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Robust fuzzy sliding mode control implementation for DC motor

Abstract. *This article presents a fuzzy sliding mode control (FSMC) to improve the speed performance of DC motor in direct and opposite directions, where two FSMC approaches are developed and implemented based on the DSpace 1104 board and compared to SMC. Although, the SMC ensures big robustness and excellent disturbance rejection it has a limited application because of the chattering phenomenon that is the main downside of SMC. Firstly, the SMC design speed and current controllers are presented. Secondly, two FSMC approaches are shown. In the first approach, we have a similar control rule as the SMC with the exceptions of the k and ksi of discontinuous control signal parameters which are adapted by a fuzzy inference system. In the second approach, totally we delete the discontinuous control and replace it with an FLC. This article focuses on the design of the FSM speed controller and the estimation of the resistive torque. The numerical and experimental validation results of the FSM second approach have shown a robust mechanism performance with a fast dynamic response, good tracking of the reference speed, zero overshoot compared to SMC (1.22%) and FSM first approach (0.09%), and good rejection Disturbance. Besides, the FSM second approach has the best reduction of chattering phenomenon compared to the FSM first approach and classical SMC.*

Streszczenie. *W tym artykule przedstawiono rozmytą kontrolę trybu ślizgowego (FSMC) w celu poprawy wydajności prędkości silnika prądu stałego w kierunkach bezpośrednich i przeciwnych, w której opracowano i wdrożono dwa podejścia FSMC w oparciu o płytę DSpace 1104 i porównano z SMC. Chociaż SMC zapewnia dużą wytrzymałość i doskonałe tłumienie zakłóceń, ma ograniczone zastosowanie ze względu na zjawisko drgania, które jest główną wadą SMC. W pierwszej kolejności przedstawiono projektowe kontrolery prędkości/prądu SMC. Po drugie, pokazano dwa podejścia FSMC. W pierwszym podejściu mamy podobną zasadę sterowania jak SMC, z wyjątkiem parametrów k i ksi nieciągłych parametrów sygnału sterującego, które są dostosowywane przez rozmyty system wnioskowania. W drugim podejściu całkowicie usuwamy nieciągłą kontrolę i zastępujemy ją FLC. W tym artykule skupiono się na konstrukcji regulatora prędkości FSM i estymacji momentu rezystancyjnego. Numeryczne i eksperymentalne wyniki walidacji drugiego podejścia FSM wykazały solidne działanie mechanizmu z szybką odpowiedzią dynamiczną, dobrym śledzeniem prędkości odniesienia, zerowym przeregulowaniem w porównaniu z SMC (1,22%) i pierwszym podejściem FSM (0,09%) oraz dobrą odrzucenie Zakłócenie. Poza tym drugie podejście FSM ma najlepszą redukcję zjawiska drgania w porównaniu z pierwszym podejściem FSM i klasycznym SMC.* ***(Odporne Slizgowe sterowanie silnikiem DC)***

Keywords: Sliding mode control (SMC), Fuzzy logic control (FLC), Fuzzy sliding mode control (FSMC), DSpace 1104.
Słowa kluczowe: Sterowanie trybem ślizgowym (SMC), Sterowanie za pomocą logiki rozmytej (FLC), Sterowanie rozmytym trybem przesuwania (FSMC), Przestrzeń 1104.

Introduction

Direct current (DC) motor was the first electrical machine used in industry, especially in rail transport. This machine has the best control since the induced current is the image of the torque. The advantages of a DC motor over an AC motor are numerous. These benefits reside in the linearity of the motor's mathematical model and the simple implementation. Furthermore, DSpace 1104 supports its model in the case of an experimental realization. In automatic mode, the majority of non-linear control approaches or with non-standard parameters. Hence, the conventional control laws may be insufficient. Robust control laws that are insensitive to parameter variations must be used. To this object, many strategies are proposed in the literature, including the variable structure control (VSC) and the fuzzy logic (FLC) [1, 3]. The sliding mode control gives many advantages like simplicity, robustness and insensitivity [4]. The discontinuous part of the SMC and the technological imperfections create unwanted oscillations called the Chattering phenomenon, the latter remains an obstacle to achieve SMC [5, 2]. Many techniques have been proposed to reduce this phenomenon. Among these techniques are presented two fuzzy-sliding approaches control. Fuzzy logic control is an intelligent control used on complex and poorly defined systems. The basic idea of this approach is to use the experience of a human operator on a process for controller synthesis [6]. Control algorithm is constructed with language terms defined as fuzzy sets. These rules can be obtained from the system model to be ordered. To check the different control strategies [7], we will present a comparative study. Finally. The experimental implementation based on DSpace 1104 and simulation results using MAT-LAB/ Simulink were used to show results in order to meet our demands, this result prove the success of the FSM second approach to reduce chattering phenomenon and give a great performance from the first approach and the conventional SMC.

Modeling of DC motor with separate excited

Fig. 1 shows the model of a general motorized system and the equivalent circuit with armature voltage control. If the field winding is physically and electrically separate from the armature winding, then the machine is known as a separately excited motor whose equivalent circuit is shown in below:

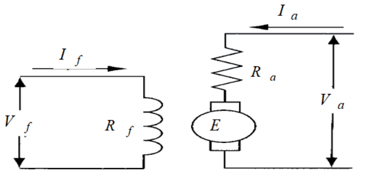


Fig. 1. Equivalent circuit of a separately excited DC Motor

The differential equations can be written in the following form to facilitate their solutions by numerical integration:

$$\frac{\mathrm{d}i_a}{\mathrm{d}t} = \frac{(V_a - R_a\, i_a + L_m\, i_f\, \omega r)}{L_a} \tag{1}$$

$$\frac{\mathrm{d}i_f}{\mathrm{d}t} = \frac{(V_f - R_f\, i_f)}{L_f} \tag{2}$$

$$\frac{\mathrm{d}\omega_r}{\mathrm{d}t} = \frac{(L_m\, i_f\, i_a - f_c\, \omega_r - T_L)}{J} \tag{3}$$

Where : i_a: armature current, i_f: Field current, V_a: Armature voltage, V_f: Field voltage, Ra: Armature resistance, R_f: Field resistance, L_m: Mutual inductance, E: electro-motrice force.

Application of sliding mode control in DC motor

Variable structure system is a scheme with a changing structure that is characterized by a choice of function and switching logic during operation. This choice makes it possible to switch between each structure at any time, in order to combine the useful properties of each of these structures. In sliding mode, the state trajectory is brought to a hyperplane then using the commutation law, it is forced to stay in the vicinity of this hyperplane [8]. The latter is called the sliding surface and the movement along which it occurs is called the sliding movement [9]. Fig. 2 illustrates this explication. A sliding mode controller's structure is made up of two parts: Ueq and Un.

$$U = U_n + U_{eq} \tag{4}$$

$$U = K * sign(s) + U_{eq} \tag{5}$$

Where U_{eq} indicates equivalent control which is employed when the system state is in the sliding mode, and K indicates the controller output's maximum value. Because the control action changes its sign on both sides of the switching surface, S is a switching function ,we can describe S as [10]:

$$s = e + \lambda e \tag{6}$$

Where :

$$e = x^* - xe \tag{7}$$

x^* is the wanted expression. λ is a constant and $sign(s)$ is a sign function distinct as:

$$sign[s(x)] = \begin{cases} 1 & if \quad s(x) < 0 \\ 1 & if \quad s(x) > 0 \end{cases} \tag{8}$$

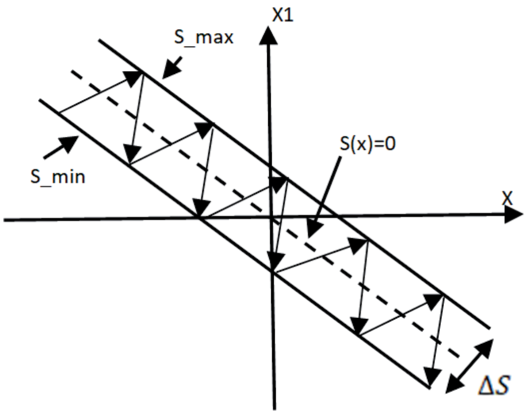


Fig. 2. Real sliding regime

Design of sliding mode speed controller

The regulated control scheme must be defined before sliding mode control can be developed. The speed is the desired sliding mechanism in our scenario [11]. The mathematical equation for a DC motor is as follows:

$$\dot{\omega}_r = \frac{1}{J}(T_e - T_L) - \frac{f_c}{J}\omega_r \tag{9}$$

Where: J is inertia moment; F_c is coefficient of friction, T_L is load torque. The sliding surface is described as follows in steady-state:

$$\begin{cases} s_1 = \omega^* - \omega \\ \dot{s}_1 = \dot{\omega}^* - \dot{\omega} \end{cases} \tag{10}$$

It will be as follows if the equation 10 is replaced in the equation of the derivative of the velocity surface:

$$\dot{s}(\omega) = \dot{\omega}^* - (T_e - T_L - f_c\omega_r) \tag{11}$$

It became as :

$$\dot{s}(\omega) = \dot{\omega}^* - (L_m \, i_f \, i_a - T_L - f_c \, \omega_r) \tag{12}$$

Using the sliding mode concept as follows :

$$i_a = i_a^n + i_a^{eq} \tag{13}$$

When the sliding mode state $\dot{s}(\omega) = 0$ is used to define the equivalent control signal as follows :

$$i_a^{eq} = \frac{1}{L_m \, i_f}(\dot{\omega}^* + \frac{1}{J}\, T_L + \frac{1}{J} f_c \, \omega_r) \tag{14}$$

T_L is the estimated resistance torque value; it can be defined using the MRAS estimation technique by sliding mode that will be presented in the next part.The discontinuous command is given by:

$$i_a^n = K_\omega \cdot sat(\frac{s(\omega)}{\xi \cdot \omega}) \tag{15}$$

$(K_\omega > 0)$

Design of sliding mode current controller

The current loop is frequently the inside regulated loop in the command of a DC motor, and the converter's overall performance is largely dependent on its performance. To obtain excellent static and dynamic performance for motor DC control, precise and fast current control is required [12, 4]. The controller is designed in a single step:

$$\begin{cases} s_2 = i_a^* - i_a \\ \dot{s_2} = \dot{i_a}^* - \dot{i_a} \end{cases} \tag{16}$$

Next, we develop a voltage control equation that causes the system to advance in a finite period towards the sliding surface. Using the sliding mode concept as follows:

$$\dot{S}(\omega) = \dot{i_a^*} - (V_a - R_a i_a - L_m i_f \omega) \tag{17}$$

Using the sliding mode concept as follows :

$$V_a = V_a^n + V_a^{eq} \tag{18}$$

When the sliding mode state $\dot{S}(\omega) = 0$ is used to define the equivalent and discontinuous control signals as follows :

$$V_a^{eq} = L_a \cdot (\dot{i_a}^* + \frac{R_a}{L_a} \cdot i_a + \frac{K_{i_a}}{L_a}\, \omega) \tag{19}$$

$$V_a^n = K_{i_a} \cdot sat(\frac{s\ (i_a)}{\xi \cdot i_a}) \tag{20}$$

$(K_{i_{i_a}} > 0)$

Estimation of the resistive torque by the MRAS technique

In the control law developed in the preceding section, knowledge of the resistive torque (Tr) is necessary for its calculation. Indeed, in the case where the direct current motor is started it is generally difficult to know the value of the resistive torque [13, 4]. To fix this issue, we use a resistive torque estimator based on the MRAS technique. This technique is composed of a reference model and an adjustable model, with an adaptation mechanism. The reference model is independent of the resistive torque information while the adaptive model depends on it [14]. The two models are compared, and the following error is added into the resistive torque-generating adaptation mechanism. The sliding mode hypothesis underpins the adaptation mechanism. It is based on the integration of the mechanical speed equation to compare the measured and estimated speeds. Fig. 3 shows the principle of torque estimation using the MRAS techniqu[15, 14]. The sliding surface is selected as follows:

$$S = \omega_{mes} - \omega_{ref} \tag{21}$$

$$\dot{S} = \dot{\omega_{mes}} - \frac{1}{J}(T_e - T_r - f_c\, \omega_r) \tag{22}$$

$$\dot{S} = \dot{\omega_{mes}} - \frac{1}{J}(L_m\, i_f\, i_a - T_r - f_c\, \omega_r) \tag{23}$$

During the sliding mode and steady state we have $s(\omega) = \dot{s}(\omega) = 0$:

$$T_r^{eq} = -J\, \dot{\omega}_{mes} + L_m\, i_a\, i_f - f_c\, \omega_r \tag{24}$$

the discontinuous part is given as:

$$T_r^n = K_{T_r}.\, sat(x) \tag{25}$$

To ensure the stability of the system, the constant K_{T_r} must be positive. By defining the Lyapunov function:

$$v(x) = \frac{1}{2}\, s^2(x) \tag{26}$$

It derivative is:

$$\dot{v}(x) = s(x)\, \dot{s}(x) \tag{27}$$

For the function $v(x)$ to decrease, it suffices to ensure that its derivative is negative. We determine the control law as follows:

$$T_r^{estimated} = T_r^{eq} + T_r^n \tag{28}$$

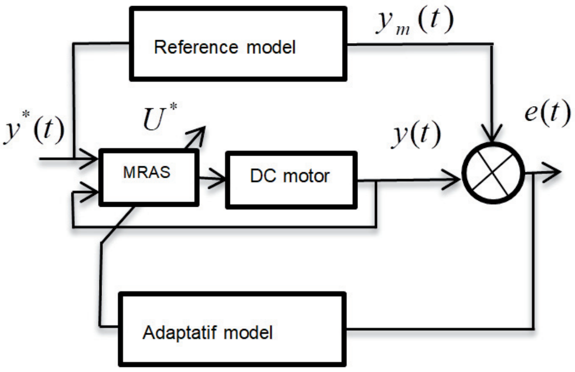


Fig. 3. Basic configuration of the MRAS technique

Fuzzy sliding mode control (FSMC)

The major disadvantage of SMC is that it produces frequency oscillations due to a short time delay, which causes chattering, the last of which is created in a discontinuous signal and flips between two values at an infinite frequency(k). The objective in this study is to minimize switching frequency by using two fuzzy sliding approaches [16, 17].

Design of the first FSM approach

Fig. 4 present the combination between fuzzy logic controller and sliding mode control. The controller resulting from this combination has the same control law as the SMC except for the parameter k and ζ of the component Un given by equation15, which will be adapted by a fuzzy inference system [18, 17, 16]. The central idea behind this combination is that in the ideal case, when:

- S(t) is far from hyperplan, the parameter k and ζ should have a big value.
- S(t) is close to the hyperplan, the fitted parameter k and ζ should have a small value.

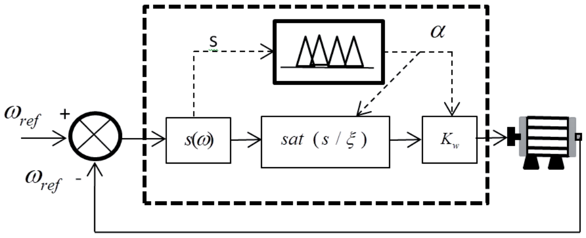


Fig. 4. Approach control scheme of the first FSM

Membership functions and rule base

The terms K and ζ are adjusted by a fuzzy adapter having two inputs s and $\dot{s}$ and they have five membership functions and the output α has five membership functions which are shown in Fig. 5 :

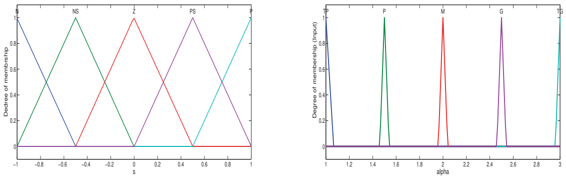


Fig. 5. The membership functions of the first FSM approach inputs (left) and output (right)

Basic table of the rules of the 1st approach

Table 1. Basic rules of the first FSM approach

s ds	N	NS	Z	PS	P
N	VB	V	M	S	S
NS	B	M	S	M	S
Z	M	S	VS	S	M
PS	S	M	S	M	VB
P	S	S	M	B	VB

This example can be used to explain the concept of a fuzzy logic mechanism:

- If (s) and (ds) are both Negative then (alpha) is Very Big (VB).
- If (s) is Negative (N) and (ds) is Positive (P) then the output (Alpha) is Small (S).

The rules which govern the gain adaptation law K and the parameter ζ are shown in table 1 .As a result, the equation 15 of the discontinuous control law becomes:

$$i_n^{fl} = K_v^{fl}\ sat\,(\frac{s(\omega)}{\xi_n^{fl}}) \tag{29}$$

With :

$$\begin{cases} k_n^{fl} = \alpha\, K_v \\ \xi_n^{fl} = \alpha\, \xi_v \end{cases} \tag{30}$$

For the control law we will see in transient mode a series of values of K_v and ξ_v which gives an infinity of functions . As shown in Fig. 6. In permanent mode the quantity ‘alpha’ equal to '1' which implies that the command is equal to the equation 15:

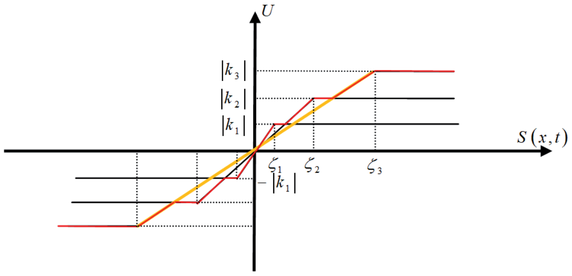


Fig. 6. Fuzzy-sliding regulator control signal

Design of the second FSM approach

The use of a fuzzy mechanism in conjunction with sliding mode control is designed to improve the solidity and efficiency of the nonlinear control [5]. The chattering phenomenon is the main drawback of SMC in the discontinuous control part which is produced by little-period delays in the system. The FSM regulator is designed in this part where a fuzzy inference system is employed to construct the equivalent law parameters and the discontinuous control is replaced by the fuzzy system inference in the SMC schema. Fig. 7 illustrates the suggested combination FSM regulator architecture for DC motor speed control. The fuzzy controller described in this work is built using the following IF-THEN rules [19, 1].

- NB : Negative Big
- N : Negative
- ZE : Zero
- PS : Positive Small
- PB : Positive Big

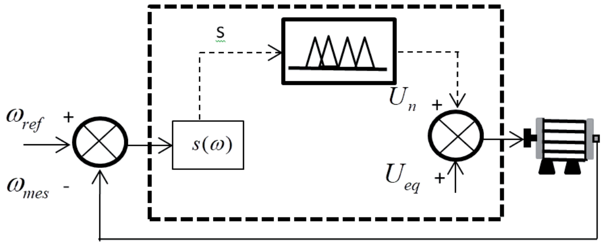


Fig. 7. Approach control scheme of the second FSM

Membership functions and rule base of the FSM second approach

The fuzzy controller in this case has an input of five membership functions and an output of five membership functions shown in Fig. 8 :

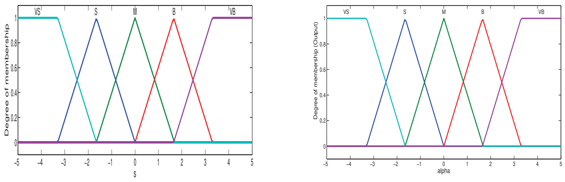


Fig. 8. The membership functions of the second FSM approach input (left) and output (right)

Basic table of the rules of the second approach

The suggested fuzzy controller's rule base is shown in Table 2:

Table 2. Basic rules of the second FSM approach

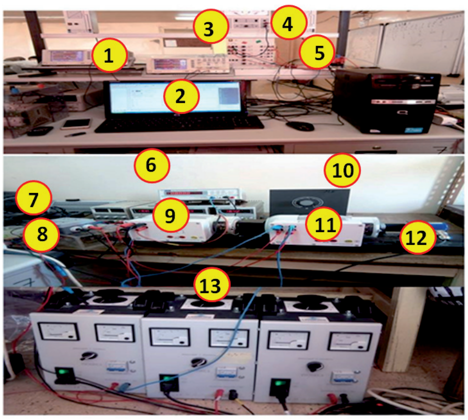
Input (s)	NB	NS	ZE	PS	PB
Output (Alpha)	VB	B	M	S	VS

We can be explaining the concept of a fuzzy logic system:

- If (s) is Negative Big (NB) then the output (Alpha) is Very Big (VB).
- If (s) is Zero (NS) then (alpha) is Big(B).

Simulation and experimental result

The simulation was carried for DC motor with independent excitation using MATLAB/Simulink and to investigate this results an experimental test platform connected by dSpace 1104 card are used to simulate the control system strategies. Firstly, the effectiveness of two FSM approaches is compared to the sliding mode control for speed, armature current and electromagnetic torque. Then, the estimation of the resistive torque is presented based on MRAS technique which a novel adaptation structure is used like a reference model and the estimated speed obtained from DC motor state-space resolution is applied in the adaptive model. Secondly, analyze the performance of a speed shift with the reference speed reversed are presented. The DC motor is started with zero load then an additional load torque of 0.49N.m has applied. Finally, a comparative study of chattering phenomenon is presented to show the effectiveness of FSM proposed approaches compared to SMC. Fig. 9 shows the experimental test set-up where the experimental section includes the same scenarios testing with those utilizing in the simulation.



1-Oscilloscope
2-Pc
3-Ampermeter
4-Current sensor
5-dSPACE1104
6-Power supplies
7-buck
8-Bridge H
9-Dc motor
10-resistor
11-Generator
12-Incremental encoder
13- Power supplies

Fig. 9. Experimental setup

Simulation result and discussion

Two different scenarios for the DC motor are applied to confirm the robustness of the simulation results of the suggested controllers, Where:

- Test 1: The first scenario includes of constant speed where the DC motor is running at 100 (rad/s). Next, a nominal load torque (0.49 N.m) is added and removed at 2 sec, 4 sec respectively.
- Test 2: The second scenario includes a variation of speed reference against 1500 (rpm) to -1500 (rpm) where reference speed is suddenly inversed at 6 sec.

Fig.10 to Fig.13 show the speed, the armature current, the electromagnetic torque and the estimated torque for SMC and FSM of the first and second approaches, respectively.

- a for speeds
- b for armature current i_a
- c for electromagnetic torque T_{em}

- d for estimated torque T_r

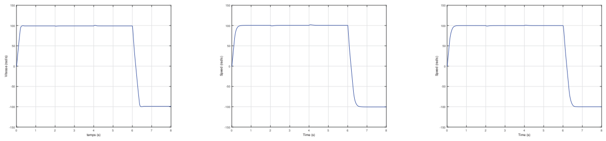

a b c

Fig. 10. simulation result of the speed (a) SMC (b) FSM first approach (c) FSM second approach

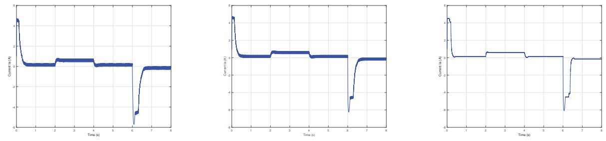

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Fig. 11. simulation result of armature current (a) SMC (b) FSM first approach (c) FSM second approach

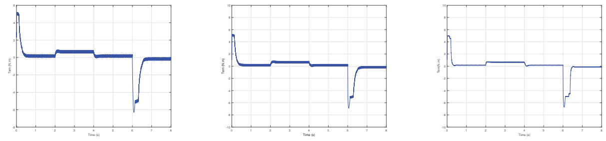
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Fig. 12. simulation result of the electromagnetic torque (a) SMC (b) FSM first approach (c) FSM second approach

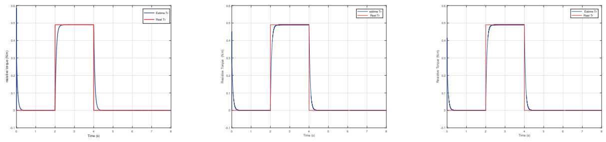
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Fig. 13. simulation result of the Real and estimated torque (a) SMC (b) FSM first approach (c) FSM second approach

Fig.9 . illustrate the efficacy of the suggested velocity control system the comparison between the proposed controllers shows that the FSM control of the second approach gives a good performance and it shows that the speed tracks its reference value and has a fast response with zero overshoot in FSM second approach compared to FSM first approach 0.12% and SMC 1.22‘%. Clearly, it has an instant quick response. Fig.10 . present that the armature current is limited to an acceptable value and has a lower ripple level compared to SMC and FSM's first approach. Fig.12 . shows that electromagnetic torque takes the same form of armature current and it has less oscillation ripple then SMC and FSM first approach,it has a high ability to reject perturbations in the load torque. For the estimated resistant torque presents in Fig. 13 it is clear that its estimated value is not far from the real value in the three cases. table.3. shows the comparison of the three techniques :

Table 3. comparative studies of SMC, FSMC1 and FSMC2

Controller	SMC	FSMC1	FSMC2
Overshoot (%)	1.22	0.09	0.01
Rising time (s)	0.8	0.7	0.4
Distrubance rejetction	slow	Fast	Very fast
Simplicity of schemes	Very Simple	complex	Very complex
Reducing chattering	bad	Good	Very good

Experimental result and discussion

The experimental testing in this part will verify the suggested control system that was developed in MATLAB/Simulink software in the previous paragraph.To compare the findings of the digital simulation with the experimental vali-dation of the DC motor drive connected with the dSpace 1104 card. This section includes the same scenario testing with those utilizing in the simulation.

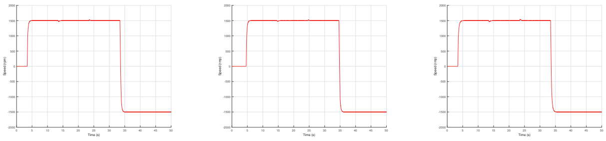
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Fig. 14. experimental result of the speed (a) SMC (b) FSM first approach (c) FSM second approach

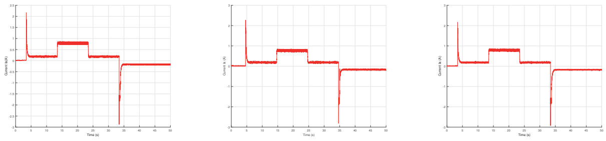
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Fig. 15. experimental result of the armature current (a) SMC (b) FSM first approach (c) FSM second approach

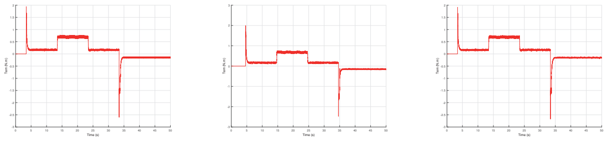
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Fig. 16. experimental result of the electromagnetic torque (a) SMC (b) FSM first approach (c) FSM second approach

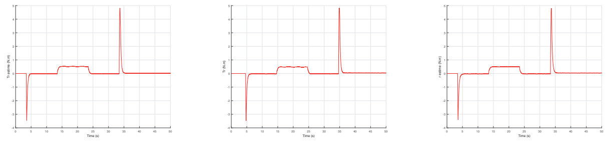
a b c

Fig. 17. experimental result of the estimated torque (a) SMC (b) FSM first approach (c) FSM second approach

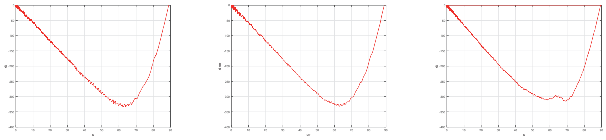
a b c

Fig. 18. experimental result of the chattering (a) SMC (b) FSM first approach (c) FSM second approach

The robustness tests were done under the same conditions as those performed in the simulation. It is clear that the adaptive FSM second approach is the best control compared to the classic SMC and the FSM first approach, it achieves rapid convergence and better tracking. All the simulation results obtained for the two approaches are carried out to design a robust controller under the internal and external disturbances. The results are very similar for the two FSM's controllers but the most satisfactory for us is the FSM second controller. We can see from the analysis of the experimentation results, that:

- A small rising time.
- In Fig.14 . speed follows its reference value with no overshoot and zero steady state error.
- FSM second approach has a best rejects of the load disturbance.
- The speed has a fast response at starting and when reversing speed.
- Fig.15 that the FSM second approach minimizes the armature current ripple level.
- Fig.16 shows that The electromagnetic torque takes the form of armature current which justifies the proportionality between them.

  We can observe a good convergence between the reel and estimated value of resistive torque with zero error in Fig. 17. Observably, Fig. 18 present that the FSM second approach has a good reduction of chattering ripples.

Conclusion

This article presents an experimental study to ameliorate sliding mode control for speed performance of a separately excited DC motor. Firstly, a sliding mode control of a separately excited DC motor is designed. Then, The SMC design is examined in order to realize a speed tracking aim under the different perturbations (application of load torque and speed reversing). Secondly, two fuzzy sliding mode approaches are implemented to improve SMC performances. The simulation analysis and experimental validation have effectively confirmed the efficiency of the suggested controllers. the findings display clearly that the proposed FSM second approach presents good performances which provide a fast response with no overshoot in the two directions with the high reject disturbance. Moreover, it provides the best minimization of the chattering phenomenon compared to SMC and FSM first approach

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