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A Novel fuzzy vector control scheme for 3 phase induction motor

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Abstract— Classical vector control method is a widely accepted induction motor control algorithm, and is adopted in most of the modern induction motor drives. Classical vector control is quiet efficient and precise; but requires complex mathematical calculations. Also, various parameters of the controlled motor or system has to be predefined in the control algorithm part. Another problem associated with this control is its sensitivity to parameter variation. Parameters referred here are directly related to motor parameters like its resistance, self and mutual inductance etc. These are prone to variation with change of motor speed, operating frequency, temperature and even the environmental conditions.

A novel motor control algorithm is proposed here which uses fuzzy logic to generate the decoupled current components without going for complex mathematical calculations to achieve good dynamic performance with minimum loss. The decoupled current components are then converted into the form of three phase voltages using a current hysteresis controller and then fed to induction motor.

Fuzzy Logic Control is actually giving the output voltages in a manner similar to human response at a particular scenario, keeping certain constrains or facts in mind. The fuzzy logic controller has certain rule base like a lookup table and depending on degree of various factors, it will decide the output. This is a novel attempt to model the system based on fuzzy logic for the basic control algorithm.

Index Terms—Control strategy, decopled currents, Fuzzy logic, Induction motor, Matlab simulation, reduced torque ripple, Vector control.

1 Introduction

Variable speed motor drives constitute the driving force of automated processes in most of the industries. And when it comes to choosing the motor, Three-phase induction motors will have the first preference due to low cost and durability. However, induction motor speed depends on supply voltage frequency, and therefore they cannot be operated smoothly without an associated driver circuit. Due to this shortcoming of induction motor, DC motors were preferred in earlier days when large speed variations were required at the motor output. Induction motors, in the absence of a drive, will have only a constant speed at any load..

A variable speed induction motor drive will have a control algorithm to change the phase and frequency, and will provide sinusoidal PWMs to drive the motor. The conventional control algorithms include scalar control, vector control, DTC, etc. Scalar control is the easiest algorithm among these. Though it provides good steady state response, dynamic stability is poor compared to the other control algorithms. Its dynamic instability is a result of variation of air gap flux linkages. Scalar control, though easy to implement, can only be used in applications where dynamic response is of minimal importance. However it is not generally used because of its sluggish response caused due to inherent coupling effect. In an application where the output speed has to be increased using scalar control, the output frequency will be increased. But the flux tends to drop when frequency is increased and to compensate that, the voltage has to be increased along with frequency.

The problem here is, the flux loop is somewhat sluggish and with proportional variation of voltage, the response will be slower, and the overall motor output will be sluggish in nature. The coupling effect, and problems associated with it can be eliminated by employing vector control or field oriented control. In the field oriented control, the induction motor is controlled in a decoupled manner, as in case of a separately excited dc motor. Introduction of vector control brought about a revolution in the high-performance control of ac drives.

In the case of separately excited dc motor, decoupled control of torque and flux is possible. Using vector control, performance of an induction motor can be made similar to that of a dc motor. The torque and flux components can be differentiated by considering a synchronously rotating reference frame, where sinusoidal waves of voltage appear as dc quantities in steady sate. A standard induction machine drive should provide fast torque response below base frequency and constant power above base frequency. There are industrial and process applications requiring good dynamic and steady state performance. Such applications require high performance drive system, and the motor speed should closely follow the reference trajectory independent of load disturbances and variation in motor parameters. Field Oriented Control (direct Vector Control) is used in most of the modern high performance drives.

In vector control, frequency and phase are varied based on a unit vector. In normal cases, Vector control works in stable region. If not, it automatically comes back to the stable region. It is possible to control the speed in four quadrants without any additional control equipment.

This paper discusses the simulation of a variable speed in-

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duction motor drive using vector control based on fuzzy logic. P and PI controllers are normally used for dealing with problems associated with motor control, such as sluggish response, torque ripples etc. But these controllers, having fixed gains are very sensitive to load disturbances and parameter variations. Conventional P and PI controllers have difficulties in meeting a wide range of tracking performance. The conventional controllers exhibit poor performance whenever detuning occurs. Thus for efficient control the controller parameters will have to be continually adapted.

The design of an adaptive control technique will require the mathematical model of exact system. But unknown load variation and system disturbances will make it difficult to define an accurate mathematical model of the system. These problems can be taken care of, by replacing traditional controller with fuzzy logic controller.

2 Three Phase induction Motor

2.1 Construction

The stator of an induction motor carries a 3-phase winding (stator winding) while the rotor carries a short- circuited winding (rotor winding). Only the stator winding need to be fed from 3-phase supply. The rotor winding gets energized from the stator winding by means of electromagnetic induction and hence the name, induction motor. The induction motor can be considered similar to a transformer, with a rotating secondary winding and hence be described as a transformer type a.c. machine which converts electrical energy in to mechanical energy.

The main advantages of choosing an induction motor is its low cost and rugged construction It requires lesser maintenance, and doesn't require complex starting mechanisms. However, it has some drawbacks like starting torque is inferior to d.c. shunt motor. Also, it is essentially a constant speed motor in the absence of a dedicated drive system and its speed cannot be changed easily.

2.2 Principle of operation

Three phase power supply provides a rotating magnetic field for the induction motor. This rotating magnetic field is the same as that in a synchronous motor, except that induction motor will run at a slower speed compared to the speed of its rotating magnetic field, while synchronous motor will run in synchronism with the stator magnetic field. The induction motor stator's magnetic field is changing, or rotating relative to the rotor. As the rotor is not in synchronism with stator magnetic field, it will induce an opposing current in the induction motor's rotor, such that the rotating magnetic flux induces currents in the windings of the rotor; in a manner similar to currents induced in a transformer's secondary winding. The currents in the rotor windings will create magnetic fields in the rotor that opposes the stator field. Due to Lenz's Law, the direction of the magnetic field created will be such as to oppose the change in current through the rotor windings. Here, the rotating stator magnetic field is the cause of induced current in the rotor windings, so to oppose the change in currents flowing in rotor-winding the rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor will accelerate until the magnitude of induced rotor current and torque balances the load on motor shaft. An induction motor, will operate slower than synchronous speed, as rotation at synchronous speed would result in zero induced rotor current. The slip between actual and synchronous speed varies from about 0.5 to 5% for standard induction motors. The induction machine's essential character is that it is created solely by induction instead of being separately excited as in synchronous or DC machines or being self-magnetized as in permanent magnet motors. For rotor currents to be induced the speed of the physical rotor must be lower than that of the stator's rotating magnetic field; otherwise the magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque.

The ratio between the rotating speed of rotor and the rotation speed of the stator's rotating field is called slip. When under load, the rotor speed drops and the slip increases enough to create required torque to turn the load. An induction motor can be used as an induction generator, or it can be modified to form a linear induction motor which can directly generate linear motion.

3 The Vector Conrol Strategy

Vector control, or field-oriented control (FOC), is a variable frequency control strategy which controls three-phase AC electric motor output by means of two controllable VFD inverter output; output voltage magnitude and frequency.
FOC is a control technique that can be used in AC synchronous and induction motor application, that was actually developed for high-performance motor drives. Using this control strategy, motor will operate smoothly over the full speed range, and can generate full torque at standstill condition. It is also capable of producing fast acceleration and deceleration.
The vector control strategy for three phase induction motor can be explained as a step by step process. It is a closed loop operation so that it has to be analyzed starting from a point in the loop.

Starting from the motor side, three phase stator currents and the rotor velocity is measured and fed back to the processing unit where the 3 phase currents are transformed into a 2 axis system. Here i_a, i_b, i_c is transformed into i_α and i_β which are time varying quadrature current components with respect to the stator. This two axis system is rotated to align with rotor flux using a transformation angle obtained during iterations in the control loop. Thus current components in the rotating coordinate system are obtained. These components (i_q, i_d) will be constant for steady state conditions. Error signals of i_q and i_d are used to generate v_q and v_d using PI controllers. These voltage components are transformed in to v_α and v_β and then to v_{abc}. The three phase voltages are then used to generate the required PWM signals.

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4 FUZZY LOGIC

Fuzzy logic can be said analogous to human thinking; taking necessary steps according to the situation, without going for much analytical calculations. The response may be a result of previous experiences or foretold knowledge about that situation. For an example, consider the case when a person is crossing the road. Suppose the car is coming at a nominal speed from a distance and he starts to cross the road. And when he sees that the car is accelerating towards him, he will increase his speed such that the car won't hit him. If the same person stands there for a moment calculating the acceleration the car and his required velocity, he would possibly get hit. The main distinguishing factor between fuzzy control and conventional control is the lack of analytical description. In fuzzy logic we define a subset of a system and a characteristic function that describes the degree of membership of that subset. Let U be the universe and let X be a subset of U. In conventional control systems, it will be crisp subsets, having definite boundaries and fixed members. Fuzzy control algorithm defines a degree of membership for various members within the subset. There will be conditions such that a single member can be defined as member of a 2 subsets, defined by a degree of membership of that member in each of these subsets. The degrees of membership of different members are defined by characteristic functions associated with each subset. The fuzzy subset transforms the idea of a crisp subset by converting the range of the characteristic function from binary pair 0, 1 to the unit interval [0, 1]. In case of a fuzzy logic controller we define subsets for different inputs and output, and define certain IF-THEN rules, relating the input to output. Fuzzy logic controller should have a knowledge-based system consisting of IF-THEN rules with vague predictions and a fuzzy logic inference mechanism. Mamdani type fuzzy logic controller is adopted here for simulation purposes. Input variables are speed error and the change in the speed error and torque producing current component is the output. Inputs are fuzzified, and based on knowledge base output is derived in a fuzzy format. It has to be defuzzified and the output is given out.

In theoretical viewpoint, fuzzy logic has three main steps namely fuzzification, decision making based on the defined knowledge base and defuzzification. Fuzzification is more or less defining the inputs based on membership functions and the degree of membership. Membership functions may be sigmoid, trapezoidal, triangular etc, according to the application. The knowledge base has information related to the way in which the output has to vary with respect to variation of various inputs. Next stage is defuzzification where the output value obtained from fuzzy logic controller is transformed in to normal magnitude. A defuzzifier performs the exact opposite function of a fuzzifier. It transforms the fuzzy variables (which are obtained as output after processing of the inputs) to crisp sets. The defuzzifier is necessary because in the real world the crisp values can only be taken as inputs to the other systems. Even though the fuzzy sets resemble the human thought process, their functionality is limited only to the above processes. These steps are explained in the next chapter, designing of the fuzzy logic control for the specific application of finding i_q from speed error and change in speed error.

5 DESIGN OF FUZZY LOGIC CONTROLLER FOR INDUCTION MOTOR DRIVE

5.1 Fuzzification

In this stage called fuzzification, crisp input variables are transformed in to linguistic variables or fuzzy variables. Input variables here are speed error and change in speed error. The input here actually a crisp integer value. After the process of fuzzification, these crisp values are transformed in to linguistic variables, where magnitude of each variable will be represented as a degree of membership function. The linguistic labels used here are NB, NM, NS, ZE, PS, PM, PB, representing negative big, negative medium, negative small, zero, positive small, positive medium, positive big. Degree of membership in each of these linguistic variables is determined by triangular shapes assigned to each of these seven membership functions as shown in fig.5.1 to 5.3.

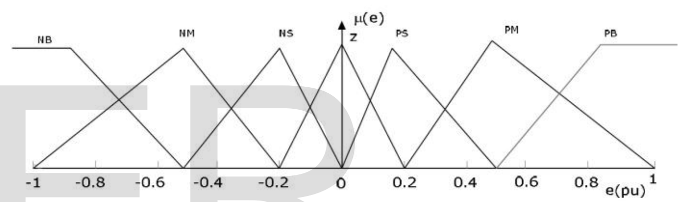

Fig.5. 1: Membership Function for e

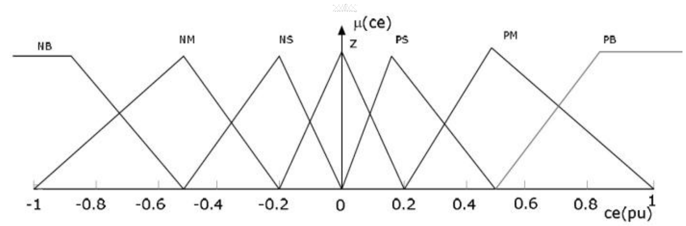

Fig.5. 2: Membership Function for Ce

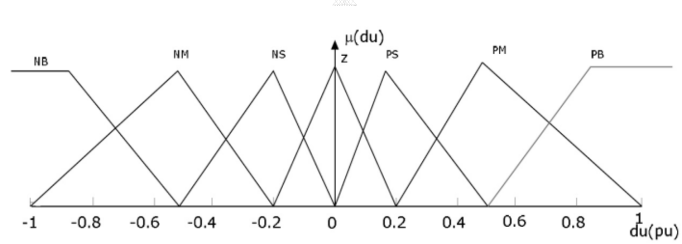

Fig.5. 3: Membership Function for output iqs

5.2 Knowledge base and inference stage

Knowledge base defines the relation between inputs and outputs in the form of if then rules, in terms of the membership functions defined for various inputs and outputs. If then rules in knowledge base is usually represented in tabular form relating the membership functions of various inputs and output. The rule base of this system is represented in Fig 5.4 representing the membership functions of input variables and output. For example consider the table given in Fig 5.4. there, the first rule states that if the change in speed is negative big, and change in speed error is negative big, then the output should be negative big. Mamdanis algorithm for inference mechanism was used for the simulation purpose.

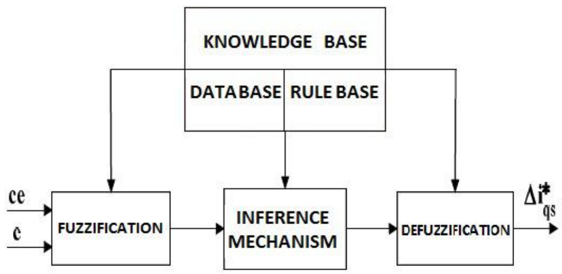

Fig 5.4: Fuzzy Logic Controller Internal structure

$C_e(pu)/e(pu)$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
ZE	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Fig 5.5: Rule Base Table

6 SIMULATION

Simulation of the fuzzy logic based vector control was did in Matlab. Matlab model of the system is given Fig 6.1.
Fig 6.2 shows the Matlab model of conventional vector control using conventional equations and PI controllers.
Equations used in this simulation are given in (1).
The torque equation is given as
$T=(3/4)P(L_m/L_r)\lambda_{dr}I_{qs}$
That is, torque is dependent on the quadrature component of current, and it can be controlled independently. In conventional vector control scheme I_{qs} is calculated as shown in the Matlab model, and is dependent on the motor parameters which are assumed to be constant. There are instances where the motor parameters don't remain the same, and this will lead to torque ripples and dynamic instability.

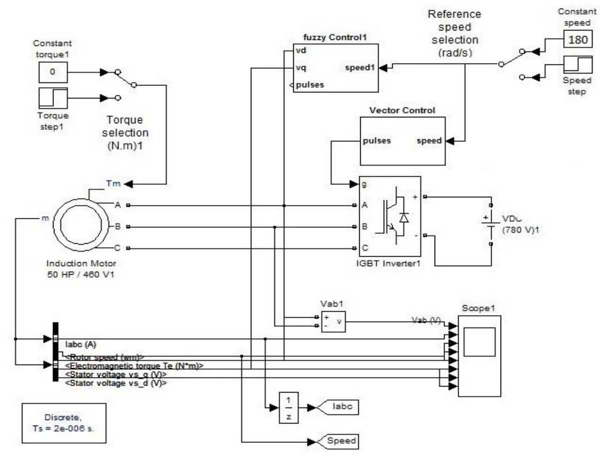

Fig 6.1: Matlab model for comparison of Fuzzy and Conventional Vector control

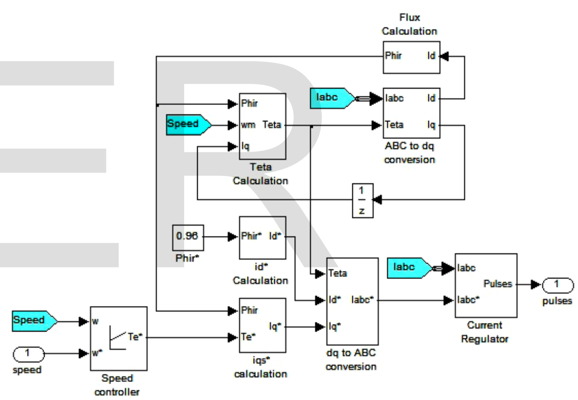

Fig 6.2: Vector control Pulse Generator

$$i_d=\sqrt{\frac{2}{3}}\left(\cos(\theta_e)i_a+\cos(\theta_e-2.094)i_b+\cos(\theta_e-4.188)i_c\right)$$
$$i_q=\sqrt{\frac{2}{3}}\left(-\sin(\theta_e)i_a-\sin(\theta_e-2.094)i_b-\sin(\theta_e-4.188)i_c\right)$$
$$i_a=\sqrt{\frac{2}{3}}\left(\cos(\theta_e)i_d-\sin(\theta_e)i_q\right)$$
$$i_b=\sqrt{\frac{2}{3}}\left(\cos(\theta_e+4.188)i_d-\sin(\theta_e+4.188)i_q\right) \qquad (1)$$
$$i_c=\sqrt{\frac{2}{3}}\left(\cos(\theta_e+2.094)i_d-\sin(\theta_e+2.094)i_q\right)$$
$$i_{ds}^*=\psi_r^*/L_m$$
$$\theta=\int(\omega_r+\omega_m)$$
$$\omega_r=L_m*i_q/T_r*\psi_r$$
$$\omega_m=\text{ Rotor mechanical speed }(\text{rad}/\text{s})$$

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The proposed scheme utilizes a fuzzy logic controller to determine the I_{qs} with help of speed error and change in speed error as the inputs. This scheme doesn't rely on motor parameters to generate I_{qs}, and thus, provides better dynamic response and lesser torque ripples.

Fig 6.3 shows the Matlab model for the proposed scheme of fuzzy vector controller where iq* is generated from speed error and change in error.

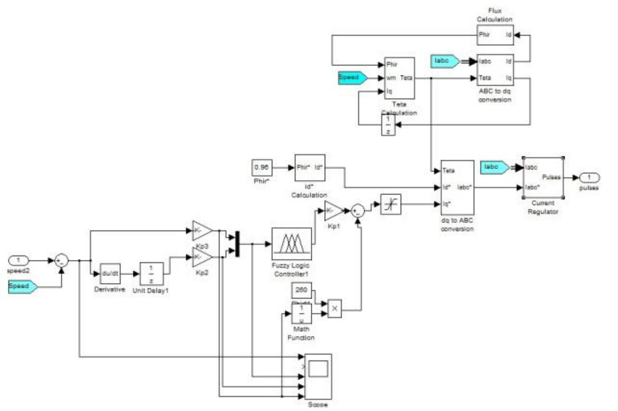

Fig 6.3: Fuzzy Vector control Pulse Generator

Here, iq* is generated using fuzzy mechanism while id* and teta were calculated using conventional vector control equations. If teta is also generated using speed and speed error feedback, the system can operate without current sensors, which will further simplify the system.

7 Simulation Results

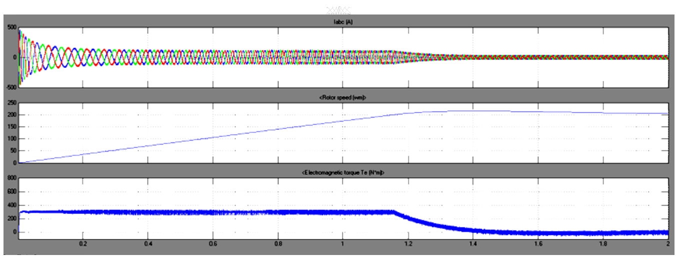

Fig 7.1: Speed Response of Conventional Vector Control

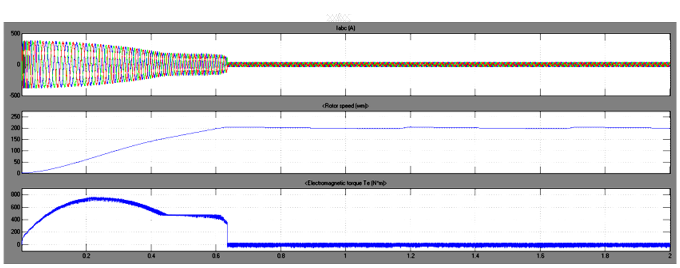

Fig.7. 2: Speed Response of Proposed Fuzzy Vector Control

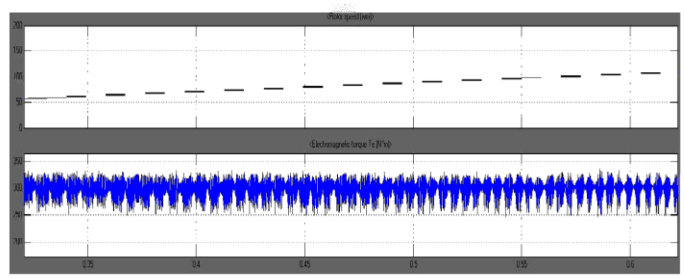

Fig.7.3: Comparison of Torque profile for fuzzy vector control and conventional vector control

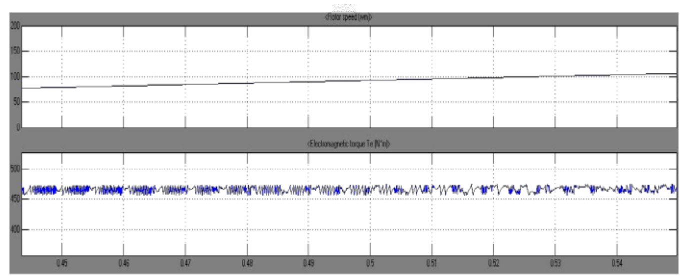

Fig.7.4: Enhanced view of Torque ripples of Fuzzy Vector Control

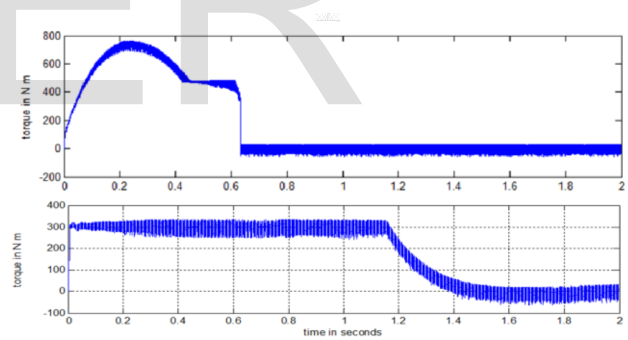

Fig.7. 5:Comparison of Torque profile for fuzzy vector control and conventional vector control

7.1 Knowledge base and inference stage

Fuzzy logic controller for the control of an indirect vector controlled induction motor was simulated, and compared with conventional vector controlled motor performance.

Comparing Fig 7.1 and Fig 7.2, we can observe Fuzzy vector control system attained the reference speed of 180 radians per second in about .83 seconds, when conventional vector control attained the same reference speed at about 2 seconds. Also, Fuzzy vector control has no initial current surge as in case of conventional vector control.

Fuzzy vector control also exhibits lesser torque ripples during dynamic and steady states. This can be compared using Fig 7.5 . In fuzzy vector control the torque ripples were limited in a band of about 50 N-m, compared to a torque ripple band of about 75 N-m for conventional vector control. Here simulation results shows that the designed fuzzy logic controller realizes a good dynamic behavior of the motor with a rapid settling time, no overshoot and has better performance than PI controller.

8 Conclusion

Research on fuzzy logic and its applications of are on developing stage, with promising impacts on electric drives and power electronics in future. Fuzzy hard ware systems have been developed, which includes fuzzy rule board, and optical fuzzy inference devices. The main problems faced in case of fuzzy logic controllers are difficulty of acquiring expert knowledge and uncertainty about the linguistic variables used in fuzzy logic. The speed responses were observed under different operating conditions for which PI controller gave an optimum response at rated condition, but the fuzzy controller exhibited better performances - faster speed response and lower starting current. The proposed system followed the command speed without much current overshoot and smoothly handles sudden change of command speed. Thus a good tracking has been achieved using FLC, whereas the PI controller shows greater steady state error with a high starting current. Another drawback of PI controller is that the speed response is affected by the load conditions. The torque response shows minimal ripples for FLC and comparatively large ripple content for PI controller. Simulated results suggest that the FLC based drive system can smoothly handle the sudden change in command speed without overshoot and steady state error, and comparatively the response of drive system using PI controller is not as fast as FLC.

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