Journal of Process Control 66 (2018) 59–67

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Economic model predictive control of boiler-turbine system

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ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 20 February 2018
Accepted 28 February 2018

Keywords:
Economic model predictive control
Boiler-turbine
Stability
Feasibility

ABSTRACT

In a modern power plant, the economy of boiler-turbine system has recently aroused too much concern, while load tracking is no longer the only significant task for control and optimization purpose. Traditionally, the economy of the boiler-turbine system has been handled in a multi-layer hierarchical architecture, which neglects the economy of the dynamic tracking process. In this paper, an economic model predictive controller is developed. It directly utilizes the economic index of boiler-turbine system as the cost function and realizes the economic optimization as well as the dynamic tracking. A stable Sontag controller and corresponding region are designed to ensure the stability of the closed-loop system. Then, the optimization problem of this economic model predictive control is solved on-line using Laguerre functions. Simulations are given to show the effectiveness of the proposed controller.

1. Introduction

During the past decades, model predictive control (MPC) has developed considerably and become a high-performance control strategy for power plant control. The major advantage of MPC is that the power plant physical constraints can be incorporated into the multivariable optimization problem. For this purpose, the earliest and timely attempt in power plant control was made by Hogg and El-Rabaie, who constituted generalized predictive control (GPC) on boiler system [1]. The Hogg's group then extended this method to nonlinear boiler-turbine model based on the nonlinear neural networks [2]. Liu and Chan developed neuro-fuzzy generalized predictive control (GPC) strategy for boiler steam temperature control [3]. Later on, Liu fully developed nonlinear-constrained optimization for the coordinated control system using neuro-fuzzy network (NFN) and input–output linearization methods [4]. More recently, the researchers incorporated MPC with iterative learning control [5], and even with data-driven method [6], to increase its self-learning ability.

Nowadays, the major concerns of power plant operation have been changing from purely tracking control problems to the economic and environmental issues. Apart from realizing the load tracking, power plant should more concern other objectives, e.g., minimization of fuel consumption, maximization of duty life, minimization of pollutant emissions, etc. [7]. A general way of improving the economy of thermal power plant is to decompose its management and optimization into two levels [8,9]. The first level is generally called the real-time optimization (RTO), which determines the economically optimal operating set-points. The second level is responsible for deciding suitable control actions by MPCs, which can steer the system to the desired steady-state operating condition. One shortcoming of this hierarchical control is that it neglects the economy of the dynamic process. Fig. 1 gives a simple and intuitive explanation showing an economic cost surface in relationship with one state variable and one input variable. The regulatory MPC can directly reach the steady-state optimum rather than the global economic optimum, as this controller is unaware of the high profit states [10].

The economic factors must thus be taken into theoretical consideration in the design of MPC to achieve high economic performance. The recently developed economic MPC, which integrates real-time process economic optimization and feedback control into an optimal control framework [11], has attracted significant attention. In contrast to traditional tracking MPC, economic MPC uses general cost functions (containing economic index) which may not be positive definite with respect to any tracking trajectory. Thus, stability, closed-loop economic performance, and computational considerations are the major challenges in achieving high performance economic MPC [12]. Generally, the stability is guaranteed through terminal constraints based on the assumption of strong duality and dissipativity [13,14]. Paper [15] extended this closed-loop system stability to discretization process. A Lyapunov-based economic MPC using two different modes of operation was constituted to guarantee states of the closed-loop system ultimately bounded in a small region [16]. This method increased the freedom degree of dynamic optimization and expanded the feasible region.

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https://doi.org/10.1016/j.jprocont.2018.02.010
0959-1524/

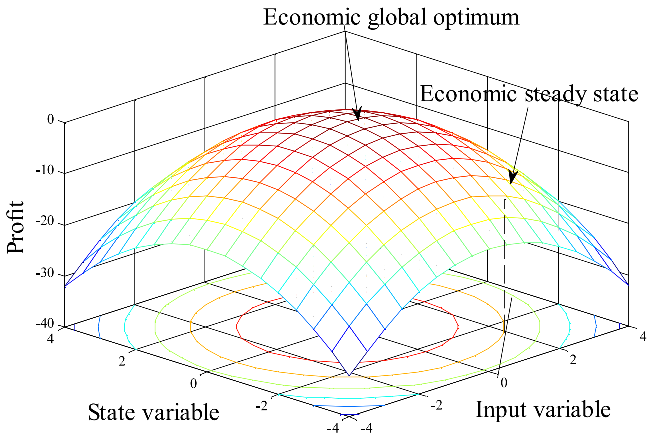

Fig. 1. Economic cost surface and the steady-state plane.

Paper [17] presented a shrinking prediction horizon with respect to fixed operation period to ensure improved performance. Paper [18] constituted a Lyapunov-based economic MPC controller based on the multi-models with guaranteeing closed-loop stability.

Although these efforts have well established the economic MPC framework, three key issues must be further addressed for power plant control tasks: (i) due to the strong nonlinearity of boiler-turbine system, an economic MPC based on multiple linear models must be formulated, in which the states over future time can be expressed explicitly; (ii) a proper dynamic economic optimization mode, together with the guaranteeing stability mode, should be utilized to improve the economy of boiler-turbine system, and (iii) a Lyapunov-based auxiliary controller steering the boiler-turbine system into the stable region, should be designed based on multiple linear models.

This paper presents an economic MPC with two modes for boiler-turbine applications based on multiple linear models. The first mode optimizes the economic cost function while maintaining the system states within a feasible region. The second mode steers the state of the system to the optimal operating point using the stable Sontag controller. The resulting convex program can be solved efficiently based on Laguerre functions modeling.

The rest of the paper is structured as follows: In Section 2, a description of the boiler-turbine system and the economic performance index is given. In Section 3, the economic MPC formulation for boiler-turbine system, together with the designing Sontag controller and the stable region, is presented. Section 4 gives detailed economic MPC simulation and analysis on the boiler-turbine system. Finally, Section 5 concludes the paper.

2. Problem statement

The nonlinear boiler–turbine model representing a 160 MW drum-type power plant is originally established by Aström [19]:

$$\dot{x}(t) = F(x(t)) + G(x(t))u(t) \tag{1}$$

where

$$F(x(t)) = \begin{bmatrix} 0 \\ -0.1x_2 - 0.016x_1^{9/8} \\ 0.0022x_1 \end{bmatrix}$$

$$G(x(t)) = \begin{bmatrix} 0.9 & -0.0018x_1^{9/8} & -0.15 \\ 0 & 0.73x_1^{9/8} & 0 \\ 0 & -0.0129x_1 & 1.6588 \end{bmatrix}$$

The three inputs $u = \begin{bmatrix} u_1 & u_2 & u_3 \end{bmatrix}^T$ are the positions of the valves that control the flow rates of fuel (u_1 in pu), steam to the turbine (u_2 in pu), and feedwater to the drum (u_3 in pu), respectively. The three state variables $x = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T$ are drum steam pressure (P in kg/cm2), electric power (E in MW) and steam–water density ρ_f respectively.

In the boiler-turbine system, the three controlled variables are drum steam pressure, electric power, and drum water level deviation (L in m). Thus, the three states are chosen almost identically to the three controlled variables, except that the drum water level output is calculated using an algebraic equation relating to the state fluid density, i.e.,

$$L = 0.05\left(0.13073x_3 + 100\alpha_s + q_e/9 - 67.975\right)$$

where $q_e = (0.854u_2 - 0.147)x_1 + 45.59u_1 - 2.51u_3 - 2.096$ is the evaporation rate, and $\alpha_s = \frac{(1-0.001538x_3)(0.8x_1-25.6)}{x_3(1.0394-0.0012304x_1)}$ is the steam quality.

The amplitudes and rates of change of the three inputs are constrained to

$$\begin{cases} -0.007 \le \dfrac{du_1}{dt} \le 0.007 & 0 \le u_1 \le 1 \\ -2.0 \le \dfrac{du_2}{dt} \le 0.02 & 0 \le u_2 \le 1 \\ -0.05 \le \dfrac{du_3}{dt} \le 0.05 & 0 \le u_3 \le 1 \end{cases} \tag{2}$$

Define the following economic indexes [7]:

$$\begin{cases} l_{e1}(x,u) = (Euld - x_2)^2 \\ l_{e2}(x,u) = u_1 \\ l_{e3}(x,u) = -u_2 \\ l_{e4}(x,u) = -u_3 \end{cases} \tag{3}$$

where *Euld* is the unit load demand (MW). $l_{e1}(x, u)$ denotes the power generation error for load-tracking purpose. $l_{e2}(x, u)$ denotes the fuel valve position representing the fuel usage. $l_{e3}(x, u)$ and $l_{e4}(x, u)$ denote steam valve throttle losses and feed-water valve throttle losses respectively. The greater the valve opens, the smaller the throttling loss is.

In designing the economic MPC, the economic stage cost function of boiler-turbine system can be obtained using the linear weighted method:

$$l_e(x,u) = \beta_1 l_{e1} + \beta_2 l_{e2} + \beta_3 l_{e3} + \beta_4 l_{e4} \tag{4}$$

where β_1, β_2, β_3, β_4 are the weighted coefficients.

A general economic MPC optimization problem with stability terminal constraints on this boiler-turbine system can be denoted as

$$\min_{u(t)} \int_{t_k}^{t_k+T_p} \left(\beta_1(Euld - \tilde{x}_2(\tau))^2 + \beta_2 u_1(\tau) - \beta_3 u_2(\tau) - \beta_4 u_3(\tau)\right) d\tau \tag{5a}$$

$$s.t.\, \tilde{x}(t_k) = x(t_k) \tag{5b}$$

$$\dot{\tilde{x}}(t) = F(\tilde{x}(t)) + G(\tilde{x}(t))u(t) \tag{5c}$$

$$u_{\min} \le u(t) \le u_{\max} \tag{5d}$$

$$\begin{aligned} &\Delta u_{\min} \le \dot{u}(t) \le \Delta u_{\max} \\ &t_k \le t \le t_k + T_p \end{aligned} \tag{5e}$$

$$\tilde{x}\left(t_k + T_p\right) = x_s \tag{5f}$$

where t_k represents the current moment and T_p is the predictive horizon. $x(t_k)$ in (5b) is the state variable obtained at time t_k. (5c) is the nonlinear state-space representation of boiler-turbine. The