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Nonlinear dynamics and control of bifurcation to regulate the performance of a boiler–turbine unit

Hamed Moradi *, Aria Alasty, Gholamreza Vossoughi

Centre of Excellence in Design, Robotics and Automation (CEDRA), School of Mechanical Engineering, Sharif University of Technology, PO Box 11155-9567, Tehran, Iran

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ABSTRACT

The economical operations of power plants and environmental awareness are the major factors affecting the importance of control in boiler–turbine units. In this paper, a multivariable nonlinear model of boiler–turbine unit is considered. Drum pressure, electric output and water level of drum (as output variables) are adjusted at desired values by manipulation of valve positions for fuel, steam and feed-water flow rates (as input variables). Nonlinear dynamics of the unit is investigated through the concepts of bifurcation and limit cycles behaviour. In the presence of harmonic disturbances, some coefficients of the dynamic model, fuel and steam flow rates play as the bifurcation parameters. It is shown that variation of bifurcation parameters leads to the occurrence of secondary Hopf (Neimark) and symmetry-breaking bifurcations (in drum pressure or electric output). To improve the aperiodic and quasi-periodic behaviour of the system to the stable periodic one, a control regulator is designed based on feedback linearization approach. It is shown that the controller acts efficiently in disturbance rejection and guarantees the stable periodic solutions with low oscillatory behaviour (which is essentially demanded by the power grid).

1. Introduction

Boiler unit, that produces steam, is one of the critical components of the power plant systems. Industrial boiler–turbine units are extensively used for steam generation as a source of power or for achieving heating capabilities in thermal plants. These units constitute complex nonlinear systems due to dynamic interaction between the various components such as furnace, evaporator, super-heaters, economizer, attemperator and drum. Although the steam production is varied during plant operation, output variables such as steam pressure, electric output and water level of drum must be maintained at their respected values. Therefore, regulation of water level of drum and tracking the load variation commands of drum pressure and power output are expected from a boiler–turbine system [1,2].

For the electricity generation, two configurations exist. In the first one, as called boiler–turbine unit, the steam is produced by a single boiler and is fed to a single turbine, as shown in Fig. 1 [3]. In the second one, several boilers generate total steam conducted to a collector and then distributed to several turbines. Since the boiler–turbine units show quick responses for electricity demand from a power network, they are preferred to collector type systems [1].

In the early works, simplification of nonlinear models of boiler–turbine unit [4], dynamic modelling of a boiler–turbine unit based on parameter estimation [5], system identification using neural networks [6], modelling based on data logs [7], and simple dynamic modelling and stability analysis of a steam boiler drum [8] have been done. Moreover, computer simulation packages such as SYNSIM for steam plants [9], simulation of large boilers with natural recirculation [10], and a computer program for simulation of boiler start up behaviour in natural and controlled circulations (DBSSP) [11] have been carried out. Also, application of a computational model for analysis and minimizing the fuel and environmental costs of a 310 MW fuel oil fired boiler has been studied [12].

Using physical principles and neural networks, dynamic nonlinear modelling of power plant has been investigated [13,14]. In addition, other various nonlinear models of boiler–turbine units, by using data logs and parameter estimation [15,16] and fuzzy auto-regressive moving average model [17] have been presented. Recently, modelling of a 1000 MW power plant including ultra super-critical boiler system using fuzzy-neural network methods [18] and numerical simulations of a small-scale biomass boiler unit [19] have been presented.

Various control methods have been used for boiler or boiler–turbine controller design. Effective control systems must be developed to have an appropriate performance of the boiler–turbine unit for large changes in the operating conditions. Linear optimal regulators [20,21] and decoupling controller [22] for performance control of boiler–turbine units have been designed. Also, multivar-

* Corresponding author. Tel.: +98 21 66165694; fax: +98 21 66000021.
E-mail addresses: hamedmoradi@asme.org, hamedmoradi@mech.sharif.ir (H. Moradi).

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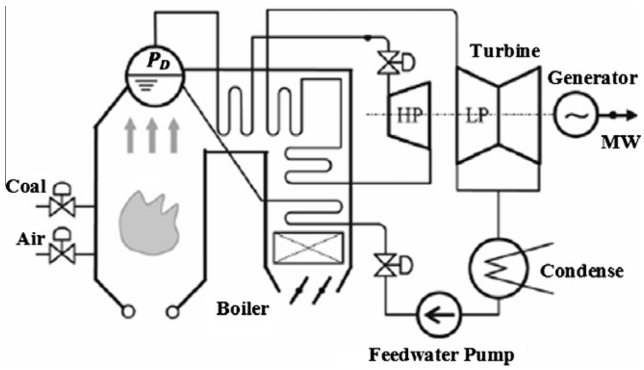

Fig. 1. Schematic of a boiler–turbine unit [3].

iable long-range predictive control based on local model networks [23], fuzzy model predictive control based on genetic algorithm [24], fuzzy based control systems for thermal power plants [25,26] and neuro-fuzzy network modelling and PI control of a steam-boiler system [27] have been presented.

In some works, model nonlinearity is avoided by selecting the appropriate operating zones such that the linear controller can perform effectively [1,3]. In other works, by constituting a linear parameter varying model of nonlinear boiler–turbine unit, gain scheduled optimal control have been used [28,29]. Also, nonlinear stable inversion theory and a multivariable output tracking control structure based on the approximate feedback linearization method have been applied [29–32]. In these works, a two-degree-of-freedom I-PD or PI structure was presented to improve the exact tracking of the pseudo-linear boiler–turbine system which was obtained by the feedback control law.

For robust performance of the boiler–turbine units, a controller based on adaptive Grey predictor algorithm [33], backstepping-based nonlinear adaptive control [34], adaptive dynamic matrix control with fuzzy-interpolated step-response model [35], sliding mode and H_∞ robust controllers [2,36–39] and a comparison between them [2,38] have been presented Also, for robust state estimation of the process and improving its performance, an optimum robust minimum-order observer has been designed [40].

As it is observed, many investigations have been devoted to the dynamic modelling and performance control of boiler–turbine units. Moreover, in the majority of them, linear theories have been used to predict the approximate dynamic system response. But, their nonlinear dynamics analysis has not been studied in the previous works. As discussed, due to dynamic interaction between various components, these units constitute complex nonlinear systems. Without an extensive pre-knowledge of these units behaviour against possible disturbances (which is common in any industrial unit), the designed controllers may lead to the aggressive response of output variables and also increase in energy consumption.

In this paper, nonlinear dynamics of a multivariable model of boiler–turbine unit is studied, in the presence of realistic harmonic disturbances. Drum pressure, electric output and water level of drum are the output variables while fuel, steam and feed-water flow rates are the control efforts. The effects of various parameters on limit cycle behaviour of drum pressure and electric output are studied (for the sake of brevity, similar analysis is not presented for the water level of drum). It is shown that some model coefficients, fuel and steam flow rates play as the bifurcation parameters; leading to the occurrence of secondary Hopf (Neimark) and symmetry-breaking bifurcations. To improve the aperiodic and quasi-periodic behaviour of the system to the stable periodic one, a control regulator is designed based on feedback linearization approach.

From practical point of view, having a pre-knowledge of the nonlinear dynamics and bifurcation cases of the boiler–turbine unit can be used as a passive control approach. It means that by nonlinear dynamics analysis, it is possible to identify the conditions leading to the unsatisfactory quasi-periodic behaviour. Accordingly, input variables or model parameters can be adjusted to prevent such inappropriate performance. This nonlinear dynamics analysis, as a passive control approach, is carried out in the first part of the research (first novelty).

However, for tracking objectives in the presence of bifurcation, such tuning in the model parameters or control efforts does not guarantee the desired performance of the system. Therefore, second part of this research is devoted to the design of a nonlinear regulator based on the feedback linearization method (second novelty). According to the results obtained, this controller acts efficiently in periodic regulation of the model around desired operating points (in the presence of bifurcation). Finally it should be mentioned that results of this research can be extended to other industrial boiler–turbine units, which their dynamic models are extracted from experimental data logs.

2. Process description and its nonlinear dynamic model

A water-tube boiler is considered in which preheated water is fed into the steam drum and flows through the down-comers into the mud drum (as shown in Fig. 1 [3]). Passing through the risers, water is heated and changed to the saturation condition. The saturated mixer of steam and water enters the steam drum, where the steam is separated from water and flows into the primary and secondary super-heaters. Then, steam is more heated and is fed into the header. There is a spray attemperator between two super-heaters that regulates the steam temperature by mixing low temperature water with the steam.

In this paper and as a real case study, the nonlinear dynamic model of a boiler–turbine unit presented by Bell and Astrom is considered [15]. This practical model has been used in many of previous works, especially to investigate control aspects of the problem. Parameters of this model were estimated by data measurement from the Synvendska Kraft AB plant in Malmo, Sweden. As shown in Fig. 2 [28], output variables are denoted by y_1 for drum pressure (kgf/cm^2), y_2 for electric output (MW) and y_3 for drum water level (m). Input variables are denoted by u_1, u_2 and u_3 for valves position of the fuel flow, steam control, and feed-water flow, respectively. Dynamics of this 160 MW oil-fired unit is given in the state space representation as [15]:

$$\begin{aligned}
\dot{x}_1 &= -\alpha_1 u_2 x_1^{9/8} + \alpha_2 u_1 - \alpha_3 u_3 \\
\dot{x}_2 &= (\beta_1 u_2 - \beta_2) x_1^{9/8} - \beta_3 x_2 \\
\dot{x}_3 &= [\gamma_1 u_3 - (\gamma_2 u_2 - \gamma_3) x_1]/\gamma_4 \\
y_1 &= x_1 \\
y_2 &= x_2
\end{aligned} \tag{1}$$

where x_3 denotes the fluid density (kg/m^3) and coefficients α_i, β_i, γ_j, $i = 1,\ldots,3$, $j = 1,\ldots,4$ are given in Table 1. The output vector is defined as $\mathbf{y} = [x_1\ x_2\ y_3]^T$, as given by Eq. (1), while the drum water level (y_3) is given in terms of the steam quality a_{cs} and evaporation rate q_e (kg/s) as:

$$y_3 = 0.05\left(0.13073 x_3 + 100 a_{cs} + \frac{q_e}{9} - 67.975\right) \tag{2}$$

where

$$a_{cs} = \frac{(1 - 0.001538 x_3)(0.8 x_1 - 25.6)}{x_3(1.0394 - 0.0012304 x_1)}$$