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Improved Coordinated Control of Coal-fired Power Units with Large-scale Renewable Energy Integration by Introducing Battery Energy Storage System

Guangming Zhang[1,*], Yuguang Niu[1], Wei Wang[1], Zhiyong Gan[2] and Ningning Tang[1]

[1]State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing, China
[2]State Grid Tianjin Electric Power Company Electric Power Research Institute, Tianjin, China

*Corresponding author email: gmzhang@ncepu.edu.cn

Abstract. With a high proportion of renewable energy being connected to the grid, the stable operation of the power system has been severely challenged. Conventional coal-fired power units need to take measures to compensate for random fluctuations in renewable power generation. This study introduces the battery energy storage system (BESS) to the coordinated control system (CCS) of the coal-fired units to improve the load regulation. Firstly, the dynamic models of boiler-turbine unit and BESS are set up. Furthermore, an improved coordinated control system combined with boiler, turbine, and BESS is designed. A dual controller that consists of BESS and fuel control is proposed to improve the power ramp rate. Finally, a power step simulation in a 330 MW coal-fired power unit is conducted. The simulation results show that the power ramp rate is 60 MW/min and the AGC performance index reaches 7.68 with the improved strategy.
Keywords: Renewable energy; Coal-fired power units; Battery energy storage system; Coordinated control system; Automatic generation control.

1. Introduction

With the rapid development of wind power [1], solar power [2] and other renewable energy power generation in recent years [3], traditional coal-fired power units are challenged severely [4]. Due to the random volatility of renewable energy sources, the coal-fired units are required to have a high response speed of power load to maintain frequency stability [5].

Generally, the power command is issued by the automatic generation control (AGC). The coordinated control system (CCS) is usually used for load control [6]. For the load control system, some studies apply intelligent control algorithms to optimize the coordinated control system, such as robust control [7], sliding mode control [8], and T-S fuzzy control [9]. Most studies employ the thermal energy storage contained in the unit to respond to power command as soon as possible, such as condensate throttling [10], cold source throttling [11], and heat-source regulation control [12]. Long et al. [10] models the relationship between condensate water flow and the power load, and designs the control system. Wang et al. [12] analyzes the effect of heat-source steam on electrical power and used heat-source to track to load command.

In addition to the energy storage inside the unit, some studies employ battery energy storage system (BESS) to increase the ramp rate of power [13]. Lu et al. [14] establishes a model of battery energy storage system in multi-time scale. Xie et al. [15] introduces the Multi-MW scale BESS for coordinated control to improve the AGC performance. The research results show that the BESS has enhanced load response rates and tracking capabilities. However, most of these studies focus on the application of BESS on the power grid, and there are few studies on BESS participating in the coordinated control system of boiler and steam turbine.

In this study, the battery energy storage system is introduced into the conventional CCS to improve the response rate of power. In the design of the improved control system, considering the effect of action of BESS and coal flow rate on the power load, a dual controller is proposed. The rest of this study is arranged as follows. Section 2 sets up the boiler-turbine and battery energy storage system model. Section 3 designs an improved coordinated control based on the dual control of BESS and fuel control. Section 4 conducts the simulation of improved strategy in a 330 MW power unit. At last, Section 5 draws the conclusions.

2. Mechanism Modelling

2.1. Boiler-turbine System

A coal-fired power unit which consists of boiler and turbine has various systems. It's schematic is shown in Figure 1. Where, HPC means high pressure cylinder, IPC means intermediate pressure cylinder, LPC means low pressure cylinder, μ_B is the feed-coal flow, t/h, μ_T is the main steam valve position, %, p_T is the main steam pressure, MPa, and P is the power output, MW. As can be seen in Figure 1, dynamic processes in the boiler-turbine unit can be divided into three parts. Detailed processes and respective differential equation models are given below.

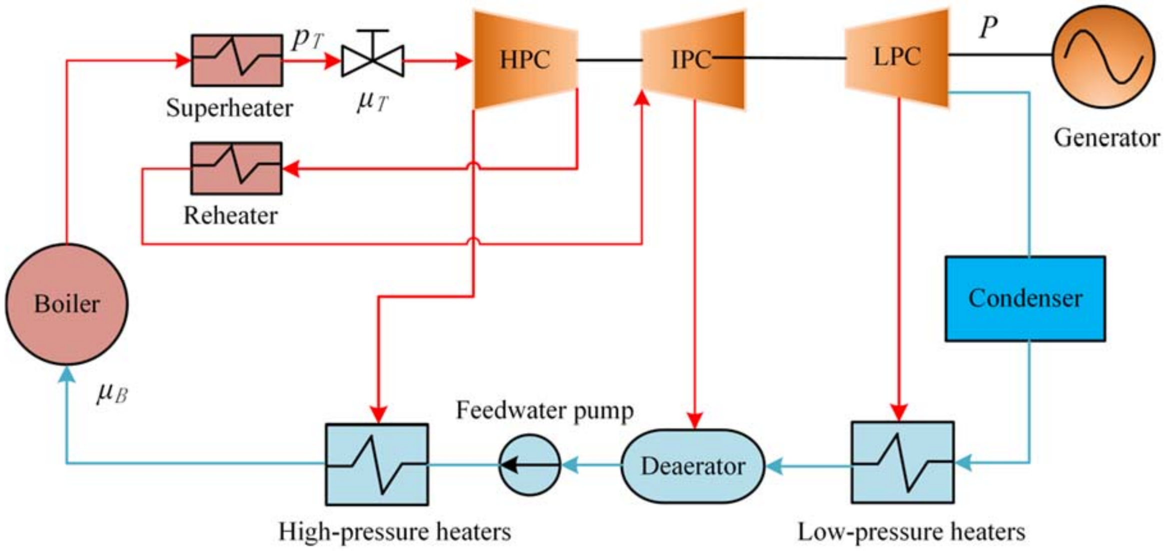

Figure 1. Diagram of boiler-turbine system for a coal-fired power unit.

(1) Combustion and heat transfer process

Pulverizing and feeding coal is a dynamic process, which can be expressed in terms of first-order inertia and pure retardation links.

$$T_P \frac{dr_B(t)}{dt} = -r_B(t) + \mu_B(t-\tau) \tag{1}$$

where T_P and τ are the inertia time and delay time of the powder process, respectively, s, and r_B is the boiler burning rate, t/h.

(2) Thermal transmission in steam turbine

In the thermal transfer process, the drum pressure is an important parameter to indicate the quality of steam and can be expressed as

$$C_D \frac{dp_D(t)}{dt} = K_B r_B(t) - K_T p_T(t) \mu_T(t) \quad (2)$$

$$p_T(t) = p_D(t) - K_D \left[K_B r_B(t)\right]^{\beta} \quad (3)$$

where p_D is the drum pressure, MPa, β, C_D, K_T, K_B and K_D are the constants.
(3) Turbine dynamic process

$$T_T \frac{dP(t)}{dt} = -P(t) + \alpha K_T p_T(t) \mu_T(t) \quad (4)$$

where T_T is the inertia time of turbine, s, α is the proportion of turbine.
In conclusion, the boiler-turbine system contains two inputs (μ_B, μ_T) and two outputs, i.e., the electric power (P), and the main steam pressure (p_T). It's linear model can be expressed as follow:

$$\begin{bmatrix} P \\ p_T \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{22}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} \mu_B \\ \mu_T \end{bmatrix} \quad (5)$$

2.2. Battery Energy Storage System
The BESS consists of battery packs, inverters, control devices and transformers. Thevenin's equivalent circuit model is generally used to represent battery energy storage systems [16], which is shown in Figure 2. Where, E_b is the power source, V, R_S and R_C are the internal resistance, Ω, C is the capacitance of the battery, F.

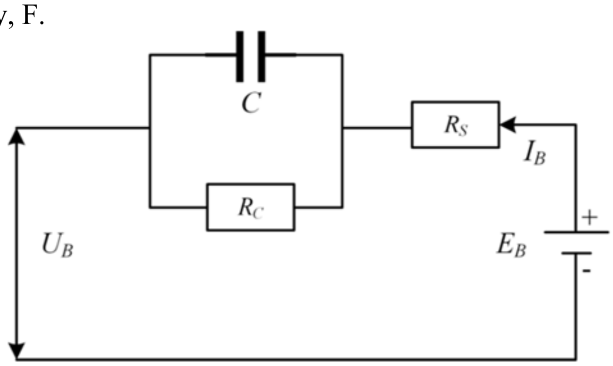

Figure 2. Thevenin's equivalent circuit of battery energy storage system.

The electrochemical reaction mechanism of the battery in the process of charging and discharging is difficult to express with a mathematical model. Considering that the various parameters are seriously coupled in the dynamic process, the complex mathematical model is not suitable for the optimization of the coordinated control system of coal-fired power units. According to the output characteristics of the battery during charging and discharging, it can be simplified as a first-order inertia link [17]. The dynamic of the battery can be expressed as follow:

$$\frac{\Delta P_{BES}}{\Delta U_{BES}} = \frac{K_{BES}}{T_{BES} s + 1} \quad (6)$$

where, ΔU_{BES} is the control input of the battery, ΔP_{BES} is the charge or discharge power of the battery, K_{BES} and T_{BES} are the coefficient and the time constant of the energy conversion, respectively.

3. Control System Design and Evaluation

3.1. Control System Design
The goal of the CCS is to make the power and pressure track the set point. Its realization includes two ways. The first way applies the valve opening of the turbine to control the load and the amount of coal to control the main steam pressure, which is called boiler-follow CCS. Another method regulates the power load by feed-coal, and the valve position of the turbine responds to the main steam pressure,

which is called turbine-follow CCS. In the boiler-follow operation mode of the unit, the steam turbine valve can actively respond to load changes, and the unit has a good load tracking ability. However, due to the large inertia and pure delay of the boiler, the unit cannot replenish energy in time, resulting in fluctuations in the main steam pressure. Dissimilarly, in the turbine-follow mode, the main steam pressure of the unit runs smoothly. At this time, the response of the power load mainly relies on the coal supply, and the response speed is difficult to satisfy the demand of the power grid. Taking into account the rapid response of battery energy storage, this study will adopt the turbine-follow strategy.
The turbine-follow CCS controls the load by regulating the coal flow. With the introduction of BESS, the variables for controlling the load are increased to two, i.e., the coal flow and the action of BESS. Battery energy storage mostly discharges in the initial process of control for the electric power rapid ramp, and coal adjustment operates in the final period of control. Considering the effect of two control variables on the power load, a dual controller is proposed in this study. Besides, The global diagram of the improved strategy is represented in Figure 3.

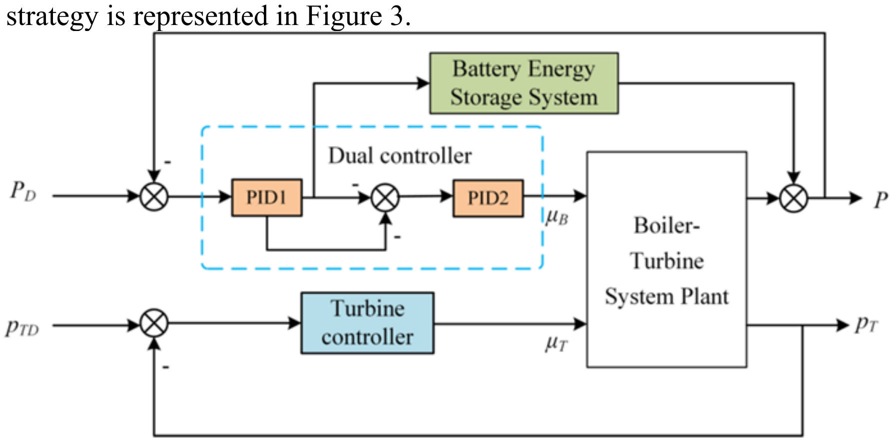

Figure 3. Diagram of the improved strategy for the boiler-turbine system.

The response speed of battery energy storage control is much faster than it of feed-coal control. So the energy storage is applied as the primary control, and the feed-coal as the secondary control. This can ensure that the battery discharge in time when the unit power command increases. During the process control, the output of the primary controller is used as the command of secondary controller. The primary controller controls the charge and discharge of the battery. When the battery is discharged, it is necessary to replenish energy in time by increasing the amount of coal. The setting value of the secondary controller is the opposite of the battery's action command, which indicates that the battery needs to be charged after being discharged. Besides, the main steam pressure of the unit remains the constant when the power command changes. The primary controller, secondary controller, and turbine controller are selected as PID controllers in this study.

3.2. Performance Evaluation

To achieve quantitative evaluation of the control performance and differences between controllers, a widely used power plant related criterion is introduced. In China, most coal-fired grid-connected power units are required to regulate and adjust their frequency and peak, respectively. The AGC performance indicator K_p is evaluated as the standard. The factors affecting K_p, consists of regulation rate K_1, steady-state accuracy K_2 and response time K_3. The three factors can be calculated with the following equations:

$$K_1 = 2 - \frac{v_N}{v_1} \tag{7}$$

where v_N is the standard regulation rate, and v_1 is the actual regulation rate.

$$v_1 = \frac{N_1 - N_0}{t_2 - t_1} \tag{8}$$

where t_1 is the dead time, N_1 and t_2 are the power and the time when the process achieves under steady regulation, respectively.

$$K_2 = 2 - \frac{\Delta N_1}{\Delta N_N} \tag{9}$$

where ΔN_N is the standard power error, and ΔN_1 is the accurate power deviation.

$$\Delta N_1 = \frac{\int_{t_2}^{t_3} \left| N_e(t) - N_{ed} \right| dt}{t_3 - t_2} \tag{10}$$

where t_3 is the ending time of the steady regulation.

$$K_3 = 2 - \frac{t_d}{t_N} \tag{11}$$

where t_N and t_d are the standard and actual response times, respectively.
Then, K_p can be calculated by using Equations (7), (9) and (11) as follows:

$$K_p = K_1 \cdot K_2 \cdot K_3 \tag{12}$$

4. Simulation and Discussion

A 330 MW coal-fired power unit is used to test the improved strategy. It's a subcritical and single-reheat cycle unit. The rated operating parameters of the unit are given in Table 1. The boiler-turbine model is illustrated as follows [18]:

$$G_{11} = \frac{2.069(311s+1)}{(149s+1)^2(22.4s+1)} \tag{13}$$

$$G_{12} = \frac{4.665s(399s+1)}{(58^2 s^2 + 50s+1)^2(4.1s+1)} \tag{14}$$

$$G_{21} = \frac{1.265(205s+1)}{(128s+1)^2(11.7s+1)} \tag{15}$$

$$G_{22} = -1.42(0.04 + \frac{0.96}{70s+1}) \tag{16}$$

Table 1. Rated operating parameters of a 330 MW unit.

Power (MW)	Main steam pressure (MPa)	Main steam temperature (℃)	Reheat steam temperature (℃)	Feed-water temperature (℃)	Turbine rotating speed (rpm/min)
330	17.7	540	540	255	3000

The maximum power and energy of BESS are 10 MW and 5 MWh, respectively. Then, the simulation with the improved strategy showed in Section 3.1 is conducted. The initial power state is selected 250 MW, and the main steam pressure is 16.7 MPa. Before 2000 s, the power unit operates in the steady state. Then, the command of power load step increases by 10 MW, and the power load must ramp to 260 MW as soon as possible. To verify the control effect of improved strategy, traditional boiler–turbine CCS is chosen as the comparison strategy. The controllers parameters of improved strategy and traditional CCS are presented in Table 2. With these controllers, the response curves of the electric power output and main steam pressure are presented in Figure 4 and Figure 5, respectively.

Table 2. Parameters of PID controllers.

Method	Controller	P	I	D
Traditional CCS	Boiler PID	10	0.2	0
	Turbine PID	-500	3	-100
Improved strategy	Primary PID	0.1	0.12	40
	Secondary PID	0.1	-0.02	0
	Turbine PID	-500	3	-92

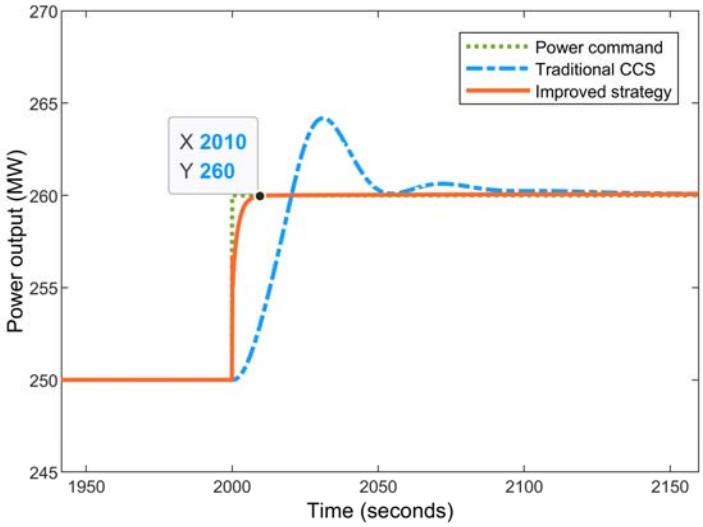

Figure 4. Response curves of the electric power output with improved strategy and traditional CCS.

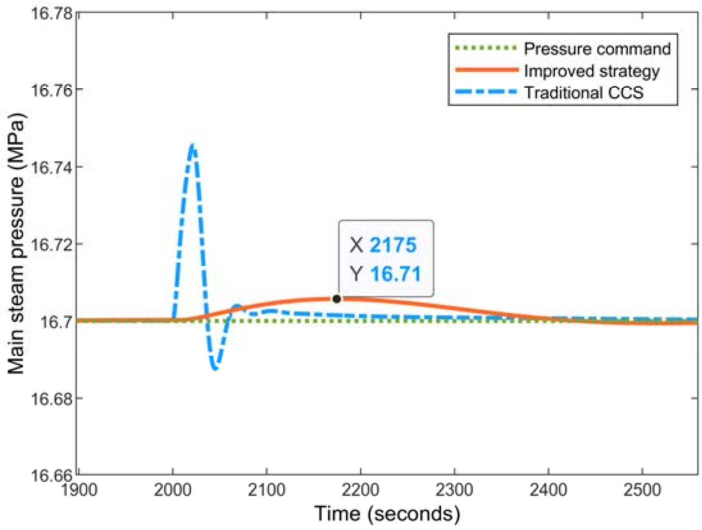

Figure 5. Response curves of the main steam pressure with improved strategy and traditional CCS.

From Figure 4, we can see that the power load by improved strategy reaches 260 MW after 10 s because of the rapid response of the BESS. The power ramp rate is 60 MW/min. In contrast, the power output by traditional CCS reaches 260 MW after 41 s. The regulation rate of traditional CCS is relatively slow and there is a significant overshoot.

From Figure 5, the maximum fluctuation of main steam pressure through improved strategy does not exceed 0.1 MPa, which is remarkably less than that though traditional CCS. This is because the BESS has a very fast power regulation rate, so that the unit does not need to employ internal energy storage to respond to the load. Therefore, the main steam pressure has a slight fluctuation.

The AGC performance can be calculated by Equations (7)-(12). Its results are listed in Table 3. This table shows that the AGC performance of the improved strategy than of traditional CCS. Higher index means that the units can be more economically compensated for participating in auxiliary peaking services.

Table 3. AGC performance of the control system.

Control strategy	K_1	K_2	K_3	K_p
Improved strategy	1.93	2	1.99	7.68
Traditional CCS	1.88	1.31	1.87	4.61

The response of the power output involves in two aspects: battery energy storage and fuel control. The contribution of each aspect is shown in Figure 6, where the shadow is the contribution power of the battery energy storage. It can be seen that the battery is responsible for the initial load regulation. Then, the actual energy required by the unit is supplemented by fuel gradually. The BESS ensures a fast load response rate at the beginning of a load change. The precise energy balance of the unit is achieved through the coordinated control of BESS and fuel.

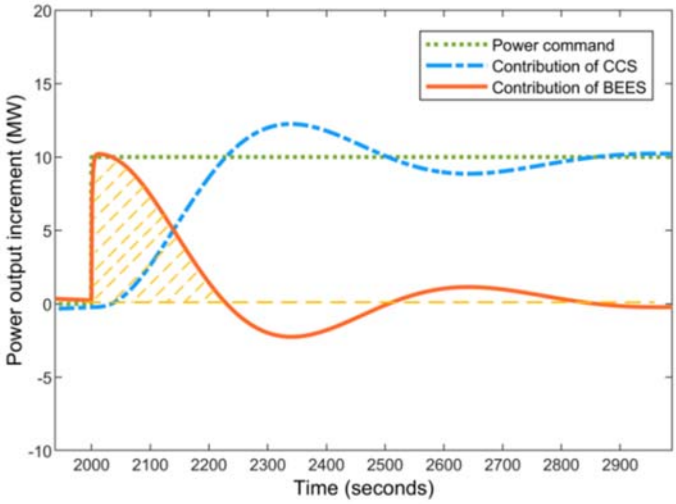

Figure 6. Contribution power of each part in the power regulation.

5. Conclusions

In this work, the battery energy storage system is introduced into the coordinated control system to improve the flexible load regulation. The model of CCS and BESS is set up firstly. Then, a dual controller is designed to coordinate the double variables which insists of fuel flow and action of battery. Finally, the effectiveness of the proposed strategy is demonstrated by the simulation experiments on a 330 MW coal-fired power unit. The results show that, the unit has higher load tracking capability and lower main steam pressure fluctuations with BESS. At the same time, the AGC performance index is also significantly improved, which demonstrates the significance of BESS' involvement in load regulation on the unit side. However, due to the high equipment cost of BESS, how long it takes for the unit to recover its cost after adopting BESS needs to be further studied in future work.

Acknowledgments

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