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Improved BP-NN Controller of PMSM for Speed Regulation

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Abstract

We have studied the speed regulation of the permanent magnet synchronous motor (PMSM) servo system in this paper. To optimize the PMSM servo system's speed-control performance with disturbances, a non-linear speed-control technique using a back-propagation neural network (BP-NN) algorithm for the controller design of the PMSM speed loop is introduced. To solve the slow convergence speed and easy to fall into the local minimum problem of BP-NN, we develope an improved BP-NN control algorithm by limiting the range of neural network outputs of the proportional coefficient Kp, integral coefficient Ki of the controller, and add adaptive gain factor β, that is the internal gain correction ratio. Compared with the conventional PI control method, our improved BP-NN control algorithm makes the settling time faster without static error, overshoot or oscillation. Simulation comparisons have been made for our improved BP-NN control method and the conventional PI control method to verify the proposed method's effectiveness.

Keywords: *Improved BP Neural Network (BP-NN) Control Algorithm, Permanent Magnet Synchronous Motor (PMSM), Adaptive Gain Factor, Speed Regulation.*

1. Introduction

Permanent magnet synchronous motor(PMSM) has been widely developed and applied due to its high performance, such as compact structure, high air-gap flux density, and high efficiency. However, the PMSM is a non-linear and strongly coupled system [1]. The conventional proportional-integral (PI) control method, as one of the linear control methods, is easily affected by uncertain factors such as parameter variations and load disturbances, which cannot guarantee sufficiently high performance for the PMSM servo system [2]. To enhance the control performance, in recent years, many nonlinear control methods have been developed for the PMSM system. For example, Zhang proposed a novel sliding mode reaching law to suppress the chattering problem existing in sliding mode controllers [3]. Bolognani developed a new model predictive control method, speed and current controllers are combined together, instead of keeping the conventional cascade structure [4]. Sant used a hybrid fuzzy-PI controller to ensure that the motor has better dynamic performance and steady-

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state performance at the same time [5]. Wang proposed a new neural-network-based self-tuning PI control system. In this approach, a well-trained neural network supplies the PI controller with suitable gain according to each operating condition pair detected [6].

In neural network algorithms, Back-Propagation neural network (BP-NN) is well known for the ability to approximate any nonlinear function and the good effect on solving nonlinear modeling problems [7]. So it has been applied in many fields. Shi used BP neural network to improve classification performance in image recognition [8]. Cheng proposed an innovative nanopositioning control scheme for different travel lengths based on BP-NN proportional-integral-differential(PID) conrtoller [9]. However, the conventional BP algorithm has shortcomings of the slow convergence speed and easy to fall into a local minimum [10]. Therefore, an improved BP-NN control algorithm is developed in this paper by limiting the range of neural network outputs Kp, Ki and adding adaptive gain factor β.

The simulation results have validated that the servo system under the improved BP-NN controller method can obtain satisfying performance such as fast transient response, good disturbances rejection ability. By setting constant speed command of 700r/min with the conventional PI controller for PMSM starting, the simulation results shows the settling time is very long as 0.025s with an overshoot of 94r/min; however, with the improved BP-NN controller, the settling time is very short of 0.014 seconds without overshoot. Also, when the load torque of the PMSM is changed from 0 to 8N·m in the steady-state, the dynamic response for the conventional PI controller has a large speed fluctuation of about 28r/min and a long settling time of 0.02s. However, the speed fluctuation of PMSM is reduced as low as only 8r/min, and the recovery time is only 0.004s for the improved BP-NN controller.

2. Improved BP-NN Controller Algorithm for PMSM

2.1 Mathematical Model of PMSM

In this section, we perform the mathematical modeling on the interior of the PMSM. Suppose that the three-phase stator windings of PMSM are sinusoidally distributed in space; the PMSM model in the rotor *d-q* coordinates can be expressed as follows [11]:

$$\begin{cases} u_d = Ri_d + L_d \dfrac{di_d}{dt} - \omega_e L_q i_q \\ u_q = Ri_q + L_q \dfrac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_f \end{cases} \tag{1}$$

$$T_\mathrm{e} = \frac{3}{2} P_n [\psi_f i_q + (L_d - L_q) i_d i_q] \tag{2}$$

$$T_\mathrm{e} - T_l = J \frac{d\omega_m}{dt} + B\omega_m \tag{3}$$

$$\omega_\mathrm{e} = P_n \omega_m \tag{4}$$

where u_d and u_q represent the stator voltages of d and q axes, respectively; i_d and i_q are the stator currents of d and q axes, respectively; R is stator resistance; L_d and L_q are the stator inductances of d and q axes, respectively; ω_m the rotor mechanical angular velocity; ω_e the rotor electrical angular velocity; ψ_f the rotor flux linkage; T_e the electromagnetic torque; T_l the load torque; J the rotational inertia; B the viscous friction damping; P_n the number of pole pairs.

2.2 BP Neural Network Controller Algorithm

The control scheme based on BP neural network for the PMSM is shown in Figure 1. BP-NN is a multi-layer feedforward network based on "error back propagation algorithm training". The BP-NN controller takes the square of the error between the actual speed and the reference speed as the objective function and uses the gradient descent method to approximate the minimum value of the objective function in Figure 1. The BP neural network makes the actual speed of the PMSM converge to the reference speed quickly by optimizing the speed controller's proportional, integral, and differential coefficients continuously.

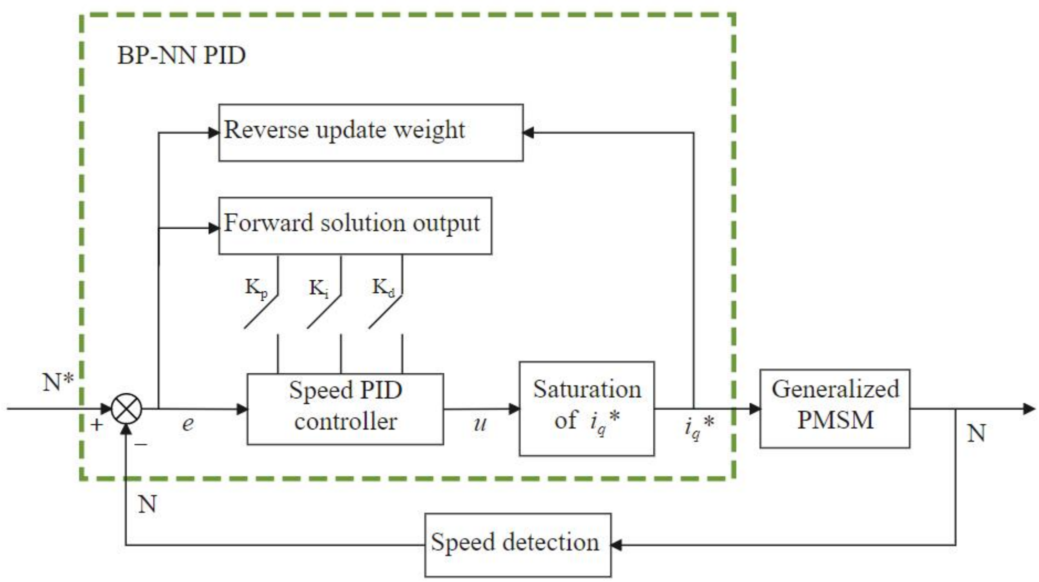


Figure 1. Block diagram of BP-NN controller for the PMSM system

Note that a limit is imposed on the commend current i_q*. From the consideration of saturation, the absolute value of i_q* should be limited not to exceed a given value i_{qmax}=25A. k represents the sampled value at the kth moment [2].

$$i_q^*(k) = sat(u(k)) = \begin{cases} u(k), & |u(k)| \le i_{q\max} \\ i_{q\max} \cdot sign(u(k)), & |u(k)| > i_{q\max} \end{cases} \tag{5}$$

Incremental digital PID control algorithm [10]:

$$u(k) = i_q^*(k-1) + K_p[e(k) - e(k-1)] + K_i e(k) + K_d[e(k) - 2e(k-1) + e(k-2)] \tag{6}$$

The structure of BP-NN is shown in Figure 2, it consists of input layer, hidden layer and output layer. The inputs are the four variables on the right side of Equation (6): $i_q*(k-1)$, $e(k)-e(k-1)$, $e(k)$, $e(k)-2e(k-1)+e(k-2)$, The outputs are proportional, integral, and differential coefficients Kp, Ki, Kd. The controller output information propagates forward, and the speed error information propagates backward.

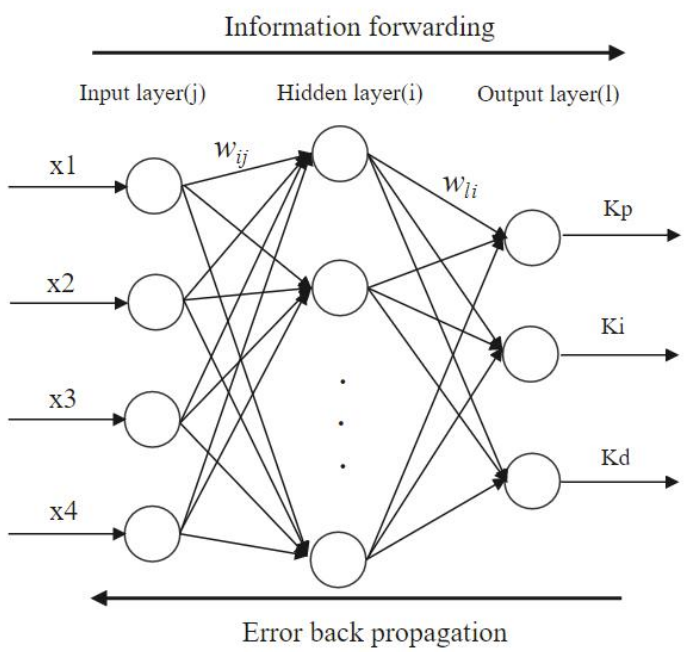


Figure 2. Structure of BP-NN

The activation function of hidden layer neurons:

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{7}$$

The activation function of output layer neurons:

$$g(x) = \frac{(1 + \tanh(x))}{2} = \frac{e^x}{e^x + e^{-x}} \tag{8}$$

Performance indicator function [10]:

$$E(k)=\frac{(r(k)-y(k))^{2}}{2} \tag{9}$$

Among them, *r(k)*: reference speed, *y(k)*: actual speed of the PMSM.

We modify the weight of the network according to the gradient descent method, that is, E(k) is searched and adjusted according to the negative gradient direction of the weight. In order to speed up the convergence rate, an inertia term is added [10].

$$\Delta w_{li}^{(3)}(k)=-\eta\frac{\partial E(k)}{\partial w_{li}^{(3)}}+\alpha\Delta w_{li}^{(3)}(k-1) \tag{10}$$

In Equation (10), η: learning rate, α:inertia factor.

1) Limit the Range of the Neural Network Output Coefficients

The output of the BP-NN is a sigmoid function in the interval range [0 1], and the range corresponding to the proportional coefficient Kp and the integral coefficient Ki is also [0 1]. The function of the proportional coefficient Kp is to speed up the response speed of the system. The larger the Kp, the faster the system response speed. If Kp is too small, the adjustment time will be prolonged. Therefore, the range of the proportional coefficient Kp is limited between 0.2 and 1. The integral coefficient Ki has the effect of eliminating the steady-state error of the system. If Ki is extremely small, it will cause a static error in the system. Therefore, limiting the range of the integral coefficient Ki between 0.5 and 1 can eliminate the static error and solve the problem that the BP neural network is easy to fall into Local minimum.

2) Adding Adaptive Gain Factor

The BP-NN speed controller's sampling time is $Ts=10^{-5}$s, which is the same as the conventional PI controller sampling time, so the actual integral coefficient is Ki/Ts. The integral coefficient Ki needs to be multiplied by a variable factor β. When the reference speed is fast and load torque is large, a larger value of 0.01 for β can make the system reach the steady state quickly and solve the problem of slow convergence speed of the BP-NN; if the reference speed is lower, β takes a smaller value of 0.001 to eliminate the system oscillation.

2.3 Model Establishment

The general structure of the PMSM servo system based on field-oriented control (FOC) is shown in the Figure 3. The controllers employ a structure of cascade control loops, including a speed loop and two current loops. Here, two PI controllers are adopted in the two current loops, and the improved BP-NN controller is adopted in the speed loop. The voltage-source inverter uses the mode of space vector pulse width modulation (SVPWM), the reference current i_d* is set to be zero to maintain a constant flux operating condition.

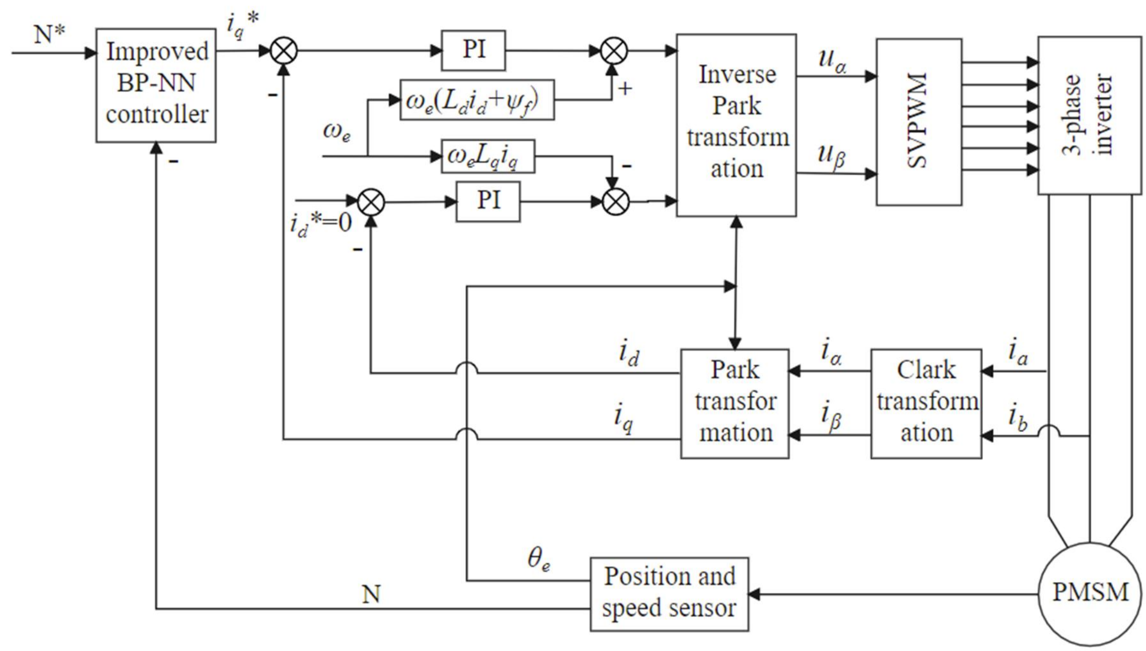


Figure 3. Improved BP-NN control scheme of the PMSM speed-regulation system based on vector control

The PMSM parameters setting in the simulation model are shown in Table 1 [12].

Table 1: PMSM parameter

Parameters	Value
Stator resistance	0.958Ω
Stator d-axis inductance	5.25mH
Stator q-axis inductance	12.5mH
Flux linkage	0.1827Wb
Inertia	0.003J(kg.m^2)
Viscous damping	0.008F(N.m.s)
Pole pairs	4

3. Simulation Results

In this section, to demonstrate the effectiveness of the proposed improved BP-NN controller, simulations are established in MATLAB/Simulink.

3.1 Starting Up at Medium or High Reference Speed

In Figure 4, PMSM starts up with no load at the reference speed N*=1000r/min under the BP-NN controller. When the adaptive factor β=0.001 in Figure 4(a), the motor speed can slowly converge to the reference value. While the adaptive factor β=0.01 in Figure 4(b) , the speed response becomes fast, and it takes a short time to reach steady state, but there is a static error of about 8r/min. We observe the proportional, integral, and differential coefficients at this time as shown in Figure 4(c), the integral coefficient Ki is 0, which causes a static error, so it is necessary to limit the range of Kp and Ki. After limiting the range of Kp and Ki in Figure 4(d), the motor speed can quickly reach the reference speed, and there is no static error.

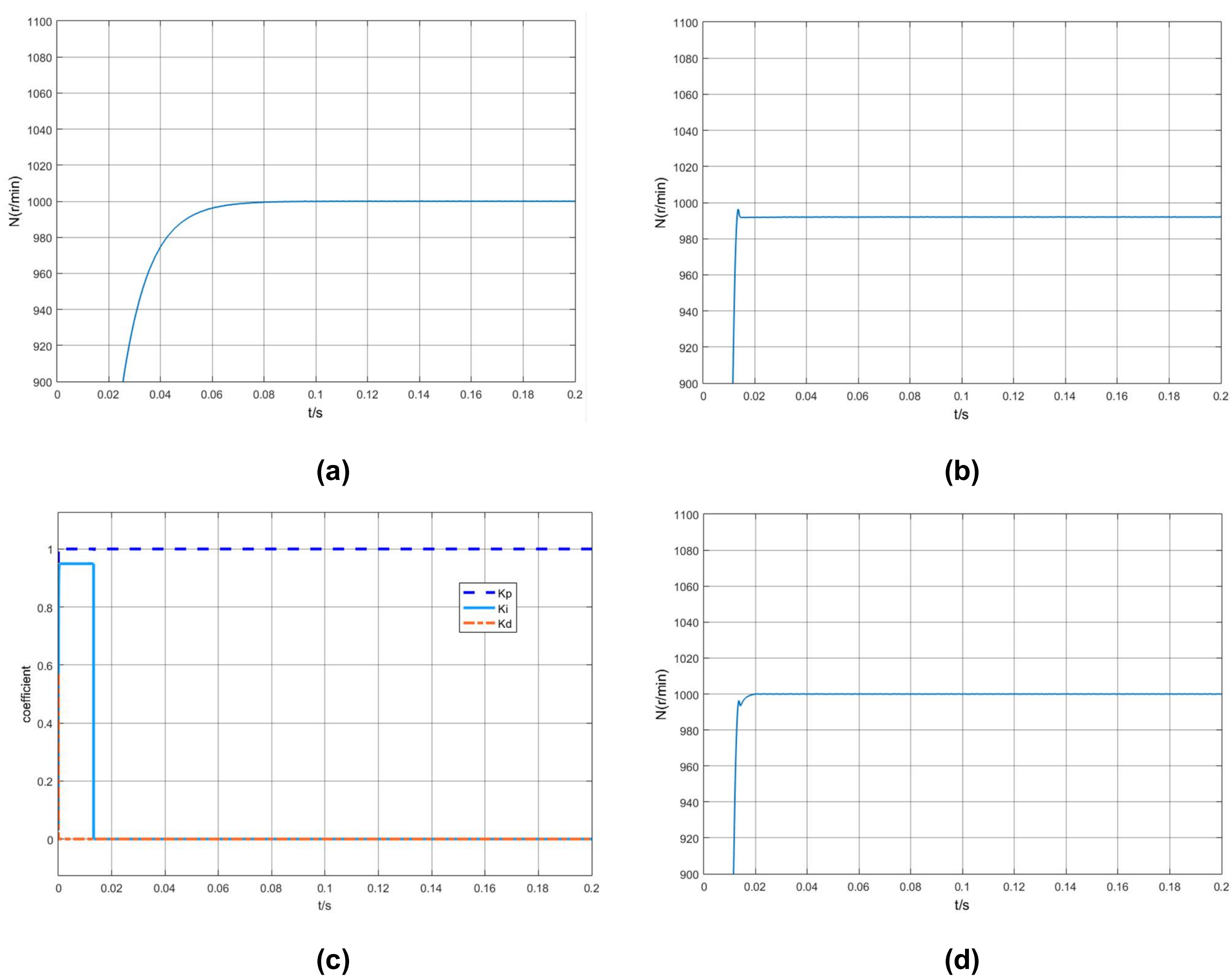
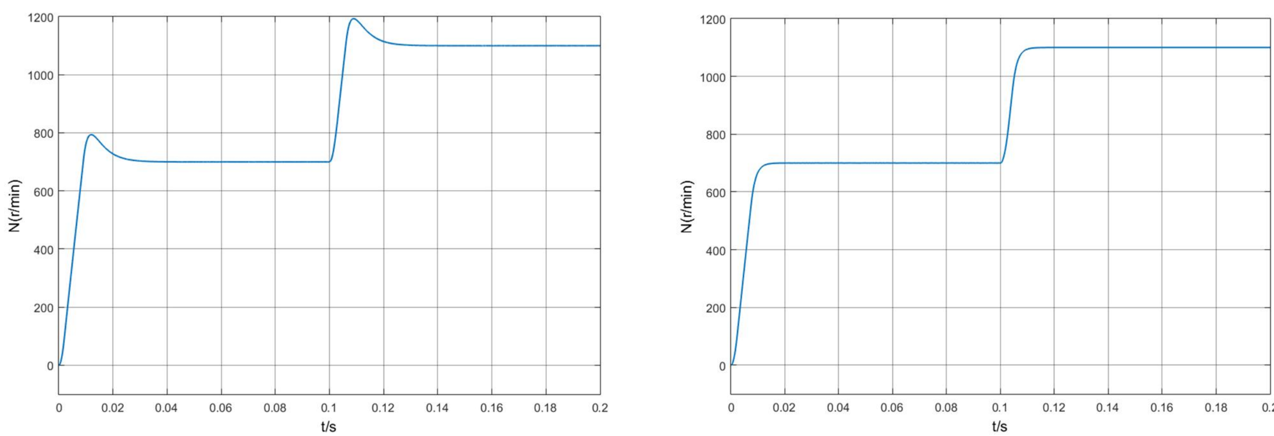


Figure 4. Simulink results under BP-NN controller (a): β=0.001,no limit for Kp,Ki (b): β=0.01,no limit for Kp,Ki (c): Kp, Ki, Kd coefficients corresponding to figure (b) (d): β=0.01, limit for Kp,Ki

3.1.1 Transient Response for Charging Reference Speed

Figure 5 shows the speed response waveforms when the reference speed N* of PMSM is increased from 700 rpm to 1100 rpm at t=0.1s using the conventional PI controller and the improved BP-NN controller, respectively. In Figure 5, the PMSM initial speed is 0 rpm and operates without load. Also, the β of the improved BP-NN controller is set to 0.01. Figure 5(a) shows an overshoot of nearly 100r/min and a long settling time under the conventional PI controller, no matter when the motor starts up or the reference speed changes suddenly. While Figure 5(b) indicates that the motor speed can quickly converge to the reference value without overshoot or static error under the improved BP-NN controller.

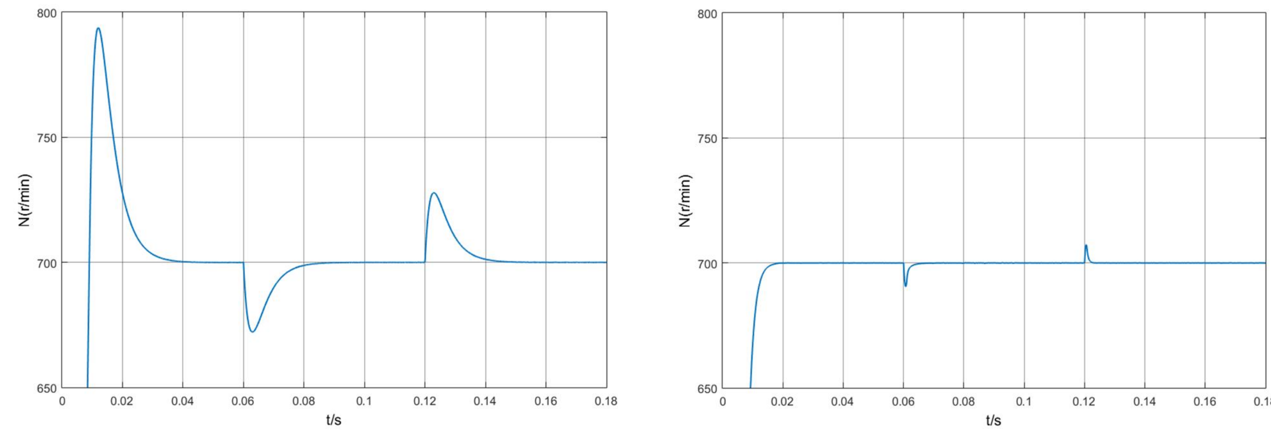


(a) (b)

Figure 5. Speed responses of PMSM (a): for applying conventional PI controller (b): for applying improved BP-NN controller (β=0.01)

3.1.2 Dynamic Response for Charging Load Torque

The PMSM starts up at the reference speed N*=700r/min with no load in Figure 6, a load torque Tl=8N·m is applied at t=0.06s and removed at t=0.12s. Figure 6(a) shows a large speed fluctuation of about 28r/min and a long settling time of 0.02s applying conventional PI controller when the load torque increases or decreases suddenly. However, by applying the improved BP-NN controller in Figure 6(b), the speed fluctuation amplitude of the PMSM is small, just nearly 8r/min, and it has a short recovering time of only 0.004s. Therefore, we can conclude that the improved BP-NN controller makes the PMSM strong in anti-load interference ability.

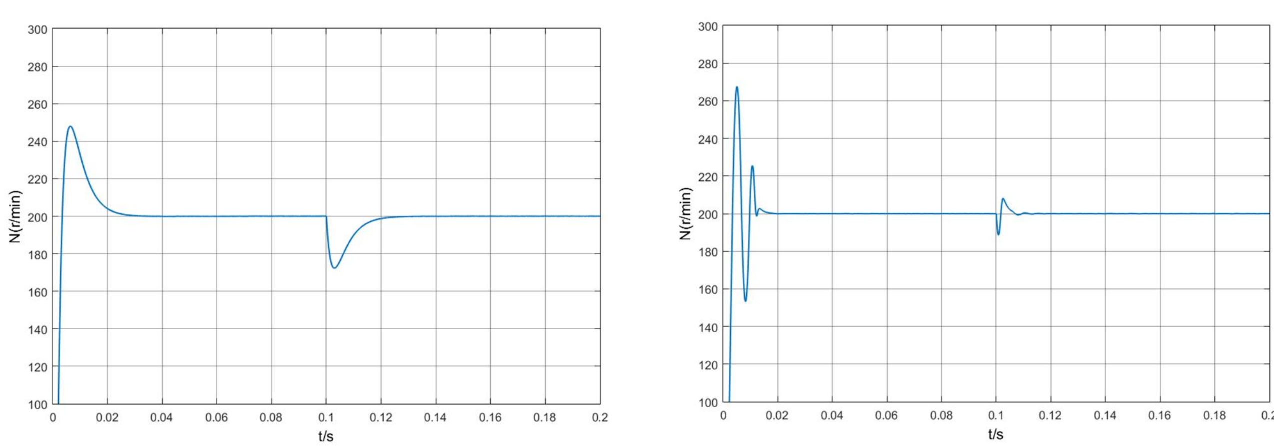


(a) **(b)**

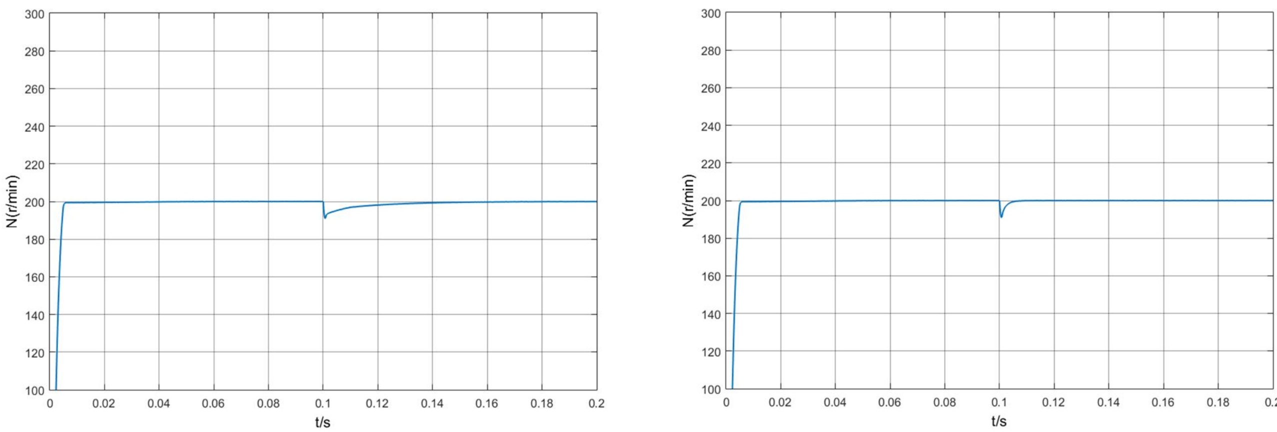
Figure 6. Speed responses of PMSM (a): for applying conventional PI controller (b): for applying improved BP-NN controller (β=0.01)

3.2 Starting Up at Low Reference Speed

Figure 7 is the starting up speed responses of PMSM for a low reference speed. In Figure 7, the PMSM starts up with no load at a low reference speed N=200r/min, and a load torque Tl=8N·m is applied at=0.1s. In Figure 7(a), the speed has a large overshoot of nearly 48r/min when the PMSM starts up under the conventional PI controller, and there exists a large speed fluctuation of 27r/min with the load torque changing. Figure 7(b), 7(c), and 7(d) are about the BP-NN controller. When the adaptive factor β=0.01 in Figure 7(b), the speed reaches a steady state after a short oscillation with the PMSM starting up. The transient response of PMSM quickly reaches the reference speed by applying the adaptive factor β = 0.001 in Figure 7(c), and there is no overshoot or oscillation, but when the load torque increases at 0.1s, the dynamic response speed is very slow, and the long recovery time is about 0.02 seconds. Therefore, to realize fast dynamic response, it is necessary to increase the adaptive factor β to 0.01 at this time, as shown in Figure 7(d), which can make the PMSM faster dynamic response speed just 0.004s with the load torque increasing. Comparing Figure 7(a) with Figure 7(d), we can find that the PMSM applying the improved BP-NN controller can obtain a satisfying performance with a fast transient response, good disturbances rejection ability for a low reference speed.



(a) **(b)**

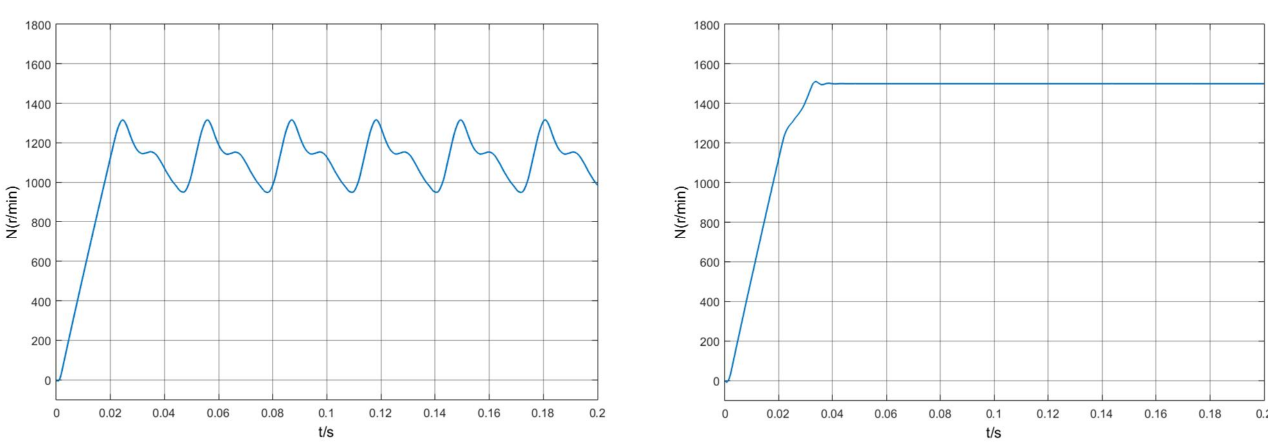


(c) (d)

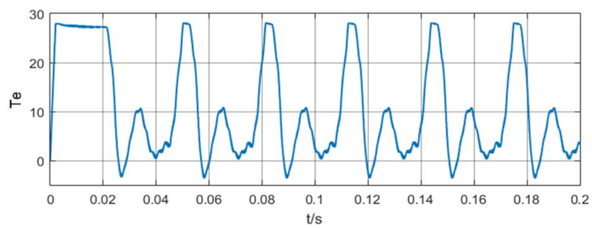
Figure 7. Speed responses of PMSM (a):under conventional PI controller (b):β=0.01 (c): β=0.001 (d):under improved BP-NN controller. before 0.1s, β=0.001. after 0.1s, β=0.01.

3.3 Starting Up Transient Response at High Reference Speed with Large Load Lorque

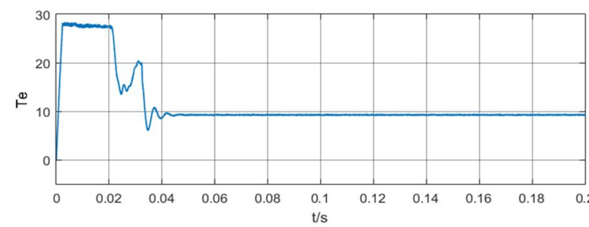
When the PMSM starts up at a higher reference speed of N*=1500r/min with a larger load torque Tl=8N·m. The PMSM cannot reach the reference speed 1500r/min under the conventional PI controller in Figure 8(a). The speed will oscillate between 948r/min and 1317r/min, and the corresponding electromagnetic torque also oscillates severely in Figure 8(c). However, the PMSM can reach the reference speed N*=1500r/min for improved BP-NN controller in Figure 8(b), the corresponding electromagnetic torque can also reach the steady state after 0.046s in Figure 8(d). The severe oscillation of the speed and electromagnetic torque will affect the life of the machine and cause safety accidents.



(a) (b)



(c)



(d)

Figure 8. Speed and electromagnetic torque responses for PMSM. (a) Speed response for conventional PI controller (b) Speed response for improved BP-NN controller (c) Electromagnetic torque for conventional PI controller (d) Electromagnetic torque for improved BP-NN controller (β=0.01)

4. Conclusion

The improved BP-NN controller algorithm proposed in this paper for PMSM， by limiting the range of neural network outputs Kp, Ki and adding adaptive gain factor β， effectively solves the problems that BP neural network has slow convergence speed and it is easy to fall into a local minimum. The simulation results show that the closed-loop systems for the suggested improved BP-NN controller method have achieved a satisfying performance. The dynamic response speed of PMSM is faster, the anti-load interference ability is stronger, and there is no static error or oscillation for the improved BP-NN controller. This algorithm is suitable for the PMSM application in a wide range of reference speed and load torque.

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