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Neural Network Control of Induction Motor Speed Control System

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Abstract

Aiming at the characteristics of the inverter and induction motor system in V/F mode, a full digital control of induction motor frequency control system is designed in this paper. BP neural network is adopted to adjust the parameters of PID controller online, so as to perform closed-loop control of the system. The full digital, distant and intelligent control experimental platform is built based on three communication modes, such as OPC, MPI and PROFIBUS-DP. Practical experiments are debugged based on the system designed. The results show that, the control system has good real-time performance, strong resistance to interference, and higher dynamic and static performances and following performances.

Keywords: *Induction motor, frequency control, digital control, inverter, BP neural network*

1. Introduction

The general inverter has the features of small volume, light weight and high reliability. Therefore, the induction motor fed by a general inverter, named as a variable frequency speed control system, is widely used in industrial production field. It is taking place of DC motor speed control system. But the induction motor speed control system is a complex, strong coupling, multi-variable and nonlinear system. As we all know, conventional constant parameters PID control is widely used. But it is sensitive to the variation of system parameters and external load disturbances. Therefore, if conventional PID control is adopted to control the system, it has poor robustness. As a result, the control performance can hardly meet the requirements of speed control. How to improve its control performance without changing the original structure of variable frequency speed control system, has become an urgent problem to be solved [1].

In this paper, induction motor variable frequency speed control system based on BP neural network PID is designed. The full digital, distant and intelligent control experimental platform is established based on Siemens industrial configuration software WinCC, S7-300 PLC and PROFIBUS-DP field bus[2]. The experiments of starting property, anti-disturbance performance and tracking performance were performed. The results prove that the control system has stronger robustness, higher static-dynamic and following performance. Thus, the control effect is satisfactory.

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2. Mathematical Model of Induction Motor Speed Control System

If the inverter and induction motor is regarded as a whole controlled object, then its mathematical model can be depicted by the state equation of induction motor, as is shown in Figure 1. Here, the input variables are synchronous frequency ω_1 and voltage magnitude V , and the output variables are speed ω_r and stator flux ψ_s .

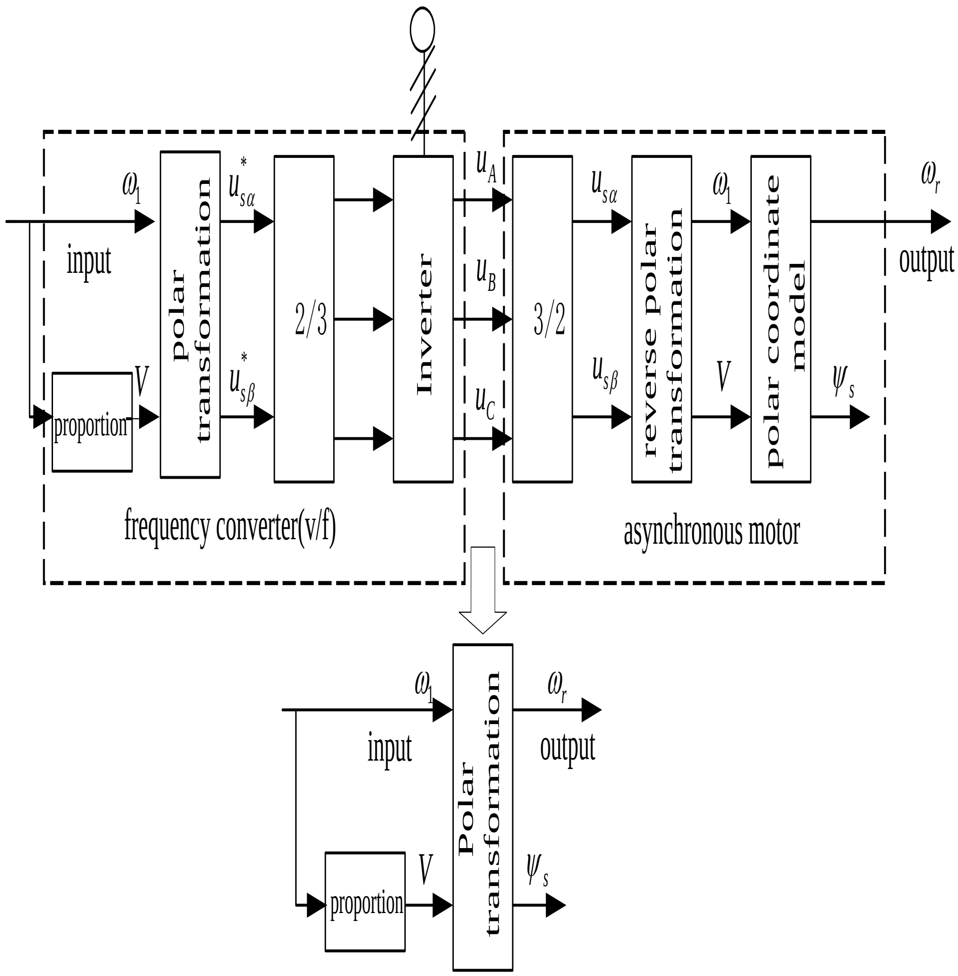

Figure 1 Variable Frequency Speed Control System in V/F Mode

When the motor runs at low frequency, the stator voltage often needs some voltage-drop compensation, so as to enhance the load-bearing ability of induction motor. When the inverter is set in V/F mode, the relationship between voltage magnitude V and synchronous frequency ω_1 is

$$V = k\omega_1 + C \tag{1}$$

Where, K is the proportional coefficient between voltage and frequency, C is the voltage-drop compensation value at low frequency.

Then, the mathematical model of the system is:

$$\begin{cases} \frac{d\omega_r}{dt} = \frac{n_p}{J}(T_e - T_L) = \frac{n_p^2}{J}(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) - \frac{n_p}{J} T_L \\ \frac{d\psi_{s\alpha}}{dt} = V\cos(\omega_1 t) - R_s i_{s\alpha} \\ \frac{d\psi_{s\beta}}{dt} = V\sin(\omega_1 t) - R_s i_{s\beta} \\ \frac{di_{s\alpha}}{dt} = \frac{R_r}{L_s L_r - L_m^2}\psi_{s\alpha} + \frac{L_r}{L_s L_r - L_m^2}\omega_r \psi_{s\beta} - \frac{R_r L_s + L_r R_s}{L_s L_r - L_m^2} i_{s\alpha} - \omega_r i_{s\beta} \\ \quad + \frac{L_r}{L_s L_r - L_m^2} V\cos(\omega_1 t) \\ \frac{di_{s\beta}}{dt} = \frac{R_r}{L_s L_r - L_m^2}\psi_{s\beta} + \frac{L_r}{L_s L_r - L_m^2}\omega_r \psi_{s\alpha} - \frac{R_s L_r + L_s R_r}{L_s L_r - L_m^2} i_{s\beta} + \omega_r i_{s\alpha} \\ \quad + \frac{L_r}{L_s L_r - L_m^2} V\sin(\omega_1 t) \end{cases} \quad (2)$$

Where,

$i_{s\alpha}, i_{s\beta}$: stator current at α, β axis; $\psi_{s\alpha}, \psi_{s\beta}$: stator flux at α, β axis

R_s, L_s : stator resistance and inductance; R_r, L_r : rotor resistance and inductance

T_L : load torque J : moment of inertia

L_m : mutual inductance n_P : number of pole pairs

ω_r : rotor speed ω_1 : synchronous frequency

The inverter is reversible when it works in V/F mode, and the whole system can be simplified as single input and single output system [3].

3. The Application of Neural Network Control in Speed Control of AC Variable Frequency Induction Motor System

In order to further improve control performance of induction motor variable frequency speed control system, a new digital control speed control system is designed based on neural network control in this paper. Neural network control does not know the precise model of a controlled object beforehand, which is especially applicable for nonlinear, time-variable and uncertain system [4]. The principle structure diagram of actual variable frequency speed control system in V/f mode based on BP neural network PID is shown in Figure 2.

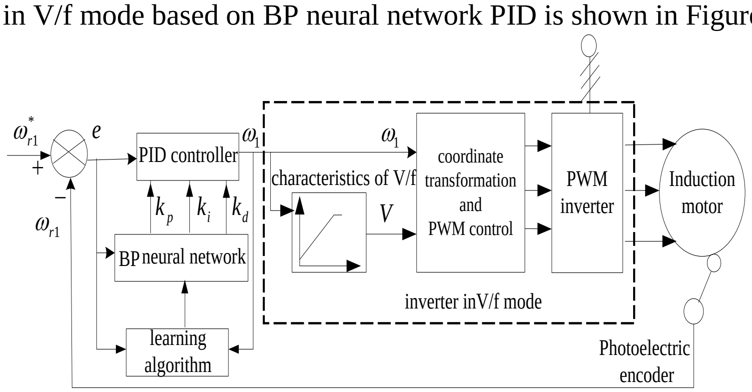

Figure 2. Actual Variable Frequency Speed Control System in V/f Mode Based on BP Neural Network PID

3.1. Algorithm Principle of BP Neural Network PID

The whole neural network controller is composed of two parts:

Incremental digital PID controller. The closed-loop control is used to the controlled objects directly, and the three parameters k_p, k_i and k_d are obtained by on-line setting [6].

The commonly used incremental digital PID algorithm is

$$u(k) = u(k-1) + k_p(e(k) - e(k-1)) + k_i e(k) + k_d(e(k) - 2e(k-1) + e(k-2)) \quad (3)$$

Where, $u(k)$ is the output of PID controller, e(k) is the error between the given and actual output, k_p, k_i and k_d are proportional, integral and differential coefficients.

If they are regarded as adjustable parameters rely on the running state of the system, Eq.3 can be described as

$$u(k) = f[u(k-1), K_p, K_i, K_d, e(k), e(k-1), e(k-2)] \quad (4)$$

Where, $f(\cdot)$ is nonlinear function, related to $u(k-1)$, k_p, k_i, k_d, $e(k)$, $e(k-1)$, $e(k-2)$ and $u(k)$. Therefore, The $f(\cdot)$ can be approximated by training and learning BP neural network to find out k_p, k_i and k_d, which make the value of $f(\cdot)$ minimum, that is, optimal control law.

BP Neural Network. According to the running state of the system, neural network automatically adjust the parameters of the incremental digital PID controller so as to get the optimal performance index [7].

With the arbitrary nonlinear expressiveness, neural network can help to realize PID control with the best combination by means of the understanding of the system performance [8]. The parameters self-adjusting PID controller can be established based on BP neural network. Aiming at the induction motor variable frequency speed control system, the incremental digital PID controller is adopted. The BP neural network adopts 3-8-3 network topology, as is shown in Figure 3 [9].

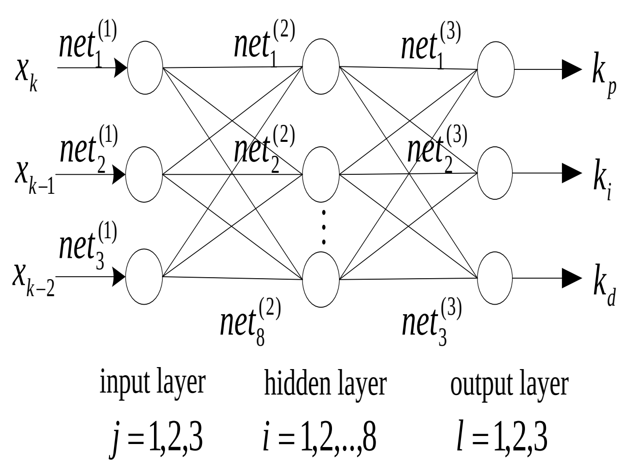

Figure 3. BP Neural Network Model

The input variables of BP network are

$$o_j^{(1)} = x_{k-j+1} = e(k-j+1) \ (j = 1, 2, 3) \quad (4)$$

Each neuron of input layer is in charge of receiving input information from external environment. In the application of PID control, the input layer receives the error information feedback [10].

The input and output variables of hidden layer are

$$\begin{cases} net_i^{(2)}(k) = \sum_{j=0}^{3} w_{ij}^{(2)} o_j^{(1)}(k) \\ o_i^{(2)}(k) = f[net_i^{(2)}(k)] \end{cases} (i = 1, 2, \ldots, 8) \tag{5}$$

Where, $w_{ij}^{(2)}$ is the weight coefficient of hidden layer, the superscript (1), (2) and (3) denotes respectively input, hidden and output layer.

The hidden layer is the internal information processing layer of neural network, in charge of information transformation. The activation function of hidden neurons take symmetrical sigmoid function.

$$f(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{6}$$

The input and output variables of output layer are

$$\begin{cases} net_l^{(3)}(k) = \sum_{i=0}^{8} w_{li}^{(3)} o_i^{(2)}(k) \\ o_l^{(3)}(k) = g[net_i^{(3)}(k)] \\ o_1^{(3)}(k) = k_p \\ o_2^{(3)}(k) = k_i \\ o_3^{(3)}(k) = k_d \end{cases} (l = 1, 2, 3) \tag{7}$$

Where, $o_l^{(3)}(k)$ represents three output nodes of output layer, exporting the results of information processing. The three output nodes are respectively corresponding to the three adjustable parameters of PID controller, which are k_p, k_i and k_d. The activation function of output neurons take nonnegative sigmoid function.

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

The performance index function is selected as follows

$$E(k) = \frac{1}{2}[y_r(k) - y(k)]^2 \tag{9}$$

According to $E(k)$, the whole neural network searches along the negative gradient direction of weight coefficient, modify the weight coefficient of the network, and add an inertia item which makes search quickly convergence. Then,

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

Where, η is learning rate, α is inertial coefficient. The $\partial E(k) / \partial w_{li}^{(3)}$ in Equation (10) can be expressed as

$$\frac{\partial E(k)}{\partial w_{li}^{(3)}} = \frac{\partial E(k)}{\partial y(k)} \frac{\partial y(k)}{\partial u(k)} \frac{\partial u(k)}{\partial o_l^{(3)}(k)} \frac{\partial o_l^{(3)}(k)}{\partial net_l^{(3)}(k)} \frac{\partial net_l^{(3)}(k)}{\partial w_{li}^{(3)}} \tag{11}$$

According to Equation (9),

$$\frac{\partial E(k)}{\partial y(k)} = -(y_r(k) - y(k)) = -e(k) \tag{12}$$

Because $\partial y(k)/\partial u(k)$ is unknown, sign function $\mathrm{sgn}(\partial y(k)/\partial u(k))$ is adopted to replace it. This inaccurate calculation may be compensated by adjusting learning rate η .

According to Equation (3)-(7), then

$$\begin{cases} \dfrac{\partial u(k)}{\partial o_0^{(3)}(k)} = e(k) - e(k-1) \\ \dfrac{\partial u(k)}{\partial o_1^{(3)}(k)} = e(k) \\ \dfrac{\partial u(k)}{\partial o_2^{(3)}(k)} = e(k) - 2e(k-1) + e(k-2) \end{cases} \tag{13}$$

$$\frac{\partial o_l^{(3)}(k)}{\partial net_l^{(3)}(k)} = g'[net_l^{(3)}(k)] \tag{14}$$

$$\frac{\partial net_l^{(3)}(k)}{\partial w_{li}^{(3)}} = o_i^{(2)}(k) \tag{15}$$

The learning algorithm of output layer weight coefficient can be obtained as follows, by substituting correlative items in Equation (12) with Equation (13)-(15).

$$\begin{cases} \Delta w_{li}^{(3)}(k) = \alpha \Delta w_{li}^{(3)}(k-1) + \eta \delta_l^{(3)} o_i^{(2)}(k) \\ \delta_l^{(3)} = e(k)\,\mathrm{sgn}\left(\dfrac{\partial y(k)}{\partial u(k)}\right) \dfrac{\partial u(k)}{\partial o_l^{(3)}(k)} g'[net_l^{(3)}(k)] \end{cases} \quad (l = 1, 2, 3) \tag{16}$$

Where, $g'(x) = g(x)[1 - g(x)]$

Similarly, the learning algorithm of hidden layer can be derived

$$\begin{cases} \Delta w_{ij}^{(2)}(k) = \alpha \Delta w_{ij}^{(2)}(k-1) + \eta \delta_i^{(2)} o_j^{(1)}(k) \\ \delta_i^{(2)} = f'[net_i^{(2)}(k)] \sum_{l=0}^{2} \delta_l^{(3)} w_{li}^{(3)}(k) \end{cases} \quad (i = 1, 2, \ldots, 8) \tag{17}$$

Where, $f'(x) = [1 - f^2(x)]/2$

Based on the above algorithms, the three parameters of PID controller, which are the output signals of output layer, can be adjusted according to the environmental change.

3.2. Algorithm Flow

Based on above analysis, the summary of the algorithm flow of parameters self-adjustment PID control based on BP neural network is shown in Figure 4.

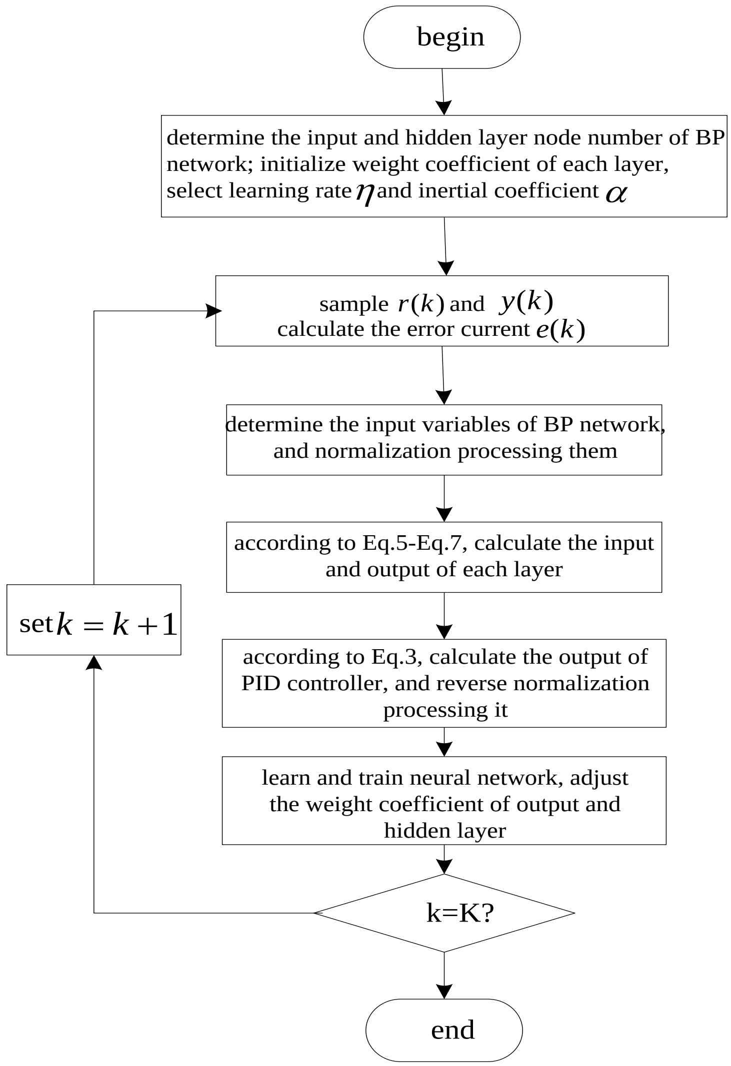

Figure 4. The Algorithm Flow of BP Neural Network PID Controller

4. Experiments

4.1. Hardware connection of the System

Figure 5 is neural network control of variable frequency speed control experimental system in V/F mode. Industrial control computer is used as upper computer, running the monitor software WinCC6.0 and compile software Step7-V5.4. Siemens S7-300 PLC is used as lower computer, controlling one set of the Siemens MMV inverter. Incremental circular grating encoder is adopted. Parameters of induction motor are $p_e = 2.2kW$, $U_e = 220/380V$, $n_p = 2$, and $n_N = 1420 \ r/\min$ [11]

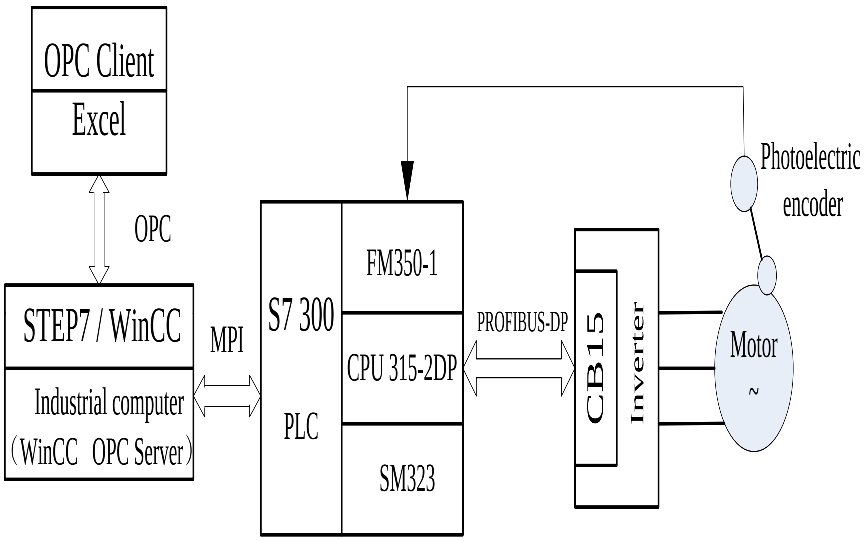

Figure 5. Experiment System

4.2. Experimental Results and Its Analysis

The inverter is set in V/F mode. Figure 6 is the characteristic of motor starts under the condition of no and full load with neural network control. As can be seen from the wave, it has little effect on the starting performances of the system under different load. Figure 7 is the characteristic of motor starts with two different control methods. As can be seen from the wave, both of the actual output speed can trace given speed, but neural control of speed control system has better performances of dynamic and static characteristic than traditional PID control. Figure 8 is the system response curves with PID control when load sudden change under different given speed. Figure 9 is the contrast diagram with neural network control in the same condition. As can be seen from the curves, neural control of speed control system has stronger anti-interference ability, better adaptability and robustness.

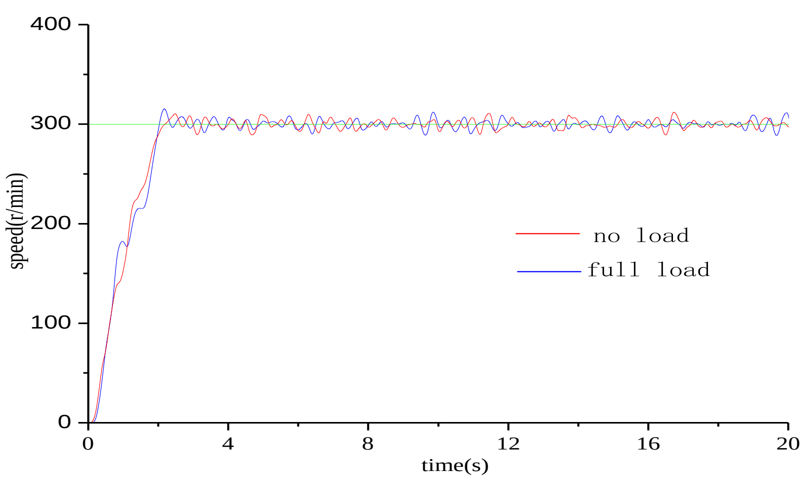

Figure 6. No/full Load Starting Characteristics with Neural Network Control

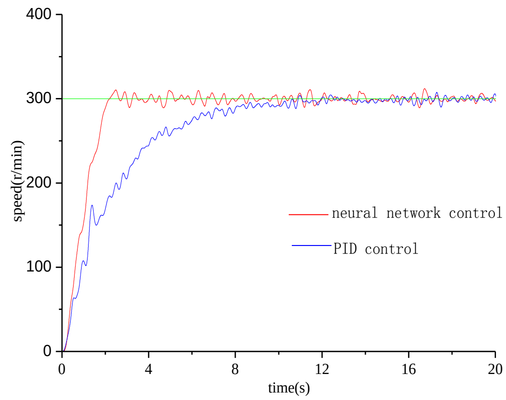

Figure 7. Response of Step Change with Two Control Methods

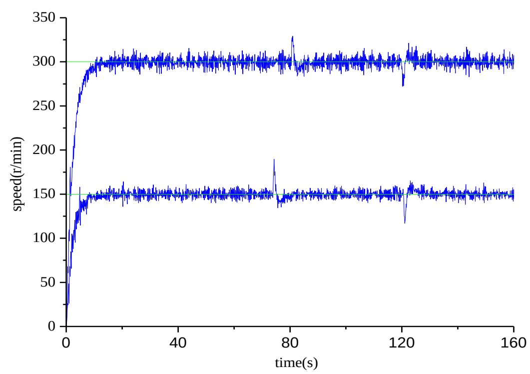

Figure 8. Sudden Load Change Characteristics with PID Control

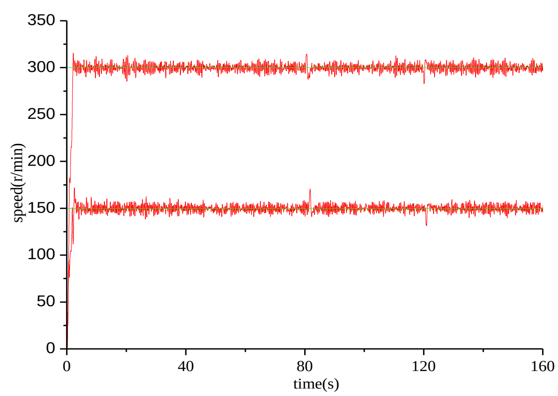

Figure 9. Sudden Load Change Characteristics with Neural Network Control

When the speed of motor sudden changes, the response to the output of speed is shown in Figure 10. Compared with traditional PID control, neural network control of induction motor speed control system has faster dynamic response, higher steady precision and smaller overshoot. Thus, the actual wave with neural network control can better trace the given wave. The above experiments show that the proposed method in this paper can be applied effectively and practically in the variable frequency speed control system in V/F mode which is non-linear, fast changeful and difficult to be modeled. The actual control effect is satisfactory.

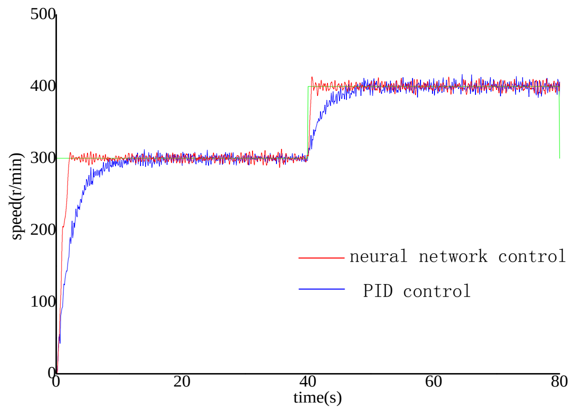

Figure 10. Square Wave Response Curve of Speed Tracking with Two Control Methods

5. Conclusion

Induction motor variable frequency speed control system fed by a general inverter is widely used in industrial production field. Aiming at the problems that its control performances need to be further improved, this paper established the mathematical model of variable frequency speed control system in V/F mode under stator voltage of α , β axis. Considering the inverter and the induction motor as a whole controlled object, neural network control method is adopted to control the system. The full digital, distant and intelligent control of induction motor speed control system is designed in this paper. The experimental results show that, neural network control method is feasible, and the running performance of variable frequency speed control system in V/F mode is greatly improved, meeting the requirements of high performance control.

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