BP-PID Control Applied in Evaporator of Organic Rankine Cycle System

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Abstract: According to the problem that the selection of traditional PID control parameters is too complicated in evaporator of Organic Rankine Cycle system (ORC), an evaporator PID controller based on BP neural network optimization is designed. Based on the control theory, the model of ORC evaporator is set up. The BP algorithm is used to control the K_p, K_i and K_d parameters of the evaporator PID controller, so that the evaporator temperature can reach the optimal state quickly and steadily. The MATLAB software is used to simulate the traditional PID controller and the BP neural network PID controller. The experimental results show that the K_p, K_i and K_d parameters of the BP neural network PID controller are 0.5677, 0.2970, and 0.1353, respectively. Therefore, the evaporator PID controller based on BP neural network optimization not only satisfies the requirements of the system performance but also has better control parameters than the traditional PID controller.

Key words: Organic Rankine Cycle; PID Controller; Evaporator; BP Neural Network

1 Introduction

Energy is the basis for human survival and evolution, the effective utilization of industrial waste heat plays an important role in the current energy utilization. As one of the technology of waste heat recovery, ORC waste heat recovery is used in the low temperature because of its economy and feasibility [1]. For ORC system, one of the challenges on optimization is controller design. When the waste heat sources are disturbed, it is necessary to control the ORC process in order to keep the key operating parameters within allowable ranges[2].

Generally, the PID controller could be used to control the dynamic model of evaporator[3]. The PID control is a common and typical control method in industrial control. However, the choice of parameters is too complicated [4]. The BP-PID control strategy of ORC system was investigated. BP (back propagation) neural network is a multi-layer feedforward neural network which is trained by the error reverse propagation algorithm. The BP is used to optimize the PID parameters in order to solve the shortcomings of traditional methods and ensure the evaporator temperature quickly and accurately to reach the optimal state.

2 Modeling

The Organic Rankine Cycle is a Rankine cycle in which low-boiling organic refrigerants are used as circulating working fluids instead of water. The ORC power generation system is mainly composed of evaporator, expander, condenser, industrial pump and other main equipment and auxiliary parts[5]. The principle is shown in Fig1. The working fluids are turned into vapor in the evaporator. Then, the vapor enters into expander to produce work. The exhaust vapor enters the condenser to emit heat to cool water. Finally, the liquid working fluids are pressurized by pump and enter the evaporator again.

The evaporator is the object of study. The temperature of working fluids at outlet of evaporator must be maintained at a proper range to ensure the highest efficiency of ORC system. The characteristics of evaporator are large-lag, time-varying and nonlinear, etc. Therefore, the influence of the outlet temperature of the evaporator for working fluids can be written as the form of first-order inertia with delay as follows:

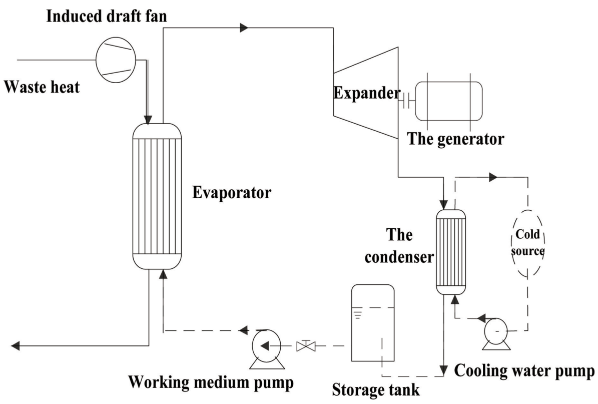

Fig. 1 The principle of ORC

$$G(s) = \frac{ke^{-\tau s}}{1 + Ts} \quad (1)$$

Where $G(s)$ is the transfer function, k is the gain of evaporator which is belongs to the static error of system, τ is the delay time of evaporator, T is the time constant of evaporator. The parameters were determined by system configuration and operating conditions, etc.

According to the temperature response curve of evaporator outlet, the k, τ and T can be set to 80.8, 7 and 33.4, the transfer function can be written as follows:

$$G(s) = \frac{80.8e^{-7s}}{1 + 33.4s} \quad (2)$$

3 Design of PID Controller

PID control is a control algorithm which based on the proportion, integral and differential of system deviation. It is widely used in process industries, because its structure and principle are simple[6]. The fundamental controller is the component of proportional cycle, integration cycle and differential cycle. The schematic diagram of PID controller is shown in Fig.2.

The general form of PID controller is shown as follows:

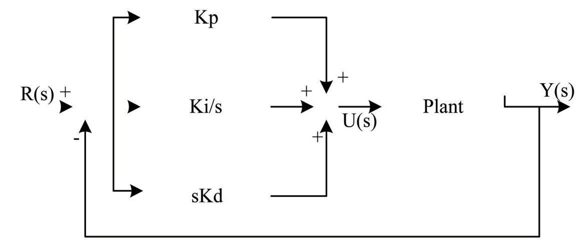

Fig. 2 Schematic diagram of PID controller

$$G(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \quad (3)$$

Where K_p is the proportional coefficient, K_i is the integral coefficient, K_d is the differential coefficient.

The evaporator of ORC system is selected as the control object in this paper. Then the PID parameters are received by critical proportioning method. The vibrate period T_u and amplitude K_u can be obtained for controller parameters in the critical proportioning method[7].

The calculation formula of critical proportioning method is shown in Table 1.

Table 1 Calculation formula of critical proportioning method

Type	K_p	T_i	T_d
P	$0.5K_u$	0	0
PI	$0.455K_u$	$0.833T_u$	0
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

K_p, T_i, T_d are calculated with formula in Table 1, then the formula (4) and (5) are used to calculate the K_i and K_d.

$$K_i = \frac{K_p}{T_i} \quad (4)$$

$$K_d = K_p T_d \quad (5)$$

By adjusting K_p, K_i, K_d parameters ($K_p = 0.06048$, $K_i = 0.00484$, $K_d = 0.189$), the control of the object can be realized.

4 Design of BP-PID Controller

4.1 BP Algorithm

8David Rumelhart and J. McClelland proposed the BP network error Back propagation learning algorithm in 1986[8]. Its basic idea is the gradient descent method, using the gradient search technique to minimize the mean square error of the actual output value and the expected output value of the network.

4.2 Principle of Controller

PID control based on BP neural network can be simplified as BP-PID. Its basic principle is the ability to use BP neural network to approximate any nonlinear function[9] Through the learning of the network´s own performance, the best set of PID parameters is found under the requirements of a performance index. Its system structure is shown in Fig.3.

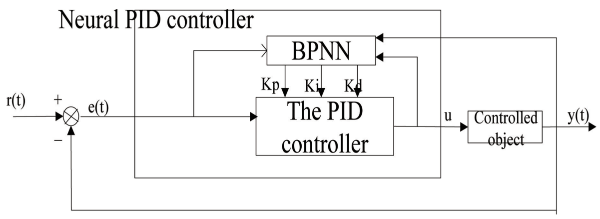

Fig. 3 Schematic diagram of BP-PID controller

The core is the PID controller based on the BP neural network in the box in Fig3. The structure of the controller consists of two parts: (1) BP Neural Network (BPNN): The self-learning of the neural network is mainly to modify and adjust the weighting coefficients, which is the process to form the control rules. (2) Conventional PID controller: The closed loop control of the control object is carried out directly, in which the three parameters of K_p , K_i and K_d are on line setting. An incremental PID controller is used in the neural PID controller in this paper:

$$u(k) = u(k\text{-}1) + K_p[e(k)\text{-}e(k\text{-}1)] + K_i e(k) + K_d[e(k) + e(k\text{-}2)\text{-}2e(k\text{-}1)] \quad (6)$$

In the formula: $u(k)$、$u(k\text{-}1)$ is the output of k、$(k\text{-}1)$ time controller respectively; $e(k)$ is the error.

In this paper, a three-layer BP neural network is adopted, the structure is M-N-3, as shown in figure 4. M, N, and 3 represent the number of input layer, hidden layer and output layer node. The selection of the number of input variables(M) should be based on the complexity of the controlled system. The input node is also the input of the network to select the real time state of the system[10]. The output node is also the output of the network, which must be the three adjustable parameters of the PID controller, K_p , K_i and K_d .

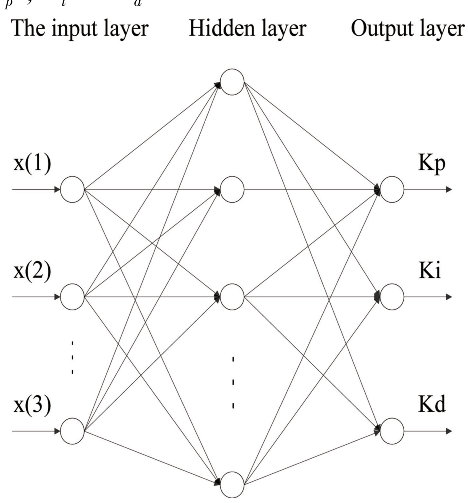

Fig. 4 Three layer BP neural network structure

Because the three parameters of K_p , K_i and K_d cannot be negative, so the paper uses the non-negative Sigmoid function as the activation function of the output layer, while the activation function of the hidden layer uses the positive and negative symmetric Sigmoid function.

The input of the network input layer is:

$$O_j^{(1)} = x(j), j = 1,2,\ldots M \quad (7)$$

The number of input variables in (7). It is according to the complexity of the controlled system and the actual needs.

The input of the hidden layer of the network is:

$$net_i^{(2)}(k) = \sum_{j=0}^{M} \omega_{ij}^{(2)} O_j^{(1)} \quad (8)$$

Output is

$$O_i^{(2)}(k) = f(net)_i^{(2)}(k)(i = 1,2\ldots,Q) \quad (9)$$

In formula (8) and formula (9), it is the weighted coefficient of the hidden layer. On the corner (1), (2) and (3) respectively represent the input layer, hidden layer and output layer.

The Sigmoid function of positive and negative symmetry of the activation function of the neurons in the hidden layer:

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \qquad (10)$$

The input of the network input layer is:

$$net_i^{(3)}(k) = \sum_{i=0}^{Q} \omega_{ij}^{(3)} O_i^{(2)}(K) \qquad (11)$$

Output is:

$$O_i^{(3)}(k) = g\,(net)_i^{(3)}(k)\,(l = 1,2,3) \qquad (12)$$

The weight of the input layer to the hidden layer:

$$W_i(O) = \begin{bmatrix} 0.1850 & 0.3630 & -0.3492 & -0.1723 \\ -1.957 & 0.4927 & -0.3608 & -0.1611 \\ 0.5682 & -0.0258 & 0.0277 & 0.5030 \\ -0.2202 & 0.0786 & 0.2271 & 0.2690 \\ 0.0357 & -0.0086 & -0.1074 & -0.2447 \end{bmatrix}$$

The weight of the hidden layer to the output layer:

$$W_o(O) = \begin{bmatrix} 0.5776 & 0.2809 & -0.3789 & -0.3311 & -0.3680 \\ 0.2400 & 0.2654 & -0.1383 & 0.4525 & 0.3335 \\ -0.1706 & -0.2657 & -0.2839 & -0.2201 & 0.1361 \end{bmatrix}$$

5 Results

In order to verify the effectiveness of BP neural network PID controller. The BP-PID controller and the conventional PID controller are simulated and compared. The simulation results are shown in Fig.5 and Fig.6.

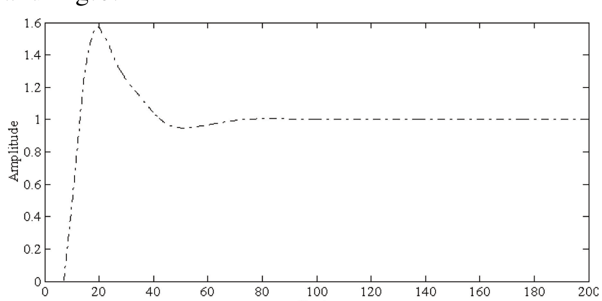

Fig. 5 Curve of PID controller

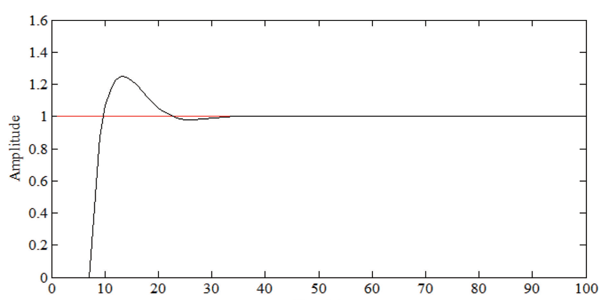

Fig. 6 Curve of BP-PID controller

After using the BP algorithm to optimize the parameters as follows: K_p is 0.5677 , K_i is 0.2970 and K_d is 0.1353.

6 Conclusion

In this thesis the BP-PID controller is studied to test the temperature of evaporator quickly to reach the optimum state. The following conclusions can be drawn: The amplitude of traditional PID control is 1.6 and the system takes 75 seconds to achieve stability. With the BP-PID control, the amplitude is about 1.25 and the response time of system is the same as the traditional PID control, but the settling time is shortened by 22%. It can be seen from the analysis that the BP-PID controller has faster convergence ability, faster response speed and more stable response, and the PID parameter setting is more rapid and stable. The BP-PID control can meet the evaporator of ORC system performance requirements, and improve the dynamic and static performance of evaporator.

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