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Fuzzy modeling and predictive control of superheater steam temperature for power plant

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ABSTRACT

This paper develops a stable fuzzy model predictive controller (SFMPC) to solve the superheater steam temperature (SST) control problem in a power plant. First, a data-driven Takagi–Sugeno (TS) fuzzy model is developed to approximate the behavior of the SST control system using the subspace identification (SID) method. Then, an SFMPC for output regulation is designed based on the TS-fuzzy model to regulate the SST while guaranteeing the input-to-state stability under the input constraints. The effect of modeling mismatches and unknown plant behavior variations are overcome by the use of a disturbance term and steady-state target calculator (SSTC). Simulation results for a 600 MW power plant show that an offset-free tracking of SST can be achieved over a wide range of load variation.

1. Introduction

Superheater steam temperature (SST) is one of the most critical variables to be controlled in a steam power plant. It must be tightly controlled within a small variation range, as shown in Fig. 1, for the following security and economy reasons:

(i). excessively high temperature will lead to a material damage on the superheater steam pipes and the inlet of the high pressure turbine;
(ii). lower temperature will reduce the efficiency of the plant, moreover, it will build up the humidity of the steam in the rear of the low pressure turbine that would erode the turbine blades; and
(iii). large temperature variation will increase the thermal stress of the material and magnify the variations of the air gap between rotor and cylinder of the turbine, thus threatening the safety of the plant.

However, control of the SST is challenging due to its large thermal inertia. In addition, to meet the unit load demand at all times, most of the power plants have to change power generation frequently over a wide range, and thus the nonlinear behavior becomes significant. Consequently, the conventional PI/PID based controllers are no longer sufficient in meeting the performance specifications, even if they are tuned well at a given loading condition [1–3]. Thus, various control strategies have been explored in recent years.

To overcome the nonlinearity of the SST system, many kinds of artificial intelligence techniques have been applied. In Ghaffari et. al. [4] a genetic-algorithm (GA) based PI controller is developed on the basis of adaptive neuro-fuzzy inference model. A neural-network (NN) model is built in Zhang et. al. [5] for online tuning of the PID parameters. In Sanchez-Lopez et. al. [6], a fuzzy logic controller is applied to the SST system of a 300 MW plant and an inverse dynamic neuro-controller is designed in Ma et. al. [7], where the results show that the computational intelligence techniques achieve a much better performance than the fixed parameter PID controllers and linear model based controllers.

However, none of these approaches can effectively deal with the input constraints in the controller design stage. Considering this factor and the large thermal inertia characteristics of the SST system, model predictive control (MPC) has been applied in recent years. In [6,8] dynamic matrix controllers (DMC) are employed for the SST system based on the step-response model, but the

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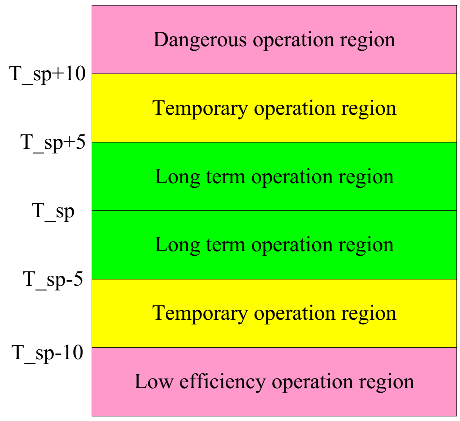

Fig. 1. Operation regions of superheater steam temperature (T_sp is the temperature set-point and the numbers represent temperature deviations in Celsius degree).

performance of these linear controllers is degraded for a wide range operation. Nonlinear MPCs are designed in [9,10] on the basis of dynamic NN models. Although the control performance is improved, the nonlinear optimization lacks in robustness and suffers from computational requirement.

To overcome these issues the fuzzy modeling technique [11], which uses a fuzzy combination of several linear models to approximate the nonlinear behavior of the plant, has been used in the MPC design for SST system [12,13]. However, in these works, the structure of the fuzzy model is designed by simply dividing the operation range evenly, which would reduce the accuracy of the model, and the issue of unavoidable modeling mismatch and unknown plant behavior variation are not taken into account. Moreover, the stability of the control system desirable for industrial processes such as steam power plant cannot be guaranteed by any of the aforementioned approaches.

For these reasons, we propose an offset-free stable fuzzy model predictive controller (SFMPC) based on a fuzzy model to solve the SST control problem.

Firstly, a Takagi–Sugeno (TS) fuzzy model [11] is developed to approximate the behavior of the SST system. Compared with the usual method which linearizes the nonlinear analytical model around different operating points, we utilize the subspace method [14–16] to identify the local state-space models using input–output data. However, the state variables of the identified model do not have physical meanings, which makes the interpretation of the model difficult. Moreover, for different local models, the state-variables do not share a common basis such that the models cannot be algebraically combined to form a fuzzy model. To overcome this problem in the subspace identification method, similarity transformations are devised to give the state variables common fictitious physical meanings, so that all local models can be transformed into the common basis. A nonlinearity analysis is performed to determine the number of fuzzy rules and the corresponding local linear models, which are then connected by the fuzzy membership functions to form an integrated fuzzy model.

A stable fuzzy model predictive controller (SFMPC) [17–21] is then designed on the developed fuzzy model to achieve a satisfactory steam temperature performance, while satisfying the input constraints and guaranteeing the closed-loop system stability. To improve the output regulation performance, an output variable based objective function is used in the SFMPC formulation. Offset-free control is achieved by the use of a disturbance term and steady-state target calculator (SSTC) [22,23], even in the case of modeling mismatches and unknown plant behavior variations. It is shown that the proposed SFMPC can be realized by solving a set of linear matrix inequalities (LMIs), which is known to be a computationally efficient algorithm [17–21].

The proposed data-driven modeling and control approaches are applied to the SST system in a large-scale 600 MW power plant simulator. The remainder of this paper is organized as follows: Section 2 introduces the SST system dynamics. Section 3 establishes the TS-fuzzy model of the SST system using the subspace identification method. The stable fuzzy model predictive controller is presented in Section 4. Simulation results are given in Section 5 and conclusions are drawn in Section 6.

2. System description

The power plant under consideration is a 600 MW oil-fired drum-type boiler-turbine-generator unit shown in Fig. 2. The model of this plant is developed from the first-principles as used in a power plant simulator and is validated in the MATLAB environment. The model is grouped into boiler, turbine, feedwater, and condenser modules and composed of 31 subsystems and 12 control valves associated with physical processes as shown in Fig. 2 [24].

The Superheater system of this plant is mainly composed by three parts: primary superheater, secondary superheater and water-spray attemperator between the two superheaters. Its task is to regulate the saturated steam out of the drum to a rated temperature (1005 °F, 540 °C) before delivering it to the turbine.

During the operation of the power plant, there are many factors that will influence the superheater steam temperature; mostly the rate of the steam flow, the heat transfer from flue gas and the rate of spray water flow. For this power plant, three valves can be manipulated to regulate the SST, which are: gas recirculation u_2, combustion gun (burner) tilt u_5 and superheater spray flow u_6. In general, since u_2 and u_5 will greatly influence the plant power output and burning security of the boiler, they are fixed at a given level and superheater spray flow u_6 becomes the only variable to control the SST.

However, the influence of spray flow to the SST has a relatively large thermal inertia property, as shown in Fig. 3 for a step response test around the 600 MW operating point. Moreover, the frequent unit load demand change calls for the change of steam flow rate and flue gas heat transfer, which will influence the SST more quickly. Therefore, advanced control techniques are needed to improve the conventional PI/PID controllers.

3. Data-driven modeling of superheater steam temperature system

Fuzzy model strategy which utilizes the combination of several linear models to approximate the behavior of nonlinear plant has been widely used in power plant modeling and control recently, and the state-space model has been adopted as a local model because of the availability of advanced control theories for linear systems [19,21,25–28]. In these works, an approximation or transformation of the nonlinear system has been used to obtain the state-space model. However, for complex systems such as SST system, it is a challenge to develop an accurate analytical model without the knowledge of thermodynamics and design specifications of many components. This has become one of the main limitations for designing controllers for real power plants.

Subspace identification (SID) method provides an alternative way to develop the state-space model directly from the input–output data of the plant [14,15]. Based on computational tools such as QR factorization and singular value decomposition (SVD), the SID extracts the model from subspaces of data Hankel matrices. Thus