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Fuzzy Gain Scheduling and Fuzzy Logic Control Based Induction Motor Drives Using Variable Structure Control Methodology

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Abstract
Induction motor drives are widely used in industries for its simple and easy control. Variable structure controller (VSC) for an induction motor drive is an effective method of control in case of non linearities and uncertainties to enhance robustness. Dynamic performance of Induction motor drives is an essential characteristic for many industrial applications. Quality of the product is an industry and the profit of the industry are mainly depends on the performance of the induction motor drive. Transient state performance of the VSC based an induction motor drive to be improved. Since conventional VSC based induction motor drive has PI controller based speed controller. To enhance the performance of the system this paper proposes Fuzzy logic controller and Fuzzy Gain Scheduling controller as speed controller in VSC. The design is simple and easy to be implemented. The entire system is simulated using Matlab / Simulink to analyse the performance of a drive. Performance of a drive using Fuzzy Gain Scheduling VSC is analysed and compared with conventional Proportional and Integral VSC. To analyse the dynamic performance of the system machine is subjected to constant and variable load in this paper.
Keywords: Induction Motor, Variable structure controller, Fuzzy Gain Scheduling, Fuzzy Logic Controller, PI Controller

I. Introduction

In many industries Induction motors plays vital role like backbone of an industry. It is used for its reliability and low cost. Performance of an induction motor drive decides the efficiency of an industry. So many reasearchers analysed to enhance the performance of a drive. Recently, many researchers presented the advanced control strategies for PWM inverter fed induction motor drive. Particularly, the vector control, which guarantees high dynamic and static performances like DC motor drives, has become very popular and has been developed and improved. Fast digital processor and power devices in the vector control drives provides the possibility of achieving high performance induction motor drive control. There are many works devoted to the vector control, but only few deals with the improving the performance of controller structure [1]. Classical control theory using Conventional PI controllers, provides good performance only in case of linear processes whose exact model is known. However, it is not possible to deal always with linear process. To achieve effective control using PI controller needs precise knowledge of motor and load parameters which is not possible in always. Variable structure controller (VSC) is a sysetm to deal with nonlinearities[2]. The variable structure system is inherently aimed at dealing with system uncertainties, lead to good performances even in presence of strong and fast variations of the motor parameters. Many authors analysed the performance of variable structure systems with a sliding mode [3-5]. The VSC works on the principle of imposing the system motion to occur on a given manifold in the state space, which is defined according to the control tasks. VSC is more advantageous for its robustness, insensitivity to parameter variations, fast dynamic response. In the conventional VSC based induction motor drive PI controller is used [6]. Again it leads to all drawbacks by the PI controller in the VSC system too. So In this paper a VSC via Fuzzy logic controller (FLC) and Fuzzy Gain Scheduling (FGS) Controller are proposed for the speed control in the induction motor drive. Since the, fuzzy logic control has become an active and fruitful research area with many theoretical works and industrial applications being reported [7] [8]. So in this paper FGS is proposed for VSC control of induction motor. The main advantage of FGS based VSC induction motor drive is it requires only the speed data. Therefore it is simple and reliable control.

II. VARIABLE STRUCTURE CONTROL ALGORITHM DESCRIPTION

The vector controlled induction motor drives are easily adoptable to VSC algorithm. In a sliding mode (SM) control, the reference model is stored in the form of a predefined phase plane trajectory, and the system response is forced to follow or slide along the trajectory by a switching control algorithm [9]. Sliding surface or sliding line is defined as the starting point of a sliding mode control design [10]. Ensuring the ablity of the system to reach or cross the chosen sliding line is the next stage of a control algorithm. After the system crossing the Sliding line, it will be able to cross it again for an infinite number of times.

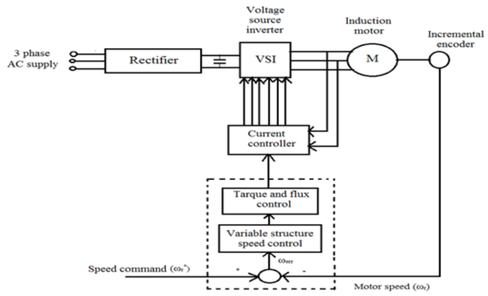

Fig. 1. Configuration of the control system

In this paper, the motor speed is controlled in order to obtain a constant motor speed. So, the vector control task is to impose the convergence of the motor speed magnitude to a reference one. This goal can be fulfilled applying the VSC synthesis procedure to the error speed system equation. The block diagram of the vector control with speed controller is shown in Fig. 1.

The error between the motor speed and its reference can be obtained as follows;

$$\omega_{err}(t) = \omega_r^*(t) - \omega_r(t) \quad (1)$$

and its derivative can be obtained as [2];

$$\omega_{err}^0(t) = \left(-\frac{B}{J} + \frac{3P}{2}\frac{L_m}{L_r}k\right)\omega_{err}(t) \quad (2)$$

Where, k is a linear feedback-gain, B is the viscous friction, J is the moment of inertia, p is the number of pair poles, Lm is the mutual inductance, and Lr is the self inductance of the rotor per phase of the induction motor. So, the equivalent dynamic behavior of control system can be rewritten as [1];

$$\omega_{err}^0(t) = (a + bk)\,\omega_{err}(t) \quad (3)$$

Where, £ = −B/J, ¥ = 3p/2. Lm/Lr, k is a feedback gain, and (£ + ¥k) is designed to be strictly negative. The switching surface with an integral component for the sliding mode speed controller is designed as follows [1];

$$S(t) = \omega_{err}(t) - \int_0^t (a + bk)\,\omega_{err}(\Gamma)\,d\Gamma \quad (4)$$

It is obvious from the equation (3) that the speed error will converge to zero exponentially if the pole of the system is strategically located on the left-hand plane. Thus, the overshoot phenomenon will not occur, and the system dynamic will behave as a state feedback control system. Based on the developed switching surface, a switching control law, which satisfies the hitting condition and guarantees the existence of the sliding mode, is then designed. So, the variable structure speed controller is designed as the following,

$$I_q^s(t) = k\,\omega_{err}(t) - \beta\,\mathrm{sgn}(S(t)) \quad (5)$$

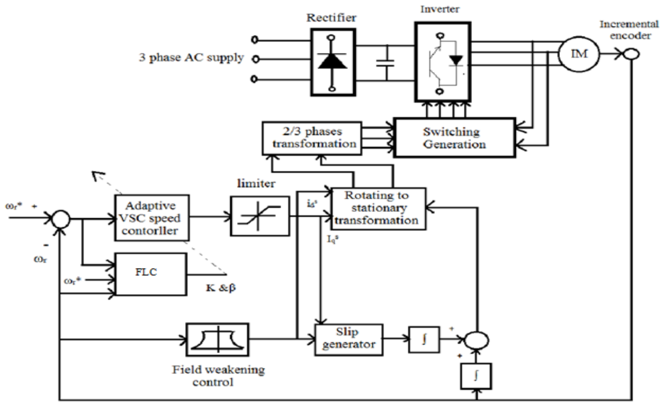

Fig. 2. FLC VSC based vector controlled induction motor drive

Where, β is denoted as switching gain, with the following assumption, β≥ 0, Iq is the reference torque component current, and sgn(·) is a signum function defined as,

$$\mathrm{Sgn}(S) = \begin{cases} 1 & \text{for } S > 0, \\ 0 & \text{for } S = 0, \\ -1 & \text{for } S < 0, \end{cases} \quad (6)$$

Hence, the dynamic behavior on the sliding surface can be described by Equation (3), and the tracking error err (t) converges to zero exponentially. The torque current command can be obtained according to Equation (5). The values of k and β plays an important role in control structure. In this paper PI and Fuzzy controller based determination of these parameters and performance of drive are analysed.

III. VSC USING PI CONTROLLER

PI controller is the simple method of control and widely used in industries. Proportional plus Integral Controller increases the speed of response of the system [11]. It produces very low steady state error. Two PI controllers are proposed in this paper for k and β. In this paper speed Error (e) is given as input to both PI controllers. General equation of the PI controller is

$$U(s) = K_p E(s) + \frac{K_i}{s} E(S) \quad (7)$$

Where K_p is proportional gain, K_i is the integral gain, E(s) is the controller input and U(s) is the controller output. Fig 3 shows the block diagram of PI controller.

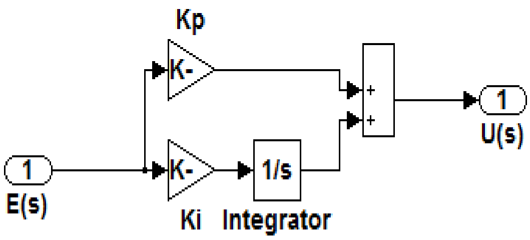

Fig. 3 Block diagram of PI controller

In this paper Ziegler Nichols' method of tuning is implemented to find the optimum value of K_p & K_i values. But the drawback of this controller is, it produces the high overshoot and long settling time.

IV. VSC USING FUZZY LOGIC CONTROLLER

In this paper Fuzzy Logic Controller (FLC) is implemented to reduce overshoot and settling time. Fuzzy logic is the mathematical technique for dealing with imprecise data and problems have multiple solutions rather than one. Linguistic, non numerical, variables are used, making it similar to the way humans think. Fuzzy control methodology is considered as an effective method to deal with disturbances and uncertainties in terms of ambiguity. Fig. 4 shows the basic block diagram of fuzzy logic controller [12].

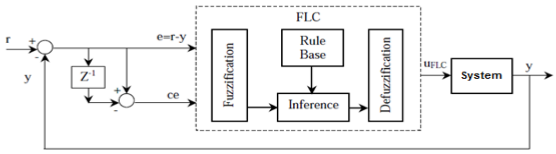

Fig. 4 Block diagram of Fuzzy Logic controller

Fuzzy inference system is the overall name for a system that uses fuzzy reasoning to map an input space to an output space. There are several ways to define the result of a rule; this paper implies max-min method of inference. Here, two fuzzy controllers of Mamdani type are implemented. Each has two inputs such as speed error (e) and change in error (ec) . FLC 1 produces k as output and FLC2 produces β as output.

$$E=w^*-w \quad (8)$$

Both inputs and outputs have five membership functions such as NB-negative big, NS-negative small, Z –zero, PS-Positive Small, and PB-Positive Big [r6]. Defuzzification is the mathematical procedure to convert fuzzy values into crisp values. Many methods of defuzzification are available. In this study we have selected centroid method of defuzzification. Tab I shows the fuzzy rules. Fig.5, Fig.6 & Fig.7 shows the input membership functions, Output membership functions of k and beta respectively [13].

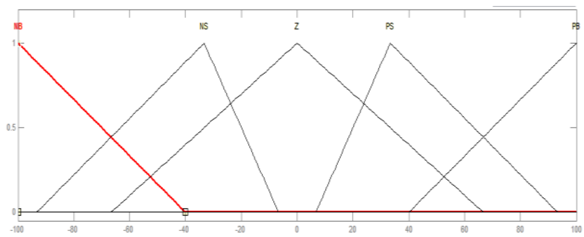

Fig. 5 membership functions of input e & ec

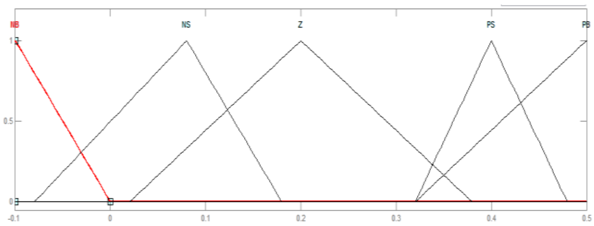

Fig. 6 output membership functions of k

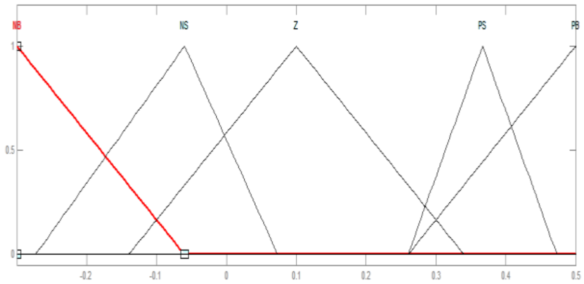

Fig. 7 output membership functions of beta

Table 1 Fuzzy Rules of k and beta

Error \ Change in error	NB	NS	Z	PS	PB
NB	NB	NS	NS	Z	PS
NS	NB	NS	NS	PS	PB
Z	NB	NS	Z	PS	PB
PS	NB	NS	PS	PS	PB
PB	NS	Z	PS	PS	PB

V. VSC USING FUZZY GAIN SCHEDULING CONTROLLER

Fixed value of K_p and K_i in a PI controller produces the high overshoot, settling time and speed drop during change in load. Online tuning of K_p and K_i in a PI controller can conquer this problem. It necessitates the Fuzzy PI controller for online tuning of K_p and K_i.

In a Fuzzy Gain Scheduling controller Fuzzy logic module is considered as an auto tuning module for parameters K_p and K_i in PI controller. The Fuzzy Gain Scheduling controller is considered the major contribution in this research. The fuzzy inference of FGS controller is based on the fuzzy associative matrices. The calculation speed of controller is very quick, which can satisfy the rapid need of controlled object. The block diagram of control system is shown in Fig.8.

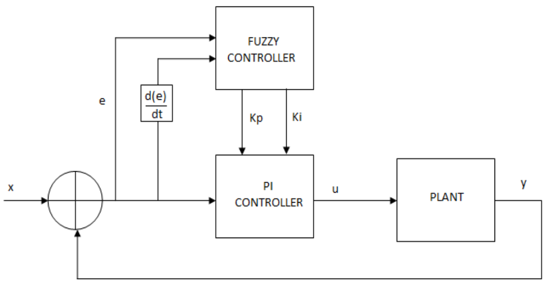

Fig. 8. Fuzzy PI controller block diagram

The control algorithm of traditional PI controller can be described as

$$u(k) = k_p e(k) + k_i \int e(k)$$

Where, k_p is the proportional gain, k_i is the integral gain and e (k) is the speed error. The design algorithm of Fuzzy PI controller in this paper is to adjust the k_p and k_i parameters online through fuzzy inference based on the current e and ec to make the control object attain the good dynamic and static performances [14]. This paper proposes two Mamdani FGS controllers for tuning k and β.

Speed error e and error change rate ec are used as fuzzy input and the proportional factor k_p the integral factor k_i are used as fuzzy outputs. The degree of truth of E and EC are configured as 5 degrees, all defined as {NB, NS,ZO, PS, PB}, where NB, NS, ZO, PS and PB represent negative big, negative small, zero, positive small and positive big respectively [15][16].

The degree of truth of KP and KI are configured as 4 degrees, are defined as {Z, S, M, B}, where Z, S, M and B represent zero, small, medium and big. The membership functions of E, EC, KP and KI are triangular distribution functions. The membership functions for each variable are shown in Fig .9, Fig .10 and Fig.11 respectively.

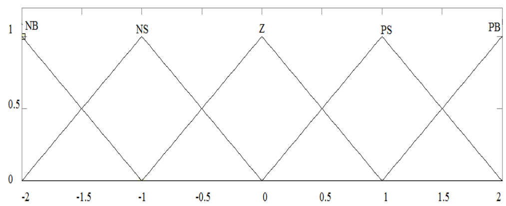

Fig .9 Fuzzy membership functions of E and EC

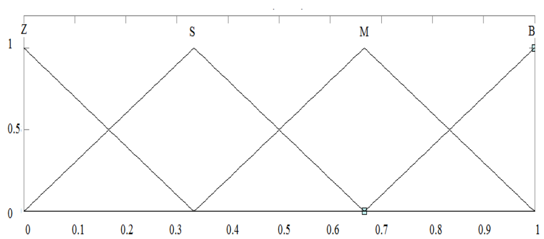

Fig .10 Fuzzy membership functions of KP

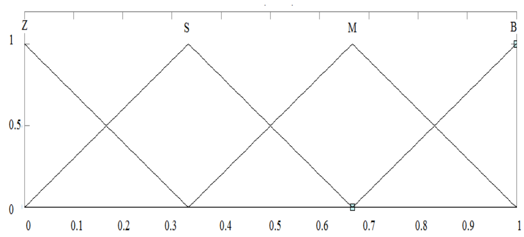

Fig .11 Fuzzy membership functions of KI

The principle of designing fuzzy rules is that the output of controller can make the system output response dynamic and static performances optimal. The fuzzy rules are generalized as table 2 and table 3 according to the expert experiment in IM drive system and simulation analysis of the system. The MIN - MAX method of fuzzification is applied. The weighted average method is adopted for defuzzification.

TABLE 2

The Control Rules for K_p

e \ ec	NB	NS	ZO	PS	PB
NB	Z	Z	Z	Z	Z
NS	M	M	M	M	M
ZO	B	B	Z	B	B
PS	S	M	M	M	M
PB	Z	S	B	B	B

TABLE 3

The Control Rules for K_i

e \ ec	NB	NS	ZO	PS	PB
NB	B	B	B	B	M
NS	M	B	S	S	S
ZO	M	B	Z	S	B
PS	S	S	S	S	S
PB	M	B	B	M	B

Fuzzy Gain Scheduling controller reduces the overshoot, settling time and drop in speed during load change.

VI. SIMULATION RESULTS AND ANALYSIS:

To analyze the performance of variable structure controlled induction motor 5 HP squirrel induction motor is taken. It is analyzed using various controllers like PI ,Fuzzy logic controller and Fuzzy Gain Scheduling under various speeds and loads. Parameters of induction motors are shown in table 4:

Table 4 Motor Parameters

Line Voltage	415
Frequency	50 Hz
Stator Resistance (R_s)	1.15Ω
Rotor Resistance (R_r)	1.083Ω
Stator inductance (L_s)	5.974 mH
Rotor inductance(L_r)	5.974 mH
Mutual inductance(L_m)	0.2037H
Moment of Inertia (J)	0.02 $Kg.m^2$
Number of poles (P)	4

The performance of the motor using PI based VSC are shown in figure 12. The performance is analyzed under No load while the machine is running. The reference speed of the machine is set at 1500 rpm.

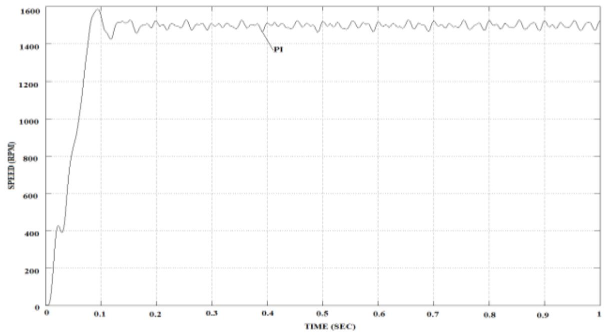

Fig.12 Speed performance of PI based VSC control

The performance of the motor using FLC based VSC are shown in figure.13 Conditions for analyses are same as a PI controller test.

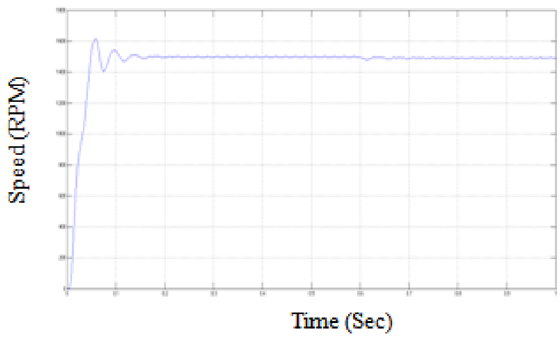

Fig.13 Speed performance of FLC based VSC control

The performance of the motor using FGS based VSC are shown in figure.14 Conditions for analyses are same as a PI controller test.

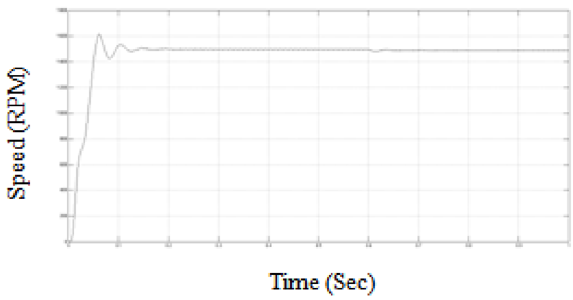

Fig.14 Speed performance of FGS based VSC control

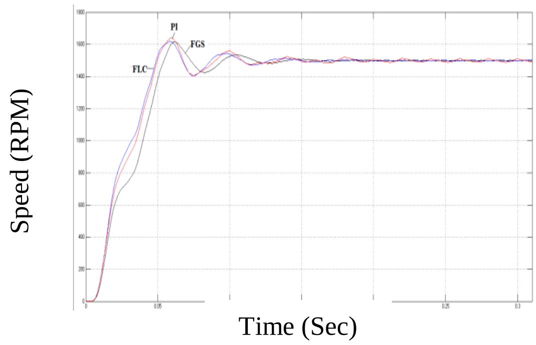

Fig.15 Comparison of Speed performance of PI, FLC and FGS based VSC control

The performance of the motor using PI based VSC are shown in figure16. The performance is analyzed under a load while the machine is running. The reference speed of the machine is set at 1500 rpm.

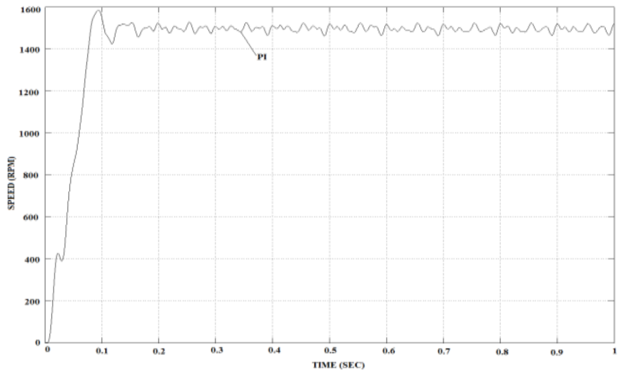

Fig.16 Speed performance of PI based VSC control

The performance of the motor using FLC based VSC are shown in figure 17. Conditions for analyses are same as a PI controller test.

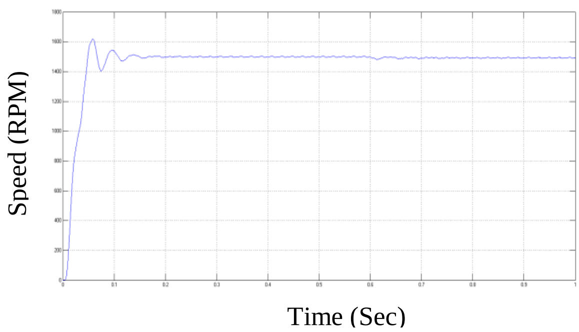

Fig.17 Speed performance of FLC based VSC control

The performance of the motor using FGS based VSC are shown in figure 18. Conditions for analyses are same as a PI controller test.

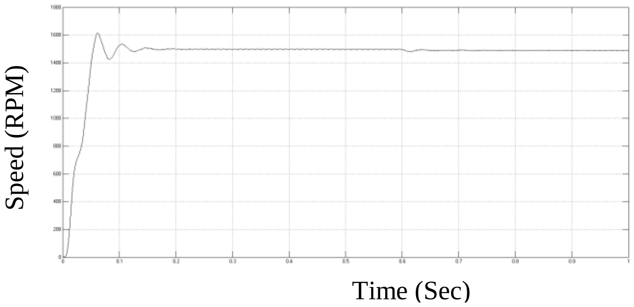

Fig.18 Speed performance of FGS based VSC control

Figure 19 and Table 5 shows the comparative performance of PI, FLC and FGS based VSC under step change in load at 0.6 seconds and reference speed as 1500 rpm.

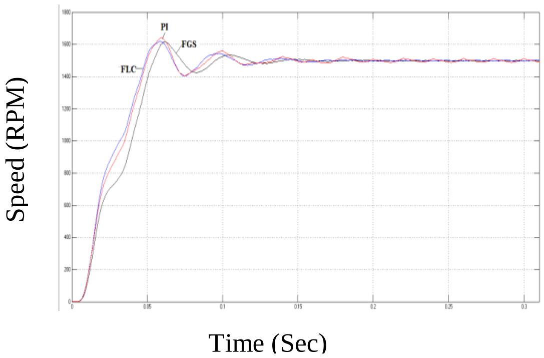

Fig.19 Comparison of Speed performance of PI, FLC and FGS based VSC control

Controller	Peak overshoot in %	Rise Time in Sec	Settling Time in Sec	Steady State error in %	Change in speed during Load Change in %
PI	**5.67**	**0.082**	**0.2**	**2.667**	**0.4**
FLC	**4.2**	**0.072**	**0.2**	**0.4**	**0.26**
FGS	**4.1**	**0.07**	**0.18**	**0.4**	**0.26**

Table 5 Performance comparison of PI, FLC and FGS Controller

Conclusion

A Induction motors are widely used in many industries in daily applications. Performance enhancement of it is necessary to improve quality of product. The Variable structure control is proposed in this for induction motor drive for its high robustness. It means that the system is completely insensitive to parametric uncertainty and external disturbances. Variable structure controlled Induction motor is analyzed in this paper with PI and Fuzzy gain scheduling. Simulation is done using Matlab. Performance of VSC based IM using both controllers are analyzed under various speeds and loads. From the simulation results it is obvious that PI controller gives almost quick response but it produces large overshoot, steady state error and high fluctuation in speed while sudden change in load. The Fuzzy gain scheduling controller performs well in all aspects such as overshoot, steady state error and change in speed while sudden change in load. Therefore it is optimum to use Fuzzy gain scheduling controller for VSC based Induction motor control.

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