Research Article

Artificial Intelligence Based First Order Adaptive Sliding Mode Controller for Position Control of a DC Motor Actuator

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Abstract

This paper presents an Artificial Intelligence (AI) based approach uniquely applied to permanent magnet DC motor actuator for position control. The AI method employed in this work is fuzzy logic. A first order lag sliding mode controller is tuned and combined with an adaptive Fuzzy-PI controller architecture which operates in parallel. The controller architecture proposed in this study is aimed at improving the disturbance rejection capability, steady state as well as transient performance of the conventional adaptive Fuzzy-PI controller and sliding mode controller. Hence, the robust control law of the proposed controller (SM+FZ-PI) consists of a discontinuous sliding mode output added to a continuous adaptive Fuzzy-PI controller output. The sliding mode controller switches on only when disturbance in the system is detected. The performance of the proposed controller architecture has been compared with a conventional PID and adaptive Fuzzy-PI controllers for performance evaluation with respect to several operating conditions such as load torque disturbance injection, noise injection in feedback loop, motor non-linearity exhibited by parameters variation, and a step change in reference input demand. The proposed controller (SM+FZ-PI), had the best disturbance rejection and steady state error elimination.

Keywords: Sliding mode control, Adaptive Fuzzy control, DC motor position control, PID controller

1 Introduction

The Permanent Magnet Direct Current (PMDC) motor can be operated within a wide range of speed (position) while rendering high performance delivery. The use of DC motor is extensive and has application in: the Industry; rolling mills, electric cranes, electric locomotives; trains, trams, cars, and robotics [1]–[8].

The speed of a DC motor and torque depend proportionally on the applied voltage and armature current respectively. This is such that in order to sustain a constant motor speed in a situation of sudden load torque on the rotor, the current drawn increases and if not meet, stalling occurs [9], [10]. Therefore, in speed or position control a controller of high performance which is defined by a good load torque disturbance rejection, and exhibits minimal or no overshoot is desirable. The conventional proportional-integral-controller family is very popular for industrial control system use. The PID controller can be tuned by Ziegler-Nichols (Z-N), root locus pole placement, trial and error method or by some form of optimization technique such as genetic algorithm or particle swarm optimization.

The conventional controller does not guarantee an optimal response after tuning as a degree of overshoot, steady state error and long settling time are often a trade-off for a fast rise time [11]. During the drive operation, since the conventional controller gains tuned offline remain static and non-varying in the prevalence

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of nonlinearities, motor parameter changes caused by mechanical wear and tear in motor drive as well as disturbance, the output response is affected [11]. The fuzzy logic controller is famous for negating the effect of non-linearity. In dealing with motor non-linearity, a more robust architecture, Fuzzy-PI has been presented in papers [2], [12], [13] which are adaptive and consists of a fuzzy controller structure for varying the fixed gains of a PID controller. Authors of paper [2], [14], [15] have presented sliding mode control as a simple robust solution for dealing with dynamic higher order plant operating under stochastic conditions. The ideal sliding mode requires switching at an infinite frequency in other to stay on the sliding surface. Hence, exhibits chattering which is undesired oscillations of finite frequency due to practical limitations in ON/OFF switching. However, chattering may be reduced to a satisfactory level by employing a hysteresis boundary [16], [17]. The PID controller generally exhibits offset and overshoot when implemented in position control due to the incrementing action of the integrator. The fuzzy controller has poor disturbance rejection despite the advantage of an excellent no overshoot transient performance. Also sliding mode controller exhibits chattering and tends to overshoot despite being robust to disturbance rejection. This paper therefore suggests an architecture that takes all the merits of the three controller types and neglects their shortcomings. Also, the proposed first order lag fuzzy adaptive sliding mode controller architecture method is geared towards handling the peculiar problems which are associated with DC motor position control (load torque disturbance, change in reference input, non-linearity and sensitivity to noise).

In this work, the sliding mode and PI controller outputs are adaptive in the sense that the fuzzy logic controller automatically tuned the gains of these controllers to negate parameter variations. On the one hand, fuzzy logic controller is to tune the PI controller during transient state. However, it exhibits a wide dip during load torque injection. On the other hand, sliding mode controller when used alone exhibits chattering during steady state, but has a great load torque disturbance rejection. Hence, to have an adaptive controller, fuzzy logic was used to tune PI for transient state and a combination of sliding and PI tuned by fuzzy logic was used to reject load torque disturbance at steady state.

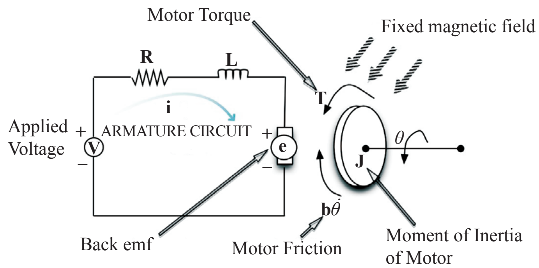

Figure 1: A schematic diagram of a DC motor [9].

2 Materials and Methods

2.1 *DC motor modelling*

The mathematical equation required for modelling the DC motor is derived using Kirchhoff's voltage law and Newton's second law of motion for the armature circuit and mechanical rotor shaft respectively. The DC motor schematic diagram is shown in Figure 1.

By Kirchhoff's voltage law, the armature circuit equation is determined according to [5], [9]:

$$L\frac{di}{dt} + Ri = V - E \tag{1}$$

Also by Newton's second law of motion, the mechanical rotor equation is given:

$$J\ddot{\theta} = T - b\dot{\theta} \tag{2}$$

Where,

$$w = \frac{d\theta}{dt} = \dot{\theta} \tag{3}$$

By applying Laplace transform to equation (1) and (2) the equations become:

$$LSI(s) + RI(s) = V - KW \tag{4}$$

$$JSW(s) + bW(s) = KI(s) \tag{5}$$

By the elimination of I (s) in equation (4) and (5) and applying (3) the transfer function encompassing output position and input voltage is derived:

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{K}{\left\{(JS+B)(LS+R)+K^2\right\}S} \tag{6}$$

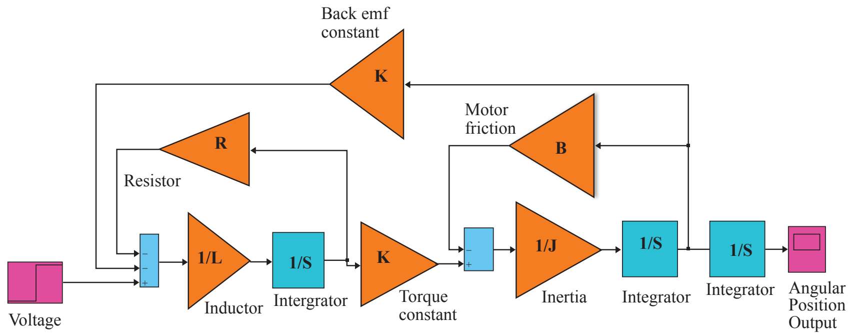

Figure 2: DC motor model in Simulink.

Where,
I is the current in the armature winding (in ampere)
E is the armature winding back E.M.F (in volt)
R is the armature winding resistance (in ohm)
V is the armature voltage (in volt)
T is mechanical torque (in Nm)
K is the motor torque and back E.M.F constant (Nm/A)
L is the armature winding inductance (in Henry)
J is moment of inertia of the motor (in Kgm^{-2})
B is the motor's coefficient of frictional (in Nm/(rad/sec))
ω is angular velocity of the mechanical rotor shaft (rad/sec)
θ is the angular position of the mechanical rotor shaft (rad)

The DC motor SIMULINK model which is modelled from the mathematical differential equations for the motor is shown in Figure 2.

2.2 *PID conventional controller*

The conventional Proportional-Integral-Derivation (PID) controller with subsets Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD) are the most extensively used in the industry for controlling linear systems. The PID controller is popular because it offers fairly good response, it is modest and can be built easily [3], [18]. However, in the prevalence of motor parameter changes due to motor operation, non-linearity, model uncertainty as well as the effect external disturbance during operation, the linear PID controller falls short in performance due to unvarying controller gains. [18]. The mathematical representation of the PID controller is:

$$U_{PID}(t) = K_P e(t) + K_I \int e(t)dt + Kd * \frac{de(t)}{dt} \qquad (7)$$

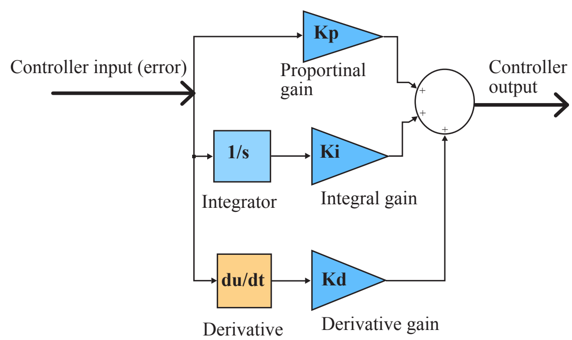

Figure 3: Schematic of the PID controller.

Where: e signifies error, K_P denotes the proportional gain constant, K_D represents the derivative gain constant, is K_I the integral gain constant, T_d is the derivative time and T_i is the integral time. [3]. The gains of the PID controllers are determined Root locus method and thereafter optimized. The SIMULINK model of PID controller is shown in Figure 3.

2.3 *Fuzzy logic controller*

The fuzzy logic theory was first introduced by L.A Zadeh in 1973, afterwards in 1974, Mamdani applied it for controlling systems structurally complex to model. In a typical control problem the input to the fuzzy controller is the error signal; error and change in error [3], [5]. The constituents of the fuzzy controller are the fuzzification interface, rule base, the inference mechanism and defuzzification interface. Optimum response depends not only on tuning the scaling input and output gains, but also on the rules and membership functions [2], [20]–[22].

2.3.1 Fuzzification

This interface receives the fuzzy input data which are converted to a degree of membership in one or more than one membership function depending on the linguistic rules [23].

2.3.2 Membership function

The Membership Function (MF) shape usually depends on trial and error and also in the control process. The triangular and trapezoidal MFs are easy to implement hence commonly selected. At the initial design a starting point is to keep the MFs equal also they have to overlap at least 50% in order to avoid null firing rule or undefined function. The fuzzy set typically consists of "NB (Negative Big)", "NM (Negative Medium)", "Z (Zero)", "PM (Positive Medium)" and "PB (Positive Big)" membership functions [23].

2.3.3 Rule base

The fuzzy rules are heuristic logical rules that depend basically on operator's experience with the system and necessary for handling the control task and may involve observing the phase plane of the error and derivative error and also the consequent step response of the closed loop system.

Typical fuzzy rules are of the form:

If error is Negative Big (NB) and Change in Error is Zero (Z) then Control output is NB.

This is logical as the rule seeks to reduce the output since a negative error signifies an overshoot situation and has been presented by authors [9], [23], [24].

2.3.4 Defuzzification

The output necessary for plant actuation is a crisp value and it is calculated from the overall fuzzy set using the defuzzification method. The common defuzzification methods are: [19]

i. Center of Gravity (COG):

$$U_{COG} = \frac{\sum_i U_c(x_i) X_i}{\sum_i U_c(x_i)} \tag{8}$$

ii. Bisector of Area (BOA):

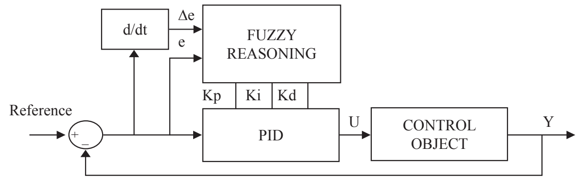

Figure 4: The adaptive Fuzzy-PID controller schematic [1].

$$\left|\sum_{i=1}^{n} U_c(x_i) - \sum_{i=n+1}^{i_{\max}} U_c(x_i)\right|; i \angle n \angle i_{\max} \tag{9}$$

Where, x_i depicts the point on the universe of discourse ($i = 1,2, \ldots k$) and $U_c(x_i)$ is the degree of membership for the input set.

2.3.5 Adaptive Fuzzy-PI (FZ-PI) and Fuzzy-PID (FZ-PID) controller

The short comings of an offline method in dealing with nonlinearities and parameter variation present in drives control paved the way for a self-tuning algorithm. The armature winding resistance may vary with temperature up to 50% as well as magnetizing inductance, and friction and inertia may increase due to mechanical wear and tear during operation. Hence, in dealing with these non-linearities associated with drive control the offline tuning paved the way for the online adaptive tuning method. The fixed PID controller gains are constantly adjusted to counteract the nonlinear effect and disturbance [11]. The adaptive Fuzzy-PI controller is implemented for tuning the fixed PI controller gains by author [2] in speed control of induction motor. The adaptive Fuzzy-PID structure is presented in paper [1] and schematics shown in Figure 4.

The scaling gains of the fuzzy controller which have to be tuned go a long way in influencing the transient response of the system. However, no set standard for tuning the scaling gains exists as authors suggest using trial and error which is tedious [2], [3], [12].

3 Proposed Sliding Mode Plus Adaptive Fuzzy-PI (SM+FZ-PI) Controller Design

The proposed controller design comprises of a first order lag sliding mode controller tuned by an adaptive fuzzy logic PI controller for an improved transient and steady state performance.

The open loop third order transfer function representing the plant under investigation is given as:

$$G(s)=\frac{\theta(s)}{J(s)}=\frac{1558}{S^3+70.02S^2+1872S} \tag{10}$$

The DC motor state space representation is also shown:

$$\begin{bmatrix}\dot{\theta}\\ \dot{\omega}\\ i\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & \frac{-b}{J} & \frac{K}{J}\\ 0 & \frac{-k}{L} & \frac{-R}{L}\end{bmatrix}\begin{bmatrix}\theta\\ \omega\\ i\end{bmatrix}+\begin{bmatrix}0\\ 0\\ \frac{1}{L}\end{bmatrix}V \tag{11}$$

3.1 *Sliding mode controller design*

The presence of an integral term deployed in position control which is fundamentally an ON/OFF type of control problem, results in offset due to an incrementing action while the absence of it causes poor rejection of load disturbance. Hence a suitable approach is succinctly proposed such that the injection of an integral action needed to counteract steady state error and load disturbance is only applied for the time duration of the disturbance. The fuzzy based controllers have great control over the conditions with overshoot. Therefore, a negative rate of change observed in the output response confirms the presence of torque disturbance in the system. Hence, a redundant integral term which is switched on and added to the very small integral action of the adaptive fuzzy controller in order to preserve the steady state response. The robust adaptive fuzzy (SM+FZ-PI) controller comprises of a cascaded control architecture to improve transient response and also employs the use of a fuzzy logic to tune the static constant gains of a PI controller. A switched mode integral term is injected whenever disturbance is sensed in the DC motor system output response, for torque load disturbance rejection. As common with ON/OFF control, chattering occurs due to the high frequency. However, this problem is resolved by integrating the output of the switched integral term before it is introduced to the system input and hysteresis is introduced with dead time as a switching delay for the discontinuous control $U_{disc}(t)$. In order to detect a disturbance dip in the controlled variable output $\theta(t)$ a first order lag filter with a time constant τ of 8 mS is used to generate an advanced signal $\theta(t+1)$ from the controlled output variable $\theta(t)$ which becomes the past signal. The first order lag filter is thus expressed as a differential equation:

$$\tau*\frac{d\theta(t+1)}{dt}+\theta(t+1)=\theta(t) \tag{12}$$

And in S domain as a transfer function:

$$F(s)=\frac{\theta(t+1)}{\theta(t)}=\frac{1}{(\tau S+1)} \tag{13}$$

The sliding surface S_o is defined for tracking the controlled variable in the presence of torque load disturbance as:

$$S_o=e_o+\frac{de_o}{dt}=0 \tag{14}$$

where
$e_o=\theta(t+1)-\theta(t)$ and $e_o\neq\theta_{ref}-\theta$

The system is confined to the sliding surface as the first derivative of the sliding surface converges to zero. Hence, reaching surface is defined as:

$$S_o\left(\frac{dS_o}{dt}\right)=S_o\left(\frac{de_o}{dt}+\frac{d^2e_o}{dt^2}\right) \tag{15}$$

If $S_o\left(\frac{dS_o}{dt}\right)\leq\eta\left|\frac{S_o}{\phi}\right|$ where, η is a negative real constant (16)

Then $S_o\left(\frac{dS_o}{dt}\right)\angle 0$ will ensure sliding occurs at $S_o=0$

The Lypunove Stability Proof:
Given that

$$\dot{X}(t)=f(x(t),u(t),t) \tag{17}$$

Let us assume that the energy associated with the system is given as V(e). For the system to remain stable, then derivative of the energy associated with the system must be less than zero (or negative).

$$\frac{dV(e)}{dt}\leq 0 \tag{18}$$

V(e) is known as Lyapunov quantity.

For the system under consideration, the reaching surface is described as:

$$\frac{de_o}{dt}+\frac{d^2e_o}{dt^2} \tag{19}$$

Let us assume a Lyapunov function:

$$V(e) = 2e^2 – e \tag{20}$$

Therefore, the differential of V is given as:

$$\frac{dV(e)}{dt}=4e-1 \tag{21}$$

Now at $e = 0$, then the above equation becomes:

$$\frac{dV(o)}{dt}=-1 \tag{22}$$

This shows that the system is stable, since the derivative of the Lyapunov scalar quantity is less than zero.

The robustness of the controller to a great extent depend on the boundary layer thickness ϕ. Also to inhibit chattering in the output response a dead time with upper and lower boundary threshold ϕ is selected as $\pm 10^{-4}$

The DC motor control law $U_{SM+FZ-PI}(t)$ expressed mathematically, as the continuous $U_{cont}(t)$ and discontinuous $U_{disc}(t)$ functions is given as:

$$U_{SM+FZ-PI}(t)=U_{cont}(t)+U_{disc}(t) \tag{23}$$

$$U_{cont}(t)=-K_1\times\theta(t)-K_2\times\frac{d\theta(t)}{dt}+K_pe(t)$$
$$+K_1\left[\Delta K_{p\min}-\Delta K_{p\max}\right]+K_1\int_0^T e(t)dt+K\times$$
$$\left[\Delta K_{i\min}-\Delta K_{i\max}\right] \tag{24}$$

Where,
$\Delta K_{p\min}$ and $\Delta K_{p\max}$ are the fuzzy output finite range for incrementing proportional control action.
$\Delta K_{i\min}$ and $\Delta K_{i\max}$ are the fuzzy output finite range for incrementing integral control action.
Ki and Kp are the PI controller integral and proportional gains.

Furthermore, for an improved damping during transient state, the DC motor output and derivative of the DC motor output are scaled and utilized as damping feedback loop to motor input.

The discontinuous control law $U_{disc}(t)$ runs in parallel with $U_{cont}(t)$ and triggered ON only if the resultant summation of $\theta(t + 1)$ and $\theta(t)$ is negative since this depicts injected disturbance in the system.

The chattering problem associated with Bang-Bang control is eliminated by integrating the output of the discontinuous controller and also selecting suitable hysteresis boundary layer [16], [17]. The mathematical representation of the sliding mode discontinuous control is represented:

$$U_{disc}(t)=\int_0^T sat(\frac{S_o}{\phi})dt \tag{25}$$

$$\mathrm{Sat}(S_o/\phi)=\left\{\begin{matrix}1\to\theta(t+1)-\theta(t)<0\\0\to\theta(t+1)-\theta(t)\geq 0\end{matrix}\right\},\ t = 1,2,3\ldots n \tag{26}$$

Where,
K1 and K2 are scaling factors for position and velocity feedback attenuators
$sat(S_o/\Phi)$ is the discontinuous saturation term with the hysteresis boundary for robust control
$\theta(t + 1)$ and $\theta(t)$ (t) are present and past DC motor angular position responses respectively

The SIMULINK model of SM+FZ-PI controller is shown in Figure 5.

3.2 *Fuzzy logic design*

The robust first order lag adaptive sliding mode controller's fuzzy rule base for Kp and Ki control action is designed to deal with parameter variations and model uncertainty. The MF consists of seven fuzzy sets, 'NB', 'NM', 'NS', 'Z' ,'PS', 'PM', 'PB'. All the fuzzy sets are triangle MFs except the NB and PB which are both trapezoidal MFs. The MFs are adjusted by trial and error to ensure optimal response. By adjusting the base of the error and change in error, triangular MF to be narrow, a tight control is achieved which improves the steady state response. The universe of discourse ranges is [–3 3] for all MFs. The MF set for error and change in error, Kp and Ki as well as the 3D surface plot are shown in Figure 6, 7 and 8 respectively. Table 1, shows the 49 fuzzy rules for tuning Kp and Ki.

The fuzzy sets used for position control, is such that the MFs overlap in order to ensure rules are fired for all time. Also the defuzzification method implemented for position control is the Bisector of Area (BOA).

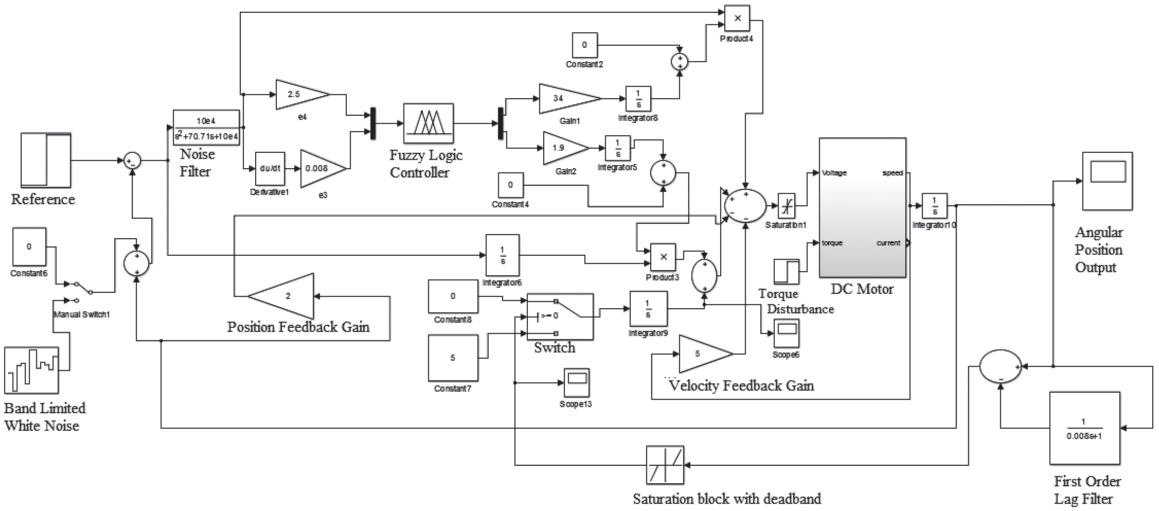

Figure 5: First order lag adaptive sliding mode controller architecture modelled in SIMULINK.

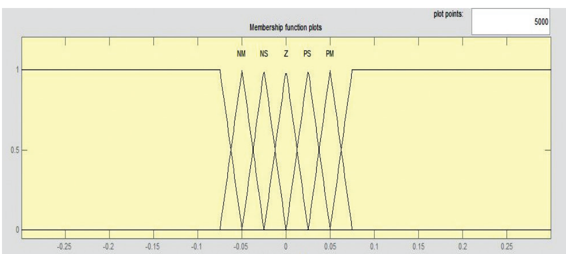

Figure 6: MF for error and change in error input variables.

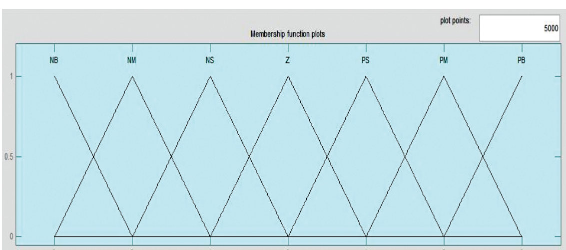

Figure 7: MF for Kp and Ki output variables.

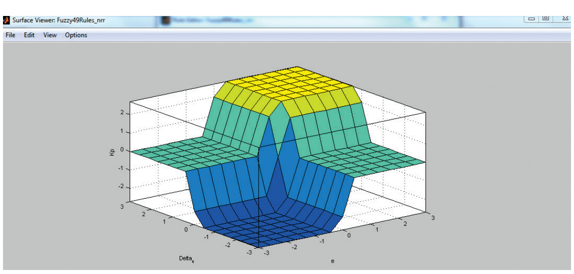

Figure 8: 3D surf mapping of the adaptive rules for position control.

Table 1: Fuzzy control rules for ΔKp and ΔKi

e/de	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NM	NM	NS	NS	Z	PS	PS
ZE	NM	NS	NS	Z	PS	PS	PM
PS	NS	NS	Z	PS	PS	PM	PM
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PS	PM	PB	PB	PB

4 Simulation Results and Discussion

The DC motor closed loop control simulation was performed in MATLAB/SIMULINK environment using the SIMULINK controller models presented. The motor parameters are shown in Table 2, while Table 3 and 4 shows the controller gains.

The conventional PID, the adaptive FZ-PI and robust first order lag adaptive sliding mode controllers are tuned by trial and error. The DC motor position responses-of the controllers are compared like-for-like with the aim of sorting out the optimal controller. The performance evaluation, therefore investigates the aptness of each of the optimized controllers to counteract the effect of disturbances and response to change reference demand during the normal operation, motor parameter variations (increased resistance and motor inertia) and noise injection.

During, the noise disturbance test a second order low pass filter of 77Hz bandwidth is used to block-off the high frequency components of the derivative block introduced by the noise signal. The transfer function is given as:

$$T(s) = \frac{K_{DC} w_o}{S^2 + \frac{w_o}{Q_f} + w_o} \tag{27}$$

Where, K_{DC} is the DC gain, wo is frequency of roll-off and Q_f is pole quality factor.

$$T(s) = \frac{10^4}{S^2 + 70.71S + 10^4} \tag{28}$$

The evaluation for optimal position controller is made strict as many position control processes require precision and critically damped response with good torque rejection and ideally zero steady state error.

The classical method of system response performance evaluation; rise time *(tr)*, settling time *(ts)*, Maximum percentage overshoot *(Mp)* and the integral error criterion; Integral Absolute Error *(IAE)* and Integral Time Absolute Error *(ITAE)*, are used normal and abnormal operations. The IAE gives an estimate of the overall error during the simulation runtime without adding any weight while the ITAE is similar to the IAE but it is weighted by the simulation time. In the simulation procedure a step input of 1 rad was applied and later increased to 2 rads during the first steady state and thereafter a 0.3Nm disturbance torque load was injected during the second steady state. During the simulation, the change in step input, torque load injection, and overall simulation runtime used was 7s, 15, 30s for all performance evaluation tests.

4.1 *Simulation results*

4.1.1 Motor's performance during normal operation

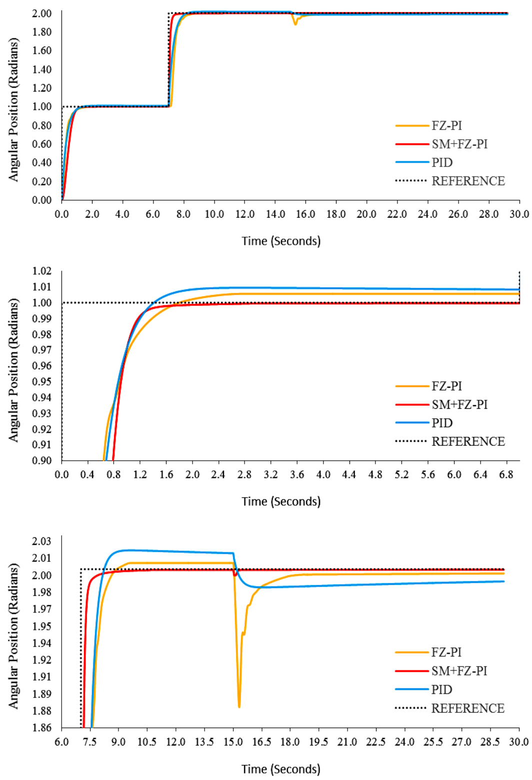

Figure 9: DC motor position response during normal operation.

Table 2: Dc motor parameters

Motor Parameters	Value
Back E.M.F constant 'K'	1.2 *Nm/A*
Moment of inertia for motor rotor 'J'	0.022 $Kg.m^2$
Mechanical damping (friction) factor 'B'	0.0005 *Nms*
Resistance of the armature 'R'	2.45 Ω
Inductance of the armature 'L'	0.035 *H*

Table 3: PID controller gain

Controller Type	KP	KI	KD
PID	20.1862	0.6504	5.001

Table 4: SM+FZ-PI and FZ-PI controller gains

Controller Type	Ke	dKe	K1	K2	KP initial	KI initial	Velocity Feedback	Position Feedback
SM+FZ-PI	2.5001	0.0080	34	1.9	0	0	5	2
FZ-PI	0.3012	0.1001	80	1.9	0	0	-	-

4.1.2. Increase in motor inertia by 50%

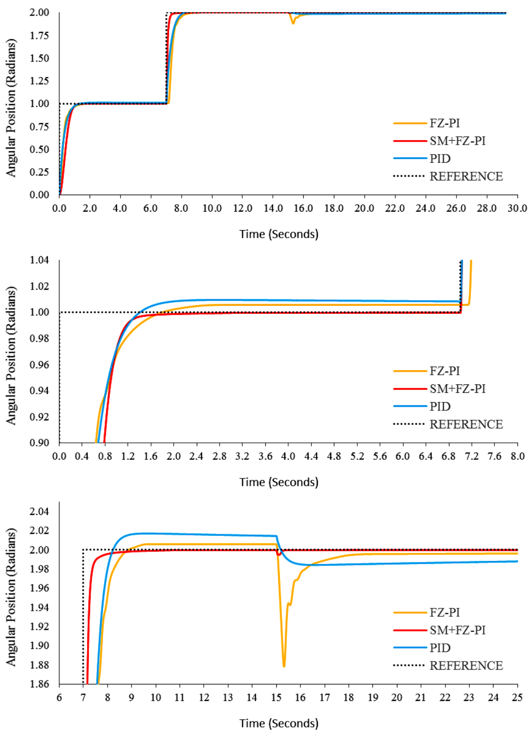

Figure 10: DC motor position response during 50 percent increase in motor inertia.

4.1.3 Increase in motor resistance by 50%

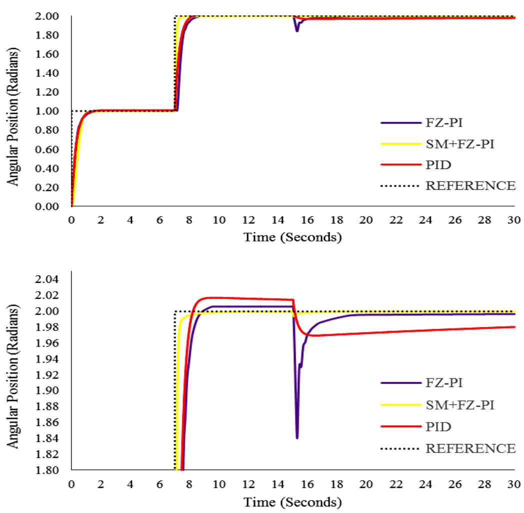

Figure 11: DC motor position response to torque load during 50 percent increase in resistance.

4.1.4 Sensitivity to noise

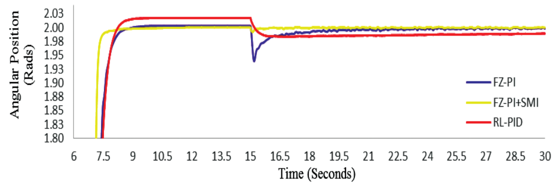

Figure 12: Effect of feedback loop random white noise.

Table 5: DC motor transient and steady state performance for normal operation

Controller Structure	Percentage Overshoot (%)	Rise Time (sec)	1st Steady State Error	Settling Time (sec)	Reaction to Torque and 2nd Steady State Error
FZ-PI	0.59	0.07	–0.00058	0.9	1.878 rads, 0.0035 after 4s
SM+FZ-PI	0	0.46	0.0004	0.4	1.995 rads, 0.0004 after 0.4s
PI	0.92	0.138	–0.00093	0.4	1.985 rads, 0.015 after 5s

Table 6: ITSE and ISE DC motor controllers performance indices

Operational Condition	Controller Type	ITSE	ISE
Normal operation	FZ-PI	6.3485	0.5106
	SM+FZ-PI	1.0155	0.3506
	PI	7.7567	0.3134
50% increase in Inertia	FZ-PI	6.1404	0.4934
	SM+FZ-PI	1.0708	0.3776
	PI	7.8538	0.3172
50% increase in Resistance	FZ-PI	6.6628	0.5159
	SM+FZ-PI	1.0969	0.3568
	PI	11.8197	0.3241
Noise Injection	FZ-PI	4.4824	0.4141
	SM+FZ-PI	1.1220	0.3841
	PI	8.1400	0.3105

4.2 *Discussion*

The results for the performance of all three controllers; PID, FZ-PI, SM+FZ-PI during normal and irregular operations have been presented in Table 5 and 6 respectively. As seen in Figure 9 during normal operation, upon initialization the SM+FZ-PI controller exhibits the slowest rise time but has the fastest settling time. Furthermore, upon a step change in reference demand the SM+FZ-PI has the fastest rise time. The SM+FZ-PI has the least ITAE value for all operating conditions this indicates it has the best precision when compared with the other controllers. In addition, SM+FZ-PI also has the best torque rejection capability and remains stable in the presence of noise and parameter change. For torque rejection capability PID controller follows closely the SM+FZ-PI controller, however, it exhibits the largest steady state error for all time. The effect of noise causes chattering in both the SM+FZ-PI and FZ-PI controllers as seen in Figure 12 due to high frequency switching caused by the noisy signal which constantly triggers the change–in-error rules. The PID controller is the most affected as its voltage spikes up tremendously. Adding a noise filter bring PID controller's voltage to normalcy. Both fuzzy controllers' responses show no change in the prevalence of a 50 percent increase in armature resistance and inertia due to the adaptive nature of the controllers, while the PID controller exhibits a larger overshoot as seen in Figure 10 and 11. Generally, the conventional PID exhibits the most overshoot followed by the FZ-PI controller. The SM+FZ-PI controller does not exhibit overshoot.

5 Conclusion

The proposed artificial intelligence based adaptive sliding mode controller has been shown to be highly effective against disturbances such as load torque and feedback noise. When compared against the adaptive Fuzzy-PI and PID conventional controllers it has the least (negligible) steady state error, hence, it will be more suitable for purposes requiring high precision position control. The manually tuned gains of both the conventional PID, adaptive Fuzzy-PI and the proposed controllers were optimized using genetic algorithm. From the performance indices of the evaluated controllers, the proposed controller has the best accuracy and torque load disturbance rejection during steady state response. During the first reference tracking it has the slowest rise time compared to the adaptive Fuzzy-PI, which exhibits the fastest transient response followed by the PID controller. However, it exhibits the fastest transient when a step change in reference input is applied. The heuristic fuzzy rules and membership function sets have been adjusted to render optimal control.

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