MPC of Sewage Treatment Process

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Abstract: Sewage treatment is one of the main methods to promote the recycling of water resources. The control goal of sewage treatment process is to reduce energy consumption under the premise that the effluent quality reaches the standard. In recent years, model predictive control (MPC) has attracted some attention in sewage treatment. Neural network is widely used in control field because of its strong online learning ability. BP neural network is selected as the prediction layer and control layer of MPC and applied to sewage treatment plant to realize on-line control of dissolved oxygen and nitrate. The training index of traditional neural network usually only selects the error between measured value and set value as the variable, and now the change of control quantity is also taken as the training index variable of control layer to adjust the weight relation between them to get the best control effect. Considering that different weather conditions will have a greater impact on the water inflow, different coefficients of the two can be selected to achieve better results in different weather.

Keywords: Sewage Treatment; Model Predictive Control

1. Problem description

1.1 BP neural network

The three-layer BP neural network is shown in Figure 1, which is composed of input layer, hidden layer and output layer. The calculation process of BP neural network consists of forward calculation process and reverses calculation process. In the forward propagation process, the input mode is processed layer by layer from the input layer to the hidden unit layer and then to the output layer. The state of neurons in each layer only affects the state of neurons in the next layer. If the desired output cannot be obtained at the output layer, the error signal will be returned along the original connection path and the error signal will be minimized by modifying the weights of each neuron.
Model predictive control (MPC)

Model predictive control has been implemented in several control areas. Sun Haotian et al.\textsuperscript{[1]} proposed a large aperture fast swinging mirror following system based on model predictive control. Li Demin et al.\textsuperscript{[2]} applied the model predictive control to the secondary regulation of isolated island microgrids to make them have faster transient response characteristics and stronger robustness. Jiancai Cheng et al.\textsuperscript{[3]} proposed the model predictive control of the constant switching frequency of the three-level grid-connected inverter, which reduces the computation and has better static and dynamic performance.

Model predictive control can effectively deal with problems with multiple variables and constraints. Model predictive control has three elements: prediction model, rolling optimization and feedback correction. The prediction model predicts the future output of the system based on the historical information and future input of the controlled object. Model predictive control does not have high requirements on the model, and the modeling is simple. Instead of adopting a fixed global optimal goal, rolling optimization is repeated online. It has a local optimization performance index at every moment, which can get better dynamic optimization performance. Model-based predictions cannot be completely consistent with reality. In the actual model predictive control, the prediction error of the model can be obtained by comparing the actual measured value of the output with the predicted value of the model, and then the prediction error of the model can be used to correct the predicted value of the model. Feedback correction can compensate for interference in the system.

2. Comprehensive application of MPC in sewage treatment

2.1 Principle and formula derivation

The modeling and control structure diagram is shown in Figure 2.
The application of BP neural network combined with model predictive control in sewage treatment plant, namely, the control network and the modeling network both adopt BP neural network. In the modeling and control structure diagram, the purpose of the control process is to achieve the set value of nitrate nitrogen and dissolved oxygen concentration, in which the set value of nitrate nitrogen concentration is 1 mg/L and the set value of dissolved oxygen concentration is 2 mg/L. In Figure 2, e stands for the deviation between the actual output concentration of dissolved oxygen and nitrate nitrogen and their set values; u represents the control quantity. The control quantity of dissolved oxygen is $K_L\Delta u$, and the control quantity of nitrate nitrogen is the internal return flow. They all have a certain limit, which should not be exceeded in actual operation. $\Delta u$ is the change of control quantity, that is, the difference between the control quantity at a certain moment and the control quantity at the previous moment; y is the actual measured value of nitrate nitrogen and dissolved oxygen; $y_m$ is the predicted value obtained by the prediction model.

As shown in Figure 3, in the modeling network, the input is $\Delta u$ and the output is $y_m$. $W_{L1}^M$ is the connection weight matrix between the input layer and the hidden layer of the modeling neural network, and $W_{L2}^M$ is the connection weight matrix between the hidden layer and the output layer of the modeling neural network.

As shown in Figure 4, in the control network, the input and output of the network are e and $\Delta u$, $W_{L1}$ is the connection weight matrix between the input layer and the hidden layer of the neural network controller, and $W_{L2}$ is the connection weight matrix between the hidden layer and the output layer of the neural network controller.
Figure 4. Control network structure diagram.

The derivation of the relevant formulas is shown below.

\[ f(x) = f_M = \frac{1}{1 + e^{-x}} \]  
\[ \text{Eq. (3-1)} \]

The function in Eq.(3-1) is the Sigmoid function.

\[ \Delta u = W_{L2} f(e \cdot W_{L1}) \]  
\[ \text{Eq. (3-2)} \]

\[ y_m = W_{L2}^M f_M(u \cdot W_{L2}^M) \]  
\[ \text{Eq. (3-3)} \]

\[ \Delta W_{L2} = \eta \frac{\partial J_c}{\partial W_{L2}} \]  
\[ \text{Eq. (3-4)} \]

Eq.(3-4), refers to the learning rate of weight updating, while \( J_c \) is the training performance index of the network, which can be seen from Eq.(3-5). Eq.(3-5) is an online correction of the control network.

\[ \frac{\partial J_c}{\partial W_{L2}} = \frac{1}{2} \frac{\partial (e^2 + \frac{1}{2} \Delta u^2)}{\partial W_{L2}} = \frac{1}{2} \frac{\partial e^2}{\partial W_{L2}} + \frac{1}{2} \frac{\partial \Delta u^2}{\partial W_{L2}} \]
\[ = \frac{1}{2} e \frac{\partial e}{\partial W_{L2}} + \frac{1}{2} 2 \frac{\Delta u}{\partial W_{L2}} \frac{\partial \Delta u}{\partial W_{L2}} = e \frac{\partial u}{\partial W_{L2}} + \frac{\partial \Delta u}{\partial W_{L2}} \]
\[ = e \frac{\partial (r - y)}{\partial W_{L2}} + \frac{\partial \Delta u}{\partial W_{L2}} \]
\[ = -e \frac{\partial y_m}{\partial W_{L2}} + \Delta u \frac{\partial \Delta u}{\partial W_{L2}} \]
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\[ = -e \frac{\partial y_m}{\partial W_{L2}} + \Delta u \frac{\partial \Delta u}{\partial W_{L2}} \]
\[ \text{Eq. (3-5)} \]

Eq. (3-6) gives the change of WL1.

\[ \Delta W_{L1} = \eta \frac{\partial J_f}{\partial W_{L1}} \]  
\[ \text{Eq. (3-6)} \]
\[
\eta \frac{\partial J}{\partial W_{T_1}} = \frac{1}{2} e^2 + \frac{1}{2} \Delta u^2 \frac{\partial}{\partial W_{T_1}} = e \frac{\partial e}{\partial W_{T_1}} + \Delta u \frac{\partial \Delta u}{\partial W_{T_1}} = e \frac{\partial (r - y)}{\partial W_{T_1}} + \Delta u \frac{\partial \Delta u}{\partial W_{T_1}}
\]

\[
= -e \frac{\partial y}{\partial W_{T_1}} + \Delta u \frac{\partial \Delta u}{\partial W_{T_1}} = -e \frac{\partial y}{\partial W_{T_1}} + \Delta u \frac{\partial \Delta u}{\partial W_{T_1}}
\]

\[
= -e \frac{\partial y}{\partial u} \frac{\partial u}{\partial W_{T_1}} + \Delta u \frac{\partial \Delta u}{\partial W_{T_1}} = -e \frac{\partial y}{\partial u} \frac{\partial (u (k - 1) + \Delta u)}{\partial W_{T_1}} + \Delta u \frac{\partial \Delta u}{\partial W_{T_1}}
\]

\[
(3-7)
\]

\[
\frac{\partial \Delta u}{\partial W_{L_2}} = W_{L_2} f(1 - f) e f_f M (1 - f_M) W_{L_1} e \cdot f(1 - f) + \Delta u W_{L_2} e (1 - f) e
\]

\[
(3-8)
\]

\[
\frac{\partial}{\partial W_{L_1}} W_{L_1}^M = \frac{1}{2} e_m^2 \frac{\partial}{\partial W_{L_1}} = \frac{\partial (y - y_M)}{\partial W_{L_1}} = -e_m \frac{\partial y}{\partial W_{L_1}} = -e_m W_{L_2}^M f_M (1 - f_M) \Delta u
\]

\[
(3-9)
\]

\[
\frac{\partial}{\partial W_{L_2}} W_{L_2}^M = -e_m \frac{\partial y}{\partial W_{L_2}} = -e_m f_M
\]

\[
(3-10)
\]

3. Experimental results and analysis

According to the above contents, the error between the measured value and the set value and the change of the control quantity are regarded as the training index variables of the traditional neural network control layer, and the weight relation between them can be adjusted to obtain the best control effect.

AA: Change in the controlled amount of dissolved oxygen and coefficient of output deviation.
BB: Change of control amount and output deviation coefficient of nitrate nitrogen.

The four coefficients are slightly different for sunny days, rainy days and rainstorm days. The experimental results are shown in Figure 5. The abscissa is the days, and the ordinates are So, which means concentration mg/L in the fifth zone and SNo, which means concentration mg/L in the second zone.
Figure 5. (a) Operation results on sunny days; (b) Operation results on rainy days; (c) Operation results on rainstorm days.

4. Conclusion

In order to solve the problem of balance between energy consumption and effluent water quality in sewage treatment plants, a real-time optimal control method based on model predictive control is proposed in this paper. BP neural network was used in both controller and model prediction. The experiment shows that this method can reduce energy consumption under the premise of ensuring effluent quality. The following conclusions can be drawn in this paper:

1. The $e$ and $\Delta u$ coefficients of dissolved oxygen in sunny days are 10 and 0.5 respectively, and the $e$ and $\Delta u$ coefficients of nitrate nitrogen are 1300 and 0.05 respectively reach the control requirements.

2. The rainy day, dissolved oxygen $e$ and $\Delta u$ coefficient are 10 and 0.15 respectively, nitrate nitrogen $e$ and $\Delta u$ coefficient are 1500 and 0.05, respectively, when the control requirements.

3. At the time of rainstorm, the $e$ and $\Delta u$ coefficients of dissolved oxygen are 10 and 0.15 respectively, and the $e$ and $\Delta u$ coefficients of nitrate nitrogen are 1500 and 0.03 respectively to meet the control requirements.

References