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State space predictive functional control optimization based new PID design for multivariable processes

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ABSTRACT

Proportional-integral-derivative (PID) controller encounters challenge when dealing with the multiple input and multiple output (MIMO) industrial processes, because the coupling, time delay and other characteristics make the design of PID controllers complicated. A novel PID controller based on extended non-minimal state space predictive functional control (ENMSSPFC) is proposed to control the chamber pressure of an industrial furnace where the process is a typical MIMO process. ENMSSPFC is an improved predictive functional control (PFC) algorithm in which the state variables and the tracking error are combined and regulated separately, so that more freedom can be offered in the adjustment and better performance can be provided. The new PID controller inherits the simple structure and the improved performance of ENMSSPFC, and two case studies of pressure regulation in the industrial chamber and Vinante and Luyben (VL) column system are introduced to show the effectiveness of proposed method.

1. Introduction

PID controller is the most practical controller in industrial processes because of its simple structure and hardware requirement [1]. With the increasing demands of product quality, the requirement of control performance is also stricter. Research on PID control has never stopped since it was proposed, and there are many classic tuning methods [2–5]. For multivariable processes, the application of PID control may not be very effective or the corresponding tuning processes may become very complex for conventional PID controllers [6–8]. Based on the aforementioned background, many research results were put forward. A tuning criterion for multi-input multi-output (MIMO) PID controllers based on characteristic matrix eigenvalues and Lyapunov functions was proposed in [9]. The conditions for closed-loop stabilizability of linear time-invariant (LTI) MIMO plants with I/O delays (time delays in the input and/or output channels) using PID controllers were presented in [10]. A multivariable fractional order PID controller was designed to get suitable coefficients for the controller, and a genetic algorithm with a new topology was proposed to generate a new population [11]. In [12], the design of decentralized PID controller for interactive and delay time processes was proposed. Many other researchers also contribute to the design of PID controller for MIMO processes [13–16].

It is further illustrated by several researchers that traditional PID can hardly be sufficient enough in dealing with coupling, time delay or even nonlinear dynamics [17–23]. Following the development of computer control technology, model predictive control (MPC) was proposed as an effective control algorithm, and has acquired extensive research and applications [24–33]. However, with the limitations of cost, hardware and so on, the applications of MPC controllers are less than conventional PID controllers. It is of great significance to find a way to simplify the implementation of MPC controllers or improve the control performance of PID controllers via the combination with MPC algorithms. A new generalized predictive control (GPC) based PID controller was proposed in [34], which inherits the similar performance as GPC and the simple structure as conventional PID controller. Incorporating the fuzzy and PID control approaches into MPC framework, a new multivariable predictive fuzzy-PID control system was developed in [35]. On the basis of simplified GPC, a novel PID controller was presented successfully in [36]. Zhang et al. proposed a new PID controller through combining predictive functional control (PFC) with conventional PID control, and tested the performance of the resulting controller on an industrial fractional tower [37]. There is also a lot of other progress made in the research of PID controllers optimized by other advanced algorithms [38–45].

It is worth mentioning that the new state space model in which state variables and tracking error are combined and regulated separately proposed in [46], provides more freedom for the design of controllers. Based on the extended non-minimal state space model (ENMSS), several control strategies have been proposed [47–49]. ENMSS has also been adopted to derive a novel PID controller by introducing the framework of conventional PID controller into MPC algorithm [50].

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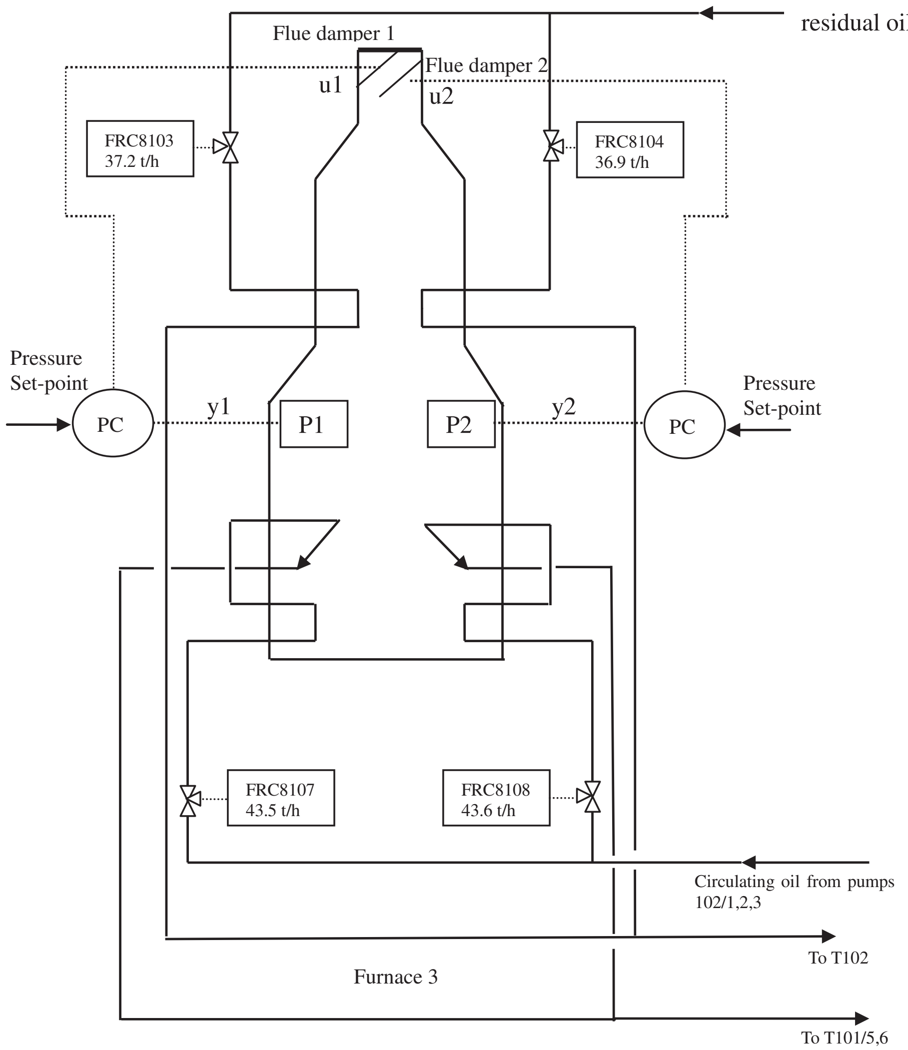

Fig. 1. Overall flow of coke unit.

A novel multivariable PID controller based on ENMSSPFC is proposed in this study. With the regulation freedom provided by ENMSS model, better ensemble control performance is obtained by incorporating the conventional PID control and PFC algorithm. Two case studies of chamber pressure in the industrial coke furnace and VL column system are introduced to verify the improved performance of the proposed PID controller compared with PID controller optimized by non-minimal state space (NMSS) PFC algorithm. What is more, the dynamic matrix control (DMC) algorithm is also introduced to serve as the benchmark to evaluate the performance of the proposed PID controller.

2. Non-minimal state space model and its extended form

Here we suppose that the controlled process has p inputs and q outputs, then the corresponding difference equation model of the system can be described as follows:

$$\begin{aligned} y(k+1) + L_1 y(k) + L_2 y(k-1) + \cdots + L_n y(k-n+1) \\ = S_1 u(k) + S_2 u(k-1) + \cdots + S_n u(k-n+1) \end{aligned} \quad (1)$$

where $y(k)$ and $u(k)$ are the output and input of the system at time instant k, respectively. $L_1, L_2, \cdots, L_n$ and $S_1, S_2, \cdots, S_n$, are the coefficients of the output and input, respectively.

By adding the back shift operator Δ to Eq. (1), we can obtain the following model

$$\begin{aligned} \Delta y(k+1) + L_1 \Delta y(k) + L_2 \Delta y(k-1) + \cdots + L_n \Delta y(k-n+1) \\ = S_1 \Delta u(k) + S_2 \Delta u(k-1) + \cdots + S_n \Delta u(k-n+1). \end{aligned} \quad (2)$$

Table 1
Steady state operating conditions.

Coke furnaces	
Radiation output temperature	495 °C
Convection output temperature	330 °C
Chamber temperature	800 °C
Oxygen content	5%
Circulating oil flow	35 t/h
Coke fractionating tower	
Tower bottom temperature	350 °C
Tower liquid level	70%
Coke towers	
Tower top temperature	415 °C
Tower bottom temperature	300 °C
Temperature after cooling	85 °C
Tower top pressure	0.25 Mpa