# Speed Control Of Three Phase Induction Motor By Fuzzy Sliding Mode And Genetic algorithm

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## Abstract

**This paper describes the use of robust control systems using fuzzy sliding mode and genetic algorithm (FSMC-GA) to control the speed of a three phase induction motor. First, sliding mode control that incorporates a fuzzy tuning technique (FSMC) is used to overcome the high control gains and chattering of the classical SMC. However, the fuzzy control rules are always built by designers with trial and error. We propose an optimization technique of FSMC using genetic algorithm. GA is used for determination of different controller parameters due to their fast convergence and their reasonable accuracy. The effectiveness of the complete proposed control scheme is verified by numerical simulation. The results of simulation showed that (FSMC-GA) presents better performances compared to the (FSMC).**

***Index Terms***—Induction motor, Vector control, Fuzzy control, Sliding mode control, Genetic algorithm.

## I. INTRODUCTION

With this control strategy, the decoupled control of IM is guaranteed, and can be controlled and provide the same performance as achieved from separately excited DC machine. However, conventional proportional integral derivative (PID) control has difficulty in dealing with dynamic speed tracking, parameter variations and load disturbances [1]. As a result the motion control system must tolerate a certain level of performance degradation. In order to solve some of the problems of FOC, the motor drive must be techniques that are appropriate to discontinues operation of the switching devices and allow the robustness of the algorithm, with regard to changing parameters and external disturbances. This common drawback can be overcome by using variable structure control (VSC).

The variable structure strategy using sliding mode is one of the effective nonlinear robust control approaches. The goal of VSC is to constrain the system trajectory to the sliding surface via the use of the appropriate switching logic. The sliding mode control can offer good properties, such as insensitivity to parameter variations, external disturbance rejection, and fast dynamics response. However, in SMC, the high frequency chattering phenomenon that results from the discontinuous control action is a severe problem when the state of the system is close to the sliding surface [2]. To deal with these problems, fuzzy controller is recently a popular method to combine with sliding mode control method that can improve some disadvantages in this issue.

Comparing with the classical control theory, the fuzzy control theory does not pay much attention to the stability of the system, and the stability of the controlled system cannot be so guaranteed. In fact, the stability is observed based on following two assumptions:

First, the input/output data and system parameters must be crisply known. Second, the system has to be known precisely. The fuzzy controller is weaker in stability because it lacks a strict mathematics model to demonstrate, although many researches show that it can stabilized anyway [3-4]. Nevertheless, the concept of a sliding mode controller can be employed to be a basis to ensure the stability of the controller. The feature of a smooth control action of FLC can be used to overcome the disadvantages of the SMC systems. This is achieved by merging of the FLC with the variable structure of the SMC to form a fuzzy sliding mode controller (FSMC) [5-6].

In this hybrid control system, the strength of the sliding mode control lies in its ability to account for modeling imprecision and external disturbances while the FLC provides better damping and reduced chattering. However the major drawback in fuzzy control is the lack of design technique. The selection of suitable fuzzy rules, membership functions and their definition along universe of discourse always involves a painstaking trial and error process [7].

In this paper, the genetic algorithm (GA) is applied for the automatic design of fuzzy-sliding mode control system. In this GA based approach, the genetic algorithm is applied to determine the parameter set, consisting of the width of boundary layer ($\phi$) and control gain (k) of fuzzy sliding mode controller. An optimal fuzzy sliding mode controller has been achieved, fulfilling the robustness criteria specified in the sliding mode control and yielding a high performance in implementation to induction motor speed control.

## II. INDIRECT FIELD ORIENTED CONTROL OF IM

Under the assumptions of linearity of magnetic circuit iron losses, the dynamic model of three-phase, induction motor (IM) can be expressed in the d-q synchronously rotating frame as (1), where:

The state variables are the stator currents $\left(i_{sd}, i_{sq}\right)$, the rotor fluxes $\left(\phi_{rd}, \phi_{rq}\right)$ and the rotor speed $\omega_r$ .

Stator voltages $\left(V_{sd}, V_{sq}\right)$ and slip frequency $\omega_{sl}$ are the control variables.

$$\begin{cases} \frac{d}{dt} i_{sd} = \frac{1}{\sigma L_s}\left[ -(R_s + \frac{L_m^2}{L_r T_r}) i_{sd} + \omega_s \sigma L_s i_{sq} + \frac{L_m}{L_r T_r}\phi_{rd} + \frac{L_m}{L_r}\omega_r \phi_{rq} + V_{sd} \right] \\ \frac{d}{dt} i_{sq} = \frac{1}{\sigma L_s}\left[ -\omega_s \sigma L_s i_{sd} - (R_s + \frac{L_m^2}{L_r T_r}) i_{sq} + \frac{L_m}{L_r}\omega_r \phi_{rd} + \frac{L_m}{L_r T_r}\phi_{rq} + V_{sq} \right] \\ \frac{d}{dt}\phi_{rd} = \frac{L_m}{T_r} i_{sd} - \frac{1}{T_r}\phi_{rd} + (\omega_s - \omega_r)\phi_{rq} \\ \frac{d}{dt}\phi_{rq} = \frac{L_m}{T_r} i_{sq} - (\omega_s - \omega_r)\phi_{rd} - \frac{1}{T_r}\phi_{rq} \\ \frac{d}{dt}\omega_r = \frac{p^2 L_m}{L_r J}(i_{sq}\phi_{rd} - i_{sd}\phi_{rq}) - \frac{f_c}{J}\omega_r - \frac{p}{J}T_L \end{cases} \quad (1)$$

The main objective of the vector control of induction motors is, as in DC machines, to independently control the torque and the flux; this is done by using a d-q rotating reference frame synchronously with the rotor flux space vector. In ideally field-oriented control, the rotor flux linkage axis is forced to align the d-axes, and it follows that

$$\phi_{rd} = \phi_r = constant, \phi_{rq} = 0 \quad (2)$$

Applying the result of (2), namely field-oriented control, the torque equation become analogous to the DC machine and can be described as fellow:

$$T_{em} = \frac{pL_m}{L_r}\phi_r i_{sq} \quad (3)$$

And the slip frequency can be given as:

$$\omega_{sl} = \frac{L_m . R_r}{L_r . \phi_r} . i_{sq} \quad (4)$$

Consequently, the dynamic equations (1) yield:

$$\begin{cases} \frac{d}{dt}\omega_r = f_1 \\ \frac{d}{dt}\phi_{rd} = f_2 \\ \frac{d}{dt} i_{sd} = f_3 + \frac{1}{\sigma L_s} V_{sd} \\ \frac{d}{dt} i_{sq} = f_4 + \frac{1}{\sigma L_s} V_{sq} \end{cases} \quad (5)$$

$$f_1 = \frac{p^2 L_m}{L_r J}(i_{sq}\phi_r) - \frac{f_c}{J}\omega_r - \frac{p}{J}T_L) \quad (6)$$

$$f_2 = \frac{L_m}{T_r} i_{sd} - \frac{1}{T_r}\phi \quad (7)$$

With the torque and flux as commands, the FOC regulator calculates the required current magnitudes $i_{sd}$ and $i^*_{sq}$ and the slip command $\omega^*_{sl}$

From equation (3) we evaluate:

$$i^*_{sq} = \frac{L_r T_{em}}{pL_m \phi^*_{rd}} \quad (10)$$

From equation (4) we evaluate:

$$\omega^*_{sl} = \frac{2L_r T_{em}}{3pT_r (\phi^*_r)^2} \quad (11)$$

From equation (5) and (7) we evaluate:

$$i^*_{sd} = \frac{1}{L_m}\left(\frac{L_r}{R_r}\frac{d\phi^*_{rd}}{dt} + \phi^*_{rd}\right) \quad (12)$$

The decoupling control method with compensation is to choose inverter output voltages such that:

$$V^*_{sd} = \left(k_p + k_i\frac{1}{s}\right)\left(i^*_{sd} - i_{sd}\right) - \omega_s \sigma L_s i^*_{sq} \quad (13)$$

$$V^*_{sq} = \left(k_p + k_i\frac{1}{s}\right)\left(i^*_{sq} - i_{sq}\right) + \omega_s \sigma L_s i^*_{sd} + \omega_s \frac{L_m}{L_r}\phi_{rd} \quad (14)$$

According to the above analysis, the indirect field-oriented control (IFOC) of induction motor can reasonably presented by the block diagram shown in the Figure.1.

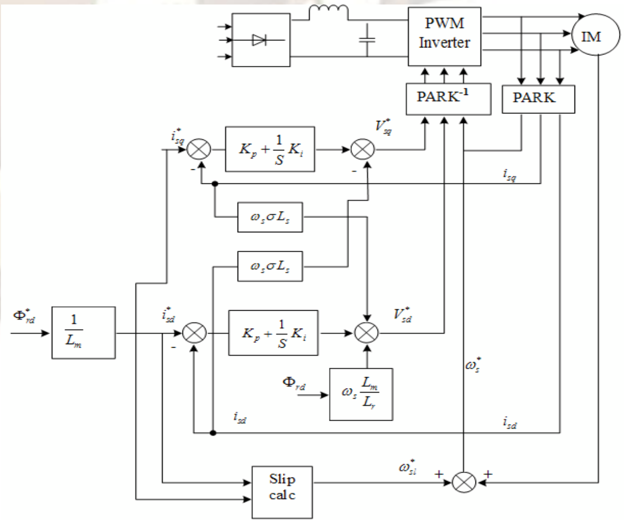



Figure. 1. Bloc diagram of IFOC for an IM

Where:
The rotor flux is obtained by:

$$f_3 = -\frac{1}{\sigma L_s}\left(R_S + \left(\frac{L_m}{L_r}\right)^2 R_r\right) i_{sd} + \omega\, i_{sq} + \frac{L_m R_r}{\sigma L_s L_r^2}\phi_r \tag{8}$$

$$f_4 = -\omega\, i_{sd} - \frac{1}{\sigma L_s}\left(R_S + \left(\frac{L_m}{L_r}\right)^2 R_r\right) i_{sq} - \frac{L_m}{\sigma L_s L_r}\phi_r\,\omega \tag{9}$$

$$k_p = 2\sigma . L_s \rho - R_s\,,\ k_i = 2\sigma . L_s \rho^2\,,\ \rho > 0$$

III. SLIDING MODE CONTROL

Sliding mode control is developed from variable structure control. It is a form of linear control providing robust means of controlling the nonlinear plants with disturbances and parameters uncertainties.

The Sliding mode is a technique to adjust the feed-back by previously defining a surface so that the system which is controlled will be forced to that surface, then the behavior system slides to the desired equilibrium point. This control consists of two phases:

The first phase is choosing a sliding manifold having a desired dynamics, usually linear and of a lower order. The second phase is designing a control law, which will drive the state variable to the sliding manifold and will keep them there.

The design of the control system will be demonstrated for a following nonlinear system:

$$\dot{x} = A(x,t).x + B(x,t).u \tag{16}$$

Where: A(x,t), B(x,t) are two nonlinear functions, and u is the control vector.

From system (16), it is possible to define a set S of the state trajectories x such as:

$$S = \{x(t)/s(x,t) = 0\} \tag{17}$$

$$\bar{S}(x,t) = [s_1(x,t), s_2(x,t), \ldots, s_m(x,t)]^T \tag{18}$$

S is called the sliding surface. To bring the state variable to the sliding surfaces, the following two conditions have to be satisfied:

$$s(x,t) = 0\,,\ \dot{s}(x,t) = 0 \tag{19}$$

The control law satisfying the precedent conditions is presented in the following form:

$$U = U^{eq} + U^{n} \tag{20}$$

Here U is the control vector, $U^{eq}$ is the equivalent control vector, $U^{n}$ is the switching part of control (the correction factor). $U^{eq}$ can be obtained by considering the condition for the sliding regime; $s(x,t) = 0$ the equivalent control keeps the state variable on the sliding surface, once they reach it. $U^{n}$ is needed to assure the convergence of the system states to sliding surfaces in finite time.

In order to alleviate the undesirable chattering phenomenon, Slotine proposed an approach to reduce it, by introducing a boundary layer of

$$\phi_r^* = \begin{cases} \phi_{rN} & if \quad \Omega \le \Omega_N \\ \dfrac{\Omega_N}{|\Omega|}\phi_{rN} & if \quad |\Omega| \ge \Omega_N \end{cases}$$

$$sat\left(\frac{S}{\phi}\right) = \begin{cases} \dfrac{S}{\phi} & if \quad \left|\dfrac{S}{\phi}\right| < 1 \\ Sign\left(\dfrac{S}{\phi}\right) & if \quad \left|\dfrac{S}{\phi}\right| > 1 \end{cases} \tag{22}$$

Sign(s) is a sign function, which is defined as:

$$Sign(S(x,t)) = \begin{cases} -1 & if \quad S(x,t) < 0 \\ 1 & if \quad S(x,t) > 0 \end{cases} \tag{23}$$

Where $\phi$ the boundary layer width and k is the controller gain

*A. Sliding mode control review of IM*

Among the various sliding mode control solutions for induction motor proposed in the literature, the one based on indirect field orientation can be regarded as the simplest one. Its purpose is to directly control the inverter switching by use of two switching surfaces.

Using the reduced non-linear IM model of (5), it is possible to design both a speed and flux sliding mode controllers. Let us define the sliding surfaces:

$$\begin{cases} S_1(\omega_r) = \lambda_\omega(\omega_r^* - \omega_r) + \dfrac{d}{dt}(\omega_r^* - \omega_r) \\ S_1(\phi_r) = \lambda_\phi(\phi_r^* - \phi_r) + \dfrac{d}{dt}(\phi_r^* - \phi_r) \end{cases} \tag{24}$$

Where $\lambda_\omega > 0, \lambda_\phi > 0$

To determine the control law that leads the sliding functions (24) to zero in finite time, one has to consider the dynamics of $\bar{S} = (S_1, S_2)^T$, described by:

$$\frac{d}{dt}\bar{S} = \dot{\bar{S}} = \bar{F} + DV \tag{25}$$

Where:

$$F = \begin{bmatrix} \ddot{\omega}_r^* + \lambda_\omega \dot{\omega}_r^* + \dfrac{f_c}{J} T_L + \left(\dfrac{f_c}{J} - \lambda_\omega\right) f_1 \\ -k_c\left(i_{sq} f_2 + \phi_r f_4\right) \\ \ddot{\phi}_r^* + \lambda_\phi \dot{\phi}_r^* + \left(\ldots - \lambda\right) f \ldots \dfrac{L_m}{\ldots} f \end{bmatrix}$$

width $\phi$ on either

side of the switching surface. Then $U^n$ is defined by:

$$U^n = k.sat\left(\frac{S}{\phi}\right) \tag{21}$$

(K high can cause the chattering phenomenon).
Saturation function is given by:

$$S^T.\dot{S} < 0 \tag{26}$$

So, it is possible to choose the switching control law for stator voltages as fellows

$$\begin{bmatrix}V_{sq}\\V_{sd}\end{bmatrix} = -D^{-1}F - D^{-1}\begin{bmatrix}k_\omega & 0\\0 & k_\phi\end{bmatrix}\begin{bmatrix}sign(S_1)\\sign(S_2)\end{bmatrix} \tag{27}$$

Where: $k_\omega > 0$, and $k_\phi > 0$

Proof (1). Let consider Lyapunov function

$$V = \frac{1}{2}s^2 \tag{28}$$

Its time derivative is

$$\dot{V} = s\dot{s} \tag{29}$$

Using Equations (25) and (27), we can rewrite (29) as:

$$\dot{V} = S^T\left(F + D\left(-D^{-1}F - D^{-1}\begin{bmatrix}k_\omega & 0\\0 & k_\phi\end{bmatrix}sign(S)\right)\right)$$

or

$$\dot{V} = -S^T\left(\begin{bmatrix}k_\omega & 0\\0 & k_\phi\end{bmatrix}sign(S)\right) \tag{30}$$

Then, the manifold S is attractive if:
$\dot{V} < 0$, i.e. $\lambda_\omega > 0$, and $\lambda_\phi > 0$

The sliding mode causes drastic changes of control variables introducing high frequency disturbances, to reduce the chattering phenomenon, a saturation function (22) has been introduced
To overcome the disadvantages of SMC, we propose in the next section a combination between two types of controllers (SMC and FLC)

## IV. FUZZY SLIDINGMODE CONTROLLER

Fuzzy sliding surface is introduced to develop a sliding

$$D = \frac{1}{\sigma L_s}\begin{bmatrix}k_c\phi_r & 0\\0 & \frac{L_m}{T_r}\end{bmatrix},\quad V_s = \begin{bmatrix}V_{sq}\\V_{sd}\end{bmatrix},\quad k_c = \frac{p^2 L_m}{JL_r},$$

Proposition (1). If the lyapunov theory of stability is used to ensure that S is attractive and invariant, the following condition has to be satisfied:

$R_i$ : if $S$ is $A_i$ then $u^n$ is $B_i$, $i = 1,\ldots 5$

Ai and Bi are triangle-shaped fuzzy number, see fig.2 and fig.3.
Let X and Y be the input and output space, and A be an arbitrary fuzzy set in X. Then a fuzzy set $A \circ R_i$ in Y, can be determined by each $R_i$ of (31).
We use the sup-min compositional rule of inference:

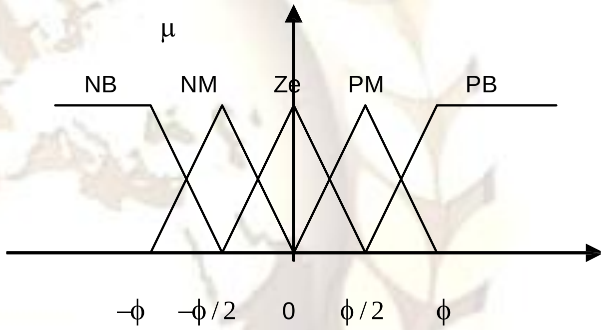



Figure. 2. The input membership function of FSMC

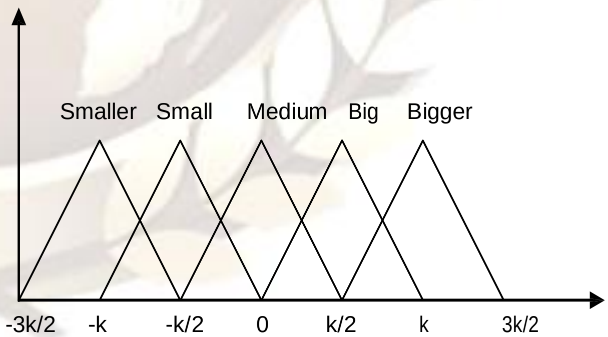



Figure. 3. The output membership function of FSMC

Fig. 4 is the result of output $u^n$ for a fuzzy input S:

mode controller. Which the expression $k.sat(S/\phi)$ is replaced by an inference fuzzy system for eliminate the chattering phenomenon.
The if-then rules of fuzzy sliding mode controller can be described by table I:

TABLE I. FUZZY RULES

| S | NB | NM | Ze | PM | PB |
|---|---|---|---|---|---|
| $i^n_{sq}$ | Bigger | Big | Medium | Small | Smaller |

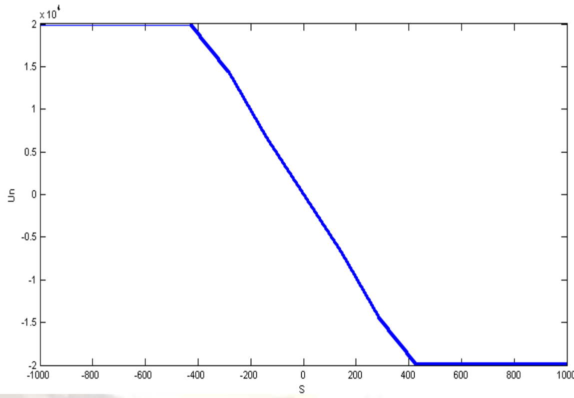
Where NB, NM, Ze, PM, and PB are linguistic terms of antecedent fuzzy set, they mean Negative Big, Negative Medium, Zero, Positive Medium and Positive Big, respectively. We can use a general form to describe these fuzzy rules:

rule base by using GA, clustering method, neural networks, least square parameter estimation method, or single value decomposition (SVD) method Obviously, GA has successfully been used to optimize the fuzzy logic input membership functions, fuzzy rules, the output membership functions, scaling factors and universe of discourse [8].
In order to improve the performance of fuzzy sliding mode controller, we try to adjust the parameters of input and output membership functions and rule base of the FLC so we adjust indirectly $\phi$ and k in the control law. We use GA to search the appropriate values of the parameters of the FLC. In GA, we only need to select some suitable parameters, such as generations, population size, crossover rate, mutation rate, and coding length of chromosome [9-10], then the searching algorithm will search out a parameter set to satisfy the designer's specification or the system requirement.
In this paper, GA will be included in the design of sliding mode fuzzy controller. The parameters for the GA simulation are set as fellows:

Initial population = 30, maximum number of generation =100, crossover is uniform crossover with probability = 0.8, mutation probability= 0.01.

The fitness is given as fellows:

Figure. 4. The control signal of FSMC




V. GA FUZZY SLIDING MODE CONTROL

The proposed sliding mode scheme uses fuzzy rules has been tested and satisfactory result are obtained, however trial-and-error always exists in building a satisfactory fuzzy rule base for controlling a nonlinear system. Designers usually cannot guarantee that the fuzzy control system designed with trial-and- error has a good performance. To avoid trial-and-error a number of papers have proposed some kinds of methods to build the fuzzy.

TABLE II. INDUCTION MOTOR PARAMETERS

| | | | |
|---|---|---|---|
| $R_s$ [Ω] | 4.850 | $I_n$ [A] | 6.5 |
| $R_r$ [Ω] | 3.805 | $\Omega_N$ [rad/s] | 149 |
| $L_s$ [H] | 0.274 | J [kg/m$^2$] | 0.031 |
| $L_r$ [H] | 0.274 | fc[Nms/rad] | 0.0014 |
| $L_m$[H] | 0.258 | P | 2 |

$$J = \int_0^t e^2 dt = \int_0^t \left(\omega^* - \omega\right)^2 dt \qquad (32)$$

The configuration of the overall control system is shown in figure 5:

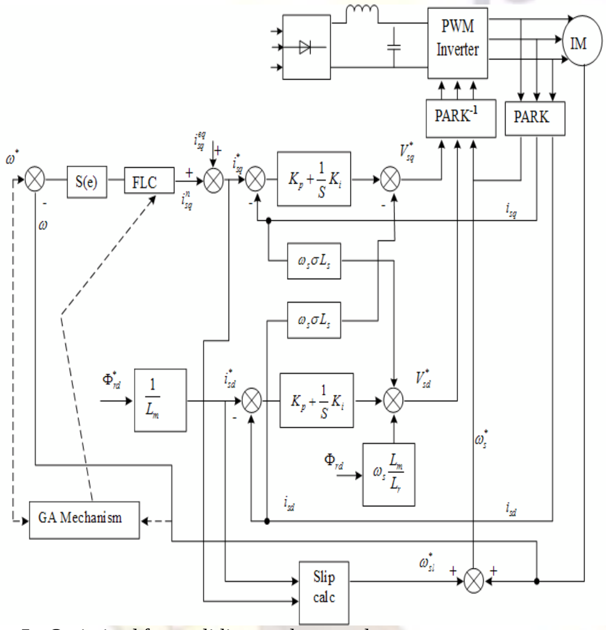



Figure. 5. Optimized fuzzy sliding mode control

## VI. SIMULATION

To prove the effectiveness of proposed control scheme, we apply the designed controller to the induction motor

Induction motor has three phase, Y connected, four pole, 1.5kW, 149 rad/s 220/380V, 50Hz.

Figure 6, and figure 7 represent respectively the membership function of S (input of FLC) and $U^n$ (output of FLC), before and after optimization by GA.

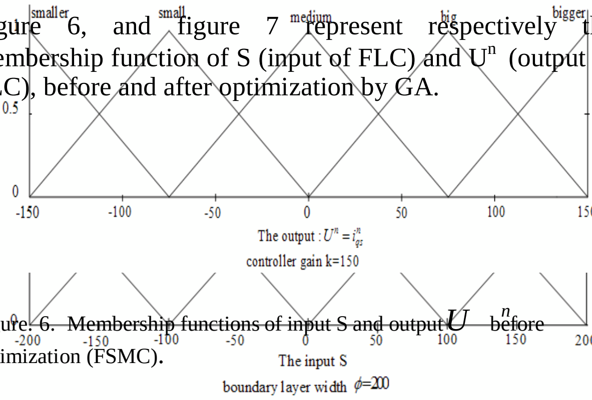



Figure. 6. Membership functions of input S and output $U^n$ before optimization (FSMC).

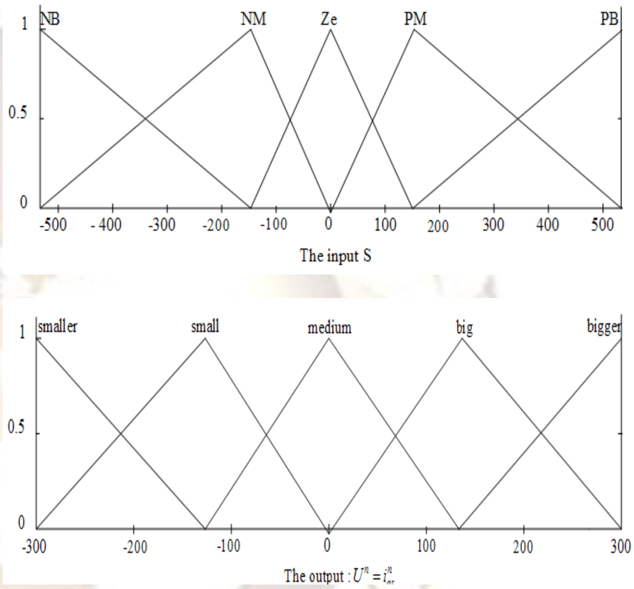



Figure. 7. Membership functions of S and $U^n$ after optimization (GA-FSMC).

## VII. RESULTS AND DISCUSSIONS

The configuration of the overall control system is shown in fig.5. It mainly consists of an induction motor, a ramp comparison current controlled pulse width modulated (PWM) inverter, a slip angular speed estimator, an inverse park, an outer speed feedback control loop and a fuz sliding mode speed controller optimized by genetic algorithm. The machine parameters are given in table II. Fig.8 shows the disturbance rejection of FSMC controller when the machine is operated at (200 rad/s) under no load and a load disturbance torque (10 Nm) is suddenly applied at (0.5sec), followed by a consign inversion (-200 rad/s) at (1 sec). The FSMC controller rejects the load disturbance very rapidly with no overshoot and with a negligible steady state error.

A comparison between the speed control of the IM by a SMC and a FSMC is presented in fig. 9. This comparison shows clearly that the FSMC gives good performances.

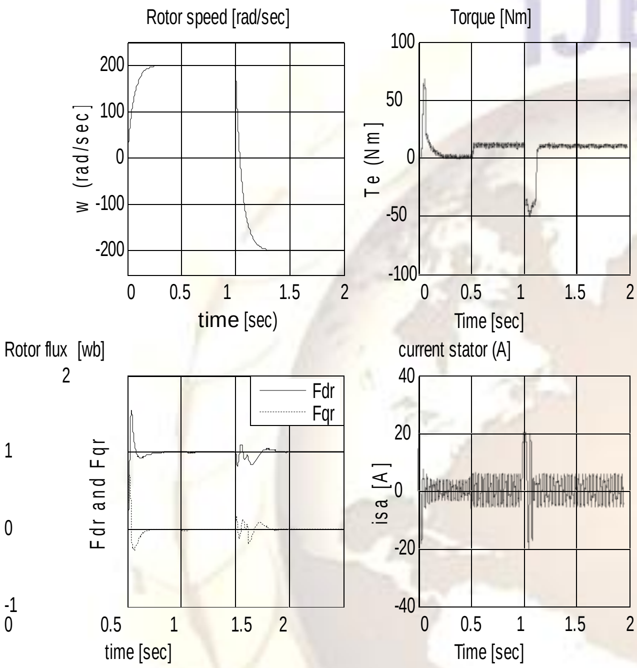



Figure. 8 Simulated results of the FSM controller of IM

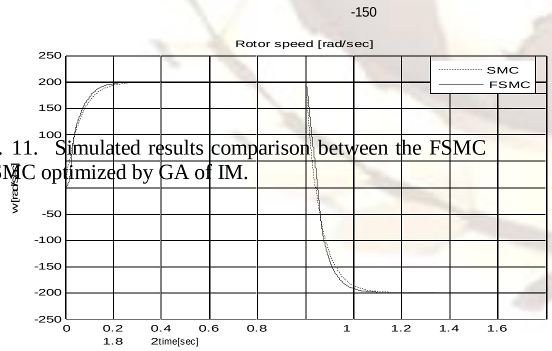



Figure. 11. Simulated results comparison between the FSMC and FSMC optimized by GA of IM.

Figure. 9. Simulated results comparison between the SM and FSM controller of IM.

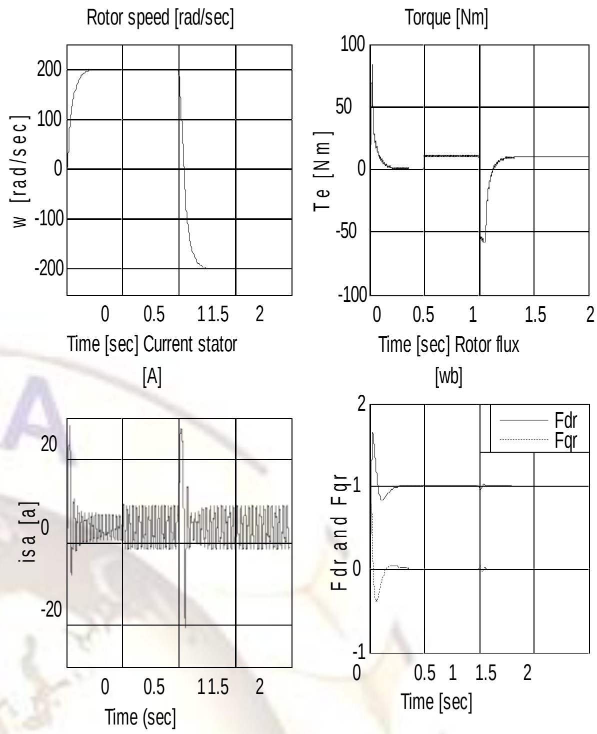
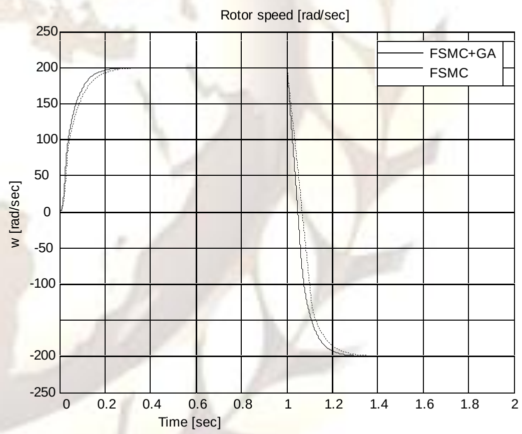



Figure. 10. Simulated results of the (FSM+GA) controller of IM.




## VIII. CONCLUSION

This paper has reported the development of an automated design approach to soft switched fuzzy sliding mode controllers using a genetic algorithm. This controller

The same tests applied for FSMC no optimized are applied with the FSMC optimized by GA. Fig 10 shows the disturbance rejection of FSMC controller optimized by GA when the machine is operated at (200 rad/s) under no load and a load disturbance torque (10Nm) is suddenly applied at 0.5sec, followed by a consign inversion (-200 rad/s) at 1 sec. This controller rejects the load disturbance very rapidly with no overshoot and with a negligible steady state error more than the FSMC witch is shown clearly in fig 11.
as been implemented for induction motor speed control. Moreover, GA is implemented for tuning of the fuzzy system parameters. First, the dynamic response of the fuzzy sliding mode controller was studied. It has been shown that the proposed controller can provide the properties of insensitivity to uncertainties and external disturbance. Then, GA, is designed to tuning the fuzzy parts of the fuzzy sliding mode controller to enhance the control performance of the induction motor. The theories of the fuzzy sliding mode controller and the implementation of the GA are described. Finally, the effectiveness of the proposed controllers has been demonstrated by simulation and successfully implemented in an IM.APPENDIX

$R_r$ , $R_s$ : Respectively rotor and stator resistance $L_r$ , $L_s$ : Respectively rotor and stator inductance $L_m$ : Mutual inductance

$T_r$ : Rotor time constant ( $T_r$ =Lr/Rr)

$p$ : Number of pairs of poles

$J$ : Moment of inertia

$f_c$ : Viscous friction coefficient

σ: Coefficient of dispersion

$T_{em}$ : Electromagnetic torque

$T_L$ : Load torque

$V_{sd}$ , $V_{sq}$ : Respectively d-axis and q-axis stator voltage

IM: Induction motor
FLC: Fuzzy logic controller
SMC: Sliding mode controller
GA: Genetic algorithm
An asterisk ($^*$) is added to indicate command signals. $[.]^T$ denotes the transposed vector

$i_{sd}$ , $i_{sq}$ : Respectively d-axis and q-axis stator current

$\phi_{rd}$ , $\phi_{rq}$ : Respectively d-axis rotor and q-axis rotor flux

$\phi_r$ , $\phi_{rN}$ : Respectively Rotor flux, and nominal rotor flux

$\omega_r$ : Rotor electric speed

$\omega_{sl}$ : Slip frequency

$\omega_s$ : Synchronous speed

$\Omega$ : Mechanical speed

$\Omega_N$ : Nominal angular speed

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