Performance Analysis of Fuzzy Based Sliding Mode and Self-Tuning Controls of Vector Controlled Induction Motor Drive

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Abstract— This paper presents the fuzzy based sliding mode and self tuning controls for Indirect vector controlled induction motor drive. Because of the low maintenance and robustness induction motors have many applications in the industries. The speed control of induction motor is more important to achieve maximum torque and efficiency. Soft computing technique – Fuzzy logic is applied in this paper for the speed control of induction motor to achieve maximum torque with minimum loss. The fuzzy logic controller is implemented using the Field Oriented Control technique as it provides better control of motor torque with high dynamic performance. The proposed adaptive controller takes advantage of sliding mode control and fuzzy logic control. The chattering effect is attenuated and robust performance can be ensured .The simulated design is tested using various tool boxes in MATLAB. Simulation results conclude that the proposed fuzzy based controller showed increased dynamic response.

Key words — Induction motor, Field Oriented Control, Fuzzy logic Controller, self tuning control and Sliding Mode Control.

1. INTRODUCTION

AC Induction motors are being applied today to a wider range of applications requiring variable speed. field-oriented control technique has been widely used in industry for high-performance induction machine (IM) drive, where the knowledge of synchronous angular velocity is often necessary in the phase transformation for achieving the favorable decoupling control. However, the control performance of the IM is still influenced by the variations of motor parameters, especially the rotor time-constant, which vanes with the temperature and the saturation of the magnetizing inductance, the uncertainties, such as mechanical parameter variation, external disturbance, unstructured uncertainty due to non ideal field orientation in transient state, and unmodelled dynamics [l].One of the possible approaches to the robust control of the uncertain systems has been found invariable structure systems and sliding mode control [4]. The sliding mode controller has been suggested to achieve robust performance against parameter variations and load disturbances.

Advanced control based on artificial intelligence technique is called intelligent control. Intelligent control, act better than conventional adaptive controls. Fuzzy logic is a technique to embody human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what

they know. Fuzzy control has been primarily applied to the control of processes through fuzzy linguistic descriptions. Sliding mode control (SMC) are widely used in the field of induction motor drive [4-8]. However, there exists a discontinuous control action, chattering phenomena will take place when implementing a sliding mode control. One common way to eliminate this drawback is to introduce a boundary layer neighboring the sliding surface .This method can lead to stable closed loop system with avoiding the chattering problem, but there exists a finite steady state error due to finite gain in steady state without switching control action. In this paper, self tuning fuzzy logic controller is used for indirect vector controlled induction motor. Self tuning control is replaced with fuzzy based sliding mode control and the dynamic response of vector controlled induction motor with the proposed controllers is compared. The basic concept of Mathematical Modeling of the induction motor is in Section 2. Field oriented control of induction is in section 3. The basic concept of sliding mode control and a brief description of controllers is in Section 4. In section 4, the fuzzy based controller is proposed. Also the adaptive fuzzy sliding mode control is proposed. Simulation results are shown in Section 5. Finally, the paper is concluded in Section 6.

2. INDUCTION MOTOR MODELING

An Induction Motor of uniform air gap, with sinusoidal distribution of mmf is considered and the dynamic model [2] of the induction motor is derived by transforming the three phase quantitiesinto two phase direct and quadrature axes quantities. The equivalence between the three-phase and two-phase machine models [1] is derived from the concept of power invariance: the power must be equal in the three phase machine and its equivalent two-phase model. The d and q axes mmfs are found by resolving the mmfs of the three phases along the d and q axes. The mathematical model of the 3-phase IM could be represented by an equivalent 2-phase, where d^s, q^s, d^r and q^r correspond to the stator, rotor, direct and quadrature axes, respectively. The stator voltage equations formulated from stationary reference frame and the rotor voltage equations formulated to the rotating frame fixed to the rotor.The 3-phase stator and rotor voltage equations written in vector-matrix can be further transformed into 2-phase stator and rotor voltage equations using the well-known Park's transformation. The 3-phase stationary reference frame variables *as-bs-cs* are transformed into 2-phase stationary reference frame variables (d^s–q^s). Furthermore, these 2-phase variables are transformed into synchronously rotating reference frame variables (d^e–q^e) and vice-versa.

The stator circuit equations can be modeled as follows:

$$v^s_{qs} = R_s i^s_{qs} + \frac{d}{dt} \psi^s_{qs}$$

-------- (2.1)

$$v^s_{qs} = R_s i^s_{ds} + \frac{d}{dt} \psi^s_{qs}$$

-------- (2.2)

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Equations (2.1) and (2.2) are further converted into $d^e - q^e$ frame. The flux linkage expressions in terms of the currents can be written as

$$\psi_{qs} = L_{ls}i_{qs} + L_m(i_{qs} + i_{qr})$$

-------- (2.3)

$$\psi_{qr} = L_{lr}i_{qr} + L_m(i_{qs} + i_{qr})$$

-------- (2.4)

$$\psi_{qm} = L_m(i_{qs} + i_{qr})$$

-------- (2.5)

$$\psi_{ds} = L_{ls}i_{ds} + L_m(i_{ds} + i_{dr})$$

------- (2.6)

$$\psi_{dr} = L_{lr}i_{dr} + L_m(i_{ds} + i_{dr})$$

------- (2.7)

$$\psi_{dm} = L_m(i_{ds} + i_{dr})$$

------- (2.8)

Using above equations in voltage equations, the electrical transient model of the IM in terms of v and i is given in matrix form. The development of torque is also very important in the modeling of IMs. The speed ωr cannot be treated as a constant and is related to the torques as

$$T_e = T_L + j\frac{d}{dt}\omega_m = T_L + \frac{2}{P}J\frac{d\omega_r}{dt}$$ ------- (2.9)

where T_L is the load torque, J is the rotor inertia and ωm is the mechanical speed of the IM. Resolving the variables into $de - qe$ components, we obtain

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\Psi_{dr}i_{qr} - \Psi_{qr}i_{dr}\right)$$

------- (2.10)

The dynamic machine model in stationary frame can be derived simply by substituting $\omega e = 0$. The corresponding stationary frame equations are given as follows:

$$v^s_{qs}R_s i^s_{qs} + \frac{d}{dt}\Psi^s_{qs}$$

------- (2.11)

$$v^s_{ds}R_s i^s_{ds} + \frac{d}{dt}\Psi^s_{ds}$$

------- (2.12)

$$0 = R_r i^s_{qr} + \frac{d}{dt}\Psi^s_{qr} - \omega_r \Psi^s_{dr}$$

------- (2.13)

$$0 = R_r i^s_{dr} + \frac{d}{dt}\Psi^s_{dr} - \omega_r \Psi^s_{qr}$$

------- (2.14)

The torque Equations can also be written with the corresponding variables in the stationary frame as follows:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\Psi^s_{dr}i^s_{qr} - \Psi^s_{qr}i^s_{dr}\right) \quad \text{------- (2.15)}$$

The equations (2.1) and (2.15) form the mathematical model equations of a three phase induction motor.

3. VECTOR CONTROL OR FIELD ORIENTED CONTROL (FOC)

The Vector Control or Field Oriented Control is used to control Induction motor like a dc motor. Using vector control strategy, the torque and flux components can be controlled independently like dc motor. The basic principles of vector control can be explained with the help of dynamic model of induction motor where we need to convert 3Φ quantities into 2-axes system by 3Φ/2Φ transformation called d-q machine model. There are two methods of vector control, Direct Vector Control method & Indirect Vector Control (IFOC) method. In indirect vector control strategy rotor flux vector is estimated using the field oriented control equations requiring a rotor speed measurement. Due its implementation simplicity, Indirect Vector Control method is more popular than Direct Vector Control in industrial applications.

3.1 INDIRECT FIELD ORIENTED CONTROL (IFOC)

In the Indirect Vector Control method, by using summation of rotor speed and slip frequency, the rotor flux angle is calculated. Hence the unit vectors are obtained indirectly. Then the d-q axis currents are obtained from the torque and flux producing components of stator current.

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{st})dt = \theta_r + \theta_{st} \quad \text{----- (3.1)}$$

The rotor circuit equations

$$\frac{d\psi_{dr}}{dt} + \frac{R_r}{L_r}\psi_{dr} - \frac{L_m}{L_r}R_r i_{ds} - \omega_{sl}\psi_{qr} = 0 \quad \text{----- (3.2)}$$

$$\frac{d\psi_{qr}}{dt} + \frac{R_r}{L_r}\psi_{qr} - \frac{L_m}{L_r}R_r i_{qs} - \omega_{sl}\psi_{dr} = 0 \quad \text{----- (3.3)}$$

For decoupling control $\Psi_{qr} = 0$,So the total flux Ψ_r directs on the d^e axis. Now from equations 3.1 and 3.2, we get

$$\frac{L_r}{R_r}\frac{d\psi_{dr}}{dt} + \psi_r = \frac{L_m}{L_r}i_{ds} \quad \text{---- (3.4)}$$

As well , the slip frequency can be calculated as

$$\omega_{sl} = \frac{L_m}{\psi_r}\frac{R_r}{L_r}i_{qs} = \frac{R_r}{L_r}\frac{i_{qs}}{i_{ds}} \quad \text{---- (3.5)}$$

The slip gain is

$$K_s = \frac{\overset{\bullet}{\omega}_{sl}}{\overset{\bullet}{i}_{qs}} = \frac{L_m R_r}{L_r \psi_r} \quad \text{---- (3.6)}$$

It is found that the ideal decoupling can be achieved if the above slip angular command is used for making field orientation. The constant flux Ψ_r and $\Psi r^I = 0$ can be substituted in equation 3.4 , so that rotor flux sets as

$$\psi_r = L_m i_{ds}$$

---- (3.7)

The electromechanical torque developed is given by

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} \psi_r i_{qs}$$

---- (3.8)

4. CONTROLLERS DESIGN

Speed controller is necessary to control the speed of the induction motor drive. Design of this speed controller greatly affects the performance of the electric drive. PI controllers are the most commonly used speed controllers before the introduction of fuzzy controller. Design and tuning of the fuzzy based controllers are defined in this section.

4.1 FUZZY LOGIC CONTROLLER

Fuzzy Logic implementation requires no exact knowledge of a model. The block diagram of a FLC is shown in Fig. 4.
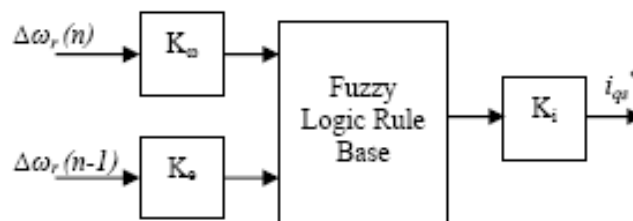

Fig. 4. Fuzzy Logic Based Controller block

It involves the use of the concept of fuzzy subset and rule based modeling. By permitting certain amount of imprecision, complex solutions are modeled with ease.

4.2 PROPOSED ADAPTIVE FUZZY CONTROL SCHEMES

4.2.1 SELF TUNED FUZZY LOGIC INTELLIGENT CONTROLLER

The fuzzy logic control (FLC) has been an active research topic in automation and control theory since Mamdani proposed in 1974 based on the fuzzy sets theory of Zadeh (1965) to deal with the system control problems that are not to model the fuzzy logic can serve as a tool in developing intelligent control systems. It has ability to plan via decomposition of a complex task into manageable subtasks and adapt to new situations. The structure of a complete fuzzy control system is composed of the following blocs: Fuzzification, Knowledge base, Inference engine, Defuzzification. The membership functions can be triangular, trapezoidal. Its actual operation

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can be divided into three steps: i) Fuzzification – actual inputs are fuzzified and fuzzy inputs are obtained. ii) Fuzzy processing – processing fuzzy inputs according to the rules set and producing fuzzy outputs. iii) Defuzzification – producing a crisp real value for a fuzzy output.

This concept helps a lot to improve the relationship between human and computers. Then the steps for creations a proto typed fuzzy logic controller (FLC) attained. The basic paradigm for fuzzy logic control is shown in fig 4.1 that is based on linguistic semantics control strategy.
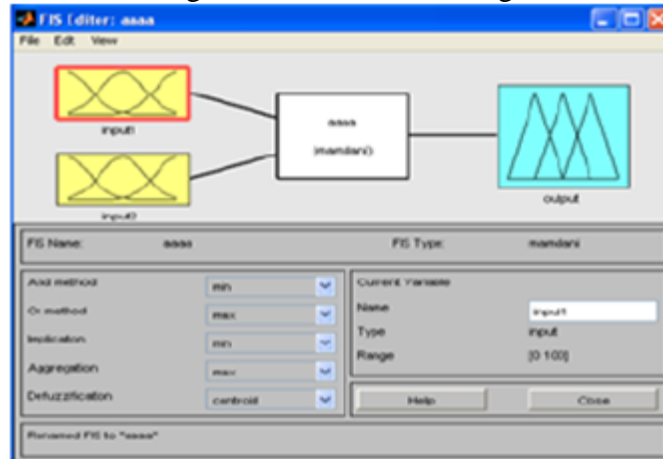

Fig 4.1 Mamdani architecture approach with input OA1.OA2 and output CA1.CA2

Desigining fuzzy Rule based System using Fuzzy logic tool box Fuzzy logic toolbox for Matlab provides several built in membership functions like triangular trapezoidal, Gaussian.in fig 4.1 shows fuzzy inference system its properties are: And method : min Or method : max Implication : min Aggregation : max Defuzzification : centroid. Which maps the observable attributes (OA1,OA2.....,)of the given physical system into its controllable attributes (CA1, CA2....).

The inference engine is the heart of a fuzzy controller operation which consists of fuzzy matching , inference system, combination and defuzzification. Whereas fuzzy matching calculate the degree to which the input data match the condition of the fuzzy rules and its output given to the inference system which calculates the rule's conclusion based on its matching degree and its output given to the combination which combine the conclusion inferred by all fuzzy rules into a final conclusion and lastly for application that need a crisp output an additional step is used to convert a fuzzy conclusion into crisp (non fuzzy) value. There are two major defuzzification techniques (a)the Mean of Maximum method (MOM) and (b) The Center of Area (COA) or centroid method.

4.2.2 Fuzzy based SLIDINGMODE CONTROL BASIC CONCEPT

The basic principle of the sliding mode control consists in moving the state trajectory of the system toward a surface $S(X) = 0$ and maintaining it around this surface with the switching logic function Un. The basic sliding mode control law is expressed as.

$$Uc = Ueq + Un \quad \text{----- (4.1)}$$

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This expression uses two terms, *Ueq* and *Un* . *Ueq* : is determined off line with a model that represents the plant asaccurately as possible. It is used when the system state is in the sliding mode. The term *Un* : is a sign function defined as *Un= k* sgn(*S(X)*), where

$$sgn\big(S(X)\big) = \begin{cases} 1, & if \quad S(x) < 0 \\ -1, & if \quad S(x) > 0 \end{cases} \quad \text{----- (4.2)}$$

This will guarantee that the state is attracted to the switching surface by satisfying the Lyapunov stability criteria .

$$S(x)\dot{S}(x) < 0 \quad \text{----- (4.3)}$$

This strategy enforces the system trajectory to move toward and to stay on the sliding surface from any initial condition.Using a sign function often causes chattering in practice. One solution to reduce chattering is to introduce a boundary layer around the sliding surface [5], [6]. This is expressed by:

$$Un = \begin{cases} \frac{k}{\varepsilon}S(x), & if|S(x)| < \varepsilon \\ ksign\big(S(x)\big), & if|S(x)| > \varepsilon \end{cases} \quad \text{------ (4.4)}$$

with *k* , a positive coefficient and ε, the thickness of the boundary layer. However, a small value of S might produce a boundary layer so thin that it can excite high frequency dynamics.

4.2.2.1   IM SLIDING MODE CONTROL

The 'd' axis, has the stator current component (Ids) loop and the 'q' axis allows the control stator current component (Iqs), whereas the external loop provide the regulation of the speed.

A. Speed SMC

Under field oriented assumptions, the electromagnetic torque can be expressed as:

$$Te = \frac{P \, lm}{lm+ir}(Iqs)\phi^{*}_{r} = k_T \, I \, qs \quad \text{------- (4.5)}$$

Basically, the control law for Tm_ is divided into two parts: equivalent control Um9 which defines the control action when the system is on the sliding mode and switching part U: which ensures the existence condition of the sliding mode. If the friction k_f is neglected expressions for Ueq and Us can be written as:

$$\begin{cases} Ueq = ke(t) \\ Us = -\beta sign(s(t)) \end{cases} \quad \text{------- (4.6)}$$

To guarantee the existence of the switching surface consider a Lyapunov function [6, 9]:

$$V(t) = \frac{1}{2} S^2(t) \qquad \text{------- (4.7)}$$

Based on Lyapunov theory, if the function VG_t_ is negative definite, this will ensure that the system trajectory will be driven and attracted toward the sliding surface *s(t)* and once reached, it will remain sliding on it until the origin is reached asymptotically.

$$S(t)\dot{S} = S(t)\{-\beta sign(s(t)) - d(t)\} \leq 0 \quad \text{------ (4.8)}$$

To ensure that above function will be always negative definite, the value of the hitting control gain β should be designed as the upper bound of the lumped uncertainties d(t), i.e.

$$\beta \geq |d(t)| \quad \text{-------- (4.9)}$$

Therefore the speed control law defined previously will guarantee the existence of the switching surface s(t) and when the error function e(t) reaches the sliding surface, the system dynamics will be governed by equation which is always stable . Moreover, the control system will be nsensitive to the uncertainties Oa, Ob and the load disturbance Tw. The use of the sign function in the sliding mode control will cause high frequency chattering due to the discontinuous control action which represents a severe problem when the system state is close to the sliding surface. To overcome this problem an approach which combines FL with SM is used. The saturation function is replaced by a fuzzy inference system to smooth the control action. The membership functions for the input and output of the FL controller are obtained by trial error to ensure optimal performance.

B. Current SMCs

$$S(Iqs) = (Iqs^* - Iqs)$$

$$S(Ids) = (Ids^* - Ids)$$

The control law development for each variable in sliding mode theory is deduced from the reaching condition () and is indicated below

The current regulators laws in the 'd' axis and '*q*' axis can be written as

Current Sliding Mode Control Law of Iqs

$$S(Iqs).\dot{S}(Iqs) < 0 \Rightarrow Vqs^S = Vqs\_eq + Vqs\_n \qquad \text{------- (4.10)}$$

$$Vqs_{eq} = RsIqs + IsIqs + \omega_s^*(IsIds + \phi^*_r) \qquad \text{------- (4.11)}$$

$$Vqs\_n = \begin{cases} \frac{kq}{\varepsilon q} S(Iqs), & if \quad |S(Iqs)| < \varepsilon q \\ kqsign(S(Iqs)) & if \quad |S(Iqs)| > \varepsilon q \end{cases} \quad \text{------ (4.12)}$$

Current Sliding Mode Control Law of Ids

$$S(Ids).\dot{S}(Ids) < 0 \Rightarrow Vds^S = Vds\_eq + Vds\_n \qquad \text{------- (4.13)}$$

$$Vds_{eq} = RsIds + IsIds + \omega_s^*(IsIqs + T_r \phi^*_r \omega_{sl}^*) \qquad \text{------- (4.14)}$$

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$$Vds\_n = \begin{cases} \frac{kd}{\varepsilon d}S(Ids), & if \quad |S(Ids)| < \varepsilon d \\ kqsign(S(Ids)) & if \quad |S(Ids)| > \varepsilon d \end{cases} \quad \text{------ (4.15)}$$

To verify the system stability condition, the gains kd, kq, and εd, εq should be taken positive by selecting the appropriate values. This sliding mode functions introduce some undesirable chattering. Hence, we will substitute it by the fuzzy logic function. In order to reduce the chattering, two current FSMCs are added to FSMC of the speed outer loop. These controllers are used under the same rules IF…THEN, max-min inference mechanism and center of gravity defuzzyfier. The FSMCs are chosen as follows

$$\begin{cases} Vds^f & = Vds\_eq + Vds\_f \\ Vqs^f & = Vqs\_eq + Vqs\_f \end{cases} \quad \text{------- (4.16)}$$

Vds_f, Vqs_f are calculated with the fuzzy sliding rules described up.

5. SIMULATION RESULTS

The performance of indirect vector control induction motor drive has been simulated in MATLAB environment using simulink.

5.1 Simulation Model of Indirect Vector Control

The model for indirect vector control induction motor drive is shown in the Figures below. The induction motor output results with Self tuned fuzzy logic controller and Fuzzy based sliding mode controller are obtained using simulation and are analyzed in Table.1. The results are shown in below figures5.2 and 5.4
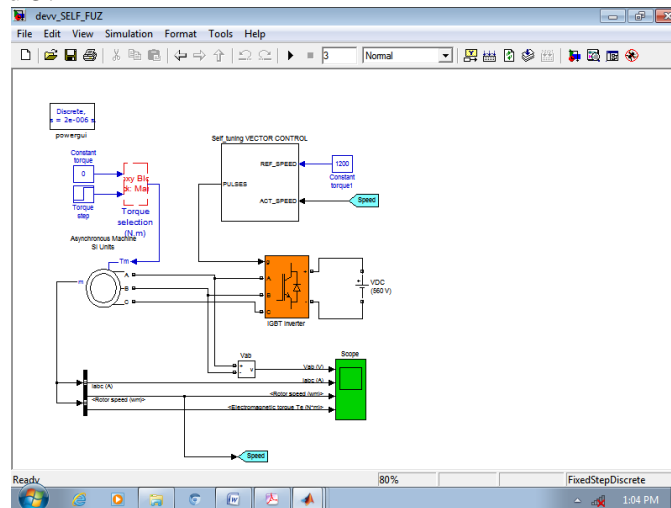

Fig 5.1. Simulation Model for Indirect Vector Control with self-tuned FLC controller
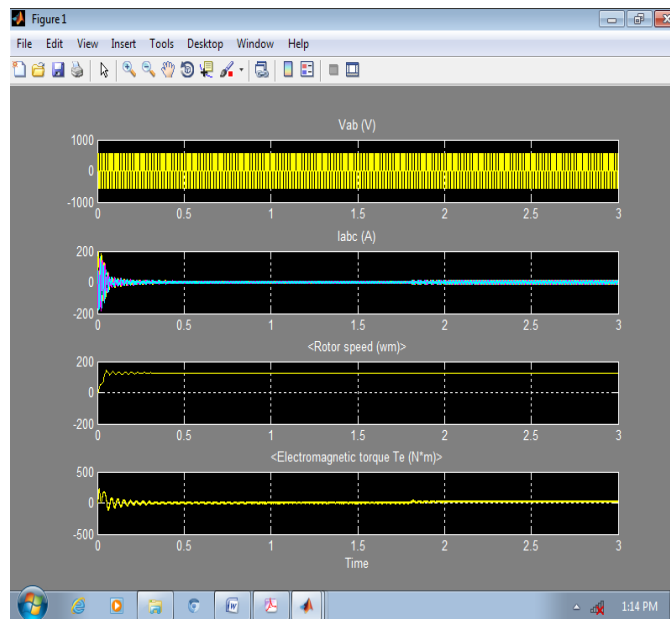
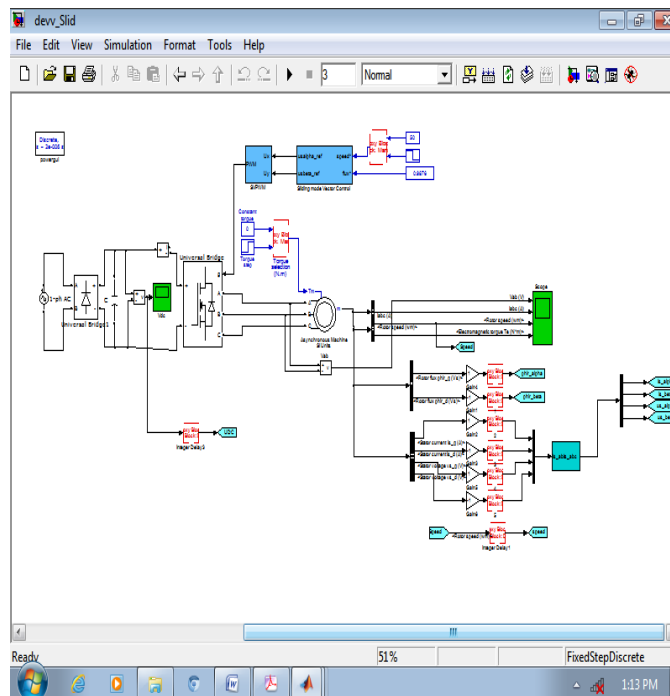**Fig 5.2 Simulation results with self-tuned FLC controller**

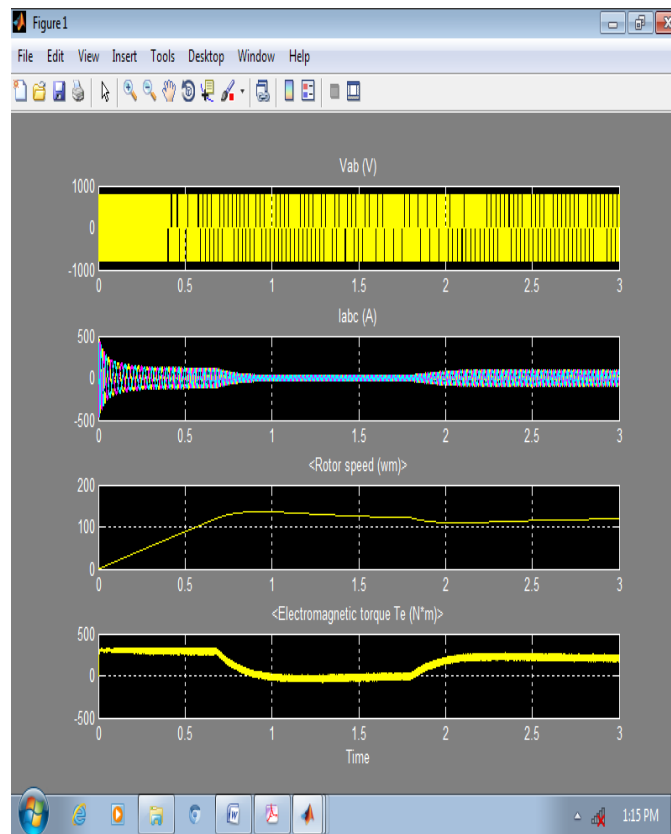**Fig 5. 3. Simulation Model for Indirect Vector Control with Fuzzy based SMC controller**

Fig 5.4 Simulation results with Fuzzy based SMC controller

Table.1 Summary of Results

Controller	Rise Time (sec)	Settling Time (sec)	Peak overshoot (%)
Self Tuned FLC controller	0.1	0.25	5
Fuzzy based SMC	0.07	0.17	4.3

6.CONCLUSION

In this paper, fuzzy based sliding mode control and self tuning control of vector controlled induction motor drive are proposed and the performances are analyzed. From simulation results it was shown that the proposed Fuzzy Sliding Mode Controller (FSMC) is robust to external variations (application of the load torque) and has given satisfactory performances in speed response with no overshoot, rapid time response error and a good tracking reference speed. The decoupling between the stator flux and the torque (speed) is maintained with regard to the application of external load disturbance. The FSMC performs a good reduction of the chattering effect (less fluctuation) references. The results obtained from simulation shows that the FSMC has increased dynamic response and superior performance.

REFERENCES

[1] Casadei, D., Profumo, F., Serra, G., Tani, A.; "FOC and DTC: Two Viable Schemes for Induction Motor Torque Control". IEEE Transactions in Power Electronics, Vol. 17, No. 5, pp 779-787,Sep 2002.

[2] Yen-Shin Lai, "Machine modeling and universal controller for vector Controlled Induction Motor drives," *IEEE Transactions on Energy Conversion*, vol. 18, No. 5, pp. 23-32, Mar. 2003.

[3] Y. Tang and L. Xu, "Fuzzy logic application for intelligent control of a variable speed drive," *IEEE Trans. Energy Convers.*, vol. 9, no. 4, pp. 679– 685, Dec. 1994.

[4] C.M. Lin and C.F. Hsu, "Adaptive fuzzy sliding mode control for induction servomotor systems," IEEE Trans.Energy Convers., Vol.19, No. 2, 2004, pp. 362-368.

[5] J.E. Slotine and W.P. Li, 'Applied Nonlinear Control'(Prentice Hall, 1991).

[6] F. F. Cheng and S. N. Yeh, "Application of fuzzy logic in the speed control of AC servo system and an intelligent inverter," *IEEE Trans. Energy Convers.*, vol. 8, no. 2, pp. 312–318, Jun. 1993.

[7] C.Y. Su and Y. Stepanenko, "Adaptive control of a class of nonlinear systems with fuzzy logic," IEEE Trans. Fuzzy Syst., Vol.2, 1994, , pp.285-294.

[8] B. Yoo and W. Ham, "Adaptive fuzzy sliding mode control of nonlinear system," IEEE Trans. Fuzzy Syst., Vol.6, 1998,pp.315-321.

[9] J. Wang, A.B. Rad, and P.T. Chan, "Indirect adaptive fuzzy sliding mode control: Part I-Fuzzy Switching," Fuzzy Sets and Systems, Vol. 122, No 1, 2001, pp. 21-30.

[10] L.X. Wang, "Stable adaptive fuzzy control of nonlinear systems," IEEE Trans. Fuzzy Syst., Vol.1, 1993, pp.146-155.

[11] G.W. Chang, G. Espinosa-Perez, E. Mendes, and R. Ortega, "Tuning rulesfor the PI gains of field-oriented controllers of induction motors," *IEEE Trans. Ind. Electron.*, vol. 47, no. 3, pp. 592–602, Jun. 2000.

[12] M. N. Uddin, T. S. Radwan, and M. A. Rahman, "Performances of fuzzy-logic-based indirect vector control for induction motor drive," *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1219–1225, Sep./Oct. 2002.

[13] E. C. Shin, T. S. Park, W. H. Oh, and J. Y. Yoo, "A design method of PI controller for an induction motor with parameter variation," in *Proc. IEEE IECON*, 2003, vol. 1, pp. 408–413.

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