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Affine nonlinear control for an ultra-supercritical coal fired once-through boiler-turbine unit

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ABSTRACT

The ultra-supercritical once-through boiler (OTB) unit is an advanced power generation technology with high plant efficiency, high coal utilization, and low emission. However, it is difficult to realize a coordinate control for the ultra-supercritical OTB unit to achieve fast and stable dynamic response during load tracking and grid frequency disturbances, and its complexity and nonlinearity result in the ultra-supercritical OTB unit becoming a multiple-input and multiple-output system filled with severe coupling and interference. According to the affine nonlinear system theory, a nonlinear control method is developed to solve nonlinear decoupled optimal control problems of a nonlinear ultra-supercritical OTB unit. Firstly, the exact linearization technique is used to transform the nonlinear ultra-supercritical OTB system into a linear one and an optimal LQR is designed for the corresponding nominal system. The optimal nonlinear control law can be derived by coordinate conversion and condition feedback and the study can be conducted for reasonable experiments and analysis. Then, compared with the linear PID control and model predictive control, the effectiveness and superiority of the proposed nonlinear optimal control have been verified through different loads disturbances from 50% to 100% using the Matlab/Simulink Toolbox.

1. Introduction

With the fast development of China's economy, the demand for electricity has increased rapidly. Although smart grid techniques put a large amount of renewable energy into the traditional power system, more than 65% of the electric energy production still depends on the fossil fired plants [1,2]. Moreover, more than 60 ultra-supercritical once-through boiler (OTB) coal-fired 1000-MW power plants are currently being developed to increase the efficiency of standard fossil fuel power plants in China [3]. The ultra-supercritical OTB units gives an efficiency of 46%, and provides stable and high-quality electricity. It also provides a better solution for reducing pollutants.

Due to the high complexity, nonlinearity, multi-variable, strong coupling and large delay characters of the ultra-supercritical OTB dynamics in high temperatures [4,5], controlling the ultra-supercritical OTB units faces great challenges. Specifically, when the steam temperature of the ultra-supercritical OTB unit is seriously affected by the small changes in fuel and feed-water, resulting in the strong coupling effect among boiler parameters, the system shows inherent nonlinearity due to the wide range of operating conditions. Meanwhile, the grid-frequency change can be a serious disturbance to the output power of renewable energy sources, which needs a fast load response for load frequency regulation [6].

In addition, with the emergence of smart grid technology, renewable energy sources have been incorporated into the grid. Whereas the output power of renewable energy sources usually affected by seasons and weather, and the randomness and volatility are very strong [7–9], which makes its ability of peak modulation and frequency modulation very weak. Therefore, the task of peak shaving and frequency modulation for large coal-fired ultra-supercritical OTB units has been increased, which makes it necessary to carry out peak shaving and frequency modulation for the power grid in a larger load range [10]. Thus, the traditional control based on linearized model at a certain equilibrium state of the ultra-supercritical OTB system may cause intolerable errors, even take

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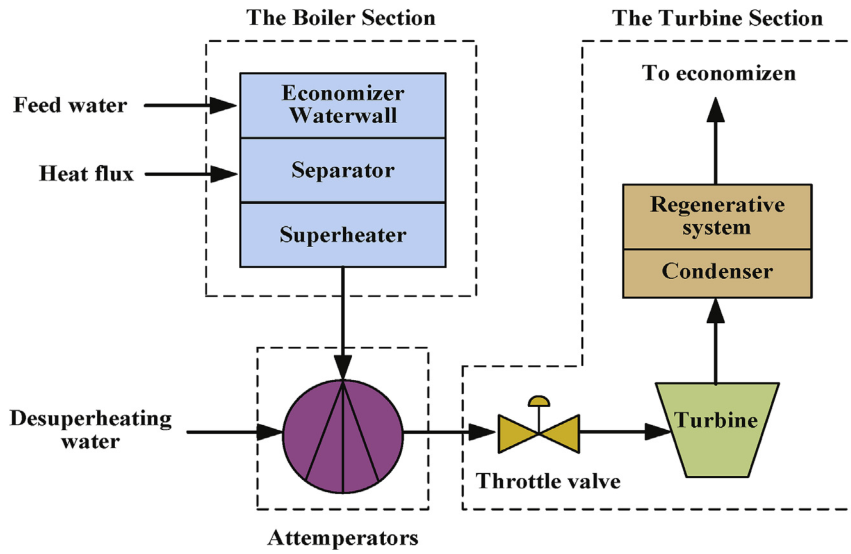

Fig. 1. Simplified block of the ultra-supercritical OTB unit.

wrong action, while the state point of the power system is changed away from the equilibrium point at which the linearization is realized.

So far, the researches on modeling and control of the ultra-supercritical OTB system are quite limited [2], [11]. In previous studies, the proportional-integral-derivative (PID) control method is widely adopted in power plant unit, which provides a simple structure and stabilized performance. However, this controller has weakness in highly complex and time-varying nonlinear systems with multi-input multi-output variables, thus it can't supply a satisfactory control performance throughout the power plant operating space because of its linearized model at a certain equilibrium state of the system-based control mechanism [12]. This leads to the original control strategies based on the linear model, which has shown their adequacy for the regulation of small load variation range, but can be seriously challenged by the wide-range load-following operation requirements.

To overcome this weakness, several advanced control strategies have been developed. In Ref. [13], a genetic algorithm is used to find the "best" proportional-integral gains and state feedback gains on a linearized boiler-turbine system. Compared with the conventional PI scheme, the disturbance observer-enhanced PI strategy achieves overall improvement and can even be comparable with the complex model predictive control in some aspects. In Ref. [14], an H_∞ controller is designed for a linearized boiler-turbine system. However, this design shows a good system response long when the change in operating points is sufficiently small. The resulting controller performs well over a well-defined range, but cannot guarantee robust performance over a wide operating range. In Ref. [15], an adaptive dynamic matrix control for a drum-type boiler-turbine system using a third-order model was developed. Applied inverse dynamic control and neural network control for a type of once-through boiler was proposed in Ref. [16], which no longer depends on complex mathematical models. One of the draw backs of this neural network approach is that, it requires a complicated online learning technique. The model predictive control has also been incorporated with iterative learning control [17] to compute the control signals for the decentralized PI controller. Inevitably, it brings more complexities and uncertainties into the system. A nonlinear hierarchical model predictive control was proposed to incorporate both the plant-wide economic process optimization and the regulatory process control for the fuzzy model of ultra-supercritical OTB unit into a hierarchical control structure in Ref. [18]. A data-driven method was proposed in Ref. [19], which is more practical and flexible, but these models are excessively dependent on the sample data and have no clear general structure.

Although the aforementioned control algorithms for complex nonlinear ultra-supercritical OTB units can of course improve the control performance. However, the present control strategies, either utilize linearized model-based control mechanism which is unsuitable for a wide range of load adjustment, or are excessively dependent on the sample data and have no clear general structure. In practice, it is desirable to have a controller which guarantees the nonlinear ultra-supercritical OTB unit achieve wide-range operation, meanwhile, clear general system structure. Alternatively, based on nonlinear dynamic model of ultra-supercritical OTB units, the nonlinear control methods should be studied for a wide range of load adjustment. In this paper, the nonlinear control strategy based on the nonlinear model can supply proper effects with the ultra-sup ercritical boiler system even during its violent swings caused by a large disturbance. To best of our knowledge, this is the first time that the affine nonlinear systems theory is employed to the research of ultra-supercritical OTB units. The main contributions of this paper lie in the following aspects: Firstly, the affine nonlinear systems theory will be introduced to design affine nonlinear control to achieve nonlinear ultra-supercritical OTB unit wide-range operation. Secondly, the linearization of the nonlinear system achieves according to feedforward compensator for multivariable systems.

The rest of this paper is organized as follows. In Section 2, the nonlinear model of the ultra-supercritical OTB unit is formulated. Then, the affine nonlinear control method for the nonlinear ultra-supercritical OTB unit is developed in Section 3. Section 4 gives some typical simulation results to verify the effectiveness of the proposed affine nonlinear control method. Finally, some concluding remarks are drawn in Section 5.

2. Nonlinear model of ultra-supercritical OTB system

The simplified block diagram of the ultra-supercritical OTB unit, consisting of the boiler section, the attemperation section and the turbine section, is shown in Fig. 1.