Fuzzy Logic and Sliding-Mode Speed Control Based Direct Torque and Flux Control Scheme to Improve the Performance of an Induction Motor Drive

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Abstract: In this research study, the performance of direct torque and flux control (DTFC) induction motor drive (IMD) is presented using four different speed control techniques. The performance of IMD mainly depends on the design of speed controller. The PI speed controller (PISC) requires precise mathematical model, continuous and appropriate gain values. Therefore, adaptive control based speed controller is desirable to achieve high performance drive. The sliding-mode speed controller (SMSC) is developed to achieve continuous control of motor speed and torque. Furthermore, the fuzzy logic speed controller (FLSC) and fuzzy sliding-mode speed controller (FSMSC) is designed to obtain high performance, dynamic tracking behavior, speed accuracy and also robustness to parameter variations. The performance of each control technique has been tested for its robustness to parameter uncertainties and load disturbances. The detailed comparison of different control schemes are carried out in a MATLAB/Simulink environment at different speed operating conditions, such as, forward and reversal motoring under no-load, load and sudden change in speed.

Keywords: Direct torque control, induction motor drive, fuzzy logic speed controller, sliding mode speed controller, fuzzy sliding mode speed controller.

1. Introduction

In recent times, the adjustable speed drives (ASDs) with induction motor drives (IMDs) are making significant inroads because of robustness, high performance, and rugged structure and widely used in industrial applications such as; electric and hybrid vehicles, traction locomotives, electric propulsion ships. The scalar control schemes are simple to implement and gives good steady state response, but poor in dynamic response. However, the vector control method gives good steady state as well as transient response [1]. In the vector control scheme, one of the most popular control method of induction motor drive is known as field oriented control (FOC). It controls an induction motor drive like a separately excited DC motor and it was proposed by F. Blaschke (Direct FOC) and Hasse (Indirect FOC) in early 1970's [2]. The FOC method has an attractive features but it suffers with some drawbacks, such as; requirement of co-ordinate transformations, current controllers, sensitive to parameter variations. The drawbacks of FOC schemes are minimized with the new control strategy i.e., direct torque control (DTC) scheme, which is proposed by Isao Takahashi and Toshihiko Noguchi, in the mid 1980's [3].

The performance of IMD mainly depends on the design of speed controller. The PISC is widely used in industrial applications as it has a simple structure and offers a good satisfactory performance over a wide range of normal operation. But, the PISC scheme may not give satisfactory performance under load disturbances and it requires precise mathematical model, continuous tuning and accurate gain values of proportional (K_p) and integral (K_i) to achieve high performance drive. It is quite difficult to gain high performance of an IMD using PISC, because of the nonlinear model of IMD. For example, if any sudden or unexpected change in motor speed or load disturbance occurs, that results to an undesired overshoot in motor speed,

long settling time, high stator flux and torque ripples. In the literature survey, lots of control strategies has been proposed to tune the gain values of PISC, like Ziegler-Nichols, root locus, pole assignment design and etc [4]. Therefore, on-line tuning based speed controller is in demand to get high performance drive. To overcome the above mentioned drawbacks and improve the system performance, adaptive control based speed controllers are required, such as self tuning PISC, SMC, artificial intelligent based controllers like FLSC, neural networks, neuro-fuzzy, genetic algorithms (GA) [5-11].

The SMSC is a nonlinear, high switching speed and feedback control strategy, which offers an effective and robust control for motor drive. The sliding mode control scheme has been proposed in [12] for stator flux oriented control and also for the vector control IM drives in [13-16].

The fuzzy logic controller (FLC) is a nonlinear control, it is robust to parameter variations in IMD and it does not requires precise mathematical models, it is based on human knowledge. The author of [17] has proposed a SMSC and FLSC for vector control of induction motor drive, a new hybrid fuzzy logic controller has been presented in [18].

This paper presents a comparative study between four different speed controller techniques. The SMSC scheme is implemented to improve the dynamic response and also minimize the ripple contents of stator flux and torque, it is derived based on Lyapunov theory. Furthermore, the FLSC and FSMSC schemes are implemented to enhance the dynamic as well as steady state performance and robustness to parameter uncertainties. The performances of DTFC IMD using different speed control techniques have been tested in MATLAB/Simulink at different operating speed conditions. The simulation results are presented in different operating conditions such as forward and reversal motoring under no-load, load and sudden change in speed conditions.

2. Mathematical Modeling of Induction Motor

The mathematical model of IMD is developed using the stator and rotor flux linkage equations, which are referred to a general reference frame [18-19], it is indicated by the superscript 'a' and the following equations are shown as:

Electrical equations:

$$\text{Stator flux} \quad : \quad \Psi_{dqs}^a = L_s i_{dqs}^a + L_m i_{dqr}^a \quad (1)$$

$$\text{Rotor flux} \quad : \quad \Psi_{dqr}^a = L_r i_{dqr}^a + L_m i_{dqs}^a \quad (2)$$

$$\text{Stator voltage} \quad : \quad U_{ds}^a = (R_s + \partial L_s) i_{ds}^a + \partial L_m i_{dr}^a + j \omega_a \Psi_{qs}^a \quad (3)$$

$$: \quad U_{qs}^a = (R_s + \partial L_s) i_{qs}^a + \partial L_m i_{qr}^a + j \omega_a \Psi_{ds}^a \quad (4)$$

$$\text{Rotor voltage} \quad : \quad 0 = (R_r + \partial L_r) i_{dr}^a + \partial L_m i_{ds}^a - (\omega_a - \omega_r) \Psi_{qr}^a \quad (5)$$

$$: \quad 0 = (R_r + \partial L_r) i_{qr}^a + \partial L_m i_{qs}^a + (\omega_a - \omega_r) \Psi_{dr}^a \quad (6)$$

$$\text{Mechanical equation} \quad : \quad T_e - T_L = J_m \partial \omega_r + B_m \omega_r \quad (7)$$

$$\text{Electro-magnetic torque : } T_e = \frac{3}{2} \frac{P}{2} (\psi_{ds}^a i_{qs}^a - \psi_{qs}^a i_{ds}^a) \quad (8)$$

The above induction machine model equations are referred to a stationary reference frame. It is simply derived by substituting ' $\omega_a = 0$ ' in the Eqs. (3), (4), (5) and (6) and indicated by the superscript 'p', which is with d-axis attached on the stator phase 'A' winding. The machine model can be rewritten in a stationary frame as follows:

$$\text{Stator flux : } \psi_{dqs}^p = L_s i_{dqs}^p + L_m i_{dqr}^p \quad (9)$$

$$\text{Rotor flux : } \psi_{dqr}^p = L_r i_{dqr}^p + L_m i_{dqs}^p \quad (10)$$

$$\text{Stator voltage : } U_{ds}^p = (R_s + \partial L_s) i_{ds}^p + \partial L_m i_{dr}^p \quad (11)$$

$$\text{ : } U_{qs}^p = (R_s + \partial L_s) i_{qs}^p + \partial L_m i_{qr}^p \quad (12)$$

$$\text{Rotor voltage : } 0 = (R_r + \partial L_r) i_{dr}^p + \partial L_m i_{ds}^p + \omega_r (L_r i_{dr}^p + L_m i_{ds}^p) \quad (13)$$

$$0 = (R_r + \partial L_r) i_{qr}^p + \partial L_m i_{qs}^p - \omega_r (L_r i_{qr}^p + L_m i_{qs}^p) \quad (14)$$

$$\text{Mechanical equation : } T_e = J \partial \omega_r + B \omega_r + T_L \quad (15)$$

$$\text{Electro-magnetic torque : } T_e = \frac{3}{2} \frac{P}{2} (\psi_{ds}^p i_{qs}^p - \psi_{qs}^p i_{ds}^p) \quad (16)$$

The above two axis stator and rotor voltage state Eqs. (11), (12), (13), and (14) of induction motor in a stationary reference frame can be written in a state space matrix form as:

$$\begin{bmatrix} U_{ds}^a \\ U_{qs}^a \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s \partial & 0 & L_m \partial & 0 \\ 0 & R_s + L_s \partial & 0 & L_m \partial \\ L_m \partial & \omega_r L_m & R_r + L_r \partial & \omega_r L_r \\ -\omega_r L_m & L_m \partial & -\omega_r L_r & R_r + L_r \partial \end{bmatrix} \begin{bmatrix} i_{ds}^a \\ i_{qs}^a \\ i_{dr}^a \\ i_{qr}^a \end{bmatrix} \quad (17)$$

The two-axis (d-q) stator and rotor current as the state variables of IMD is acquired by rewritten matrix Eq. (17) as:

$$\begin{aligned} \frac{d}{dt} (X) &= AX + BU \\ X &= \begin{bmatrix} i_{ds}^p & i_{qs}^p & i_{dr}^p & i_{qr}^p \end{bmatrix}^T; \quad U = \begin{bmatrix} U_{ds}^p & U_{qs}^p & 0 & 0 \end{bmatrix}^T \\ A &= \frac{1}{L_\sigma} \begin{bmatrix} -R_s L_r & \omega_r L_m^2 & R_r L_m & \omega_r L_r L_m \\ -\omega_r L_m^2 & -R_s L_r & -\omega_r L_r L_m & R_r L_m \\ L_m R_s & -\omega_r L_s L_m & -R_r L_s & -\omega_r L_s L_r \\ \omega_r L_s L_m & R_s L_m & \omega_r L_s L_r & -R_r L_s \end{bmatrix}; \quad B = \frac{1}{L_\sigma} \begin{bmatrix} L_r & 0 \\ 0 & L_r \\ -L_m & 0 \\ 0 & -L_m \end{bmatrix} \end{aligned} \quad (18)$$

Where $\partial = d/dt$, $L_\sigma = L_s L_r - L_m^2$, i_{ds} , i_{dr} : d-axis stator and rotor current, i_{qs} , i_{qr} : q-axis stator and rotor current, ψ_{ds} , ψ_{dr} : d-axis stator and rotor flux linkages, ψ_{qs} , ψ_{qr} : q-axis stator and rotor flux linkages, L_s , L_r : stator and rotor leakage inductances, L_m : mutual inductance, R_s , R_r : stator and rotor resistances, P : number of poles, and T_e : electromagnetic torque.

3. Direct Torque and Flux Control

The schematic model of direct torque and flux control (DTFC) IMD is shown in Figure. 1. The principle of DTFC is to directly control the stator flux and electromagnetic torque without using coordinate transformation and current regulators, unlike vector control or FOC. The flux and torque hysteresis band controllers are trigger one of the eight possible (six active and two zero) voltage vectors which is generated by two level voltage source inverter (VSI) to keep the stator flux and torque ripples within the hysteresis band limits. Proper selection of voltage vectors allows a decoupled control of stator flux and torque.

The stator flux (ψ_s) is estimated using the measured stator current and voltages, which is given by:

$$\psi_s = \sqrt{(\psi_{ds}^p)^2 + (\psi_{qs}^p)^2} \quad (19)$$

Where

$$\psi_{ds}^p = \int (U_{ds}^p - i_{ds}^p R_s) dt; \quad \psi_{qs}^p = \int (U_{qs}^p - i_{qs}^p R_s) dt$$

The expression for estimating electromagnetic torque and angle between the stator and rotor flux are:

$$T_e = \frac{3P}{2} (\psi_{ds}^p i_{qs}^p - \psi_{qs}^p i_{ds}^p) \quad (20)$$

$$\theta_e(k) = \tan^{-1} \left(\frac{\psi_{qs}^p}{\psi_{ds}^p} \right) \quad (21)$$

Figure 1. Schematic model of direct torque and Flux control induction motor drive

4. Construction of Speed Controller

The high performance of the IMD is largely depended upon the choice of the robust speed controller.

A. Construction of PI-Speed Controller

The conventional PI-speed controller (PISC) requires precise mathematical model of the system and appropriate gain values of K_p (proportional gain) and K_i (integral gain) to achieve high performance drive. The gain values of $K_p = 30$ and $K_i = 2$ are obtained based on hit and trial method.

$$T_e^* = \left(k_p + \frac{k_i}{s} \right) e\omega_r \quad (22)$$

B. Sliding Mode Speed Controller

The sliding mode speed control (SMSC) is a nonlinear, adaptive control structure and offers an effective and robust control performance in load disturbance condition. The system response is insensitive to motor parameter uncertainties, as IMD is a multivariable and nonlinear system, it faces lot of disturbances during experimental implementation. The SMSC scheme is implemented to replace the PISC. The SMSC principle defines a high speed switching control law to drive the nonlinear state trajectory onto a switching surface and maintain the state trajectory on sliding surface for all subsequent interval of time [12]. The system response in the phase plane is forced to follow a sliding surface. The dynamics of error speed ' $e\omega_r$ ' and its derivative error speed ' $\Delta e\omega_r$ ' need to be driven to zero along the sliding surface $s(t) = 0$. In time domain, the corresponding response is exponentially decaying to zero. Its time constant (λ) depends on the slope of the sliding surface and the control signal forces the response to slide on the sliding surface and the system state error always remains on zero state [13-15]. This switching process easily implemented by using back and forth between positive and negative controller gains. The system error not only made zero, but also independent on the IM parameter variations. To design a SMSC, it starts by defining the error speed as:

$$e\omega_r = \omega_r^* - \omega_r \quad (23)$$

The Eq. (15) can be rewritten as:

$$\dot{\omega}_r = -\frac{B}{J}\omega_r + \frac{1}{J}(T_e - T_L) \quad (24)$$

Where $a = B/J$; $d = T_L/J$; $b = 1/J$

Consider the electromechanical Eq. (24) with uncertainties is shown in Eq. (25):

$$\dot{\omega}_r = -a\omega_r + bT_e - d = -(a + \Delta a)\omega_r + (b + \Delta b)T_e - (d + \Delta d) = f(t) + x(t) \quad (25)$$

Where $f(t) = -a\omega_r + bT_e - d$; $x(t) = -\Delta a\omega_r + \Delta bT_e - \Delta d$ and Δa , Δb and Δd denotes the external disturbances and uncertainties of the terms a , b and d , respectively.

Taking the time derivative of error speed Eq. (23) and substituting the expression of $\dot{\omega}_r$ from Eq. (25) gives:

$$\dot{e}\omega_r = \dot{\omega}_r^* - (f(t) + x(t)) \quad (26)$$

The sliding surface $s(t) = 0$ with integral components can be defining as:

$$s(t) = e\omega_r(t) + \lambda \int_0^t e\omega_r(t) dt = 0 \quad \lambda > 0 \quad (27)$$

Where, λ is the positive constant gain and it depends on bandwidth of the system.

Taking time derivative of the sliding surface $s(t) = 0$ in the Eq. (27). The error dynamics at the sliding surface $s(t) = 0$ will be forced to exponentially decay to zero. The best approximation of input control without uncertainties is expressed as:

$$\dot{s} = \dot{\omega}_r - f(t) + \lambda e\omega_r = h(t) \quad (28)$$

The SMC law can be found using Lyapunov theory and defining the Lyapunov function as

$$v = \frac{1}{2}s^2 \quad (29)$$

According to Lyapunov's method, it is found that $v(t)$ is clearly positive definite and the derivative of $v(t)$ is negative definite, this means the state trajectory will be driven and attracted toward the sliding line 's' and once it reaches sliding surface, then it will remain on the sliding surface. Taking the time derivative of the Eq. (29) and substitute the Eq (28) in Eq (30), then the Lyapunov function is given as:

$$\dot{v} = s\dot{s} = s(h(t)) \quad (30)$$

The Eq (30) is negative definite if:

$$h(t) \begin{cases} < 0 & \text{for } s > 0 \\ = 0 & \text{for } s = 0 \\ > 0 & \text{for } s < 0 \end{cases} \quad (31)$$

The switching control law is defined as:

$$u_s = -\beta \text{sgn}(s); \quad \text{sgn}(s) = \begin{cases} -1 & \text{for } s < 0 \\ +1 & \text{for } s > 0 \end{cases} \quad (32)$$

Where, $\text{sgn}(s)$ is signum of 's' function and ' β ' is a positive constant of respective switching gain and must be choosen as greater than the total uncertainties present in corresponding model guaranteed by the Lyapunov stability principle. Unfortunately, the use of signum function causes high switching frequency chattering phenomenon due to discontinues control action, which creates problem when the system state is close to the sliding surface. In [20] J. J. E. Slotine has introduced the boundary layer of width ' ϕ ' on both side of the switching surface to reduce the chattering phenomenon is shown in Figure. 6 (b). Then the Eq. (32) can be modified as:

$$u_s = -\beta \text{sat}\left(\frac{s}{\phi}\right); \quad \text{sat}\left(\frac{s}{\phi}\right) = \begin{cases} \frac{s}{\phi} & \text{for } |s| \leq \phi \\ \text{sgn}(s) & \text{for } |s| > \phi \end{cases} \quad (33)$$

Where ' ϕ ' represent the thickness of the boundary layer.

The ‘ u_{eq} ’ is a best approximation input control without uncertainties. Then, the sliding mode speed controller is designated as:

$$T_e = u_{eq} + u_s; \quad T_e = \frac{1}{b} \left(\dot{\omega}_r^* + a\omega_r + d + \lambda e\omega_r - \beta \text{sat}\left(\frac{s}{\phi}\right) \right) = T_e^* \quad (34)$$

C. Fuzzy Logic Speed Controller

The Fuzzy logic speed controller (FLSC) is a adaptive control approach and offers robust performance with parameter uncertainties. The FLSC can handle complicated nonlinear systems which have a degree of uncertainty. It does not require precise mathematical modeling and parameters unlike PISC, which makes the controller suitable for the induction motor control [19]. The FLSC has two input variables, error speed ‘ $e\omega_r$ ’ see in Eq. (23) and rate of change in error speed ‘ $\Delta e\omega_r$ ’ in Eq. (35). The actual speed ‘ ω_r ’ is compared with a set reference speed ‘ ω_r^* ’. The error speed signal ‘ $e\omega_r$ ’ is then processed through a FLSC, which contributes to zero steady error in tracking the reference speed signal. The block diagram of a FLSC is shown in Figure 2.

$$\Delta e\omega_r(k) = e\omega_r(k) - e\omega_r(k-1) \quad (35)$$

Figure 2. Block diagram of fuzzy logic speed control (FLSC).

C.1. Fuzzy inference system

The Fuzzy Inference System (FIS) is a popular computing framework based on the concepts of fuzzy set theory, fuzzy IF-THEN rules and fuzzy reasoning. It has found successful applications in a wide variety of fields, such as expert systems, robotics, time-series prediction, data classification automatic control, pattern recognition, and decision analysis. Because of its multi-disciplinary nature, the FIS is known by various other names, such as fuzzy expert system, fuzzy rule based system, fuzzy model, fuzzy associative memory, fuzzy logic controller and simply fuzzy system.

The basic structure of a FIS consists of three components; a data base, which describes the membership functions (M.Fs) used in the fuzzy rules, a rule base, which contains a selection of rules and a reasoning mechanism, which performs the inference technique upon the fuzzy rules and given facts to derive a reasonable output.

The basic FIS can take either crisp inputs or fuzzy singletons, but it produces output, which are almost always fuzzy sets. Sometimes it is necessary to have a crisp output, especially in a position where a FIS is used as a controller. Therefore, we need a method of defuzzification to extract a crisp value that best represents a fuzzy set. A FIS with a crisp output is shown in

Figure. 3. Where the dashed line indicates a basic fuzzy inference system with fuzzy output and defuzzification block serves the purpose of transforming an output fuzzy set into a crisp value.

Figure 3. Block diagram of fuzzy inference system.

C.2. Construction of Fuzzy Inference System

The fuzzy inference system (FIS) is designed (selected) using MATLAB/Simulink shown in Figure 4.

- ❖ No. of inputs and outputs (2 – i/p and 1 – o/p),
- ❖ No. of rules (25 rules),
- ❖ Type of membership function (triangular),
- ❖ No. of membership functions (Five),
- ❖ Type of implication (Mamdani Max–min operation),
- ❖ Type of defuzzification method (centroid of area method).

The FIS consists of 1. Fuzzy inference system (FIS) editor, 2. Membership function (MF) editor, 3. Rule editor, 4. Rule viewer, and 5. Surface viewer.

The FIS editor handles the high-level control issues for the system: How many input variables and output variables are required and give their names. The M.F editor is used to describe the shapes of all the input and output M.Fs associated with each variable. The rule editor is used for adding or removing the list of fuzzy rules that define the performance of the system. In the present model 25 rules are developed. The rule viewer and the surface viewer are used for looking at, as opposed to editing, the FIS. They are strictly read-only tools. Used as a diagnostic, it can show which rules are active, or how individual MF shapes are influencing the responses. The surface viewer is used to display the dependency of one of the outputs on any one (error speed) or two (error speed and change in error speed) of the inputs, it generates and plots an output surface map for the system.

Figure 4. Fuzzy inference system with triangular membership function.

C.3. Design of defuzzification

The rules of the FLC generate required output in a linguistic variable (fuzzy number), according to the real world requirements and the linguistic variables have to be transformed to crisp output.

$$\mu_A(x) = \text{defuzz}(x, \text{mf}, \text{Type}) \quad (36)$$

Where $\text{defuzz}(x, \text{mf}, \text{Type})$ returns a defuzzified value out, of a M.F positioned at associated variable value x , using one of several defuzzification strategies, according to the argument Type. The variable type can be one of the following: COA: centroid of area, BOA: bisector of area, MOM: mean value of maximum, SOM: smallest (absolute) value of maximum and LOM: largest (absolute) value of maximum. After the inference step, the overall result is a fuzzy value. This result should be defuzzified to obtain a final crisp output. For the defuzzification purpose, the centroid of area (COA) method (often called the center of gravity) is chosen in this paper. Centroid defuzzification returns the center of area under the curve. The mathematical expression of centroid of area (COA) can be as follows:

$$COA = \frac{\int_a^b \mu_A(x) \cdot x \cdot dx}{\int_a^b \mu_A(x) \cdot dx} \quad (37)$$

With a discretized universe of discourse, the expression is

$$COA = \frac{\sum_{i=1}^n \mu_A(x) \cdot x \cdot dx}{\sum_{i=1}^n \mu_A(x)} \quad (38)$$

The triangular curve is a function of vector x , and depends on three scalar parameters a , b , and c are shown in the Eq. (39):

$$\mu_A(x) = \max \left(\min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right) \quad (39)$$

C.4. Design of Fuzzy Rule Base

The FLC converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by an expert knowledge or experience database. The FLSC rule base design involves defining rules that relate the input variables to the output model properties. Initially, the error speed ' $e\omega_r$ ' and the rate of change in error speed ' $\Delta e\omega_r$ ' have been placed in the input variables of the FLSC. Then the output variable of the FLSC generates the controlled reference torque ' T_e^* '. The fuzzy rules are expressed in English like language with syntax such as; If {error speed ' $e\omega_r$ ' is X and rate of change of error speed ' $\Delta e\omega_r$ ' is Y} then {control output ' T_e^* ' is Z}. To convert these numerical variables into linguistic variables, the following five fuzzy levels or sets are chosen as: NL (negative large), NS (negative small), ZE (zero), PS (positive small), and PL (positive large) and summarized in Table 1. These five MFs are same for the input and output variables and characterized using triangular M.F [19, 21], as it can be seen in figure. 5.

Rule 1: If error speed ($e\omega_r$) is "NL" and change_in_error speed ($\Delta e\omega_r$) is "NL" then output (T_e^*) is "NL",

Rule 13: If error speed ($e\omega_r$) is “ZE” and change_in_error speed ($\Delta e\omega_r$) is “ZE” then output (T_e^*) is “ZE”,.

Rule 25: If error speed ($e\omega_r$) is “PL” and change_in_error speed ($\Delta e\omega_r$) is “PL” then output (T_e^*) is “PL”.

Figure 5. The fuzzy input variables (i). Triangular M. F, (ii) error speed ($e\omega_r$) and change in error speed ($\Delta e\omega_r$) normalized Triangular M. F and output variable (iii) reference torque (T_e^*) normalized Triangular M. F.

Table 1. Fuzzy logic control rules

$\Delta e\omega_r(t)$ $e\omega_r(t)$	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

D. Fuzzy Sliding Mode Speed Controller

The fuzzy sliding mode speed controller (FSMSC) scheme is replacing the PISC to minimising the chattering phenomenon with combine the fuzzy logic controller (FLC) and a sliding mode control (SMC) schemes. The FSMSC scheme serves robustness in parameter uncertainties and ensures the system stability and also improves the system performance. The design of SMC includes the selection of sliding surface and the control law. To eliminate the chattering, usually a boundary layer is introduced neighbouring the sliding surface and the control law, it is written in Eq. 33.

Figure 6. Switching function are: (a) sliding-mode, (b) sliding-mode with boundary layer and (c) fuzzy sliding mode.

From the Eq. 33, it is clear that the system robustness becomes highly dependent on the boundary layer thickness. The selection of ' ϕ ' is crucial. If the $|s| \geq \phi$ system states move toward the sliding surface and if the $|s| < \phi$, the control changes linearly and chattering is minimized. But, with the boundary layer introduction, a steady state error problem appears [22]. The smaller value of ' ϕ ' may not solve the chattering problem with the less steady state error and with the larger value of ' ϕ ' may increase the steady state error. To minimize the steady state error and chattering phenomenon as well as achieve fast dynamic response, the switching control law of $-\lambda \text{sat}(s/\phi)$ is replaced by a FIS in shown in Figure. 7. Here, the FIS is employed to improve the system dynamic as well as steady state performance and also minimize the steady state error, as a result the selection of boundary layer thickness limit of SMSC is relaxed to some extent. The schematic model of FSMSC and the Mamdadi triangular M.F based input-output variables of FLSC are shown in figure 7 and figure 5.

Figure 7. Schematic model of fuzzy sliding mode speed controller (FSMSC).

5. Simulation Results

In order to verify the effectiveness of the SMSC, FLSC and FSMSC schemes has been simulated using MATLAB/Simulink environment. For MATLAB/Simulink implementation, we have been considered 4-pole machine with a power rating of 1.5 kW and rated speed of 1440 rpm induction motor. The IM model is developed using the parameter values are shown in the Table 2.

The performance of IMD is tested under no-load torque with a reference flux $\psi_s^* = 1 \text{ Wb}$ and reference speed $\omega_r^* = 1200 \text{ rpm}$ in forward motoring mode is shown in Figure. 8 (a). The motor speed reaches its reference speed +1200 rpm at 0.614 sec using PISC, 0.585 sec using SMSC and 0.573 sec using FSMSC scheme with less ripple contents of torque and stator current

compared to PISC. Then the IMD is tested under no-load operating condition with +900 rpm speed is shown in Figure. 9 (a).

Table 2. Parameter and values of induction motor drive

Parameters	Nominal values
Stator Resistance (R_s)	1.57 Ω
Rotor Resistance (R_r)	1.21 Ω
Mutual Inductance (L_m)	0.165 H
Stator Inductance (L_s)	0.17 H
Rotor Inductance (L_r)	0.17H
Inertia (J)	0.089 kg.m ²
Frequency (F)	50 Hz
Speed (W_e)	1440 RPM

Figure. 8 Simulation responses of DTC IMD under 1200 rpm operating conditions are:

- (a) Forward motoring mode with No-load torque condition are:
 - (i). Torque, (ii). Stator Current and (iii). Speed.
- (b) Forward motoring mode with Load torque of 4 N-m condition are:
 - (i). Torque, (ii). Stator Current and (iii). Speed.
- (c) Reverse motoring mode with No-load torque condition are:
 - (i). Torque, (ii). Stator Current and (iii). Speed.
- (d) Reverse motoring mode with Load torque of 4 N-m condition are:
 - (i). Torque, (ii). Stator Current and (iii). Speed.

(c)

Figure 9. Simulation responses of DTC IMD under 900 rpm operating conditions.

The performance of IMD is tested under 1200 rpm and 900 rpm with a load torque of 4 N-m is applied at a time interval of 0.7 sec under forward motoring mode is shown in Figure 8 (b) and Figure 9 (b), respectively. When a load is applied, the motor speed drops to 1200.81 to 1198.71 rpm using PISC, and a slight drop from 1200 rpm to 1199.73 rpm using FSMSC.

The performance of IMD is tested by applying a speed reversal from +1200 rpm to -1200 rpm and +900 rpm to -900 rpm under no-load condition is shown in Figure 8 (c) and Figure 9 (c), respectively. The reversal motoring is applied at a time interval of 1sec. The response of motor speed reaches its reference speed faster and also the ripple contents are less in SMSC and FMSC compared to PISC.

Then the performance of IMD is tested under -1200 rpm and -900 rpm with a load torque of - 4 N-m is applied at a time interval of 2.2 sec under reversal motoring is shown in Figure 8 (d)

and Figure (d), respectively. The motor speed drops from -1201.54 to -1199.50 with a steady state error of 0.01167% using PISC and a slight drop in speed response from -1200 rpm to -1199.73 rpm with a steady state error 0.0040 % using FSMSC.

The performance of IMD is tested by applying sudden change in motor speed from 600 rpm to 900 rpm at 0.7 sec and again speed changes from 900 rpm to 1200 rpm is applied at 1.2 sec is shown in Figure 10 (e). The settling time of motor speed response is less in SM and FLSC compared to PISC.

Figure 10. Simulation responses of DTC IMD are:

- (e) Sudden Change in Speed responses are: (i). Torque, (ii). Stator Current and (iii). Speed
- (f) Sudden Change in Speed from 200 rpm to 0 rpm responses are:
 - (i). Torque, (ii). Stator Current and (iii). Speed
- (g) Motor speed response from +900 rpm to -900 rpm are: (i). Torque,
 - (ii). Stator Current and (iii). Speed

The performance of IMD when a sudden zero speed from 200 rpm to 0 rpm is applied at a time interval of 0.8 sec and it is removed at 1.6 sec is shown in Figure 10(f). There are some ripple contents in torque and stator current response with the SMSC approach under sudden zero speed condition compared to FLSC. The performance of IMD is tested under from +900 rpm to -900 rpm is shown in Figure 10(g). The detailed comparison between the PISC, SMSC, FLSC and FSMSC schemes under 1200 rpm is shown in Table 3 and under 900 rpm is shown in Table 4.

Table 3. Ripple contents of stator current, Torque, and motor speed Drops under 1200 RPM

Type of control	Torque Ripples	Current Ripples	Speed Drops under Load and steady state error %	Speed Settling Time
PISC	5.8 N.m	0.74 A	2.05 rpm & 0.01167%	0.614 sec
SMSC	3.92 N.m	0.42 A	0.61 rpm & 0.01025%	0.585 sec
FLSC	2.12 N.m	0.095 A	0.35 rpm & 0.00428%	0.582 sec
FSMSC	1.96 N.m	0.094 A	0.27 rpm & 0.0040 %	0.573 sec

Table 4. Ripple contents of stator current, Torque, and motor speed Drops under 900 RPM

Type of control	Torque Ripples	Current Ripples	Speed Drops under Load and steady state error %	Speed Settling Time
PISC	4.6 N.m	0.705 A	1.9 rpm & 0.01222%	0.459 sec
SMSC	2.41 N.m	0.392 A	0.56 rpm & 0.01022%	0.453 sec
FLSC	2.1 N.m	0.08 A	0.31 rpm & 0.00422%	0.441 sec
FSMSC	1.82 N.m	0.078	0.255 rpm & 0.0039%	0.437 sec

6. Conclusion

In this paper, direct torque and flux control of induction motor drive using four different speed controller techniques have been tested in MATLAB/Simulink in order to obtain the high performance drive. The PISC works well under normal operation but less capable of sudden change in speed and load torque disturbance rejection due to the fixed gain values. Adaptive speed control structures shows good disturbance rejection capability and robustness against to parameter uncertainties in IMD compared to fixed gain controller. SMSC scheme works well and give high performance drive but robustness of the system becomes highly dependent on the boundary layer thickness. FLSC having capability of disturbance rejection and robustness to parameter variations, but still needs some modifications to improve the performance of IMD. FSMSC scheme has a fast load torque disturbance rejection capability and robustness to parameter variations but it needs some modifications to minimise the chattering phenomenon in the steady state condition. A detailed comparison between the four speed control techniques has been carried out in DTFC IMD.

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