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Research article

Application of multi-model switching predictive functional control on the temperature system of an electric heating furnace

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ABSTRACT

A method of multi-model switching based predictive functional control is proposed and applied to the temperature control system of an electric heating furnace. The control strategies provide the effective and independent control modes of the electric heating furnace temperature in order to obtain improved control performance. The method depends on conventional implementation of the multi-model switching state, which requires some endeavors to tune the switching model in the model predictive control and allows a reduction of the calculation compared with the weighted multiple model algorithms. In order to test the advantage of the proposed method, experimental equipment is set up and experiments are done on the temperature process of a heating furnace, which verify the validity and effectiveness of the proposed algorithm.

1. Introduction

Electric heating furnace is a kind of equipment that is widely used in industrial processes [1]. It is characterized with large inertia, time delay and uncertainty and it is very hard to obtain high control precision by traditional control methods. The performance of electric heating furnace has a direct impact on the efficiency of the subsequent product, so it is important to find effective control methods.

Proportional-integral-derivative (PID) control algorithm is the most commonly used method in industry [2]. Most researchers have been directed towards the PID design so far in the process control field, primarily because the algorithm is easily implemented with acceptable performance. However, the control system's speed and overshoot are affected by the control parameters and how to adjust these parameters is the key issue that influences the performance of the control system. Some papers have been published to present different control strategies for tuning the parameters of PID. In [3], a method for adjusting the parameters of the PID controller based on the steady state characteristic and the stability margin of the feedback closed loop system is proposed. Internal model control (IMC) schemes are common in this field and usually involve the use of a model to form an equivalent PI controller [4]. However, PID control algorithms can hardly meet the situation that industrial processes are becoming more and more complex with large inertia and time delay.

Nowadays, model predictive control (MPC) is seen as a promising alternative to typical control schemes like PID [5–8] because it can effectively deal with industrial processes with uncertainty. MPC cascade feedback control has also been proposed for the control of chemical industrial furnace in different fields [9–11]. The authors in [12] present an application of nonlinear MPC with a dead time compensator to control a distributed solar collector. An input-output feedback linearization scheme for doubly-induction generators has been proposed in [13]. In [14], the authors investigated MPC schemes for a reactive distillation column used for the hydrogenation of benzene. MPC in precision tracking control and constraint handling of mechatronic servo systems is proposed in [15]. In [16], a MPC scheme for industrial coke fractionation tower was presented. The control algorithm is a kind of MPC cascade control that the inner P control system is treated as a new state space model for MPC design.

In spite of its advantages, the classical implementation of MPC also suffers from some disadvantages, namely the insufficient precision of offline identified modes in the nonlinear system. Hence, the phenomena of delay, large inertia and time varying of parameters in the process should be considered not only in the control algorithm but also in the mathematical models. In nonlinear systems, the dynamic response of the process is ultimately limited by the model precision. Moreover, some efforts have to be made to develop new modeling approaches in order to improve the accuracy of the process model [17].

Multiple model control strategy is effective for processes with strong nonlinearity and time-varying parameters [18,19]. In [20], a switching multi-model predictive control strategy is used for hypersonic vehicle with strong nonlinearity. In [21], the authors proposed multiple models combined with Bayes theorem to describe the nonlinear hybrid systems. In [22], a multiple-model

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predictive control strategy for the component content in the rare earth extraction process is discussed. It's no doubt that we can effectively combine MPC with the multiple models to deal with the large inertia phenomenon and nonlinearity issues in the processes [23–25].

Motivated by the above-mentioned situation, the main contribution of this paper is to propose a multi-model switching based predictive functional control (PFC) method to cope with the nonlinearity and uncertainty of industrial processes. In this paper, the multi-model switching based PFC algorithm is first designed and then implemented on the temperature process of a SFX-40 electric heating furnace. The main contributions of this paper are as follows:

(1) Implement the inner PI control in the temperature loop to form a PI control system.
(2) Divide the working conditions into several submodels to increase the modeling precision.
(3) Design the multi-model switching PFC for the local models to increase the overall performance.

This paper is organized as follow. In Section 2, the process modeling and the multi-model switching based on predictive functional control method are introduced. In Section 3, the experimental setup, the system hardware, software and the temperature process are described. In Section 4, experiment results of implementing the proposed algorithms on the temperature of the electric heating furnace are shown. Finally, conclusion is given in Section 5.

2. Mathematical models and the PFC control algorithm

2.1. Process model

The implementation of modeling requires large amounts of data, which is the first step in the controller design. For convenience of the subsequent controller design, a typical first order plus dead time (FOPDT) model is adopted here.

$$G(s) = \frac{y(s)}{u(s)} = \frac{K}{Ts+1}e^{-\tau s} \tag{1}$$

where $G(s)$ is the Laplace transform of the process model, $y(s)$ and $u(s)$ are the Laplace transforms of the process output $y(t)$ and input $u(t)$, respectively. K is the steady process gain, T is the time constant and τ is the time delay.

Identification of the three parameters is the key step in process modeling. The process output change divided by the input change can be calculated to obtain the process gain. The delay and the time constant are estimated by the two-point method in the literature [26]. The response of $y(t)$ to the step input is

$$y(t) = \begin{cases} 0 & , t < \tau \\ K - Ke^{-\frac{t-\tau}{T}} & , t \geq \tau \end{cases} \tag{2}$$

Denote $y(\infty)$ as the steady value of $y(t)$ and U as the input step signal change. The steady process gain K is then calculated as $K = \frac{y(\infty) - y(0)}{U}$.

The typical two different time points t_1 and t_2 are chosen such that

$$\begin{aligned} y(t_1) &= 0.39(y(\infty) - y(0)) + y(0) \\ y(t_2) &= 0.63(y(\infty) - y(0)) + y(0) \end{aligned} \tag{3}$$

Then the time constant T and the delay τ are derived as follows:

$$\begin{aligned} T_1 &= 2(t_2 - t_1) \\ \tau_1 &= 2t_1 - t_2 \end{aligned} \tag{4}$$

2.2. Predictive functional control design

Firstly, the model of the process without the delay part will be considered as follows:

$$G(s) = \frac{y(s)}{u(s)} = \frac{K}{Ts+1} \tag{5}$$

Based on the sampling time of T_s, the discrete model of the process is expressed as:

$$y_m(k) = a \cdot y_m(k-1) + K \cdot (1-a) \cdot u(k-1) \tag{6}$$

where $a = e^{-\frac{T_s}{T}}$. $y(k)$ and $u(k-1)$ are the discrete output variable and input variable of the process model at corresponding time instants, respectively. k is the current time instant.

According to the above prediction model, the future H step predicted value of the model can be calculated by the current model output value $y_m(k)$ and control input $u(k)$ under the condition that $u(k) = u(k+1) = \cdots = u(k+H-1)$:

$$y_m(k+H) = a^H \cdot y_m(k) + K_m \cdot \left(1 - a_m{}^H\right) \cdot u(k) \tag{7}$$

For the above process model, we choose the following first order reference trajectory:

$$y_r(k+H) = y_p(k) + (c - y_p(k))\left[1 - e^{\left(-H \cdot \frac{Ts}{Tr}\right)}\right] \tag{8}$$

where $y_p(k)$ is the process output, Tr is the time constant of the reference trajectory.

In order to improve the robustness of the control system, the error feedback correction is introduced as follows:

$$y_m(k+H) + e(k) = y_r(k+H) \tag{9}$$

where $e(k)$ is the deviation of the model output and the actual output at the time instant k:

$$e(k) = y_p(k) - y_m(k) \tag{10}$$

Consider the following objective function:

$$J = \min\,(y_m(k+H) + e(k) - y_r(k+H))^2 \tag{11}$$

then the input control of the current instant can be obtained as:

$$u(k) = \frac{(c - y_p(k)) \cdot (1 - \beta^H) + y_m(k)(1 - a_m{}^H)}{K_m \cdot (1 - a_m{}^H)} \tag{12}$$

Now, consider the time delay in the process, the difference equation is expressed as:

$$y(k) = a \cdot y(k-1) + K \cdot (1-a) \cdot u(k-d) \tag{13}$$

where $d = \frac{\tau}{T_s}$.

By reference to the idea of Smith predictor, we use a process model with no delay time to correct the measured process output values. The process output of the controlled process is:

$$y_p(k) = a \cdot y_p(k-1) + K \cdot (1-a) \cdot u(k-1-d) \tag{14}$$

The process output of the model with delay is:

$$y_m(k) = a \cdot y_m(k-1) + K \cdot (1-a) \cdot u(k-1-d) \tag{15}$$

Since the process model output without time delay is expressed as:

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