Proceedings of the 6th WSEAS Int. Conf. on NEURAL NETWORKS, Lisbon, Portugal, June 16-18, 2005 (pp230-238)

Intelligent Model-Following Position Control for PMSM Servo Drives

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

Abstract:- In this paper, an intelligent robust position controller for permanent-magnet synchronous motor (PMSM) servo drives is proposed. The intelligent robust position controller consists of a two-degrees-of-freedom integral plus proportional & rate feedback (2DOF I-PD) controller in addition to an on-line trained neural-network model-following controller (NNMFC). This controller, 2DOF I-PD NNMFC, combines the merits of the 2DOF I-PD controller and the NNMF controller for PMSM servo drives position control. A systematic mathematical procedure is derived to find the parameters of the 2DOF I-PD position controller according to the required specifications for the PMSM servo drive system. Then, the resulting closed loop transfer function of the servo drive system including the current control, speed control and position control loops is used as the reference model. In addition to the 2DOF I-PD position controller, a neural-network model-following controller whose weights are trained on-line is designed 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 servo drive system, the NNMFC generates two adaptive control signal which are added to the 2DOF I-PD 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 2DOF I-PD NNMF position controller. The results confirm that the proposed 2DOF I-PD NNMF position controller produces robust performance, rapid and accurate response to the reference model regardless of load disturbances or PMSM parameter variations.

Key-Words: PMSM Servo Drives, Vector Control, 2DOF I-PD Controller, 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 servo 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. When compared with an induction motor servo drive, the PMSM has many advantages. For instance, it has higher efficiency, resulting from the absence of rotor losses and lower no-load current below the rated speed. Utilizing the vector control technique simplifies the dynamic model of the PMSM and control scheme. Also, the vector control technique is employed in order to obtain high torque capability of the PMSM drive through the decoupling control of *d-q* axes stator currents in the rotor reference frame. For a PMSM, the PM provides the flux linkage, λ_m.

By keeping *d*-axis current, $i^r_{ds} = 0$, the PMSM torque may vary linearly with the *q*-axis current component, i^r_{qs}, and the maximum torque per ampere is achieved which is similar to the control of separately excited DC motor [1-4].

Several control techniques in many researches have been developed to improve the performance of the PMSM servo 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 them. It is well known that the neural networks need to be trained and its training is time consuming. High convergence accuracy and high convergence rate are desirable for the training of the neural network. The most popular training algorithm for a multi-layer neural network is the back propagation [5-12].

In the previous work [13], the field oriented control transfer functions of the PMSM has been derived from the dynamic model at the synchronously rotating rotor reference frame with nominal parameters. On the basis of these transfer functions, the *d-q* axes synchronous PI current controllers has been designed to achieve the time domain specifications of the current control loops. Also, the 2DOF I-PD speed controller has been designed to accomplish specifications of the speed control loop. In addition to the 2DOF I-PD speed controller, a neural-network model-following speed controller has been designed to produce a good model following speed response. The proposed PMSM servo drive system is shown in Fig. 1.

The aim of this paper is to design a proposed intelligent position controller for PMSM servo drive system. The proposed controller consists of a 2DOF I-PD servo controller and a neural-network model-following controller (NNMFC). A proposed on-line trained NNMF position controller is designed in addition to the 2DOF I-PD position controller to improve the dynamic performance of the servo drive system. The output of the NNMF position controller is added to the 2DOF I-PD speed controller output to compensate the error between the reference model and the PMSM servo 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.

The PMSM parameters are: 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, β_m=0.0009 N.m/rad/sec

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, 13]. The stator voltage equations in the d^r-q^r synchronously rotating rotor reference frame can be carried out as follows:

$$\begin{aligned} V_{qs}^r &= R_s i_{qs}^r + L_{ss}\frac{d}{dt} i_{qs}^r + \omega_r L_{ss} i_{ds}^r + \omega_r \lambda_m^{'} \\ V_{ds}^r &= R_s i_{ds}^r + L_{ss}\frac{d}{dt} i_{ds}^r - \omega_r L_{ss} i_{qs}^r \end{aligned} \tag{1}$$

The electromagnetic torque can be expressed as:

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

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

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. θ_r, ω_r, J_m , β_m and P are the rotor position, electrical rotor speed, effective inertia, friction coefficient and the number of poles of the motor respectively. T_e, T_L, and τ_s are the electromagnetic torque, the load torque and the stator time constant of the motor respectively. λ_m, e_{qs} and e_{ds} are the flux linkage, back *emfs* in the *d-q* axes rotor reference frame respectively.

3 The Proposed PMSM Servo Drive System

The configuration of the proposed position control for a field oriented PMSM servo drive system is illustrated in Fig. 2. It basically consists of four control loops. Two PI current controllers in *d-q*-axes, a 2DOF I-PD speed controller with neural-network model-following controller and a 2DOF I-PD position controller with neural-network model-following controller. The PI current controllers and 2DOF I-PD NNMF speed controller has been designed and analyzed in [13]. After decoupling control is realized, there are three control loops in cascade; the *q*-axis current control loop, the speed control loop and the position control loop. At nominal operating condition of PMSM dynamic model, a 2DOF I-PD position controller is proposed to achieve the desired tracking and regulation position control performance. Then, the reference model is derived from the closed loop transfer function of the PMSM servo drive system shown in Fig. 2. Although the desired tracking and regulation position control can be realized using the 2DOF I-PD position controller with the nominal PMSM parameters, the performance of the servo drive system still sensitive to parameter variations because the position controller parameters are based on the PMSM model. To solve this problem, we propose an intelligent robust hybrid position controller which combining the 2DOF I-PD position controller and the neural-network model-following controller. The adaptive control law is designed based on two on-line trained NNMF speed and position controllers as follows:

$$i_{qs}^{rc} = i_{qs}^{r*} + \delta i_{qs}^{r\theta} + \delta i_{qs}^{r\omega} \tag{4}$$

The *q*-axis current command, i_{qs}^{r*} , is generated from the 2DOF I-PD speed controller, $\delta i_{qs}^{r\omega}$ is the adaptive control signal generated from the NNMF speed controller and $\delta i_{qs}^{r\theta}$ is the second adaptive control signal generated by the proposed NNMF position controller. These two adaptive control signals are automatically compensate the performance degradation due to load disturbances and PMSM parameter variations. The inputs to the NNMF speed controller are the error between the reference model actual rotor speed, e_ω^{mf} , and the derivative of the rotor speed, $k_\omega \dot{\omega}_r$, that are used to train the weights of neural-network model-following speed controller on-line. While the inputs to the NNMF position controller are the error between the reference model actual rotor position, e_θ^{mf} , and the rate of change of the rotor position (acceleration), $k_\omega \dot{\theta}_r$, which are used in on-line learning for the weights of neural-network model-following position controller.

$$\begin{aligned} e_\omega^{mf} &= (\omega_r^{mf} - \omega_r) \\ \dot{\omega}_r &= k_\omega d\omega_r / dt \end{aligned} \tag{5}$$

$$\begin{aligned} e_\theta^{mf} &= (\theta_r^{mf} - \theta_r) \\ \dot{\theta}_r &= k_\theta d\theta_r / dt \end{aligned} \tag{6}$$

where θ_r^{mf} and ω_r^{mf} are the outputs of the reference model while θ_r and ω_r are the rotor position and speed of the PMSM respectively.

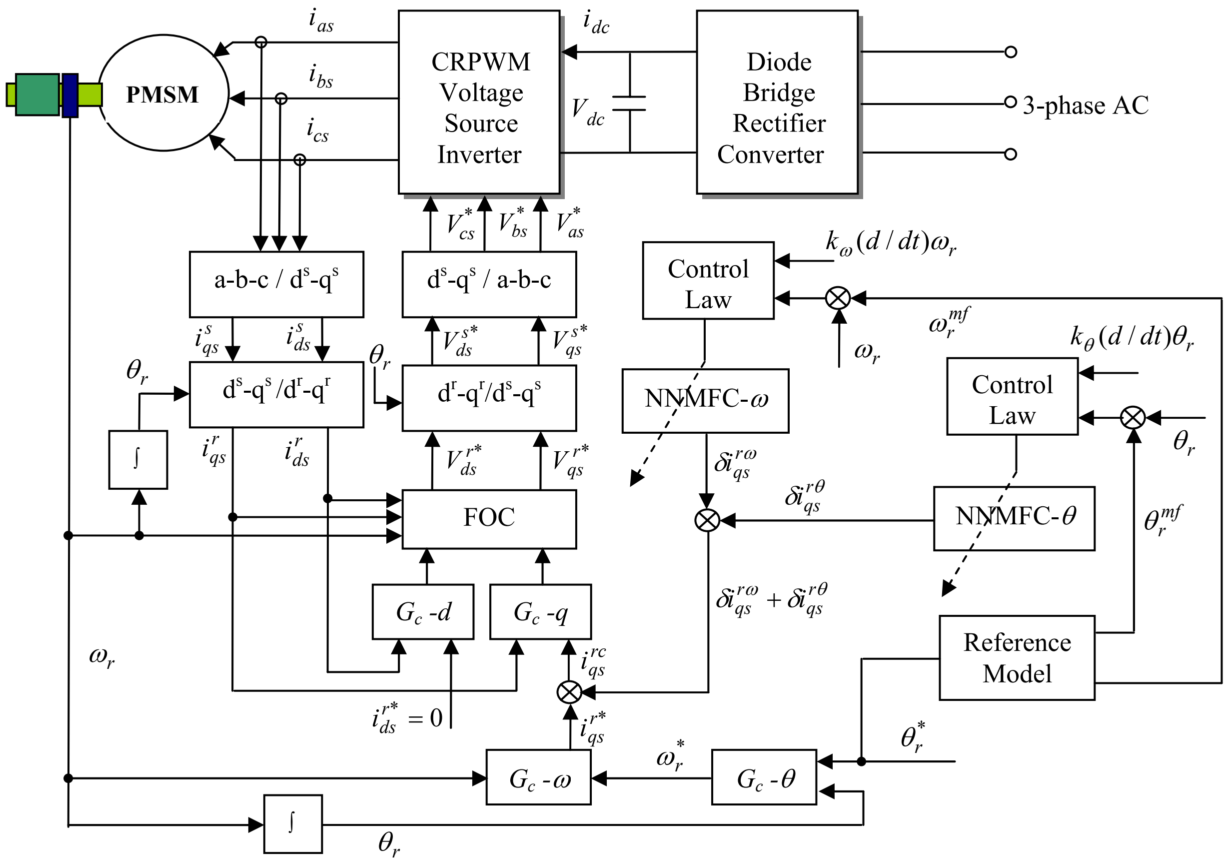


Fig. 1 The block schematic diagram of a vector controlled PMSM servo drive system

4 The Design of the Proposed 2DOF I-PD Position Controller

The position controller consists of an I-PD feed-back controller and a feed-forward controller to realize both the disturbance rejection and tracking characteristics of the PMSM servo drive system as illustrated in Fig. 2. The feed-back I-PD position controller is designed for load regulation or disturbance rejection performance, while the feed-forward controller to attain the desired tracking position response. To accomplish this objective, the denominator of the feed-forward controller is selected to cancel the numerator of the closed loop transfer function of the servo drive system [5]. The currents and speed controllers are designed and analyzed in [13].

4.1 The Feed-back I-PD Position Controller

According to Fig. 2, the closed loop transfer function of the PMSM drive system is derived. The controller parameters relationships are derived from (7).

$$\frac{\theta_r(s)}{\theta_r^{d*}(s)} = \frac{d_\circ(1+K_{PI}^c s)}{d_5 s^5 + d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s^1 + d_\circ} \triangleq \frac{\omega_n^5}{s^5 + 2.8\omega_n s^4 + 5\omega_n^2 s^3 + 5.5\omega_n^3 s^2 + 3.4\omega_n^4 s^1 + \omega_n^5} \tag{7}$$

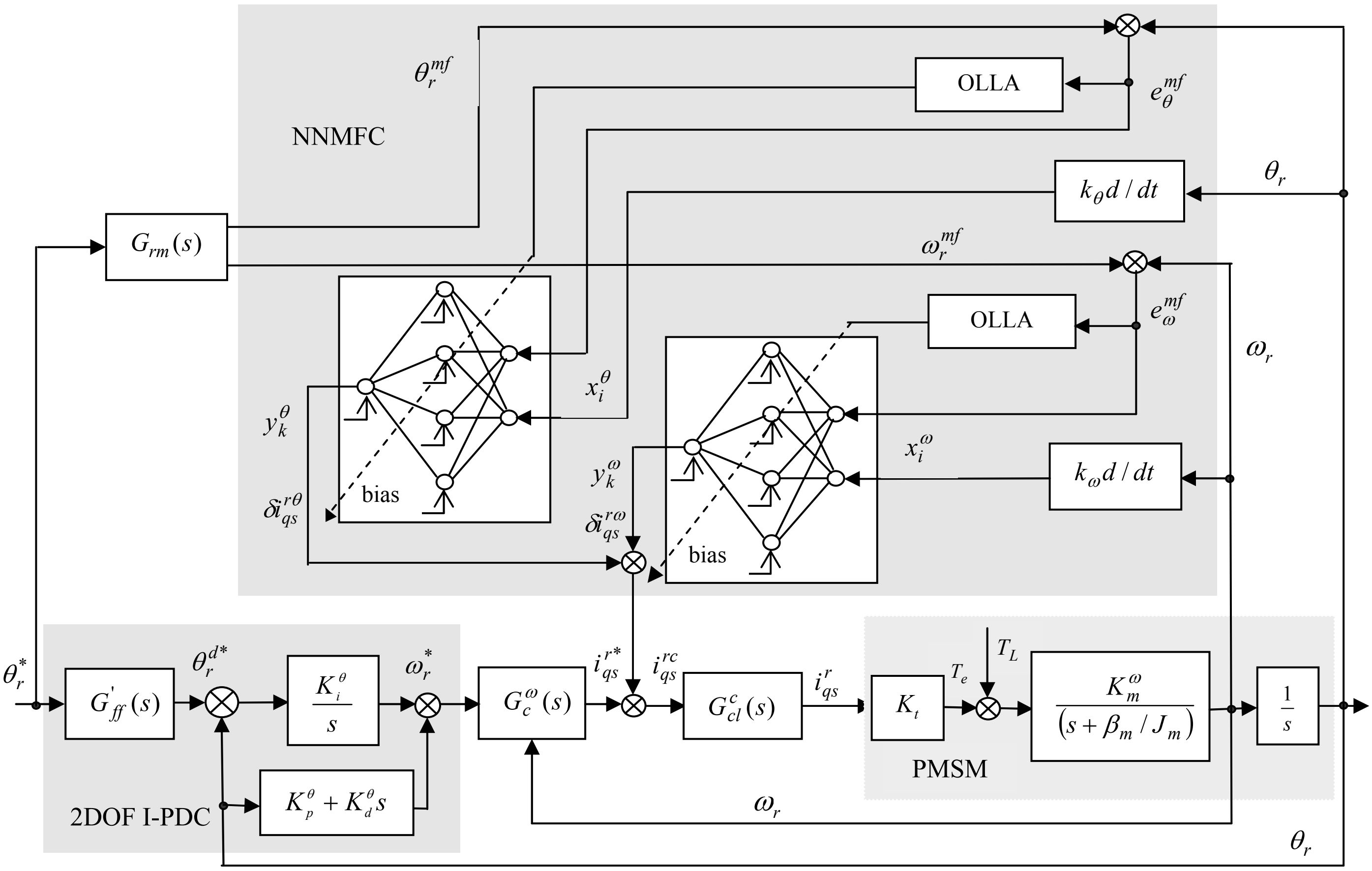


Fig. 2 Configuration of the proposed NNMF position controller for a vector controlled PMSM servo drive system

$$K_p^\theta = \frac{1}{c_\circ \overline{K}}(3.4\omega_n^4 - \tau_1\omega_n^5) \tag{8}$$

$$K_i^\theta = \frac{\omega_n^5}{c_\circ \overline{K}} \tag{9}$$

$$K_d^\theta = \frac{1}{c_\circ \tau_1 \overline{K}}(5\omega_n^2 - c_1) \tag{10}$$

4.2 The Feed-forward Position Controller

According to Fig. 2, the closed loop transfer function of the PMSM servo drive system including the feed-forward position controller at no load is deduced as follows.

$$\frac{\theta_r(s)}{\theta_r^*(s)} = \frac{d_\circ(1+\tau_1 s)}{d_5 s^5 + d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s^1 + d_\circ} . G_{ff}^\theta(s)$$

$$\stackrel{\Delta}{=} \frac{\omega_n^5}{s^5 + 2.8\omega_n s^4 + 5\omega_n^2 s^3 + 5.5\omega_n^3 s^2 + 3.4\omega_n^4 s^1 + \omega_n^5} \tag{11}$$

From (11), the feed-forward controller transfer function is given by:

$$G_{ff}^\theta(s) = \frac{\omega_n^5}{K_i^\theta c_\circ \overline{K}(1+\tau_1 s)} \tag{12}$$

The derived controller is a lag compensator but to improve the relative stability of the position response, we suggest a lead compensator in addition to the lag compensator. So, the feed-forward controller is chosen as a lead/lag controller with the following transfer function.

$$\overline{G}_{ff}^\theta(s) = K^\theta . \frac{(1+\tau_1^\theta s)}{(1+\tau_2^\theta s)} \tag{13}$$

The reference model transfer function of the PMSM servo drive system is derived according to the block diagram shown in Fig. 2.

$$G_{rm}^\theta(s) = \frac{K^\theta d_\circ(1+\tau_1^\theta s)}{d_5 s^5 + d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s^1 + d_\circ} \tag{14}$$

5 Proposed Neural-Network Model-Following Position Controller

In this section, a proposed neural-network model-following (NNMF) position controller with on-line trained is established. The on-line trained NNMFC consists of two controllers for the speed and position. The NNMF speed controller has been designed in

[13] and the position controller for PMSM servo drive system is shown in Fig. 2. As mentioned before, the inputs to the NNMF position controller are the error signal e_θ^{mf} and the rate of change of the rotor position (acceleration), $k_\omega \dot{\theta}_r$ while the output is the observed compensation signal $\delta i_{qs}^{r\theta}$. The error between the reference model and the output position of PMSM is used to train the weights and biases of the neural-controller to provide a good model-following position response. The weights and biases are adjusted on-line to give the required adaptive control signal. Utilizing these adaptive control signals resulting from the two NNMF speed and position controllers will make the servo drive system to follow the reference model.

5.1 Neural-Network for PMSM Servo Drive System

The NNMF position controller comprises a three layers neural-network as shown in Fig. 2. The signal propagation and activation functions are introduced in [13].

5.2 On-Line Training Algorithm

The back propagation training algorithm is an iterative gradient algorithm designed to minimize the mean square error between the actual output of a feed-forward net and the desired output. This technique uses a recursive algorithm starting at the output units and working back to the hidden layer to adjust the neural weights according to the following equations. The desired position reference is obtained from the reference model as given by (14), thus the energy error function is defined as follows:

$$E_\theta = \frac{1}{2}\sum_N [\theta_r^{mf}(N) - \theta_r(N)]^2 = \frac{1}{2}\sum_N e_\theta^2(N) \qquad (15)$$

where $\theta_r^{mf}(N)$ and $\theta_r(N)$ are the outputs of the reference model and PMSM servo drive system at the Nth –iteration. Within each interval from N-1 to N, the back propagation algorithm [13-15] is used to update the weights of the hidden and output layers in NNMFC. To increases the on-line learning rate of the weights, a control law is proposed as follows.

$$\frac{\partial E_\theta}{\partial y_k} = e_\theta^{mf} - k_\theta (d/dt)\theta_r \qquad (16)$$

6 Simulation Results

6.1 Dynamic Performance at Nominal Parameters

The simulations results of the PMSM servo 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 2π rad under no-load and full load of 3.6 N.m is predicted as illustrated in Figs. 3-5. The disturbance rejection capabilities have been checked when a load of 3.6 N.m is applied to the shaft at t = 1.0 s and removed t = 3.0 s. The simulation results of the proposed 2DOF I-PD position controller are shown in Figs. 3-a, 4-a that include the command and actual responses for position, speed, load regulation and model following errors (MFE) while the dynamic performance utilizing the proposed intelligent 2DOF I-PD NNMF position controller are represented in Figs. 3-b, 4-b. Fig. 5 provide a comparison between the MFE and load regulation performance for both position 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 augmenting the proposed 2DOF I-PD NNMF position controller can be observed from the obtained results in command tracking and load regulation characteristics as illustrated in Fig. 5. It is clear from this Figure that the proposed 2DOF I-PD NNMF position controller provides a rapid and accurate response for the reference model within 0.75 s. Also, the proposed controller quickly returns the position to the reference under full load with a maximum dip of 0.01 rad. While the 2DOF I-PD position controller gives a slow response for the reference and a large dipping in position of about 0.48 rad. The model-following response and model-following error (MFE) for the PMSM servo drive system with both position controllers are shown in Fig. 8. It is evident that from this Figure an obvious model-following error (MFE) due to the 2DOF I-PD position controller reaches to 1.3 rad while the MFE due to 2DOF I-PD NNMF position controller is about 0.05 rad. Therefore, the proposed model-following neural network controller provides a good model-following response.

6.2 Consideration of Parameter Variations

The simulation results of the dynamic response for both currents, speed and position controllers are plotted in Figs. 6-8. To investigate the effectiveness of the proposed intelligent robust position controller, three cases with parameter variations in the stator resistance, self inductance, motor inertia and load torque disturbance are considered. The following possible ranges of parameter variations and external disturbances are considered.

Case 1: $R_s=R_s^*$, $L_s=L_s^*$, $J_m=J_m^*$, T_L=0-3.5 *N.m*.

Case 2: $R_s=0.5\times R_s^*$, $L_s=0.5\times L_s^*$, $J_m=0.5\times J_m^*$, T_L=0-3.5 *N.m*.

Case 3: $R_s=1.5\times R_s^*$, $L_s=1.5\times L_s^*$, $J_m=5.0\times J_m^*$, T_L=0-3.5 *N.m*.

The position response and the load regulation performance of the drive system with the 2DOF I-PD and 2DOF I-PD NNMF position controllers are shown in Figs. 6-7 under the cases of PMSM parameter variations. Fig. 6 illustrates the position tracking and torque current responses for both position controllers. At the same conditions, the load regulation performance and torque current responses are given in Fig. 7. The results shown in Figs. 6-7 clearly indicate that as the variations of the PMSM parameters occurred, the responses deviate significantly from those nominal case with 2DOF I-PD position controller but the 2DOF I-PD NNMF position controller confirms the correct operation and slightly influenced by parameter variations. The results confirm the robust performance with the 2DOF I-PD NNMF position controller. The model-following error for both controllers under parameter variations are shown in Fig. 8. We can observe from this Figure that a large MFE with 2DOF I-PD position controller while the MFE is very small and insignificantly affected by parameter variations utilizing 2DOF I-PD NNMF position controller. From the above simulation results, it is evident that the 2DOF I-PD NNMF position controller illustrates satisfactory performance of the PMSM servo drive system, even under load disturbances and parameter variations. Good model-following tracking responses at all cases are observed from these results, and the resulting regulation performances are also much better, in both position dip and recovery time, than those obtained by the 2DOF I-PD position controller.

7 Conclusions

This paper proposes an intelligent robust 2DOF I-PD NNMF position controller for PMSM servo drive system which guarantees the robustness in the presence of load disturbances and parameter variations. First, the I-PD position controller was designed according to the given command tracking specifications and the closed loop transfer function was chosen as the reference model. Then, the feed-forward controller was designed as a lead/lag compensator to improve the disturbance rejection characteristics of the servo drive system. To improve the dynamic performance of the servo drive system, a NNMF position controller with on-line learning was designed and added to the 2DOF I-PD position controller to preserve the good model-following characteristics under the conditions of parameter variations and external disturbances. The NNMF position and speed controllers provide two adaptive feed-back control signals based on the error between the reference model and the output position and speed of the PMSM in order to allow the servo drive system to follow the reference model. As a result, the rotor position and rotor speed tracking responses can be controlled to closely follow the response of the reference model under a wide range of operating conditions. The performance of the drive system and the effectiveness of the proposed controllers have been demonstrated by a wide range of simulation results. Simulation results have shown that the proposed 2DOF I-PD NNMF position controller grants accurate tracking and regulation characteristics under parameter variations and external load disturbance.

References

[1] P.C. Krause, *Analysis of Electric Machinery*, New York, McGraw Hill, 1986.

[2] B. K. Bose, *Modern Power Electronics and AC Drives,* Prentice Hall, Upper Saddle River, 2002.

[3] Peter Vas, *Vector Control of AC Machines*, Oxford: Clarendon Press, 1990.

[4] Ned Mohan, *Advanced Electric Drives: Analysis*, control, and Modeling using Simulink, MNPERE Press, USA, 2001.

[5] 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.

[6] C. M. Liaw, Design of a two-degrees-of-freedom controller for motor drives, *IEEE Trans. Automatic Control*, Vol. AC-37, No. 4, Aug./Sept., 1992, pp. 1215-1220.

[7] 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)*, Vol. 3, No. 2, April, 2003, pp. 115-123.

[8] M. A El-Sharkawy, Neural network application to high performance electric drive system", *Proceeding of ICEON'95*, November 1995, pp. 44-496.

[9] 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)*, Vol. 4, No. 1, January 2004, pp. 28-38,.

[10] K. S. Narenda and K. Parthasarathy, Identification and control of dynamical systems using neural networks, *IEEE Trans., Neural Network*, NN-1, 1990, pp. 4-27.

[11] T. Fukuda and T. Shibata, Theory and applications of neural networks for industrial control systems, *IEEE Trans., Ind. Electr.*, IE-39, 1992, pp. 472-491.

[12] Yang Yi, D. Mahinda Vilathgamuwa and Azizur Rahman, Implementation of an Artificial-Neural-Network-Based Real-Time Adaptive Controller for an Interior Permanent-Magnet Motor Drive, *IEEE Trans., Ind. Applic.*, IA-39, No. 1, 2003, pp. 96-104.

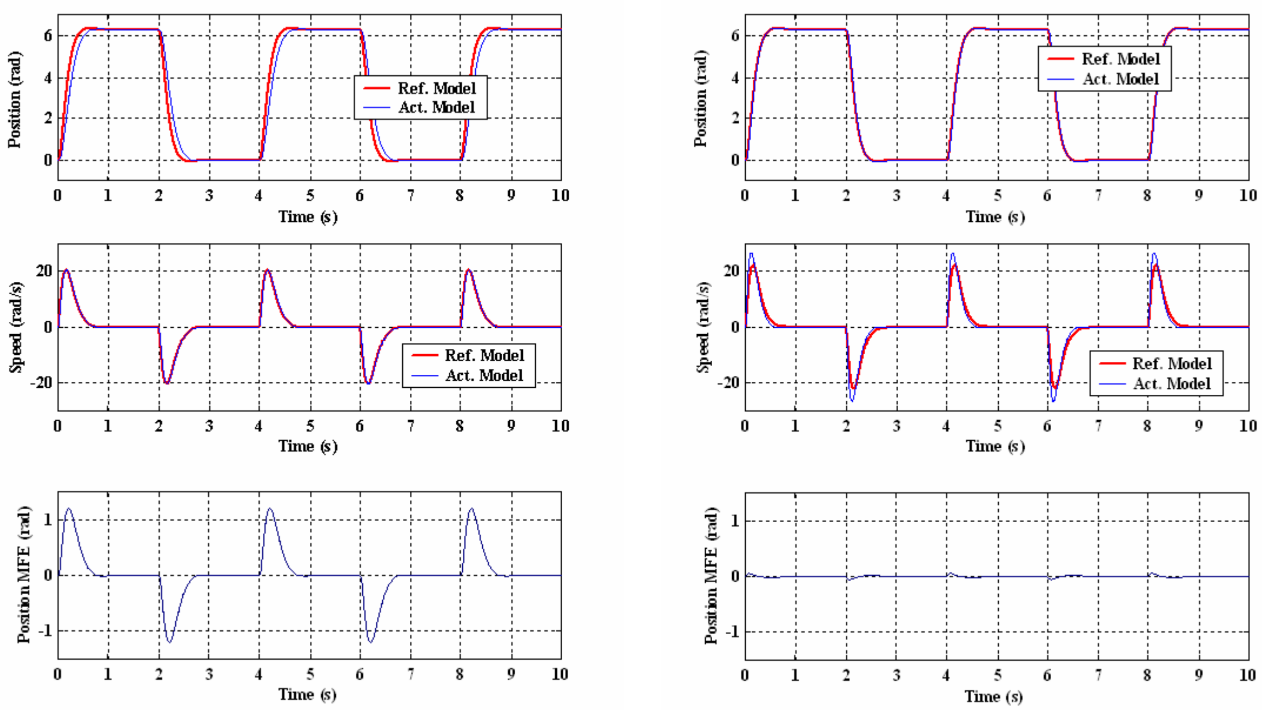
[13] Fayez F. M. El-Sousy**,** " A Vector-Controlled PMSM Drive with a Continually On-Line Learning Hybrid Neural-Network Model-Following Speed Controller" *The Korean Institute of Power Electronics (KIPE), Journal of Power Electronics (JPE)*, Vol. 5, No. 2, pp. 197-210, April, 2005.

[14] Faa-Jeng and Chih-Hong Lin, A Permanent-Magnet Synchronous Motor Servo Drive Using Self-Constructing Fuzzy Neural Network Controller, *IEEE Trans., Energy Conversion*, EC-19, No. 1, 2004, pp. 66-72.

[15] Fayez F. M. El-Sousy and M. M. Salem, High Performance Simple Position Neuro-Controller for Field-Oriented Induction Motor Servo Drives, WSEAS Transactions on Systems, Issue 2, Vol. 3, April 2004, pp. 941-950.

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

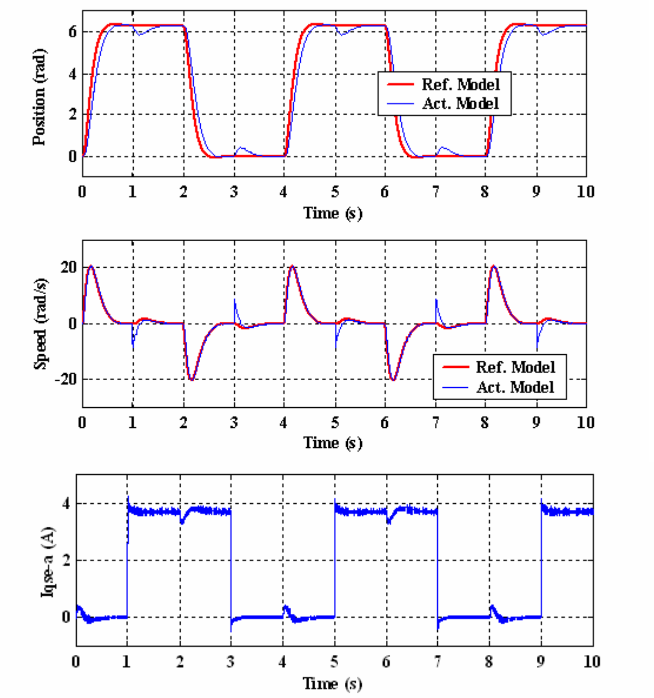
[17] C. M. Ong, *Dynamic Simulation of Electric Machinery Using Matlab and Simulink,* Printice Hall, 1998.



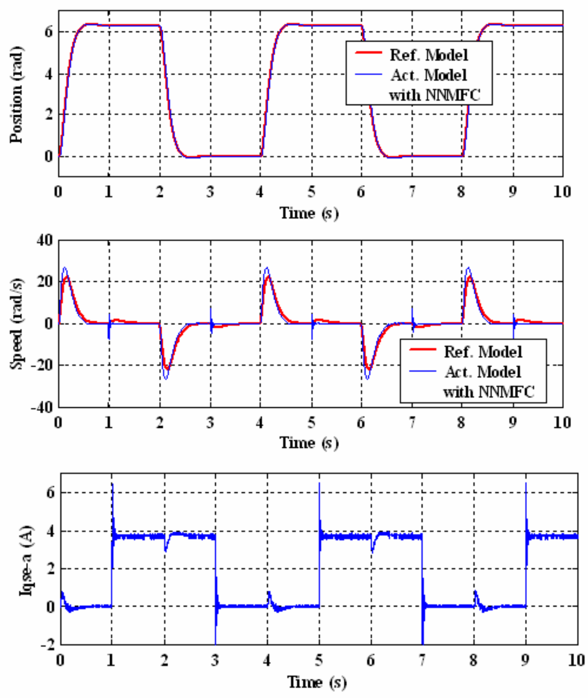
(a) Using 2DOF I-PD position controller

(b) Using 2DOF I-PD NNMF position controller

Fig. 3. The position, speed and model-following error (MFE) responses of the servo drive system at no-load for both 2DOF I-PD and 2DOF I-PD NNMF position controllers

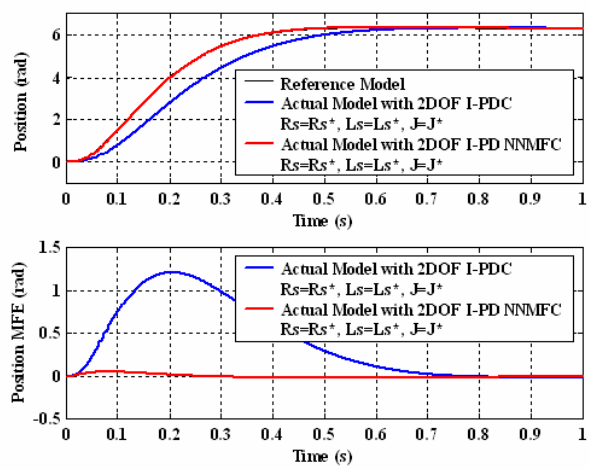


(a) Using 2DOF I-PD position controller

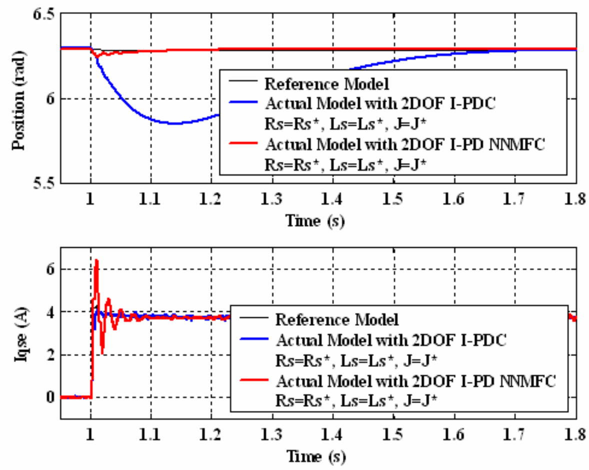


(b) Using 2DOF I-PD NNMF position controller

Fig. 4. The position, speed and torque current responses of the servo drive system at full-load for both 2DOF I-PD and 2DOF I-PD NNMF position controllers

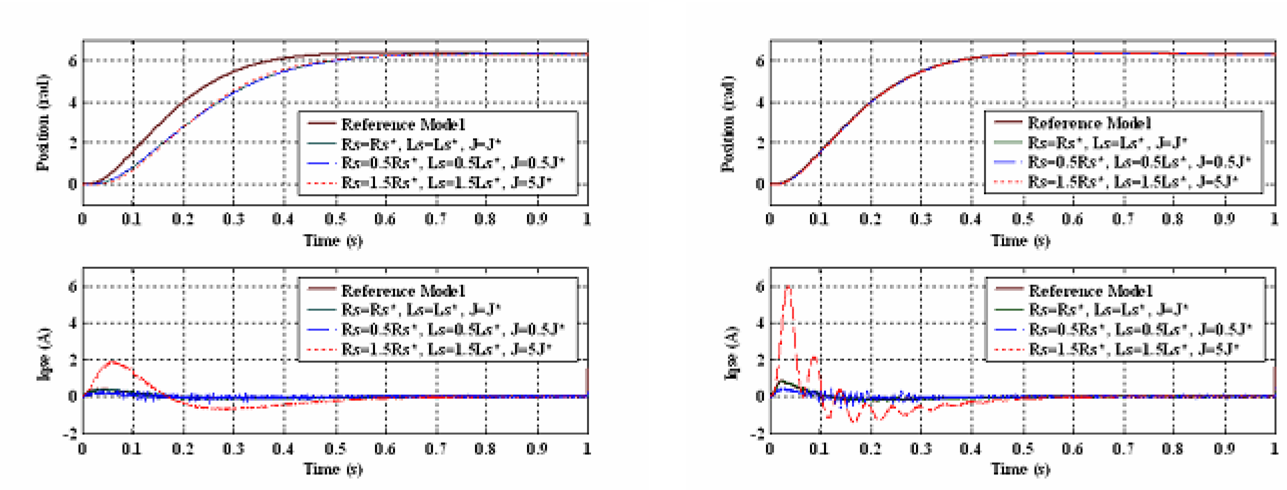


(a) Model-following response using 2DOF I-PD position controller



(b) The load regulation performance using 2DOF I-PD NNMF position controller

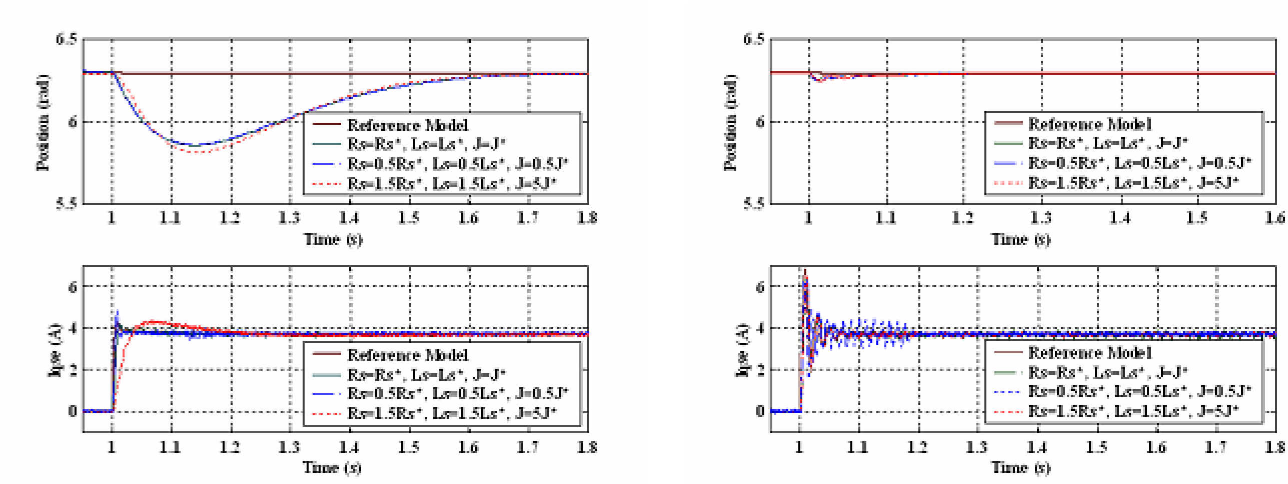
Fig. 5. The Model-following response and load regulation performance of the servo drive system for both 2DOF I-PD and 2DOF I-PD NNMF position controllers



(a) Using 2DOF I-PD position controller

(b) Using 2DOF I-PD NNMF position controller

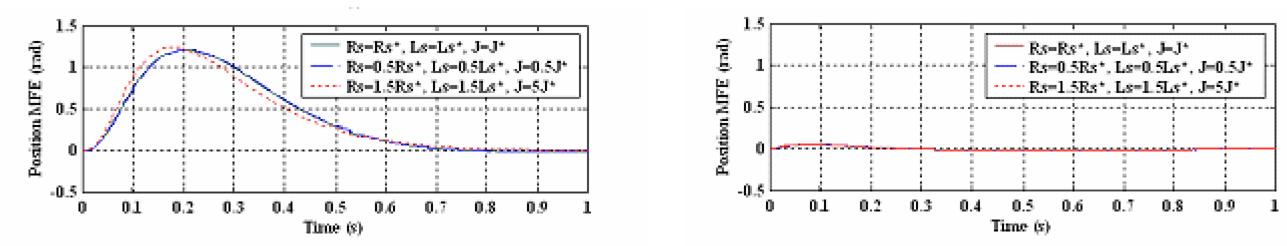
Fig. 6. The position model-following and torque current responses of the servo drive system under parameter variations for both 2DOF I-PD and 2DOF I-PD NNMF position controllers



(a) Using 2DOF I-PD position controller

(b) Using 2DOF I-PD NNMF position controller

Fig. 7. The load regulation performance of the servo drive system under parameter variations for both 2DOF I-PD and 2DOF I-PD NNMF position controllers



(a) Using 2DOF I-PD position controller

(b) Using 2DOF I-PD NNMF position controller

Fig. 8. The model-following error (MFE) of the servo drive system under parameter variations for both 2DOF I-PD and 2DOF I-PD NNMF position controllers