Applied Thermal Engineering 108 (2016) 546–554

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

A mathematical model suitable for simulation of fast cut back of coal-fired boiler-turbine plant

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HIGHLIGHTS

- Establish a model suitable for simulation of fast cut back.
- Important auxiliary facilities of power plant are considered.
- The model is verified by the FCB field test under 50% and 100% ECR load.
- The simulation results are in conformity with the field tests.

ARTICLE INFO

Article history:
Received 5 May 2016
Revised 25 June 2016
Accepted 24 July 2016
Available online 25 July 2016

Keywords:
Blackout
Fast cut back
Thermal power plant
Modeling
Bypass system

ABSTRACT

Recently, blackouts have occurred frequently due to various reasons. When the fault in the power grid is repaired, fast cut back (FCB) technology can restore power quickly. Therefore, it is necessary to establish a dynamic mathematical model of thermal power plant to simulate FCB. In this paper, a dynamic mathematical model of 300 MW thermal power plant was built up, which was based on the principles of mass and energy balance. The model considered feed water heater systems, bypass system, and feed water pumps. The heat absorption characteristics of steam-water systems during FCB were considered as well. This model has been verified by the FCB field tests under the conditions of 50% and 100% economize continue rate (ECR) load.

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1. Introduction

Electric power, a basic industry of the national economy, is crucial to both production and daily-life of people. In recent years, some clean energy, such as nuclear energy, wind energy and biomass energy, have been researched deeply and applied widely. But, about 70% of China's power generation is offered by the thermal power industry [1], and the dominant situation of thermal power units in the power generation will not be changed for a long time [2]. At the same time, thermal power units confront with many control problems of extreme conditions, and the feasibility of the control strategy can only be testified by model with high accuracy and applicability [3]. So far, many achievements have been made in the research of thermal system model basing on energy, mass and momentum balance [4–6], combined with the field tests [7,8], or prediction algorithms [9,10], which provide references for thermal power units simulation and control [11].

Aiming at the special conditions, great research results have been obtained, such as the influence of fast gas turbine start-up on the dynamic behavior of heat recovery steam generator (HRSG) [12,13], dynamic characteristics of hot start-up and shut-down procedure of triple-pressure combined-cycle plant [14], dynamic behavior of the HRSG during cold start-up [15], and the dynamics of oxyfuel coal fired boiler during main fuel trip and blackout [16]. Additionally, the start-up process optimizations taking into account thermal stresses for the natural circulation boiler has been solved [17], feed water control strategy during start-up has been proposed [18].

Power grid blackouts occurred frequently in recent years, such as North American on Aug. 14, 2003 [19], and South China in 2008 [20], which brought great damages to people's production and life. FCB technology of thermal power plant can restore load quickly when the fault of power grid is removed [21]. Recently, some progress has been made in the research of FCB technology,

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http://dx.doi.org/10.1016/j.applthermaleng.2016.07.170
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Nomenclature

D	flow rate (kg/s)
p	pressure (MPa)
Q	heat exchange (kJ/s)
M	metal mass (kg)
V	volume (m^3)
ρ	density (kg/m^3)
h	enthalpy (kJ/kg)
H	drum water level (m)
l	drum length (m)
R	drum diameter (m)
μ	valve opening (%)
T	temperature (°C)
W	power (kW)
n	rotor speed ($r{\cdot}min^{-1}$)
D_f	amount of coal in the mill (kg)
r'_B	mass flow rate of fuel to the mill (kg/s)
r_B	mass flow rate of fuel to the furnace (kg/s)
u_B	fuel flow rate command (kg/s)
T_T	steam torque (N·m)
T_L	load torque (N·m)
T_f	friction torque (N·m)
τ	time of steam flowing out water level (s)
v	steam rising speed in water (m/s)
N_{fe}	number of pulverized coal nozzles (–)
ε_{ec}	drag coefficient of economizer outlet (–)
ε_s	drag coefficient of drum outlet (–)
k_{fw}	drag coefficient of feed water pipe (–)
k_{dr}	gain of coal calorific value (kJ/kg)
c_m	specific heat capacity of metal (kJ/(kg·°C))

Subscripts

ec	economizer
fw	feed water
super	superheater
m	main steam
s	saturation steam
w	saturation water
t	steam turbine
spray	spray water
HPbypass	high pressure bypass
LPbypass	low pressure bypass
in	inlet
out	outlet
dr	drum
HPT	high pressure turbine
IPT	intermediate pressure turbine
LPT	low pressure turbine
de	deaerator
iEX	the *i*th extraction of steam turbine
p	pump
re	reheater
sfw	feed water flow rate of single feed pump
0	rated condition

the introduction of main control technology during FCB test at Tanagawa No. 2 oil-fired power plant provided references for the similar type plants [22], selecting of bypass, design of the chain protection for FCB have been studied [23], boiler feed water control technology and fuel control technology during FCB contributed to the control system optimization greatly [24,25]. Previous studies based on field tests have provided reference for FCB control, however, it is also easy to cause equipment damage, and some great loss in case of the test failure. At the moment, modeling technology is an efficient way to study FCB, but there is little research on it. To solve these problems, a dynamic mathematical model of thermal power plant for FCB simulation was built, verified by FCB tests of 300 MW unit under the conditions of 50% and 100% ECR. The results showed that the model is correct and credible, providing model support for the FCB control.

2. Description of thermal power plant

In this paper, the research object is a 300 MW sub-critical coal-fired unit applied in Haiphong, Vietnam. Its steam turbine is a sub-critical re-heat steam cylinder, produced by Fuji Corp of Japan, moreover, it has three electric feed water pumps and a sub-critical natural circulation boiler made in China. Fig. 1 shows its structure diagram.

3. Mathematical model of boiler-turbine

Since the thermal power plant is a non-linear, complex system, it is unrealistic to take all details into account. In order to simplify the model, some assumptions were made as follows:

(1) The heat transfer characteristics of gas and water wall are considered in the milling system.
(2) Parameters of working fluid in economizer, evaporation system, super-heater and re-heater are lumped.
(3) The influence of different phase states in the water wall on heat transfer is ignored.
(4) Steam-water system pipe does not have leakage.

3.1. Boiler model

3.1.1. Economizer

Economizer uses the waste heat from boiler tail gas to heat the boiler feed water, which can reduce the temperature difference between drum wall and the water inlet.

Mass balance equation:

$$V_{ec}\frac{d\rho_{ec}}{dt} = D_{fw} - D_{ec} \tag{1}$$

Energy balance equation:

$$V_{ec}\frac{d(\rho_{ec}h_{ec})}{dt} = D_{fw}h_{fw} - D_{ec}h_{ec} + Q_{ec} \tag{2}$$

Because boiler feed water density changes little during FCB, the outlet flow rate of economizer is:

$$D_{ec} = \varepsilon_{ec}\sqrt{p_{ec} - p_{dr}} \tag{3}$$

Generally, the heat absorption of steam-water system is mainly relevant to the fuel quantity. Nevertheless, during FCB, the fuel quantity change is less than feed water flow rate, so, the heat absorption of economizer is mainly contingent on the feed water flow rate. This paper presents the dynamic characteristics of economizer heat absorption during FCB under different load. The heat absorption is shown as Eq. (4) [26,27]:

$$Q_{ec} = 1000D_{fw}\cdot\beta_{ec} \tag{4}$$

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