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Fuzzy Supervisory control of a steam power plant during load rejection

HABBI AHCENE, ZELMAT MIMOUN
Applied Automation Laboratory, F.H.C
University of Boumerdès, 35000 Boumerdès, Algeria
Phone/Fax: +213-24816905

Abstract–In this paper, an intelligent coordinated control scheme for a fossil-fuelled drum boiler-turbine plant is presented. It consists of a two-level hierarchical control strategy. At the supervisory level, a fuzzy reference governor generates the water level set-point deviations during load rejections according to a fuzzy rule-based policy. At the control level, a robust control system via LQG/LTR is implemented. The performance of the proposed fuzzy supervisory control system is demonstrated by simulations under various conditions and results are compared to those obtained by only considering the robust controller without the supervisory reference governor.

Keywords: Fuzzy supervisory control; Robust control; Reference governor; Boiler-turbine.

1. Introduction

An optimal power plant operation depends on the performance of the individual components: boiler, turbine and generator. Drum boiler system is an energy conversion device which transforms the input chemical energy of fuel into the mechanical energy acting on the turbine and the generator. For an effective participation of a power plant unit in load-following duties, stringent requirements on control performance and life extension of major equipment have to be fulfilled. Hence, the implemented control strategies need to efficiently orchestrate all energy transformations taking place in the steam power unit and to undertake large steam and power demands as well as random fluctuations about their patterns. Therefore, the performance of a drum boiler-turbine controlled system can be addressed for tracking load changing commands of power output and drum pressure, and regulating deviations of drum water level. Since the drum boiler-turbine system is nonlinear with many complicated physical phenomena, a great deal of attention has been devoted to the control of its strongly interacting variables [5,7,8,9]. In [7], a linear quadratic gaussian (LQG) with loop transfer recovery (LTR) approach is conducted for a linear time invariant boiler model with the emphasis on the robustness against uncertainties and modeling errors. On the issue of the optimal control theory, Chen and Shamma proposed in [9] a gain-scheduled ℓ^1-optimal control approach for boiler-turbine controller design. In their design procedure, state constraints and control saturations are explicitly addressed. Coordinated control schemes for boiler systems were also investigated in many papers. In [8], Ben-Abdennour and Lee proposed a fuzzy supervisory scheme to improve the performance of a boiler system. The controller is synthesized using the boiler model without taking into account the electrical part of the plant i.e., the turbine and the generator. These approaches were successful to a large extent in providing robustness to variations in the operating points. This paper presents yet another alternative to the classical approach for boiler-turbine control. Here, a mixed fuzzy logic and robust control strategy is used to improve the control performance of a drum boiler-turbine system, especially during severe disturbances such as load rejections. The effectiveness of the fuzzy knowledge based representation is exploited at the supervisory level by considering a fuzzy logic based set-point generator to monitor the set-point deviations during plant operations in order to enhance the performance of the implemented robust controller.

2. Boiler-turbine dynamics

For this study, a 160MW oil-fired boiler-turbine nonlinear model is used. It was developed by Bell and Åström for a P16/G16 power plant [1,2]. The model is based on the basic conservation laws which govern the boiler operation while maintaining an emphasis on simpler structure. The inclusion of the extra evaporation equation and fluid dynamics delivered a reasonable depiction of the drum water level dynamics. The model is obtained through both

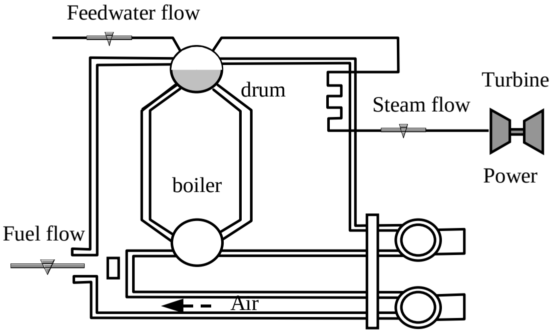


Fig.1. Schematic of the drum boiler-turbine system.

physical and empirical methods and compared well against actual plant data. The plant dynamics are described by the following nonlinear equations:

$$
\begin{aligned}
\dot{x}_1 &= -0.0018u_2\sqrt[8]{x_1^{9}} + 0.9u_1 - 0.15u_3 \\
\dot{x}_2 &= (0.073u_2 - 0.016)\sqrt[8]{x_1^{9}} - 0.1x_2 \\
\dot{x}_3 &= \frac{1}{85}(141u_3 - 1.1u_2x_1 - 0.19x_1)
\end{aligned}
\tag{1}
$$

where x_1 denotes the drum pressure (kg/cm²), x_2 denotes the electrical output (MW), and x_3 denotes the fluid density in the system (kg/cm^3). The inputs to the system are the valve positions for fuel flow, u_1, steam control, u_2, and feedwater flow, u_3. The control inputs are subject to magnitude and rate saturations as follows:

$$0 \le u_1, u_2, u_3 \le 1 \tag{2}$$

$$-0.007 \le \dot{u}_1 \le 0.007 \tag{3}$$

$$-2 \le \dot{u}_2 \le 0.02 \tag{4}$$

$$-0.05 \le \dot{u}_3 \le 0.05 \tag{5}$$

Another quantity of interest is the water level deviation which is given by:

$$L = 0.05(0.13073x_3 + 100\alpha_s + q_s/9 - 67.975) \tag{6}$$

where the quality factor of steam, α_s, and the evaporation mass flow rate, q_s, are expressed by:

$$\alpha_s = \frac{(1-0.001583x_3)(0.8x_1 - 25.6)}{x_3(1.0394 - 0.0012304x_1)} \tag{7}$$

$$q_s = (0.854u_2 - 0.147)x_1 + 45.59u_1 - 2.514u_3 - 2.096 \tag{8}$$

By taking a Taylor's series approximation of the nonlinear model at half load, we derive a state space representation defined by constant matrices *A*, *B*, *C* and *D*.

3. The intelligent coordinated control scheme

The performance of a boiler-turbine controlled system can be addressed for tracking load changing commands of power output and steam generation, keeping the drum water level around a small deviation in order to avoid the shrink-and-swell effect associated with the water dynamics, satisfying the physical constraints imposed on control efforts and achieving wide range control. For this purpose, a robust controller based on the linear quadratic Gaussian with loop transfer recovery approach (LQG/LTR) is designed for the drum boiler-turbine plant. This approach guarantees an adequate degree of robustness and performance for a wide range of operating conditions and system disturbances. These features can be complemented with the capabilities of fuzzy logic in knowledge representation to get improved performance even further as will be shown by simulations. The fuzzy reasoning is introduced at the supervisory level in order to monitor the system outputs and to generate the set-points deviations to the robust controller. Qualitatively speaking, the fuzzy reference governor specifies and coordinates the desired responses of the boiler, steam turbine and electric generator so that better performance can be achieved with a particular emphasis on the drum water level control which is a critical variable of the plant. It was stated that about 30% of emergency shutdowns in thermal power plants are caused by the poor control of water level [1].

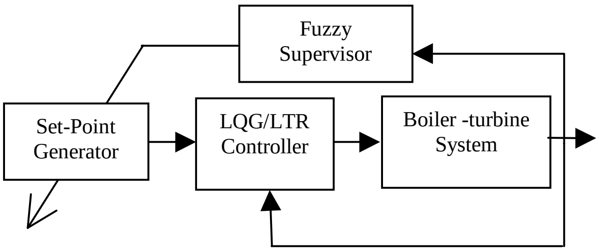


Fig.2. Block diagram of the coordinated control scheme

3.1 Robust LQG/LTR controller

The LQG/LTR approach uses two design steps to realize a robust controller. The first step consists of an optimal control design problem. The second step consists of a Kalman filter design where uncertainties in the system are modeled as process and measurement noises. Since the boiler-turbine system has a non-minimum phase behavior, dynamics augmentation is introduced, first, to meet the design specifications. The state space representation of the augmented system is given by:

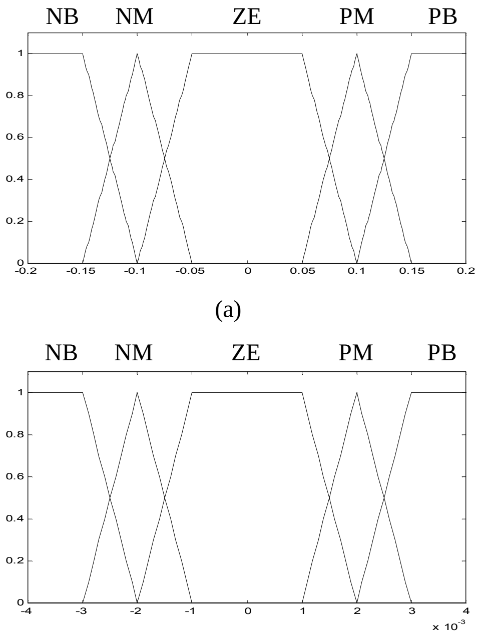
$$
\begin{aligned}
\dot{x}_a(t) &= A_a x_a(t) + B_a u_a(t) + w \\
\delta y(t) &= C_a x_a(t) + v
\end{aligned}
\tag{9}
$$

where *w* and *v* are zero-mean Gaussian white noise processes with covariances Q_f and R_f, respectively, and

$$x_a = \begin{bmatrix} \delta x \\ \delta u \end{bmatrix},\ A_a = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix},\ B_a = \begin{bmatrix} 0 \\ H \end{bmatrix} \text{ and } C_a = \begin{bmatrix} C \\ D \end{bmatrix}^T$$

The control variable u_a satisfies the following equation:

$$\delta\dot{u}(t) = H u_a(t) \tag{10}$$



(a)

(b)

Fig. 3. Fuzzy partitions: (a) water level deviation, (b) rate of change of water level deviation

where H is obtained by using the pseudo-diagonalization method and a column scaling diagonal matrix [10]. The introduction of this constant matrix into the state equations plays the role of achieving weak interactions between the system variables and forcing the local dynamics to meet the desired specifications in the control design procedure. The first step of the design process is to select the parameters of the optimal state feedback regulator Q_c and R_c to construct a target frequency response loop. In the second step, the Kalman filter parameters are adjusted so that the target loop is recovered. The frequency domain specifications imposed on the target loop are: high gain at low frequency with minimum 20 dB roll-off, low gain at high frequency, and a cut-off frequency in the order of 0.01 rad/sec.

3.2 Fuzzy set-point generator

In order to enhance the performance of the drum boiler-turbine plant operation in general and the water level control in particular, a fuzzy logic based supervisor is incorporated to the control scheme. Since our main concern is to improve the level performance during disturbance rejections, we focused on the level set-point modifications while designing the fuzzy set-point generator. This mixed approach of fuzzy logic and optimal control theory combines the advantages of both schemes to form a hybrid controller capable of improving the boiler-turbine response. The block diagram of the intelligent coordinated control scheme is shown in Fig.2.

The inputs to the fuzzy supervisor are the water level deviation (L) and its rate of change ΔL. For each variable, triangular/trapezoidal shape membership functions are constructed based on the specifications of the level performance. The following linguistic terms are used: NB (Negative Big), NM (Negative Medium), ZE (Zero), and PB (Positive Big), PM (Positive Medium). The high drum level alarm is known to be around 0.25m and normal level deviation is around 0m. These fuzzy partitions are depicted in Fig. 3. Using an approximate reasoning, a fuzzy rule base including twenty five fuzzy rules is determined for the fuzzy supervisor which can be completely defined by the fuzzy set-point generation surface shown in Fig. 4. Defuzzification of the fuzzy output is done using the center of gravity (COG) method.

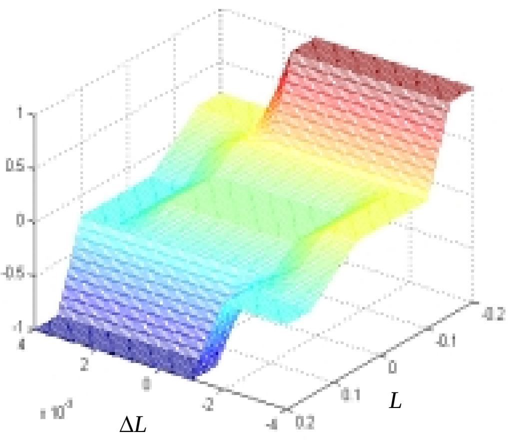


Fig. 4. Fuzzy level set-point generation surface

4. Simulation results

In order to demonstrate the effectiveness of the proposed coordinated control scheme, disturbance rejection test is carried out with the assumption that that a step change in drum pressure has occurred at t = 50 seconds. The performances of the two control schemes (LQG/LTR, and coordinated control) applied to the nonlinear boiler-turbine model are compared in Fig. 5. The main objective of level control is to maintain the drum water level around small deviations to guarantee the equipment safety.

Fig. 5 shows the input and output time responses of the boiler-turbine plant under the two control schemes. These responses are noticeably different. The improvement provided by the fuzzy coordinated control system is significant. It can be seen that the drum water level performance is substantially improved in terms of the magnitude of the fluctuation. In addition, we can see that the LQG/LTR controller has a slow rising time and large overshoot. In the LQG/LTR case, the maximum magnitude of water level is around 0.15m while the fuzzy supervisor enhances such performance even further by keeping it to well below 0.1m. Also, better handling of the control inputs saturations is obtained especially for the feedwater valve and the steam valve. Variations in the steam valve are considered to be as one of the major

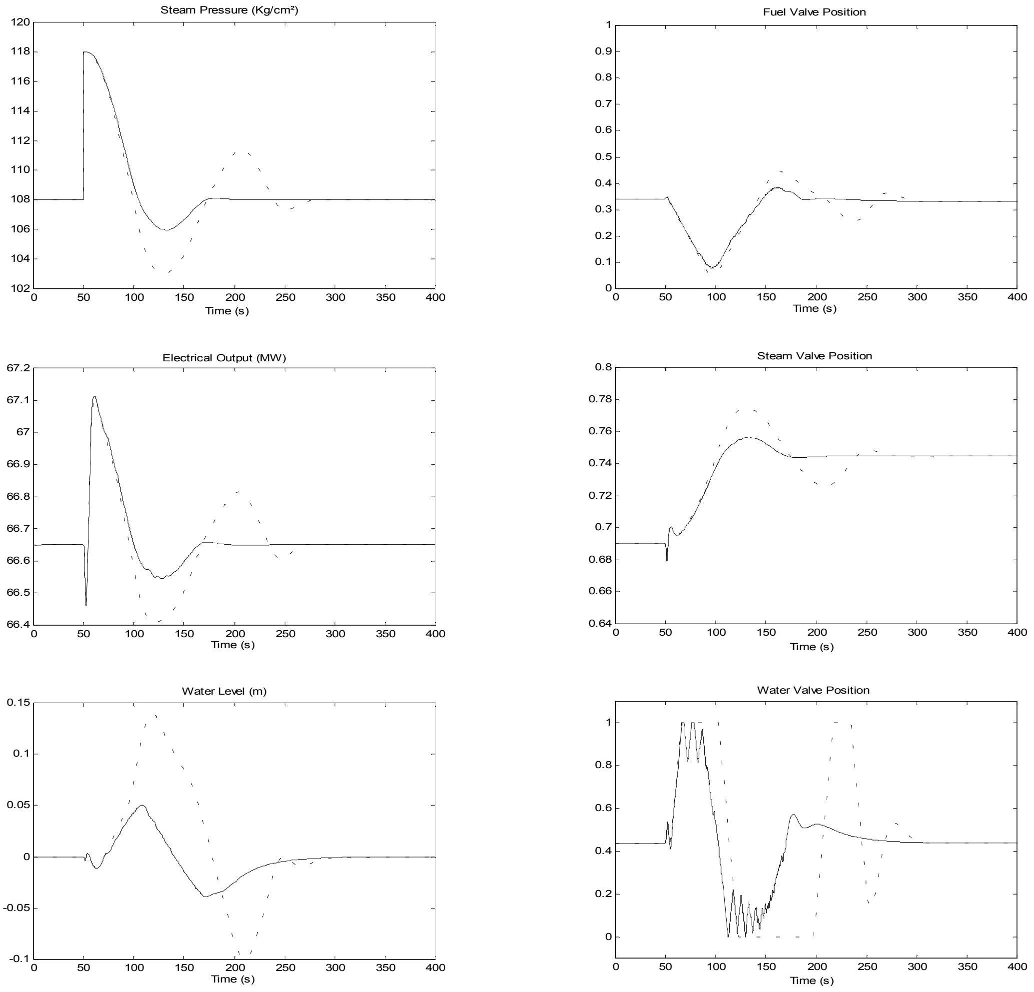


Fig.5. Boiler-turbine input and output time responses during disturbance rejection (solid : intelligent coordinated control system, dashed : LQG/LTR controller).

sources of uncertainties. The proposed coordinated control scheme has considerably reduced these variations by dumping out the oscillation modes much more quickly than the LQG/LTR controller.

5. Conclusion

In this paper, a coordinated control scheme is proposed for the nonlinear oil-fired boiler-turbine system. A fuzzy logic based set-point generator and an LQG/LTR controller are combined together in order to enhance the performance of the nonlinear plant operation and to improve the drum water level control. As can be noticed, adding a fuzzy logic based supervisory loop to monitor the level deviation can significantly improve the robustness and the performance of the existing robust controller. Additionally, control constraints on control inputs magnitude are handled better by the proposed hybrid scheme and fluctuations of the plant controlled variables about their patterns are considerably reduced.

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