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A hybrid of sliding mode control and fuzzy logic control using a fuzzy supervisory switched system for DC motor speed control

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Abstract: In many applications of DC motor speed control systems, PID controllers are mostly used. Such control schemes do not show good performance when input and load torque disturbances are applied. This paper shows that sliding mode (SM) can give better control due to its robust property but it has an unwanted chattering problem associated with it, which is harmful to the plant. To limit this problem a hybrid controller is presented in which a fuzzy controller is combined with the SM controller by a fuzzy supervisory system in such a way that the SM controller works in transient state and the fuzzy controller in steady state. The simulation results show that the SM controller is more robust when compared to PID and fuzzy control and hybrid control gives overall better system performance and reduced chattering when compared to SM control. Simulations are done using MATLAB software.

Key words: Sliding mode control (SMC), fuzzy control, hybrid control, DC motor

1. Introduction

Recently, DC motors have been mostly used in motion control as actuators and direct drive applications like robotics, actuators for automation process and computer peripherals. These applications of DC motors are due to their simple controllable feature and also the torque produced by this is continuous. Therefore, the study of speed control of DC motors is important. In all industrial and robotics processes there are lots of systems that have inherently nonlinear properties. These properties are unknown and time varying. Due to their simple structure PID controllers are the most common controllers used, but they respond poorly if the system has uncertainties and nonlinearities [1]. Recently in the category of robust control, intelligent systems like fuzzy logic, neural network, and sliding mode control (SMC) have been used [2–4].

Variable structure systems and sliding mode control are found to be best for robust control in uncertain systems [5,6]. The SMC technique utilizes a discontinuous control that forces the system state to remain in a certain predefined manifold known as sliding hypersurface. During the sliding mode, the system becomes a lower order unforced system that shows the desired property, i.e. insensitive to parameter variation and rejection of disturbances that satisfy the matching condition [7,8]. Basic sliding mode controllers are characterized by high frequency switching control, due to finite speed of switching devices, resulting in chattering, which can create mechanical resonance and is harmful to plants [9,10]. Several methods were proposed to reduce chattering, like modifying the discontinuous control action, such that instead of forcing the states to lie on the sliding surface they are forced to remain within a small boundary layer about the surface by using a saturation rather than

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the sign discontinuous function [11]. A boundary layer near the switching surface is employed using fuzzy logic to reduce chattering [12].

The chattering problem can also be overcome by intelligent systems such as GA, which can be utilized in choosing the sliding surface slope and thickness of the boundary layer [13,14]. The zigzag motion in SMC can also be avoided by using fuzzy logic techniques. The knowledge base feature of FLC, which provides the steady control action, can be utilized in reducing the chattering problem of SMC. This is achieved by utilizing the feature of FLC with SMC to form a fuzzy sliding mode control (FSMC) [15]. This type of hybrid control system proves the strength of the SMC, known for its robustness, and chattering is reduced by the FLC.

Hybridization of two types of controllers like PID and FLC is done to achieve better performance [16–18]. In this paper, it is proposed that a fuzzy supervisory system can be introduced in combining the SMC and FLC, which form the hybrid system, to achieve good dynamic response and reduced chattering. SMC and FLC are combined by a fuzzy supervisory system to achieve good dynamic response [19].

The fuzzy supervisory system produces the output by taking the knowledge of error and rate of change of error, and then combines the output of the SMC and FLC in such a way that during the transient period the SMC gives output while during steady state the FLC gives output. In this way, a fast dynamic and reduced chattering response is achieved. The simulation results show the superiority of the proposed control when compared to SMC and FLC also proves the robustness of SMC. The rest of this paper is organized as follows. In Section 2, the DC motor model is presented. In Sections 3 and 4, SMC and FLC are described. Section 5 describes the hybridization by using the fuzzy supervisory system. Section 6 describes the results and discussion. Finally Section 7 gives the overall conclusion of the paper.

2. DC motor model

DC motors are classified as separately and self-excited types. In this paper, a separately excited DC motor is considered for speed control via armature voltage control. The electrical circuit model of the DC motor is given in Figure 1 and the simulation model in Figure 2.

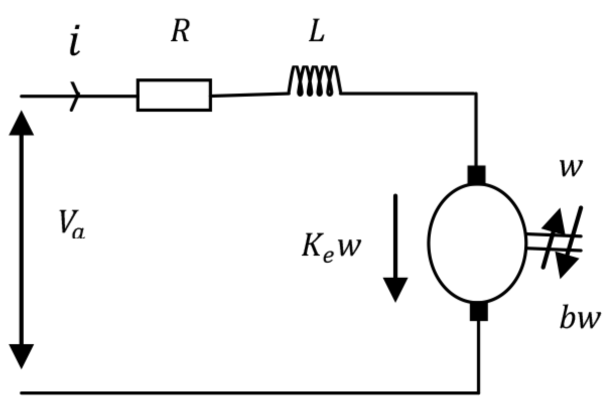

Figure 1. DC motor model.

The dynamics of the motor are represented by two first-order differential equations in terms of armature current and shaft speed [3,4]:

$$L\frac{di}{dt} = u - Ri - K_e w \tag{1}$$

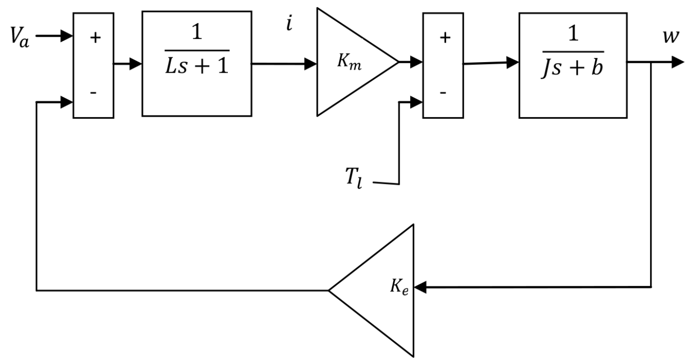

Figure 2. Simulation model for DC motor.

$$J\frac{dw}{dt} = K_m ibw, \tag{2}$$

where L represents the armature inductance, R the armature resistance, i the armature current, K_e the back EMF constant, w the shaft angular velocity, J the moment of inertia, b the coefficient of viscous friction, K_m the motor torque constant, and u the terminal armature voltage v_a.

The state space model of the DC motor is as follows:

$$\begin{bmatrix} \dot{w} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} & \frac{K_m}{J} \\ -\frac{K_e}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} w \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} u \tag{3}$$

By using the Laplace transformation of (1), the transfer function of the system according to angular speed of shaft $(W(s))$ and armature voltage $(U(s))$ can be calculated:

$$\frac{W(s)}{U(s)} = \frac{\frac{K_m}{JL}}{s^2 + \left(\frac{R}{L} + \frac{b}{J}\right) s + \left(\frac{Rb + K_e K_m}{JL}\right)} \tag{4}$$

(4) in the time domain is as follows:

$$\frac{d^2w}{dt^2} + \left(\frac{R}{L} + \frac{b}{J}\right)\frac{dw}{dt} + \left(\frac{Rb + K_e K_m}{JL}\right) w = \frac{K_m}{JL} u \tag{5}$$

The above equation can be converted into the following form:

$$\ddot{w} + A\dot{w} + Bw = Cu \tag{6}$$

By choosing the variable

$$x_1 = w \tag{7}$$

$$\dot{x}_1 = x_2 \tag{8}$$

$$\dot{x}_2 = -bx_1 - Ax_2 + Cu \tag{9}$$

In matrix form

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ -A & -B \end{bmatrix} x + \begin{bmatrix} 0 \\ C \end{bmatrix} u, \tag{10}$$

where $A = \left(\frac{R}{L} + \frac{b}{J}\right)$, $B = \left(\frac{Rb + K_e K_m}{JL}\right)$ and $C = \frac{K_m}{JL}$

Let $w_r(t)$ represent a reference speed and $e = w_r - w$ tracking error. By choosing the variables $\bar{x}_1 = e$ and $\bar{x}_2 = \dot{e}$ as state space variables, the state space equation of the system is as follows:

$$\dot{\bar{x}}_1 = \bar{x}_2 \tag{11}$$

$$\dot{\bar{x}}_2 = -\frac{R}{L}\bar{x}_2 - \frac{k_m k_e + b}{JL}\bar{x}_1 - \frac{k_m}{JL}u + \ddot{w}_r + \frac{R}{L}\dot{w_r} + \frac{k_m k_e + b}{JL}w_r \tag{12}$$

3. Sliding mode control

The sliding surface and discontinuous control are designed as

$$\sigma = \rho\bar{x}_1 + \bar{x}_2 \tag{13}$$

$$\sigma = \rho(w_r - w) + (\dot{w}_r - \dot{w}) \tag{14}$$

Design a discontinuous control as

$$u = U_0 sgn(\sigma), \tag{15}$$

where U_0 denotes the supplied armature voltage.

This design makes the speed tracking error e tend to zero exponentially as sliding mode occurs in $s = 0$, where ρ is a positive constant determining the convergence rate, and for implementation of control (14) angle of acceleration $\bar{x}_2 = \dot{e}$ is needed. In order to attain the controller objective such that to drive the plant state and maintain it on the surface for all time a generalized Lyapunov approach is used [5].

$$V = 0.5\sigma^2 \tag{16}$$

The system should be stable and the sufficient condition is

$$-\frac{d}{dt}\left(\frac{1}{2}\sigma^2\right) = \sigma\dot{\sigma} < 0 \tag{17}$$

$$\dot{\sigma} = \rho\dot{w}_r + \ddot{w} - \rho(K_m - bw) + \frac{1}{J}b\dot{w} + \frac{K_m}{JL}(Ri + K_m w) - \frac{K_m}{JL}u \tag{18}$$

$$= h(t) - \frac{K_m}{JL}u, \tag{19}$$

where $h(t) = \rho\dot{w}_r + \ddot{w} - \rho(K_m - bw) + \frac{1}{J}b\dot{w} + \frac{K_m}{JL}(Ri + K_m w)$

$$\text{if} \quad U_0 > \frac{JL}{k_t}|h(t)|, \quad \sigma\dot{\sigma} < 0 \tag{20}$$

Then sliding mode will happen [10].

4. Fuzzy controller

Fuzzy set theory basically deals with uncertainty and provides a new control technique when mathematical models of plants are poorly defined and input data are not precise. In fuzzy logic, knowledge is expressed in linguistic form, i.e. if–then rules, to create a conceptual framework. Once the knowledge is acquired from the expert it is easy to handle its vagueness and imprecision with the help of fuzzy logic [20–22].

The fuzzy logic controller (FLC) can be built with the help of a classical PID controller. The PID controller is expressed by the following equation:

$$u(t) = k_p e(t) + k_i \int e(t)\,dt + k_d \frac{de(t)}{dt}, \tag{21}$$

where $u(t)$ is the control signal and $e(t)$ the error signal.The PID controller works faithfully if some issues are taken into account like transients due to change in parameter (aging effect), the effects of nonlinear actuators, and wind-up of the integral term. It is found that practically PID control cannot be handled by theory alone; some history of control must also be taken into account. The discrete form of Eq. (24) can be represented as

$$e(n) = k_e(w_r(n) - w(n)) \tag{22}$$

$$ce(n) = k_{ce}(e(n) - e(n-1)) \tag{23}$$

$$u(n) = u(n-1) + dn_{cu} cu(n), \tag{24}$$

where

$$cu(n) = g(e(n),\ ce(n), \ldots) \tag{25}$$

i.e. incremented controller output $cu(n)$ is some function of error, change in error, and other terms related to present and past status of error, where k_e, k_{ce} are normalizing coefficients and dn_{cu} denormalizing coefficients.

Thus heuristic rules can be framed for the FLC, deciding the output of the FLC by taking the knowledge of the PID control system behavior and experience of the operator into account.

The fuzzy logic controller essentially does the following tasks.

In fuzzification module (FM) conversion of crisp to fuzzy values takes place. Secondly, the knowledge base has a database and rule base in which rules are made to frame the control policy. The fuzzy inference engine provides the input–output relationship. Finally, defuzzification converts the fuzzy output into a crisp control signal. The defuzzification method most used is 'center of gravity' or 'center of area':

$$cu(n) = \frac{\sum_{j=1}^{n} cu(cu_j)cu_j}{\sum_{j=1}^{n} cu(cu_j)}, \tag{26}$$

where $cu(u_j)$ is the membership grade of the element cu_j, $cu(n)$ is the fuzzy control output, and n is the number of discrete values on the universe of discourse.

4.1. Implementation of FLC

The block diagram of the FLC is shown in Figure 3. There is always an input output limitation for the FLC, so that for conventional inputs i.e. e and ce and controller output cu are defined on the common normalized domain [–1, 1] and the membership function are shown by symmetric trapezoidal and triangular with equal base and 0.5 crossover with neighboring MFs as shown in Figure 4. The linguistic labels are Negative High (NH), Negative Low (NL), Zero (ZO), Positive Low (PL), and Positive High (PH). The output of the controller is the change in the motor input voltage. The possible rule base used in the design of the FLC is given in Table 1.

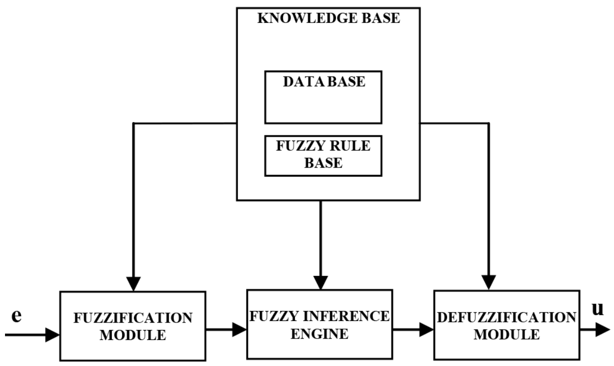

Figure 3. Fuzzy logic controller structure.

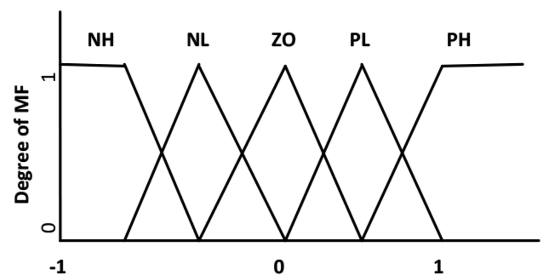

Figure 4. Membership function for e and ce & cu.

Table 1. Fuzzy control rule for $cu(t)$

ce/e	NH	NL	ZO	PL	PH
NH	NH	NH	NL	NL	ZO
NL	NH	NL	NH	ZO	PL
ZO	NL	NL	ZO	PL	PL
PL	NL	ZO	PL	PL	PH
PH	ZO	PL	PH	PH	PH

5. Fuzzy supervisory hybrid control

In this paper, a fuzzy supervisory system is used to calculate the value k. However, SMC controllers are better able to control and give fast dynamic response but the drawback associated with them is chattering in steady state. Hence, to reduce this chattering a fuzzy supervisory hybrid system is developed to utilize the advantages of both the SMC and fuzzy controller. Figure 5 represents the overall block diagram of the supervisory hybrid system. Figures 6 and 7 show the Simulink model of the DC motor control and switching system between the SMC and the fuzzy controller, where the position of the switch depends on the value of k. The outputs of the SM controller and the fuzzy controller are then multiplied by both the values $(1-k)$ and k, which is the deciding factor of the mixing part of the switching mechanism. These factors help in deciding the best effort of contribution by each controller action for overall best performance keeping in view that higher control action should produce faster system response [16–19].

$$U_{hybrid} = kU_{SMC} + (1-k)U_{FUZZY} \tag{27}$$

or

$$U_{hybrid} = kU_{FUZZY} + (1-k)U_{SMC} \tag{28}$$

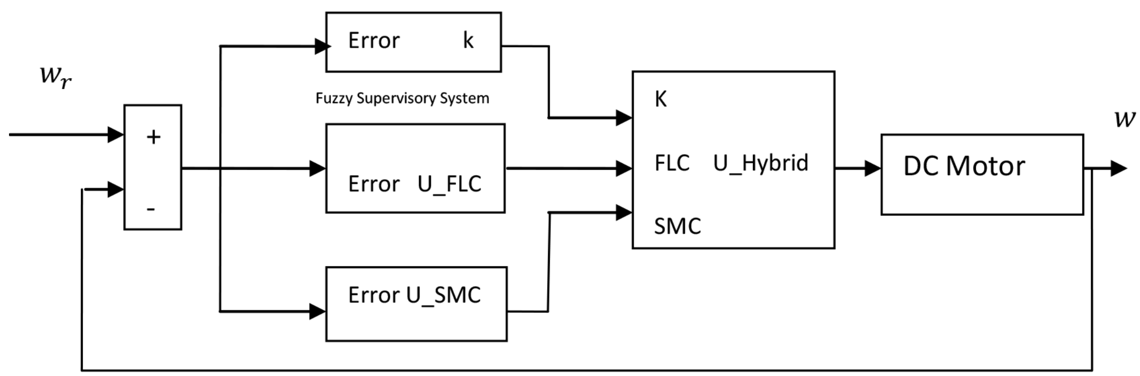

Figure 5. Simulation block diagram of the DC motor hybrid control.

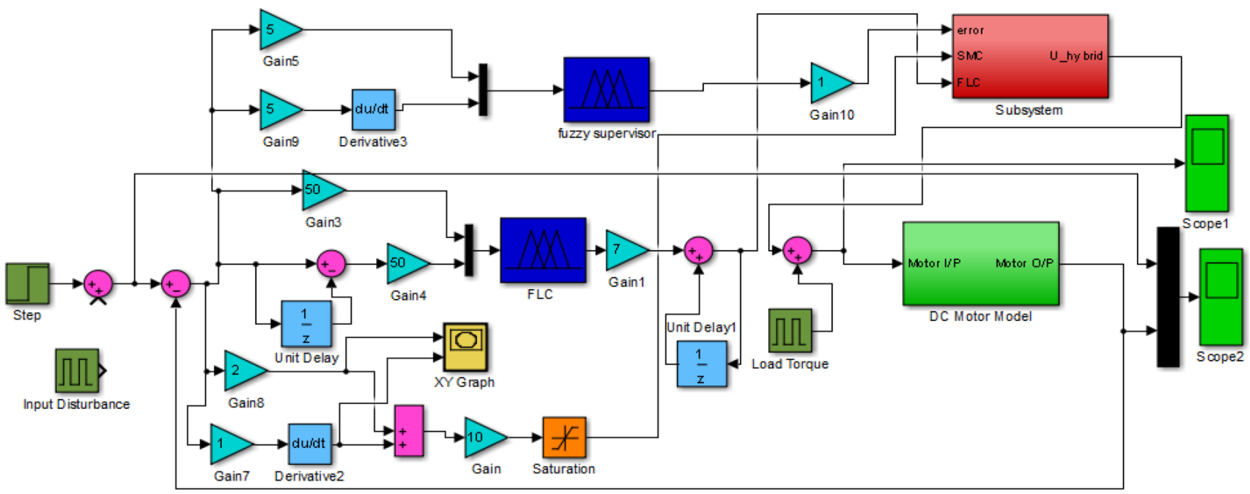

Figure 6. Hybrid control Simulink model.

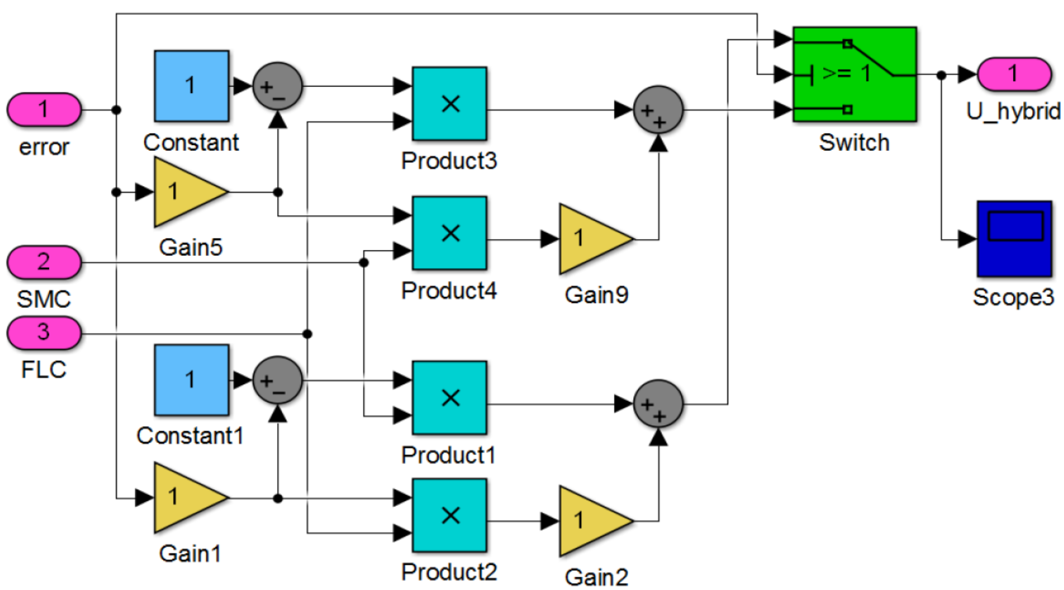

Figure 7. Switching mechanism Simulink model.

It is obvious that when the error and its change in error with respect to time in absolute value are large the hybrid system applies the SMC, which has a fast rise time and a small amount of overshoot, to the system in order to correct the position with respect to the reference point. When an error and its change in error with respect to time in absolute value are small, the hybrid system shifts control to the fuzzy, which has better accuracy near the set position and reduces the chattering caused by the SMC.

Figures 8 and 9 show the supervisory fuzzy inference system. The membership functions are triangular ones for input and output. Definitions of symbols for output are zero (Z), medium (M), and large (L) and similarly for input are: Positive Big (PB), Big (B), medium (M), small (S), and zero (Z).

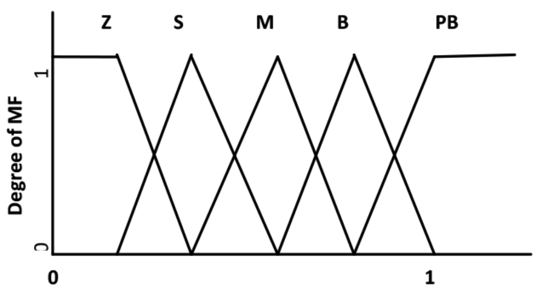

Figure 8. Membership functions for e and ce.

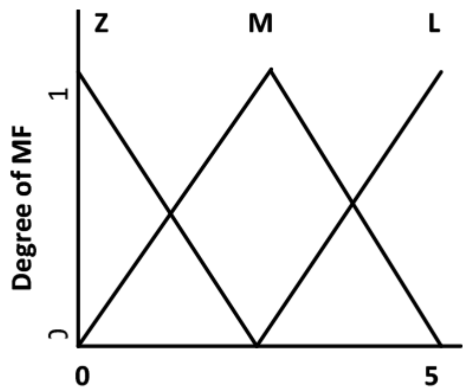

Figure 9. Membership functions for k.

Rules for the supervisory system are defined in Table 2; for example, a rule in Table 2 can be stated as follows: "If absolute value of error is zero and absolute value of the change in error is zero, then k is positive big." Once the value k is obtained the final control action is determined by (27) and (28).

6. Results and discussion

In order to verify the performance of the proposed hybrid speed control of a DC motor, computer simulations were performed using MATLAB/Simulink under three conditions, i.e. normal, load torque, and input disturbance. The ratings and parameters of the DC motor used are given in Table 3 and the speed reference taken as 1000 rpm applied to the DC motor.

Table 2. Tuning rule for k.

ce/e	Z	M	L
Z	PB	B	M
M	S	S	Z
L	Z	Z	Z

Table 3. Ratings and nominal parameters of DC motor.

L	0.001 mH	R	0.5 ohm
J	0.001 kg m^2	k_m	0.001 Vsrad-1
K_e	0.008 NmA-1	b	0.01 Nmsrad-1

The PID controller used here is tuned using the optimization method given in MATLAB. The optimized values of these parameters are $K_p = 1.6$, $K_i = 0.062$, and $K_d = 0.231$. The FLC is applied by using above rule base table (1) and SMC is applied by considering the switching function as

$$\sigma = \rho e + \dot{e}$$

The simple relay control law for SMC used here is given by $u = U_0 sgn(s)$. With these chosen values of $\rho = 2$ and $U_0 = 10V$ sliding mode conditions are fulfilled.

Figure 10a shows the simulation results of speed response under normal condition for PID, SMC, fuzzy, and hybrid controllers. This figure show that SMC gives better response but chattering in control law is present there; on the other hand, reduced chattering appears in the hybrid system (Figure 10b). In Figure 11a, another comparison is made after applying the load torque disturbance from time $t = 15s$ to $t = 20s$. The PID controller gives poor performance. It is clear from the figure that SMC rejects this disturbance but again chattering is present there and reduced chattering is present in the hybrid system (Figure 11b). Finally in Figure 12a, an input disturbance is applied from time $t = 15s$ to $t = 20s$; the proposed hybrid controller rejects this disturbance faithfully, which shows the robustness of proposed controller, and also gives less chattering

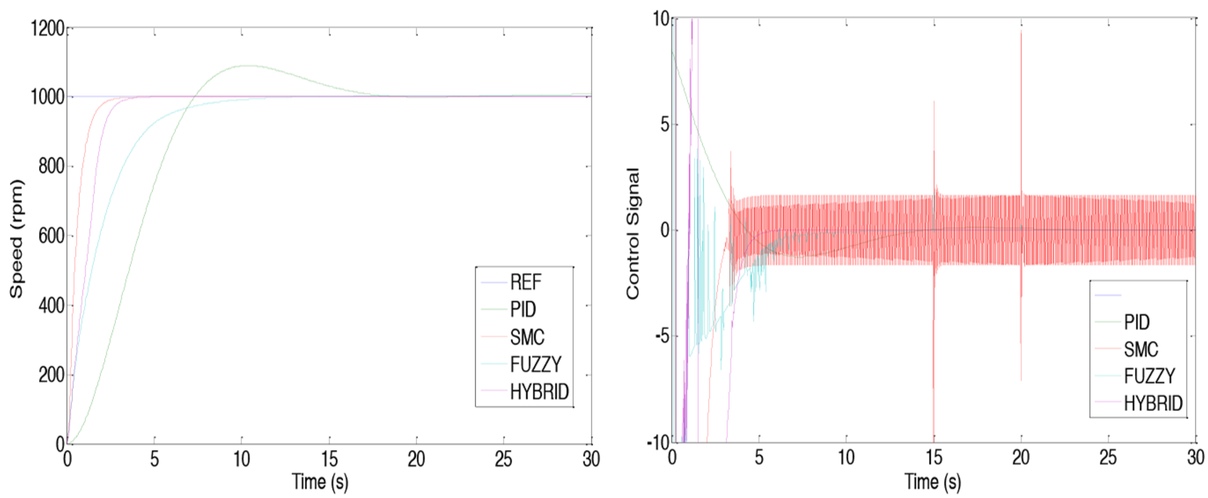

Figure 10. a) Speed response under normal conditions; b) Control signal.

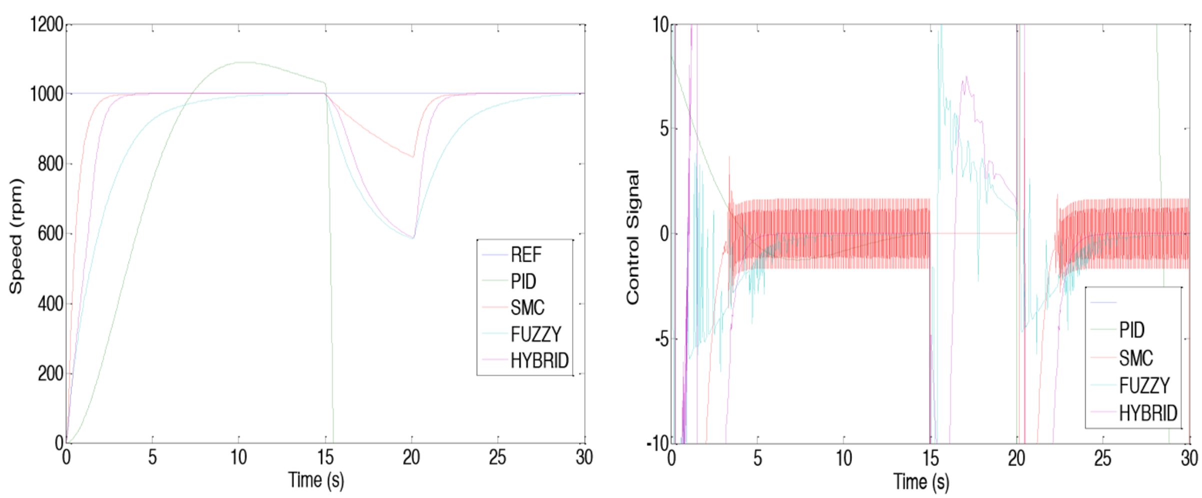

Figure 11. a) Speed response under load torque disturbance; b) Control signal.

(Figure 12b). Figures 13a and 13b show the sliding surface for the SMC and hybrid controller under normal conditions. It is clear from all figures that the conventional PID controller is not suitable to achieve the desired speed reference of the DC motor without overshoot or steady state error and is not robust under the variation of load torque and parameters. The proposed controller works faithfully.

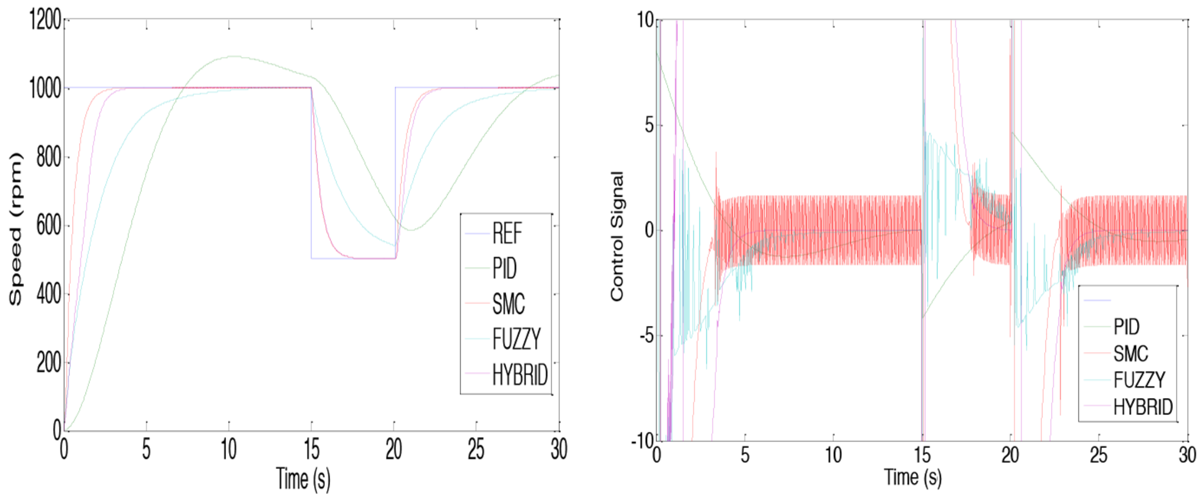

Figure 12. a) Speed response under input disturbance; b) Control signal.

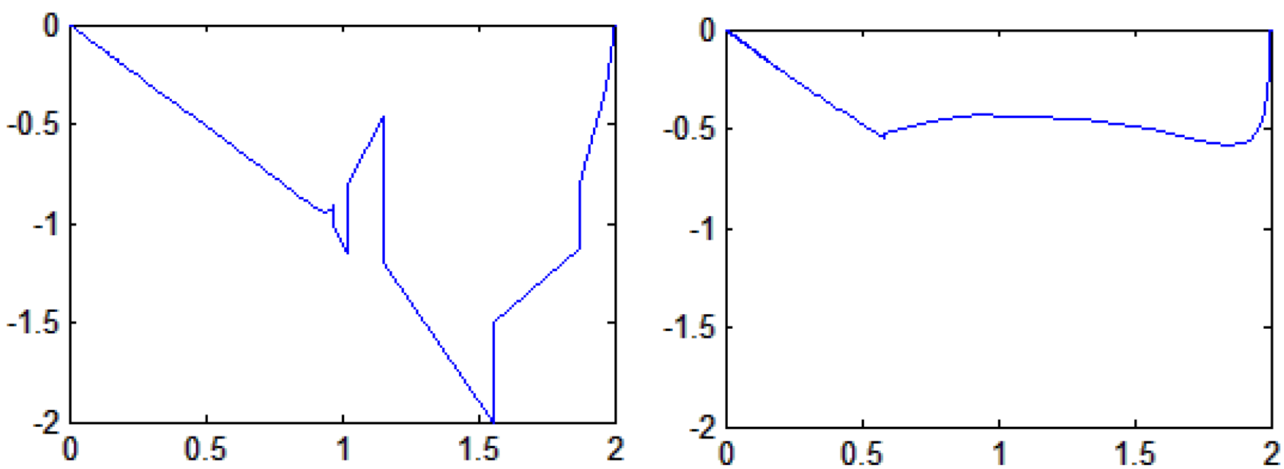

Figure 13. a) Sliding surface for SMC; b) Sliding surface for hybrid controller.

Table 4. Performance comparison of PID, SMC, fuzzy, and hybrid.

	T_r (s)	M_p (%)	e_{ss} (%)
PID	6	20	2
SMC	1	0	0
FUZZY	3.5	0	0
HYBRID	1.5	0	0

7. Conclusion

DC motor applications such as in industries, home appliances, and robotics result in great attention towards its speed control. In this paper, a structure for speed control of a DC motor is presented in which SMC and fuzzy controller outputs are mixed with the help of a fuzzy supervisory system. Thus a new intelligent hybrid controller has been achieved. The simulation results show that the response of the system using the proposed controller is better when compared against a classical PID controller and fuzzy controller. In addition, in steady state, chattering is also decreased when compared with a SM controller. Finally, the simulation results have shown that the proposed hybrid structure has provided a good and effective performance on system response and gives robust performance when compared to other controllers. Table 4 provides the performance comparison between SMC, fuzzy, and hybrid controllers.

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