Hybrid Neural-Network Model-Following Speed Controller with On-Line Learning for Vector-Controlled PMSM Drive

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Abstract:- A high-performance robust hybrid speed controller of permanent-magnet synchronous motor (PMSM) drive with on-line trained neural-network model-following controller (NNMFC) is proposed. The robust hybrid controller is a two-degrees-of-freedom (2DOF) integral plus proportional & rate feedback (I-PD) with neural-network model-following (NNMFC) speed controller (2DOF I-PD NNMFC). The robust controller combines the merits of the 2DOF I-PD controller and the NNMFC controller for PMSM drives speed control. First, a systematic mathematical procedure is derived to find the parameters of the *d-q* axes PI current controllers and the 2DOF I-PD speed controller according to the required specifications for the PMSM drive system. Then the resulting closed loop transfer function of the PMSM drive system including the current control loop is used as the reference model. To realize high dynamic performance in disturbance rejection and tracking characteristics, a neural-network model-following controller whose weights are trained on-line is designed in addition to the 2DOF I-PD controller. 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 2DOF I-PD speed controller output to attain robust model-following characteristics under different operating conditions due to parameter variations and load disturbances. Computer simulation is developed to demonstrate the effectiveness of the proposed 2DOF I-PD NNMFC controller. The results confirm that the proposed 2DOF I-PD NNMFC speed controller grant a rapid, robust performance and accurate response for the reference model regardless of whether a load disturbance is imposed and PMSM parameters vary.

Key-Words: PMSM Drive, 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 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 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. In addition, its decoupling control performance is less sensitive to parameter variations of the PMSM.

To achieve fast dynamic response, smooth starting, the field oriented control (FOC) technique is used in the design of the PMSM drive system. Like any other machine, the PMSM is inherently non-linear and possesses a multivariable coupled control system with high-order complex dynamics [1-4]. Utilizing the FOC technique simplifies the dynamic model of the PMSM and control scheme. The electromagnetic torque is generated proportional to product of stator current and PM rotor flux. The two components are orthogonal that result high-performance similar to separately excited DC motor.

Feed-back control is a common requirement for PMSM drive system. The most widely used controllers in industrial applications is the proportional plus integral plus derivative (PID) controllers. Also, modified structures of the PID such as proportional plus integral & rate feed-back (PI-D) and integral plus proportional & rate feed-back (I-PD) controllers are developed. However, as these controllers have one-degree-of-freedom, it may not have a good command tracking and load regulation response simultaneously. The 2DOF configuration has the advantage that it allows the controller to achieve the command tracking and disturbance regulation performance separately.

The controller consists of two parts, the feed-back controller and the feed-forward controller. The feed-back controller ensures the closed loop stability and provides a good rejection of load disturbance while the feed-forward controller meets the desired command tracking specifications [5-7]. The 2DOF I-PD configuration is proposed in this paper. The proposed FOC PMSM drive system is shown in Fig. 1.

Recently, several control techniques have been developed for improving the performance of the PMSM drives. Many researches have been carried out to apply neural network to the control of PMSM drive system to deal with the nonlinearities and uncertainties of the dynamic model of PMSM [8-9]. 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 [10-12].

The aim of this paper is to design *d-q* axes current controllers and a proposed robust hybrid speed controller. The proposed controller consists of a 2DOF I-PD controller and neural-network model-following controller (NNMFC) for PMSM drive system. In order to design these feed-back controllers to meet robust stability and disturbance rejection specifications, a quantitative analysis and design procedures are developed to find the parameters of the currents and speed controllers. First, the field oriented control transfer functions of the PMSM are derived from the dynamic model at the synchronously rotating rotor reference frame with nominal parameters. Next, on the basis of these transfer functions, the *d-q* axes PI current controllers are designed to achieve the time domain specifications of the current control loops. After that, the 2DOF I-PD speed controller is designed to accomplish specifications of the speed control loop. The closed loop transfer function of the whole drive system is chosen as the reference model. A proposed on-line trained NNMFC is designed and added to the 2DOF I-PD speed controller output to compensate the error between the reference model and the PMSM drive system output under parameter variations and load disturbances. When the error occurs, an adaptive control signal will be generated automatically from the NNMFC to maintain the desired model following performance for the PMSM drive system. To verify the design of the proposed controllers and PMSM drive system performance, the overall system is simulated. The dynamic performance of the PMSM 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 stationary and synchronously rotating rotor reference frames can be derived as follows [1-2].

2.1 PMSM Model in d^s-q^s Stationary Frame

The stator voltage equations in the d^s-q^s stationary frame can be expressed as follows:

$$\begin{aligned} V_{qs}^s &= R_s i_{qs}^s + L_{ss}\frac{d}{dt}i_{qs}^s + \omega_r \lambda_m \cos(\theta_r) \\ V_{ds}^s &= R_s i_{ds}^s + L_{ss}\frac{d}{dt}i_{ds}^s - \omega_r \lambda_m \sin(\theta_r) \end{aligned} \tag{1}$$

The electromagnetic torque can be expressed as:

$$T_e = \frac{3}{2}.\frac{P}{2}\lambda_m\left[i_{qs}^s\cos(\theta_r) - i_{ds}^s\sin(\theta_r)\right] \tag{2}$$

The mechanical equation of the PMSM and load may be expressed as:

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

By choosing $(i_{qs}^s, i_{ds}^s, \omega_r)$ as state variables, the PMSM state space representation in the stationary can be derived as follows:

$$\begin{aligned} \begin{bmatrix} \frac{d}{dt}i_{qs}^s \\ \frac{d}{dt}i_{ds}^s \end{bmatrix} &= \begin{bmatrix} -\frac{1}{\tau_s} & 0 \\ 0 & -\frac{1}{\tau_s} \end{bmatrix}\begin{bmatrix} i_{qs}^s \\ i_{ds}^s \end{bmatrix} + \frac{\lambda_m}{L_{ss}}\omega_r\begin{bmatrix} -\cos(\theta_r) \\ +\sin(\theta_r) \end{bmatrix} \\ &+ \begin{bmatrix} -\frac{1}{L_{ss}} & 0 \\ 0 & +\frac{1}{L_{ss}} \end{bmatrix}\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \end{bmatrix} \end{aligned} \tag{4}$$

$$\frac{d}{dt}\omega_r = T_e K_m - \frac{\beta_m}{J_m}\omega_r - K_m T_L \tag{5}$$

2.2 PMSM Model in d^r-q^r Rotor Frame

The variables and parameters represented in the stationary reference frame can be transformed into these in the rotor reference frame. The stator voltage equations in the d^r-q^r synchronously rotating rotor reference frame can be carried out as follows:

$$\begin{aligned} V_{qs}^r &= R_s i_{qs}^r + L_{ss}\frac{d}{dt}i_{qs}^r + \omega_r L_{ss} i_{ds}^r + \omega_r \lambda_m^{'} \\ V_{ds}^r &= R_s i_{ds}^r + L_{ss}\frac{d}{dt}i_{ds}^r - \omega_r L_{ss} i_{qs}^r \end{aligned} \tag{6}$$

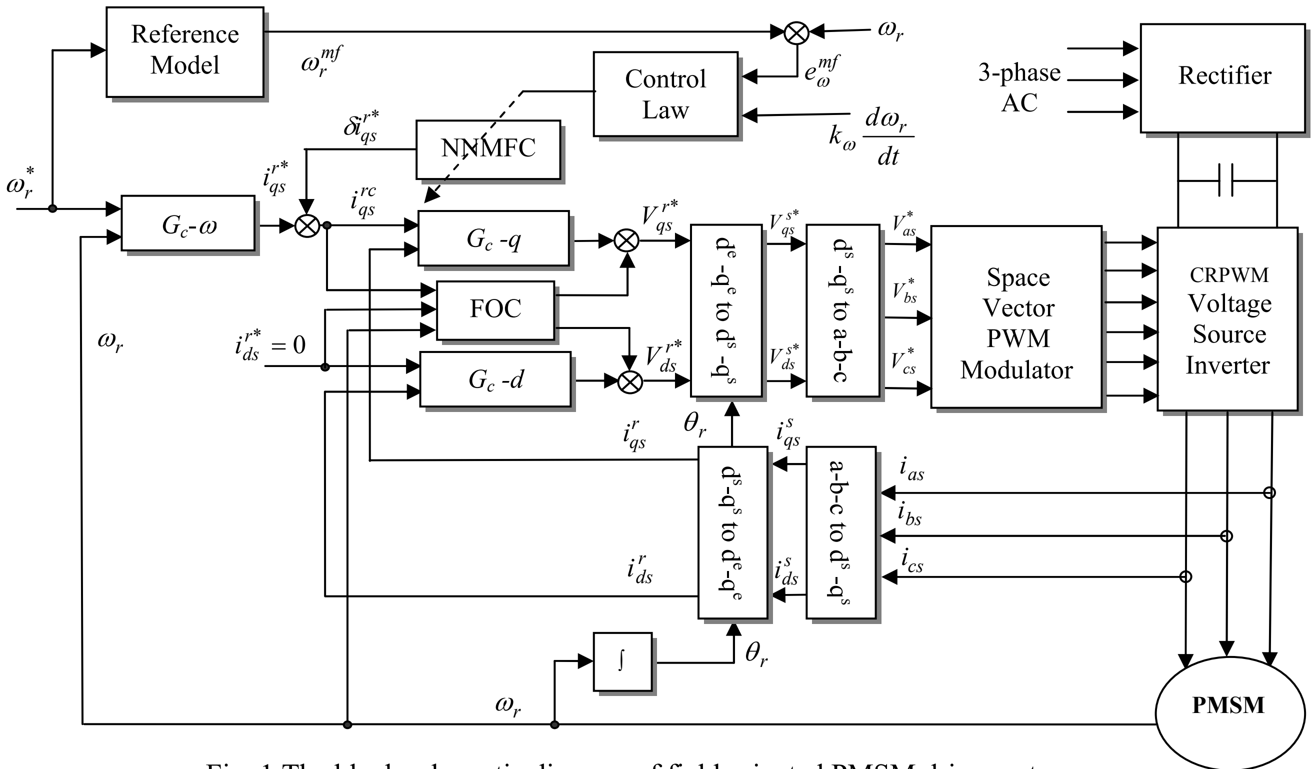

Fig. 1 The block schematic diagram of field oriented PMSM drive system

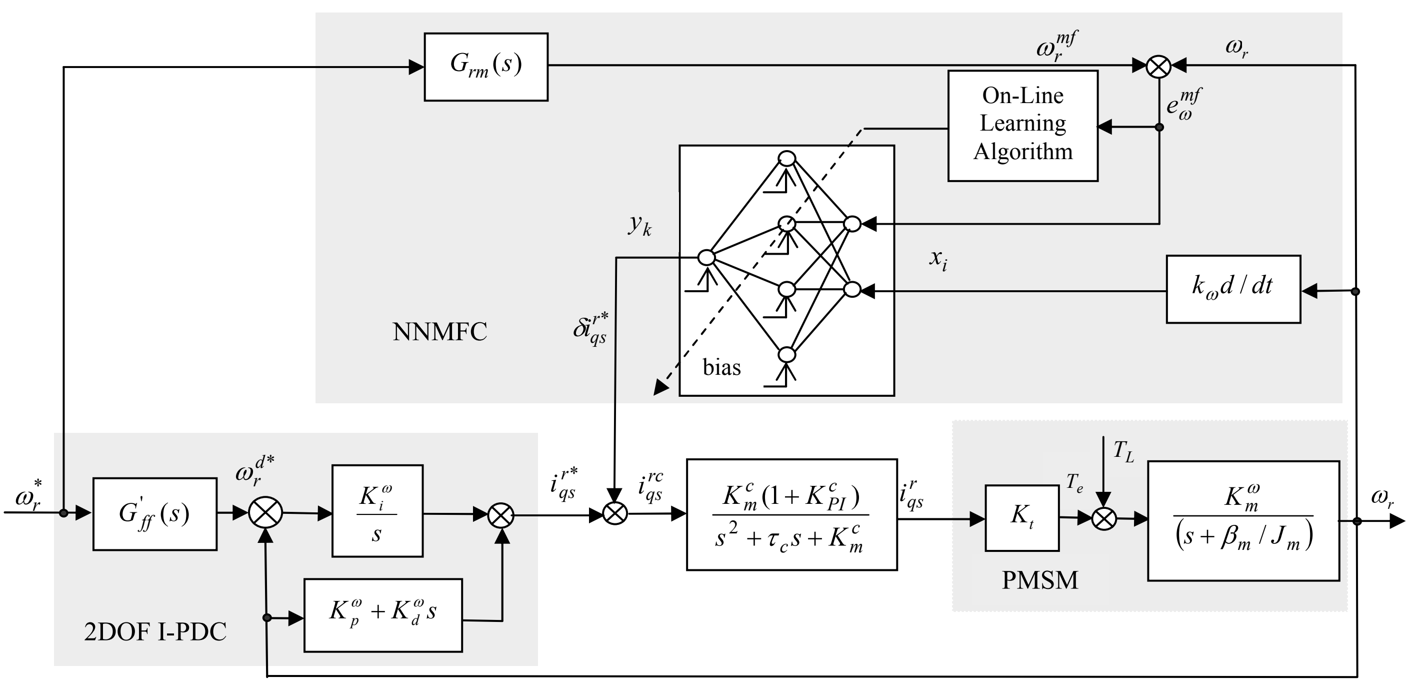

Fig. 2 Configuration of the proposed NNMFC speed controller for field oriented PMSM drive system

The electromagnetic torque can be expressed as:

$$T_e = \frac{3}{2}.\frac{P}{2}.\lambda_m i_{qs}^r \quad (7)$$

By selecting $(i_{qs}^r, i_{ds}^r, \omega_r)$ as state variables, the state space equation of the PMSM can be given as follows:

$$\begin{bmatrix} \frac{d}{dt} i_{qs}^r \\ \frac{d}{dt} i_{ds}^r \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_s} & \omega_r \\ \omega_r & -\frac{1}{\tau_s} \end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} + \frac{\lambda_m}{L_{ss}} \begin{bmatrix} -\omega_r \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{ss}} & 0 \\ 0 & \frac{1}{L_{ss}} \end{bmatrix} \begin{bmatrix} V_{qs}^r \\ V_{ds}^r \end{bmatrix} \quad (8)$$

$$\frac{d}{dt}\omega_r = K_t K_m .\lambda_m i_{qs}^r - \frac{\beta_m}{J_m}\omega_r - K_m T_L \quad (9)$$

3 Field Oriented Control of PMSM

In this paper, the field oriented control (FOC) 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, $i_{ds}^r = 0$, 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 [4].

4 Formulations and Configuration of the Proposed PMSM Drive System

The system configuration of the proposed speed control for a FOC PMSM drive system is illustrated in Fig. 2. It basically consists of a PI current controller in *q*-axis and a 2DOF I-PD controller and a neural-network model-following controller. First, at nominal operating condition, the PI current controller is designed based on the time domain specifications of the current loop and then the 2DOF I-PD speed controller is designed based on the PMSM model to achieve the desired tracking and regulation speed control performance. After that, a reference model is derived from the closed loop transfer function of the PMSM drive system shown in Fig. 2. Although the desired tracking and regulation speed control can be obtained using the 2DOF I-PD 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 2DOF I-PD speed controller and the neural-network model-following controller (NNMFC) is proposed. The control law is designed as:

$$i_{qs}^{rc} = i_{qs}^{r*} + \delta i_{qs}^{r*} \quad (10)$$

Where i_{qs}^{r*} the *q*-axis current command generated from the 2DOF I-PD speed controller and δi_{qs}^{r*} is 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 that are used to train the weights of neural-network controller on-line.

$$\begin{aligned} e_\omega^{mf} &= (\omega_r^{mf} - \omega_r) \\ \omega_r^{\bullet} &= k_\omega d\omega_r / dt \end{aligned} \quad (11)$$

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

5 Designs of the Proposed Current and Speed Controllers

5.1 The *d-q* axes PI Current Controllers

This section considers the design of the current controller based on the voltage equation of the PMSM under FOC. The block diagram of the current control loop of the PMSM is shown in Fig. 3. The closed loop transfer function of the system is derived as follows.

$$\begin{aligned} \frac{i_{qds}^r(s)}{i_{qds}^{r*}(s)} &= \frac{(1/R_s\tau_s).(K_p^c s + K_i^c)}{s^2 + s(1/\tau_s + K_p^c/R_s\tau_s) + K_i^c/R_s\tau_s} \\ &\stackrel{\Delta}{=} \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \end{aligned} \quad (12)$$

From this equation the parameters of PI controller can be founded.

$$\begin{aligned} K_p^c &= \left(\frac{2\zeta\omega_n - 1/\tau_s}{R_s\tau_s} \right) \\ K_i^c &= \omega_n^2 R_s \tau_s \end{aligned} \quad (13)$$

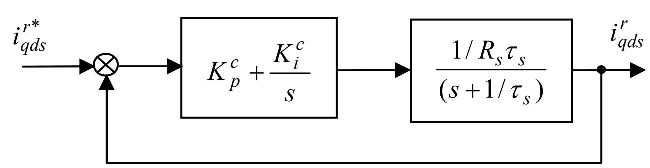

Fig. 3 Configuration of the PI controller current

5.2 The Proposed 2DOF I-PD Speed Controller

The controller consists of an I-PD feed-back controller and feed-forward controller as shown in Fig. 4. The type I-PD feed-back controller is designed for load regulation or disturbance rejection while the feed-forward controller to attain the desired tracking speed 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 drive system [5].

A. The Feed-back I-PD Speed Controller

According to Fig. 4, the closed loop transfer function of the PMSM drive system with only the feed-back speed control at no load is derived. The controller parameters relationships are derived from equation (14) as follows:

$$\frac{\omega_r(s)}{\omega_r^{d*}(s)} = \frac{a_o(1+K_{PI}^c s)}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_o} \triangleq \frac{\omega_n^4}{s^4 + 2.1\omega_n s^3 + 3.4\omega_n^2 s^2 + 2.7\omega_n^3 s^1 + \omega_n^4} \tag{14}$$

$$K_p^\omega = \left(\frac{2.7\omega_n^3 - K_m^c \beta_m / J_m}{K_m^\omega K_m^c K_t}\right) \tag{15}$$

$$K_i^\omega = \frac{\omega_n^4}{K_m^\omega K_m^c K_t} \tag{16}$$

$$K_d^\omega = \left(\frac{3.4\omega_n^2 - K_m^c - \tau_c \beta_m / J_m}{K_m^\omega K_m^c K_t}\right) \tag{17}$$

B. The Feed-forward Speed Controller

According to Fig. 4, the closed loop transfer function of the PMSM drive system including the feed-forward speed controller at no load is derived as follows.

$$\frac{\omega_r(s)}{\omega_r^{*}(s)} = \frac{a_o(1+K_{PI}^c s)}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_o} . G_{ff}(s) \triangleq \frac{\omega_n^4}{s^4 + 2.1\omega_n s^3 + 3.4\omega_n^2 s^2 + 2.7\omega_n^3 s^1 + \omega_n^4} \tag{18}$$

From equation (18), the feed-forward controller transfer function is given by:

$$G_{ff}(s) = \frac{\omega_n^4}{K_m^\omega K_m^c K_t K_i^\omega (1+K_{PI}^c s)} \tag{19}$$

The above controller is a lag compensator but to improve the relative stability of the speed response, we suggest a lead compensator which is added to the feed-forward controller transfer function as follows.

$$G_{ff}^{'}(s) = \overline{K}.\frac{(1+\tau_1 s)}{(1+\tau_2 s)} \tag{20}$$

The transfer function of the reference model with the 2DOF I-PD speed controller according to the block diagram shown in Fig. 4 is derived as follows.

$$G_{rm}(s) = \frac{\omega_r(s)}{\omega_r^{*}(s)} = \frac{b_o \overline{K}(1+\tau_1 s)}{b_3 s^3 + b_2 s^2 + b_1 s^1 + b_o} \tag{21}$$

6 The Proposed Neural-Network Model-Following Controller (NNMFC)

In this section, a proposed neural-network model-following controller (NNMFC) with on-line learning is introduced. The on-line trained NNMFC for PMSM drive system is shown in Fig. 5. 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.

6.1 Neural-Network for PMSM Drive System

The NNMFC comprises a three layers neural-network as shown in Fig. 5. The signal propagation and activation functions are introduced as follows.

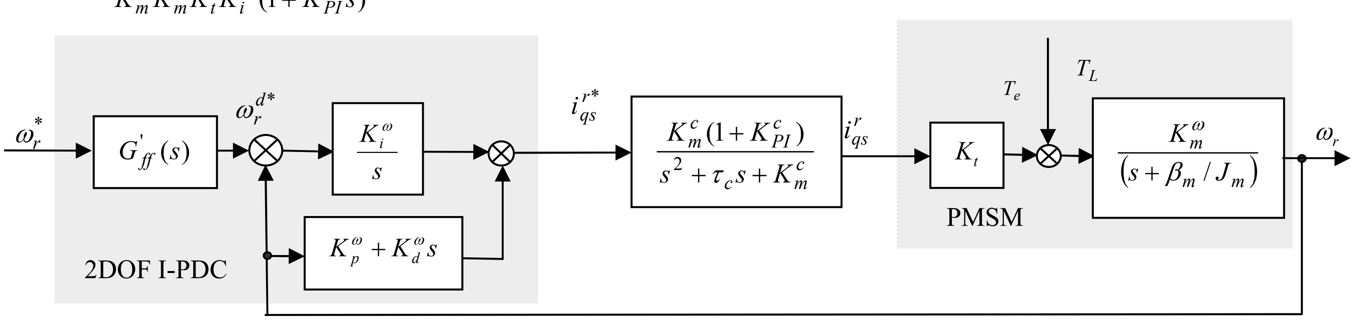

Fig. 4 Configuration of the speed control for PMSM using 2DOF I-PD speed controller

A. Input Layer

For every node i in the input layer, the neural-network input and output are expressed as:

$$nn_i = x_i \tag{22}$$

$$y_i = f_i(nn_i) \qquad i = 1,2 \tag{23}$$

$$x_1 = e_\omega^{mf}(t), \qquad x_2 = k_\omega \frac{d}{dt}\omega_r \tag{24}$$

B. Hidden Layer

The input and output of the hidden layer to a node j are introduced as follows respectively.

$$nn_j = \sum_i (W_{ji} y_i) + \phi_j \quad (25)$$

$$y_j = f_j(nn_j) \qquad j = 1,........m \quad (26)$$

$$f_j(nn_j) = \frac{1}{1 + e^{-nn_j}} \quad (27)$$

C. Output Layer

The input of the output layer to a node *k* is given by:

$$nn_k = \sum_j (W_{kj} y_j) + \phi_k \quad (28)$$

And the corresponding output is

$$y_k = f_k(nn_k) = \frac{1}{1 + e^{-nn_k}} \quad (29)$$

$$y_k = \delta i_{qs}^{r*} \quad (30)$$

6.2 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 speed ω_r^{mf} is obtained from the reference model as given by equation (21), thus the energy error function is defined as follows:

$$E_\omega = \frac{1}{2}\sum_N [\omega_r^{mf}(N) - \omega_r(N)]^2 = \frac{1}{2}\sum_N e_\omega^2(N) \quad (31)$$

Where $\omega_r^{mf}(N)$ and $\omega_r(N)$ are the outputs of the reference model and PMSM drive system at the N^th^ – 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 according to the following equations:

$$W_{ji}(N+1) = W_{ji}(N) - \varepsilon \frac{\partial E_\omega}{\partial W_{ji}(N)} + \gamma \Delta W_{ji}(N-1) \quad (32)$$

$$W_{kj}(N+1) = W_{kj}(N) - \varepsilon \frac{\partial E_\omega}{\partial W_{kj}(N)} + \gamma \Delta W_{kj}(N-1) \quad (33)$$

$$\Delta W_{ji}(N-1) = W_{ji}(N) - W_{ji}(N-1) \quad (34)$$

$$\Delta W_{kj}(N-1) = W_{kj}(N) - W_{kj}(N-1) \quad (35)$$

The required gradient of E_ω in equation (31) between the output and hidden layers is determined according to the following equation.

$$\frac{\partial E_\omega}{\partial W_{kj}} = \frac{\partial E_\omega}{\partial nn_k} . \frac{\partial nn_k}{\partial W_{kj}} = \frac{\partial E_\omega}{\partial nn_k} . y_j \quad (36)$$

The error term to be propagated is given by:

$$\delta_k = \frac{\partial E_\omega}{\partial nn_k} = \sum \frac{\partial E_\omega}{\partial \omega_r} . \frac{\partial \omega_r}{\partial i_{qs}^{c*}} . \frac{\partial i_{qs}^{c*}}{\partial y_k} . \frac{\partial y_k}{\partial nn_k} \quad (37)$$

The gradient of E_ω between the hidden and input layers is determined according to the following equation.

$$\frac{\partial E_\omega}{\partial W_{ji}} = \frac{\partial E_\omega}{\partial nn_j} . \frac{\partial nn_j}{\partial W_{ji}} = \frac{\partial E_\omega}{\partial nn_j} . y_i \quad (38)$$

The error term to be propagated is given by:

$$\delta_j = \frac{\partial E_\omega}{\partial nn_j} = \sum \frac{\partial E\omega}{\partial nn_k} . \frac{\partial nn_k}{\partial y_j} . \frac{\partial y_j}{\partial nn_j} \quad (39)$$

$$\delta_j = \sum \delta_k W_{kj} f^{'}(nn_j) \quad (40)$$

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

$$\frac{\partial E_\omega}{\partial y_k} = e_\omega^{mf} - k_\omega (d/dt)\omega_r \quad (41)$$

Where, x_i: is the inputs to the nodes of the input layer; $y_{i,j,k}$ is the outputs for the nodes of the input , hidden and output layers; $f_{i,j,k}$ is the sigmoid functions of input, hidden and output layers; W_{ji} is the weights between the input and hidden layers; W_{kj} is the weights between the input and hidden layers; $\phi_{k,j}$ is the bias in hidden and output layers; γ is the momentum factor; and ε is the learning rate.

7 Simulation Results of the PMSM Drive

The efficacies of the proposed scheme of PMSM drive system shown in Fig. 1 is verified by computer simulations based on MATLAB/SIMULINK [4, 16-17]. The parameters of the PMSM are given in Table (1). As mentioned before, this paper proposes a robust hybrid 2DOF I-PD NNMFC speed controller.

7.1 Dynamic Performance at Nominal Parameters

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. 6-7. The disturbance rejection capabilities have been checked when a load of 3.6 N.m is applied to the shaft at t = 0.75s and removed after a period of 1.8s. The simulation results of the proposed 2DOF I-PD speed controller are shown in Fig. 6 that includes the command and actual responses for speed, load regulation, torque, *d-q* axes stator currents while the dynamic performance utilizing the proposed hybrid 2DOF I-PD NNMFC speed controller are represented in Fig.7. These Figures clearly illustrate good dynamic performances in command tracking and load regulation performance are realized for both controllers.

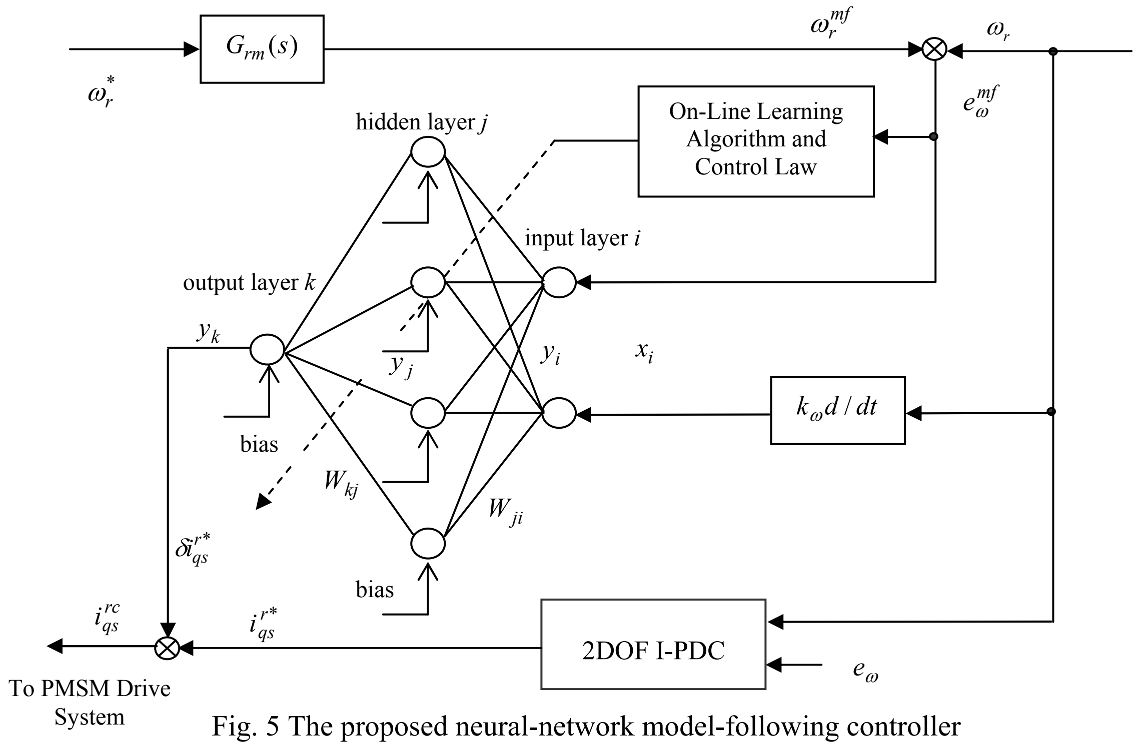

Fig. 5 The proposed neural-network model-following controller

Improvement of the control performance by augmenting the proposed 2DOF I-PD NNMFC speed controller can be observed from the obtained results in command tracking and load regulation characteristics as illustrated in Fig. 8. It is clear from this Figure that the proposed 2DOF I-PD NNMFC 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 8 rad/sec. While the 2DOF I-PD speed controller gives a slow response for the reference and a large dipping in speed of about 35 rad/sec. The model-following response and model-following error (MFE) for the PMSM drive system with both speed controllers are shown in Fig. 9. It is evident that from this Figure an obvious model-following error (MFE) due to the 2DOF I-PD speed controller reaches to 60 rad/sec while the MFE due to 2DOF I-PD NNMFC speed controller is about 5 rad/sec. Therefore, the proposed model-following neural network controller provides a good model-following response.

7.2 Consideration of Parameter Variations

The robustness of the proposed 2DOF I-PD NNMFC approach against large variations of PMSM parameters and external load disturbances has been simulated for demonstration. The simulation results of the dynamic response for both speed controllers are plotted in Figs. 10-12. To investigate the effectiveness of the proposed hybrid speed controller, three cases with parameter variations in the motor inertia and load torque disturbance are considered. The following possible ranges of parameter variations and external disturbances are considered.

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

Case 2: $J_m=0.25\times J_m*$, T_L=0-3.5 *N.m*.

Case 3: $J_m=5\times J_m*$, T_L=0-3.5 *N.m*.

The speed response and the load regulation performance of the drive system with the 2DOF I-PD and 2DOF I-PD NNMFC speed controllers are shown in Figs. 10-11 under the three cases of PMSM parameter variations. Fig. 10 illustrates the speed tracking and torque responses for both speed controllers. At the same conditions, the load regulation performance and torque response are given in Fig. 11. The results shown in Figs. 10-11 clearly indicate that as the variations of the PMSM parameters occurred, the responses deviate significantly from those nominal case with 2DOF I-PD speed controller but the 2DOF I-PD NNMFC speed controller confirms the correct operation and slightly influenced by parameter variations. The results confirm the robust performance with the 2DOF I-PD NNMFC speed controller. The model-following error for both controllers under parameter variations are shown in Fig. 12. We can observe from this Figure that a large MFE with 2DOF I-PD speed controller while the MFE is very small and insignificantly affected by parameter variations utilizing 2DOF I-PD NNMFC speed controller. From the above simulation results, it is evident that the 2DOF I-PD NNMFC speed controller illustrates satisfactory performance of the PMSM 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 speed dip and recovery time, than those obtained by the 2DOF I-PD speed controller.

8 Conclusions

This paper proposes a robust hybrid 2DOF I-PD NNMFC speed controller for PMSM drive system under FOC which guarantees the robustness in the presence of parameter variations. Quantitative design procedures for the 2DOF I-PD and 2DOF I-PD NNMFC controllers have been successfully developed. First, the I-PD speed 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 drive system. The performance of the drive system is still sensitive to parameter variations using the 2DOF I-PD speed controller. To solve this problem, a NNMFC with on-line learning was designed and added to the 2DOF I-PD 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 in order to make the drive system to follow the reference model. 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. 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 NNMFC speed controller grant accurate tracking and regulation characteristics in the face of PMSM parameter variations and external load disturbance. Also, a robust model-following tracking response is obtained utilizing the I-PD NNMFC speed controller.

Appendix: PMSM Parameters

Table 1. Machine parameters

Type: three-phase PMSM, 1 hp, 4 poles, 208 V, 60 Hz, 1800 rpm, Voltage constant: 0.314 V.s/rad, Torque constant: 0.95 N.m/A, R_s=1.5 Ω, L_{ss}=L_d=L_q=0.05 H, J_m=0.003 kg.m^2, β_m=0.0009 N.m/rad/sec

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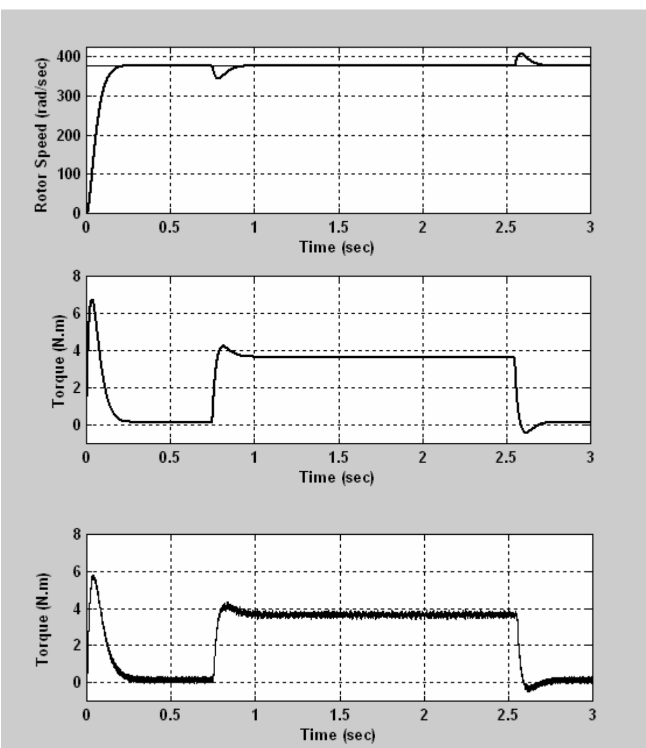
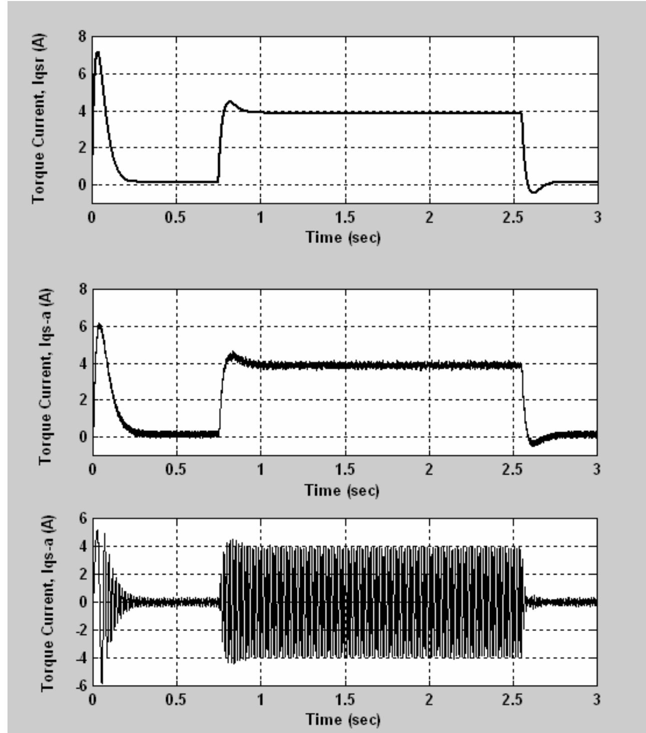
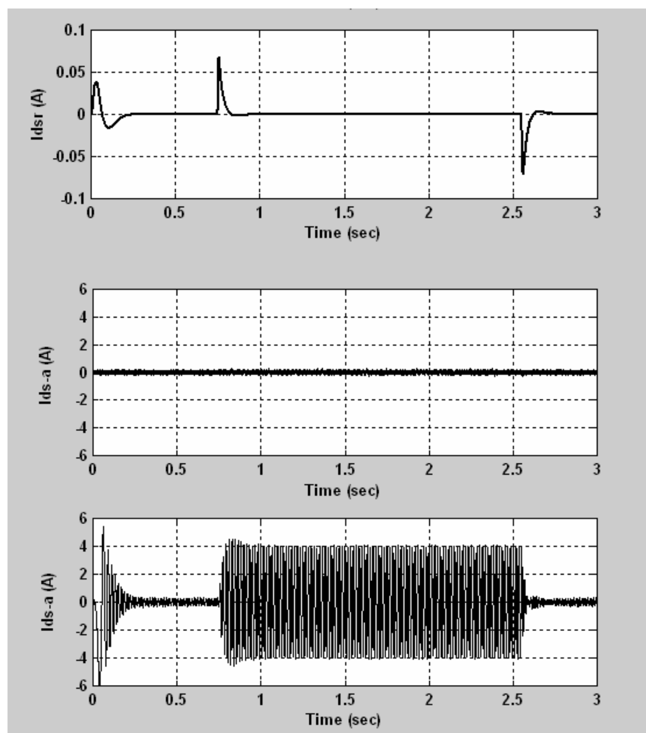


(a)

Fig. 6 Step speed response for a reference speed of 377 rad/sec and loading of 3.6 N.m using 2DOF I-PD speed controller. (a) Speed and torque responses.



(b)

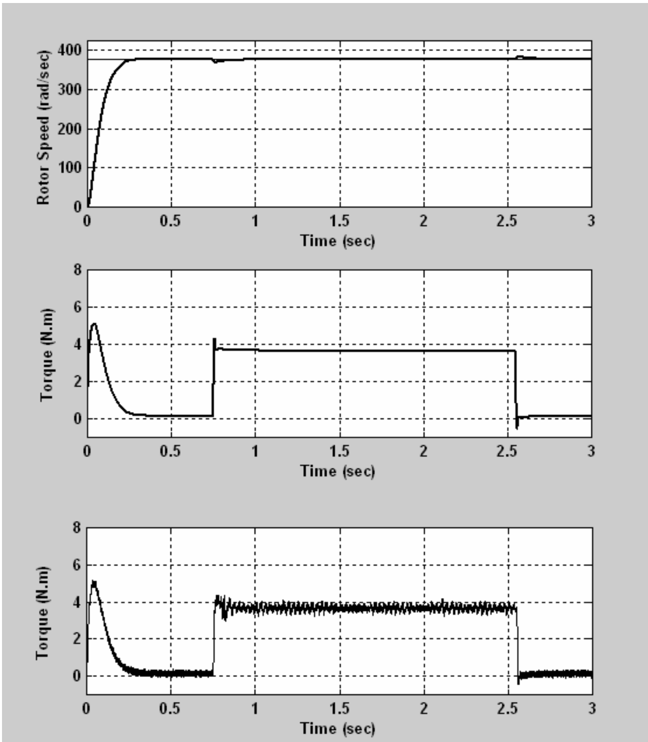


(c)

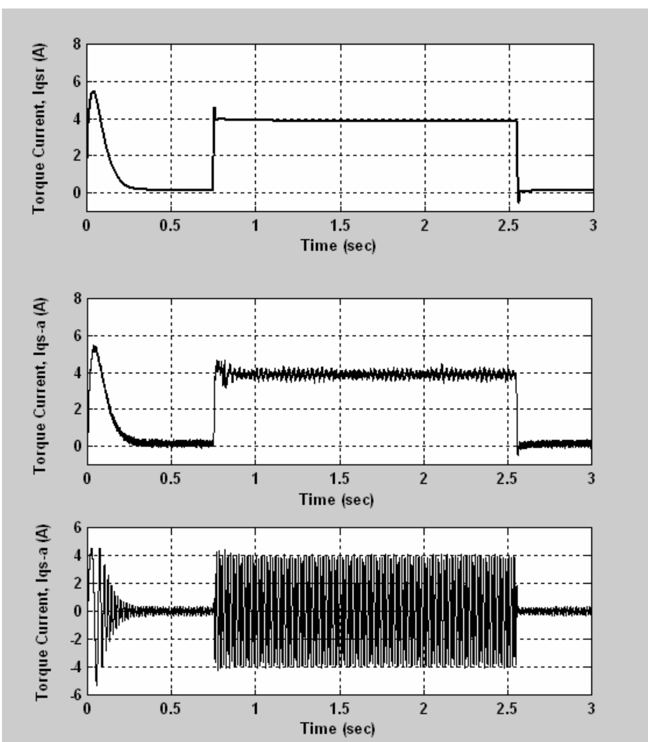
Fig. 6 Continued

(b) Reference and actual *q*-axis stator current responses

(c) Reference and actual *d*-axis stator current responses

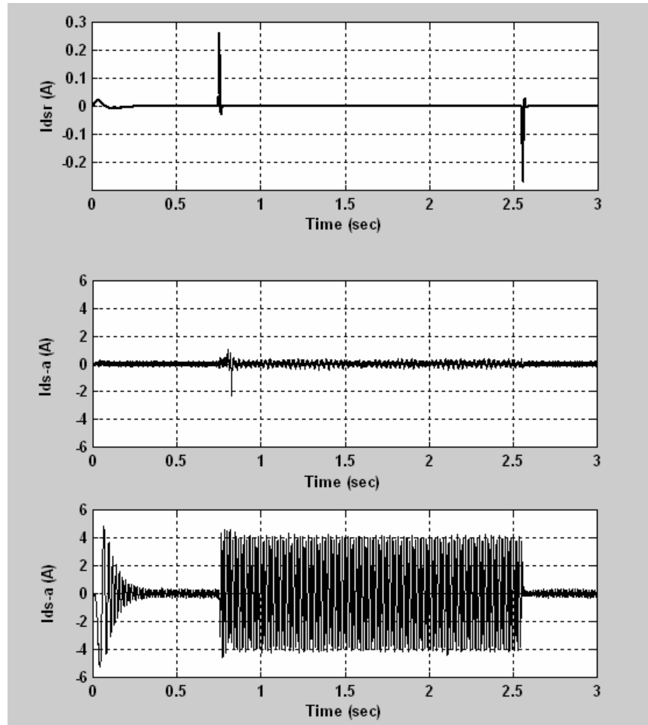


(a)



(b)

Fig. 7 Step speed response for a reference speed of 377 rad/sec and loading of 3.6 N.m using 2DOF I-PD NNMFC speed controller. (a) Speed and torque responses. (b) Reference and actual *q*-axis stator current responses.



(c)

Fig. 7 Step speed response for a reference speed of 377 rad/sec and loading of 3.6 N.m using 2DOF I-PD NNMFC speed controller, continued

(c) Reference and actual *d*-axis stator current responses

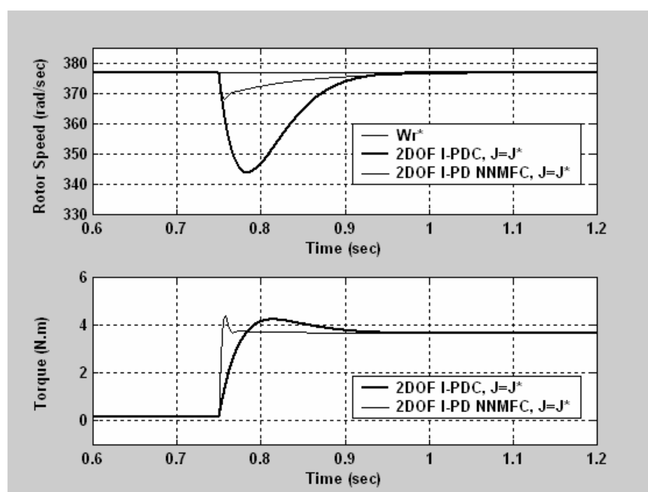


Fig. 8 Comparison between the load regulation performance for both speed controllers with nominal parameters

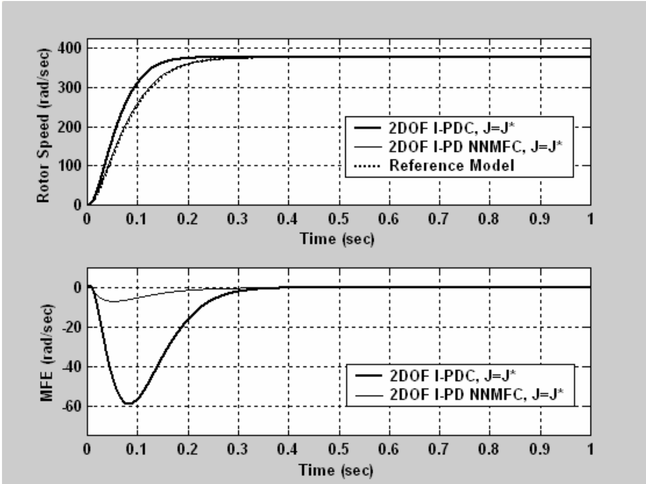
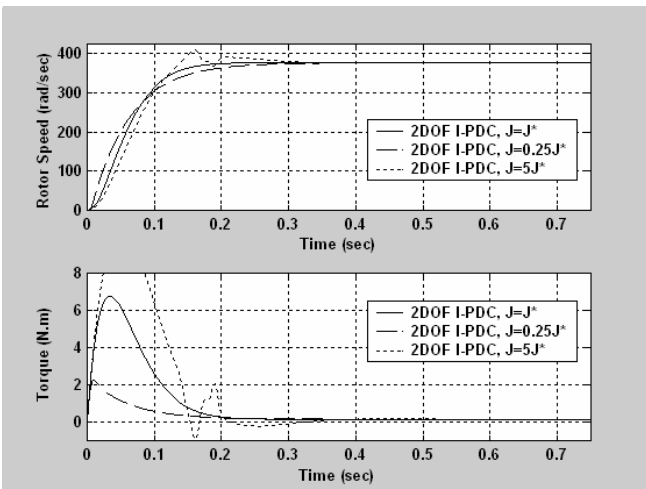
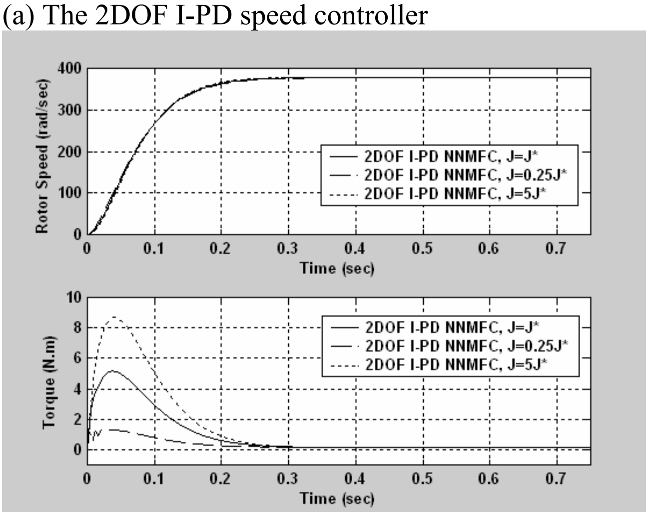


Fig. 9 The speed tracking response and (MFE) for both speed controllers under nominal parameters



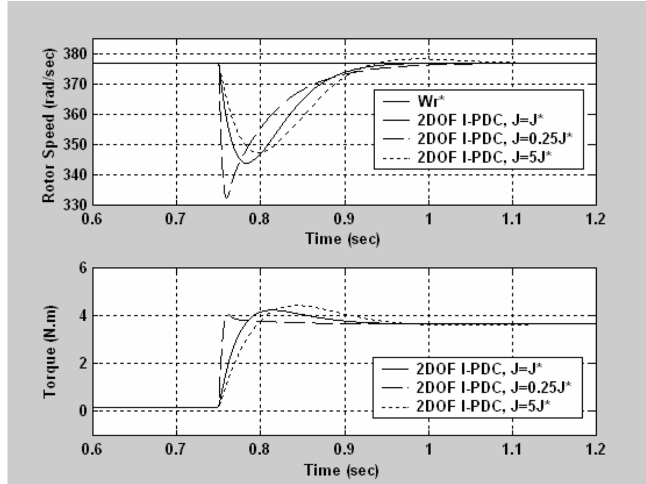
(a)

Fig. 10 The speed model following response of the drive system under parameter variations
(a) The 2DOF I-PD speed controller

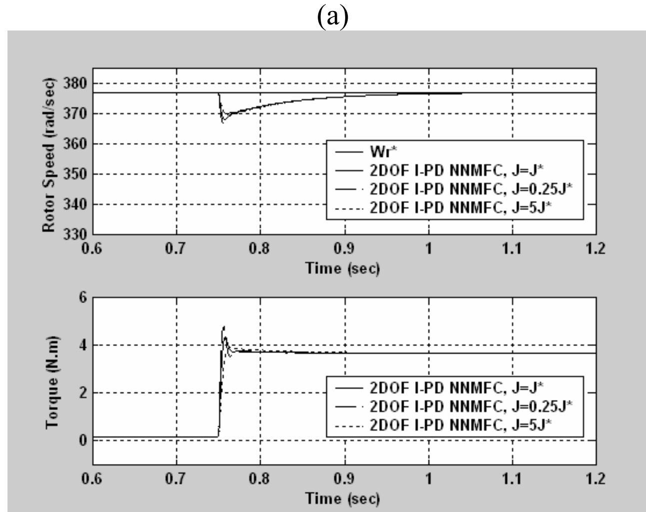


(b)

Fig. 10 Continued, (b) The 2DOF I-PD NNMFC



(a)



(b)

Fig. 11 The the load regulation performance of the drive system under parameter variations
(a) The 2DOF I-PD speed controller
(b) The 2DOF I-PD NNMFC speed controller

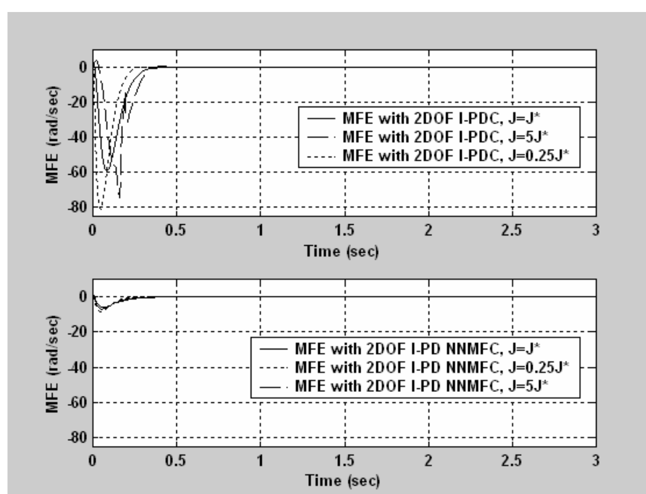


Fig. 12 The model-following error (MFE) for both speed controllers under parameter variations