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An improved coordinated control strategy for boiler-turbine units supplemented by cold source flow adjustment

Wei Wang*, Jizhen Liu, Deliang Zeng, Yuguang Niu, Can Cui

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China

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A B S T R A C T

CCS (coordinated control strategy) is widely used for boiler-turbine units to change their steam turbine load. However, it is almost impossible to make a breakthrough in the load change performance just through CCS on account of the boiler's large delay. In order to accelerate the unit load response speed through the CSFA (cold source flow adjustment), the static and dynamic influence model of CSFA on the turbine power output is firstly set up in this paper. Then an improved strategy which combines CCS with CSFA control is brought forward to be used for the flexible load control. Another innovation of the improved strategy is to tie the output of CSFA controller to the measurement signal of the boiler controller, through which CSFA is used to quicken the turbine load response, the coal feeder rate to ensure the steady load accuracy, and the turbine governor valve to stabilize the main steam pressure. Furthermore, the condenser pressure will be recovered to its normal value for the next load dispatch use. Finally, simulation results confirm the effectiveness of the improved strategy compared to CCS, and moreover the extra coal consumption during the control process has been proved to be very small.

1. Introduction

With more and more wind and solar power integration on power system, there has been an increased demand on the load following capability of the other units [1]. As the coal-fired power plants account over 63% of the total installed power capacities in China up to the end of 2013, it might be a necessary choice for China to improve the load following capability of coal-fired power plants. Boiler-turbine CCS (coordinated control strategy) has being widely used in coal-fired power plants. As there exist strong couplings between the main steam pressure control loop and the power output control loop in the boiler-turbine unit with large time-delay and uncertainties, the automatic coordinated control of the two loops is a very challenging problem [2]. Self-tuning techniques [3], robust techniques [4], nonlinear control techniques [5], and other intelligent control techniques [6–8] are successively used to improve the control performance of CCS. However, it has become more and more difficult to improve the control performance just through control methods' innovation because of the boiler's slow dynamics in nature.

So, it would be an effective idea to search for a manipulated variable with quick response to turbine power but no influence on the main steam pressure. Condensate throttling, which was proposed by Lausterer G K [9] in 1998, is an efficient choice as it would lead to a short and rapid increase of the electric power output of up to 7% and has no impact on the main steam pressure. Regrettably, it might have rather complicated dynamics as it would result in the variations of the 4th to 8th extraction steam flow, as well as the change of deaerator level. The CSFA (cold source flow adjustment) [10], by contrast, is relatively easy to be controlled on account that it has no influence on other equipment or sections. And it would contribute about 2% of the full turbine power output in 20–30s, which shows outstanding potential to improve the load change capability of units. Furthermore, it has been proved that CSFA would not raise the coal consumption significantly in such little time [11].

It is worth emphasizing that CSFA method can only be used as an auxiliary means because the fuel supply is the energy source of turbine power output. So, fuel supply, as the decisive factor of turbine load, must satisfy the energy demand at the end of the load control, and any other load change strategies must be based on the coordinated control strategy. Now, there are two troublesome problems need to be solved. The first is how to obtain the improved

* Corresponding author. Tel.: +86 010 61772965; fax: +86 010 61772849.
E-mail addresses: wwang@ncepu.edu.cn, ncepuww@163.com (W. Wang).

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strategy combining the traditional CCS with CSFA. The second is how to recover the condenser pressure to its normal level so as to guarantee the low coal consumption and what's more, to make preparations for the next load dispatch. For solving the two problems, it seems essential to set up the dynamic model for the influence of condenser cooling water flow rate on turbine power output (as condenser pressure is determined by the condenser cooling water flow rate in certain steam turbine load and environmental conditions) and develop an improved coordinated control strategy for boiler-turbine units combined with CSFA.

This paper is organized as follows: Section 2 builds the dynamic model for the influence of condenser cooling water flow rate on the turbine power output. Section 3 makes some simulations for CSFA to prove the effectiveness of condenser pressure regulation for load control. Furthermore, Section 4 develops an improved coordinated control strategy combined with CSFA to improve the load following capability. The control performance comparison between traditional CCS and our improved CCS, and the extra coal consumption during the control process are discussed through a case study in Section 5. Finally, conclusions are given in Section 6.

2. Modelling for CSFA

It is known to all that condenser pressure has a significant influence on the turbine power output for the condensing power plants. However, condenser pressure is actually a state variable, not a decisive variable for the turbine load. This is because condenser pressure in a certain steam turbine load is determined by the condenser cooling water temperature and flowrate. As the water temperature is usually invariant in a certain time range, the condenser cooling water flow rate becomes the only variable affecting the turbine power output. So the motor speed of condenser cooling water pump is chosen as the decisive variable for CSFA, and the model of which describes the relationship between the motor speed of condenser cooling water pump and the turbine power output. This model can be divided into three parts, condenser cooling water pump model which reflects the relationship between pump motor speed and output water flow rate, the condenser model which describes the relations between condenser cooling water flow rate and condenser pressure, and the turbine load model which reports the relationship between the condenser pressure and turbine power output.

2.1. Effect of pump motor speed on cooling water flow

It is evident that the condenser cooling water pump has no dynamics on account that the output water flow rate would change immediately its pump motor speed varies. So, the relationship between pump motor speed and output water flow rate is just a static correspondence.

As the operating point of a condenser cooling water pump is the crossover point of the pump characteristic curve and pump piping head loss curve. As for a variable speed pump whose net head is not zero, its pump characteristic curve and pump piping head loss curve can be respectively fitted as:

$$H = a_1 Q^2 + b_1 \alpha Q + c_1 \alpha^2 \tag{1}$$

$$H = H_0 + kQ^2 \tag{2}$$

where H is the pump head, H_0 is the net head, Q is the pump flow, α is the speed ratio, a_1, b_1, c_1 and k are constant.

Two pumps would always be in parallel as the flow rate of one pump is not enough. For research convenience, the two paralleled pumps is assumed to operate in the same speed. According to the principle of paralleled pumps, the total output flow rate is the solution of the equation sets:

$$\begin{cases} H = a_1 \left(\dfrac{Q_{total}}{2}\right)^2 + b_1 \alpha \dfrac{Q_{total}}{2} + c_1 \alpha^2 \\ H = kQ_{total}^2 + H_0 \end{cases} \tag{3}$$

where Q_{total} is the total pump flow rate output.

Then, the total pump flow rate output can be calculated through:

$$Q_{total} = \frac{-b_1 \alpha - \sqrt{(b_1 \alpha)^2 - 4(a_1 - 4k)(c_1 \alpha^2 - H_0)}}{(a_1 - 4k)} \tag{4}$$

As a nonlinear expression, Eq (4) is not convenient for simulation. So, several discrete flow rate points in different speed ratios calculated through Eq (4) are fitted to be a polynomial to replace Eq (4). Fig. 1 shows an example of such fitting instead method, through which the linear model for the condenser cooling water pumps is obtained.

2.2. Effect of cooling water flow on condenser pressure

2.2.1. Static model

It is evident that the pressure of a water-cooled condenser is influenced by the inlet cooling water temperature, the exhausted steam flow from the LP cylinder, the cooling water flow, and the overall heat transfer coefficient [12]. Commonly, it is assumed that the condenser tube side was clean enough and the vacuum was tight enough so that the empirical equations can be used to calculate the heat transfer coefficient. However, the condenser with long-running operation is usually off its design conditions, which leads to the calculating error of condenser pressure. So, an ANN (artificial neural network) [13] model for condenser pressure evaluation is set up by use of the plant operating data so that it can factually reflect the current operating condition of condenser.

The architecture of the ANN for the condenser with the names of input and output parameters is schematically illustrated in Fig. 2. The inputs to ANN are the inlet cooling water temperature (t_{w1}), the cooling water flow rate (D_w), the exhaust steam flow rate (D_c). And

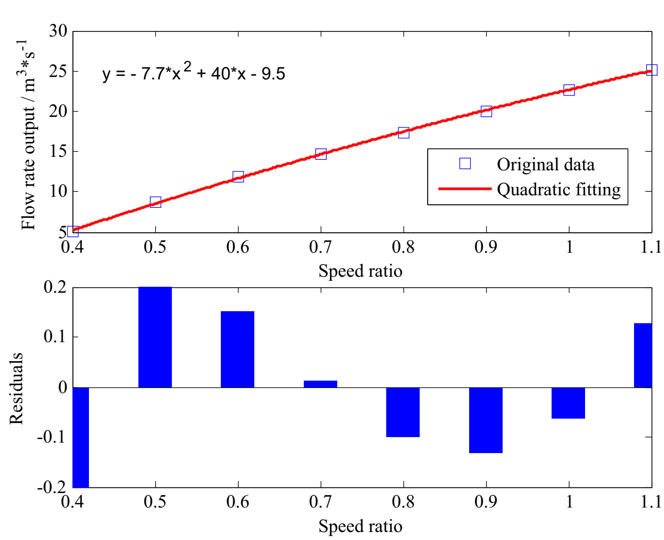

Fig. 1. The relationship between cooling water flow rate and motor speed of CCWP.