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Practical dynamic matrix control for thermal power plant coordinated control

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ABSTRACT

This paper proposes three practical strategies for the coordinated control (CC) of a thermal power plant using dynamic matrix control (DMC) that can be directly applied to industrial power plants. The three strategies are the replacement of conventional CC using DMC, the inclusion of disturbance variables, and a supplementary reference correction of the conventional CC. The performance during wide range operation of the three DMC–CCs is compared and discussed with the simulation results of a large-scale power plant model.

1. Introduction

In recent years, the competition among energy suppliers has become intense in the energy market. Accordingly, the need for tight and economical operation of power plants is increasing. The main purpose of the fossil power plant control is to meet the various load demands for electric power while maintaining steam pressure and temperature at reasonable values. The load demand is determined by the power grid operation center for power system frequency control and economic dispatching (Flynn, 2003; Wood, Wollenberg, & Sheblé, 2014).

A thermal power plant is a large and complex system that is multi-input and multi-output (MIMO) and has high nonlinearity and various different time constants and strong coupling among variables (Dukelow, 1986; Go & Moon, 2014; Maffezzoni, 1997). These difficulties have resulted in many kinds of advanced control research such as generalized predictive control (GPC) (Hogg & El-Rabaie, 1990, 1991), robust control (Ben-Abdennour & Lee, 1996; Tan, Marquez, & Chen, 2002), and artificial intelligence techniques (Dimeo & Lee, 1995; Heo & Lee, 2008; Liu & Chan, 2006; Moon & Lee, 2003; Prasad, Swidenbank, & Hogg, 1998; Wang, Li, & Zhang, 2002) to overcome theoretical limitations of the classic PID-based multi-loop control. However, these types of advanced controllers are still far from being widely used.

In practice, many power plant manufacturers have similar philosophies. Two major control loops are the boiler components and turbine components, which are equipped with many local single-input single-output (SISO) control loops. In higher-level loops, the set points of local SISO loops are generated by considering variables such as the load demand, thermal variables, interaction, and disturbances (Dukelow, 1986; Flynn, 2003). In practice, a conventional multi-SISO structure implemented with PID modules in a distributed control system (DCS) is a well-assessed procedure. Although a separate local SISO loop does not consider the interactions mathematically, this structure can help field engineers and operators deal with emergencies. Therefore, the conventional multi-SISO solution cannot be completely abandoned (Poncia & Bittanti, 2001).

For practical implementation, coordinated control (CC) is an effective application of advanced MIMO control for industrial thermal power plants. Coordinated control between boiler and turbine systems is the uppermost layer of power-plant control. During an emergency, CC can be disconnected anytime without stopping the local SISO loops. Poncia and Bittanti (2001) used a model predictive control (MPC) approach based on a state–space model. Li, Liu, Cai, Soh, and Xie (2005) proposed a supervisory level that uses fuzzy inference and online parameter identification to modify the PID gains of the conventional CC. Liu, Guan, and Chan (2010) developed several linear state–space models at each operating point, and applied a neuro-fuzzy network to overcome the nonlinearity. However, developing a state–space model and obtaining training data from an operating power plant are not easy goals to achieve.

In this paper, for the practical implementation of CC, several dynamic matrix control (DMC) structures are proposed. DMC is a field-proven MPC algorithm for process control that assumes a step-response model for the underlying system. The step-response model is cost effective and relatively easy to develop. This model has been successfully

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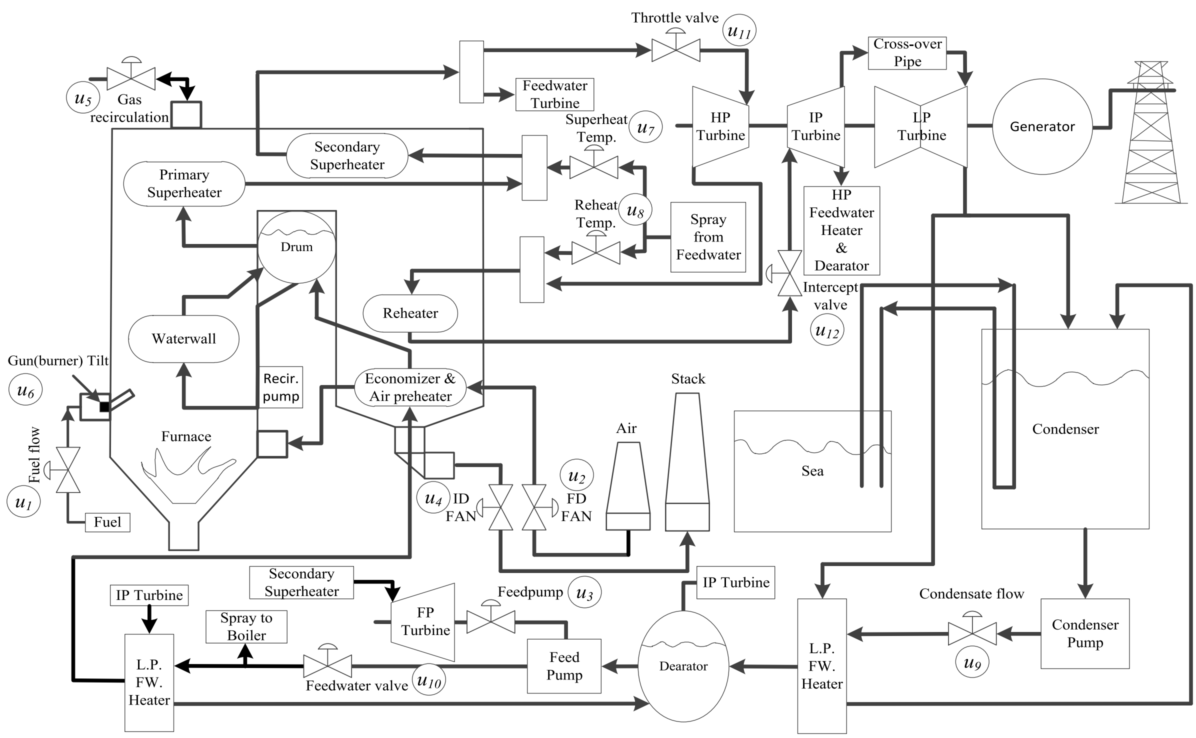

Fig. 1. Large-scale model of a thermal power plant.

applied to numerous industrial processes by Aspen Technology, Honeywell Hi-Spec, Invensys, and others. Many commercial software packages have been developed, including DMC+, SMC, RMPCT, HIECON and PFC (Qin & Badgwell, 2003). Moon and Lee (2009, 2011) demonstrated the possible use of DMC in a thermal power plant with a simplified model. The industry is mature enough to implement DMC in practical power plants.

In this paper, three alternative structures of DMC–CC for a large-scale thermal power plant model are developed according to the selection of input, output, and disturbance variables. The first DMC–CC is a two-input two-output structure, which is the same structure as a conventional CC. The second DMC–CC considers additional disturbance variables with the same input and output variables as in a conventional CC. The output of the third DMC–CC is a supplementary reference change from the conventional CC. Each DMC–CC is independently applied to a large-scale thermal power plant model. The performances in various electric load demands are compared and discussed.

2. Boiler-turbine system

2.1. 600 MW thermal boiler-turbine system

Fig. 1 shows a complete diagram of the 600 MW oil-fired drum-type boiler-turbine system model that is the subject of this study. This model was validated with practical plant (Usoro, 1977) and extensively analyzed in the work of Heo and Lee (2008) and has been referred in many literatures (Chanda & Subbarao, 2016; Los Arcos, Angulo, Sanchez, Sabugo, & Burguera, 1992; Soares, Gonçalves, Silva, & Lemos, 1997). The model consists of four modules: the boiler system, turbine-generator system, condenser system, and feedwater system. This power plant model has 23 state variables. Each component in Fig. 1 is modeled with the thermodynamic first principle with mass, energy, and momentum balances.

These first-principle equations result in severe nonlinear dynamics. For example, Moon, Lim, and Lee (2016) presented an analysis of the water wall system in Fig. 1. They pointed out that the linearized transfer function model of the water wall system has poor quality and that a nonlinear neural network is suitable to describe the water wall dynamics in Fig. 1. The power plant model in Fig. 1 is composed of consecutive connections of subsystems, which are described with mass, energy, and thermal balance equations. Therefore, the overall power plant is very complex and has severe nonlinearity.

Table 1
Control valves of boiler-turbine model.

Module		Control valve
Boiler system	Combustion controller	Fuel flow, (u_1) Forced draft fan, (u_2)
	Local controllers	Feedpump turbine flow, (u_3) Induced draft fan, (u_4) Gas recirculation, (u_5) Combustor gun, (u_6) Superheater spray flow, (u_7) Reheater spray flow, (u_8) Condensate valve, (u_9) Feedwater valve, (u_{10})
Turbine-generator system		Governor valve, (u_{11}) Intercept valve, (u_{12})

The model is equipped with a multi-loop control system that has many SISO control loops. Twelve manipulated control valves, from u_1 to u_{12} in the boiler and turbine systems are listed in Table 1 and Fig. 1. In the boiler system, a combustion controller manipulates the fuel flow (u_1) and forced draft fan (u_2) that provides air to the boiler. Local controllers in the boiler system have eight control valves (u_3 to u_{10} in Table 1) that manipulate various aspects of the system ranging from the feedpump turbine flow (u_3) to the feedwater (u_{10}). In the turbine system, a governor valve (u_{11}) adjusts the steam flow from the boiler to the turbine and controls the output power. Each control value has an operation limit. This large-scale power plant model was developed in the MATLAB environment.

2.2. Conventional coordinated control

Usual terminologies in power plant control are the boiler following, turbine following and coordinated control. In the boiler following mode,