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Nonlinear control of coal-fired steam power plants

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ABSTRACT

This work proposes a nonlinear control strategy for steam power plants that efficiently controls the superheated steam temperature while accommodating large and frequent variations in power demand. The variables to be controlled are the pressure in the boiler, power generation, and superheater/reheater temperatures. The proposed strategy decomposes the overall plant into three separate subsystems and applies decoupling with deadtime compensation for each one of them. The derived strategy is implemented within a MATLAB/Simulink environment for different setpoint tracking and disturbance rejection cases, showing excellent performance and robustness.

1. Introduction

The control of power generation remains an important open problem due to the simultaneous increase of power demand and of environmental concerns regarding fossil fuels emissions. The net worldwide power generation is anticipated to increase by 2.2% annually until the year 2040 (International Energy Outlook, 2013 report, 2013). In efforts to decrease the environmental impact of fossil fuels emissions and due to governmental policies and incentives, the use of renewable sources for power generation is expected to increase at an annual rate of 2.8%, resulting in the production of 25% of the worldwide power by 2040 (International Energy Outlook, 2013 report, 2013). The operation of existing conventional power plants faces several challenges as renewable power is incorporated into the grid. A key one is that the power demanded from conventional power plants will continuously change to recover the production shortages caused by the intermittent nature of renewable power sources. Continuous change of power demand also implies continuous introduction of disturbances to different parts of the plant. These challenges can be addressed by designing a control strategy for conventional power plants that accommodates large and frequent variations in power demand and ensures a stable operation of the different parts of the plant involved in power generation.

Power generation has two main features that may complicate the design of such a control strategy. First, there exist strong nonlinear interactions between the different components of the plant, specifically between the steam turbines, superheaters, reheaters, and the boiler. Second, in plants utilizing solid fuels, there exists a deadtime associated with the fuel supply to the process when fuel flow adjustment is necessary. In the authors' previous work (Alamoodi & Daoutidis, 2016), the focus was on designing a deadtime compensated nonlinear controller for the control of the boiler pressure and power generation, in this paper, the focus is on the control of superheated and reheated steam temperatures inline with the control of power generation.

Different forms of analytical and model predictive control strategies have been studied for the control of superheated steam temperatures (Blaazer, 2010; Hlava et al., 2013; Liang et al., 2013; Matsumura et al., 1994; Prasad et al., 2000; Sanchez-Lopez et al., 2004; Wu et al., 2015; Zhang et al., 2012). In Hlava et al. (2013), multi model MPC based on several linear models was designed, whereas in Sanchez-Lopez, Arroyo-Figueroa, and Villavicencio-Ramirez (2004) a Dynamic Matrix Control based on an empirical model and an intelligent Fuzzy Logic Control were designed and implemented. Matsumura, Ogata, Fujii, Shioya, and Nakamura (1994) implemented a discrete time adaptive control system. In Liang, Li, and Li (2013), the application of an active disturbance rejection controller (ADRC) designed based on feedback linearization was studied for the regulation of superheated steam temperature. The ADRC improves the control of superheated steam temperature by incorporating an extended state observer that can estimate the disturbances in real time. The drawback of these methods is the use of linear or approximate models to predict the superheater temperature, which may fail to reflect the temperature dynamics at different operating points, or neglecting significant dynamics of the power plant such as the boiler pressure or the turbine dynamics.

The purpose of this paper is to develop a control strategy for the temperature of the superheated steam that accounts directly for the effect of nonlinearities and dynamics with inverse response. The objective is to provide stable closed-loop performance and efficient

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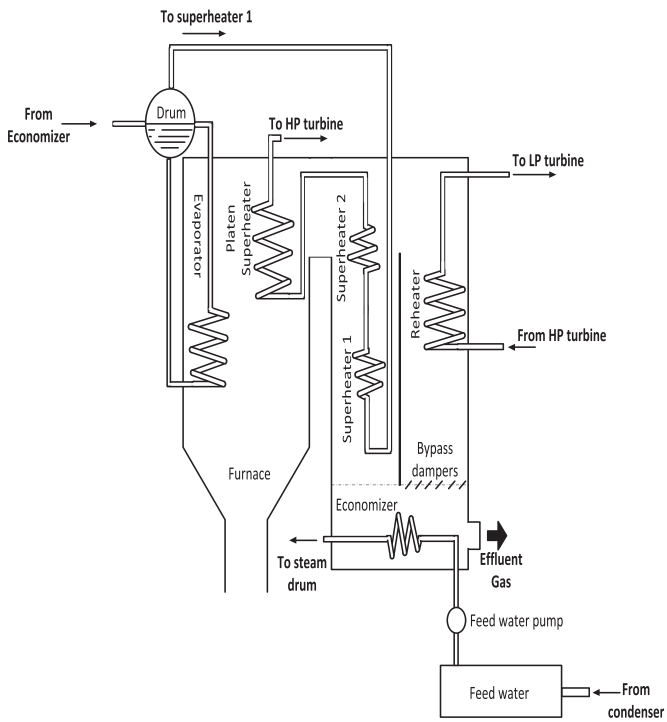

Fig. 1. Steam generator schematic.

temperature regulation without forsaking efficient wide range setpoint tracking of power demand. The proposed control structure involves elimination of inverse response, decomposition of the power plant model into three subsystems with minimum interactions among them, and the use of nonlinear decoupling feedback controllers with deadtime compensation for each subsystem. In the rest of the paper, first dynamic models for the pressure in the boiler, for the temperature of steam in the superheaters and reheater, and for power generation by the turbine-generator system are presented. The control problem is then defined and the proposed control strategy is described. Finally the implementation of the controllers is presented, and their performance and robustness are analyzed for different setpoint tracking and disturbance rejection scenarios.

2. Modeling of steam power plant

2.1. Process description

Fig. 1 illustrates a detailed schematic of a steam generator; it is mainly composed of a furnace, steam drum and water walls, a convection-type primary and secondary superheaters, a platen superheater and an economizer. The furnace is composed of a combustion chamber which includes the water walls and the platen superheater and of a bypass duct. The bypass duct is divided into two sections having convection-type superheaters in one section and a reheater in the other; at the end of the duct both divisions merge again and enclose the economizer. Utilizing the heat of combustion of the fuel in the furnace, boiling of saturated water is achieved in the water walls as well as final stage heating of superheated steam is achieved in the platen (radiant-type) superheater. The combustion effluent gas, which contains a large amount of energy, then travels to the bypass section and is divided to provide the required amount of energy to convert saturated steam to superheated one. In the superheaters division of the bypass duct, the secondary superheater is arranged such that it receives the flue gas prior to the primary superheater. Following the steam path, saturated steam flows from the steam drum to the first stage of heating in the primary superheater where the flue gas in this position is at the lowest temperature in the bypass duct. The low temperature superheated steam then goes through a second stage of superheating in the secondary superheater and a final stage of superheating in the platen superheater. Once the steam leaves the platen superheater it is then utilized in a high pressure turbine (HP) for power generation. The partly expanded steam then returns to the reheater and leaves as low pressure superheated steam to a low pressure turbine (LP) where most power is being generated.

The boiler pressure and power generated are controlled at desired values by varying the fuel flow rate and the valve opening of the steam turbine, while the superheated steam temperatures are controlled by spraying feed water into the superheated steam at the outlets of the primary and secondary superheaters. Spraying feed water decreases the enthalpy of the steam and thus decreases its temperature prior to entering the next stage of heating; this process is called attemperation. Spraying feed water in these locations avoids overheating of steam and over heating of the heat exchanger tube walls, protecting it from damage (Drbal, Boston, Westra, & Erickson, 1996). The reheated steam temperature is kept at the desired temperature by varying the amount of energy it receives from the flue gas; this is achieved through bypass dampers located after the reheater. Depending on the opening of the dampers the amount of flue gas passing the reheater is changed (Drbal et al., 1996). The temperatures of the superheated and reheated steam are desired to be maintained within ± 6 °C of the setpoints (Steam, 2005; Basu et al., 2000).

2.2. Process model

An effective control strategy requires a dynamic model that captures the behavior of the units of significant dynamics in the process. These units are the boiler, superheaters, reheater, and the turbine-generator systems.

2.2.1. Drum-type boiler

A drum type boiler comprises a drum and tube bundles of downcomers and risers. Risers, where vaporization of the saturated water occurs, are located inside the furnace. Due to the difference in density between the produced steam in the risers and the water inside the drum, a circulation loop between the riser-drum-downcomer is created. The dynamics of the boiler is described by the steam pressure. This choice is made to reflect the strong coupling between the boiler, superheaters, and the turbine-generator system. For the modeling of the dynamics of the boiler the work of Astrom and Bell (2000) is followed.

The mass balance around the boiler is:

$$\frac{d(\rho_w V_w + \rho_s V_s)}{dt} = q_f - q_s \tag{1}$$

where ρ denotes density, V denotes volume, and q denotes the mass flow rate of the fluid. The subscripts w, s, f denote water, steam and feed respectively. Since ρ is a function of pressure, is it best to describe it in terms of its dependence on P. Thus by using $V_s = V_t - V_w$ and the following relation:

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial P}\frac{dP}{dt}$$

the mass balance becomes:

$$(\rho_w - \rho_s)\frac{dV_w}{dt} + \left[V_w\left(\frac{\partial\rho_w}{\partial P}\right) + V_s\left(\frac{\partial\rho_s}{\partial P}\right)\right]\frac{dP}{dt} = q_f - q_s \tag{2}$$

where V_t is the total volume of the boiler. The mass flow rate of steam entering the turbine is manipulated using a governing steam valve, thus expressing q_s as a function of the turbine valve opening gives:

$$q_s = \frac{kP}{\sqrt{T_{PSH}}}u_s \tag{3}$$

where k denotes the valve gain, T_{PSH} denotes the temperature of the