Artificial Neural Network to Improve Speed Control of Permanent Magnet Synchronous Motor

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Abstract — This paper presents the design of a Neural Network based approach to improve efficiency in a vector control of Permanent Magnet synchronous Motors (PMSM). The conventional Proportional-Integral (PI) controller is largely used in industry because of the robustness this regulator procures. But in some case, when the dynamics of the system vary over time or with operating conditions, the performance of the controller will be spoiled. The Artificial Neural Networks (ANN) used as a speed controller seems to be a promising solution in this purpose.
In this study we apply a multivariable (MIMO) neural network regulator in place of PI controllers of the vector control scheme of the PMSM. Analysis and simulation results are presented to demonstrate the validity of the proposed controller to ensure robustness against load and parameters variations and to achieve the required performances.

Keywords — Neural Networks, Vector Control, Permanent Magnet synchronous Motors.

1 Introduction

Recent developments in power semiconductor technology, digital electronics, magnetic materials and control theory have enabled modern ac motor drives to face challenging high efficiency and high performance requirements in the industrial sector. Due to its high efficiency, high power factor and robustness, the permanent magnet synchronous motor (PMSM) has been often used in high performance applications such as robots and machine tools [1]. Usually high performance motor drive systems used in these domains require fast and accurate speed response, quick recovery of speed from any disturbance and uncertainties. This makes the control of PMSM difficult at different dynamic operating conditions.

To achieve the best dynamic behavior, the vector control method is often used so that the PMSM can achieve the dynamic performance capabilities of the separately excited DC machine, while retaining the general advantages of AC over DC motors [2]. The vector control is an efficient method to control a synchronous motor in adjustable speed drive applications in wide range of speeds. However, the performance of present methods is not good enough. The conventional proportional-integral (PI), used for the speed and the currents in axis d and q, have some limitations, as their design depend on exact machine model and accurate parameters. Moreover, the conventional fixed gain PI controllers are very sensitive to disturbances such as parameter variation and load disturbances [3]. These difficulties lead to cumbersome the control design approach. On the other hand, the designs of intelligent controllers do not need the exact mathematical model of the system. Due to there capabilities to solving nonlinear problem by learning, Artificial Neural Networks are very useful in this area [4], [5].

In this work, a neural network controller is developed, for speed control of high performance PMSM drive systems, to improve efficiency of a vector control drive. Because of the electrical model of PMSM is nonlinear two inputs two outputs systems which need a multivariable current controller, we propose in this paper a new multi input multi output (MIMO) neural network controller to replace both of the speed regulator and d-q axis currents regulators. Firstly, the latter were designed in conventional way. In the second step, an ANN-based MIMO controller will be used.

Thus, the main objective of this paper is to develop and study an ANN controller that overcomes nonlinear nature of PMSM and ensure robustness of speed control against parameter variation and load disturbances.

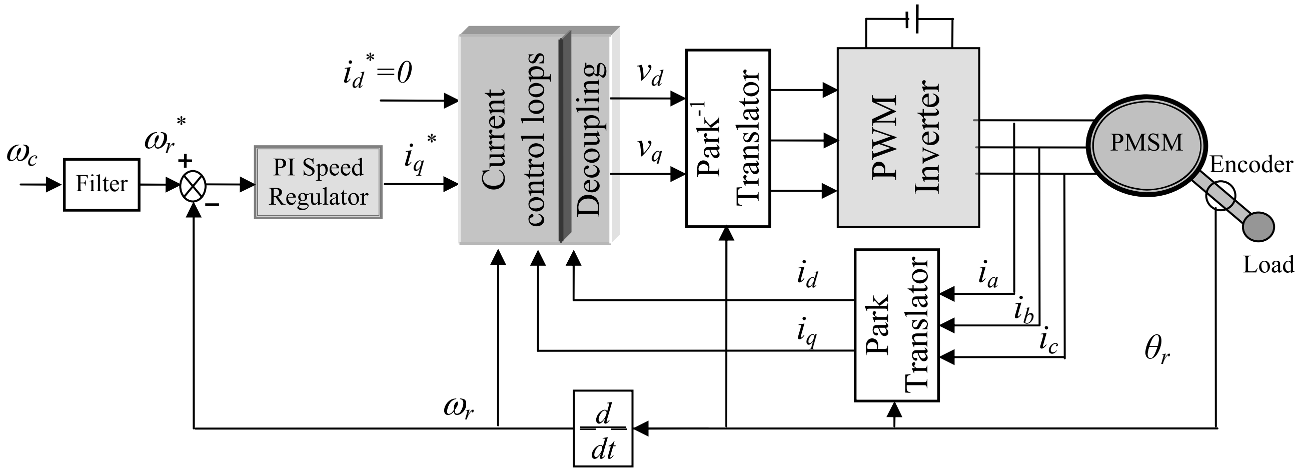


Fig. 1. Vector control structure of the PMSM drive

Simulation results are given to establish the performance and robustness of the proposed controllers at different operating conditions.

2 Motor Model of PMSM

The unsaturated mathematical model of a sinusoidal PMSM drive can be described by the following equations in a rotor d-q reference frame as [1], [6]:

$$v_d = Ri_d + L_d \frac{di_d}{dt} - L_q \omega_s i_q$$
$$v_q = Ri_q + L_q \frac{di_q}{dt} + L_d \omega_s i_d + \omega_s \psi_f \qquad (1)$$

with:

$$\psi_d = L_d i_d + \psi_f$$
$$\psi_q = L_q i_q \qquad (2)$$

The mechanical equation is:

$$J_m \frac{d\omega_r}{dt} = T_e - T_L - f_m \omega_r \qquad (3)$$

In which the electromagnetic torque is given by:

$$T_e = P\left[(L_d - L_q) i_d i_q + \psi_f i_q\right] \qquad (4)$$

where, v_d, v_q = d, q-axis stator voltages;
i_d, i_q = d, q-axis stator currents;
R = stator resistance;
L_d, L_q = d, q-axis stator inductances;
T_e, T_L = electromagnetic and load torques;
J_m = moment of inertia of the motor and load;
f= friction coefficient of the motor;
P = number of pole pairs;
ω_r = rotor speed in angular frequency;
p = differential operator (=d/dt);
ψ_f = rotor magnetic flux linking the stator.
The inverter frequency is related as follows: $\omega_s = P\omega_r$

3 Vector Control of a PMSM

The basic principle in control of PMSM drive is based on field orientation. The flux position can be determined by the shaft position sensor because the magnetic flux generated by permanent magnet is fixed in relation to the rotor shaft position [6], [7]. To ensure the vector control of the PMSM, the technique i_d=0 is the optimal strategy where the motor produce the maximum torque. If i_d is forced to be zero by closed loop control, then:

$$\psi_d = \psi_f \qquad (5)$$

and

$$T_e = P\psi_f i_q \qquad (6)$$

Since ψ_f is constant, the electromagnetic torque is then directly proportional to current i_q. The torque equation is similar to that of separated excited DC motor. It is evident from equations (3) and (6) that the speed control can be achieved by controlling the q-axis current component i_q as long as the d-axis current i_d is maintained at zero.
After decoupling the d,q-axis components i_d and i_q, the field oriented PMSM drive scheme is shown in Fig. 1.

4 Artificial Neural Network Controller

4.1 Speed ANN controller

The control objective aims to bring the motor speed ω_r to the desired speed reference ω_r^*.
To replace the PI speed controller in Fig. 1, the new ANN controller must describe the relationship between

the q-axis current i_q and the speed error $\Delta\omega_r = \omega_r^* - \omega_r$.

After some performed tests, the most convenient ANN architecture is proven to be as depicted in Fig. 2. This feedforward network is structured with four inputs, one hidden layer with 5 neurons and one output. This simple structure is chosen in order to reduce the memory space and computational time.

A nonlinear sigmoid transfer function is used in the hidden layer and a linear transfer function is used in the output layer. The inputs are the speed error in present and previous two sample times, and previous sample time q-axis current. The output target is the q-axis reference current.

To train the designed neural network, it is necessary to have enough sets of input-output patterns. Since our aim is to obtain an ANN speed controller witch cover all the drive speed range and operating conditions, the appropriate input and output vectors for the ANN are obtained by the simulation of the vector control scheme of the PMSM drive using the best PI regulator for different operating points.

The training process is performed off-line and accomplished using the Levenberg-Marquardt back-propagation algorithm [5].

A step reference speed input is applied to the closed loop system. During this time, i_q current and rotational speed responses are collected. This data is then used to train the neural network. The output of the network, representing the control input, is compared with the known PI regulator output and the error is used to adjust the network weights [5]. The training process is represented in Fig.3 with the mean square error (MSE) convergence and the validation test of the obtained ANN.

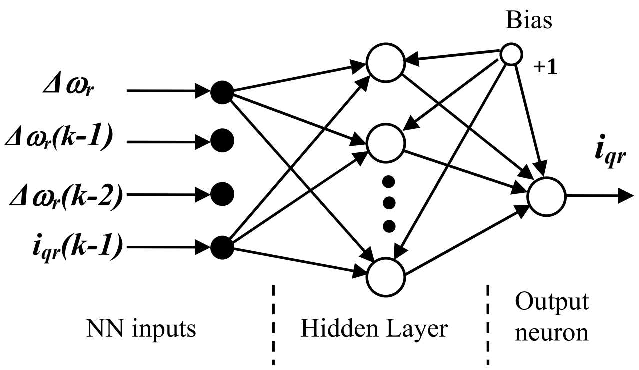
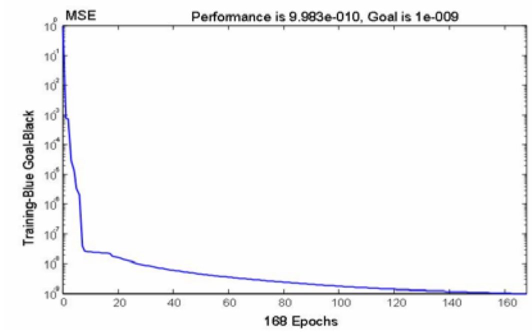
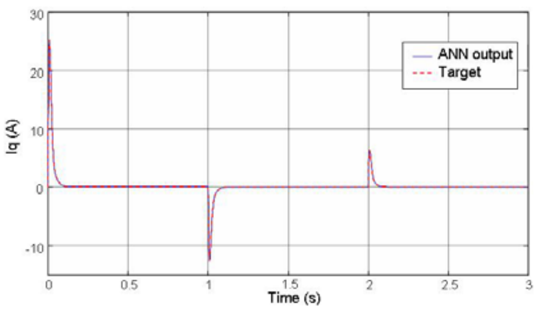


Fig. 2. Architecture of the ANN



(a) Mean Square Error convergence



(b) ANN Validation test

Fig. 3. Training neural network results

4.2 ANN-based MIMO controller

The new multi input multi output based ANN controller replace both of the speed regulator and d-q axis regulators in the classical vector control scheme. This controller can realize the multivariable control of the currents d-q components and the rotor speed performance goal.

The structure of the ANN-based MIMO controller is chosen after some performed tests referring to the performance goal achieved with in MSE convergence and complexity of the network with respect to the number of computations and running time.

The 3-layers neural network obtained after training and validation tests have 8 input nodes, 4 hidden nodes and 2 output node as shown in Fig. 4. The sigmoid transfer function is retained for the hidden layer and linear transfer function for the output layer. The same training algorithm used in the simple ANN controller is used in this case.

5 Results and Discussion

The parameters of the PMSM motor used in this work are given in Table 1.

In order to validate the efficiency of the proposed ANN controllers, the performance of the PMSM drive based on the proposed control scheme is investigated in simulation at different operating conditions. The complete controlled system has been simulated using Matlab/Simulink package.

The simulated motor speed and q-axis current component responses are presented. A reference speed trajectory is generated using a first order filter to avoid a

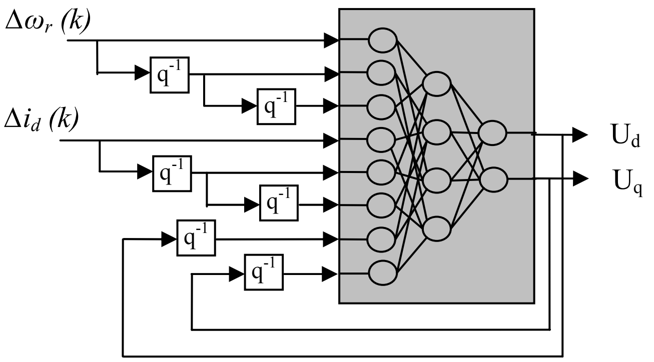


Fig. 4. Design of the MIMO neural network controller

Table 1
Machine Parameters

Motor rated power	2 kW
Rated speed	4000 r/min
Pole pairs number (P)	3
d-axis inductance, L_d	3,2 mH
q-axis inductance, L_q	3,2 mH
Stator resistance, R	1 Ω
Motor inertia, J_m	6 10^{-4} kg m^2
Friction coefficient, f_m	9,5 10^{-5} Nm s/rad
Magnetic flux constant, ψ_f	0,39 Nm/A

maximal current at the starting.

5.1 Speed ANN controller

In this case, we replace the PI speed regulator by a simple ANN controller with the structure given in Fig. 2. In Fig. 5, the performance of the conventional PI speed controller is tested. The results show the speed response to a reference trajectory in presence of step load torque disturbance at 3 levels of speed. The drive system begins from standstill to the speed reference set at 400 rad/s. A constant load step of 5 Nm is applied at t=0.3s and removed at t=0.8s. It can be seen from Fig. 5 that the rotor speed tracks the reference trajectory with zero steady-state error. The rotor speed does not change during the disturbance, while the current i_q reaches its new value corresponding to the applied load.

The test of robustness of this controller is given in Fig. 6, while a resistance parameter error is introduced (R=5R). The test shows the sensitivity of the conventional PI controller to parametric perturbation.

The use of the ANN controller in speed reference tracking with the presence of load disturbance is shown in Fig. 7.

The obtained speed response demonstrates the performance of the controller.

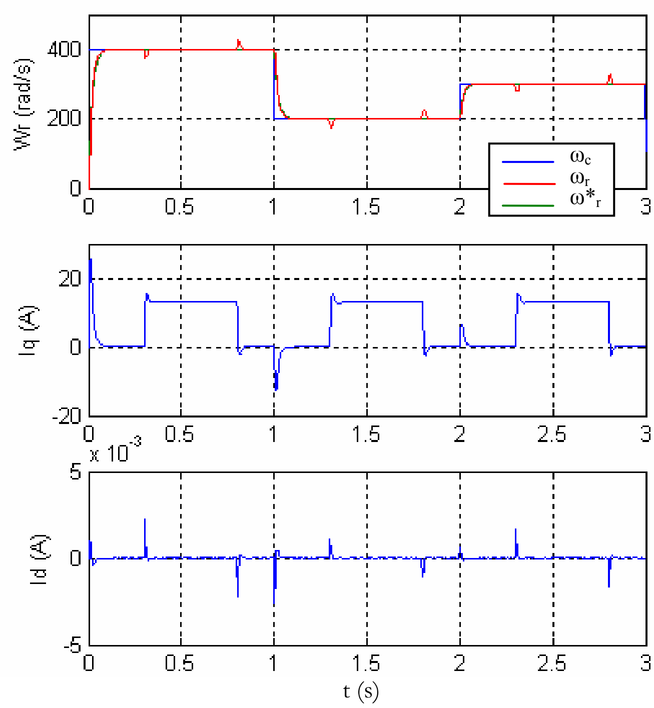


Fig. 5. Speed reference tracking response in presence of load disturbance using PI controller.

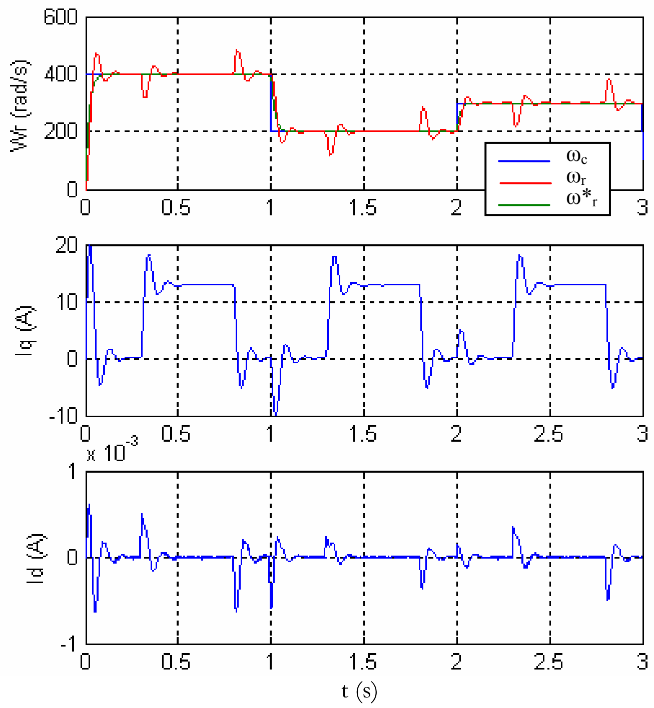


Fig. 6. Robustness against error in resistance parameter (R=5R) using PI controller.

To test the power of the proposed ANN, Figs. 8 and 9 give a comparison purpose of the robustness of the conventional PI and the ANN controller with a parameter variation of a 5R error of stator resistance and 3J_m error of inertia value. This test includes step change in speed reference and step load disturbance. We can

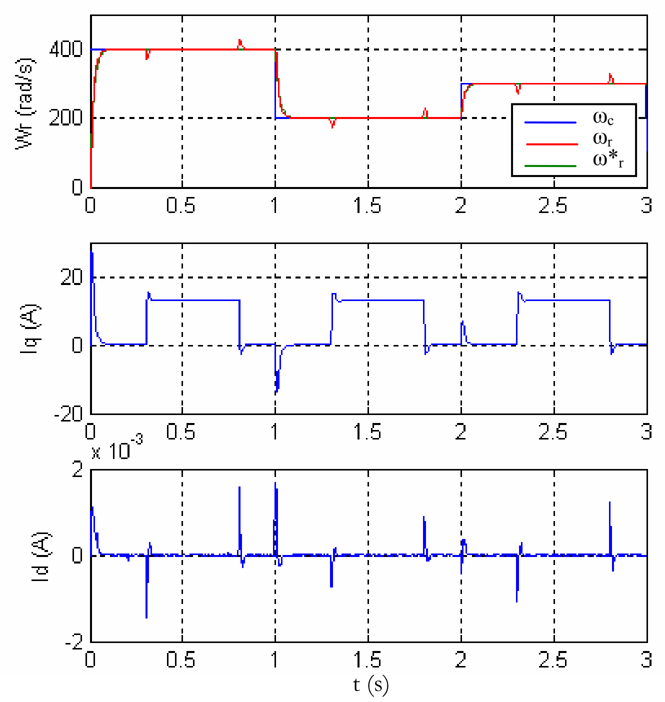


Fig. 7. Speed reference tracking response in presence of load disturbance using ANN speed controller

see that the rejection of the load disturbance with a small variation is ensured using ANN controller. This shows the capability of ANN controller to start from standstill condition to the rated speed as well as to reject the load disturbance in presence of parameter variation.

5.2 ANN-based MIMO controller

In this section, ANN-based MIMO controller with the structure given in Fig. 4, is used for both of the speed and the d-q axis current control.

Fig. 10 shows the speed reference tracking response in presence of load disturbance. This result is nearly the same as the previous neural controller.

The system robustness against $3J_m$ variation is given in Fig. 11. As can be seen, a small overshoot in the speed response appears but does not affect the control quality in the same way than in the previous control.

The Fig. 12 presents robustness test against parameters variation. The 3 curves correspond to the normal condition test, the inertia varying test and the resistance varying test. The tests results demonstrate that the obtained ANN-based MIMO controller meets difficulties to maintain the cost function imposed in presence of parameter disturbance. This is due to the complexity of the block replaced by the MIMO neural network which needs more investigation in terms of input features selection and the ANN structure.

It is evident from Figs. 11-12 that the proposed ANN-based MIMO speed controller is also capable of

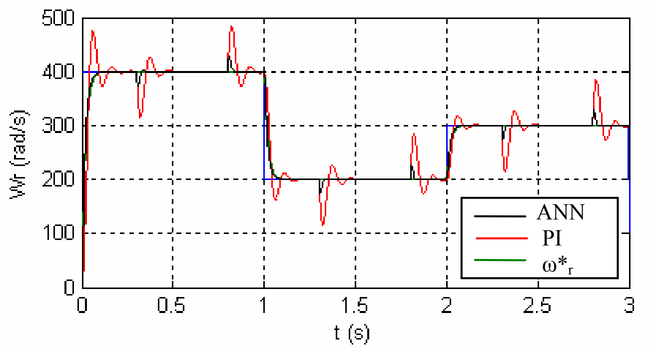


Fig. 8. Robustness against $5R$ variation using PI and ANN controller.

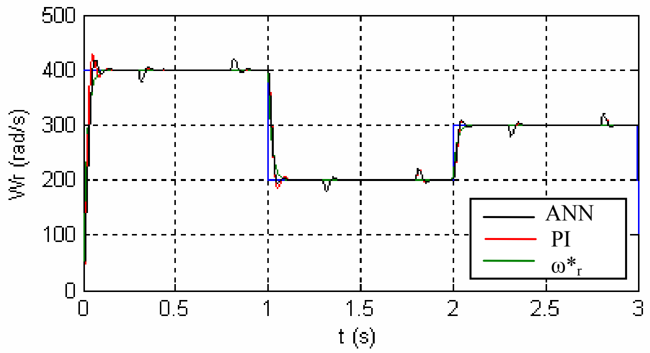


Fig. 9. Robustness against $3J_m$ variation using PI and ANN controller.

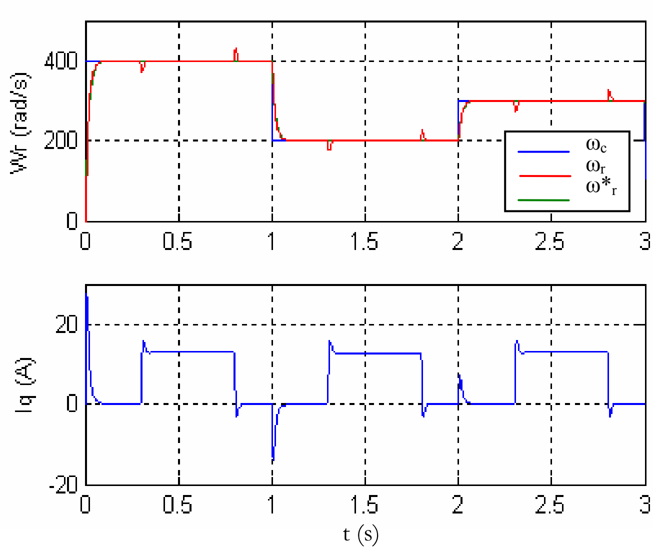


Fig. 10. Speed reference tracking response in presence of load disturbance using ANN-based MIMO controller.

tracking the speed command change and rejecting the load disturbance.

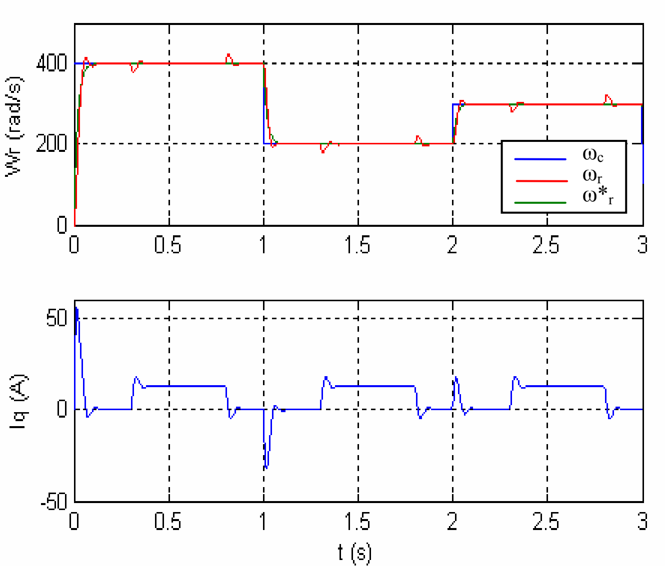


Fig. 11. Robustness against $3J_m$ variation using ANN-based MIMO controller.

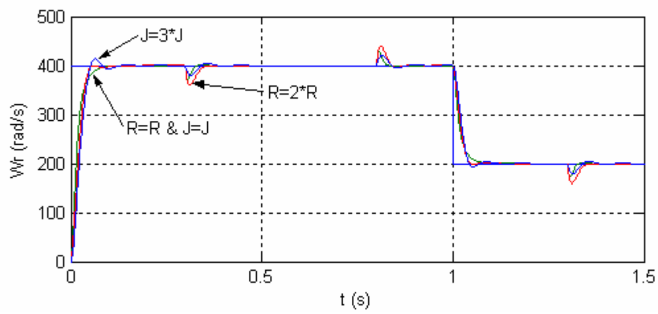


Fig. 12. Robustness against parameters variation using ANN-based MIMO controller.

6 Conclusions

The application of the ANN in speed PMSM drive and the new ANN-based MIMO controller to conduct the drive are considered in this paper. First, the neural controller was applied in place of the PI speed regulator. The effectiveness and ability of the proposed ANN controller has been demonstrated with simulation tests with regard to parameters and load disturbances. In order to verify the efficiency of the ANN-based controller, the simulation of the conventional PI regulator has also been carried out under the same conditions. The performance improvement of the ANN controller over the conventional PI regulator is clearly shown in the simulation results.

The ANN-based MIMO controller was synthesized in order to substitute the 3 PI conventional regulators in the speed PMSM control scheme. Very interesting performances in speed reference tracking with the presence of load disturbances as well as time varying parameters are obtained. Despite the fact that the proposed controller is sensitive to the stator resistance variation, it is suitable for real time applications.

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