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Performance Analysis of Field Oriented Induction Motor using Fuzzy PI and Fuzzy Logic based Model Reference Adaptive Control

Bharat Bhushan
Electrical Engineering
Department
Delhi Technological University
Delhi, INDIA

Madhusudan Singh
Electrical Engineering
Department
Delhi Technological University
Delhi. INDIA

Prem Prakash
Electrical Engineering
Department
Delhi Technological University
Delhi, INDIA

ABSTRACT

This paper presents the dynamic performances of an indirect vector controlled induction motor (IVCIM) using a fuzzy logic (FL) based model reference adaptive control (MRAC) slip gain tuner for speed regulation in the drive. In high performance AC drives the motor speed should closely match with the specified reference speed irrespective of the variations in the load, motor parameters and model uncertainties. Two fuzzy controllers combined with MRAC reactive power and stator direct axis (d-axis) voltage estimator have been used to tune the slip gain of the IVCIM drive against parameter variations and model uncertainties. An integrated mathematical model of the control scheme has been developed and simulated in MATLAB for Indirect vector control of an Induction motor. The simulated performances of the FL-MRAC slip gain tuner based IVCIM drive is compared to fuzzy PI controller. The simulated results in different dynamic operating conditions such as sudden change in command speed, step change in load, etc are demonstrated through necessary waveforms. The comparison of simulated results show that the fuzzy logic MRAC slip gain tuner based IVCIM drive is more robust and effective in minimizing the detuning effect in the drive due to parameter variations and model uncertainties.

Keywords

Fuzzy logic; PI controller; field oriented induction motor; model reference adaptive control

1. INTRODUCTION

Induction motor has a simple and rugged construction. However the speed control of the induction motors are not simple difficulties due to its complex and nonlinear mathematical model which involves parameters that vary with temperature, frequency and other operating conditions. The variations of parameters have significant effect on the accuracy of control speed and torque and other operating performance of the motor. It is therefore essential to optimize the motion control performance by designing intelligent adaptive controller based on fuzzy logic, neural network and expert systems, so that torque and flux have dynamic ideal response in high performance AC drives. Scalar control method has a simple control structure [1] and is implemented easily, for general-purpose industrial applications. However to improve speed control performance of the scalar control method, an encoder or speed tachometer is required; which is an expensive and less reliable solution. For achieving variable speed operation, the frequency control method [2] of the cage motor is the best method among all the methods of the speed control. There is a wide variety of applications such as machine tools, elevators; mill drives etc. where quick control over the torque of the motor is essential. Such applications are dominated by DC drives and cannot be satisfactorily operated by an induction motor drive with constant volt/hertz scheme. DC motors are easily controllable than AC motors but they are costly and less efficient.With the vector control or field oriented control theory [4] induction motors can be controlled like a separately excited DC motor. But implementation of vector control requires online computational capability which is achieved using micro controller Digital signal processor. A Fuzzy Learning Enhanced speed control [5] of an indirect field oriented induction motor drive is proposed such that the machine can follow a reference model to achieve desired speed performance. The analysis and design of the fuzzy logic controller an indirect vector controlled induction motor drive is investigated. The integral of time [6] by absolute error criterion is then used to evaluate the performance of the fuzzy speed controller for different operating conditions. Influence of the rotor resistance deviation to the system performance is studied and a rotor resistance estimator [7] using the fuzzy logic principles is described. A novel speed control scheme [8] of an induction motor using fuzzy logic control is described. A model reference adaptive scheme [10] is proposed in which an adaptation mechanism is executed using a PI controller and a fuzzy logic. The performance of a FLC [11] has been investigated and compared to that of the results obtained from the conventional PI controller based drive at different operating conditions such as sudden change in load. The simulation results demonstrate that the performance of the FLC is better than that for the conventional controller. Speed regulation of the field oriented induction motor is achieved by using a fuzzy model reference learning controller, [12] which is more robust and does not require rigorous tuning because of its adaptive nature as compared to the proportional integral and direct fuzzy controllers. A new design of fuzzy logic controller [13] with fuzzy adapted gains for speed regulation of an indirect field oriented induction motor is presented. A proportional-integral and fuzzy logic speed controllers operating in indirect field orientation [14] are designed and compared under no load and various load conditions with different reference speeds. An adaptive neuro-fuzzy inference system (ANFIS) based intelligent control [15] of vector controlled induction motor drive is proposed. The proposed neuro-fuzzy speed controller incorporates fuzzy logic algorithm with a five-layer artificial neural network structure. A vector control structure [16] combining the advantages of two types of field oriented procedure is proposed for a squirrel cage induction motor supplied from a voltage source inverter (VSI). Approach with reference model has [17] been chosen in terms of tracking, and disturbance rejection with high robustness. Two speed control techniques, [18] scalar control and indirect field oriented control are used to compare the performance of the control system with fuzzy logic controller [19-20]. Over the last two decades the principle of vector control of AC machines has evolved, manifold and an induction motor can be controlled to give dynamic performance comparable to what is achievable in a separately excited DC drive. M. Nasir Uddin et al. [21] pointed out the condition in which use of fuzzy logic controller with indirect vector control induction motor drive is more effective as compared to conventional linear controllers. The motor-control issues are traditionally handled by fixed-gain proportional-integral (PI) and proportional-integral-derivative (PID) controllers. However, the fixed-gain controllers are very sensitive to parameter variations, load disturbances, etc. Thus, the controller parameters have to be continually adapted or tuned. The problem can be solved by several adaptive control techniques such as model reference adaptive control (MRAC), sliding-mode control (SMC) variable structure control (VSC), and self-tuning PI controllers, etc. The design of such controllers depends on the exact system mathematical model. However, it is often difficult to develop an accurate system mathematical model due to unknown load variation, unknown and unavoidable parameter variations due to saturation, temperature variations, and system disturbances. In order to overcome the above problems, recently, the fuzzy-logic controller (FLC) [21-24] with power-full estimation technique is being used for motor control purpose. In this paper PI, fuzzy and model reference adaptive control techniques have been implemented on field oriented induction motor for speed regulation. A comparative analysis of three controllers has been shown for IVCIM in term of motor currents, speed and torque. The main advantage of fuzzy logic control method as compared to conventional control techniques resides in fact that no exact mathematical modeling is required for controller design and also it does not suffer from the stability problem. This Paper is organized in six sections 2 gives modeling of field oriented induction motor. Section 3 presents fuzzy logic and fuzzy logic model reference adaptive control. Section 4 presents the simulation results and discussion while section 5 gives conclusion followed by references in section 6.

2. MATHEMATICAL MODEL OF INDIRECT VECTOR CONTROL OF INDUCTION MOTOR

Fig.1 shows a MATLAB/SIMULINK model of indirect vector control induction motor. A 3-phase, 50 hp, 460V, 50 Hz induction motor is supplied through a current-controlled voltage source inverter (CC-VSI), realized through an universal bridge. The gate drives for universal bridge are generated by PWM current regulator. The controller makes two stage of inverse transformation, as shown so that control current i_d^*, i_q^* correspond to machine current i_d, i_q, respectively, in addition the unit vector assures correct alignment of i_d current with the flux vector ψ_r and i_q perpendicular to it . The d^s-q^s axes are fixed on the stator, but the d^r-q^r axes are fixed on rotor, moving at speed ω_r. Synchronously rotating axes d^e-q^e is rotating ahead of the d^r-q^r axes by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl}. Since the rotor pole is directed on the d^e axis and $\omega_e = \omega_r + \omega_{sl}$. The unit vector signal is determined as:

$$\theta_e = \int \omega_e \, dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl} \qquad (1)$$

It is to be noted that the rotor pole position is not absolute, but is slipping with respect to the rotor at frequency ω_{sl} .

For decoupling control, the stator flux component of current i_d should be aligned on the d^e axis, and the torque component of current i_q should be on the q^e. Control equation of indirect vector control can be written as (P.Vas and J.Li, 1993, B.K Bose, 2002):

$$R_r \, i_{qr} + \frac{d}{dt} \psi_{qr} + (\omega_e - \omega_r) \, \psi_{dr} = 0 \qquad (2)$$

$$R_r \, i_{dr} + \frac{d}{dt} \psi_{dr} - (\omega_e - \omega_r) \, \psi_{qr} = 0 \qquad (3)$$

The rotor flux linkage equation written as:

$$\psi_{qr} = L_r \, i_{qr} + L_m \, i_{qs} \qquad (4)$$

$$\psi_{dr} = L_r \, i_{dr} + L_m \, i_{ds} \qquad (5)$$

Therefore, the rotor d-q currents are :

$$i_{dr} = \frac{1}{L_r} \psi_{dr} - \frac{L_m}{L_r} i_{ds} \qquad (6)$$

$$i_{qr} = \frac{1}{L_r} \psi_{qr} - \frac{L_m}{L_r} i_{qs} \qquad (7)$$

The rotor currents can be further written in the form of rotor flux linkages:

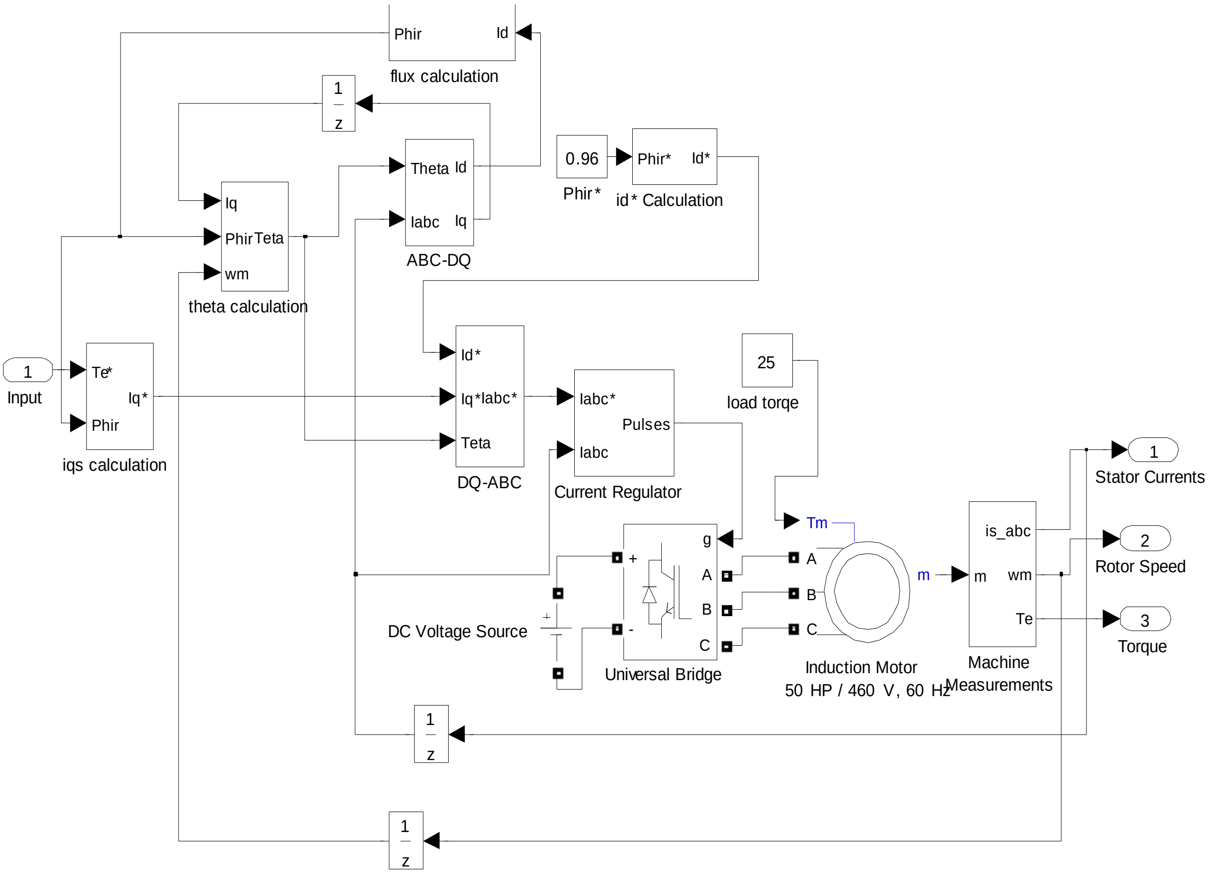

Fig.1 MATLAB model of indirect vector control induction Motor Drive

$$\frac{d\psi_{dr}}{dt} + \frac{R_r}{L_r}\psi_{dr} - \frac{L_m}{L_r}R_r\, i_{ds} - \omega_{sl}\,\psi_{qr} = 0 \tag{8}$$

$$\frac{d\,\psi_{qr}}{dt} + \frac{R_r}{L_r}\psi_{qr} - \frac{L_m}{L_r}R_r\, i_{qs} + \omega_{sl}\,\psi_{dr} = 0 \tag{9}$$

where, $\omega_{sl} = \omega_e - \omega_r$

For decoupling control

$$\psi_{qr} = 0 \tag{10}$$

$$\frac{d\psi_{qr}}{dt} = 0 \tag{11}$$

Also the total rotor flux $\hat{\psi}_r$ is directed on d^e axis :

$$\frac{L_r}{R_r}\frac{d\hat{\psi}_r}{dt} + \hat{\psi}_r = L_m\, i_{ds} \tag{12}$$

$$\omega_{sl} = \frac{L_m R_r}{\hat{\psi}_r L_r}\, i_{qs} \tag{13}$$

where $\hat{\psi}_r = \psi_{dr}$,

if rotor flux $\hat{\psi}_r$= constant ,which is usually the case equation .

$$\hat{\psi}_r = L_m\, i_{ds} \tag{14}$$

Therefore, the rotor flux is directly proportional to current i_{ds} in steady state.

3. FUZZY LOGIC AND FUZZY LOGIC BASED MODEL REFERENCE ADAPTIVE CONTROL

3.1 Fuzzy Logic:

Fuzzy logic [25-26] implementation requires no exact knowledge of a system model. Fuzzy logic applications are being studied throughout the world by control engineers. The result of these studies has shown that fuzzy logic is indeed a powerful control tool, when it comes to control system or process. The Fuzzy Logic Toolbox in MATLAB has several features which allow to create and edit fuzzy inference systems. One can create these systems using graphical tools or command-line functions, or one can generate them automatically using either clustering Fuzzy techniques. There are five primary GUI tools for building, editing, and observing fuzzy inference systems in the Fuzzy Logic Toolbox

- The Fuzzy Inference System or FIS Editor.
- The Membership Function Editor.
- The Rule Editor.
- The Rule Viewer.
- The Surface Viewer.

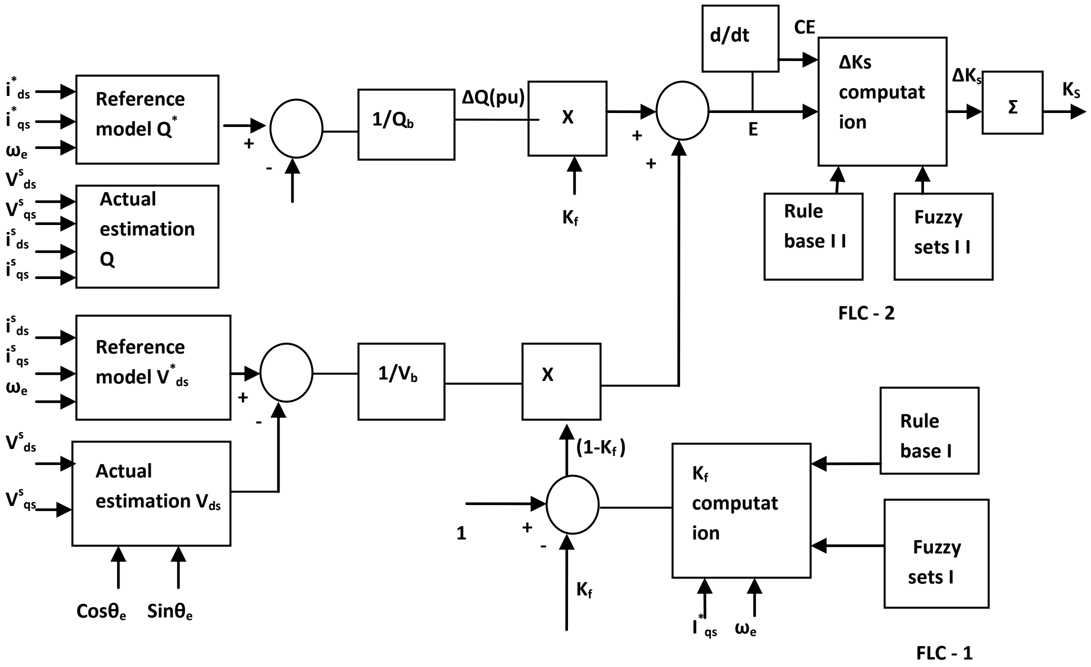

Fig.2 Model Reference Adaptive Control with Slip Gain Tuner

The MATLAB/ simulink machine implementation of a FLC involves the use of the concept of fuzzy subset, membership function and rule based modeling.

3.2 Fuzzy Logic Based Model Reference Adaptive Control with Slip Gain Tuner for IVCIM Drive:

The MRAC method based on reactive power and stator d-axis voltage are combined together with a weighting factor which is generated by a fuzzy controller. The weighting factor ensures the dominant use of reactive power method in low speed high torque region whereas the d - axis voltage method is dominant in high speed low torque region (Gilberto C.D. Sousa et al.1993). A second fuzzy controller tunes the slip gain based on combined detuning error and its slope so as to ensure fast convergence at any operating point on torque-speed plane. The rule base matrix for the fuzzy logic controller generating detuning factor (K_f) is given in Table 2: It clearly shows that if speed is low (L) and torque is high(H) then weighting factor is high(H). A block diagram of fuzzy logic based on model reference adaptive control (MRAC) of slip gain tuner is shown in Fig.3. Here the reference model output signals X* that satisfied the tuned vector control is usually a function of command current i_{ds}*, i_{qs}*, machine inductance, and operating frequency. The adaptive model X is usually estimated by machine feedback voltage and current. The reference model output is compared with that of adaptive model and the resulting error generates the estimated slip gain $\hat{K}_s$ through a fuzzy P-I controller. The slip tuning occurs when X matches with X*.The objective is to provide an adaptive feedback control for fast convergence at any operating point ,irrespective of the strength of error signal E and its derivative signal CE.

3.3 Relationship of Reactive Power (Q*) and D-Axis Voltage (V_{ds}^*) in MRAC Slip Gain Tuner

From the d^e-q^e model of IM, the stator equations are

$$v_{qs} = R_s\, i_{qs} + \frac{d}{dt}\left(\psi_{qs}\right) + \omega_e \psi_{ds} \qquad (15)$$

$$v_{ds} = R_s\, i_{ds} + \frac{d}{dt}\left(\psi_{ds}\right) - \omega_e\ \psi_{qs} \qquad (16)$$

At steady state condition under vector control,

$$\frac{d}{dt}\left(\psi_{qs}\right) = 0 \qquad (17)$$

$$\frac{d}{dt}\left(\psi_{ds}\right) = 0 \qquad (18)$$

$$\psi_{ds} = L_s\, i_{ds} \qquad (19)$$

$$\psi_{ds} = L_s\, i_{ds} - \frac{L_m}{L_r}\, i_{qs}\, L_m = \left(L_s - \frac{L_m^2}{L_r}\right) i_{qs} \qquad (20)$$

$$v_{qs} = \omega_e\, L_s\, i_{ds} \qquad (21)$$

$$v_{ds} = -\omega_e\left(L_s - \frac{L_m^2}{L_r}\right) i_{qs} \qquad (22)$$

$$Q* = v_{qs}\, i_{ds} - v_{ds}\, i_{qs} \text{ (reference)} \tag{23}$$

$$Q = v_{qs}^{s}\, i_{ds}^{s} - v_{ds}^{s}\, i_{qs}^{s} \text{ (actual)} \tag{24}$$

$$v_{ds} = v_{qs}^{s}\, sin\theta_e - v_{ds}^{s}\, cos\theta_e \text{ (actual)} \tag{25}$$

$$v_{ds}^{*} = R_s\, i_{ds}^{*} - \hat{\omega}_e\, L_\sigma\, i_{qs}^{*} \text{ (reference)} \tag{26}$$

where cos θ_e and sin θ_e are the unit vector components. The loop errors are divided by the respective scaling factor to derive the per unit variable ΔQ and the Δv_{ds} for manipulation by fuzzy controller. The combined error signal for fuzzy PI controller (FLC 2) is given as:

$$E = K_f\, \Delta Q + (1 - K_f)\Delta v_{ds} \tag{27}$$

Fuzzy controller FLC 2 generates the corrective incremental slip gain ΔK_s based on the combined detuning error E and its derivative CE as shown in figure 3 and 4. Membership function for output variable is shown in figure 5.

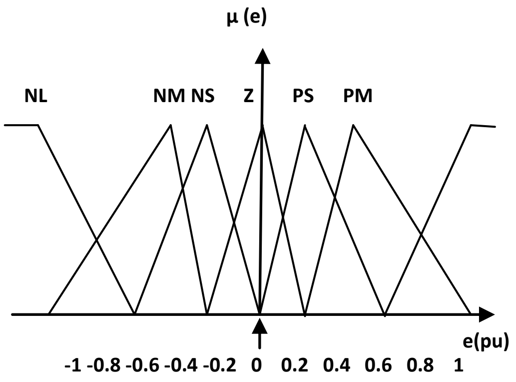

Fig. 3 Membership function for error

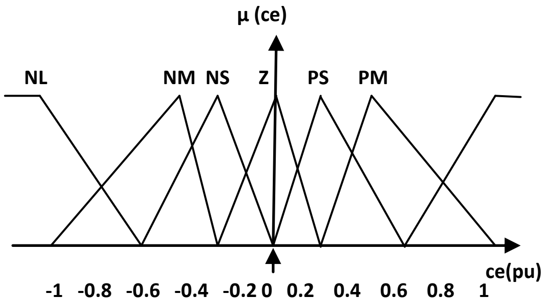

Fig. 4 Membership function for change in error

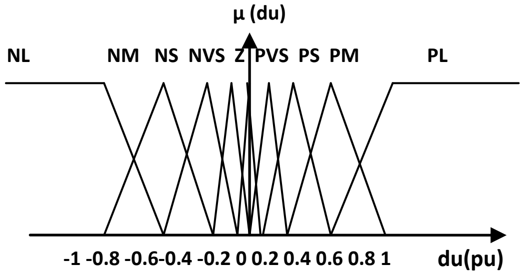

Fig. 5 Membership function for Output

Table 1 Rule Based Matrix for fuzzy controller

CE/E	NL	NM	NS	Z	PS	PM	PL
PL	Z	PS	PM	PL	PL	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PS	NM	NS	Z	PS	PS	PL	PL
Z	NL	NM	NS	Z	PM	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NM	NS	Z	PS
NL	NL	NL	NL	NL	NM	NS	Z

Table 2 Rule base matrix for weighting factor (K_f)

$I_{qs}\backslash\omega e$	H	L
H	M	H
L	L	M

4. RESULTS AND DISCUSSIONS

4.1 Performances of IVCIM Drive using Fuzzy-PI Control

Fig.6 shows the performance characteristic of a 50 hp, 460 V, 60 Hz IM, operating at no load with a fuzzy PI speed controller. The reference speed is 120 rad/sec. it is observed that motor pick up the reference speed at t = 0.6 sec Fig.7 shows the performance characteristic of motor, when a sudden change in reference speed from 120 to 160 rad/sec is made at t = 0.2 sec. it is observed from the waveform of the motor that motor speed tracks the change in reference speed quickly and steady state and there is no significant offset. This is due to the facts that the fuzzy control is a nonlinear control and the IM motor mathematical model is also non-linear and complex. Fig.8 shows the response of the fuzzy logic IVCIM with sudden change in load torque at t = 0.2 sec. the motor torque rise quickly to 200 N-m. The speed of the motor dips momentarily, FLC current regulator is able to maintain specified speed 120 rad/sec.

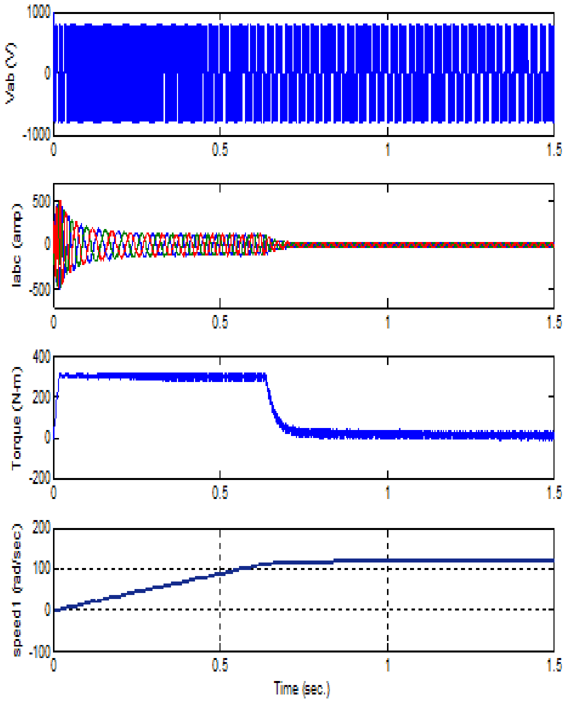

Fig.6 Performance of Fuzzy PI indirect vector control (FLIVC) at no load with reference speed 120 rad/sec

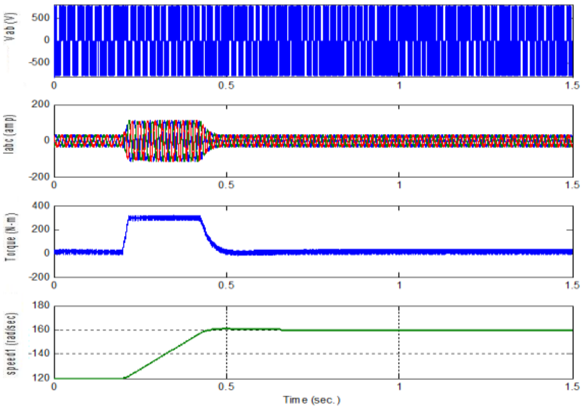

Fig.7 Response of FLIVC with a step change in reference speed (120 to 160 rad/sec) at t = 0.2 sec

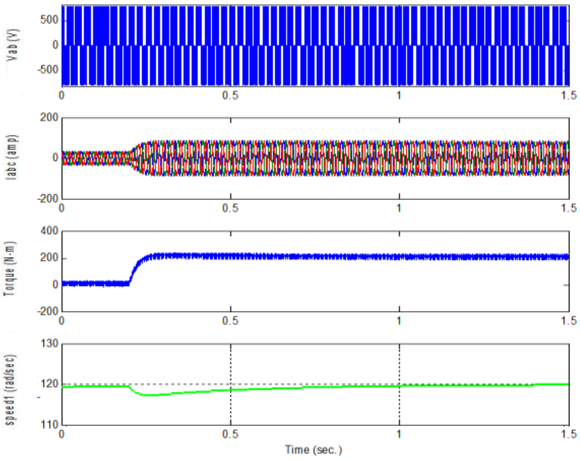

Fig.8 Response of FLIVC with a step change in load(0 to 200 rad/sec) at t = 0.2 sec.

4.2 Performance of Indirect Vector Control IM Using Fuzzy Logic Based MRAC Slip Gain Tuner

A FL based MRAC slip gain tuner is designed and used as a speed controller for a 50 HP, 460V, 4 poles squirrel cage induction motor. The simulated performances of IVCIM drive without and with MRAC slip gain tuner with variation in rotor resistance are shown in figures 9 and 10 respectively. It is observed that the MRAC based FLC controller provides a faster dynamic response of induction motor and also sensitive to variation in rotor resistance. The induction motor with conventional FLC-PI controller requires approximately 1.2 sec. to demanded speed of 120 rad/sec, while MRAC control needed 0.9 sec. achieve the reference speed.

Fig.11 shows the performance characteristics of IVICM with fuzzy PI control and fuzzy logic based MRAC tuner, when the rotor resistance is changed from 0.228 Ω to 0.171 Ω, (25% decreases in rotor resistance). It is observed that the torque decreases from 300 to 210 N-m with fuzzy PI control while performance of fuzzy logic based MRAC tuner maintains the torque 300 N-m, even though the rotor resistance decreases by 25% and makes the response independent of rotor resistance variations. Comparison of torque developed by motor with fuzzy PI controller based IVCIM drive and fuzzy logic based MRAC slip gain tuner based IVCIM drive during variation of rotor resistance shows that due to variation of rotor resistance, torque decreases to 200 N-m in fuzzy PI control of IVCIM, while it is maintained at 300 N-m by fuzzy logic MRAC based tuner. The comparison of simulated results show that the fuzzy logic MRAC slip gain tuner based IVCIM drive is more robust and effective in minimizing the detuning effect in the drive due to parameter variations and model uncertainties

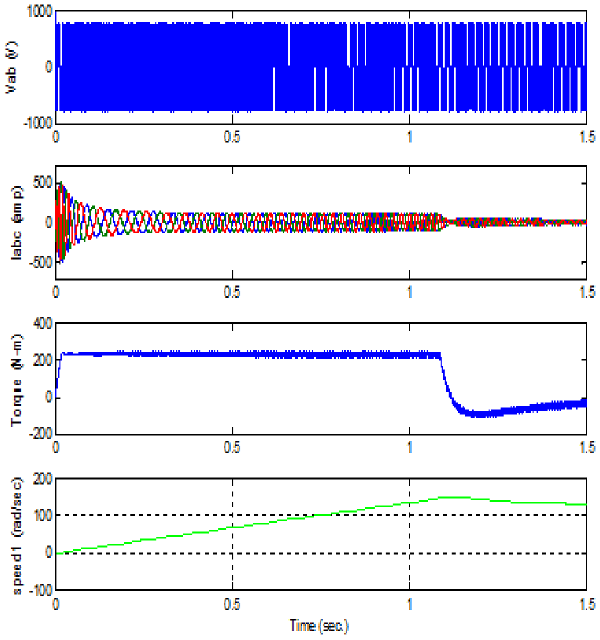

Fig.9 Performance of indirect vector control using Fuzzy logic P-I controller at R' = 0.75R

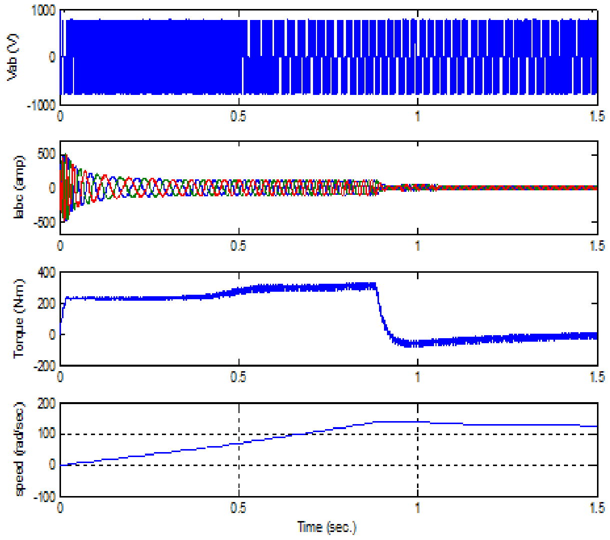

Fig.10 Performance of indirect vector control using Fuzzy logic based MRAC slip gain tuner at R' =0 .75 R

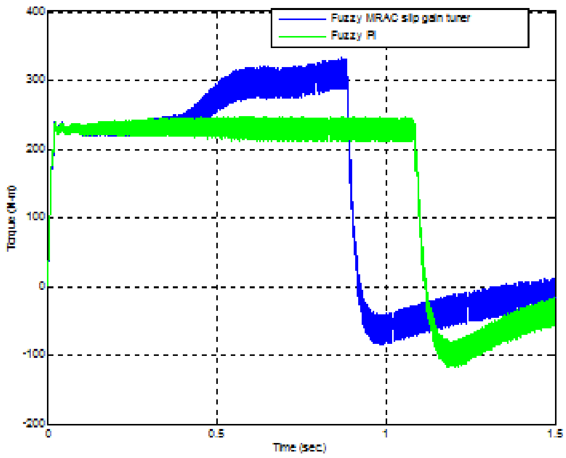

Fig.11 Torque response comparisons between FLC based IVC and fuzzy logic MRAC based IV

5. CONCLUSION

This paper presents a comparative performance study of IVCIM drive with Fuzzy-PI and FL based MRAC slip gain tuner for speed control. A FL control in IVCIM gives superior performance in terms of fast dynamic responses and stiffer speed regulation. However, a conventional FL controller is not capable in maintaining the performance of the motor due rotor to parametric variations. A FL based MRAC slip gain tuner provides an effective means in speed and torque control of the IVCIM drive even with variation rotor resistance operation of motor.

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