PID-Fuzzy Logic Position Tracking Controller for Detuned Field-Oriented Induction Motor Servo Drive

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Abstract:- In this paper, the position control of a detuned indirect field oriented control (IFOC) induction motor servo drive is studied. A PID-fuzzy logic position controller (PID-FLPC) is designed and analyzed to achieve high-dynamic performance both in the position command tracking and load regulation characteristics for robotic applications. The performance of the proposed PID-fuzzy logic and synchronous PI-D 2DOF position controllers for detuned field oriented induction motor servo drive is investigated. Simulation results show that the proposed PID-fuzzy logic position controller provides high-performance dynamic characteristics and is robust with regard to motor parameter variations and external load disturbance. Furthermore, comparing the performance of the drive system with the PID-fuzzy logic position controller and the synchronous PI-D 2DOF position controller demonstrate that the superiority of the proposed PID-fuzzy logic position controller due to attain a robust performance for IFOC induction motor servo drive system.

Key-Words: Indirect field orientation control (IFOC), PI-D 2DOFC, PID-fuzzy, induction motor drive

1 Introduction

Induction machine servo drive system is considered high-performance when the rotor position, rotor speed and stator currents can be controlled to follow a reference for tracking at all times. A track is a desired time history of the motor current, speed or position. This servo drive system is essential in many applications such as robotics, actuation, numerically controlled machinery and guided manipulation where precise control is required. Previously, dc machines were used in variable speed and position control applications because of the possibility of controlling their flux and torque independently. However, dc machines have many disadvantages. To overcome the dc machines disadvantages, the induction machines can be used because of its simple and rugged structure, easy maintenance and economical operation.

The induction motor can be controlled similar to a dc motor using field oriented control (FOC) strategy [1-2]. However, difficulties are found from modelling uncertainties due to parameter variations, magnetic saturation and load disturbances. To ensure high dynamic performance various control strategies for field oriented induction motor drive have been reported in the literature. In many industrial drives, the control of field oriented induction machine drive with a conventional controllers have gained the widest acceptance in high-performance ac drive systems. However, the conventional controllers has difficulty in dealing with dynamic speed tracking, parameter variations and load disturbances. So, the dynamic performance of a field-oriented induction motor is affected by the decoupling characteristics. It is known that for the IFOC of induction motor drive, the ideal decoupling between the flux and torque will not be obtained if the rotor parameters used in the FOC can not track their nominal values. The most important parameter to be considered is the rotor resistance. The adaptation of FOC equation, ω_{sl}, is very important to achieve ideal decoupling. To reduce the effects of rotor parameter variations on IFOC, various tuning techniques have been reported [3-5]. The optimal control rule for adaptation of rotor time constant requires many motor parameters and it is too complex to be successfully achieved. This difficulty can be overcome by fuzzy control technique instead of using mathematical derivations. Fuzzy control technique was also employed in [8-10]. However, the proposed method in [8] was applied only to speed controller while the proposed method in [9] was applied to the current controllers.

The main objective of this paper is to design and analyze a proposed PID-fuzzy logic position controller for detuned IFOC-based induction motor servo drive in order to improve the dynamic performance of the drive system . Also, a PI-fuzzy controllers are designed for the speed and current control loops. The proposed synchronous PI-D 2DOF position controller and PI-D speed controller are quantitatively designed and analyzed for the drive system to possess the position tracking and regulation responses based on the closed-loop tracking transfer function as given in [6]. The simulation results have demonstrated that robust control performances both in command tracking and load regulation are achieved by the proposed PID-fuzzy logic position controller when detuning occurs and then improve the dynamic behavior compared with the synchronous PI-D 2DOFC position controller. The results of the simulation confirm the effectiveness of the proposed PID-fuzzy position controller and its superiority as compared with the PI-D 2DOFC position controller for IFOC induction machine drive system. Also, the results demonstrate that the proposed PID-fuzzy position control scheme has robust position response and can rapidly cancel the load disturbance.

2 Induction Machine Model and IFOC for Position Control

The block schematic of IFOC-based induction machine servo drive with inverter controlled using space vector modulation (SVM) technique is shown in Fig. 1. The Figure shows that three feedback loops in the control system. The inner is the current feedback loop, the middle is the speed feedback loop and the outer is the position feedback loop. Also, the diagram includes a current regulated pulse width modulation (CRPWM) inverter with SVM technique (CRSVMPWM), indirect field orientation controller (IFOC), decoupling controlling, PI-fuzzy *d-q* stator current controllers, PI-fuzzy speed controller and PID-fuzzy position controller.

The state equation of the nonlinear dynamic *d-q* model of the induction machine at the synchronous reference frame is expressed as follows [1-2]. The IFOC dynamics for the induction machine (torque, slip angular frequency and voltage commands) can be derived from equations (1-2) respectively at $\lambda_{qr}^e = 0$ and $d\lambda_{qr}^e / dt = 0$. The torque equation and slip angular frequency for rotor field orientation are given in equations (4, 5) while the voltage commands (decoupling controller) of the IFOC are given in equations (6-9).

$$\frac{d}{dt}\begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ \lambda_{qr}^e \\ \lambda_{dr}^e \end{bmatrix} = \begin{bmatrix} -k_{ss} & -\omega_e & \frac{k_m}{\tau_r^*} & -k_m\omega_r \\ \omega_e & -k_{ss} & k_m\omega_r & \frac{k_m}{\tau_r^*} \\ \frac{L_m}{\tau_r^*} & 0 & -\frac{1}{\tau_r^*} & -\omega_{sl} \\ 0 & \frac{L_m}{\tau_r^*} & \omega_{sl} & -\frac{1}{\tau_r^*} \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ \lambda_{qr}^e \\ \lambda_{dr}^e \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} V_{qs}^e \\ V_{ds}^e \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

$$T_e = \frac{3}{2}.\frac{P}{2}.\frac{L_m}{L_r}(\lambda_{dr}^e i_{qs}^e - \lambda_{qr}^e i_{ds}^e) \quad (2)$$

$$T_e = \frac{J}{(P/2)}\frac{d^2}{dt^2}\theta_r + \frac{\beta}{(P/2)}\frac{d}{dt}\theta_r + T_L \quad (3)$$

$$T_e = \frac{3}{2}.\frac{P}{2}.\frac{L_m^2}{L_r}.i_{ds}^{e*} i_{qs}^{e*} \quad (4)$$

$$\omega_{sl} = \frac{1}{\tau_r}.\frac{i_{qs}^{e*}}{i_{ds}^{e*}} \quad (5)$$

$$V_{qs}^{e*} - e_{qs}^{e*} = \left(L_s\sigma\frac{d}{dt}i_{qs}^{e*} + R_s i_{qs}^{e*}\right) \quad (6)$$

$$e_{qs}^{e*} = \left(L_s\sigma + L_m^2 / L_r\right)\omega_e .i_{ds}^{e*} \quad (7)$$

$$V_{ds}^{e*} + e_{ds}^{e*} = \left(L_s\sigma\frac{d}{dt}i_{ds}^{e*} + R_s i_{ds}^{e*}\right) \quad (8)$$

$$e_{ds}^{e*} = \left(L_s\sigma + L_m^2 / L_r\right)\omega_e .i_{qs}^{e*} \quad (9)$$

3 Fuzzy Logic Like Conventional Controllers

Fuzzy Logic control (FLC) offers a convenient way of designing controllers from experience and expert knowledge about the system being controlled. Also, fuzzy logic control deals with systems that have uncertainty similar to induction machine and uses membership functions with values between 0 and 1 to solve the problem of the induction machine. In the following section, the different types of fuzzy logic controllers (FLC) like conventional controllers structure such as PI-fuzzy, PD-fuzzy and PID-fuzzy controllers are illustrated.

3.1 FLC Principles and Structure

The fuzzy controller consists of fuzzification process, inference process, rule base process and defuzzification process. The fuzzification process provides the input to the fuzzy set obtained by the associated membership function. The linguistic values for each fuzzy set are HP, MP, LP, ZE, LN, MN, HN and can be chosen where P, N, H, M, L and ZE denote positive, negative, high, medium, low, and zero respectively. The inference engine uses the IF-THEN rules in the knowledge base to provide the decisions of the product and min operations. The inference process produces an implied output fuzzy set corresponding to the output membership function. The defuzzification process transforms the output fuzzy sets into a crisp output value. Using the center of gravity defuzzification technique, the output is calculated utilizing equation (10). The knowledge base is very important in the design of the FLCs. It is designed by the experience about the system to be controlled. This experience is synthesized by the choice of the input-output membership functions and the rule base. Triangular membership functions for both the input and output membership functions are used [7-12].

$$u^* = \frac{\sum_{i=1}^{k} u_i \mu(u_i)}{\sum_{i=1}^{k} \mu(u_i)} \quad (10)$$

where k is the total number of rules and $\mu(u_i)$ denotes the output membership grade for i$^{\text{th}}$ rule.

3.2 PID-Fuzzy Logic Controller

The output equation of the conventional proportional plus integral plus derivative (PID) controller is given by:

$$u(t) = K_p e(t) + K_d \Delta e(t) + K_i \sum e(t) \tag{11}$$

The input variables to PID-fuzzy controller are error (e), the error rate of change (Δe) and the sum of error $(\sum e)$, the controller output signal (u) can be calculated from equation (11). Because the PID-fuzzy controller has three inputs and any rule has three conditions, we will need 7x7x7=343 rules for seven linguistic values. Therefore, we can construct the PID-fuzzy controller as parallel structure of a PD-fuzzy and PI-fuzzy controllers as given by equation (12). The first term is PD controller and the second term is the PI controller.

$$u(t) = \left(\frac{K_p}{2} e(t) + K_d \Delta e(t)\right) + \left(\frac{K_p}{2} e(t) + K_i \int e(t)dt\right) \tag{12}$$

4 Design of the Proposed Fuzzy Logic Controllers

In this section, the analysis and design procedures of the PI-fuzzy speed controller and PID-fuzzy position controller. The proposed PI-fuzzy d-q axes stator current controllers has been designed [10].

4.1 PI-Fuzzy Speed Controller

The block diagram structure of the proposed PI-fuzzy speed controller is shown in Fig. 2. The actual inputs to the fuzzy controller are the speed error, $e_\omega(k)$, and the rate of the of current error, $\Delta e_\omega(k)$, linguistic variables are considered the inputs to the controller and the output is the change of the q-axis stator current, $\Delta i_{qs}^{e*}(k)$.

$$u_\omega(k) = i_{qs}^{e*}(k) = \int \Delta i_{qs}^{e*}(k) = f(e_\omega(k), \Delta e_\omega(k)) \tag{13}$$

Where, $e_\omega(k) = \omega_r^*(k) - \omega_r(k)$ is the speed error and $\Delta e_\omega(k) = e_\omega(k) - e_\omega(k-1)$ is the change of speed error.

The scaling factors $K_p^{\Delta e\omega}$ and $K_i^{e\omega}$ are selected and can be varied to tune the output of the fuzzy controller for the desired speed response. The output gain, K_u^ω, can also be tuned for the same purpose. Fig. 3 illustrates the membership functions $e_\omega(k)$, $\Delta e_\omega(k)$ and $u_\omega(k)$ which are used for the input and output fuzzy sets. The membership functions corresponding to each element in the linguistic set can be defined using the fuzzy linguistic control rules. The linguistic rules base for PI-fuzzy speed controller are shown in Table 1. Using these rules and membership functions, the fuzzy controller produces the crisp input output map shown in Fig. 4.

4.2 PID-Fuzzy Position Controller

For the proposed PID-fuzzy position controller as shown in Fig. 5, the position error, $e_\theta(k)$, and the rate of the of position error, $\Delta e_\theta(k)$, linguistic variables are considered the inputs to the controller and the output is the reference speed, $\omega_r^*(k)$.

$$\begin{aligned} u_\theta(k) &= \omega_r^*(k) \\ &= u_{1\theta}(k) + \int u_{2\theta}(k) = f(e_\theta(k), \Delta e_\theta(k)) \end{aligned} \tag{14}$$

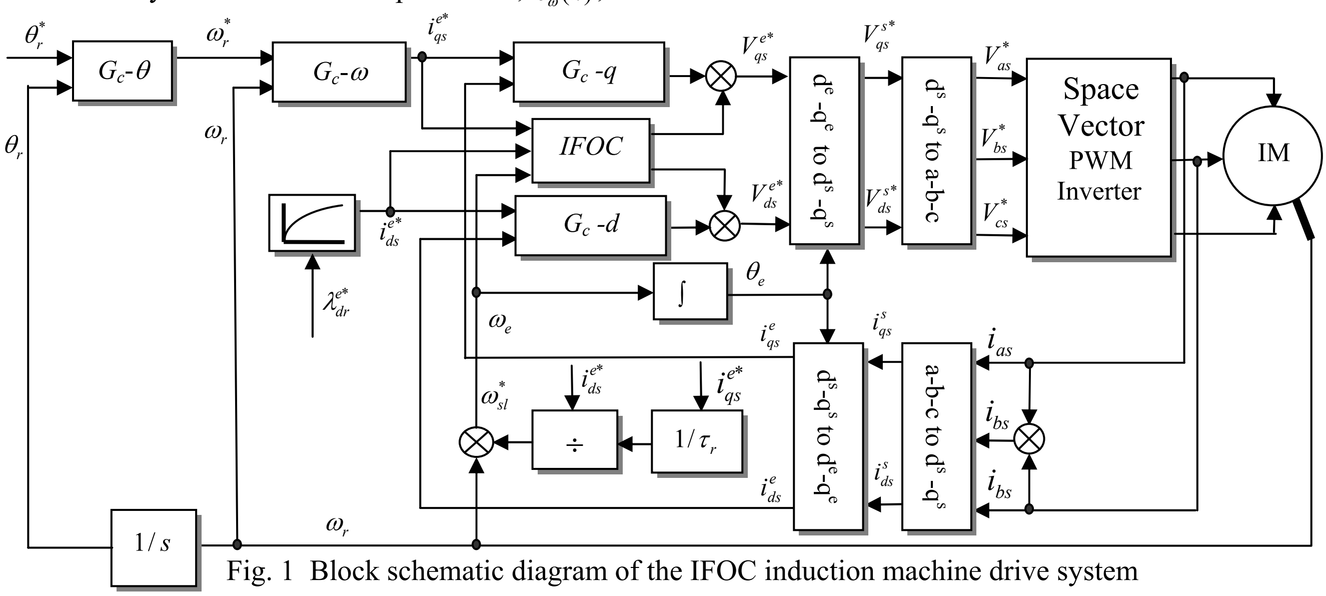

Fig. 1 Block schematic diagram of the IFOC induction machine drive system

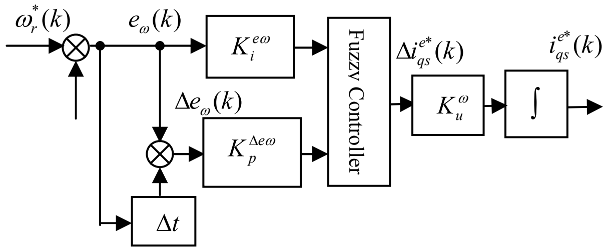

Fig. 2 PI-fuzzy speed controller

e_ω \ Δe_ω	HN	LN	ZE	LP	HP
HN	HN	HN	HN	LN	ZE
LN	HN	LN	LN	ZE	LP
ZE	MN	ZE	ZE	LP	MP
LP	MN	ZE	LP	LP	MP
HP	ZE	LP	MP	HP	HP

Table 1 The linguistic rules base for the proposed PI-fuzzy speed controller

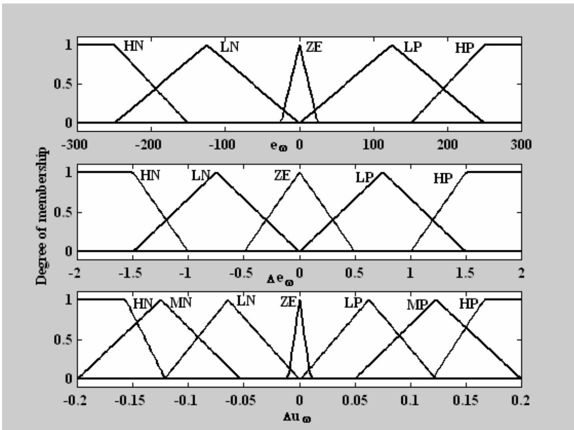

Fig. 3 Member ship function of PI-fuzzy speed controller

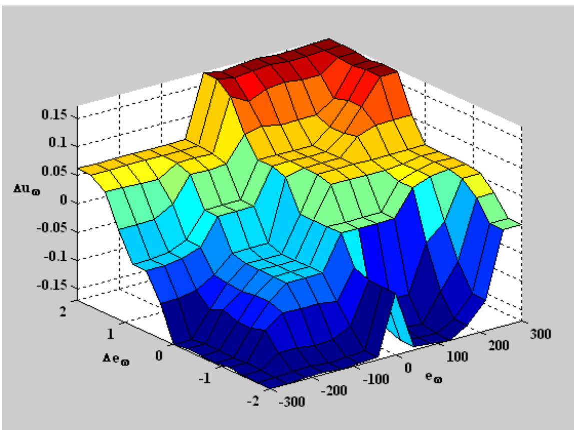

Fig. 4 Crisp I/O map of PI-fuzzy speed controller

Where, $e_\theta(k) = \theta^*(k) - \theta(k)$ is the position error and $\Delta e_\theta(k) = e_\theta(k) - e_\theta(k-1)$ is the change of position error. The scaling factors $K_{p/2}^{\Delta e\theta}$, $K_{p/2}^{e\theta}$, $K_i^{e\theta}$, and $K_d^{\Delta e\theta}$ are selected and can be varied to tune the output of the fuzzy controller for the desired q-axis current performance. The output gains, K_{u1}^{θ} and K_{u2}^{θ}, can also be tuned for the same purpose. Fig. 6 illustrates the membership functions $e_\theta(k)$, $\Delta e_\theta(k)$ and $u_\theta(k)$ which are used for the input and output fuzzy sets. The membership functions corresponding to each element in the linguistic set can be defined using the fuzzy linguistic control rules. The linguistic rules base for PID-fuzzy position controller are shown in Table 2. These rules and membership functions are used to produce the crisp input output map of the fuzzy controller as shown in Fig. 7.

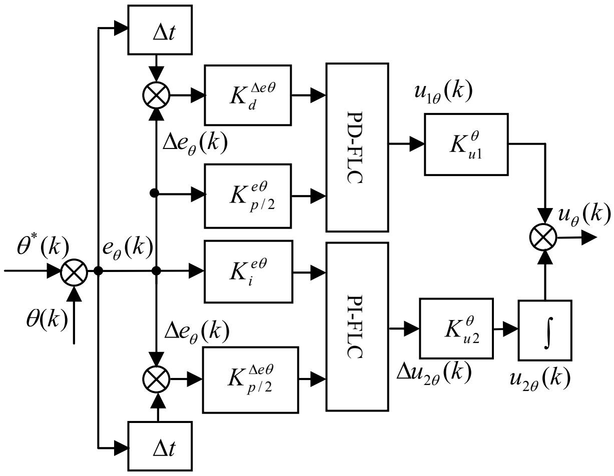

Fig. 5 PID-fuzzy position controller

e_θ \ Δe_θ	HN	LN	ZE	LP	HP
HN	HN	MN	LN	LN	ZE
LN	HN	LN	LN	ZE	LP
ZE	LN	LN	ZE	LP	MP
LP	LN	ZE	LP	MP	HP
HP	ZE	LP	MP	HP	HP

(a) PI-fuzzy position controller part

e_θ \ Δe_θ	HN	LN	ZE	LP	HP
HN	HN	MN	LN	LN	ZE
LN	HN	LN	LN	ZE	LP
ZE	LN	LN	ZE	LP	MP
LP	LN	ZE	LP	MP	HP
HP	ZE	LP	MP	HP	HP

(b) PD-fuzzy position controller part

Table 2 The linguistic rules base for the proposed PID-fuzzy position controller

5 Proposed PI-D 2DOF Controller

The analysis and design procedures of the PI-D 2DOF position controller and PI-D speed controller has been designed in [6] while the d-q axes PI current controllers has been designed in [1].

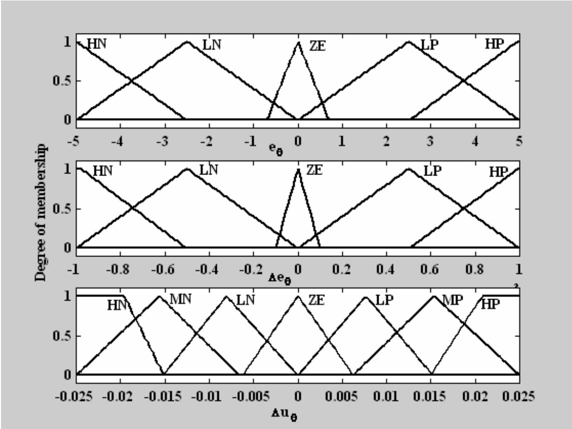

Fig. 6 Membership function of PID-fuzzy position controller

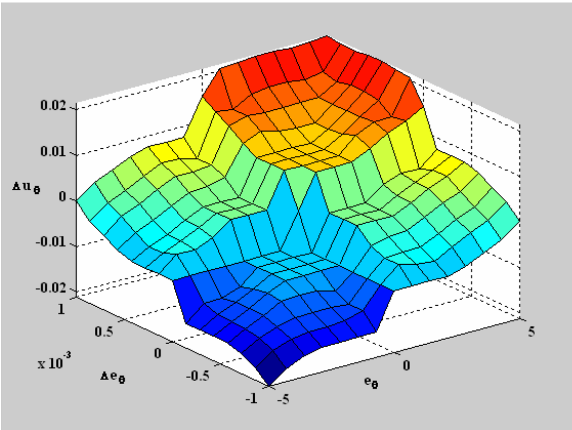

Fig. 7 Crisp I/O map of PID-fuzzy position controller

5.1 PI-D Speed Controller Parameters

The PI-D speed controller parameters are given by equations (15-17). The design depends on the desired response technique.

$$K_p^\omega = \frac{2.15\omega_n^3\tau_{sr}^{'} - 1/\tau_m}{K\tau_{sr}^{'}} \tag{15}$$

$$K_i^\omega = \frac{\omega_n^3}{K} \tag{16}$$

$$K_d^\omega = \frac{\left(1.75\omega_n - 1/\tau_{sr}^{'} - 1/\tau_m\right)}{K} \tag{17}$$

5.2 PI-D 2DOF Position Controller

The PI-D 2DOF position controller consists of feed-back controller and feed-forward controller. The design depends on the desired response technique.

5.2.1 Feed-back Controller Parameters

The feedback controller is a PI-D type. The parameters of the feedback position controller are introduced in equations (18-20).

$$K_p^\theta = \frac{2.7\omega_n^3.\tau_{2\omega} - \omega_n^4.\tau_{2\omega}.K_p^\omega / K_i^\omega}{K_t K_j K_i^\omega} \tag{18}$$

$$K_i^\theta = \frac{\tau_{2\omega}.\omega_n^4}{K_t K_j K_i^\omega} \tag{19}$$

$$K_d^\theta = \frac{\left(2.1\omega_n.\tau_{2\omega} - \tau_{1\omega}\right)}{K_t K_j K_i^\omega} \tag{20}$$

5.2.2 Feed-forward Controller Parameters

The feed-forward controller is a lead-lag compensator type and its transfer function is given in equation (21).

$$G_{ff}(s) = \overset{\approx}{K}.\frac{(1+\tau_{lead}s)}{[1+(K_p^\theta / K_i^\theta)s]} \tag{21}$$

6 Simulation Results

This section presents a computer simulation of the proposed control scheme for a 1.5 kW squirrel cage induction motor using PID-fuzzy and PI-D 2DOF position controllers respectively. The simulation of the proposed control scheme for IFOC induction machine drive system shows performance enhancements for the case when the motor is properly field oriented and when it is detuned. The dynamic performance of the drive system for different operating conditions has been studied with the application of fuzzy logic controllers (FLCs) and PI-D 2DOFC position controller. The FLCs are PI-fuzzy speed controller and PID-fuzzy position controller. The conventional controllers are the PI-D speed controller and PI-D 2DOF position controller. The dynamic performance of the drive system under the disturbances of step change in reference position and step change in load is shown in Fig. 8 and Fig. 9. Fig. 8 illustrates the dynamic response of the drive system with the application of PID-fuzzy position controller while the dynamic response of the drive system with the application of the PI-D 2DOF position controller at the same conditions is illustrated in Fig. 9. Figs. (8-9) show the position tracking, speed response, current response, torque response and load regulation performance under nominal parameters. At *t*=2 sec, an external load of 11.5 N.m is applied to the drive system for both controllers and removed at *t*=4.5 seconds.

The position response and the load regulation performance of the PID-fuzzy position controller and PI-D 2DOF position controller are shown in Figs. (10-12) respectively under the same conditions where the rotor time constant changes from 0.25 τ_r to 1.5 τ_r and the rotor inertia changes from *J* to 5 *J*. Figs. (10-12) show the position tracking and load regulation performance under nominal and detuned parameters for both PID-fuzzy position controller and PI-D 2DOF position controller. It is obvious that the proposed PID-fuzzy position controller provides a rapid and accurate response for the reference within 1.0 sec. Also, the PID-fuzzy position controller quickly return the position to the command position within 0.65 sec under full load with a maximum dip of 0.02 radian as illustrated in Figs. (10-11). While the position response of the conventional PI-D 2DOFC position controller scheme provides a slow response for the reference of about 1.5 second and has a long recovery time of 1 second and large dipping in position of about 0.38 radian under load changes as shown in Fig. 12. The proposed PID-fuzzy position controller provides rapid and accurate response for the reference, regardless of whether a load disturbance is imposed and the induction motor parameters vary as illustrated in Fig. 10. Also, proposed PID-fuzzy position controller can compensate the induction machine drive system at nominal values and is insignificantly affected by variations in the induction machine's parameters. Also, the position response of the proposed PID-fuzzy position controller was influenced slightly by the load disturbance, whether the system parameters varied or not. Computer simulation results demonstrate that the proposed PID-fuzzy position control scheme has a robust position response and can rapidly cancel the load disturbance and its superiority compared with the PI-D 2DOFC position controller for IFOC induction machine drive system.

8 Conclusion

In this paper, a PID-fuzzy position control system design for IFOC of induction machine drive system has been presented. The PID-fuzzy position controller constitute a simple structure that is applied to the induction machine drive system. In spite of the simple structure of PID-fuzzy position controller, the obtained results show that this controller can provide a fast and accurate dynamic response in tracking and disturbance rejection characteristics under parameter variations. At the same time, a reduction of the computation time of rules base has been occurred as a result of the simple construction of the PID-fuzzy position controller. The proposed PID-fuzzy position controller can compensate the induction machine drive system at nominal values and is insignificantly affected by variations in the induction machine's parameters. The position response of the proposed PID-fuzzy position control scheme was influenced slightly by the load disturbance, whether the system parameters varied or not. However, the position response of the conventional PI-D 2DOFC position control scheme did have a long recovery time. Simulation results demonstrate that the proposed PID-fuzzy position control scheme has a robust position response and can rapidly cancel a load disturbance and its superiority compared with the PI-D 2DOFC position controller for IFOC induction machine drive system.

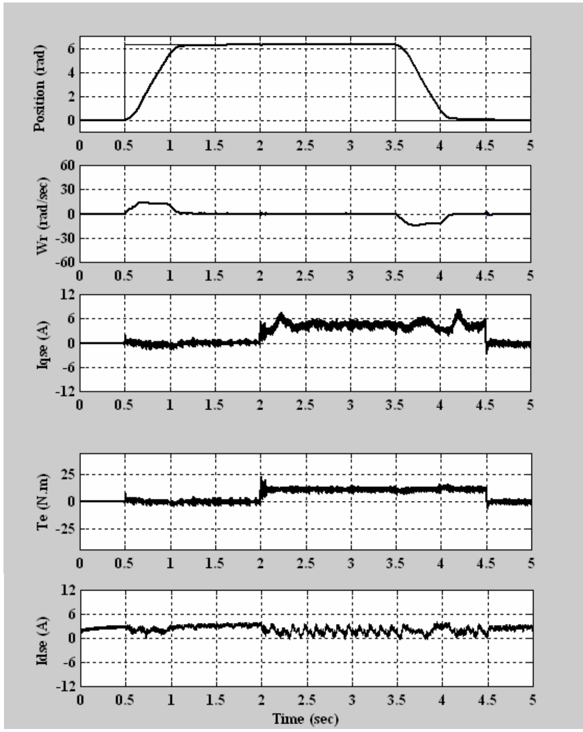

Fig. 8 Dynamic performance of the position, speed, *d-q* axes currents and torque at full load with the proposed PID-fuzzy position controller

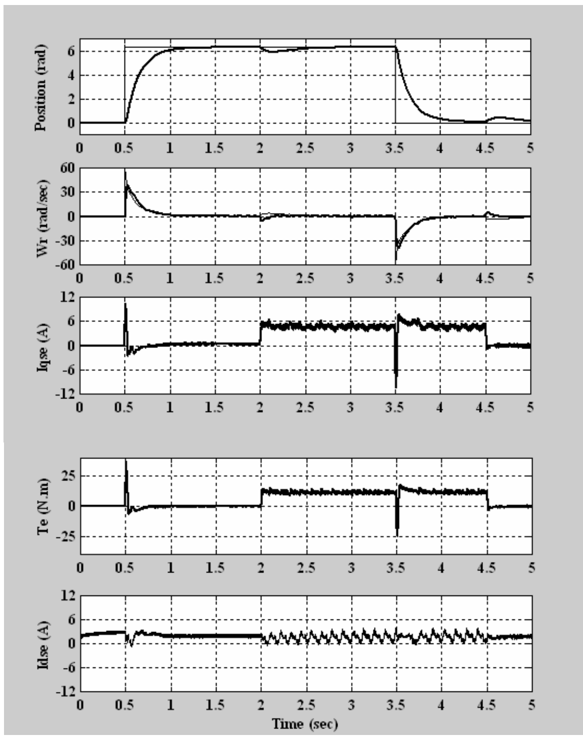

Fig. 9 Dynamic performance of the position, speed, *d-q* axes currents and torque at full load with the proposed PI-D 2DOF position controller

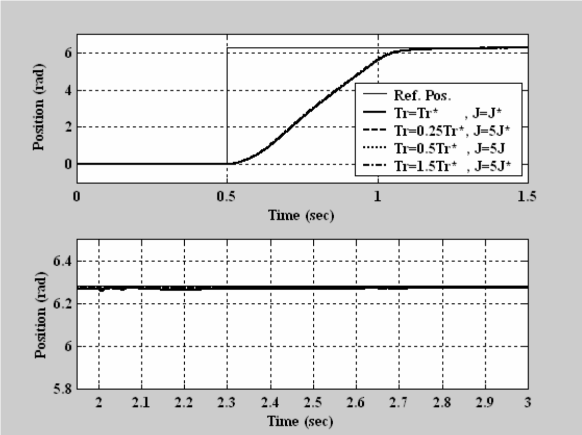

Fig. 10 The position tracking response and load regulation performance using PID-fuzzy position controller

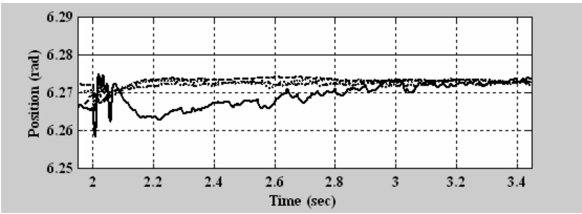

Fig. 11 Enlarge of the second view of Fig. 10.

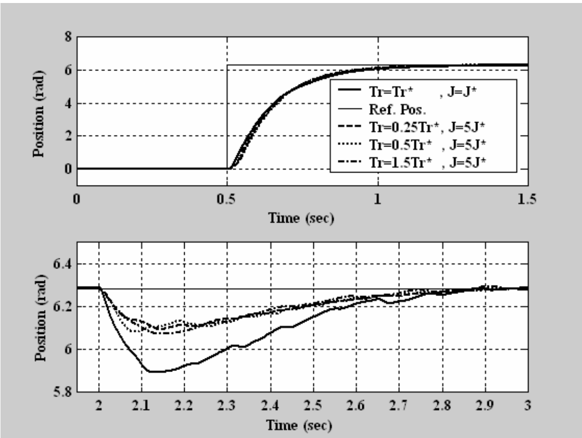

Fig. 12 The position tracking response and load regulation performance using PI-D 2DOFC position controller

9 Appendix

Table 3 shows the machine parameters measured by means of no-load and locked rotor tests.

Table 3 Machine parameters

Type: 3-phase induction motor, Y-connection, 1.5 kW, 4-poles, 380 V/3.8 A, 50 Hz
$R_s = 6.29\,\Omega, R_r = 3.59\,\Omega$,
$L_s = L_r = 480\,mH, L_m = 464\,mH$,
$J = 0.038$ kg.m^2 , $\beta = 0.008345$ N.m/rad/sec

References:

[1] Fayez F. M. El-Sousy, Faeka M.H. Khater and Farouk I. Ahmed, Analysis and Design of Indirect Field Orientation Control for Induction Machine Drive System, *Proceeding of the 38th SICE annual conference, SICE99*, Iwate, Japan, July 28-30, 1999, pp. 901-908.

[2] Fayez F. M. El-Sousy, Design and Implementation of 2DOF I-PD Controller for Indirect Field Orientation Control Induction Machine Drive System, *ISIE 2001 IEEE International Symposium on Industrial Electronics,* Pusan, Korea, June 12-16, 2001, pp. 1112-1118.

[3] Nordin K.B., Novotny D.W., and Zinger D. S., The influence of motor parameter deviations in feedforward field orientation drive systems, *IEEE Trans. Ind. Appl*., Vol. IA-21, No. 4, July/Aug. 1985., pp. 1009-1015

[4] Garces L. J., Parameter adaptation for the speed controlled static ac drive with a squirrel cage induction motor, *IEEE Trans. Ind. Appl.,* Vol. IA-16, No. 2, Mar./Apr. 1980, pp. 173-178.

[5] Matsuo T. and Lipo T.A, Rotor resistance identification in the field oriented control of a squirrel cage induction motor, *IEEE Trans. Ind. Appl.* Vol. IA-21, No. 3, May/July 1985, pp. 624-632.

[6] Fayez F. M. El-Sousy and M. M. Salem, Simple Neuro-Controllers for Field Oriented Induction Motor Servo Drive System, *The Korean Institute of Power Electronics (KIPE), Journal of Power Electronics (JPE)*, To appear in Jan. 2004.

[7] Leonid Reznik, *Fuzzy Controllers*, Biddles Ltd, Guildford and King's Lynn, England, 1997.

[8] Cheng F. and Yeh S., Application of fuzzy logic in the speed control of ac servo systems and an intelligent inverter, *IEEE Trans. Energy Conversion,* Vol-8, June 1993, pp. 312-318.

[9] Ying-Yu Tzou and Shiu-Yung Lin, Fuzzy-Tuning Current-Vector Control of a Three-Phase PWM Inverter for High-Performance AC Drives, *IEEE Trans. Ind. Elect*., Vol. IE-45, No. 5, October 1998, pp. 782-791.

[10] Fayez F. M. El-Sousy and Maged N. F. Nashed, Robust Fuzzy Logic Current and Speed Controllers for Field-Oriented Induction Motor Drive, *The Korean Institute of Power Electronics (KIPE), Journal of Power Electronics (JPE)*, April 2003, Vol. 3, No. 2, pp. 115-123.

[11] The Math Work Inc., *Matlab Simulink User Guide*, 1997.

[12] Ong. C. M., *Dynamic Simulation of Electric Machinery Using Matlab and Simulnik,* Printice Hall, 1998.