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Fuzzy Adaptive Neural-Network Model-Following Speed Control for PMSM Drives

FAYEZ F. M. EL-SOUSY MAGED N. F. NASHED
Power Electronics & Energy Conversion Department
Electronics Research Institute (ERI)
Al-Tahrir Street, Dokki, Cairo, Egypt
EGYPT

Abstract:- In this paper, a fuzzy adaptive neural-network model-following speed controller for permanent-magnet synchronous motor (PMSM) drives is proposed. The fuzzy neural-network model-following controller (FNNMFC) consist of a proportional plus integral (PI) like-fuzzy controller in addition to an on-line trained neural-network model-following controller (NNMFC). This controller, FNNMFC, combines the merits of the fuzzy logic control (FLC) and the neural-network model-following control (NNMFC) for PMSM drive. The weights of the NNMFC are trained on-line to realize high dynamic performance in disturbance rejection and tracking characteristics. According to the model-following error between the outputs of the reference model and the PMSM drive system, the NNMFC generates an adaptive control signal which is added to the fuzzy speed controller output to attain robust model-following characteristics under different operating conditions regardless of parameter variations and load disturbances. A computer simulation is developed to demonstrate the effectiveness of the proposed FNNMF speed controller. The results confirm that the proposed FNNMF speed controller produces rapid, robust performance and accurate response to the reference model regardless of load disturbances or PMSM parameter variations.

Key-Words: PMSM, Vector Control, Fuzzy Logic, Neural Network (NN), Model Following Controller (MFC).

1 Introduction

In recent years, advancements in magnetic materials, semiconductor power devices and control theories have made the permanent–magnet synchronous motor (PMSM) drives play a vitally important role in motion-control applications. PMSMs are widely used in high-performance applications such as industrial robots and machine tools because of its compact size, high-power density, high air-gap flux density, high-torque/inertia ratio, high torque capability, high efficiency and free maintenance. Utilizing the vector control technique and by keeping *d*-axis current, $i_{ds}^{r}=0$, the PMSM torque may vary linearly with the *q*-axis current component, i_{qs}^{r}, and the maximum torque per ampere is achieved which is similar to the control of separately excited DC motor [1-3]. Several control techniques in many researches have been developed to improve the performance of the PMSM drives and to deal with the nonlinearities and uncertainties of the dynamic model of the PMSM using fuzzy logic, neural network and/or the hybrid of fuzzy logic and neural network [5-7].

In the previous work [3], the vector control transfer functions of the PMSM and the *d*-*q* axes synchronous PI current controllers has been designed to achieve the time domain specifications of the current control loops.

The aim of this paper is to design a proposed fuzzy adaptive neural-network model-following speed controller for PMSM drive system. The FNNMFC consists of PI-like fuzzy controller in addition to an on-line trained neural-network model-following controller (NNMFC) to improve the dynamic performance of the drive system. The output of the NNMFC is added to the fuzzy controller output to compensate the error between the reference model and the PMSM drive system output under parameter variations and load disturbances. The dynamic performance of the PMSM servo drive system has been studied under load changes and parameter variations. The simulation results are given to demonstrate the effectiveness of the proposed controllers.

2 Mathematical Model of the PMSM

The mathematical modeling of the PMSM in the synchronously rotating rotor reference frames can be derived as follows [1-2]. The stator voltage equations in the d^r-q^r synchronously rotating rotor reference frame can be carried out as follows:

$$V_{qs}^r = R_s i_{qs}^r + L_{ss}\frac{d}{dt} i_{qs}^r + \omega_r L_{ss} i_{ds}^r + \omega_r \lambda_m^{'}$$
$$V_{ds}^r = R_s i_{ds}^r + L_{ss}\frac{d}{dt} i_{ds}^r - \omega_r L_{ss} i_{qs}^r \quad (1)$$

The electromagnetic torque can be expressed as:

$$T_e = \frac{3}{2}.\frac{P}{2}.\lambda_m i_{qs}^r \quad (2)$$

$$T_e = J_m\left(\frac{2}{P}\right)\frac{d}{dt}\omega_r + \beta_m\left(\frac{2}{P}\right)\omega_r + T_L \quad (3)$$

where V_{qs}, V_{ds}, i_{qs} and i_{ds} are the stator voltages and currents respectively. R_s and L_{ss} are the resistance and self inductance of the stator. ω_r, J_m , β_m and P are the rotor position, electrical rotor speed, effective inertia, friction coefficient and the number of poles. T_e, T_L, and λ_m are the electromagnetic torque, the load torque and the flux linkage of the motor respectively. The PMSM parameters are: three-phase, 1 hp, 4 poles, 208 V, 60 Hz, 1800 rpm, voltage constant: 0.314 V.s/rad, R_s=1.5 Ω, L_{ss}=0.05 H, J_m=0.003 kg.m^2, and β_m=0.0009 N.m/rad/sec.

3 Problem Formulations

The system configuration of the proposed speed control for a FOC PMSM drive system is illustrated in Fig. 1. It basically consists of a PI current controllers in *d*-*q*-axes and a PI fuzzy controller and a neural-network model-following controller. A reference model is derived from the closed loop transfer function of the PMSM drive system. Although the desired tracking and regulation speed control can be obtained using the PI fuzzy speed controller with the nominal PMSM parameters, the performance of the drive system still sensitive to parameter variations. To solve this problem, a hybrid speed controller combining the PI fuzzy speed controller and the neural-network model-following controller (NNMFC) is proposed. The control law is designed as:

$$i_{qs}^{rc} = i_{qs}^{r*} + \delta i_{qs}^{r*} \quad (4)$$

where i_{qs}^{r*} the *q*-axis current command generated from the PI fuzzy speed controller and δi_{qs}^{r*} is the adaptive control signal generated by the proposed NNMFC to automatically compensate the performance degradation. The inputs to the proposed NNMFC are the error signal, e_{ω}^{mf} , and the derivative of the rotor speed, ω_r , that are used to train the weights of neural-network controller on-line.

$$e_{\omega}^{mf} = (\omega_r^{mf} - \omega_r)$$
$$\dot{\omega}_r = k_{\omega} d\omega_r / dt \quad (5)$$

where ω_r^{mf} is the output of the reference model while ω_r is the rotor speed of the PMSM.

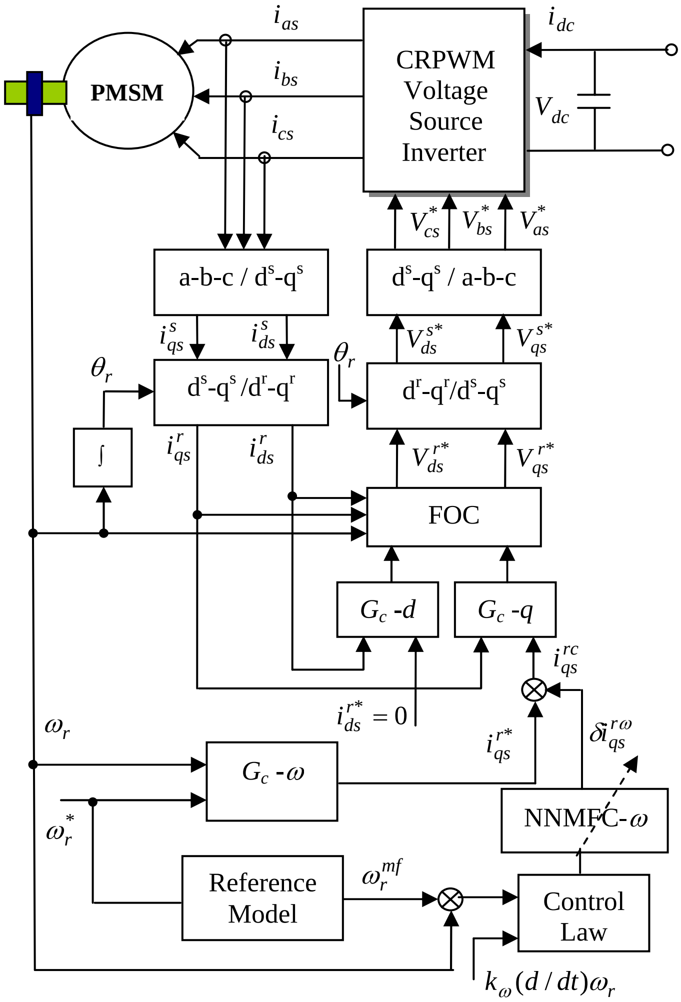

Fig. 1 The block schematic diagram of a field oriented PMSM drive system

4 Proposed Fuzzy Neural-Network Model-Following Speed Controller

4.1 PI-Fuzzy Speed Controller

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, $\Delta i_{qs}^{r*}(k)$.

$$u_{\omega}(k) = i_{qs}^{r*}(k) = \int \Delta i_{qs}^{r*}(k) = f(e_{\omega}(k), \Delta e_{\omega}(k)) \quad (6)$$

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 are selected and can be varied to tune the output of the fuzzy controller for the desired speed response. The output gain, can also be tuned for the same purpose. Fig. 2 illustrates the membership functions $e_\omega(k)$, $\Delta e_\omega(k)$ and δi_{qs}^{r*} 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.

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

Table 1 The linguistic rules base

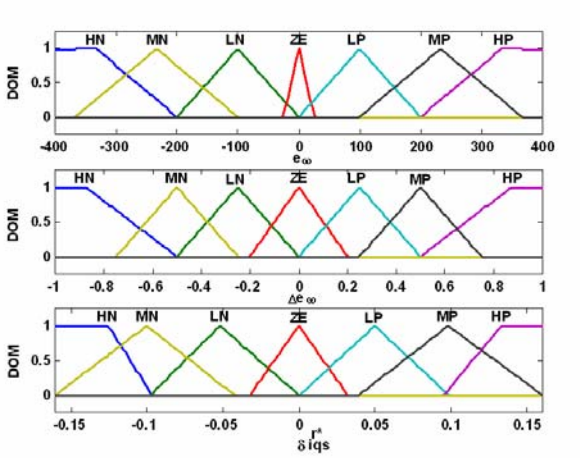

Fig. 2 Member ship function of PI-fuzzy speed controller

4.2 Neural-Network Model-Following Speed Controller

The inputs to the NNMFC are the error e_ω^{mf} and $k_\omega(d/dt)\omega_r$ while the output is the observed compensation signal δi_{qs}^{r*}. The error between the reference model and the output speed of PMSM is used to train the weights and biases of the neural-controller to provide a good model-following response. The weights and biases are adjusted on-line to produce the required compensation signal. Utilizing this adaptive control signal will make the drive system to follow the reference model. The NNMFC comprises a three layers neural-network as shown in Fig. 3. The input layer (i^{th}), the hidden layer (j^{th}) and the output layer (k^{th}). The back propagation training algorithm uses a recursive algorithm starting at the output units and working back to the hidden layer to adjust the neural weights. The desired speed ω_r^{mf} is obtained from the reference model, thus the energy error function is defined as follows:

$$E_\omega = \frac{1}{2}\sum_N[\omega_r^{mf}(N) - \omega_r(N)]^2 = \frac{1}{2}\sum_N e_\omega^2(N) \qquad (7)$$

where $\omega_r^{mf}(N)$ and $\omega_r(N)$ are the outputs of the reference model and PMSM drive system at the Nth – iteration. Within each interval from N-1 to N, the back propagation algorithm is used to update the weights of the hidden and output layers in NNMFC according to the following equations:

$$W_{ji}(N+1) = W_{ji}(N) - \varepsilon\frac{\partial E_\omega}{\partial W_{ji}(N)} + \gamma\Delta W_{ji}(N-1) \qquad (8)$$

$$W_{kj}(N+1) = W_{kj}(N) - \varepsilon\frac{\partial E_\omega}{\partial W_{kj}(N)} + \gamma\Delta W_{kj}(N-1) \qquad (9)$$

To increases the on-line learning rate of the weights, a control law is proposed as follows.

$$\frac{\partial E_\omega}{\partial y_k} = e_\omega^{mf} - k_\omega(d/dt)\omega_r \qquad (10)$$

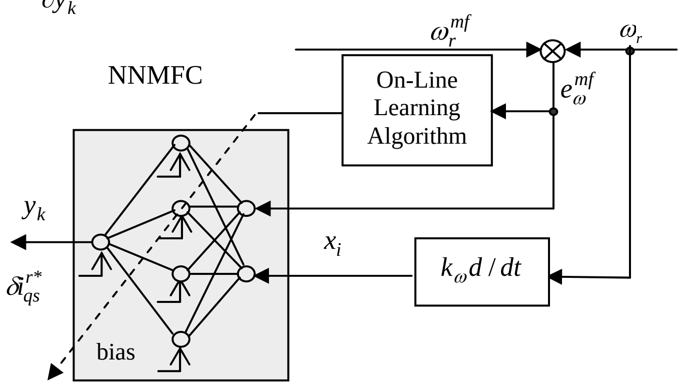

Fig. 3 The proposed NNMF speed controller

5 Simulation Results

The simulations results of the PMSM drive systems are presented to verify the feasibility of the proposed control scheme under various operating conditions. The dynamic performance of the drive system due to step speed command of 377 rad/sec under no-load and load of 3.6 N.m is predicted as illustrated in Figs. 4-7. The disturbance rejection capabilities have been checked when a load of 3.6 N.m is applied to the shaft at *t* = 1 *s* and removed after a period of 2 *s*. The simulation results of the proposed PI fuzzy and FNNMF speed controllers are shown in Fig. 4 that includes the command and actual responses for speed, *d-q* axes stator currents in the rotating and stationary reference frames for both speed controllers. These Figures clearly illustrate good dynamic performances in command tracking and load regulation performance are realized for both controllers. Improvement of the control performance by addition the proposed FNNMF speed controller can be observed from the obtained results in command tracking and load regulation characteristics as illustrated in Fig. 6-b. It is clear from this Figure that the proposed FNNMF speed controller provides a rapid and accurate response for the reference model within 0.3 s. Also, the proposed controller quickly returns the speed to the reference under full load with a maximum dip of 12 rad/sec. The robustness of the proposed F NNMF approach against large variations of PMSM parameters and external load disturbances has been simulated for demonstration. The speed response and the load regulation performance of the drive system with the PI fuzzy and FNNMF speed controllers are shown in Figs. 5-7 under the three cases of PMSM parameter variations. The control performance by addition the proposed FNNMF speed controller is robust in command tracking and load regulation characteristics as illustrated in Fig. 8. Also, the proposed FNNMF speed controller attains a rapid and accurate response for the reference model within 0.3 s and quickly returns the speed to the reference under full load with a maximum dip of 12 rad/sec under parameter variations. The results shown in Figs. 5-6 clearly indicate that as the variations of the PMSM parameters occurred, the responses deviate significantly from that nominal case with PI fuzzy speed controller but the FNNMF speed controller confirms the correct operation and slightly influenced by parameter variations. It is evident that from Fig. 7 an obvious model-following error (MFE) due to the PI fuzzy speed controller reaches to 125 rad/sec while the MFE due to FNNMF speed controller is about ±5 rad/sec. Also, good model-following tracking responses at all cases of parameters variations are observed from these results, and the resulting regulation performances are also much better, in both speed dip and recovery time, than those obtained by the PI fuzzy speed controller.

6 Conclusions

This paper proposes a robust hybrid FNNMF speed controller for PMSM drive system under FOC which guarantees the robustness in the presence of parameter variations. The design procedures for the PI fuzzy and FNNMF speed controllers have been successfully designed according to the given command tracking and disturbance rejection specifications of the drive system. The performance of the drive system is still sensitive to parameter variations using the PI fuzzy speed controller. To solve this problem, a FNNMFC with on-line learning was designed and added to the PI fuzzy speed controller to preserve the good model-following characteristics under the conditions of parameter variations and external disturbances. The NNMFC provides an adaptive feed-back control signal based on the error between the reference model and the output speed of PMSM. This error was used to train the weights and biases of the NNMFC to provide a good model-following response. So, the rotor speed tracking response can be controlled to closely follow the response of the reference model under a wide range of operating conditions. Simulation results have shown that the proposed FNNMF speed controller grant accurate tracking and regulation characteristics in the presence of PMSM parameter variations and external load disturbance. Also, a robust model-following tracking response is obtained utilizing the FNNMF speed controller.

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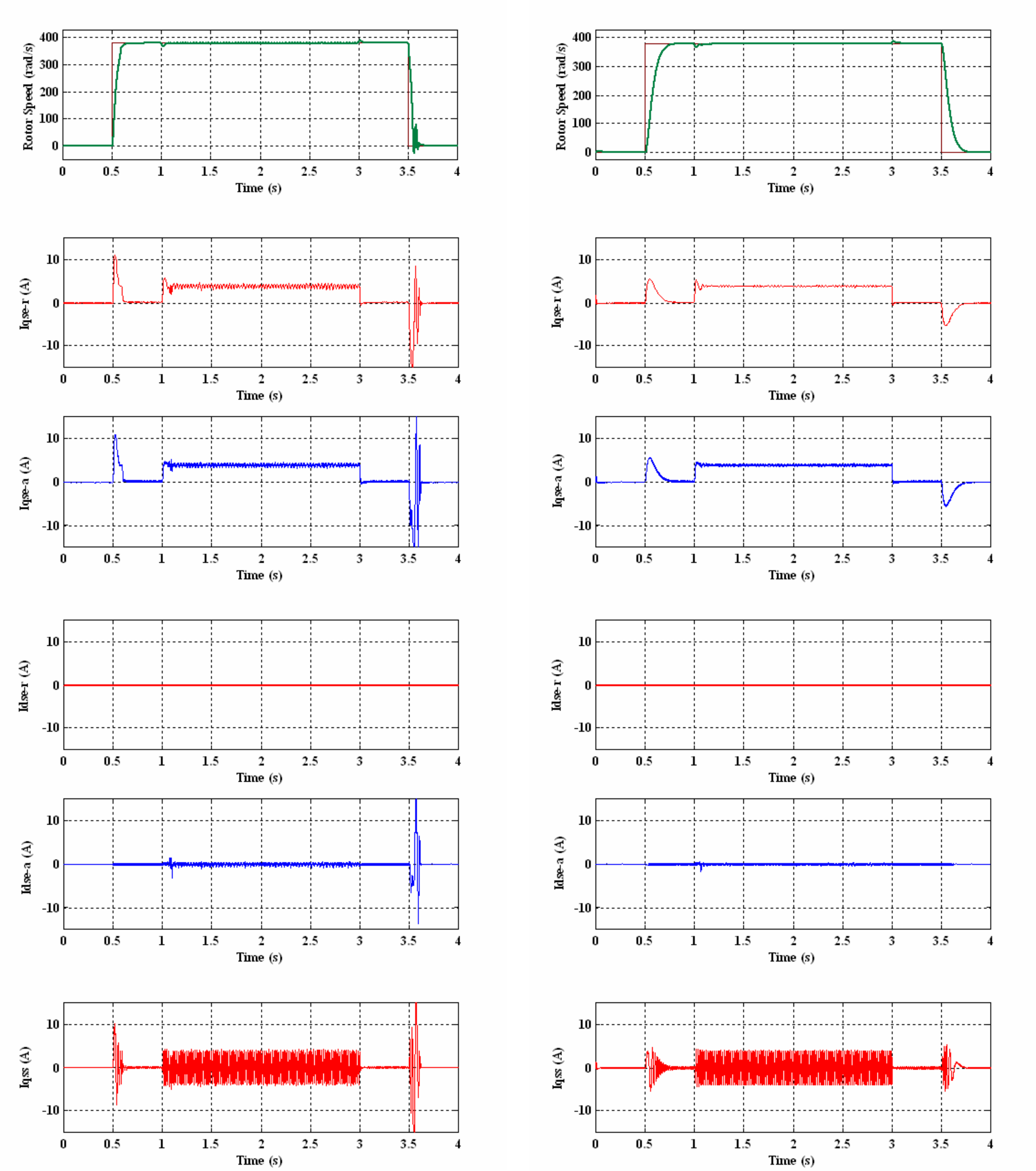
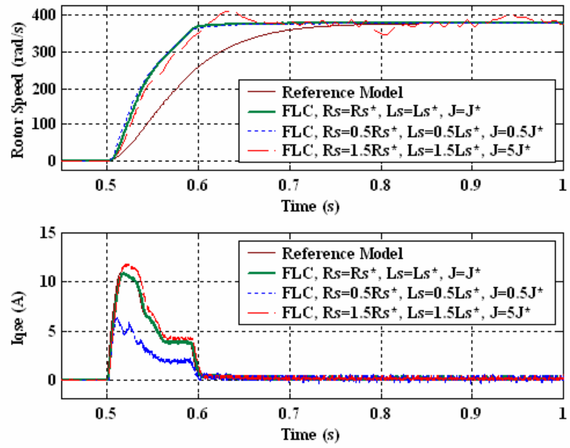


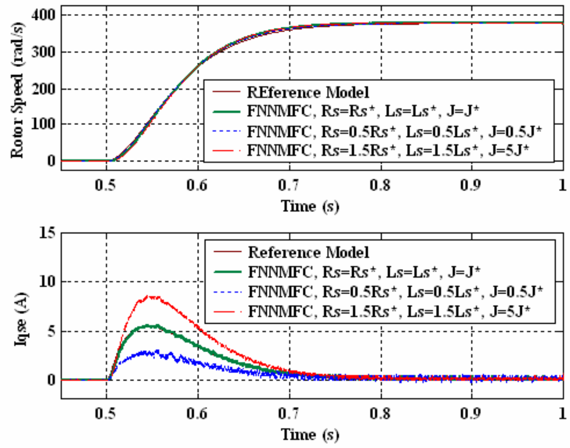
(a) Using PI fuzzy speed controller

(b) Using FNNMF speed controller

Fig. 4 Step speed response for a reference speed of 377 rad/sec and loading of 3.6 N.m

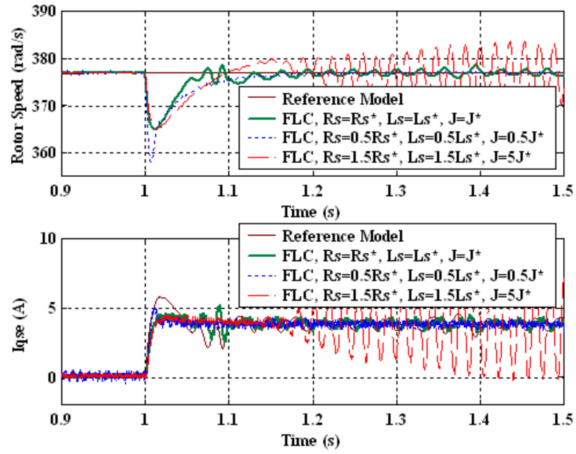


(a) The tracking speed and current responses with FLC

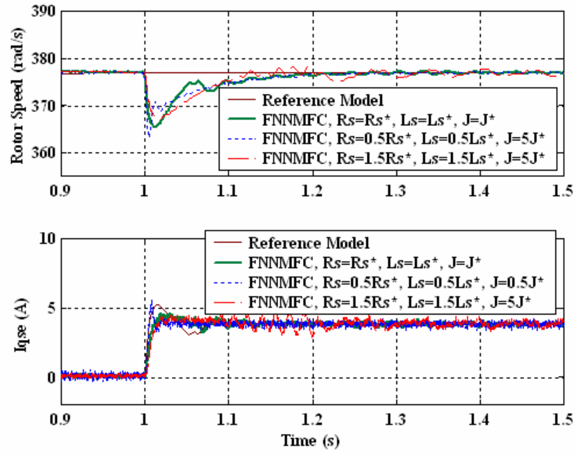


(b) The tracking speed and current responses with FNNMFC

Fig. 5. The speed model following response of the drive system under parameter variations using PI fuzzy and FNNMF speed controllers

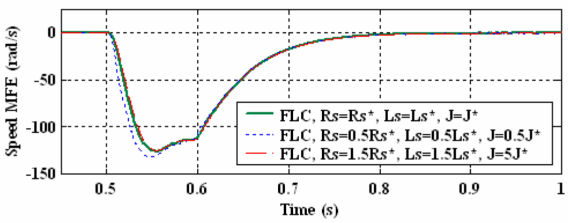


(a) The load regulation performance with FLC

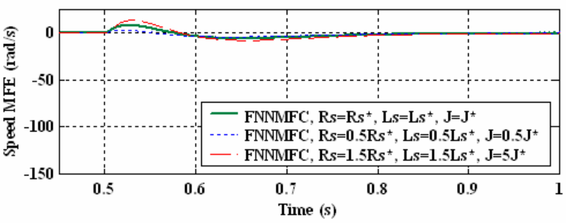


(b) The load regulation performance with FNNMFC

Fig.6. The load regulation performance of the drive system under parameter variations using PI fuzzy and FNNMF speed controllers



(a) Using PI fuzzy speed controller



(b) Using FNNMF speed controller

Fig. 7. The model-following errors (MFE) of speed response using PI fuzzy and FNNMF speed controllers under parameter variations