

# A FUZZY SLIDING MODE STRATEGY FOR CONTROL OF THE DUAL STAR INDUCTION MACHINE

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***Abstract:** This work investigates a simple design of the Fuzzy Sliding Mode Controller for speed regulation of an indirect field-oriented dual star induction motor. The influence of different combinations on the performance control is investigated and illustrated by some simulation results at different dynamic operating conditions such as sudden change in command speed, step change in load torque and some key parameters deviation. Finally the proposed controller is insensitive to parameter variations and load disturbances.*

**Key words:** (DSIM) Dual Star Induction Machine, (IFOC) Indirect Field Oriented Control, (FSC) Fuzzy Sliding Mode Controller, (SMC) Sliding Mode Controller, (FLC) Fuzzy logic Controller, Key parameters variation, robustness.

## 1. Introduction

The dual star winding induction machine with the squirrel cage rotor was recently shown to give permission in adjustable speed drives and in electric power generation in various application [1],[4], [5],The main difficulty in the asynchronous machine control resides in fact is that complex coupling exists between machine input variables, output variables and machine internal variables as the field, torque or speed, the space vector control assures that the torque has made similar as the one of a DC machine [3], the past few years have witnessed a rapid growth in the number and variety of applications of fuzzy logic, ranging from consumer products, industrial process control [18] ,[7] ,[15].

In the past decade the variable-structure control strategy using the sliding mode has been the focus of many studies and researches for the control of the machine, the feature of a sliding mode control system is that the controller is switched between two distinct control structures.

A fuzzy sliding mode control system, which combines

the merits of sliding mode control, the fuzzy inference mechanism [19],[20], [21],then fuzzy sliding mode controller is investigated in which a simple fuzzy inference mechanism is used to adaptation the gain  $K$  of the sliding mode control.

The results of simulations the speed control of a DSIM using the proposed control strategies are illustrated.

## 2. Machine model

A schematic of the stator and rotor windings for a dual three-phase induction machine is given in [1] and Fig.1.The stator six phases are divided into two wye-connected three phase sets labelled  $A_{s1} B_{s1} C_{s1}$  and  $A_{s2} B_{s2} C_{s2}$  whose magnetic axes are displaced by  $\alpha = 30^\circ$  electrical angle , the windings of each three phase set are uniformly distributed and have axes that are displaced  $120^\circ$  apart ,The three phase rotor windings  $A_r, B_r, C_r$  are also sinusoidal distributed and have axes that are displaced apart by  $120^\circ$  [16], [3], [24],The following assumptions have been made in deriving the dual-stator induction machine model:

- Machine windings are sinusoidally distributed ;
- The two stars have same parameters;
- Flux path is linear;
- The magnetic saturation and the mutual leakage are neglected .

The expressions for stator and rotor flux are:

$$\begin{cases} \varphi_{ds1} = L_{s1}i_{ds1} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qs1} = L_{s1}i_{qs1} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \\ \varphi_{ds2} = L_{s2}i_{ds2} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qs2} = L_{s2}i_{qs2} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \\ \varphi_{dr} = L_r i_{dr} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qr} = L_r i_{qr} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \end{cases} \quad (1)$$

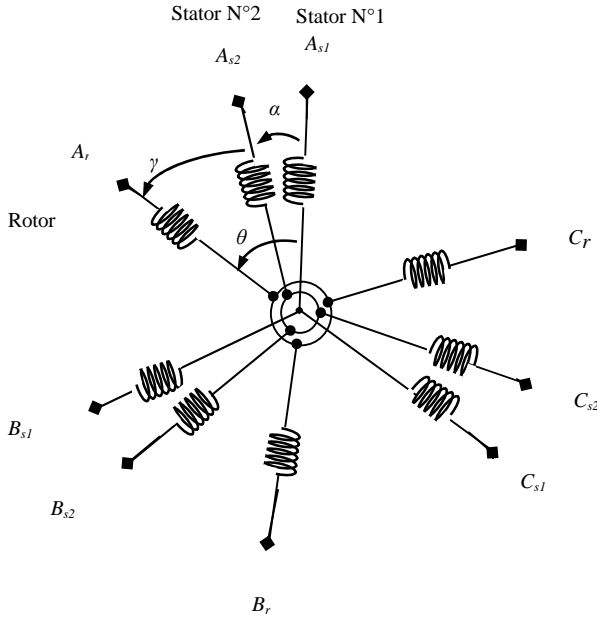


Fig.1. Schematic of the dual star induction machine .

The expressions for stator and rotor voltages are [3], [9], [10]:

$$\begin{cases}
 v_{ds1} = R_{s1}i_{ds1} + \frac{d}{dt}\varphi_{ds1} - \omega_s\varphi_{qs1} \\
 v_{qs1} = R_{s1}i_{qs1} + \frac{d}{dt}\varphi_{qs1} + \omega_s\varphi_{ds1} \\
 v_{ds2} = R_{s2}i_{ds2} + \frac{d}{dt}\varphi_{ds2} - \omega_s\varphi_{qs2} \\
 v_{qs2} = R_{s2}i_{qs2} + \frac{d}{dt}\varphi_{qs2} + \omega_s\varphi_{ds2} \\
 v_{dr} = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - (\omega_s - \omega_r)\varphi_{qr} \\
 v_{qr} = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} + (\omega_s - \omega_r)\varphi_{dr}
 \end{cases} \quad (2)$$

### 2.1. Mechanical equation

The mechanical equation is given by [3], [4]:

$$\frac{J}{P} \frac{d\omega_r}{dt} = C_e - C_r - \frac{f_r}{P} \omega_r \quad (3)$$

Expression of the electromagnetic torque

$$C_e = P \frac{L_m}{L_m + L_r} [\varphi_{dr}(i_{qs1} + i_{qs2}) - \varphi_{qr}(i_{ds1} + i_{ds2})] \quad (4)$$

$$\text{With: } \frac{3L_m}{2} = L_{ms} = L_{mr} = L_{sr}$$

In the induction machines, rotor winding has a short-circuited hence.

$$v_{dr} = 0 \quad , \quad v_{qr} = 0 \quad (5)$$

### 3. Field oriented control

The main objective of the vector control of induction motor is as in DC machines, to independently control the torque and flux, we propose to study the IFOC of the DSIM, the control strategy is used to maintain the quadrature component of the flux null  $\varphi_{qr} = 0$ , and the direct flux equals to the reference  $\varphi_{dr} = \varphi_r^*$  Fig.3. [6], [2].

The final formula of the electromagnetic torque is:

$$C_{ref} = P \frac{L_m}{L_m + L_r} \varphi_r^* (i_{qs1}^* + i_{qs2}^*) \quad (6)$$

The slip angular frequency is:

$$\omega_{sl}^* = \frac{R_r L_m}{L_m + L_r} \frac{(i_{qs1}^* + i_{qs2}^*)}{\varphi_r^*} \quad (7)$$

Expression of the direct currents:

$$i_{ds1}^* + i_{ds2}^* = \frac{\varphi_r^*}{L_m} \quad (8)$$

### 4. Fuzzy control

#### 4.1. Fuzzification

The most common controller has two inputs: error and the derivative of the error with respect to a defined reference signal, and one output, which is usually the command [11].

$$e(t) = \omega_{ref} - \omega_r(t) \quad (9)$$

The derivative of the error:

$$\Delta e(t) = \frac{e(t+1) - e(t)}{\Delta T} \quad (10)$$

#### 4.2. Fuzzy inference engine

The fuzzy rule consists of the antecedent-consequent pair is expressed by IF-THEN rules codified in a lookup table.1. The input-output mapping is an inference mechanism based on Zadeh logic .

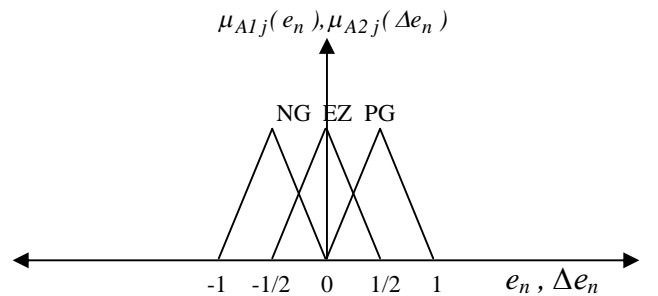


Fig.3. Membership functions of inputs ( $e_n$  and  $\Delta e_n$ ).

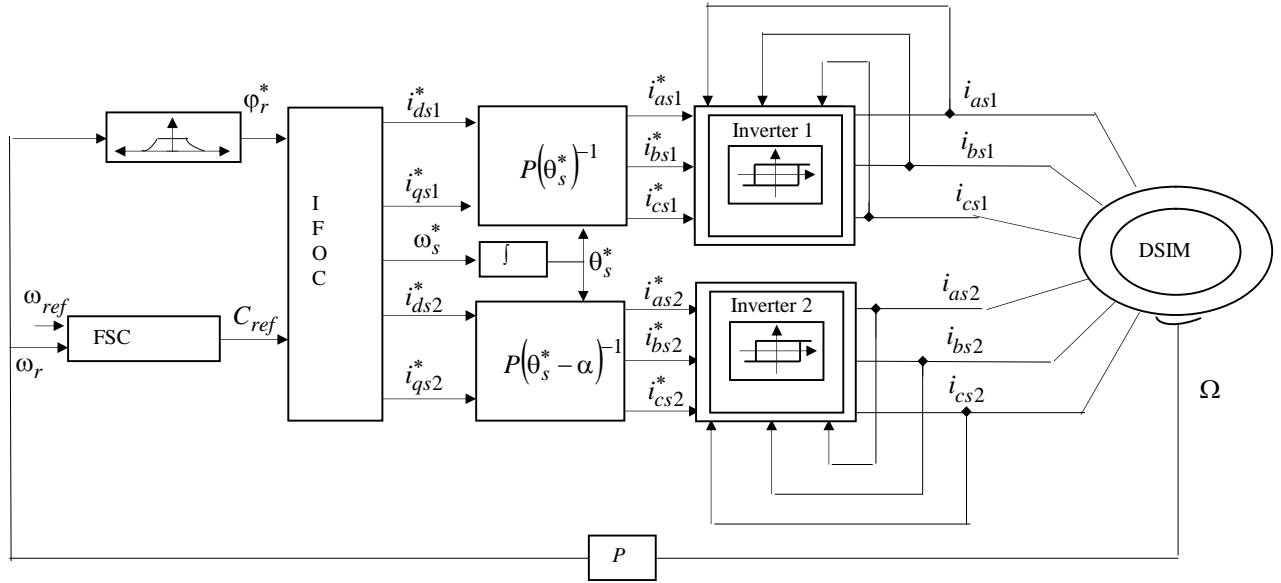


Fig. 2. Speed control of DSIM by using the fuzzy sliding mode controller.

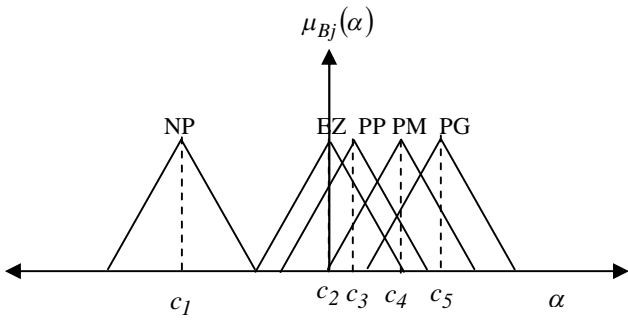


Fig.4. Membership functions of output ( $\alpha$ ).

### 4.3. Fuzzy control rules

The fuzzy inference mechanism contains nine rules for one output. However, The resulting fuzzy inference rules for the one output variable  $\alpha$  are as follows:

Table .1 the fuzzy inference mechanism  $\alpha$ .

		$\Delta e_n$		
		N	Z	P
$e_n$	N	ZE	PP	PM
	Z	PG	NP	PG
	P	PM	PP	ZE

### 4.4. Defuzzification

The centre of area defuzzification can calculate the crisp value of the output  $\alpha$  as [8]

$$\alpha = \frac{\sum_{j=1}^9 \mu_{A_{1j}}(e_n) \mu_{A_{2j}}(\Delta e_n) C_j S_j}{\sum_{j=1}^9 \mu_{A_{1j}}(e_n) \mu_{A_{2j}}(\Delta e_n) S_j} \quad (11)$$

$C_j, S_j$  are real value parameters representing the centre and surface of the membership function  $\mu_{B_j}(\alpha)$ .

Where  $A_{1j} = \{N, Z, P\}$ .

$A_{2j} = \{N, Z, P\}$ .

$B_j = \{NP, EZ, PP, PM, PG\}$ .

### 5. Fuzzy sliding mode control:

The proposed fuzzy sliding controller is shown in Fig (5).

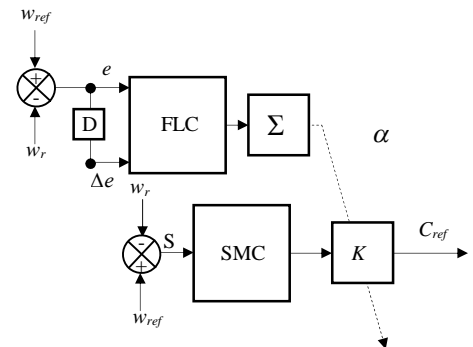


Fig.5 .Scheme of the proposed controller (FSC)

The surface is defined as follows:

$$s(\omega_r) = \omega_{ref} - \omega_r \quad (12)$$

$$\dot{s}(\omega_r) = \frac{d\omega_{ref}}{dt} - \frac{d\omega_r}{dt} \quad (13)$$

Then a mechanical equation can be represented in the following form.

$$\frac{J}{P} \frac{d\omega_r}{dt} = C_e - C_r - \frac{f_r}{P} \omega_r \quad (14)$$

The derivative surface can be written as:

$$\dot{s}(\omega_r) = \frac{d\omega_{ref}}{dt} - \frac{d\omega_r}{dt} \quad (15)$$

### 5.1.Design of the sliding-mode speed controller:

Based on the developed gain of the switching surface, a switching control law that satisfies the hitting condition and guarantees the existences of the sliding mode is designed; a speed controller is proposed in the following[12],[13],[14], [17], [25]:

$$C_{ref} = C_{eq} + C_n \quad (16)$$

Where

$C_{eq}$ :The equivalent control or the feedback linearization

$C_n$  : relay of the control or switching function.

$C_{ref}$ : Control.

For determination of the value  $C_{eq}$  , we use a formula (13 )

$$\dot{s}(\omega_r) = \dot{\omega}_{ref} - \dot{\omega}_r = -\dot{\omega}_r \quad (17)$$

Another hand

$$\dot{\omega}_r = \frac{P}{J} C_e - \frac{P}{J} C_r - \frac{f_r}{J} \omega_r \quad (18)$$

In this part, we consider a perturbation as zero ( $C_r = 0$ )

We obtain that:

$$\dot{s}(\omega_r) = -\frac{P}{J} C_e + \frac{f_r}{J} \omega_r \quad (19)$$

The dynamics of mechanical equation can be calculated by this equation:

$$C_{ref} = C_e = C_{eq} + C_n \quad (20)$$

For the study of the various parameters of the control law we replacing equation (20) , in equation (19),it possible To consider other control structures of the mechanical equation

$$\dot{s}(\omega_r) = -\frac{P}{J} C_{eq} - \frac{P}{J} C_n + \frac{f_r}{J} \omega_r \quad (21)$$

During the sliding mode,  $C_n = 0$  with  $\dot{s}(\omega_r) = 0$  ,  $s(\omega_r) = 0$  , then  $C_{eq}$  is :

$$C_{eq} = \frac{f_r}{p} \omega_r \quad (22)$$

During the convergence mode, the  $C_n \neq 0$

$$\dot{s}(\omega_r) = -\frac{P}{J} C_n \quad (23)$$

We select the switching function  $Sat(s(\omega_r))$  for assured the convergence without chattering phenomena

$$C_n = KSat(s(\omega_r)) \quad (24)$$

Where  $Sat(\cdot)$  is a sign function defined as

$$Sat(s(\omega_r)) = \begin{cases} -1 & \text{if } s(\omega_r) < -\varepsilon \\ \frac{s(\omega_r)}{\varepsilon} & \text{if } |s(\omega_r)| < \varepsilon \\ +1 & \text{if } s(\omega_r) > +\varepsilon \end{cases} \quad (25)$$

Then a derivative of the surface is  $\dot{s}$  :

$$\dot{s}(\omega_r) = -\frac{P}{J} KSat(s(\omega_r)). \quad (26)$$

In addition in the literature ,the author show that the structure of control law has the advantages of stable and simple verification the condition existence of a sliding mode as following :

$$s(\omega_r) \dot{s}(\omega_r) < 0 \quad (27)$$

$$-s(\omega_r) \frac{PK}{J} Sat(s(\omega_r)) < 0 \quad (28)$$

We remark that

When  $s(\omega_r) > \varepsilon$  and  $Sat(s(\omega_r)) = 1$  Then

$$-s(\omega_r) \frac{PK}{J} < 0 \text{ is negative}$$

When  $-\varepsilon < s(\omega_r) < \varepsilon$  and  $Sat(s(\omega_r)) = \frac{s(\omega_r)}{\varepsilon}$  then

$$-s^2(\omega_r) \frac{PK}{J\varepsilon} < 0 \text{ is negative}$$

When  $s(\omega_r) < -\varepsilon$  and  $Sat(s(\omega_r)) = -1$  with  $s(\omega_r) < 0$

then  $s(\omega_r) \frac{PK}{J} < 0$  is negative.

Finally the condition of the existence sliding mode is verified .

The condition of sliding mode existence, is used to solve the problem of the synthesis of the systems with variable structure, and allows us to determine the parameters of adjustment as long as  $s \dot{s} < 0$  is verified .

We can be obtained the control law that

$$C_{ref} = \frac{f_r}{p} \omega_r + KSat(s(\omega_r)) \quad (29)$$

Where

$C_{ref}$  is The reference torque and  $f_r$  is damping

Coefficient, and  $J$  is the moment inertia.

## 5.2. Mechanism of adaptation fuzzy-sliding mode control:

A fuzzy sliding mode controller is proposed, in which a fuzzy inference mechanism is used to estimate the gain  $K$  of the sliding mode, the fuzzy inference mechanism uses prior expert knowledge to accomplish control object more efficiently.

Define the gain of the sliding mode as

$$K = \frac{I}{|\alpha|} \quad (30)$$

Where  $K$  is estimated by fuzzy inference mechanism. Stability concepts .generally in the approach presented here we use the fuzzy logic to research the gain  $K$  of the sliding mode controller on-line for to obtain stable control.

## 6.Simulation results under proposed structure

Simulations results are presented as follows:

by figure (6) we present the DSIM response operated, respectively, at  $C_r=0$  (N.m) with load  $C_r=14$  (N.m).

Figure 6: Response of the gain  $K$ , with DSIM Operated under proposed control strategy at 100 (rd/s) with load torque variations.

By figure(7), we present the response of the DSIM with reference speed variations and with at  $t=1$  (s) and -100 (rd/s) .

As shown in figures (6) and (7), we remark than, the rotor speed, the rotor flux are converges to the reference values at the court time.

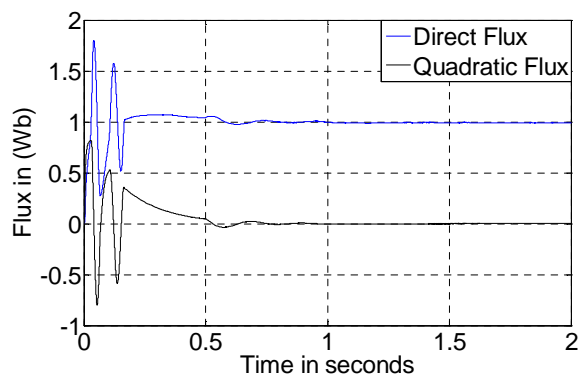
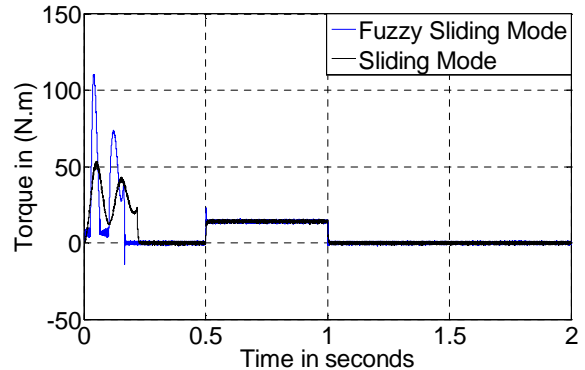
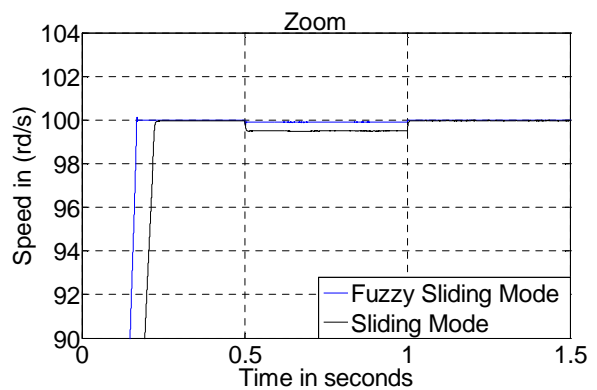
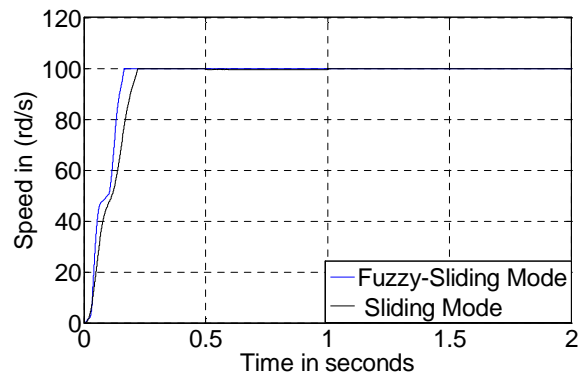
The gain  $K$  of the sliding Mode Control and the electromagnetic torque present both a high level at the started phase and the system rests stable for the after that.

For high rotor resistance, we have registered the compared results for even variables.

By figure (8), we present the DSIM response operated , at 100 (rd/s) with rotor resistance variations.

If we introduced an increase of rotor resistance we registered, as show in figure (8), a decrease of the rotor speed and of the electromagnetic torque.

By figure (9), we present the response of the Speed with rotor inertia variations.



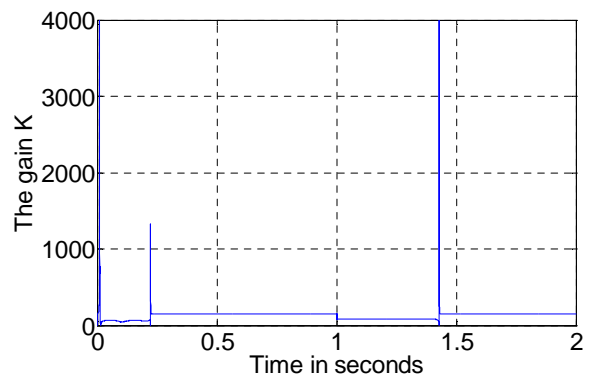
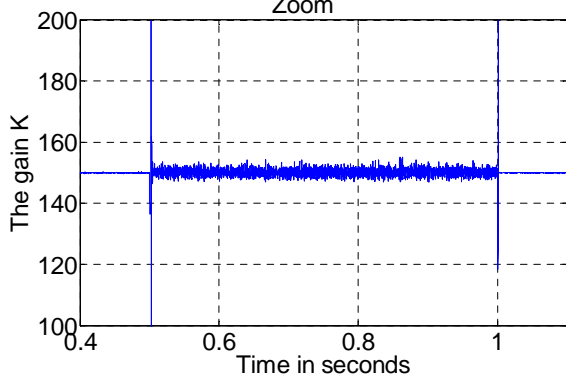
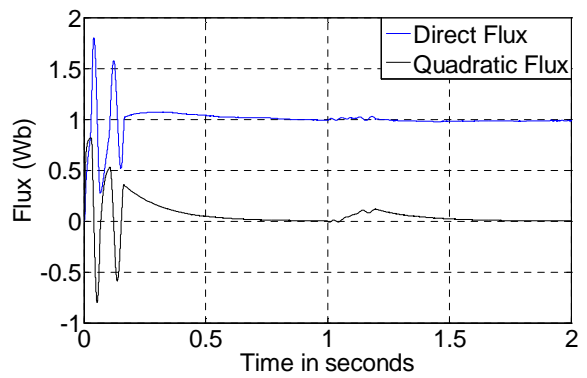
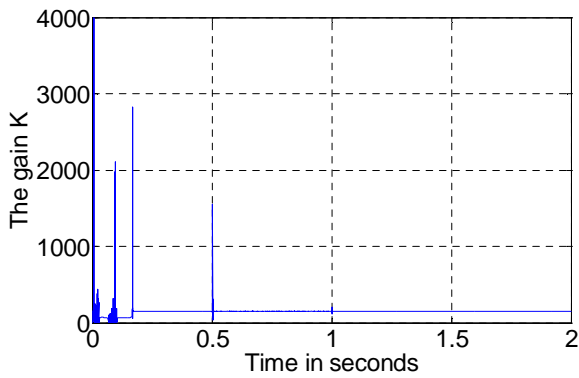


Fig. 6: The response of the machine when it is operated at 100 [rad/sec] under load 14 N.m is suddenly applied at 0.5 sec

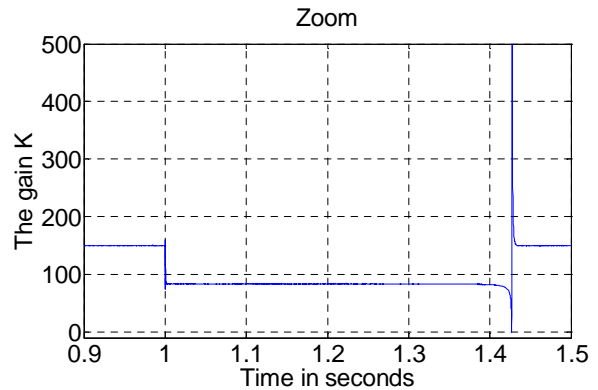
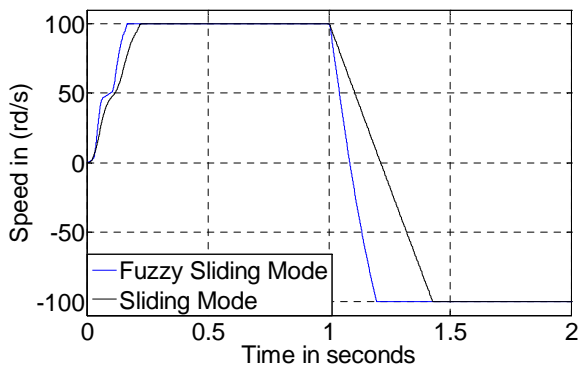


Fig.7: The response of the machine when it is operated with inversion of the rotation sense at 1

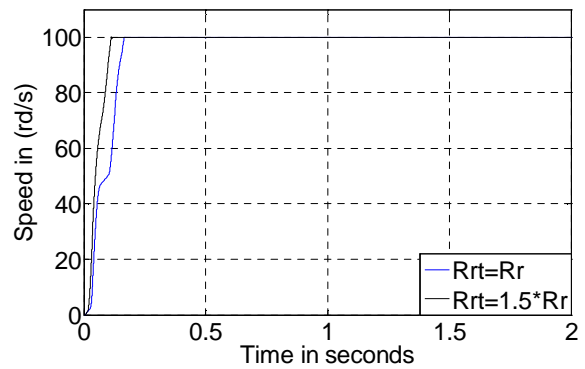
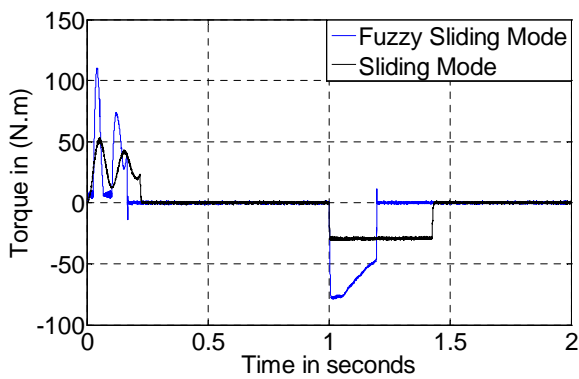


Fig 8: Simulated results test of robustness the proposed control .

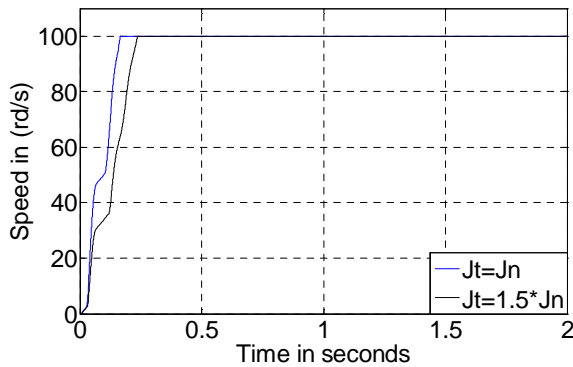


Fig 9: Simulated results test of robustness the proposed control .

## 7. Conclusion

In this paper, we have established a new Approach Sliding Mode based on the Fuzzy Logic control. The proposed control strategy uses the FOC principle. Around these control, we introduced an adapter algorithm for the variations of the parameters and Load torque.

The obtained results show the high performances of the proposed control law that is on stability and the rapidity.

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