics of system. Sometimes setting up IMC PID parameters are hard so in this paper, ANFIS is used to add proper values with IMC PID coefficients. The proposed controller used ANFIS based coefficient modifier because it can train easily and help system to achieve desired performance characteristics. The proposed system used the fuzzy system that is extracted from training ANFIS system with desired data to improve PMDC motor performance. In this paper IMC based controller is compared with proposed strategy and simulation results shows that proposed control system have acceptable characteristic in different situation such as no-load, applied-load, changing reference speed and it is effective methods to control system in noisy condition.

1 INTRODUCTION

The speed and position control of PMDC motor are very important because PMDC motor widely has been exploiting in industrail and proving ground due to simplicity, low cost and efficiency (Medewar and Munje, 2015, Angalaeswari et al., 2016). PMDC motors have uncertain and nonlinear characteristics so different control methods are applied to improve their perfomance which is sorted into three main categories:

1. Classic PID, PI, P controllers (Sreekala and Sivasubramanian, 2011).
2. Modern control system (Moussavi et al., 2012, Liu et al., 2014).
3. Intelligent control system (Sharifian et al., 2011, Wei, 2011, Blessy and Murugan, 2014, Choi et al., 2015).

The PID controllers have been utilizing to control different industrial processes from past to present and control researchers have been trying to find the best choices for PID coefficients (K_p, K_i, K_d) for various process models, simultaneously (Subramanyam et al., 2012). The many different researches are have been doing to find effective methods for setting up coefficients of PID controller and IMC which is based on rboust control procedure is one of them. The process model is embedded into control system in IMC based control method and a tunable parameter is used to ehnance controller performance (Nasir and Singh, 2015).

On the other hand, researchers try to introduce control method based on human ability such as learning and decision making for example fuzzy system and neural network. Finally, Jyh-Shing Roger Jang proposed intelligent system based on combinition of fuzzy and neural network in 1993 that has been called ANFIS (Jang, 1993). ANFIS applies learning ability of neural network to creat membership function parameters of fuzzy system. In fact, ANFIS uses advantages of neural network and fuzzy systems simultaneously.

In this paper, IMC and ANFIS are used to proposed new control strategy which ANFIS based controller find the best parameter to add with coefficients of IMC PID controller (K_p, K_i, K_d) to improve perfomance characteristics of PMDC motor.

Description of PMDC motor structure is given in section 2, then concept of IMC PID is explained in section 3. ANFIS is briefly described in section 4 and

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the proposed controller is introduced in section 5. The simulation results are considered in section 6. Finally, proposed strategy and simulation results are summarized in section 7.

2 PERMANENT MAGNET DC MOTORS

The proposed control method is designed to improve characteristics of PMDC motor so dynamic model should be investigated.

The state-space equations are extracted from both the electrical circuit and mechanical equations of motion (Shahgholian and Shafaghi, 2010):

$$\frac{di_A(t)}{dt} = -\frac{R_A}{L_A} i_A(t) - \frac{K_T}{L_A}\omega_M(t) + \frac{1}{L_A}U_T(t) \quad (1)$$

$$\frac{d\omega_M(t)}{dt} = \frac{K_T}{J_M} i_A(t) - \frac{B_M}{J_M}\omega_M(t) - \frac{1}{J_M}T_L(t) \quad (2)$$

The PMDC motor parameters are summarized in Table 1 (Moussavi et al., 2012, Shahgholian and Shafaghi, 2010).

Table 1: PMDC motor parameters.

Symbol	Description
ω_M	Rotor speed
i_A	Motor current
B_M	Viscous friction constant
J_M	Inertia of rotor
T_L	Load torque
R_A	Armature resistance
L_A	Armature inductance
K_T	back electromotive force (emf) constant or torque constant
U_T	Applied voltage to motor
T_E	Electromagnetic torque
u_b	Back emf

If the motor current and rotor speed are chosen as state variables, the state-space equations are described as below (Moussavi et al., 2012):

$$\frac{d}{dx}\begin{bmatrix} i_A \\ \omega_M \end{bmatrix} = \begin{bmatrix} \frac{-R_A}{L_A} & \frac{-K_T}{L_A} \\ \frac{K_T}{J_M} & \frac{-B_M}{J_M} \end{bmatrix} \begin{bmatrix} i_A \\ \omega_M \end{bmatrix} + \begin{bmatrix} \frac{1}{L_A} & 0 \\ 0 & \frac{-1}{J_M} \end{bmatrix} \begin{bmatrix} U_T \\ T_L \end{bmatrix} \quad (3)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_A \\ \omega_M \end{bmatrix} + \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} U_T \\ T_L \end{bmatrix} \quad (4)$$

The equations (3) and (4) are converted to transfer function model as follow (Moussavi et al., 2012):

$$\frac{\omega_M}{i_A} = \frac{K_T}{L_A J_M s^2 + (R_A J_M + L_A B_M)s + (R_A B_M + K_T K_T)} \quad (5)$$

The simplified block diagram of PMDC motor is shown in Figure 1.

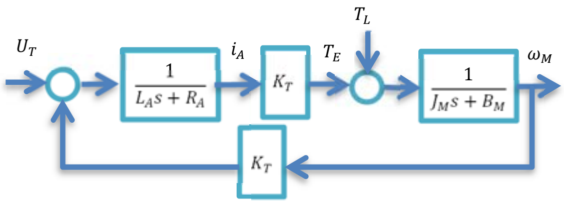

Figure 1: PMDC Motor.

3 INTERNAL MODEL CONTROL

The effective conventional control method for closed loop system is called PID controller that simplicity of structure and easy implementation are main advantages of them. PID controller has three main parameter (K_p, K_i, K_d). K_p is proportion coefficient which is applied to increases or to decreases the value of the output. K_i is called integral time and it is applied to reduce the steady-state error of the system. The other parameter is derivative time (K_d) which rises the value of output slightly fast to improve transient response (Chen and Chang, 2018). Different methods such as Ziegler–Nichols, Chien–Hrones–Reswick and Internal Model Control are used to adjust PID controller parameters.

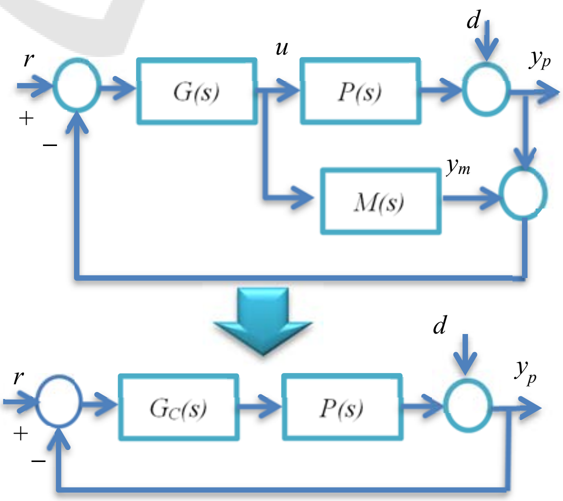

Figure 2: Equivalent the IMC to general control structure.

Equivalent the typical internal model structure to a single loop PID control structure is as Figure 2, Where *P(s)* is the actual process, *M(s)* refer to the model of the process, and *G(s)* is the IMC primary controller, *u* refer to output of internal model controller, *r, y* and d refer to the input, the output and load disturbances, respectively, and *Gc(s)* is the controller which can get the result of internal model controlling structure after varying equivalently. The IMC controller is designed as below (Naik and P.Srikanth, 2011):

$$G(s) = M(s)^{-1}\ f(s) \tag{6}$$

Where $\frac{1}{\lambda s+1}$ is the realizable factor (Naik and P.Srikanth, 2011).

$$G_C(s) = \frac{G(s)}{1 - G(s)M(s)} = K_C\left(1 + \frac{1}{T_i s} + T_d s\right)$$
$$= K_P + \frac{K_i}{s} + K_d s \tag{7}$$

Consider the plant model M(s) as the PMDC motor transfer function then (Naik and P.Srikanth, 2011):

$$M(s) = \frac{K_T}{L_A J_M s^2 + (R_A J_M + L_A B_M)s + (R_A B_M + K_T K_T)} \tag{8}$$

Substitute equation (8) in equation (7) and IMC-PID tuning parameters are given as (Naik and P.Srikanth, 2011):

$$K_p = \frac{R_A J_M + L_A B_M}{K_T \lambda}$$
$$K_i = \frac{R_A B_M + K_T K_T}{K_T \lambda} \tag{9}$$
$$K_d = \frac{L_A J_M}{K_T \lambda}$$

4 ANFIS CONTROLLER

ANFIS is most effective and important neuro-fuzzy system that was introduced by Jyh-Shing Roger Jang in 1993(Jang, 1993). ANFIS is the best combination of fuzzy controller (FC) and neural network (NN) which is applied human learning ability of neural network to provide membership functions and rules of fuzzy system(Simon and Geetha, 2013). ANFIS rules and structure are explained as below:

Rule 1: If x is A_1 and y is B_1 then $f_1=p_1 x+ q_1 y + r_1$

Rule 2: If x is A_2 and y is B_2 then $f_2=p_2 x+ q_2 y + r_2$

ANFIS architecture is shown in Figure 3. The process of every ANFIS layer is summarized as below (Chen and Chang, 2018):

Layer 1: Calculate the correct value for the parameters of the membership function.
Layer 2: Determine the value of firing strength.
Layer 3: Calculate for normalizing the firing strength.
Layer 4: Offer the result rules of the FIS.
Layer 5: Sum up all inputs to express the overall output

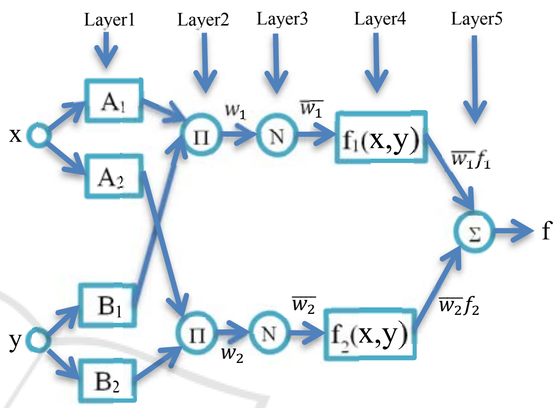

Figure 3: Equivalent ANFIS.

The proposed control system is introduced in next section.

5 PROPOSED CONTROLLER

The proposed method is designed based on IMC PID and ANFIS controllers to obtain more reasonable performance characteristics. The equation (9) is used to obtain coefficients of IMC PID controller then three ANFIS controller applied to extracted proper values of (ΔK_p, ΔK_i, ΔK_d). The coefficients of ANFIS and IMC PID controllers have been added to improve performance characteristics of PMDC motor. The block diagram of proposed controller is shown in Figure 4.

Figure 4 shows that each ANFIS controller is multi input and single output; therefore three ANFIS controllers are needed. 4001 input-output pairs are applied for training, checking and testing each of ANFIS controllers. The (ΔK_p, ΔK_i, ΔK_d) are determined according to the error and derivation of error.

The input membership functions of ANFIS controllers are shown in Figures 5, 6 and 7.

Two triangle input membership functions and four linear output membership functions are used in ANFIS controllers. The grid partition is applied to generate fuzzy inference system also optimization is done by hybrid method. The type and number of input membership functions effect on the training, checking and testing errors.

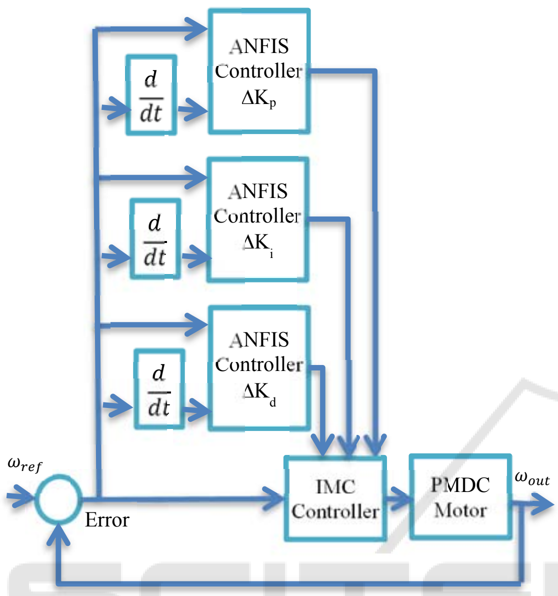

Figure 4: Proposed controller.

Training, checking and testing errors of ANFIS controllers are shown in Table 2.

Table 2: Training, checking and testing errors of ANFIS controllers.

ANFIS controller	Training Error	Checking Error	Testing Error
ΔK_p	0.0035849	0.0035722	0.0035763
ΔK_i	0.0015141	0.0015139	0.0015181
ΔK_d	4.221×10^{-5}	4.2191×10^{-5}	4.2076×10^{-5}

The values of (ΔK_p, ΔK_i, ΔK_d) are determinate based on error and derivation of error that are shown in Figure 4. The surfaces of three controllers have smooth changes so there are not any suddenly variations in (ΔK_p, ΔK_i, ΔK_d) according to (e and de/dt).

Table 3: Fuzzy rules of ΔK_p ANFIS controller.

de / e	In 2 mf1	In2mf2
In1mf1	$out1mf1 = -0.01371e - 0.001193\frac{de}{dt} + 1.113\times10^{-6}$	$out1mf2 = 6.186e - 0.001413\frac{de}{dt} - 0.001474$
In1mf2	$out1mf3 = 0.03644e - 0.2659\frac{de}{dt} + 0.0002273$	$out1mf4 = 6.249e - 0.2658\frac{de}{dt} + 0.1243$

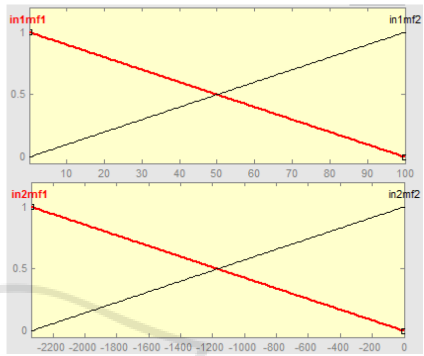

Figure 5: Input membership function of ΔK_p controller.

The membership functions and fuzzy rules of ΔK_p controller are shown in Figure 5 and Table 4, respectively. Every input have two membership functions so four linear rules describe all possible conditions.In this manner, ΔK_i and ΔK_d fuzzy controllers have same property.

Table 4: Fuzzy rules of ΔK_i ANFIS controller.

de / e	In 2 mf1	In2mf2
In1mf1	$out1mf1 = 0.05659e + 0.0007924\frac{de}{dt} - 5.158\times10^{-7}$	$out1mf2 = 21.79e + 0.0004134\frac{de}{dt} - 0.0007318$
In1mf2	$out1mf3 = 0.02298e - 0.9302\frac{de}{dt} + 0.0007956$	$out1mf4 = 21.77 - 0.9303\frac{de}{dt} + 0.4356$

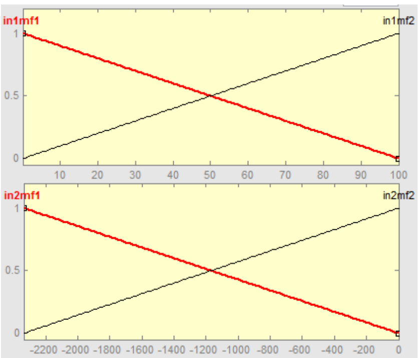

Figure 6: Input membership function of ΔK_i controller.

The number and shape of membership functions effect on performance of ANFIS controllers so changing number or shape of membership function increase designing error.

Table 5: Fuzzy rules of ΔK_d ANFIS controller.

de / e	In 2 mf1	In2mf2
In1mf1	$out1mf1 = -4.888 \times 10^{-5} e - 1.452 \times 10^{-5} \frac{de}{dt} + 1.267 \times 10^{-8}$	$out1mf2 = 0.1401e - 1.514 \times 10^{-5} \frac{de}{dt} - 1.451 \times 10^{-5}$
In1mf2	$out1mf3 = 0.0005619e - 0.005999 \frac{de}{dt} + 5.13 \times 10^{-6}$	$out1mf4 = 0.1408e - 0.005998 \frac{de}{dt} + 0.002809$

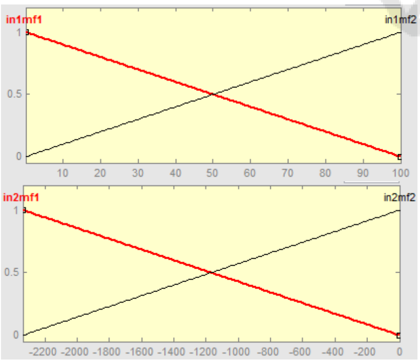

Figure 7: Input membership function of ΔK_d controller.

The simulation results that include step response of PMDC motor in different conditions such as no load, increasing reference speed, applied load and noisy load are shown in next section. The performance characteristics are expressed section 6.

6 SIMULATION RESULTS AND DISCUSSION

The case study is PMDC motor and parameters are as follows(Shahgholian and Shafaghi, 2010):
R_A=7.72 ohm, L_A= 0.16273 H, K_T=1.25 Nm, B_M=0.003 N.m.s/r and J_M= 0.0236 kg.m^2.

At first, the without controller close loop system is investigated in Figures 8-11.

The without controller system has reasonable rise time and settling time whereas steady state error is undesirable and closed loop system has overshoot.

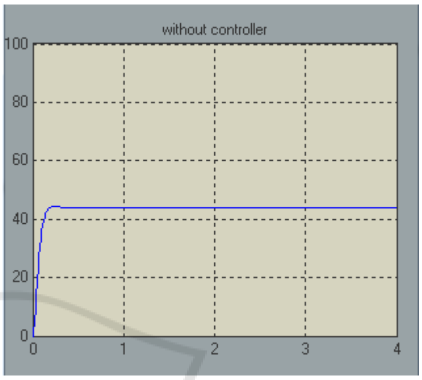

Figure 8: Step response of without controller system (no load condition).

The new reference speed that equals 120 rad/sec is applied in t=2 sec and Figure 9 shows that system cannot receive new reference speed.

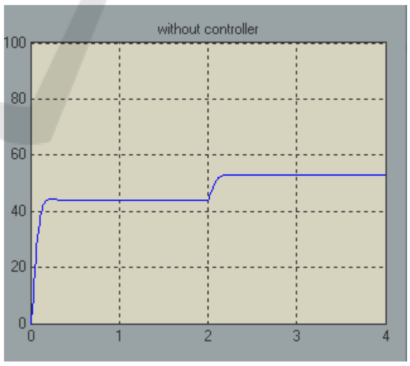

Figure 9: Step response of without controller system (increasing reference speed condition).

Load torque (10 N.m) is applied in t=2 sec. Figure 10 shows that system cannot recovery steady state speed.

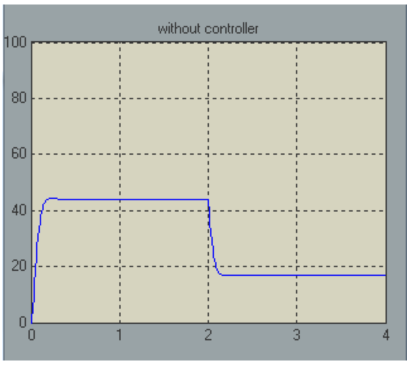

Figure 10: Step response of without controller system (applied load condition).

The noisy load is applied to system that noise power equal 0.01w. The undesirable oscillation is shown in Figure 11.

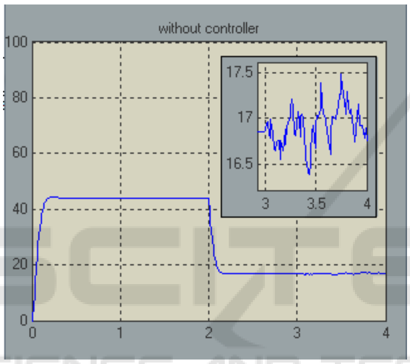

Figure 11: Step response of without controller system (applied noisy load condition).

Figure 12 shows that proposed and IMC PID systems have more reasonable overshoot and steady state error than without controller system. Moreover, Figure 12 shows that proposed controller has shorter rise time and settling time than IMC system.

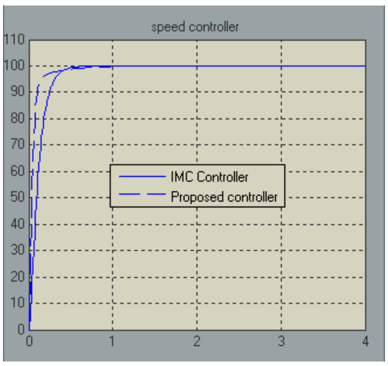

Figure 12: Step response of control systems (no load condition).

Figure 13 shows that proposed and IMC PID systems can attain new reference speed whereas without controller system doesn't have such capability. Moreover, proposed controller has the shortest rise time to reach new reference speed.

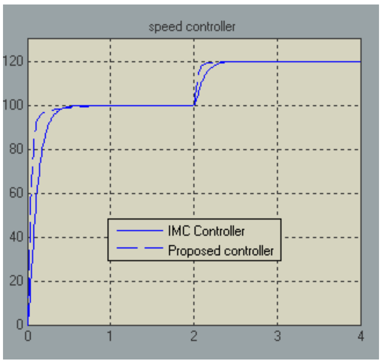

Figure 13: Step response of control systems (increasing reference speed condition).

Figure 14 shows that proposed and IMC PID systems have better performance characteristics than without controller system because they can recover steady state speed. The proposed controller has the smallest percent minimum speed due to applying load and the shortest recovery time.

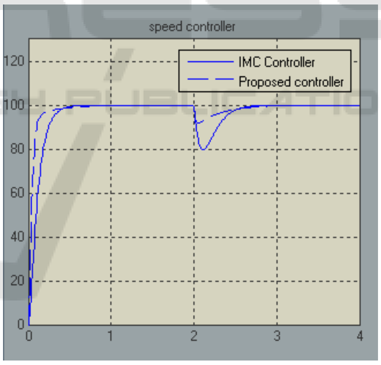

Figure 14: Step response of control systems (applied load condition).

Figure 15 shows step response of both control systems in applied noisy load condition. Proposed controller has the smallest percent oscillations in applied noisy load condition.

Tables 6-8 show the performance characteristics of control systems in different conditions. Rise time, settling time, maximum overshoot and steady state error are given in Table 6.

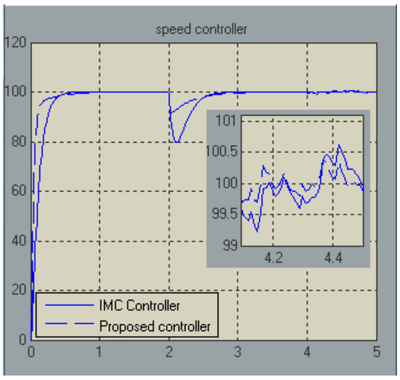

Figure 15: Step response of control systems (applied noisy load condition).

Table 6 shows that proposed controller has the shortest rise time. Moreover, proposed controller has more reasonable settling time, maximum overshoot and steady state error. Without controller has the shortest settling time whereas rise time, maximum overshoot and steady state error of without controller system are undesirable.

Table 6: Performance characteristics of control system in no load condition.

Method	Rise Time (sec)	Settling time (sec)	Maximum overshoot (%)	Steady state error (%)
Without controller	0.1024	0.1637	0.33	55.9186
IMC controller	0.219	0.3983	0	0
Proposed controller	0.0892	0.345	0	0

Table 7 shows that without controller system doesn't have reasonable behaviour in increasing reference speed whereas proposed controller has the shortest rise time to achieve new reference speed.

Table 7: Performance characteristics of control system in increasing reference speed.

Method	Final speed (rad/s)	Rise time (s)
Without controller	-------	---------
IMC controller	120	0.2209
Proposed controller	120	0.0891

Table 8 shows without controller system cannot recover steady state speed whereas proposed controller has the shortest recovery time and the smallest percent minimum speed due to applying load in applied load condition.

Moreover, Table 8 shows that proposed system has the smallest percent oscillations in applied noisy load condition. Tables 7 and 8 show that proposed controller has shorter rise time and recovery time, also smaller percent minimum speed due to applying load and percent oscillations than IMC PID controller.

Table 8: Performance characteristic of control system in applied load and noisy load condition.

Method	Applying load		Applied noisy load
	Recovery time (s)	Percent minimum speed due to applying load (%)	Percent oscillations (%)
Without controller	---------	---------------	6.5475
IMC controller	0.5214	20.2977	1.3846
Proposed controller	0.4921	8.1908	1.0462

7 CONCLUSIONS

The performance characteristics of PMDC motor in closed loop system are investigated in different condition such as No load – Changing reference speed – applied load – applied noisy load. The simulation shows that proposed controller has more reasonable rise time, settling time, overshoot and steady state error than IMC based controller in no load condition. Proposed control system has shortest rise time in increased reference speed condition. The percent minimum speed due to applying load and recovery time of proposed controller is more reasonable than IMC based system in applied load condition. When noisy load applied to PMDC motor, proposed control system shows more reasonable performance characteristic than IMC system. Percent oscillations of proposed controller and IMC based system equal 1.0462% and 1.3846%, respectively.

The computation time of Sugeno inference that is used in ANFIS is shorter than Mamdani fuzzy system. In the other hand, implementation of proposed controller because of minimum rule base is so easy.

The simulation results show more reasonable performance characteristics in different conditions.

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