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Intelligent coordinated controller design for a 600 MW supercritical boiler unit based on expanded-structure neural network inverse models ☆

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ABSTRACT

Under present widespread automatic generation control (AGC) centered on regional power grid, a large-capacity coal-fired supercritical (SC) power unit often operates under wide-range variable load conditions. Since a SC once-through boiler unit is represented by a typical multivariable system with large inertia and non-linear, slow time-variant and time-delay characteristics, it often makes the coordinated control quality deteriorate under wide-range loading conditions, and thus influences the unit load response speed and leads to heavy fluctuation of the main steam pressure. To improve the SC unit's coordinated control quality with advanced intelligent control strategy, the neural-network (NN) based expanded-structure inverse system models of a 600 MW SC boiler unit were investigated. A feedforward neural network with time-delayed inputs and time-delayed output feedbacks was adopted to establish the inverse models for the load and the main steam pressure characteristics. Based on the model, a neural network inverse coordinated control scheme was designed and tested in a full-scope power plant simulator of the given SC power unit, which showed that the proposed coordinated control scheme can achieve better control results compared to the original PID coordinated control.

1. Introduction

Supercritical (SC) and ultra-supercritical (USC) power generating units have become the dominant coal-fired power units in China and around the world (Garduno & Lee, 2005; Ma & Lee, 2011). With the widespread implementation of Automatic Generation Control (AGC) centered on power supply quality in a regional power grid, these large-capacity energy conversion units are required to participate in peaking-load regulation frequently without exception and often operates under large-scale variable load conditions (Gerhard, 1998; Jan, Tommy, Palle, & Tom, 1998; Garduno & Lee, 2000, 2002; Li & Wang, 2005; Jia, Cheng, & Xiong, 2007; Li et al., 2010; Wang & Li, 2011).

Since a SC/USC boiler unit can be described as a strongly coupled nonlinear multivariable system with large time-delay characteristics, the traditional coordinated control strategy cannot well adapt to the load regulation, and often leads to slow load response and large main steam pressure fluctuations. Therefore, considering the stability of the power grid and the safety and economy of the power unit, it is of great importance to improve the coordinated control quality of the SC/USC power unit with advanced model-based intelligent control strategies, such as neural network inverse control or predictive optimal control method (Han, Zhang, & Zhang, 2001; Heo & Lee, 2008; Lee, Helo, Hoffman, & Kim, 2007b; Lee, Ma, & Boo, 2009; Lee, Van Sickel, Hoffman, Jung, & Kim 2010; Ma & Lee, 2011, Ma, Shi, & Lee, 2010; Ma, Lee, & Ge, 2012).

With increasing number of SC/USC boiler units, many studies have been performed for modelling (Ding, Li, & Wang, 2011; Yan, Zeng, Liu, & Liang, 2012). Among them, parameter tuning for some models is complicated and the models are inaccurate. Some models are too complex to fit for intelligent coordinated controller design. Therefore, how to establish a nonlinear mathematical model with higher accuracy and simpler structure that is suitable for intelligent controller design and applicable for a SC/USC boiler unit remains an important open problem.

Self-adaptive inverse control method was firstly proposed and developed by Widrow and others (Widrow, McCool, & Medoff, 1978; Widrow, 1986; Widrow & Walach, 1996). It has drawn much

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attention in engineering applications with its advantages of clear physical concept, being intuitive and easy to understand (Yuan & Guo, 1994; Han et al., 2001; Dai, He, Zhang, & Zhang, 2003; Dai, 2005; Xie, Zhang, & Xiao, 2007). But solving for the inverse system model of a complex multivariable system is a bottleneck. At the same time, artificial neural networks (ANNs) have been widely used for modelling and control of complex industrial dynamic systems with impressive identification ability, strong fault tolerance and adaptive learning capability (Gencay & Liu, 1997; Lee, Heo, Hoffman, & Kim, 2007a). Combining them together, ANN-model based inverse control method can overcome the difficulty of solving the inverse problem, and present promising future applications. Recently, neural network inverse control has been applied in different areas, including power plant steam temperature control and optimization (Malinowski, Zurada, & Lilly, 1995; Wang, Yu, & Song, 2002; Dai et al., 2003; Dai, 2005; Lee et al., 2009; Ma & Lee, 2011).

Aimed at improving the coordinated control quality of a large-scale coal-fired power unit, the neural network inverse system models for a 600 MW SC boiler unit are studied. Two separate inverse models for the load and main steam pressure are constructed. The inputs and outputs of each model are determined by analyzing the correlation between input and output variables, and the coordinated control modes of the SC power generating unit. The models are built with time-delayed feedforward neural networks, trained and verified with abundant operating data. Based on the developed models, neural network inverse controllers are designed for the coordinated system of the 600 MW SC power unit, and the controllers are validated by real-time control simulation te1sts (Ma, Wang, & Lee, 2014).

2. Coordinated control modes and simplified model of a SC boiler unit

2.1. Coordinated control modes for a SC boiler unit

Usually, the coordinated control system of a SC/USC boiler unit includes boiler master control (BMC), turbine master control (TMC), target load and load ramping-rate setting, target pressure and pressure rate setting, primary frequency tuning and other function loops (Zhang, Yu, & Song, 2007). For the 600 MW SC boiler unit investigated in this work, based on whether BMC and TMC are put into automatic or not, there are 4 kinds of control modes: (1) manual mode (both BMC and TMC are in manual), (2) boiler-following mode (TMC is in manual while BMC is in automatic), (3) turbine-following mode (BMC is in manual while TMC is in automatic), and (4) coordinated control mode (both BMC and TMC are in automatic modes).

According to the inner logic difference, the coordinated control mode can be divided into Boiler-Following Based Coordinated Control (BFCC) mode and Turbine-Following Based Coordinated Control (TFCC) mode. Under BFCC mode, TMC is used to control the load by changing the valve opening of the turbine governor when load demand changes, and BMC is responsible for maintaining the main steam pressure by changing the fuel flow. It results in faster load response and smaller load deviation, but relatively larger main steam pressure fluctuations. Under TFCC mode, BMC is responsible for controlling the load when load demand changes, and TMC is used to maintain the pressure by changing the turbine valve opening. It results in smaller pressure deviation, but slower load response. The two different coordinated control modes are illustrated in Fig. 1.

When a coal-fired power generating unit is scheduled automatically through AGC by the regional grid load dispatch center, the power plant often puts the priority in meeting the power grid

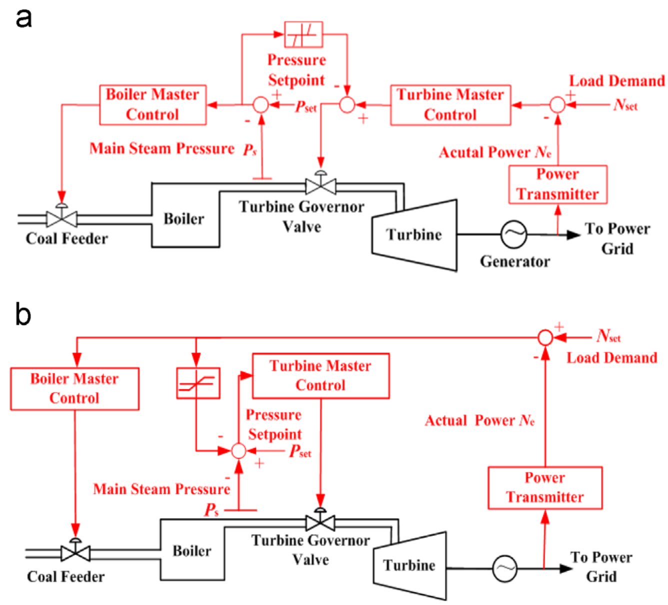

Fig. 1. Schematics of two typical coordinated control modes. (a) Boiler-following based coordinated control mode. (b) Turbine-following based coordinated control mode.

load demand to avoid additional penalty. Thus the BFCC mode, with its fast load response, is the preferred coordinated control mode under AGC control, and it is adopted by most SC/USC power units. For the 600 MW SC power unit investigated in this paper, BFCC mode is also employed. The actual control logic is shown in Fig. 2.

In Fig. 2, the three cascaded $f(t)$ functions represent three first-order inertia links; $f_1(x)$, $f_2(x)$ and $f_3(x)$ are piecewise linearization functions of different nonlinear links; APID is a general PID controller. The turbine-side PID controller is mainly used for regulating the unit's actual power. Meanwhile, the boiler-side PID

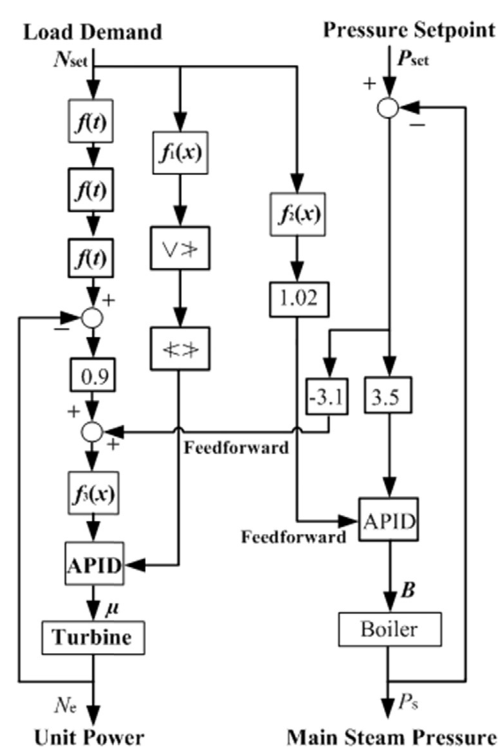

Fig. 2. Actual coordinated control logic of the given SC unit.