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Process Control

Multi-model Predictive Control of Ultra-supercritical Coal-fired Power Unit☆

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ABSTRACT

The control of ultra-supercritical (USC) power unit is a difficult issue for its characteristic of the nonlinearity, large dead time and coupling of the unit. In this paper, model predictive control (MPC) based on multi-model and double layered optimization is introduced for coordinated control of USC unit. The linear programming (LP) combined with quadratic programming (QP) is used in steady optimization for computation of the ideal value of dynamic optimization. Three inputs (*i.e.* valve opening, coal flow and feedwater flow) are employed to control three outputs (*i.e.* load, main steam temperature and main steam pressure). The step response models for the dynamic matrix control (DMC) are constructed using the three inputs and the three outputs. Piecewise models are built at selected operation points. Double-layered multi-model predictive controller is implemented in simulation with satisfactory performance.

1. Introduction

Compared to traditional coal-fired power generation, USC coal-fired power generation units are promising for its higher efficiency and less harmful emission [1]. However, USC units are characterized by the strong coupling characteristic between boiler and turbine, strong nonlinear and dead time characteristic. Without the steam drum buffer, USC boiler dynamic characteristics are affected greatly by terminal dynamic at boiler outlet header. USC units have a complex characteristic for strong nonlinearity under the different output power conditions. Along with the load changes, the dynamic characteristic parameters of units change dramatically. After fuel water ratio changes, steam temperature has a long delay response. Due to the above control difficulty, the parameters of the control system based on PID have a large fluctuation in the process of load changing.

Generally, power units run in four modes: base mode, boiler following mode, turbine following mode, and coordinated control mode. In the first mode, the boiler master and turbine master are both in manual mode. For the 2nd and 3rd modes, the boiler master and turbine master are both in auto mode, respectively [1]. Coordinated control is the main control mode of thermal power unit control now [2]. Many effective control strategies for power unit coordinated control were proposed in literatures [3]. As model predictive control (MPC) can naturally deal with the coupling and dead time problems, it also began to be applied to the power plant control. Actually, MPC has been applied successfully in chemical industry and many other fields [4]. Dynamic matrix control (DMC) method, which is an initial algorithm of MPC, is suitable for the multiple input and output system of traditional power unit [5]. Nonlinear MPC was also utilized in coordinated control of fossil power units [6]. Application of DMC method to the super-critical power units was discussed on theoretical and practical aspects [7]. The DMC was also applied to the superheater and reheater temperature control problem, which built a 4-input by 4-output model and presented the simulation results to show the effectiveness of DMC method in power industry [8].

In above literatures, step response was applied to establish dynamic response matrix. But for coal-fired USC power unit, there is a strong nonlinearity in constant load and changing load because the parameters of the units vary largely in different operation points. MPC based on multiple models were proposed to deal with nonlinearity. The basic thought of multi-model MPC was introduced in Ref. [9]. Multi-model DMC has been applied to a multi-tank process [10]. The application result shows that multi-model DMC is more reliable to keep the controlled variables at setpoints over the range of nonlinear operation. There is an intelligent model used in MPC for coordinated control of USC unit [11]. The linearized state space model was used in MPC for coordinated control of USC unit [12]. The predictive outputs of multiple models are weighted in a fuzzy manner according to the operation points and the optimization uses the DMC algorithm for main steam temperature control [13]. The different linear MPC controllers based on state space predictive model are set up for a Two Tank Conical Interacting System [14] but the constraints are not taken into account, especially theΔMV, which is important in practice. The steady-state economic objectives

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are embedded into dynamic objectives as a penalty function [15]. But the equality constraints of steady-state optimization are not considered in the literature. So, the information of steady gain of the controlled plant is missing in this manner as mentioned in Ref. [15]. A double-layered optimization structure, *i.e.* multivariable constrained predictive control (MCPC), is proposed for the coordinated control of a USC unit in [16]. The focus of the paper is on the optimization structure but not on the nonlinearity of USC unit. Considering the nonlinearity of the USC unit, a multi-model MPC based on DMC method with a double-layered algorithm is proposed for USC unit coordinated control in this paper.

2. Ultra-supercritical Unit System

Coal-fired USC unit generally is composed of boiler and turbine. The boiler includes economizer, waterwall, seperator, superheater and reheater. The turbine includes high pressure turbine (HP), intermediate pressure turbine (IP), low pressure turbine (LP) and generator. In USC unit, water and steam only flow once through economizer, seperator and superheater. Water is turned into vapor entirely under dry condition. Drum, in which steam is separated from water, is not necessary in the USC boiler.

The schematic diagram of a USC coal-fired power generation units is shown in Fig. 1. The coal burned in furnace heats all sections of the boiler. The feedwater is warmed up by an economizer in the process cycle firstly. Then hot water is converted to steam in waterwall. After passing through the separator, the steam is superheated by superheaters. The valve controls the quantity of superheated steam to the HP turbine. The extraction steam from HP turbine goes to the rehaeater inlet. The reheated steam from the reheater outlet is used to drive the IP/LP turbine. The extraction steam from IP/LP turbine goes into the feedwater pump and feedwater storage tank for the next cycle [17]. Without the buffering of steam drum, the valve influences the characteristics of turbine and terminal resistance of the boiler heavily. This leads to strong non-linearity and parameter coupling of the USC unit, which can be seen as a complicated system with multiple-input and multiple-output (MIMO) system. The design of the control system, especially the coordinated control, is of more challenge for the USC unit compared to the traditional power units. This paper will focus on the design of the three-input by three-output coordinated control system based on the MPC of the USC unit.

3. Double-layered Multi-Model MPC for Coordinated USC Unit Control

MPC arises from chemical process control [18,19]. Based on the thoughts of predictive model, online optimization and feedback correction, MPC has been successfully applied to many industry fields with satisfied results. In this paper, MPC structure used in the coordinated control of USC unit is based on DMC, taking the algorithm of QP (quadratic programming) as following:

$$\begin{aligned} &\min_{\Delta U_{\mathrm{k}}} \quad J_k = \|W_{\mathrm{k}} - Y_{\mathrm{k}}\|_{\boldsymbol{Q}}^2 + \|\Delta U_{\mathrm{k}}\|_{\boldsymbol{R}}^2 \\ &\text{s.t.} \quad C_{\mathrm{du}}\Delta U_{\mathrm{k}} \le b_{\mathrm{du}}, C_{\mathrm{y}} Y \le b_{\mathrm{y}} \end{aligned} \tag{1}$$

where W_{k} is the reference of the controlled variables (CVs), Y_{k} is the measurement of the CVs, $\boldsymbol{Q}$ and $\boldsymbol{R}$ are the weight matrices of CV and delta manipulated variables (MVs), respectively, C_{du} and C_{y} are the constraint matrix coefficients, b_{du} and b_{y} are the constraints of ΔU_{k} and Y_{k}. The solution of Eq. (1) is an $M \times m$ vector of MVs, where M is the control horizon and m is the number of CVs. Only the first of every MV vector is implemented and the rest is discarded. This is typical in MPC algorithm. The procedure is repeated at next sample time.

For coordinated control of USC unit, the purpose of the control strategy is to keep the key parameters within the safe zone and to follow the load demand as quick as possible. When USC unit runs under different conditions, its steady and dynamic characteristic varies greatly. The dynamic optimization of MPC can only track the local optimal targets in time. Steady optimization can reach the global optimal targets in certain operation point. This paper introduces a double-layered MPC with steady optimization and dynamic optimization.

Double-layered MPC comprises of upper layer as steady optimization and lower layer as dynamic optimization. The steady optimization layer of MPC is the supervisor of dynamic optimization layer. The solution of steady optimization will be used as setpoint in dynamic optimization layer. The upper layer gives the control target of the USC unit and the lower layer pushes the USC unit to the optimal target gradually. The LP (linear programming) is used as steady optimization in Ref. [16]. When the economic target is more than linear, economic objective can be expressed as the QP manner. Thus, the steady optimization uses

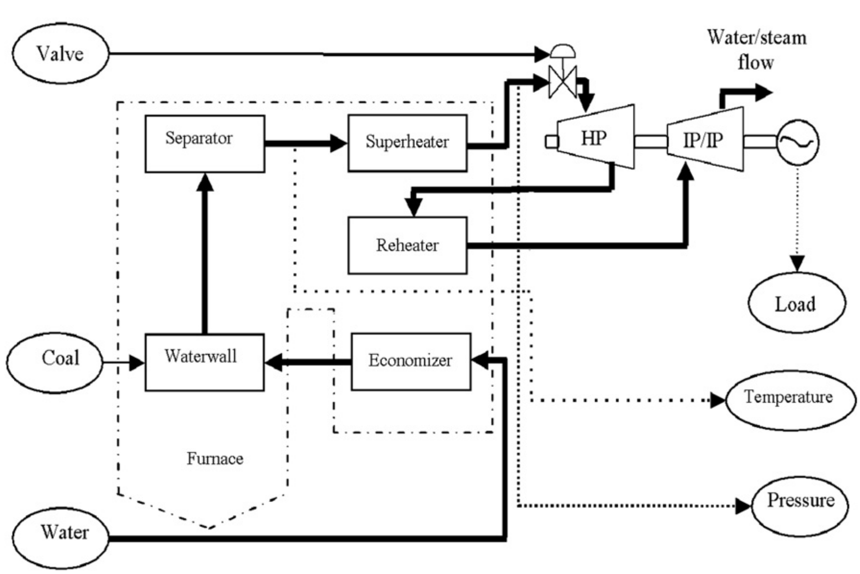

Fig. 1. Schematic diagram of USC unit.