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Adaptive Vector Control of Induction Motor Drives

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Abstract: This study deals with the design and simulation of hybrid control systems combining conventional control techniques with fuzzy logic and Model Reference Adaptive Control (MRAC) system for Indirect Field-Oriented (IFO) induction motor drives. A performance comparison between the new controller and a conventional control scheme is carried out by extensive simulation confirming the superiority of proposed MRAC.While conventional control allows different design objectives such as steady state and transient characteristics of the closed loop system to be specified, fuzzy logic is integrated to overcome the problems with uncertainties in the plant parameters. Induction motors are characterized by complex, highly non-linear and time varying dynamics and inaccessibility of some states and outputs for measurements. The advent of vector control techniques has partially solved induction motor control problems, because they are sensitive to drive parameters variations such as the rotor time constant and an incorrect flux measurement or estimation at low speeds and performance may deteriorate if conventional controllers are used. Fuzzy logic based controller and model reference adaptive controller deal such variations more effectively.

Key words: Fuzzy logic, induction motor drive, model reference adaptive control

INTRODUCTION

Intelligent, self-learning or self-organizing controls using expert systems, fuzzy logic and neural networks have been recently recognized as important tools to enhance the performance of power electronics systems. The combination of intelligent control with adaptive and robust control appears today the most promising research accomplishment in the drive control area and, in the meantime, as the best approach for the optimal exploitation of intelligent control prerogatives and practical realization of adaptive and robust ac motor drives (Cerruto *et al*., 1992, 1993; Hong *et al*., 1992).

AC Motors, Particularly the Squirrel-Cage Induction Motor (SCIM), enjoy several inherent advantages like simplicity, reliability, low cost and virtually maintenance-free electrical drives. However, for high dynamic performance industrial applications, their control remains a challenging problem because they exhibit significant non-linearities and many of the parameters, mainly the rotor resistance, vary with the operating conditions (Mouloud and Ahmed, 2002). Scalar control is somewhat simple to implement, but the inherent coupling effect gives sluggish response and the system is easily prone to instability because of a high order system effect.

Strand regulators with fixed parameters may be insufficient in controlling systems, Such as the robotic arms, that are subjected to large variations of inertia and load during their normal operating cycles (Emanuele *et al*., 1997). A PI controller that continuously adapts its parameters from plant changes (like self-tuning regulators or adaptive controllers (Wellstead and Prager, 1985) is frequently computationally complex and presents slow response when is implemented using conventional microprocessors. To solve this problem, some recent authors propose fuzzy regulators with some kind of adaptation to the process (Rommeral *et al*., 1997). In those cases, more sophicated controllers are required such as adaptive regulators, which in presence of variations of the plant parameters are able to modify their features in order to maintain the desired dynamic behavior of the system. Moreover, a long and accurate tuning of the system can be avoided, as adaptive controllers are autotunning in nature (Landau, 1979).

Indirect vector control is applied extensively to a drive system for an SCIM high performance. The PI controller is used very much in an industrial application (Hong *et al*., 2005). But, PI controller had many problems in high performance because of an induction motor non-linearity. And the PI controller cannot get satisfactory high performance and robust control to the various parameter variations such as disturbance, speed and torque etc., To solve this problems, an adaptive control has been researched and an adaptive control was better than PI controller (Astrom and Wittenmark, 1989).

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The MRAC approach requires a reduced amount of computation compared to self-tuning and other adaptive control techniques and generally represents a good compromise between performances, complexity and cost.

Two control approaches are proposed and applied to adjust the speed of the drive system. The first design combines the speed controller design with the fuzzy logic concept. In the second approach the Model Referencing Adaptive Control (MRAC) approach is used. A simulation study of vector control is presented. The effectiveness of these controllers is demonstrated for different operating conditions of the drive system.

In the literature (Cerruto *et al*., 1992, 1993, 1995; Hong *et al*., 1992; Mouloud and Ahmed 2002; Emanuele*et al*., 1997; Wellstead and Prager, 1985; Rommeral *et al*., Landau, 1979; Hong-Gyun *et al*., 2005; Astrom and Wittenmark, 1989; Bimal, 2002). Comparison of the performance of Induction motor drive with adaptive and fuzzy controllers was not presented. In the present work, an attempt is made to compare the performance with fuzzy and adaptive controllers.

These controllers are evaluated under simulations for variety of operating conditions of the drive system and the results demonstrates the ability of the proposed control structure to improve the performance and robustness of the drive system.

INDUCTION MOTOR EQUATIONS

The *d-q* dynamic model of the SCIM with the reference frame fixed to the stator is given by

$$\frac{d}{dt}\begin{bmatrix} i^s{}_{ds} \\ i_{s\ qs} \\ i^s{}_{dr} \\ i^s{}_{qr} \end{bmatrix} = \frac{1}{L^2{}_\sigma}\left(\begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_r & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix}\begin{bmatrix} V^s{}_{ds} \\ V^s{}_{qs} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} -R_sL_r & \omega L^2{}_m & R_rL_m & \omega L_rL_m \\ -\omega L^2{}_m & -R_sL_r & -\omega L_rL_m & R_rL_m \\ R_sL_m & -\omega L_sL & -R_rL_m & -\omega L_sL_m \\ \omega L_sL_m & R_sL_m & \omega L_sL_m & -R_rL_s \end{bmatrix}\begin{bmatrix} i^s{}_{ds} \\ i^s{}_{qs} \\ i^s{}_{dr} \\ i^s{}_{qr} \end{bmatrix}\right) \tag{1}$$

Where

$$L_{\bullet} = (L_sL_r\text{-}L_m{}^2)^{\ 1/2}$$

The electromagnetic torque is found as

$$T_e = (2pL_m/3L_r)(i^s{}_{qs}\bullet{}^s{}_{dr}\text{-}i^s{}_{ds}\bullet{}^s{}_{qr}) \tag{2}$$

Where

$$\begin{aligned} \phi^s_{ds} &= Lr\ i^s_{dr} + Lmi^s_{ds}, \\ T_e &= (2pL_m/3L_r)(i^s{}_{qs}\phi^s{}_{dr}\text{-}i^s{}_{ds}\ \phi^s{}_{qr}) \end{aligned} \tag{3}$$

are the rotor flux components expressed in the stator reference frame.

The field orientation principle is based on the following conditions, which are expressed in the excitation reference frame:

$$\phi^e_{qr} = 0,\ \ \phi^e_{dr} = \text{constant} \tag{4}$$

Hence the equations ensuring the field orientation are expressed as

$$\begin{aligned} i^{e*}_{ds} &= \frac{1+Trs}{Lm}\phi^{e*}_{dr}, \\ i^{e*}_{ds} &= \frac{Te*}{K_T\phi^{e*}_{dr}} \end{aligned} \tag{5}$$

Where Tr = Lr/Rr is the rotor time constant.

Under these conditions, the induction machine is transferred into a linear current/torque converter:

$$Te = K_T\phi^{e*}_{dr}\ i^e_{qs} \tag{6}$$

Hence the rotor torque and flux may be controlled separately through i_{qs} and i_{ds} , respectively. The adequate torque reference Te* is generated from the speed error via the controller while the flux reference $\bullet_r^*$ is kept constant for each operating point.

SPEED CONTROLLER DESIGN

The overall block diagram of a current controlled PWM induction motor with indirect field orientation is given in Fig. 1. The indirect field-oriented control block receives the computed torque from the speed controller and the flux from the field-weakening block. The flux is assumed to be constant when the motor operates below the rated speed and beyond the rated speed the flux speed product is held constant.

The Field Oriented Control (FOC) block performs the slip calculation and generates $i_{qs}{}^{e*}$ and $I_{ds}{}^{e*}$. Inside the *qde* to the *abc transformation* block, the following transformations are performed :

$$\begin{aligned} i^{s^*}{}_{qs} &= i^{e^*}{}_{qs}\cos\theta_s + i^{e^*}{}_{ds}\sin\theta_s, \\ i^{s^*}{}_{ds} &= -i^{e^*}{}_{qs}\sin\theta_s + i^{e^*}{}_{ds}\cos\theta_s \end{aligned} \tag{7}$$

qde-abc transformation is

$$\begin{aligned} i^*{}_{as} &= i^{s^*}{}_{qs}, \\ i^*{}_{bs} &= -(1/2)i^{s^*}{}_{qs} - (\sqrt{3}/2)i^{s^*}{}_{ds}, \\ i^*{}_{cs} &= -(1/2)i^{s^*}{}_{qs} + (\sqrt{3}/2)i^{s^*}{}_{ds} \end{aligned} \tag{8}$$

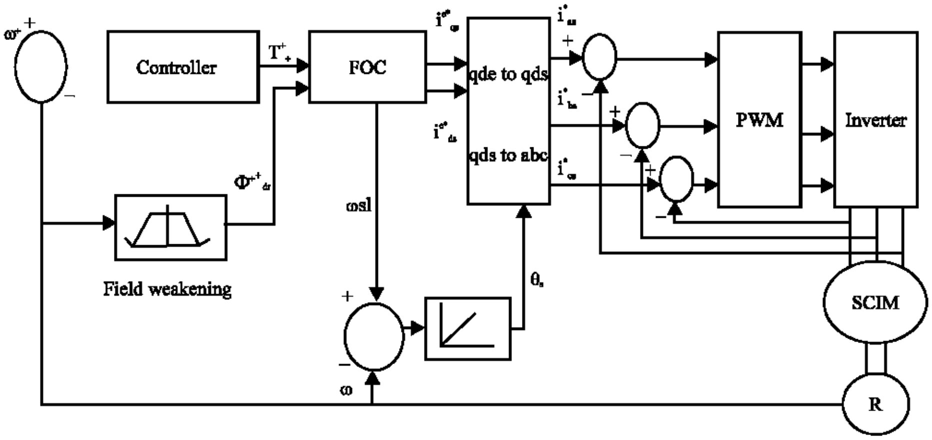

Fig 1: Speed control of the current controlled field-oriented induction motor

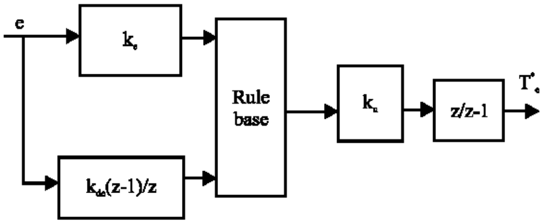

Fig. 2: Fuzzy PI controller structure

Here $\bullet_s$ represents the sum of slip and rotor angles.

A sinusoidal current source of variable magnitude and frequency is used to represent the fundamental component of the actual PWM inverter waveform. This avoids lengthy simulation times caused by the PWM switchings. Nevertheless, such a simulation study can still provide some understanding of the control strategies implementation, tuning and analysis.

FUZZY LOGIC CONTROLLER (FLC)

The structure of the basic fuzzy controller can be seen as a traditional PI controller, where the fuzzy control uses speed error, e and derivative speed error de as inputs and torque set value to torque controller as output
The FLC rules are based on

Ri: IF Ai AND Bi THEN Ci

The controller structure is Proportional- Integral (PI) and illustrated in Fig. 2.

Here Kp = k_uR (Kde) and Ki = K $\underset{u}{R}$ (Ke) are the controller proportional and integral gains and R(.) is defined by the controller rule base which is summarised in Table 1.

Table 1: FLC rule

de \ e	NB	NM	NS	Z	PS	PM	PB
NB	NVB	NVB	NB	NM	NS	NVS	Z
NM	NVB	NB	NM	NS	NVS	Z	PVS
NS	NB	NM	NS	NVS	Z	PVS	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
PS	NS	NVS	Z	PVS	PS	PM	PB
PM	NVS	Z	PVS	PS	PM	PB	PVB
PB	Z	PVS	PS	PM	PB	PVB	PVB

Input/output variables are then quantized with a suitable number of fuzzy sets. Simple belt-shaped membership functions have been selected for the input variables. Output variables are defined as singleton for the sake of simplicity and in order to speed up the defuzzfication procedure. The max-min interference method was used and the defuzzification procedure was based on the centre of area method.

DESIGN OF A CONVENTIONAL MRAC SPEED CONTROLLER

The MRAC approach regards the expected performance of the controlled system as the output of a specified mathematic reference model as shown in Fig. 3. The adaption procedure in an MARC system is performed into two phases. First, the actual output y of the process is compared with the output m_y of the reference model to obtain an error e; therefore, the parameters of the control law (k_1,k_2,.....k_n) are adjusted to reduce such an error according to a suitable algorithm.

Recent works (Bimal, 2002) have shown that by selecting MRAC for practical implementation of adaptive regulators in ac drive systems, a good compromise can be achieved between the two divergent needs of high

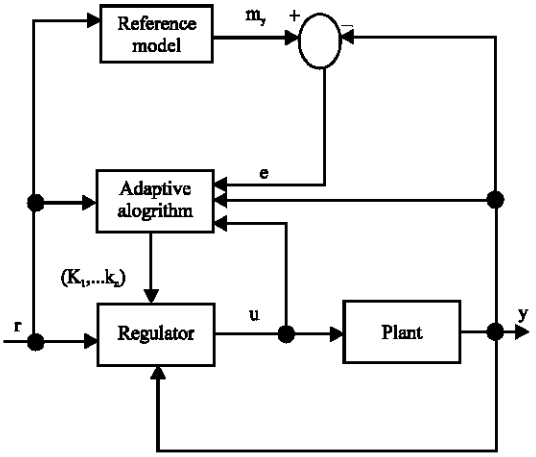

Fig. 3: Block schematic of an MRAC system

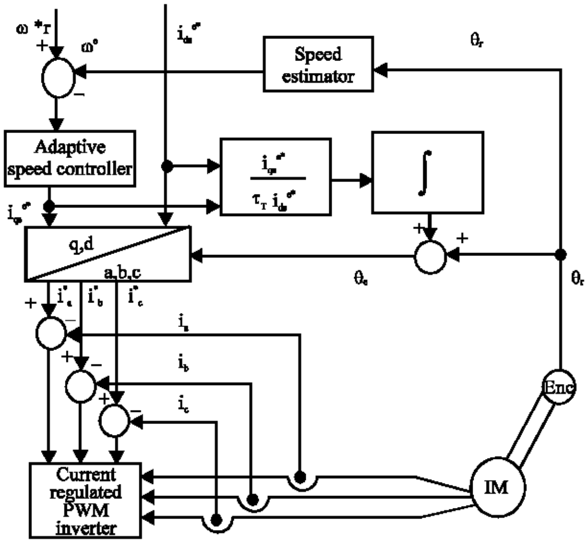

Fig. 4: Structure of an IFOC drive

performances and low computational weights. In fact, unlike other adaptive control techniques such as self tuning, an MRAC-based regulator does not require the exact knowledge of the system model nor its parameter estimation, but only a suitable reference model describing the expected dynamic.

The adaption algorithm is the core of the controller as it defines the variations of the regulator gains in order to reach the expected dynamic performance, while preserving the stability of the whole system.

The system presently considered, shown in Fig. 4, is an Indirect FOC (IFOC)-based induction motor drive, composed of a squirrel-cage induction motor and a Current-Regulated Pulse-Width Modulated (CRPWM) inverter. It can be described in a q-d reference frame by means of the following relations, where the superscript "e" denotes a rotor flux synchronous reference frame:

$$R_r\, i^e_{qr} + p\bullet^e_{qr} + \bullet_{sl}\bullet^e_{dr} = 0 \tag{9}$$

$$R_r i^e_{dr} + p\bullet^e_{dr} - \bullet_{sl}\bullet^e_{qr} = 0 \tag{10}$$

$$L_m i^e_{qs} + L_r i^e_{qr} = \bullet^e_{qr} \tag{11}$$

$$L_m\, i^e_{ds} + L_r i^e_{dr} = \bullet^e_{dr} \tag{12}$$

$$3/2\ pp\ L_m/L_r\,(\bullet^e_{dr} i^e_{qs} - \bullet^e_{qr}\, i^e_{ds}) = T_e \tag{13}$$

$$1/J\,(T_e - T_1) - (F/J)\bullet_r = p\bullet_r \tag{14}$$

It can be easily deducted from such expressions that, for a fixed stator current vector, a slip-pulsation value only exists that makes $\bullet^e_{dr}$ constant and $\bullet^e_{qr} = 0$, so allowing the field orientation.. Such slip pulsation is

$$\bullet_{sl} = (1/T_r)\,(I^e_{qs}/i^e_{ds}) = K_{sl} i^e_{qs} \tag{15}$$

Under the hypothesis of a perfect field orientation, the motor torque T_e is proportional to the amplitude of the component i^e_{qs} of the stator current by the torque constant K_T

$$K_T = 3/2\ pp(L_m/L_r)\bullet^e_{dr} \tag{16}$$

In such a case, the time-discrete mechanical model of the system, assuming constant or slowly changing friction, total inertia and load torque is given by the following equation:

$$\omega_r(k+1) = \left[1 - \frac{TsF}{J}\right]\omega_r(k) - \left(\frac{Ts}{J}\right)T_1 + \left[\frac{TsKt}{J}\right] i^e_{qs}(k) \tag{17}$$

A simple first-order difference equation can be used as the reference model for the MRAC algorithm

$$\bullet_{rm}(k+1) = n\bullet_m(k) + mr\,(k) \tag{18}$$

By rearranging (17) and (18), the following control law can be established:

$$I_{qs}^{e}(k) = K_1(k)\, a_m(k) + K_2(k)\bullet_r(k) + K_3(k) + K_e\, e\,(k) \tag{19}$$

Where $e(k) = w_m(k) - w_r(k)$

According to the conventional design approach based on the hyperstability theory, the convergence to zero of the speed error is ensured by adopting the following equations for K_1, K_2 and K_3:

$$K_1(t) = \alpha_1 \int_0^t a_m\ e\ dt + \beta_1\ a_m\ e \qquad (20)$$

$$K_2(t) = \alpha_2 \int_0^t \omega_r\ e\ dt + \beta_2\ \omega_r\ e \qquad (21)$$

$$K_3(t) = \alpha_3 \int_0^t e\ dt + \beta_3\ e \qquad (22)$$

The parameters • $_i$ and • $_i$ appearing in such adapting laws must be suitably chosen as constants in order to obtain a fast convergence to zero of the speed error without instabilities. This is a difficult task to be performed experimentally. Moreover, only a slow adapting process can guarantee the stability of the system in all operating conditions in presence of noises and unpredicted dynamics.

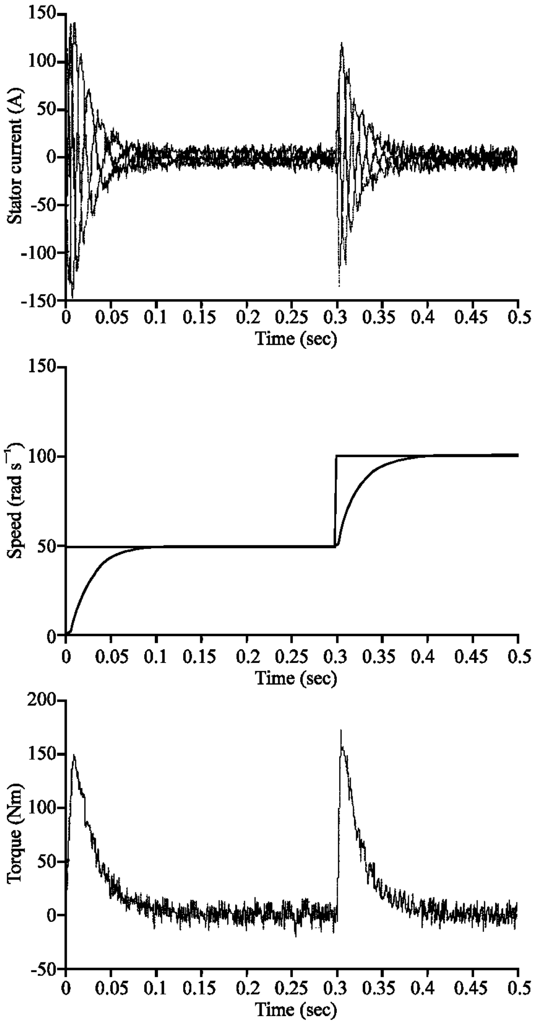

Fig. 5: Output of FOC drive with PI controller with step speed command

PERFORMANCE EVALUATION

PI controller: The performances of the proposed controllers are evaluated separately under a variety of operating conditions.

Figure 5 the speed response of the motor is shown for the step speed reference command. The figure shows the speed of the drive system with the change in reference speed. The basic speed is 50 rad s•^{1}. The steady state value reaches at 0.25 sec and the starting torque is high. The speed is increased to 100 rad s•^{1} at 0.3 sec. The Fig. 5 shows the ability of the system to reach the steady state quickly compared to conventional scalar controller. From Fig. 5 it can be seen that response is better but the oscillations are high.

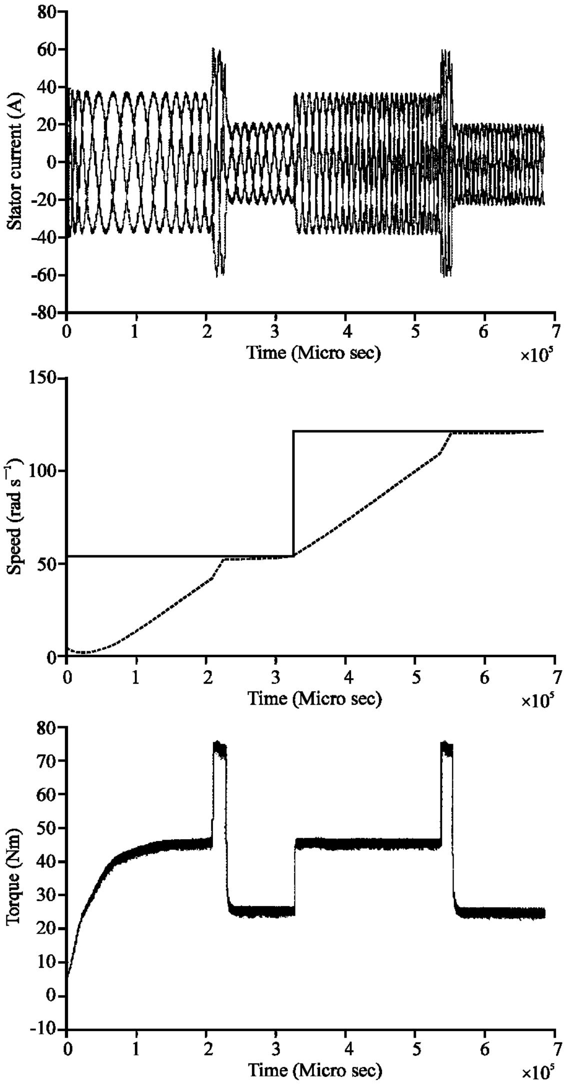

Fig. 6: Output of a FOC drive with fuzzy logic based speed controller at 25 Nm load

FUZZY LOGIC CONTROLLER (FLC)

Figure 6 shows the performance with fuzzy logic controller with a load torque of 25 Nm .The initial load and step speed command is shown in Fig. 6. The performance of the controller is similar to that of PI controller, but the starting torque is minimized to 50 Nm. Thus the fuzzy logic controller improves the robustness of the system. At the time of reaching the steady state condition, the torque reaches a value of 70 Nm only. So the highest value of the torque is only 70 Nm for the entire of operation.

Figure 7 shows the performance of the controller when the load torque is 50 Nm. The starting torque is increased to 80 Nm from 40 Nm.

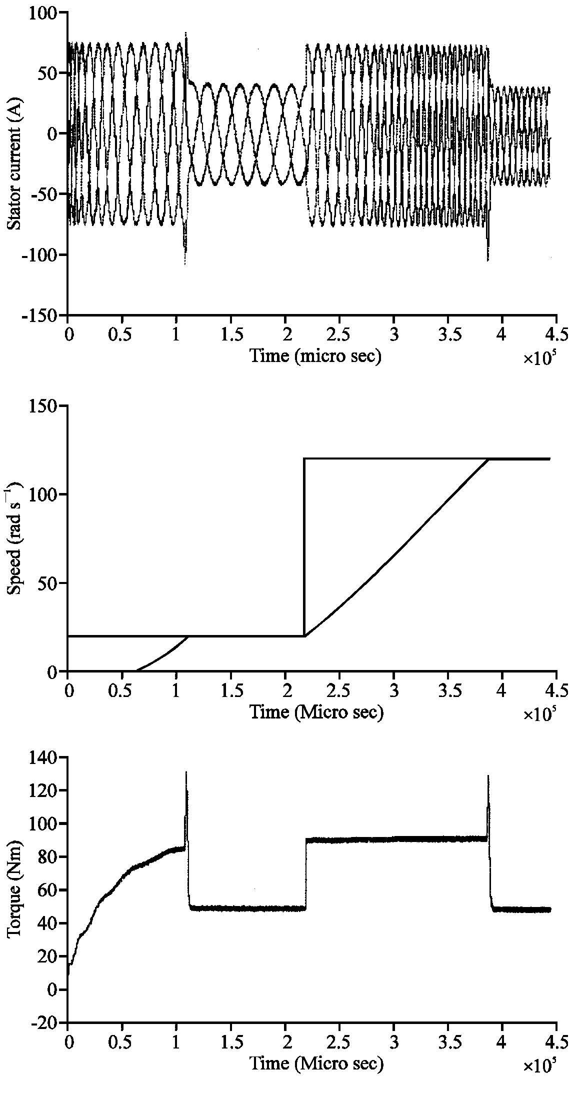

Fig. 7: Output of the FOC drive with fuzzy logic based speed controller at 50 Nm load

MODEL REFERENCE ADAPTIVE CONTROLLER (MRAC)

Figure 8 shows the response of the FOC drive with model reference adaptive controller based speed controller. The speed command is given as the reference and the step load torque is given to the motor to check the response of the system with the immediate load torque. The response of the system is same as the fuzzy logic controller when the step speed command is given as the reference speed. The load torque is stepped to 20 Nm at 0.5 sec as shown in Fig. 8.The response of the system is very good and the speed is not affected by the variation of load, when the torque is stepped down at 0.65 sec and the speed is not affected. Finally, the torque

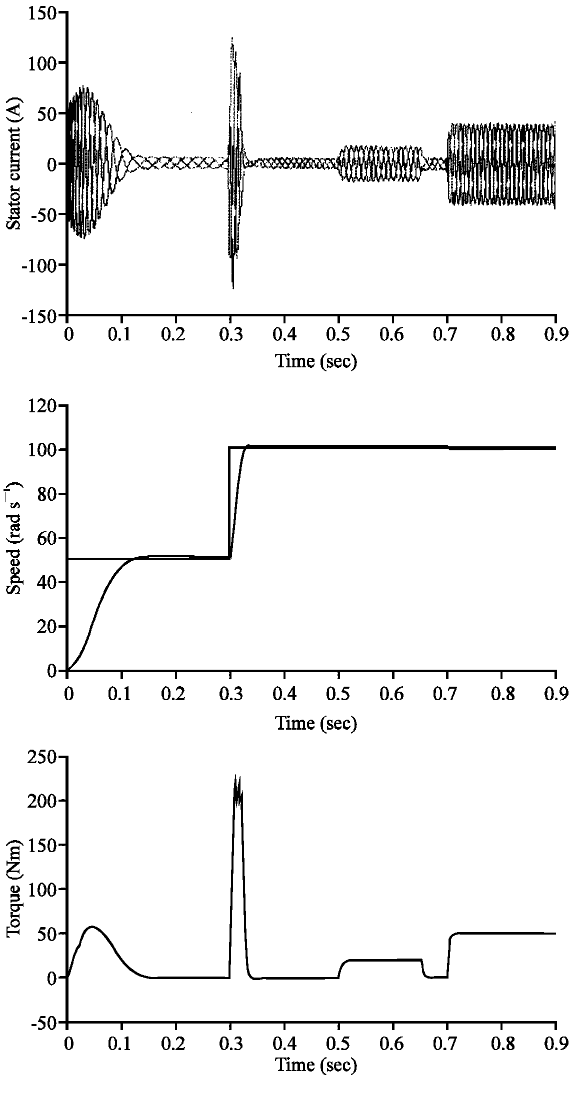

Fig. 8: Output of FOC drive with model reference adaptive controller

reaches 50 Nm at 0.7 sec. The speed increases to the reference speed at 0.1 sec. From Fig. 8, the response of the MRAC system is calculated. The conclusion from the Figure is, that the response of the given system is similar to the normal PI controller system. For the step load torque command the response of the given system is good compared to the conventional PI controller and the fuzzy logic controller. The speed reaches the steady state with in 0.1 sec.

CONCLUSION

The closed loop controlled Induction motor drive system is simulated using Matlab and results are presented. Vector control technique is used to improve the dynamic performance of induction motor drives. By using the Indirect Vector Control Method, Steady state response of the given system could be achieved nearly at 0.25 sec, which is quicker than scalar control techniques.

In this method the percentage error of speed is 0.1% which is comparable to DC motor drives and by incorporating fuzzy logic approach. By using adaptive controller the response of the controller of the system was improved. Steady state response of the given system is achieved with in 0.2 sec, which is quicker than conventional PI controllers .The speed reached the steady state condition with in 0.1 sec when the load torque is increased to 50 Nm .From the simulation results, it is observed that adaptive controller was better than fuzzy controller.

REFERENCES

Astrom, K.J. and B.Wittenmark, 1989. Adaptive control, Addison-Wesley.

Bimal, K. Bose, 2002. Modern Power Electronics and AC Drives, Pearson Education Asia, pp: 356-384.

Cerruto, E., A. Consoli, A. Raciti and A. Testa, 1992. Adaptive fuzzy control of high performance motion systems, In: Proc.IEEE. IECON. Conf. Rec., San Diego, CA, pp: 88-94.

Cerruto, E., A. Consoli, A. Raciti and A. Testa, 1995. A simple and robust adaptive controller for PM motor robotic drives, IEEE. Trans. Power Elec., 10: 62-71.

Cerruto, E., A. Consoli, P. Kucer and A. Testa, 1993. A fuzzy logic quasi sliding-mode controlled motor drive, In: Proc. IEEE. ISTE. Conf. Rec. Budapest, Hungary, pp: 652-657.

Emanuele Cerruto, Alfio Consoli, Angelo Raciti and Antonio Testa, 1997. Fuzzy adaptive vector control of induction motor drives, IEEE. Trans. Power Elec., pp: 1028-1040.

Hong, H., S. Park, S. Han, K. Cho, Y. Lim, J. Park and T. Kim, 1992. A design of auto-tuning PID controller using fuzzy logic, Iin Proc. IEEE. IECON. Conf. Rec., San Diego, CA, pp: 971-976.

Hong-Gyun Lee, Jung-Chul Lee, Su-Myeong Nam, Jung_Sik Choi, Jae-Sub Ko and Dong-Hwa Chung, 2005. The speed control and estimation of IPMSM using Adaptive FNN and ANN, ICCAS KINTEX, Gyeonggi-Do, Korea.

Landau, Y.D., 1979. Adaptive control: The Model Reference Approach. New York: Marcel Dekker.

Mouloud Azzedine Denai and Sid Ahmed Attia, 2002. Fuzzy and neural control of an induction motor, Int. J. Applied Math. Comput. Sci., pp: 221-233.

Rommeral, L., J. Llaquet, E. Aldabas and A. Arias, A simple fuzzy adaptive speed controller. Indus. Applications Conf. Rec. IEEE., pp:1249-1256.

Wellstead, P.E. and D.L. Prager, 1985. Self-Tuning Multivariable Regulators, In: Self-Tuning and Adaptive Control: Theory and Applications. C.J. Harris and S.A. Billing (Eds.), IEEE Control Engineering Serie 15. Peter Peregrinus Ltd. London.