THIẾT KẾ HỆ THỐNG ĐIỀU KHIỂN MỨC NƯỚC NỒI HƠI

Design of Control System for Regulation of Water Level in a Boiler Drum

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Tóm tắt

Bài báo đề xuất phương pháp thiết kế hệ thống điều chỉnh mức nước trong nồi hơi. Hệ thống điều khiển mức trong nồi hơi được sử dụng rộng rãi trong các hệ thống năng lượng và công nghiệp. Yêu cầu của hệ thống điều khiển là đưa nồi hơi đến nhiệt độ sôi và duy trì mức với thông số luồng hơi không đổi. Hệ thống điều khiển đề xuất sử dụng bộ điều khiển PID với các thông số được tối ưu hóa sử dụng phương pháp cross-entropy. Kết quả đạt được đã chứng minh ưu điểm của phương pháp cross-entropy, nâng cao chất lượng điều khiển.

Keywords

Boiler drum, water level control, PID control, Cross-Entropy.

Abstract

Design of a control system for regulation of water level in a boiler drum is developed in this paper. Drum level control systems are used extensively in heat power engineering and industrial process. The purpose of the control system is to bring the drum up to level at boiler point and maintain the level at constant steam load. The proposed control system is designed with a PID controller which is optimized by cross-entropy method. The received results showed advantages of the cross-entropy method in quality improvement of the designed control system.

Nomenclature

Notation	Unit	Expression
$W_O(s)$		Transfer function of boiler drum
Kp, Ki, Kd		Parameters of a PID controller
μ		Sample mean
σ^2		Sample variance
α, β		smoothing update parameters
N^{elite}		Best performing samples

Acronym

PID	Proportional-Integral-Derivative
pdf	probability density function
IMC	Internal Model Control
FLC	Fuzzy Logic Controller
CE	Cross-Entropy
ITAE	Integral Time Absolute Error

1. Introduction

Drum Level Control Systems are used extensively in the process industries, in the utilities to control the level of boiling water contained in boiler drums on process plant, and it help provide a constant supply of steam. The purpose of the drum level controller is to bring the drum up to level at boiler start-up and maintain the level at constant steam load [1]. All boilers require feedwater flow control to supplement for the steam that leaves the boiler. Most boiler designs use a steam drum where the feedwater flow enters the boiler and the steam leaves. The water level in the drum must be maintained to provide responsive and stable control of the steam flow to prevent equipment damage. To maintain drum level, the feedwater flow into the drum must equal the flow of steam out on mass basis. Therefore, boiler load changes, which change the steam flow and require the feedwater flow be changed to control and maintain the drum level. If the drum level drops too low, the boiler can suffer thermal stress damage. If the level gets too high, steam leaving the drum may carry some water particles along, which can cause damage to turbines or other steam users. Finally, oscillation in drum level cause effects on the boiler combustion controls which can carry out unstable boiler control resulting and dangerous operation. Boiler drum water level control is critical to secure operation of the boiler and the steam turbine.

Boiler drum is one of the typical systems which have high non-linearities, time-varying response, and a transportation lag. Various controlling mechanism are used to control the boiler system so that it works properly. Conventionally, such a system has been controlled in the past using control methods, such as PID controllers [2, 3], IMC theory [4], fuzzy logic controller (FLC) [5].

A PID controller is a general feedback control loop mechanism widely used in industrial process control systems. Design of the PID controller using Ziegler–Nichols and Tyreus-Luyben methods for control of water level in a boiler drum is implemented in [6], but quality metrics of transient processes in the system are not really good. Therefore, parameters of controller are required to optimize and improve the performance of drum level control system.

A Macroscopic optimization using the cross-entropy method is a general Monte Carlo approach to combinatorial and continuous multi-extremal optimization and importance sampling. This method was motivated by an adaptive algorithm for estimating probabilities or rare events in complex stochastic network [7], which involves variance minimization. A simple modification of the initial algorithm allows applying it to solve difficult combinatorial optimization problems [8]. In [9] the CE method was used to optimize the parameters of a Fuzzy-PD controller for stability regulation of a two-wheeled self-balancing robot. In this paper, the CE method is proposed to optimize the parameters of a PID controller for control of water level in a boiler drum.

2. System description

2.1 Drum level control system

Boiler drum level control is critical for the protection of plant and safety of equipment. Typically, there are three strategies used to control drum level. With each successive strategy, a refinement of the previous control strategy has been taken place. For extent of the load change requirements, the control strategy depends on the measurement and control equipment. In the paper, three-element drum level control is considered (Fig. 1). This control system is ideally suited where a boiler plant consists of multiple boilers and multiple feed water pumps or feed water valve has variation in pressure or flow. It requires the measurement of drum level, steam flow rate, feed water flow rate and feed water control valve. Mathematical model of the system can be described by the transfer function [1,6]:

$$W_O(\mathbf{s}) = \frac{0.25 - 0.25\mathbf{s}}{0.3\mathbf{s}^3 + 2.15\mathbf{s}^2 + \mathbf{s}} \tag{1}$$

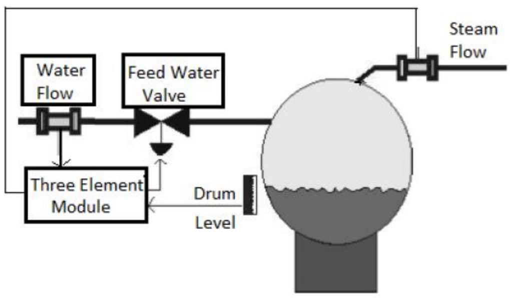

Fig. 1 *Three element boiler drum level control.*

The block diagram of typical drum level control system using the PID controller is shown in Fig. 2

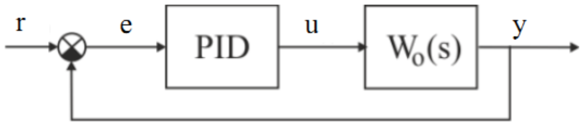

Fig. 2 *Structure of control system with PID controller.*

2.2 PID controller

PID controllers are widely used in industrial control systems. Even complex industrial control systems may consist a control network which is constructed from PID control modules. The PID controller separately calculates the three parameters i.e. the proportional, the integral, the derivative values. The proportional value determines the reaction to the current error. The integral value carries out the reaction based on the sum of recent errors as the past error. The derivative value defines the reaction based on the rate at which the error has been changing as a future error. By tuning these three constants in the PID controller algorithm, the controller can provide control action designed for specific process control requirements.

2.3 Cross-Entropy method

The factors (Kp, Kd, Ki) of the PID controller are designed using cross-entropy optimization method. This approach is based on a population and simulation optimization [10]. The CE algorithm generates a set of N PID controllers $x = (Kp, Kd, Ki)$ with $g(x,\upsilon) = (g(Kp,\upsilon), g(Kd,\upsilon), g(Ki,\upsilon))$ and calculates the cost function value for each controller. Then updates $g(x,\upsilon)$ using a set of the best controllers. This set of controllers is defined with the parameter N^{elite}. The process finish when the minimum value of the cost function or the maximum number of iterations is reached, as is shown in the Algorithm 1.

Algorithm 1. Cross-Entropy algorithm for PID controller optimization

1. Initialize $t = 0$ and $\upsilon(t) = \upsilon(0)$;
2. Generate a sample of N controllers: $(x_i(t))_{1\le i\le N}$ from $g(x,\upsilon(t))$, being each $x_i = (Kp_i, Kd_i, Ki_i)$
3. Compute $\phi(x_i(t))$ and order $\phi_1, \phi_2, \ldots, \phi_N$ from smallest $j = 1$ to biggest $j = N$. Get the N^{elite} first controllers $\gamma(t) = \chi[N^{elite}]$.
4. Update $\upsilon(t)$ with

$$\upsilon(t+1) = \arg_{\upsilon} \min \frac{1}{N^{elite}} \sum_{j=1}^{N^{elite}} I_{\{\chi(x_i(t)) \ge \gamma(t)\}} \cdot \ln g(x_j(t), \upsilon(t))$$

5. Repeat from step 2 until convergence or ending criterion
6. Assume that convergence is reached at $t = t^*$, an optimal value for ϕ can be obtained from $g(.,\upsilon(t)^*)$.

For this work the Normal (Gaussian) distribution was selected. The mean μ and the variance σ are estimated for each iteration $h = 1, 2, \ldots$ parameters (Kp, Kd, Ki) as $\tilde{\mu}_{th} = \sum_{j=1}^{elite} \frac{x_{jh}}{N^{elite}}$ and $\tilde{\sigma}_{th}^2 = \sum_{j=1}^{elite} \frac{(x_{jh} - \mu_{jh})^2}{N^{elite}}$. In order to obtain a smooth update of the mean and the variance we use a set of parameters (β, α, η), where α is a constant value used for the mean, η is a variable value which is applied to the variance to avert the occurrences of 0[s] and 1[s], β is constant value which modify the value of $\eta(t)$.

$$\begin{aligned} \eta(t) &= \beta - \beta\left(1 - \frac{1}{t}\right)^q \\ \hat{\mu}(t) &= \alpha.\tilde{\mu}(t) + (1-\alpha).\hat{\mu}(t-1) \\ \hat{\sigma}(t) &= \eta(t).\tilde{\sigma} + (1-\eta).\hat{\sigma}(t-1) \end{aligned} \quad (2)$$

The values of the smoothing update parameter are $0.4 \le \alpha \le 0.9$ and $0.4 \le \beta \le 0.9$. In order to an optimized controller the Integral Time Absolute Error criterion (ITAE) could be chosen. The block diagram of the control loop during the optimization process is shown in Fig. 3

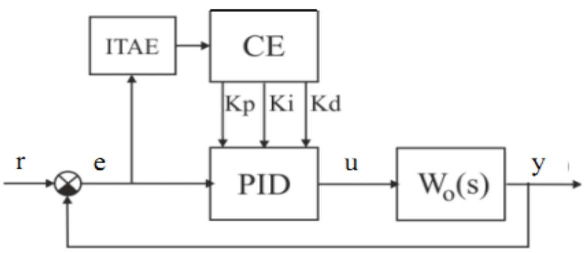

Fig. 3 *Control loop used the cross-entropy optimization method.*

3. Main results

The cross-entropy system generates N= 60 controllers per iteration based on the last update of the probability density function (pdf) for each again. From this set of controllers the ten with the lowest ITAE value are selected $(N^{elite} = 5)$ to update the next pdf parameters. The initial values for the pdf of the parameters are $\mu(0) = 1$ for Kp, Kd; $\mu(0) = 1$ for Ki; $\sigma(0) = 0.5$ for the all factors. The evolution of the mean of the ITAE value of the 5 winners from each set of 60 controllers is shown in Fig. 4. The evolution of the different parameters of the PID control during 12 iterations is shown in Fig. 5

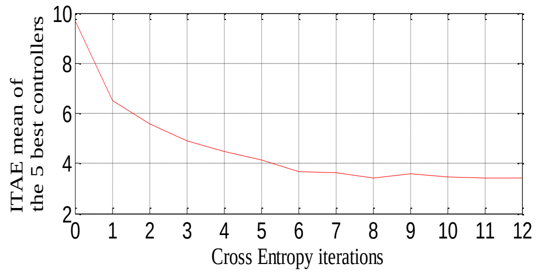

Fig. 4 *Evolution of the ITAE error during the 12 cross-entropy iterations. The ITAE value of each iteration correspond to the mean of the first 5 of 60 controllers of each iteration.*

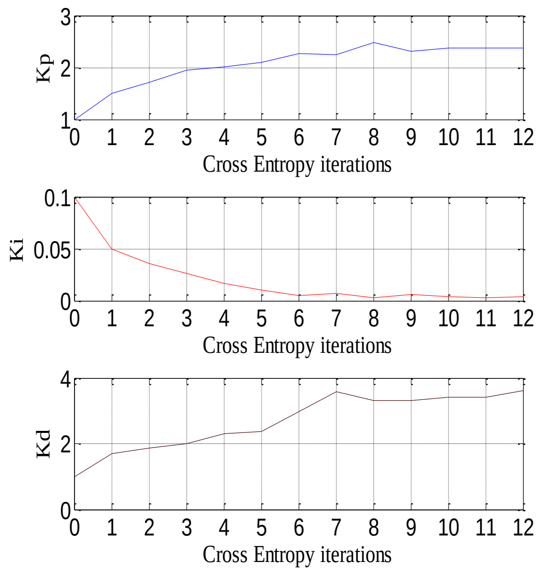

Fig. 5 *Evolution of the scaling factors of each input. The values of the scaling factor correspond to the first 5 of 60 controllers of each iterations.*

The normalized transient processes in the system which use the PID controllers turned with Ziegler-Nichols (ZN-PID), Tyreus-Luyben (TL_PID) methods and with the optimal PID based on the CE method (CE-PID) are shown in Fig. 7

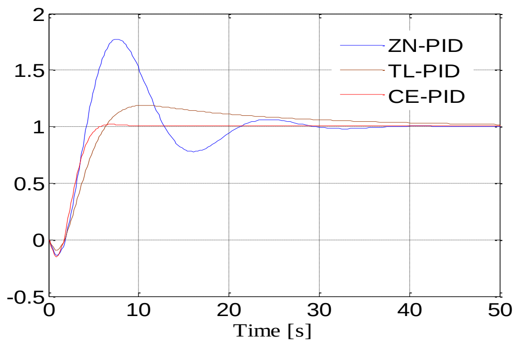

Fig. 6 *Transient processes in three systems*

Table. I QUALITY METRICS OF TRANSIENT PROCESSES

Controller	**Parameter**			
	Rise time [s]	***Peak time [s]***	***Peak overshoot [%]***	***Settling time [s]***
ZN-PID	4.22	7.62	77.89	26.67
TL-PID	6.31	10.54	19.24	33.57
CE-PID	5.12	6.02	1.02	5.12

Quality metrics of transient processes in the system are shown in Table I. Quality metrics of transient processes in the system with the CE-PID controller are better than the other controllers.

4. Conclusion

The paper presents a design of a PID controller using the cross-entropy optimization method for control of water level in a boiler drum. Simulation is implemented in the MATLAB environment. Though the simulation the cross-entropy algorithm perform an efficient search to obtain an optimal solution for the parameters of the PID controller. The comparison between the different design methods is shown. The received results showed advantages of the cross-entropy method in quality improvement of the PID controller in level control system of a boiler drum. The received parameters using the cross-entropy method let the PID control achieves better performance criterion with respect to rise time, settling time, percentage of overshoot.

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