MINIMUM RULE BASED PID SLIDING MODE FUZZY CONTROL TECHNIQUES FOR BRUSHLESS DC MOTOR DRIVES

C. Navaneethakkannan[1] and M. Sudha[2]

[1]Research Scholar, Department of Electrical and Electronics Engineering, Anna University, Coimbatore, Tamilnadu, India

[2]Professor, Karpagam Institute of Technology, Coimbatore, Tamilnadu, India

ABSTRACT

In this paper, a mathematical tunable gain model free PID-like sliding mode fuzzy controller (PIDSMFC) isdesigned to rich the best performance. Sliding mode fuzzy controller is studied because of its model free,stable and high performance. Today, most of systems are used in unknown andunstructured environment and caused to provide sophisticated systems, therefore strong mathematicaltools (e.g., nonlinear sliding mode controller) are used in artificial intelligent control methodologies todesign model free nonlinear robust controller with high performance (e.g., minimum error, good trajectory, disturbance rejection). Non linear classical theories have been applied successfully in many applications, but they also have some limitation. One of the most importantchallenging in pure sliding mode controller and sliding mode fuzzy controller is sliding surface slope. Thispaper focuses on adjusting the gain updating factor and sliding surface slope in PID-like sliding modefuzzy controller to have the best performance and reduce the limitation.

KEYWORDS: *Sliding Mode Control, Fuzzy Control, PIDControl, Brushless DC Motor, Matlab/Simulink.*

I. INTRODUCTION

The industrial world of today is fast growing and so is the demand for precision. There are several applications today that demand high performance BLDC motor drives. Among the various motors, brushless dc motors are gaining widespread popularity in electric vehicles, aerospace, military equipments, hard disk drives, HVAC industry, medical equipments etc., due to their well-known advantages like high efficiency, low maintenance and excellent speed-torque characteristics.

The conventional controllers used in high performance drives are proportional integral (PI) or proportional integral derivative (PID) controllers. These are constant gain controllers and require accurate mathematical models or system response for their design. The BLDC motor drive system is highly non-linear. It is often very difficult to obtain an accurate mathematical model for BLDC motor drive systems when the motor and load parameters are unknown and time-varying. The conventional controllers fail to give optimal performance during change in operating conditions like variations in parameters, saturation and noise propagations. This has resulted in an increased interest in intelligent and adaptive controllers.

Sliding mode control (SMC) is one of the popular strategies to deal with uncertain control systems. Sliding mode control can offer a number of attractive properties for industrial applications such as insensitivity to the parameter variations and external disturbances. The system dynamics are

determined by the choice of sliding hyper-planes and are independent of uncertainties and external disturbances.
To eliminate the chattering, a boundary layer can be introduced around the sliding surface and the tracking performance is compromised. Within the boundary layer, the control command is a linear function of the distance between the actual system state and the sliding surface. The distance is represented by a function called sliding function. The main feature of SMC is the robustness against parameter variations and external disturbances. Various applications of SMC have been conducted, such as robotic manipulators, aircrafts, DC motors, chaotic systems, and so on. Reduced chattering may be achieved without sacrificing robust performance by combining the attractive features of fuzzy control with SMC.
There has been a significant and growing interest in the application of fuzzy logic to control the complex, nonlinear systems. The design of fuzzy logic controller doesn't require mathematical model of the system, but rules describing the behavior of the system have to be framed based on the knowledge of the system. It is possible to quickly develop and implement a fuzzy controller for non-linear systems such as BLDC motor drives.
Although both SMC and FLC have been applied successfully in many applications but they also have some limitations. This paper focuses on applied sliding mode controller to proposed PID error-base fuzzy logic system with minimum rule base and adjusts the sliding surface slope to implement easily and avoid mathematical model base controller.
The information referred from various literatures for carrying out this work is as follows. The modelling of brushless dc motor, estimation of parameters and control schemes are discussed in [1]-[3]. The effect of change in motor parameters, load disturbances on the performance of the brushless dc drive system is discussed in [4]-[6].Several tuning methods for the PI and PID controllers are described in [7]-[9].Design, implementation and performance analysis of sliding mode controllers for various applications such as AC motors, BLDC motor, etc., are presented in [10]-[14].Design and implementation of fuzzy based controllers for improving the performance of dc motors and brushless dc drives under different operating conditions are discussed in [15]-[19].Controllers design with artificialtunable gainis explained in [19]-[21].The simulation software MATLAB/Simulink is explained in[22].
This paper is organized into six sections. Section 1 gives introduction to the proposed work, section 2 deals with modelling of BLDC motor drive, section 3, 4 describes the classical sliding mode, design and implementation of PID fuzzy controller based BLDC motor drives, section 5 describes the proposed method of sliding mode fuzzy controller (SMFC) based BLDC motor drive, and finally conclusion is presented in section 6.

II. MATHEMATICAL MODEL OF THE BLDC MOTOR

It is assumed that the BLDC motor is connected to the output of the inverter, while the inverter input terminals are connected to a constant supply voltage, as shown in Figure 1. Another assumption is that there are no power losses in the inverter and the 3-phase motor winding is connected instar. Brushless DC motor considered in this paper is a surface mounted, non-salient pole, permanent magnet (PM) synchronous machine with trapezoidal flux distribution in the air gap. This kind motor is very attractive in servo and/or variable speed application since it can produce a torque characteristic similar to that of a permanent magnet DC motor while avoiding the problems of failure of brushes and mechanical commutation.

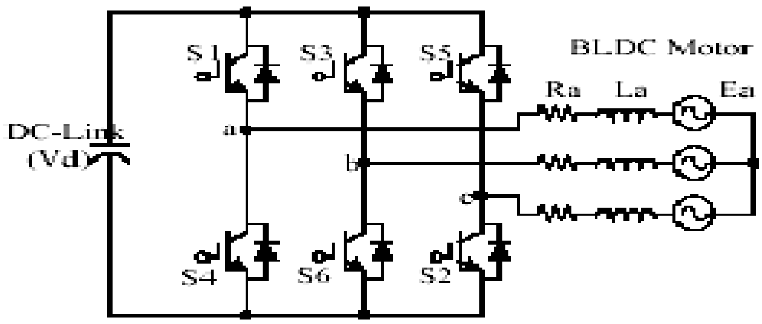

Figure 1: BLDC model.

For a symmetrical winding and balanced system, the voltage equation across the motor winding is as follows:

Applying Kirchhoff's voltage law for the three phase stator loop winding circuits' yields:

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \quad (1)$$

$$V_b = R_b i_b + L_b \frac{di_b}{dt} + M_{ba}\frac{di_a}{dt} + M_{bc}\frac{di_c}{dt} + e_b \quad (2)$$

$$V_c = R_c i_c + L_c \frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + e_c \quad (3)$$

Where

R Winding resistance per phase

L_a Self inductance per phase A

L_{ba} Mutual inductance between phases B and A

e_a Per phase A EMF

V_a Per phase A voltage

Where the back-EMF waveforms e_a, e_b and e_c are functions of angular velocity of the rotor shaft, so

$$e = k_e \omega_m \quad (4)$$

Where $K_e$is the back-emf constant. So the BLDC motor mathematical model can be represented by the following equation in matrix form:

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

If we assume that the rotor has a surface-mounted design, which is generally the case for today's BLDC motors, there is no saliency such that the stator self-inductances are independent of the rotor position, hence:

$$L_a = L_b = L_c = L$$

And the mutual inductances will have the form:

$$M_{ab} = M_{ac} = M_{ba} = M_{bc} = M_{ca} = M_{cb} = M$$

Assuming three phase balanced system, all the phase resistances are equal:

$$R_a = R_b = R_c = R$$

Rearranging the equation (5) yields;

$$\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (6)$$

The electromechanical torque is expressed as

$$T_{em} = J\frac{d\omega_r}{dt} + B\omega_r + T_L \quad (7)$$

But the electromagnetic torque for this 3-phase BLDC motor is dependent on the current, speed and back-EMF waveforms, so the instantaneous electromagnetic torque can be represented as:

$$T_{em} = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \quad (8)$$

III. CLASSICAL SLIDING MODE METHODOLOGY

SMC is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control. Surface and the switching among different functions are determined by plant state that is represented by a switching function. Without loss of generality, consider the design of a SMC for the following second order system: (here $u(t)$ is the input to the system) .

$$u = u_s + u_{eq} \quad (9)$$

Where $u_s = -k.sat(\frac{s}{\phi})$ and constant factor Φdefines the thickness of the boundary layer.

sat(s / Φ) is a saturation function that is defined as:

$$sat(\frac{s}{\phi}) = \begin{cases} \frac{s}{\phi} & if \left|\frac{s}{\phi}\right| \le 1 \\ \operatorname{sgn}(\frac{s}{\phi}) & if \left|\frac{s}{\phi}\right| > 1 \end{cases} \quad (10)$$

The function between u_s and s / Φis shown in the Figure 2.

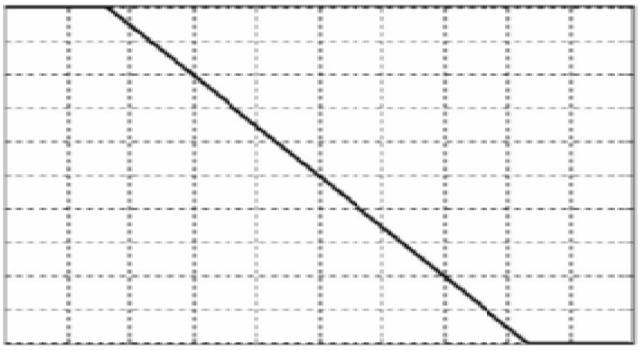

Figure 2: Switching surface in the phase plane.

The control strategy adopted will guarantee a trajectory for the system that move toward the sliding surface S=0 and stay on from any initial condition if the following condition meets:

$$S\dot{S} \le -\eta|S| \quad (11)$$

Where η is a positive constant that guarantees the system trajectories hit the sliding surface in finite time .Using a sign function often causes chattering in practice. One solution is to introduce a boundary layer around the switch surface.

This controller is actually a continuous approximation of the ideal relay control. The consequence of this control scheme is that invariance of sliding mode control is lost. The system robustness is a function of the width of the boundary layer.

The principle of designing sliding mode control law for arbitrary-order plants is to make the error and derivative of variables those are forced to zero. Switching surface design consists of the construction of the switching function. The transient response of the system is determined by this switching surface if the sliding mode exists. First, the position error is introduced: error of a variable is forced to zero. In the DC motor system the position error and its derivative are the selected coordinate

$$e(k) = \theta_{ref}(k) - \theta(k) \quad (12)$$

Where θ_{ref} (k) and θ (k) are the respective responses of the desired reference track and actual rotor position, at the k the sampling interval and e (k) is the position error. The sliding surface (s) is defined with the tracking error (e) and its integral (∫ e dt) and rate of change (ė).

$$S = \dot{e} + \lambda_1 e + \lambda_2 \int edt \quad (13)$$

Where λ1 ,λ2>0 are a strictly positive real constant. The basic control law of SMC is given by:

$$U = -k.\text{sgn}(s) \quad (14)$$

Where k is a constant parameter, sign (·) is the sign function and S is the switching function.

Also, the rotational speed is given by,

$$T(t, t+T_S) = \begin{cases} T_{min} & \Delta W(t) > 0 \\ T_{max} & \Delta W(t) < 0 \end{cases} \quad (15)$$

IV. PID FUZZY LOGIC CONTROLLER

A PID fuzzy controller is a controller which takes error, integral of error and derivative of error as inputs. Fuzzy controller with three inputs is difficult to implementation, because it needs large number of rules, inthis state the number of rules increases with an increase the number of inputs or fuzzy membershipfunctions.

In the PID FLC, if each input has 7 linguistic variables, then 7 ×7 ×7 =343 rules will be needed. The proposed PID FLC is constructed as a parallel structure of a P+D sliding surface slope and P+I+D sliding surface slope, and the output of the PID FLC is formed by adding the output of two fuzzycontrol blocks. This work will reduce the number of rules needed to 7 ×7 =49 rules only.

This controller has two inputs (S_1,S_2) and one output (τ_{fuzzy}). The inputs are first sliding surface (S_1) which measures by the equation (3), the second sliding surface (S_2) which measures by the equation (4).For simplicity in implementation and also to have an acceptable performance the triangular membershipfunction is used. The linguistic variables for first sliding surface (S_1) are; Negative Big (NB), NegativeMedium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big(PB), and it is quantized in to thirteen levels represented by: -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6 thelinguistic variables for second sliding surface (S_2) are; Fast Left (FL), Medium Left (ML), Slow Left(SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized in to thirteenlevels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6 and the linguistic variables to find the outputare; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR),Large Right (LR) and it is quantized in to thirteen levels represented by: -85, -70.8, -56.7, -42.5, -28.3, - 14.2, 0, 14.2, 28.3, 42.5, 56.7, 70.8, 85. Design the rule base of fuzzy inference system can play important role to design the best performance of sliding mode fuzzy controller, this paper focuses on heuristic method which, it is based on the behavior of the control systems.

The complete rule base for this controller is shown in Table 1. Rule evaluation focuses on operation in the antecedent of the fuzzy rules in sliding mode fuzzy controller. Max-Min aggregation is used in this work which the calculation is defined as follows;

$$\mu_U(x_k, y_k, U) = \mu_{U_{i=1}^{r}} .FR^i(x_k, y_k, U) = \max\{\min_{i=1}^{r}[\mu_{R_{pq}}(x_k, y_k), \mu_{pm}(U)]\} \quad (16)$$

The last step to design fuzzy inference in sliding mode fuzzy controller is defuzzification. In this design the Center of gravity method (COG) is used and calculated by the following equation;

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \mu_u(x_k, y_k, U_i)} \quad (17)$$

Table 1: Modified Fuzzy rule base table

Decrease the overshoot
S_2
S_1
Decrease the rise time

S_1\ S_2	FL	ML	SL	Z	SR	MR	FR
NB	LL	LL	LL	ML	SL	SL	Z
NM	LL	ML	ML	ML	SL	Z	SR
NS	LL	ML	SL	SL	Z	SR	MR
Z	LL	ML	SL	Z	SR	MR	LR
PS	ML	SL	Z	SR	SR	MR	LR
PM	SL	Z	SR	MR	MR	MR	LR
PB	Z	SR	SR	MR	LR	LR	LR

This table used to describe the dynamics behavior of sliding mode fuzzy controller. Table 2 is shown theCOG deffuzzification lookup table in fuzzy logic controller. These output values were obtained bymathematical on line tunable gain adjustment to reach the best performance in sliding mode fuzzycontroller.

Table 2: COG lookup table in fuzzy sliding mode controller

$S_2 \rightarrow$ / $S_1 \downarrow$	Membership Function												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-6	-85	-84.8	-84.8	-84	-82.1	-81	-79	-71	-68	-65	-62	-60	-54
-5	-84.8	-84	-82	-80	-78	-77	-74	-70	-64	-60	-56	-54	-47
-4	-78	-73	-70	-68	-64	-61	-60	-57	-55	-50	-47	-40	-38
-3	-70	-60	-58	-51	-42	-38	-34	-33	-31	-29	-28.4	-28.1	-28
-2	-50	-48	-45	-40	-38	-34	-32	-30	-28	-26	-25	-21	-20
-1	-30	-25	-21	-18	-16	-14	-10	-9	-8	-7	-6.8	-6	-5
0	-10	-8	-6	-1	2	3	6	7	8	10	12	15	17
1	15	18	21	22	23	25	27	28	29	30	30.5	30.8	31
2	29	29.8	31	33	34	34.6	35	35.2	36	37	38	39	42
3	40	41	42	43	45	45	46	46.3	46.8	47	48	51	52
4	48	49	50	52	53	55	56	57	58	59	60	61	63
5	60	61	62	63	64	66	67	68	68.5	69	70	70.8	71
6	66	68.7	68.9	70	72	74	75	77	78	79	81	83	84

V. THE PROPOSED METHOD

Sliding mode controller has two main parts: equivalent controller, based on dynamics formulation andsliding surface saturation part based on saturation continuous function to reduce or eliminate thechattering. Reduce or eliminate the chattering regarding to reduce the error is play important role inthis research. Applied sliding mode controller in fuzzy logic method have been proposed by severalresearchers but in proposed method the new PID method with 49 rules is implemented and adjustby on line mathematical method. SMFC is fuzzy controller based on sliding mode method to easyimplementation, stability, and robustness. A block diagram for sliding mode fuzzy controller is shown inFigure 3.

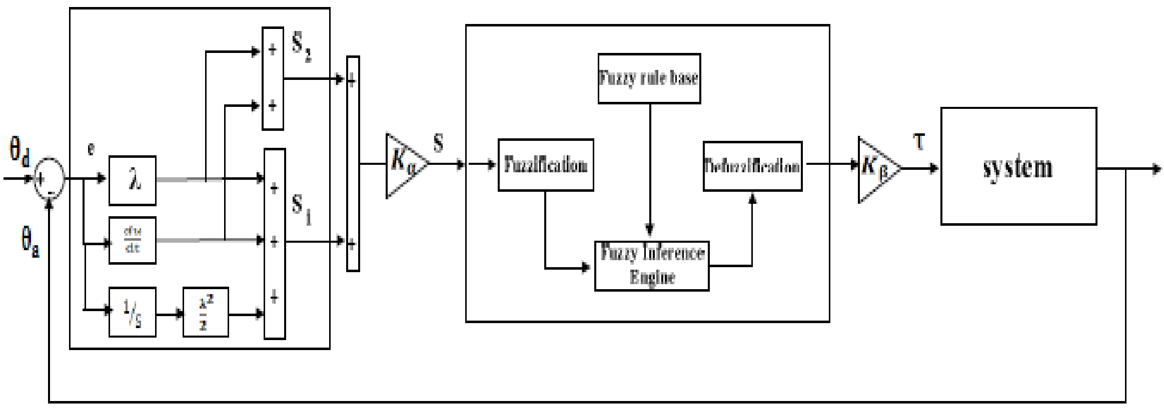

Figure 3: Sliding Mode Fuzzy Control (SMFC).

The system performance in this research is sensitive to the sliding surface slope λ input and output gain updating factor K_α& K_β for sliding mode fuzzy controller. Sliding surface slope can change the response of the output if large value of λ is chosen the response is very fast but the system is very unstable and conversely, if small value of λ considered the response of system is very slow but the system is very stable. Determine the optimum value of λ for a system is one of the most important challenging works in SMFC. For nonlinear, uncertain, and time-variant plants on-line tuning method can be used to self-adjusting all coefficients. To keep the structure of the controller as simple as possible and to avoid heavy computation, a new supervisor tuner based on updated by a new coefficient factor K_n is presented. In this method the supervisor part tunes the output scaling factors using gain online updating factors. The inputs of the supervisor term are error and change of error (e,ė) and the output of this controller is U, which it can be used to tune sliding surface slope, λ.

$$K_n = e^2 - \frac{(r_v - r_{v\min})^5}{1+|e|} + r_{v\min} \tag{18}$$

$$r_v = \frac{(de(k) - de(k-1))}{de(.)} \tag{19}$$

$$de(.) = \begin{cases} de(k) & if \;\; de(k) \geq de(k-1) \\ de(k-1) & if \;\; de(k) < de(k-1) \end{cases} \tag{20}$$

In this way, the performance of the system is improved with respect to the SMFC controller. So the new coefficient is calculated by;

$$\lambda_{new} = \lambda_{old} \times K_n \tag{21}$$

$$K_{\alpha_{new}} = K_{\alpha_{old}} \times K_n \tag{22}$$

5.1. Results and Discussions

The BLDC Model drive with speed controllers has been simulated in MATLAB/Simulink model.The conventional sliding mode fuzzy controller (SMFC) and mathematical tuneable gain model free PID-like sliding mode fuzzy controller (PIDSMFC) were tested to compare response trajectory. The conventional control scheme is easy to perform in industry due to theirsimple control structure, ease ofdesign, and inexpensive cost. However, the SMFC with fixed fuzzyrules cannot provide perfect control performance if the controlled plant is highly nonlinear anduncertain. Figure 4 is indicated the power disturbance rejection in PIDSMFC and SMFC. A band limited white noisewith predefined of 40% the power of input signal is applied to these controllers; it found slight oscillations inSMFC's trajectory responses.

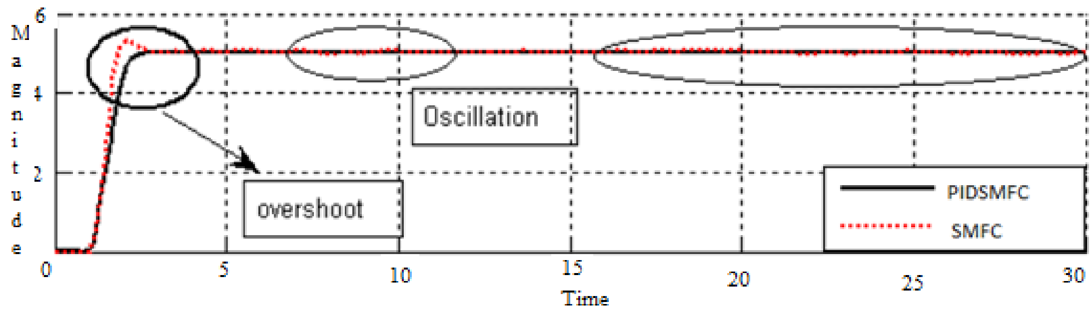

Figure4: PIDSMFC and SMFC with external disturbance.

Among above graph, relating to trajectory with external disturbance, SMFC has slightly fluctuations. By comparing overshoot; PIDSMFC's overshoot **(1%)** is lower than SMFC's **(2.2%).**Figure 5 shows the simulated results comparison between the SMFC and PIDSMFC of BLDC motor when load torque varied from 15 N-m to 11 N-m at the time of 4 sec.

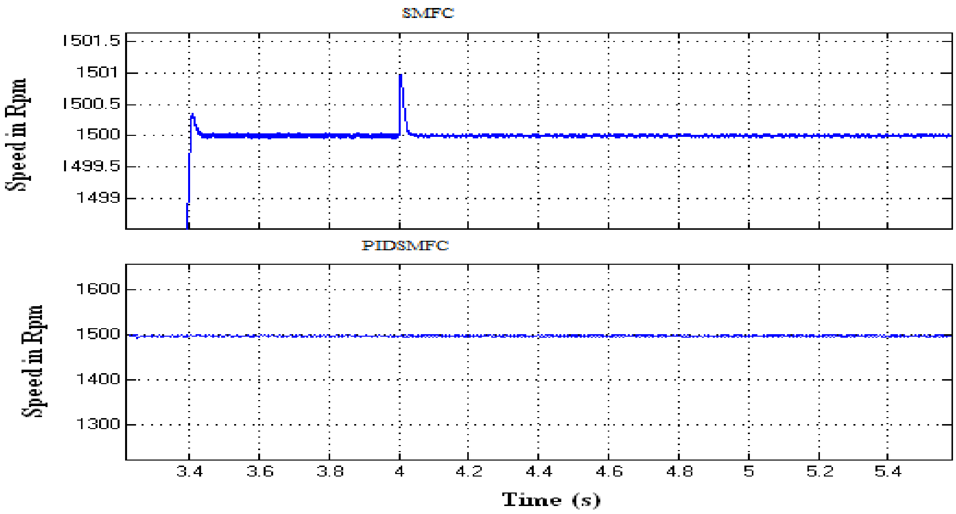

Figure 5: Simulated results comparison between the SMFC and PIDSMFC controller of BLDC motor when load torque varied from 15 N-m to 11 N-m at the time of 4 sec.

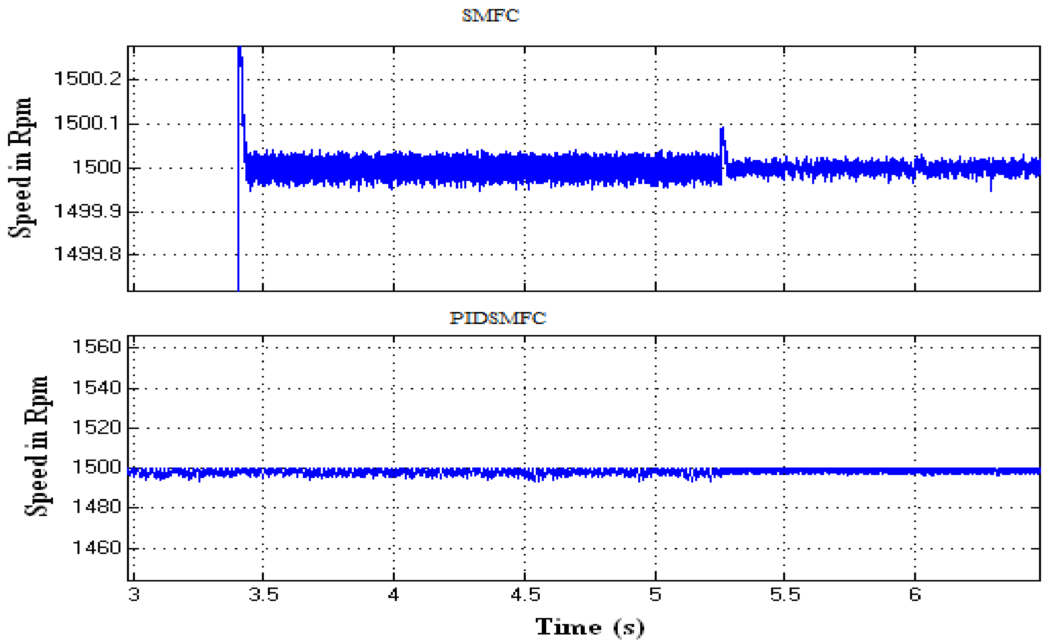

Figure 6: Simulated comparison results between the SMFC and PIDSMFC controller of BLDC motor when input V_{dc} varied from 400V to 600V at the time of 5.25 sec.

As mentioned in previous, chattering play important roles in sliding mode fuzzy controller which one of the major objectives in this research is reduce or remove the chattering in system's output with uncertainty and external disturbance. Figure 6 shows the simulation results of SMFC controller and PIDSMFC controller when varying the input voltage. It demonstrates that satisfactory trajectory tracking is achieved effectively and the input chattering is eliminated completely.

VI. Conclusions

Refer to the research, a PID-like sliding mode fuzzy controller (PIDSMFC) design and application to brushless DC motor (BLDC) has proposed in order to design high performance nonlinear controller in the presence of uncertainties. In the first part studies about classical sliding mode controller (SMC) which shows that: although this controller has acceptable performance with known dynamic parameters but by comparing the performance regarding to uncertainty, the SMC's output has fairly fluctuations and slight oscillation. Second step focuses on applied fuzzy logic method in sliding mode controller to solve the stability and robustness in pure fuzzy logic controller. The system performance in sliding mode controller and sliding mode fuzzy controller are sensitive to the sliding surface slope. Therefore, compute the optimum value of sliding surface slope for a system is the third important challenge work. This problem has solved by adjusting surface slope of the sliding mode controller continuously in real-time. The steady state error of the fuzzy control system can be reduced by choosing proper membership functions and fine tuning the membership functions. In this way, the overall system performance has improved with respect to the classical sliding mode controller. By comparing between PID-like sliding mode fuzzy controller and sliding mode fuzzy controller, found that PID-like sliding mode fuzzy controller has steadily stabilized in output response (e.g., torque performance) but sliding mode fuzzy controller has slight chattering in the presence of uncertainties.The simulation model which is implementedin a modular manner under MATLAB/Simulink environment allows that many dynamiccharacteristics such as voltage and rotor speed canbe effectively considered.

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APPENDIX

SPECIFICATIONS OF BLDC MOTOR

Rated Voltage	36V
Rated Current	5A
No. of Poles	4
No. of Phases	3
Rated Speed	4000 rpm
Rated Torque	0.42 N-m
Torque Constant	0.082 N-m/A
Mass	1.25 kg
Inertia of Motor	$23e^{-06}$ kg-m^2
Resistance per phase	0.57Ω
Inductance per phase	1.5 mH

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AUTHORS

C. Navaneethakannan received the B.E degree from Anna University, Chennai, India in the year 2006. He also received the M.E degree from Anna University, Coimbatore, India in the year 2010.He is currently pursuing the Ph.D. degree in the Department of Electrical Engineering, Anna University, Coimbatore, India. His research interests Intelligent Controllers and BLDC Motor drives.

M. Sudha received the Ph.D. degree from Anna University, Chennai, India. Her research interests are Digital Signal Processing and Embedded Systems. She has more than 15 years of teaching experience in various engineering colleges.