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SPEED CONTROL OF INDUCTION MOTOR USING FUZZY LOGIC APPROACH

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ABSTRACT

The induction motors are characterized by complex, highly non- linear and time-varying dynamics, and hence their speed control is a challenging engineering problem. The advent of vector control techniques has partially solved induction motor control problems, but they are sensitive to drive parameter variations and performance may deteriorate if conventional controllers are used. By exploiting the fuzzy logic structure of the controller, heuristic knowledge is incorporated into the design, resulting in a non-linear controller with improved large signal performance over linear PI controllers. This paper proposes a novel design procedure for speed control of induction motor using fuzzy logic controller (FLC). The input to the controller is error and change in error and output of the controller is torque producing component of current, applied for the speed control of an induction motor. The effectiveness of the controller is demonstrated on the 1 hp three phase induction motor using DSP 2407 for different operating conditions of the drive system.

Keywords

Membership Function, Rule Base, Mamdani, Vector control IM drive, Fuzzy Logic, DSP.

1. INTRODUCTION

Induction motor drives are used in control applications, where servo quality operation is required. Induction motor is normally controlled by Field Oriented control (FOC) method or vector control method. In vector control IM, fast transient response is made possible due to decoupled torque and flux control [1],[2]. However, conventional proportional integral derivative (PID) control has difficulty in dealing with dynamic speed tracking due to parameter variations, and load disturbances [3]. Hence these controllers show high performance only for one unique act point [4]. As a result, the motion control system must tolerate a certain level of performance degradation [5], [6]. Soft computing techniques such as fuzzy logic or fuzzy control (FC) provide a systematic way to incorporate human experience in the controller without the need of knowing the plant mathematic model [7], [8], [9]. Recent literature has paid much attention to the potential of fuzzy control in machine drive applications for improved transient response and steady-state error [10][11]. High quality of the regulation process is achieved through utilization of the fuzzy logic controller [12], while stability of the system during transient processes and a wide range of

operation of speed are assured through application of the vector- control induction motor [13][14]. When the optimum membership functions are chosen for input and output of the FLC then it works with self-tuning capability [15] and its stability depends upon rule base [16].

2. FUZZY LOGIC CONTROLLERS

Prof. L.A. Zadeh developed systematic treatment for Fuzzy Logic controller [17] and later on Mamdani and Assilian [18] used fuzzy sets with an adaptive feedback control strategy to control a small toy steam engine. This was the first practical applications of fuzzy logic controller (FLC).
Mamdani [19] applied FLC in the automatic control system of a rotary furnace for cement production after that and later on in the year 1980, Larsen [20] used the fuzzy logic for various industrial applications. For development of FLC in industrial applications first Fuzzy International Conference was held in 1985 in Japan [7].

Yamakawa [21] designed a super high speed fuzzy controller for the Sendai underground railways, which was utilized by Hitachi Company in Japan. This system automatically decreased the speed of a train on entering a station, ensuring that the train stopped at a predetermined place. It also had the benefit of being a highly comfortable ride through mild acceleration and braking.

Today, there are number of products in the market which are controlled by fuzzy logic [9] in which different types of FLC are used, the block diagram of the fuzzy logic controller is shown in Fig. 1. In general this type of FLC contains four main parts, two of which perform transformations; which are:

a) Fuzzifier (transformation 1)
b) Knowledge base
c) Inference engine
d) Defuzzifier (transformation 2)

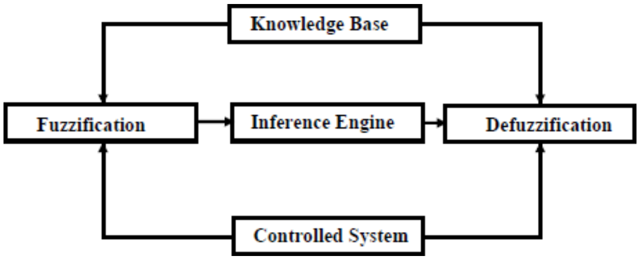

Fig. 1: Fuzzy logic controller

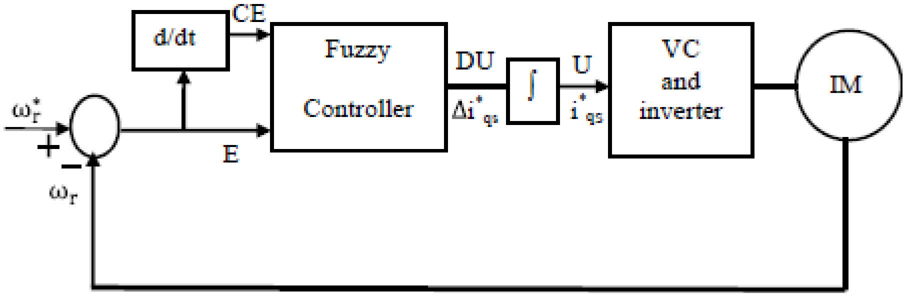

Fig. 2: Block diagram of application of FLC in IM

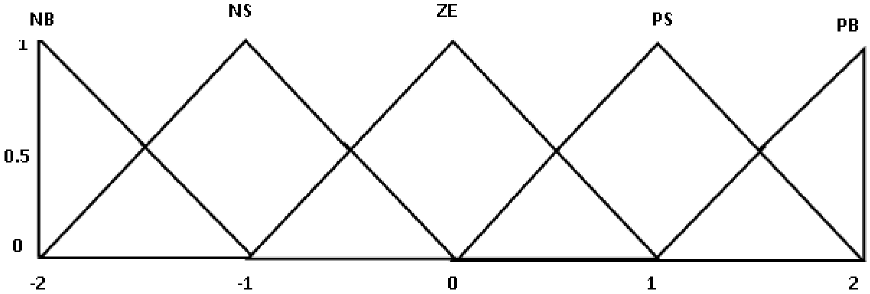

Fig. 3: Membership Functions for both the inputs

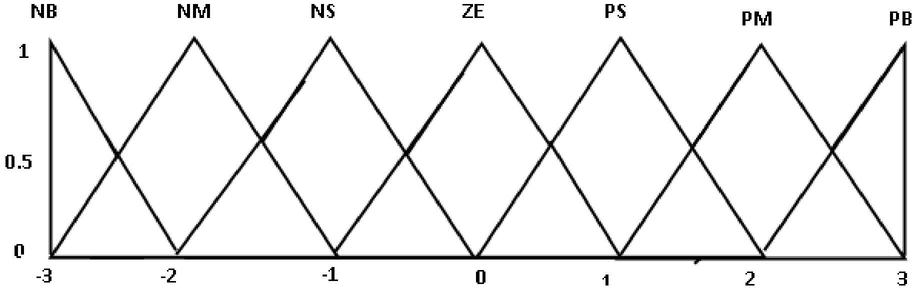

Fig. 4: Membership Functions for the output

Fuzzification measures the values of input variable and converts input data into suitable linguistic values. Knowledge base consist a database and provides necessary definitions, which are used to define linguistic control rules. This rule base characterized the control goals and control policy of the domain experts by means of a set of linguistic control rules. Decision-making logic or inference mechanism is main part of a FLC. It has the capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. Defuzzification is a scale mapping, which converts the range of values of output variables into corresponding universe of discourse and also yields a non-fuzzy control action from an inferred fuzzy control action. This transformation is performed by Membership Functions (MF). In FLC, number of MF and their shapes are initially determined by user.

3. APPLICATION OF FLC IN IM

Implementation of the fuzzy logic based speed controller of a vector –controlled drive system shown in Fig. 2., the controller observes the speed loop error signal and correspondingly updates the controller output DU so that the actual motor speed ωr matches the reference command speed ωr^{*}

There are two input signals to the fuzzy controller, the error $E=\omega r^{*}-\omega r$ and the derivative of error, CE. In a discrete system, $dE/dt = \Delta E/\Delta t = CE/Ts$, where $CE=\Delta E$ in the sampling time Ts. With constant Ts, CE is proportional to dE/dt. The controller output DU in a vector-controlled drive is torque producing components of stator current Δiqs^{*}. This signal is summed or integrated to generate the actual control signal U or current iqs^{*}.

The input variables, error and error rate and output variable, the control action, are represented as linguistic values as follows;

ZE = Zero, PS =Positive Small, PM =Positive Medium, PB =Positive Big NS =Negative Small NM = Negative Medium, NB =Negative Big

After selecting appropriate number of input and output variables and their linguistic values, we have to draw the membership function for these linguistic values.

The triangular membership function for the both input (error, error rate) and output variables are shown in Figs. 3-4.

There are five MFs for inputs e and ce signals, whereas there are seven MFs for the output. All the MFs are symmetrical for positive and negative values of the variables. Depending on these input variable values, the output variable value is to be decided from the experience encoded in the form of rules. Table 1 shows the corresponding rule table for the speed controller.

The top row and left column of the matrix indicate the fuzzy sets of the variables e and ce, respectively, and the MFs of the output variable (motor torque) operate according to the rule shown in the body of the matrix.
There are 5 x 5 = 25 possible rules in the matrix, where a typical rule reads as:
if e negative small (NS) and Δe is positive small (PS) then, T is zero (ZE).

Table 1. RULE TABLE FOR SPEED CONTROL

e/Δe	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	NB	NB	NB	NM	ZE
NS	NB	NM	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PM	PB
PB	ZE	PM	PB	PM	PB

There are two types of fuzzy inference methods namely Mamdani's method and Sugeno or Takagi–Sugeno–Kang method of fuzzy inference process to calculate fuzzy output [7][8].

The Mamdani implication is found suitable for DC machine and induction machine models. In order to convert fuzzy output in to a crisp value of the output variable, the de-fuzzification process is employed. The centre of area (COA) de-fuzzification method is generally used.

Using this method, the centroid of each output membership function for each rule is first evaluated. The final output torque is then calculated as the average of the individual centroids, weighted by their heights (degree of membership).

The fuzzy logic controller output torque is applied to the PWM using hysteresis controllers. The PWM controls the magnitude and frequency of the V/f scheme so that the desired speed of the motor can be obtained.

4. IMPLEMENTATION OF FLC ON TMSLF 2407 DSP

There are essentially two methods for implementation of fuzzy control [22]. The first involves rigorous mathematical computation for fuzzification, evaluation of control rules, and defuzzification in real time. This is the generally accepted method. An efficient C program is developed with the help of a FL tool, such as the Fuzzy Logic Toolbox in the MATLAB® environment. The program is compiled and the object program is loaded in a DSP (digital signal processor) for execution.

The second method is the look–up table method, where all the input/output static mapping computation (fuzzification, evaluation of control rules and defuzzification) is done ahead of time and stored in the form of a large look-up table for real time implementation. Instead of one look up table there may be hierarchical tables. Look up tables require large amount of memory for precision control, but their execution may be fast.

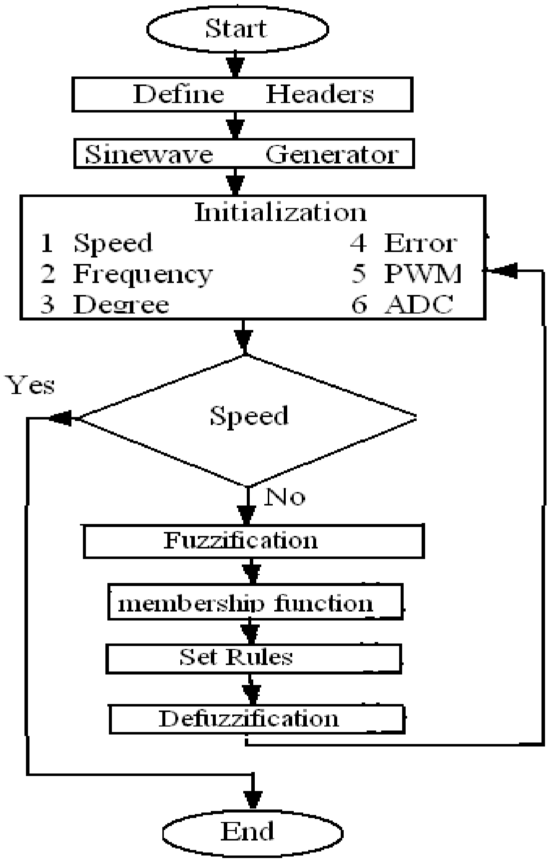

Fig. 5: Block diagram of FLC using DSP

The DSPs are a cost-effective, completely flexible and high-performance alternative to microprocessors or microcontrollers and hence can implement a fast FLC on a DSP that is both cost-effective and useful for fast processes. Some earlier work in this area was done to implement a fuzzy logic compensator on a TMS320C14 DSP based servo motor control system

[23][24][25]. Block diagram of FLC using DSP is shown in Fig. 5.

Implementation of FLC on DSP using CCS software creates a project. A ‘C’ language main program file is created in this project. This initializes all the registers and defines header files and all motor parameters such as reference speed (set speed), PWM amplitude modulation factor and signal generation are done in this file. The main program file also consists of three main functions fuzzification(), fuzzyInference(), and defuzzification().

At the programming stage first ‘e’ and ‘ce’ are calculated based on target speed (variable set_speed), current speed (variable current_speed), and the previous error value (variable last_error). These error values are then transformed into fuzzy vectors X1[ ] and X2[ ] using the function fuzzification(). After fuzzification, the fuzzy inference rules are applied and the fuzzy output vector Y[ ] is generated by calling the fuzzyInference() function. This output vector is then transformed back into a single control loop output value by calling defuzzification() and added to the current PWM duty cycle. In this way the control loop is closed. Note that the two definitions PWM_Min and PWM_Max are used to limit the motor duty cycle and may need to be adjusted depending on the application and load conditions.

5. RESULTS AND DISCUSSIONS

The performance of FLC and conventional PI controller test on Simulation model and practical three phase, 1-hp Induction Motor (See Appendix- I) at different operating conditions is shown in Figs. 6-8, as observed on digital storage oscilloscope (DSO).

Figs. 6-8 are the real time demonstration of the controlled drive on oscillograms. The smoothness of the signal permits high-accuracy position measurement with high angular resolution.

The signals permit determination of the incremental rotor position angle with the help of an up/down counter. A synthesized position signal then consists of the quasi-continuous position angle that gives a high resolution within a rotor slot pitch.

In order to get the detailed analysis of conventional PI controller in different operating regions of the speed at different load perturbation cases, these signals are stored in a data file using DSP.

In order to do the further analysis, the data is also stored in workspace of MATLAB. Speed responses are shown in Figs. 10-12 with no load torque (shown in Fig. 9) for 2 sec., where the motor speed is in RPM. The driver responses with fuzzy controller are specified as "MAMDANI" because of the implication method employed for the controller. Due to inertia of the motor, starting torque is high and its value is approximately 7 Nm. The transient time is 700 ms at no-load condition. The controller speed response has almost similar trajectory as the reference speed. The controllers have difficulty in following the command because of the current limit and the time needed to build up the flux. Once the flux is established, the controller tracks the command speed reasonably. Once the speed reaches to set value, then the torque reduces to the no load value (0.7 A). The use of conventional PI controllers to command a direct torque controlled induction motor drive is characterized by an overshoot during start up. This is mainly caused by the fact that the high value of the PI gains needed for

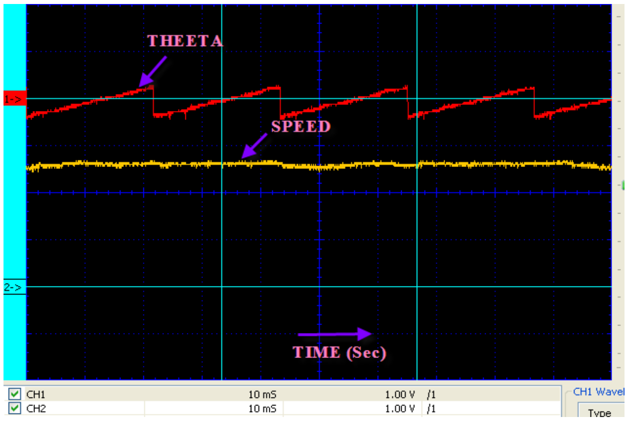

Fig. 6: Rotor angle and corresponding speed with FLC

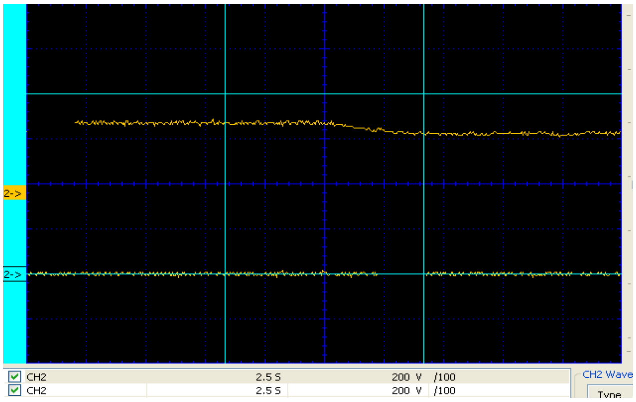

Fig. 7: Response of FLC for change in reference speed from 1400 to 1200 RPM

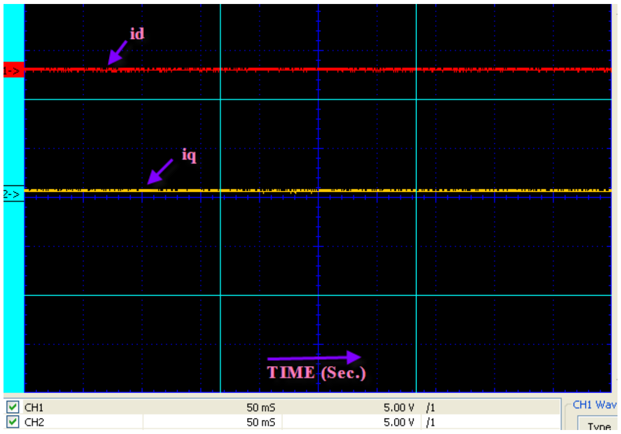

Fig. 8: Control current signals Id and Iq with FLC

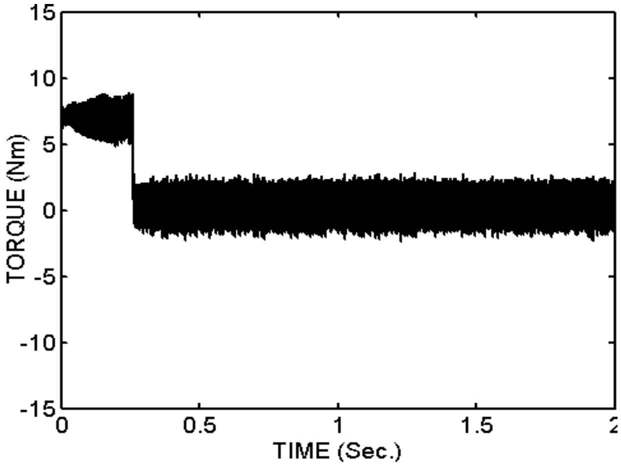

Fig. 9: Estimated value of no-load torque

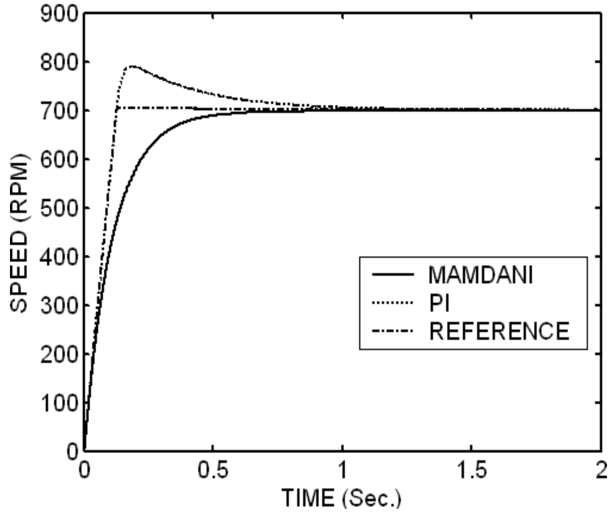

Fig. 10: Comparison of speed response at no-load (700 RPM)

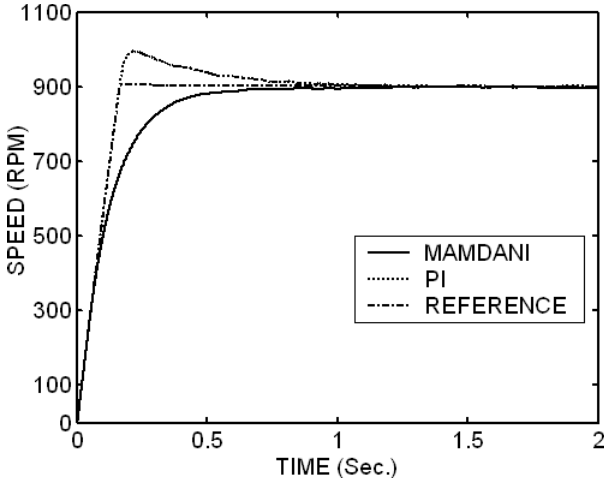

Fig. 11: Comparison of speed response at no-load (900 RPM)

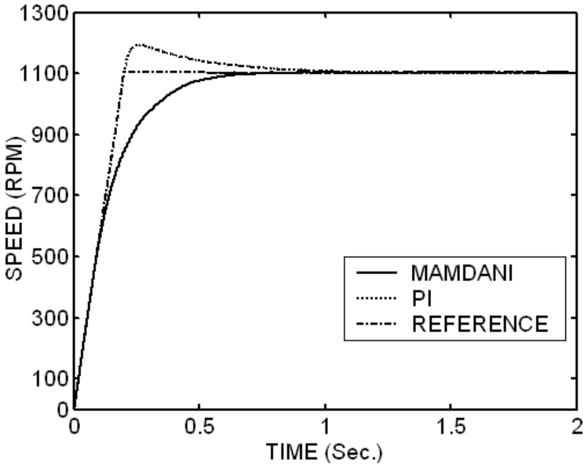

Fig. 12: Comparison of speed response at no-load at reference speed of 1100 RPM

rapid load disturbance rejection generates a positive high torque error. At start up, the conventional PI controller acts only on the error torque value by driving it to the zero border. When this border is crossed, the PI controller takes control of the motor speed and drives it to the reference speed value. To overcome this problem, variable gain PI (VGPI) controllers are implemented in place of PI controllers [26].

A variable gain PI controller is a generalization of a conventional PI controller. Tuning of the VGPI controller is based on the elimination of the speed overshoot caused by high integrator gains. This could be done by increasing the saturation time of the VGPI controller. One can choose the final value of the integrator gain needed for the application and then tune the other controller parameters so as to eliminate speed overshoot.

On the other hand, by applying fuzzy logic controller, which has auto tuning properties, it is possible to have no overshoot and the drive system behaves like a critically damped system. The transient time (in the case of FLC it is nearly 600 ms; while in the case of conventional PI controller it is nearly 800 ms) is generally higher as compared to reference command, but the advantage is that there has been no overshoot in the case of FLC.

The performance of speed response under load perturbation condition using FLC and conventional PI controller is shown in Figs. 13-16, when the motor is running at a steady state at reference set speed and load changes are applied on the motor shaft. The speed response to the sudden load application is an instantaneous fall in speed of the motor. In response to the fall in speed, the output of the conventional PI speed controller increases and consequently there is a corresponding increase in the reference torque (T*). This results in an increase in the developed electromagnetic torque of the motor, which increases the speed back to the reference value.

On the other hand, the FLC rejects the load disturbance very rapidly with no overshoot with a negligible steady state error. It is observed that sudden load application causes an instantaneous fall in speed of the motor and this leads to an increase of the motor slip above the imposed value.

The FLC controller has the capability to increase the motor current and boost the active torque, reducing the slip frequency to the initial value. It results in an increase in the developed electromagnetic torque of the motor, which increases the speed back to the reference value and maintains the speed almost constant.

Figs. 13-14 show that as the reference of speed sequence and load torque is changed, a satisfactory speed response is achieved under all conditions in the case of FLC while in case of conventional PI speed controller, the responses have overshoots. It means that torque producing stator current follows the reference value generated by fuzzy controller. As expected, the rotor flux is effectively constant, and hence the proposed controller is unaffected by parameter variations

Similarly, when the load from the shaft of the motor is suddenly decreased (or removed) as shown in Fig. 15 (where load torque value decreases from 4 Nm to 1 Nm), then there is an overshoot in the speed response in case of conventional PI speed controller as shown in Fig. 16.

Because of this overshoot, the input to the conventional PI speed controller becomes negative, and the conventional PI speed controller output, i.e. the T * signal is also reduced. The control structure results in a negative value of developed electromagnetic torque of the motor. This causes reduction in the rotor speed and it settles to the reference value due to PI controller action.

The FLC controller has the capability to increase the motor current and boost the active torque, reducing the slip frequency to the initial value. It results in an increase in the developed electromagnetic torque of the motor, which increases the speed back to the reference value and maintains the speed almost constant.

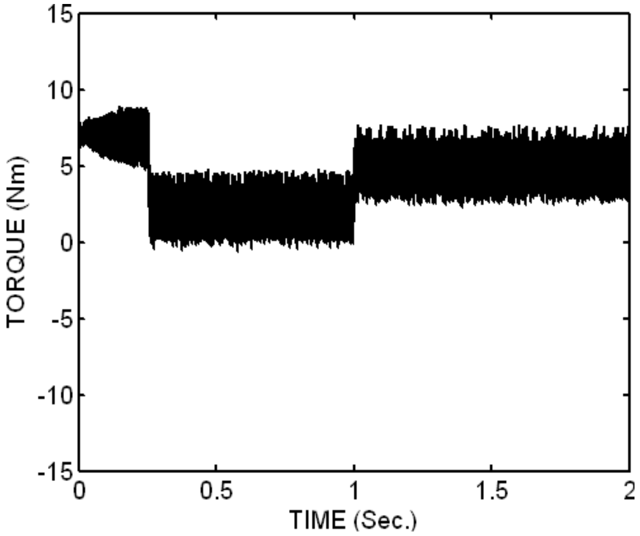

Fig. 13: Estimated torque for variation in load from 2 Nm to 5 Nm

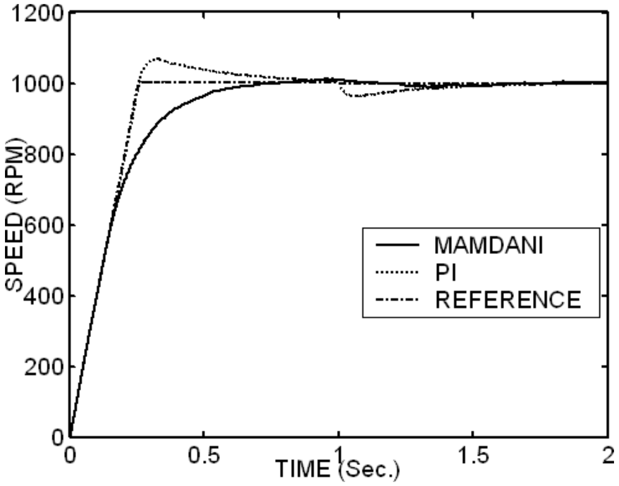

Fig. 14: Speed response for variation in load from 2 Nm to 5 Nm

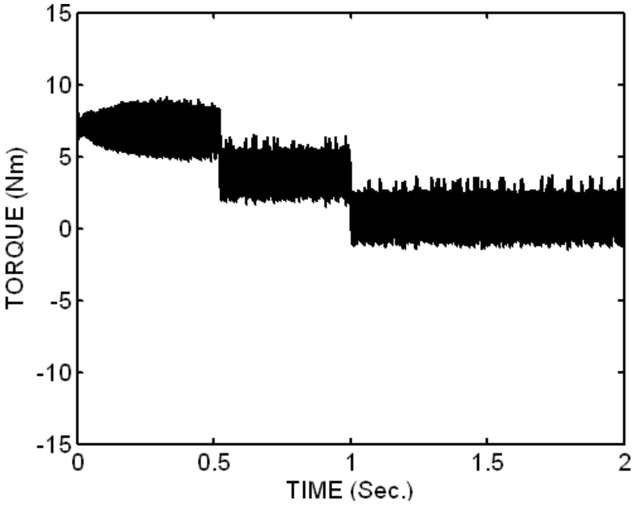

Fig. 15: Estimated torque for variation in load from 4 Nm to 1 Nm

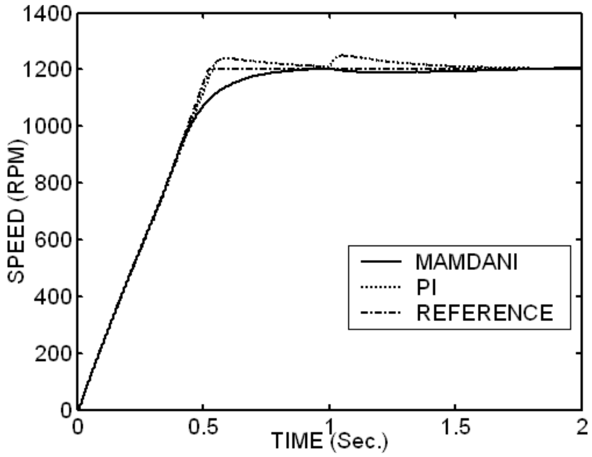

Fig. 16: Speed response for variation in load from 4 Nm to 1 Nm

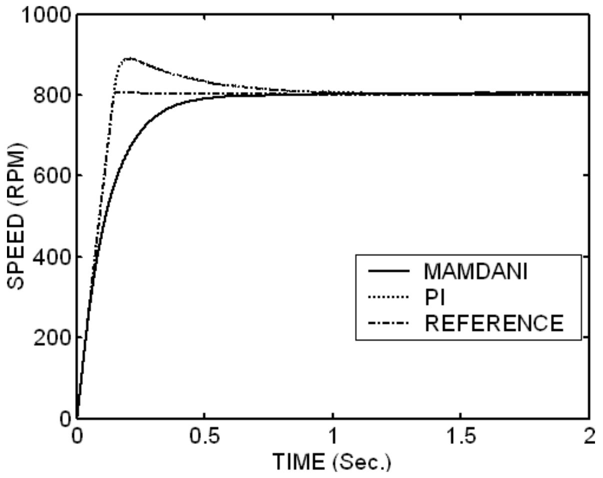

Fig. 17: Speed response at no-load (ref. speed 800 RPM)

Fig. 17 shows the performance of both controllers at no-load; conventional PI controller shows overshoots during starting and the response reaches to reference speed after 800 ms; while FLC response reaches steady state after 560 ms without overshoot. In many controller applications, the motor must be operable in both forward and reverse directions. Interchanging two phases of the stator connections to the three phase supply will reverse the stator revolving field and hence the direction of rotation of the rotor.

During the speed reversal dynamics, the motor reference speed is changed from (+) 1100 rpm to (-) 1100 rpm as shown in Fig. 18. In response to this change, the controller first reduces the frequency of the stator currents having regeneration and then phase sequence of the currents is reversed for starting in reversed direction. Since, just before and after the reversal phenomenon, the drive is in the same dynamic state, i.e., no load state, therefore, the steady state values of the inverter currents are found to be the same both in magnitude and in frequency in either direction of rotation.

However, the phase sequence of the currents in the two directions, are different. It has been observed that there is a fast change in the stator current in accordance with the change in speed. The variation in frequency of the stator current in the desired manner results in a quick accelerating torque. The control structure implements regenerative braking as well as changes the phase sequence. Figs. 19-22 show that, as the reference of speed sequence and load torque is changed, a satisfactory speed response is achieved under all conditions. It means that torque producing stator current follows the reference value generated by fuzzy controller. As expected, the rotor flux is effectively constant, and hence the proposed controller is unaffected by parameter variations. The performance of conventional PI speed controller has overshoot; while that FL auto tuning controller has no overshoot and the drive system behaves like a critical damped system. The performance of fuzzy logic controller using Mamdani and conventional PI controller in terms of settling time and speed regulation are shown in Figs. 18-22 for variation in reference speed and load torque. The corresponding values are also represented in table 2.

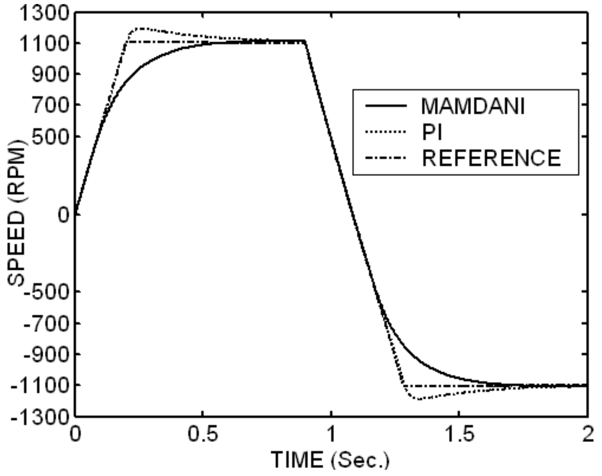

Fig. 18: Speed (reversal) response at no-load (1100 RPM)

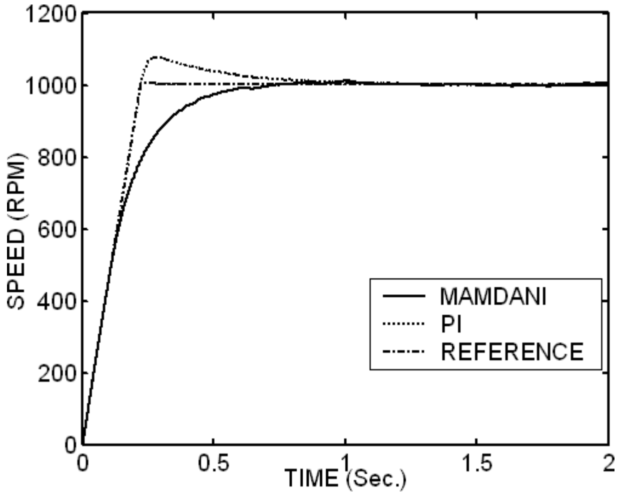

Fig. 19: Speed response at 25% of full-load (1000 RPM)

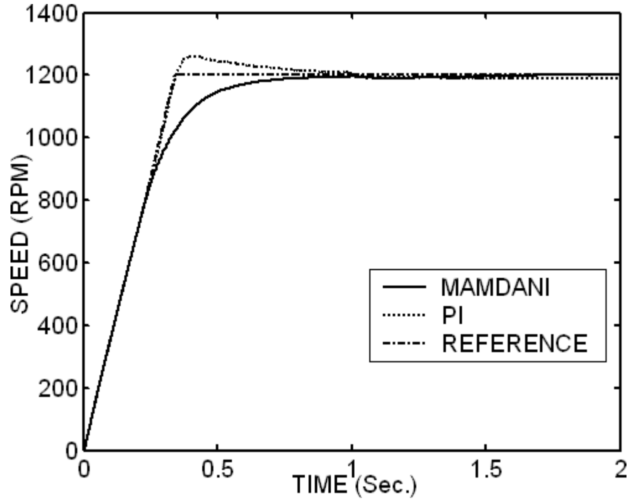

Fig. 20: Speed response at 50% of full- load (1200 RPM)

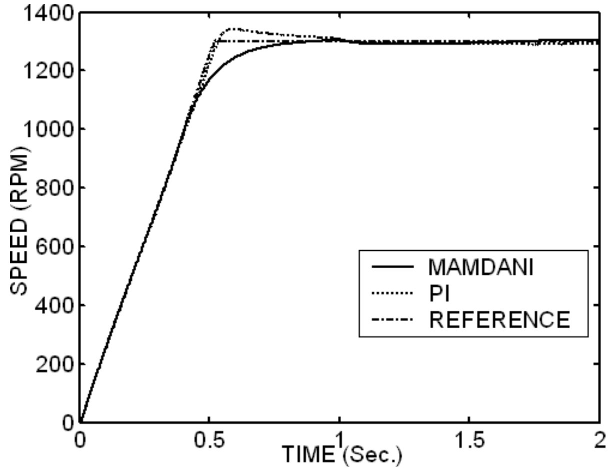

Fig. 21: Speed response at 75% full- load (1300 RPM)

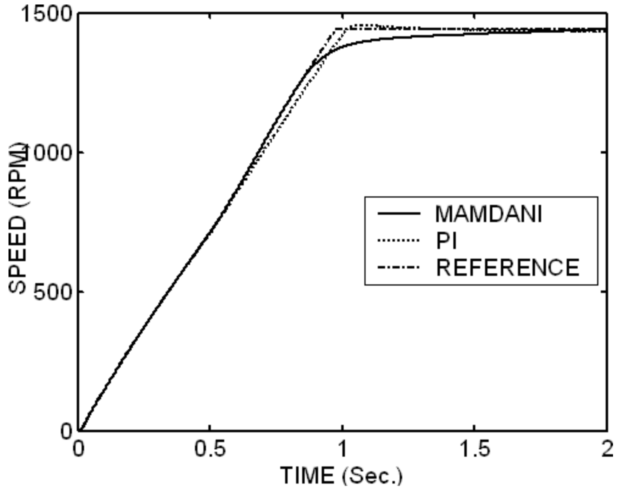

Fig. 22: Speed response at 100% full- load (1440 RPM)

TABLE 2. PERFORMANCE OF SPEED CONTROLLER

S.N.	Torque (Nm)	Reference Speed (RPM)	Settling Time (Second)		Speed Regulation (%)	
			PI	FLC	PI	FLC
1	NL	800	0.86	0.56	0	0
2		Reversal 1100	0.81	0.66	0	0
3	25% FL	1000	1.18	1.09	6	2.5
4	50% FL	1200	1.71	1.64	7.5	3.5
5	50% FL	1300	1.86	1.65	8.6	4.0
6	FL	1440	1.95	1.72	11	5.0

As mention above, using FLC there is no overshoots while in the case of conventional PI speed controller it is observed that the at no-load percentage overshoot decreases as reference speed increases; while in the case of load conditions the percentage overshoot depends on the initial load conditions as well as reference speed. The initial high load value decreases the percentage overshoot. The settling time at no-load condition is independent on the reference speed but depends on load torque and its value increases as the load torque increases. Similarly, steady state error also depends on the load. As the load increases, drop in reference speed and actual speed also increases.

6. CONCLUSION

A Fuzzy base controller has been developed for vector control of induction motors for a practical 1 hp three phase induction drive system using DSP 2407. Tests were carried out on the drive system for different operating conditions. The performance of fuzzy controller and conventional PI controller in terms of settling time and speed regulation are shown for variation in reference speed and load torque, which demonstrate the improved regulation with smaller value of settling time. In all the cases we see that for the sequence of speed reference and load torque changes, a satisfactory speed response is achieved with fuzzy logic controller.

The proposed fuzzy controller has 5 triangular membership functions with equal width and overlap for each input and the inference rule base was developed with 25 rules. Thus, a reduced number of membership functions and fuzzy rules have been established for controller. The notable feature of proposed method is that it results in a significant reduction in error as compared to classical non self-organizing fuzzy speed controller used in drives. This offers a significant advantage over conventional approach to controller design, particularly the DSP requirements for practical implementation.

APPENDIX-I

Three phase squirrel cage induction motor specifications

S.No	Parameter	Symbol	Value
1	Power Supply	3 Φ	
2	Supply Frequency	f	50 Hz
3	Power Rating	1 HP	746W
4	Voltage	V	415
5	Connection Type	γ	
6	Stator Resistance	R_s	6.03 Ω
7	Stator Inductance	L_s	29.9 mH
8	Rotor Resistance	R_r	6.085 Ω
9	Rotor Inductance	L_r	29.9 mH
10	Magnetizing Inductance	L_m	489.3 mH
11	Momentm Of Inertia	J	0.011787 kgm2
12	Damping	B	0.0027 Nm/rad/sec
13	Number Of Pole	P	4

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