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Simulation of Brushless DC Motor Speed Control Based on Sliding Mode Control Technique

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Abstract:
Introduction Abstract— Recently, the great advantages of the Brushless DC Motors (BLDCM) such as their simple design, high applied output force (torque), long term usage and speed stability encourage the designers to wide use these motors in various industries. Whilst, BLDC systems are characterized by their uncertainties and non-linearity. One of the famous control techniques in handling nonlinear and uncertain systems is the Sliding Mode Control (SMC). The main contribution in this paper is applying advanced SMC techniques such as adaptive SMC and fuzzy SMC approaches for effective speed regulation of BLDCM in the absence and presence of external load. The simulation performance of speed regulation for BLDCM using the designed approaches is compared with a classical Proportional- Integral -Derivative (PID) controller to validate the success of the proposed advanced SMC techniques in improving the system characteristics (settling time, steady state error, rise time and disturbance & noise rejection). Our simulations run under the umbrella of MATLAB 2017. .

Keywords Brushless DC Motor, Sliding Mode Control, Adaptive SMC, Fuzzy SMC.

Introduction

There are mainly two types of dc motors used in industry. The first one is the conventional dc motor where the flux is produced by the current through the field coil of the stationary pole structure. The second type is the brushless dc motor where the permanent magnet provides the necessary air gap flux instead of the wire-wound field poles. BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. Recently, high performance BLDC motor drives are widely used for variable speed drive systems of the industrial applications and electric vehicles.

Permanent Magnet Brushless DC motors, known as BLDCM succeeded to gain a great importance in various traditional and critical industries that require speed stability,high force power and high efficiency. Beside their better characteristics in affecting the performance of the whole system, BLDC is characterized by their simple structure, small size, light weight, high force power & efficiency and low maintenance & repair.
In the last decade, due to their mechanical friction and electric erosion, BLDC started to replace other famous traditional kinds of motors such as Brushed DC motor, induction motor, etc.. Moreover, BLDC guarantees high system efficiency and low audible noise by the total elimination of the brush/commutator assembly. Speed regulation of BLDC is an important control challenge for any brushless DC motor. The stability ofthe BLDC speed allows the motor

to produce a desired high torque. Conventional control techniques such as Proportional-integral-derivative (PID) and proportional integral(PI) are were used widely in the field of BLDC speed control. These control techniques are characterized by their simple structure, low cost, fast response, small settling and rise time and low overshoot.

On the other hand, advanced and intelligent control strategies such as fuzzy logic control (FLC), neural network control (NNC), genetic algorithms (GA) and sliding mode control (SMC) start to play an important role in the speed control of BLDCM individually or combined together. For instant, FLC approaches were applied for speed control of the BLDCM depending on their ability to deal with ill-defined mathematical models generating the required control commands. However, the FLC requires more time than conventional control techniques to solve the complex fuzzification and defuzzification processes .

A combination between one of the intelligent control approaches with a traditional control technique is widely used in BLDC motor control. These combinations are applied on dynamic systems guaranteeing high efficient performance with better steady state response, small rise and settling time and low overshoot. On one hand, the conventional control techniques are the main controller on the system, while on the other hand, the advanced control techniques are used in the online tunning of gains.
In two approaches to speed control of BLDC motor used with the UAV propeller were introduced. The first approach is an adaptive neuro fuzzy inference system (ANFIS) which is a hybrid control approach combining both fuzzy logic controller and artificial neural network. The second approach is a self adaptive PID controller, where it combines the advantages of both PID controller and FLC.

From all the above mentioned advanced control techniques, Sliding Mode Control (SMC) one of the unconventional control theories that was used widely in the control of BLDCM. SMC is characterized by its fast response, strong robustness, ability to handle parametric uncertainties, simple structure and easy implementation leading that SMC become an attractive and suitable control method to motion control systems such as BLDCM .

In practice, the design of the BLDCM drive involves a complex process such as modeling, control scheme selection, simulation and parameters tuning etc. An expert knowledge of the system is required for tuning the controller parameters of servo system to get the optimal performance. Recently, various modern control solutions are proposed for the speed control design of BLDC motor. However, Conventional PID controller algorithm is simple, stable, easy adjustment and high reliability, Conventional speed controlsystem used in conventional PID control . But, in fact, most industrial processes with different degrees of nonlinear, parameter variability and uncertainty of mathematical model of the system. Tuning PID control parameters is very difficult, poor robustness, therefore, it's difficult to achieve the optimal state under field conditions in the actual production. Fuzzy PID control method is a better method of controlling, to the complex and unclear model systems, it can give simple and effective control, Play fuzzy control robustness, good dynamic response, rising time, overstrike characteristics.

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conventional control techniques are the main controller on the system, while on the other hand, the advanced control techniques are used in the online tunning of gains, two approaches to speed control of BLDC motor used with the UAV propeller were introduced. The first approach is an adaptive neuro fuzzy inference system (ANFIS) which is a hybrid control approach combining both fuzzy logic controller and artificial neural network. The second approach is a self adaptive PID controller, where it combines the advantages of both PID controller and FLC. From all the above mentioned advanced control techniques, Sliding Mode Control (SMC) one of the unconventional control theories that was used widely in the control of BLDCM. SMC is characterized by its fast response, strong robustness, ability to handle parametric uncertainties, simple structure and easy implementation leading that SMC become an attractive and suitable control method to motion control systems such as BLDCM. BLDCM is a nonlinear system with parametric uncertainties where its mathematical model is very difficult to be recognized accurately.

SMC is such a suitable controller to handle ill-defined mathematical model systems. SMC, fuzzy SMC and adaptive SMC were used to control BLDCM guaranteeing fast response and high efficiencyIn this paper, two advanced SMC approaches are utilized to control the speed of BLDCM. The first approach is a combination between conventional SMC and FLC. The FLC is designed based on adaptive neuro fuzzy inference system (ANFIS) principle to compensate the conventional SMC drawbacks. While the other approach is an adaptive SMC. Online adaptation is performed by FLC to enhance the adaptation ability of the system. These approaches guarantee efficient performance with less chattering and low activity of control actions. A comparison between the results of the control approaches will be introduced. The simulation results declare the ability of the two approaches to control the BLDC speed guaranteeing high performance and efficiency. Finally, section V concludes our work and presents the future challenges in this field.

Control Design

In this chapter, SMC technique is applied to control the speed of BLDCM. The designed controller has the ability to deal with the nonlinear states and parameter uncertainty of the BLDCM guaranteeing the stability and robustness of the system. Moreover, fuzzy SMC (FSMC) and adaptive fuzzy SMC (AFSMC) are developed by combining SMC technique with FLC and FLC integrated with adaptive algorithm, respectively to reduce and prevent the chattering phenomena occurs by using SMC individually. FSMC and AFSMC are applied to enhance SMC following characteristics:

- Learning ability
- Robustness against parameters uncertainty and external disturbances / noise

Sliding Mode Control (SMC) Architecture

SMC is one of the popular control algorithms in the field of electric drives and motors. It is a variable structure nonlinear discontinuous control approach characterized by accuracy, robustness and easy implementation and tunning.

SMC combines two main steps:

- Design of sliding hyper-surface s such that design specifications are satisfied.
- Selection of a suitable control law u guarantees the attraction of the system state to the sliding surface.

The main goal of our proposed control approach is to make the speed of the BLDCM to track the desired value such that the error e and its derivatives must tends to zero. The control input u for the second order sliding mode is represented as:

$$u = -k\,\mathrm{sign}(s) \qquad (7)$$

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where u is the control input, k is the constant parameter, s is the switching function and sign(·) is the sign function In case of high frequency oscillations, chattering phenomenon, due to high frequency switching between functions, occurs affecting the performance of the system. By modifying the control law in 7 to

$$u = -k\mathrm{sat}(s/\psi) \quad (8)$$

where ψ is defines as the thickness of the boundary layer around s and sat(s/ψ) is a saturation function defined as sat(s/ψ)=s ψ if |s ψ|≤1 sign(s/ψ) if |s ψ| > 1 This control law guarantees that all the system trajectories will be attracted toward the sliding surface s =0and settle there from any initial conditions [27]. One should notice that the control law must met the reaching condition:

$$s\dot{}s<0 \quad (9)$$

The designed controller is a second order SMC where the sliding surface is given by:

$$s = d\omega edt + \omega e =\dot{}\ e + \lambda 1e \quad (10)$$

where λ1 is defined as a positive real surface parameter constant determining the slope of the sliding surface and ωe is the difference between the desired/reference rotor speed and the actual/measured speed given by:

$$\omega e = \omega ref - \omega \quad (11)$$

From 4 & 5, the state equation of the rotor speed is calculated as,

$$d\omega mdt = Temf - Tload - Vfr\omega m\ J \quad (12)$$

and the speed error is given as,

$$d\omega edt = 1\ J\ (Tref - Temf) - Vfr\ J\ (\omega ref - \omega) \quad (13)$$

whereTref is the reference electromagnetic torque derived from the rotor speed error. By substituting in 13,

$$d\omega edt = kt\ J\ (iref - i) - Vfr\ J\ (\omega ref - \omega) \quad (14)$$

wherekt is the torque constant, iref is the reference current applied to the BLDCM and i is the actual current applied to the BLDCM.

The sliding surface can be modified with respect to the error in the current and the error in the rotor speed as:

$$s = kt\ J\ ie - Vfr\ J\ \omega e + \omega e \quad (15)$$

Sliding control is a powerful approach for stabilization of nonlinear systems in the presence of modeling uncertainties and parametric disturbances scheme is based on the idea that controlling a first-order system is much easier than a general nth-order one. Usually, the sliding mode scalar function ψ is defined as follows:

$$\psi = \left(\frac{d}{dt} + \delta\right)^{n-1} e = \begin{pmatrix} n-1 \\ 0 \end{pmatrix} e^{(n-1)} + \begin{pmatrix} n-1 \\ 1 \end{pmatrix} \delta e^{(n-2)} + \ldots + \begin{pmatrix} n-1 \\ n-1 \end{pmatrix} \delta^{n-1} e,$$

(

where e is the tracking error vector, δ is a positive parameter, and binomial coefficient (n k) is defined as n!/k!(n n k)!. Equation ψ >0 defines a time-dependent surface in the space Rn, and e(t) =0 is its unique solution. Hence, the problem of tracking control will be equivalent to putting zero in the scalar function ψ. Based on the Lyapunov theory, control effort v must be selected so that the following in equality is satisfied:

$$\frac{1}{2}\frac{d}{dt}\psi^2 \leq -\eta|\psi|,$$

where η is a positive constant.

On the contrary, the sliding mode controller commonly includes two parts: the equivalent term (ueq) and the switching control law (σ sign(ψ)). (e switching control law tries to guide the system states toward the sliding surface, and the equivalent control law, which is gained from solving the equation ψ , guarantees that the system states stay onthe sliding surface and converge to zero along the sliding surface.

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Fuzzy Sliding Mode Control (FSMC) Architecture

One of the major disadvantage of SMC is the chattering phenomena due to the discontinuous control input and high frequency oscillation. FSMC is developed by combining an SMC with an FLC. The FSMC is capable of compensating the speed error aiming to improve the system performance. The aim of the FLC is to increase the learning ability of the SMC improving system robustness for parameter uncertainty and noise, shows the block diagram representing the BLDCM controlled through FSMC. The input functions of the fuzzy system are the sliding surface signal s and its rate of change ˙ s while k in 7 is the output of the fuzzy system, represent the Gaussian input for s and ˙ s inputs with 11 membership functions to the FSMC, respectively.the outputs of the FSMC can be obtained. The FSMC determines a mapping from the sliding surface to the system outputs. The control rules of the FSMC are contrary to the modified SMC on the separated semi-plane, where the magnitudes of the fuzzy control signals are proportional to the states away from the sliding surface $s = 0$. Therefore, the FSMC actions will help to ensure the system state vectors stay on the sliding surfaces, so as to realize the system optimal control performance.

The general control structure of the proposed FSMC,The gain coefficients of the SMC are determined vigorously by the FLC according to the sliding surfaces, which are defined based on the errors between the actual system performance indices and the desired system performance indices. Meanwhile, the vehicle heights at each corner are passed through a low-pass filter of 2 Hz to filter out the road roughness disturbances. Since the vehicle height and leveling adjustment system of EAS uses the on-off solenoid valves to regulate the air masses inside the air springs, the on-off statuses of the six solenoid valves are further controlled by employing the pulse width modulation (PWM) technology in this paper. The duty ratios of the on-off status of the solenoid valve are then given as

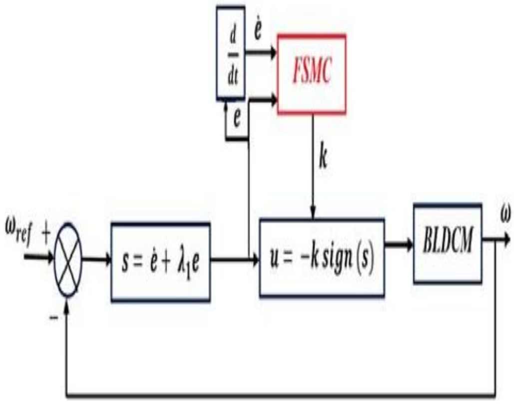

Fig. 3.1. Block diagram of BLDCM Controlled through FSMC

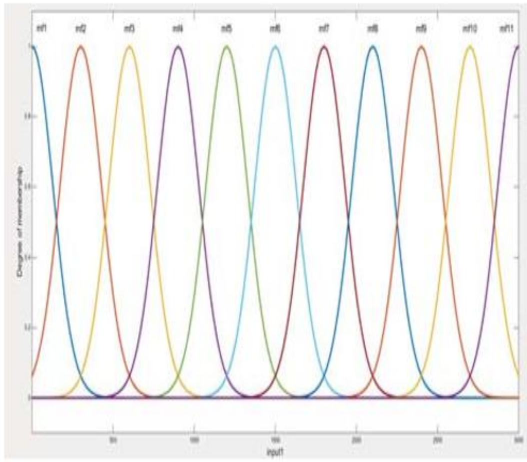

Fig. 3.2. The Gaussian input membership s.

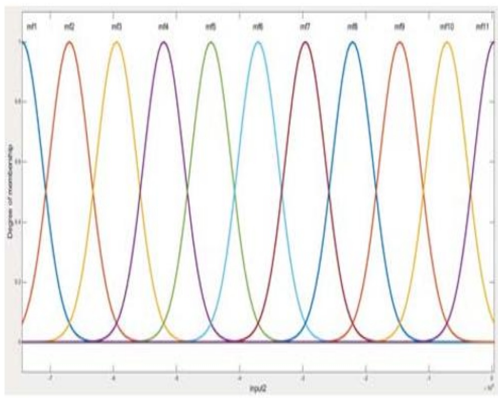

Fig. 3.3. The Gaussian input membership p˙s.

Adaptive Fuzzy Sliding Mode Control (AFSMC)

Architecture FLC integrated with adaptive algorithm combines with SMC to enhance the performance of the system and improve its robustness. AFSMC depends on Lyapunov stability theory to update the coefficients of the control rules. The adaptation ability of the system is enhanced by performing on-line adaptation on various operating conditions. Fig.3.4 shows the block diagram representing the BLDCM controlled through AFSM. Lyapunov stability is used to verify the stability of the proposed AFSMC and ensure that the system state trajectory reach the sliding surface in the proper time and converge to the desired equilibrium point. The Lyapunov function Vs1 and ˙ Vs1 is defined as

Vs1(t)= 1/2 s2(t) (16)

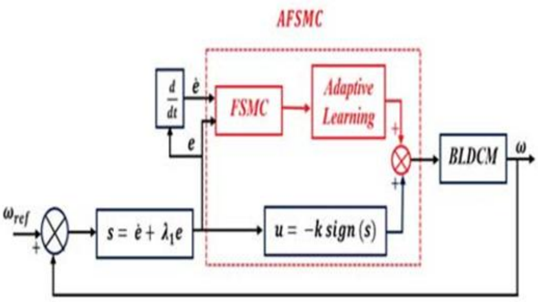

Fig. 3.4. Block diagram of BLDCM Controlled through AFSMC

Vs1(t)=s(t)˙ s(t) ≤ 0 (17)

Equation 17 ensures that increasing the process time satisfies the conditions that Vs1 is a bounded uniform and continuous function. Therefore, the system state trajectory is attracted to the sliding surface achieving sliding mode and converge to a desired equilibrium point. The input functions of the AFSMC and the output have the same membership function represented in Fig.3.5.

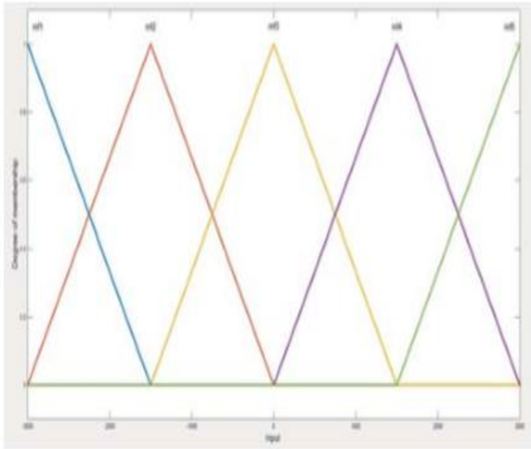

Fig. 3.5. The Triangular Input/ Output membership.

$e/\dot{e}$	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

Table 3.1. Fuzzy rules for e/e’

From our experience in the field of BLDC motor control, we designed the fuzzy rules for the different values of e/˙ e. Table 3.1 represents the fuzzy rules implemented for calculating e/˙ e. In our approach, we assume 5 equally divided levels around the zero (Z). On the left hand side, we have negative big (NB) and negative small (NS). On the right hand side, we have positive small (PS) and positive big (PB).

SIMULATION RESULTS

Concerning with approving the offered control approaches, a model of brushless DC motor was established in the simulation environment under “Simulink-Matlab” program. We run our simulation in the presence and absence of an external load and with variable speed to validate the proposed controllers. The simulation results prove the success of the designed controller (SMC & FSMC/AFSMC) to produce the desired performance. Table II represents the BLDC specifications under study. One should notice that in our simulation we compare between the proposed controllers (SMC & FSMC/AFSMC) with traditional PID.

Parameters	Value
Stator phase Resistance R_s	2.8750 ohm
Stator phase Resistance L_s	8.5 $\times 10^{-3}$ H
Voltage Constant	146.6077 Volt
Back EMF Flat Area	120^o
Inertia	8.5 $\times 10^{-3}$ Kgm.m^2
Viscous damping	1 $\times 10^{-1}$ N.m.sec
Pole Pairs	4

Table 5.1. BLDC SPECIFICATIONS

The BLDCM output response using conventional PI and traditional PID tunned by genetic algorithm (GA), SMC, FSMC and AFSMC at set point 3000 rpm with no load is presented in Fig. 5.1 Table 5.1 summarizes the results of the various control approaches from the point of view of rise time *tr*and overshoot *o.s*%.

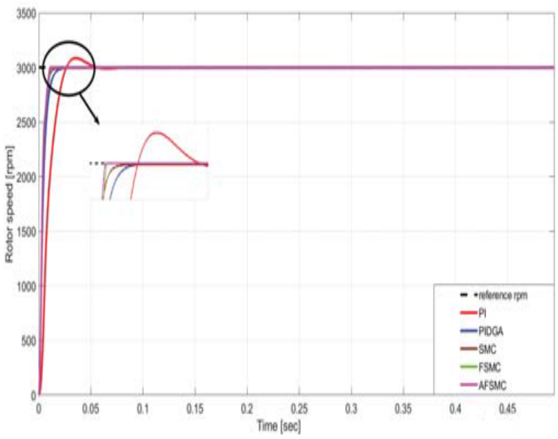

Fig. 5.1. The output responses of the BLDCM with no load

Parameters	PI	PID	SMC	FSMC	AFSMC
Rise time t_r	0.022	0.015	0.007	0.0062	0.0058
Overshoot $o.s\%$	0.02	0	0	0	0

Table 5.2 Simulation results

Moreover, the designed speed controllers are now testedto maintain the BLDCM in different speed values. Fig 5.2 shows the output responses of BLDCM with no load wherethe desired speed increases after 0.4 sec to 3400 rpm for 0.3 sec and decreased back to 3000 rpm set point. The AFSMC produces better performance compared with the ordinary SMC and FSMC.

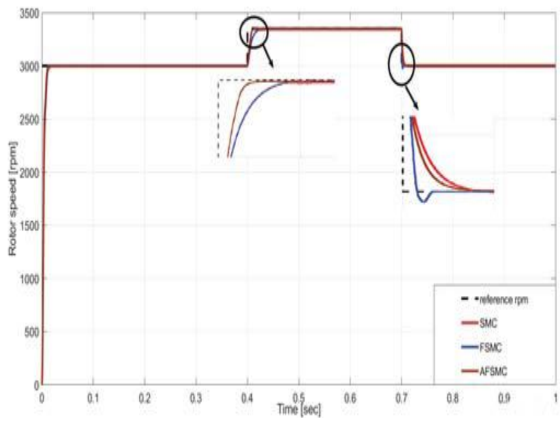

Fig. 5.2 . The output responses of BLDCM with variable set points

However, the output responses of BLDCM represented above discarded the effect of external disturbances and noise. The output responses of the BLDCM subjected to a sudden disturbance at time 0.2 sec are shown in Fig.5.3 . It is clear that the designed AFSMC produces better performance than other controller types for the disturbance rejection.

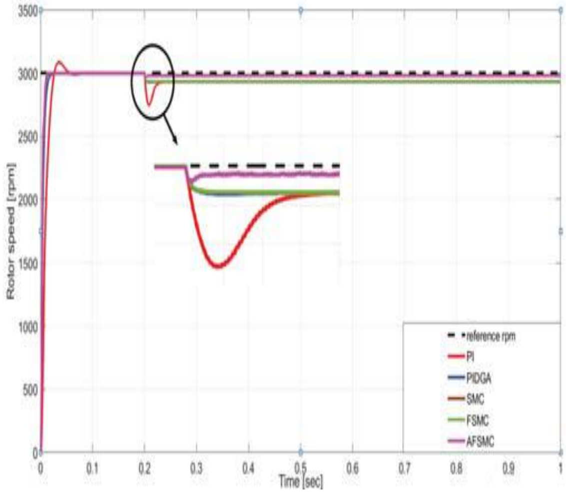

Fig.5.3 . The output responses of BLDCM exposed to external sudden disturbance at 0.2 sec

The output response of the BLDCM connected to a load are shown in Fig. 5.4 , where it is clear that the designed AFSMC produces better performance than other controller types. Finally, the output response of the BLDCM in the presence of noise is shown in Fig. 5.5 , where it is clear that the designed AFSMC succeeded to attenuate the external noise produces better performance than other controller types.

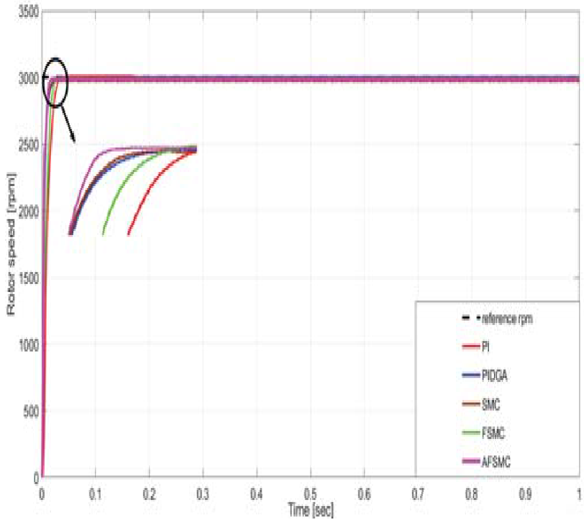

Fig.5.4. The output responses of the BLDC with load

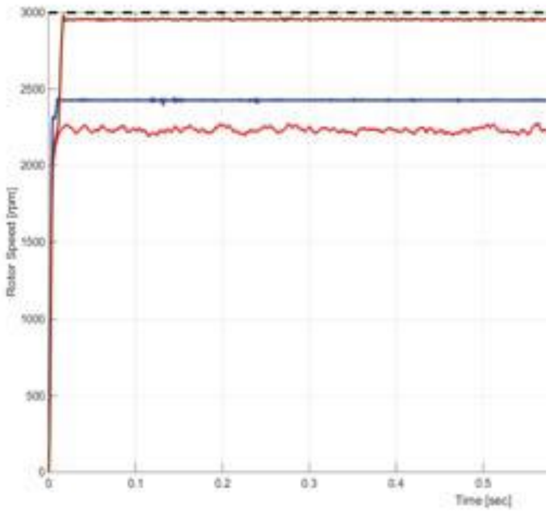

Fig. 5.5. The output responses of the BLDC in the presence of sensor noise.

Conclusion

In this project , speed control of BLDC Motor through various SMC technique is presented through simulation. The simulation results show that the proposed AFSMC and FSMC improve the performance of brushless DC motor speed in different set points and in the presence of dynamic load conditions guaranteeing the stability and robustness of the system even in the presences of external sudden disturbance. Moreover, the proposed approaches indicate that the system response is faster and can reach steady state condition better than traditional PI and PID techniques.

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