Robust Adaptive Sliding-Mode Fuzzy-Neural-Network Model-Following Position Control of PMSM Servo Drives for Robotic Applications

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Abstract

In this paper, an intelligent sliding-mode controller (SMC) for achieving favorable decoupling control and high precision position tracking performance of permanent-magnet synchronous motor (PMSM) servo drives is proposed. The intelligent position controller consists of a SMC in the position feed-back loop in addition to an on-line trained fuzzy-neural-network model-following controller (FNNMFC) in the feed-forward loop. The intelligent position controller combines the merits of the SMC with robust characteristics and the FNNMFC with on-line learning ability for periodic command tracking of a PMSM servo drive. The theoretical analyses of the SMC are described with a second order switching surface which is insensitive to parameters uncertainties and external load disturbances. The FNNMFC generates an adaptive control signal which is added to the SMC output to attain robust model-following characteristics under different operating conditions regardless of parameter uncertainties and load disturbances. The results of simulations confirm that the proposed SMC with FNNMFC grants robust performance and precise response to the reference model regardless of load disturbances and PMSM parameter uncertainties.

Keywords: PMSM Servo Drives, Sliding-Mode Control, Fuzzy-Neural-Network, Model Following Control

1 Introduction

The permanent–magnet synchronous motor (PMSM) servo drives play a vitally important role in high-performance motion-control applications such as industrial robots and machine tools. Utilizing the field-oriented control (FOC) technique simplifies the dynamic model of the PMSM and control scheme [1–10]. In recent years, the variable structure control (VSC) with sliding-mode or sliding-mode control (SMC) has received much attention to control PMSM servo drives because it can offer good properties such as insensitivity to parameter variations, external load disturbance and fast dynamic response. The first step of SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space. Then, the controller is designed such that the system state trajectories are forced toward the sliding surface. The sensitivity of the controlled system to uncertainties exists only in the reaching phase. Thus, the system dynamic in the reaching phase is still influenced by uncertainties. To keep robustness in the whole sliding-mode control system, several researchers have focused on eliminating the effects of uncertainties [3–6]. Intelligent control techniques in many researches have been developed to improve the performance of the PMSM servo drives. The concept of incorporating fuzzy logic into a neural network has grown into a popular research topic. The fuzzy neural network (FNN) possesses both their advantages; it combines the capability of fuzzy reasoning in handling uncertain information and the capability of artificial neural networks in learning from process. However, the adaptive control schemes of PMSM servo drives that incorporate the techniques of FNNs have also grown rapidly [7–10].

The aim of this paper is to design a proposed intelligent SMC for PMSM servo drive system. The intelligent position controller consists of a SMC in the position feed-back loop in addition to an on-line trained FNNMFC in the feed-forward loop. First, the SMC is designed and applied to the control of the rotor position of the PMSM servo drive. In the sliding-mode control system, when the sliding mode occurs, the servo drive system dynamic behaves as a robust state feedback control system. Then, a proposed on-line trained FNNMFC system is designed in addition to the SMC to improve the dynamic performance and to preserve a favorable model-following characteristics under various operating conditions of the servo drive system. In the proposed FNNMFC, the error between the reference model and the PMSM servo drive system output is used to train the connective weights and membership functions of the FNN. The output of the FNNMFC is added to the SMC output to compensate the error between the reference model and the PMSM servo drive system output under parameter uncertainties and external load disturbances. The dynamic performance of the PMSM servo drive system has been studied under load changes and parameter uncertainties. The simulation results are given to demonstrate the effectiveness of the proposed robust non-linear intelligent sliding-mode controller.

2 Robust Intelligent Sliding-Mode Control

2.1. Problem Formulation

To solve the problems of uncertainties, an intelligent SMC is proposed to increase the robustness of the FOC-

PMSM servo drive system. The proposed intelligent robust position controller combining the SMC and the FNNMFC. Utilizing FOC, the proposed intelligent PMSM servo drive can be simplified to the control system block diagram as shown in Fig. 1. The adaptive control law is designed as:

$$i_{qs}^{rc}(t) = U_{SMC}(t) + U_{FNNMFC}(t) = i_{qs}^{r*}(t) + \delta i_{qs}^{r*}(t) \qquad (1)$$

The q-axis current command, i_{qs}^{r*}, is generated from the SMC and δi_{qs}^{r*} is the adaptive control signal generated from the proposed FNNMFC to automatically compensate the performance degradation due to load disturbances and PMSM parameter uncertainties. The inputs to the SMC are the position error, e_θ, and the rotor speed ω_r to construct the sliding surface $S(t)$ and the sliding-mode control law to get the q-axis current command, $U_{SMC} = i_{qs}^{r*}$. While the inputs to the FNNMFC are the error between the reference model and actual rotor position, e_θ^{mf}, and the rate of change of the rotor position (speed), $K_\theta \dot\theta_r$. Those signals are used to train the connective weights and membership functions of FNNMFC. The output of the FNNMFC is the adaptive control signal, $U_{FNNMFC} = \delta i_{qs}^{r*}$.

$$e_\theta^{mf} = (\theta_r^{mf} - \theta_r)\,,\ \dot\theta_r = k_\theta d\theta_r / dt \qquad (2)$$

2.2 Sliding-Mode Position Controller

The sliding-mode control of the PMSM servo drive system is shown in Fig. 1. By considering the dynamics with parameter variations, disturbance load and unpredictable uncertainties will give:

$$\ddot\theta_r(t) = A_{mn}\dot\theta_r(t) + B_{mn}.U(t) + L(t) \qquad (3)$$

$$L(t) = \Delta A_m \dot\theta_r(t) + \Delta B_m.U(t) + (D_{mn} + \Delta D_m)T_L \qquad (4)$$

where ΔA_m, ΔB_m and ΔD_m are the uncertainties due to mechanical parameters J_m and β_m and $L(t)$ is called the lumped parameter uncertainty and is defined as:

The bound of the lumped parameter uncertainty is assumed to be $|L(t)| \le K_f$. The objective is to design a control law so that the rotor position of the PMSM can track any desired command. To achieve this control objective, we can define the error function $e_\theta(t) = (\theta_r(t) - \theta_r^*(t))$. The sliding surface can be defined as a PID performance measure with the positive constants K_1, K_2 and K_3 that are chosen based on the desired system response.

$$S(t) = K_1 e_\theta(t) + K_2 \dot e_\theta(t) + K_3 \int_0^t e_\theta(\tau)d\tau \qquad (5)$$

In (5), with K_2=1, differentiating $S(t)$ with respect to time and using the error position function $e_\theta(t)$, the tracking control law can be derived from (3-5), $U_{SMC}(t)$, so that the rotor position, θ_r, remaining on the sliding surface, $S(t)$, for all t>0. The sliding-mode control objective is given by (6). The first term in (6) describes the desired system performance, the second term is a torque estimator which is able to compensate for the nonlinear effect in the PMSM model, while the third term keeps the PMSM servo drive system dynamics on the sliding surface, $S(t)$=0 for all the time. To keep the trajectory in the sliding surface, the selection of the control gain , K_f, is very important due to its significant effect on the magnitude of the lumped parameter uncertainties of the PMSM servo drive system and hence its performance. The incorrect selection of this control gain will yield to the deviation from the sliding surface and causing chattering phenomena. To solve this problem an adaptive control signal, $U_{FNNMFC} = \delta i_{qs}^{r*}$, is generated from the proposed on-line trained FNNMFC to compensate for the error in the control effort of the sliding-mode position controller, $U_{SMC} = i_{qs}^{r*}$.

$$\begin{aligned} U_{SMC}(t) = i_{qs}^{r*} &= B_m^{-1}[(\ddot\theta_r^*(t) - K_1 \dot e_\theta(t) - K_3 e_\theta(t)) \\ &- A_m \dot\theta_r(t) - K_f \operatorname{sgn}(S(t))] \end{aligned} \qquad (6)$$

2.3 Fuzzy-Neural-Network Position Controller

The online trained FNNMFC for a high-performance PMSM servo drive system integrates the ideas of the fuzzy logic controller and neural network structure into an intelligent control system.

(A) Architecture of the FNNMFC: The architecture details of the proposed four-layers FNNMFC, the signal propagation and the basic function in each layer are given in [7]. Nodes in the input layer represent input linguistic variables. Nodes in the membership layer act as the membership functions. All the nodes in the rule layer for a fuzzy rule base. In the proposed FNNMFC, an input layer (the i layer), a membership layer (the j layer), a rule layer (the k layer) and an output layer (the o layer) are two, six, nine and one respectively [8-9]. The nodes in layer 1 transmit the input signals to the next layer. Each node corresponds to one input variable. The input variables are the error signal, e_θ^{mf}, and the rate of change of the rotor position (speed), $K_\theta \dot\theta_r = K_\theta \omega_r$. The output of the FNNMFC is given by the following adaptive control signal.

$$U_{FNNMFC}(t) = \delta i_{qs}^{r*}(t) \qquad (7)$$

(B) On-Line Training Signal Analysis for FNNMFC: The details of the on-line training signal analysis for FNNMFC will be given in the full paper. The selection of parameters for the weights and membership functions has a considerable effect on the network performance. The connecting weights between rule layer and output layer are adjusted on-line in addition to the weights and the membership functions. To describe the on-line learning algorithm of the FNNMFC using the supervised gradient descent method, the energy function is chosen as in (8).

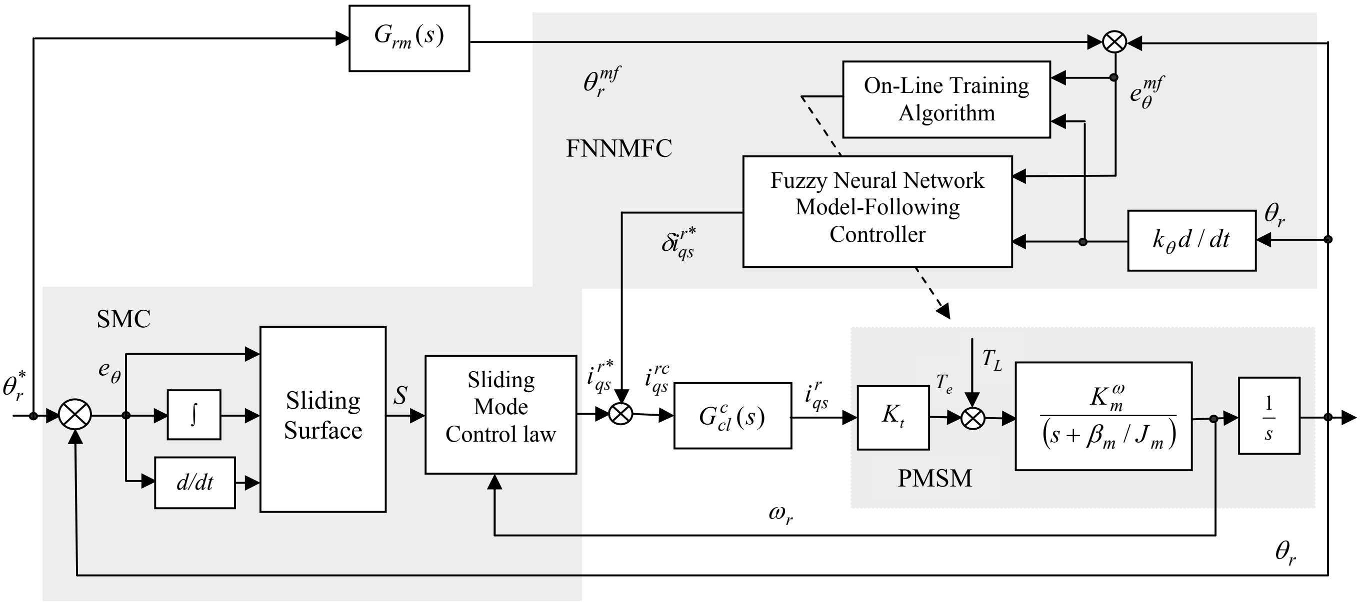


Fig. 1. Configuration of the proposed intelligent sliding-mode FNNMFC for a vector controlled PMSM servo drive system

The learning algorithm based on the backpropagation method is described in [10]. To overcome the problem of uncertainties of the PMSM due to parameter variations and to increase the on-line learning rate of the network parameters, a control law is proposed as in (9).

$$E_\theta = \frac{1}{2}(\theta_r^{mf} - \theta_r)^2 = \frac{1}{2}(e_\theta^{mf})^2 \tag{8}$$

$$\delta_o^4 = e_\theta^{mf} + K_\theta \dot{\theta}_r \tag{9}$$

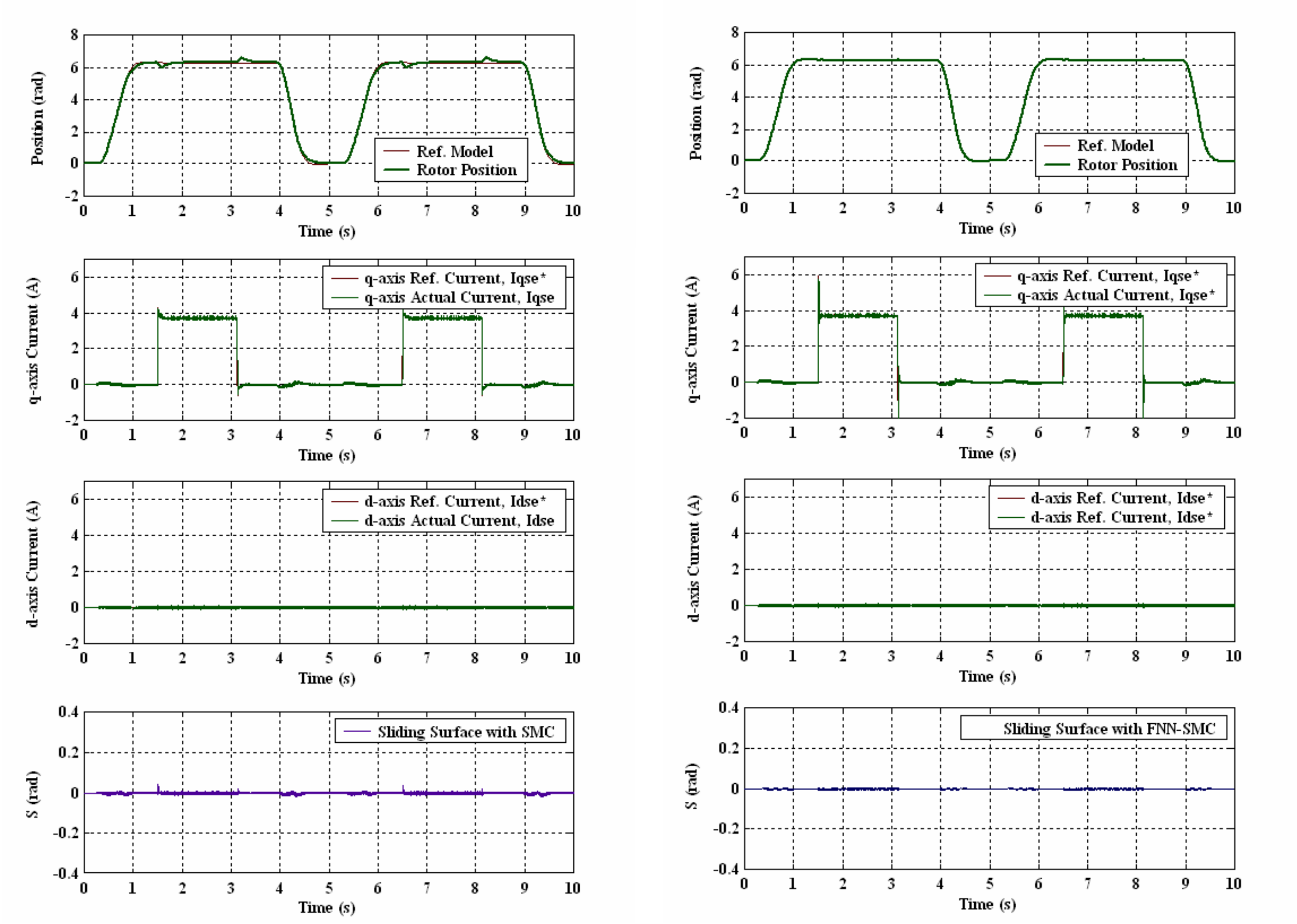
3 Simulation Results

To investigate the effectiveness of the proposed intelligent sliding-mode position controller, five cases with parameter uncertainties are considered. The PMSM used in this drive system is a three-phase type, 1 hp, four poles, 208 V, 60 Hz, 1800 rpm and has the parameters, voltage constant= 0.314 V.s/rad, 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.

Case 1: 1.0×(R_s and L_s), 1.0×(J_m and β_m), 1.00×λ_m,
Case 2: 0.5×(R_s and L_s), 0.5×(J_m and β_m), 1.00×λ_m
Case 3: 1.5×(R_s and L_s), 3.0×(J_m and β_m), 1.00×λ_m
Case 4: 1.0×(R_s and L_s), 1.0×(J_m and β_m), 0.85×λ_m
Case 5: 1.0×(R_s and L_s), 1.0×(J_m and β_m), 1.25×λ_m

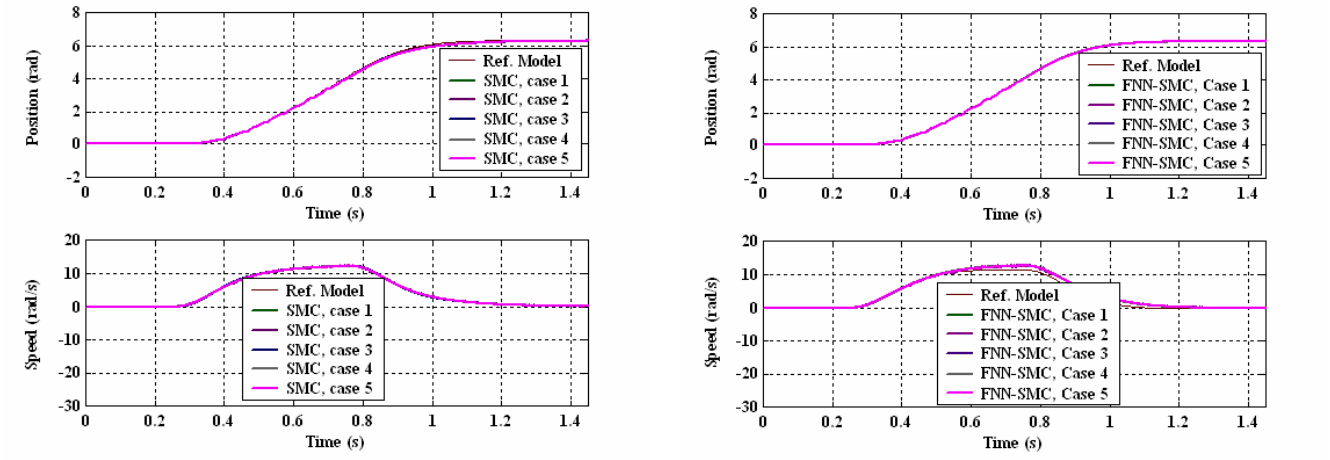
The dynamic performance of the drive system due to reference model of 2π rad under subsequent loading of 0-3.6 N.m is predicted as illustrated in Fig. 2 at Case 1. The disturbance rejection capabilities have been checked when a load of 3.6 N.m is applied to the shaft at t = 1.5 s and removed after a period of 1.625 s. These Figures clearly illustrate favorable tracking responses and robust characteristics in command tracking and load regulation performance are realized for both controllers. The sliding motion characteristics without reaching phase are obvious by determining the sliding-surface shown in Fig. 2.

Improvement of the control performance by augmenting the proposed FNNMFC to the SMC shown in Fig. 1 can be observed from the obtained results in command tracking and load regulation characteristics. The simulation results of the dynamic response for both position controllers under parameter variations are plotted in Figs. 3-4. The position response, speed response and the load regulation performance of the servo drive system with the SMC and SMC with FNNMFC are shown in Figs. 3-4 under the cases of PMSM parameter uncertainties. Fig. 3 illustrates the position and speed tracking responses for both position controllers. At the same conditions, the load regulation performance and torque current responses are given in Fig. 4. The results shown in these Figures clearly indicate that as the uncertainties of the PMSM parameters occurred, the responses deviate insignificantly from the nominal case for both SMC and SMC with FNNMFC but the SMC with FNNMFC confirms the correct operation and slightly influenced by full load conditions under the five cases of PMSM uncertainties. The proposed intelligent controller quickly returns the rotor position to the reference model under full load condition with a recovery time of 0.05s and a maximum dip of 0.053 rad while the SMC provides a slow response for the reference model under full load condition with a long recovery time of about 0.5s and a large dipping in the rotor position of about of 0.28 rad under the five cases of PMSM uncertainties. Therefore, robust control characteristics under occurrence of uncertainties can be clearly observed utilizing both the proposed position controllers. An obvious model-following error (MFE) due to the SMC reaches to 0.15 rad while the MFE due to SMC with FNNMFC is about 0.05 rad. Also, good model-following and tracking responses using SMC with FNNMFC at all cases of parameters uncertainties 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 SMC. Therefore, the SMC and SMC with FNNMFC are more suitable to control the rotor position of the PMSM servo drives considering the existence of parameters uncertainties.



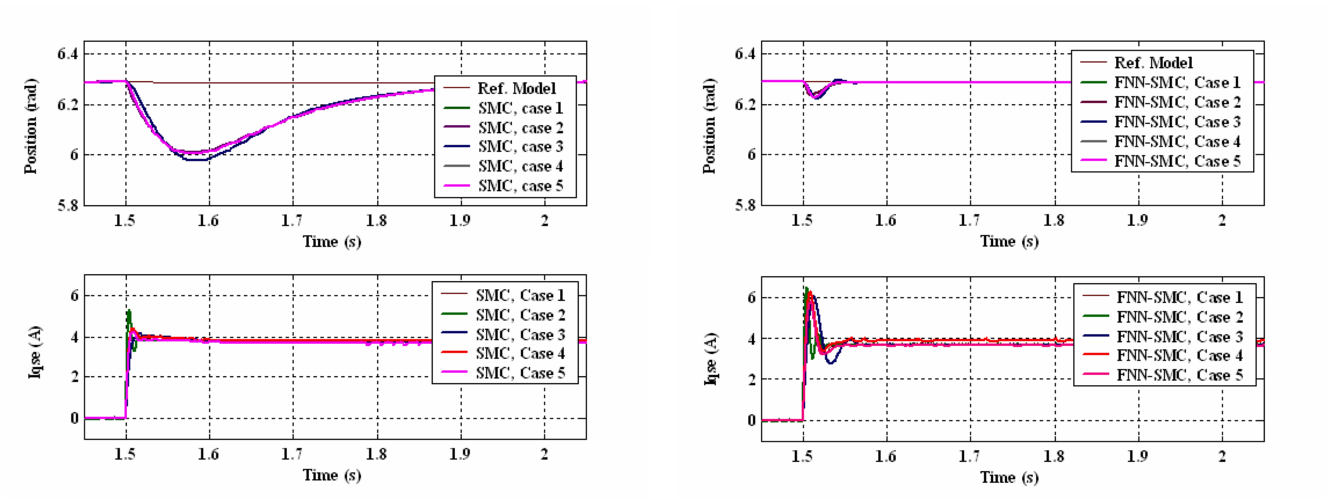
(a) Dynamic response using SMC (b) Dynamic response using SMC with FNNMFC

Fig. 2. Dynamic response for a reference model of 2π rad and loading of 3.6 N.m of the servo drive system for both position controllers



(a) Model-following response using SMC (b) Model-following response using SMC with FNNMFC

Fig. 3. The model-following position and speed responses of the servo drive system under parameter variations for both position controllers



(a) Load regulation performance using SMC (b) Load regulation performance using SMC with FNNMFC

Fig. 4. The load regulation performance of the servo drive system under parameter variations for both position controllers

4 Summary

This paper proposed a robust intelligent and adaptive position controller for PMSM servo drive system under field orientation control which guarantees the robustness in the presence of parameter uncertainties. The proposed robust position controllers (SMC and SMC with FNNMFC) consists of a feed-back SMC in addition to an on-line trained FNNMFC. The theoretical bases and the stability analyses of the proposed SMC and SMC with FNNMFC control systems were described in details. An adaptive control signal is generated from the proposed FNNMFC and was added to the SMC output to preserve good model-following response under various operating conditions. Simulation results have shown that the proposed SMC and SMC with FNNMFC grant robust model-following tracking response and good regulation characteristics in the presence of PMSM parameter uncertainties and external load disturbance. Finally, the major contributions of this paper are the successful development of the intelligent SMC system, in which a FNNMFC is utilized to compensate the uncertainty bound in the SMC system on-line and the successful application of the proposed SMC with FNNMFC system methodology to control the rotor position of the PMSM with the existence of parameters uncertainties.

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