Energy 93 (2015) 2069–2078

Contents lists available at ScienceDirect

Energy

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

A dynamic model used for controller design of a coal fired once-through boiler-turbine unit

Ji-Zhen Liu, Shu Yan, De-Liang Zeng, Yong Hu*, You Lv

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form
1 August 2015
Accepted 19 October 2015
Available online 19 November 2015

Keywords:
Once-through boiler
Nonlinear model
Modeling for control optimization
Parameter identification

ABSTRACT

Supercritical OTB (once-through boiler) units with high steam temperature and pressure have been widely used in modern power plants due to their high cycle efficiency and less emissions. To ensure the effective operation of such power generation systems, it is necessary to build a model for the design of the overall control system. There are already detailed models of once-through boilers; however, their complexity prevents them from being applied in the controller design. This study describes a lumped parameter dynamic model that has a relatively low complexity while faithfully capturing the essential overall plant dynamics. The model structure was derived by fundamental physical laws utilizing reasonable simplifications and data analysis to avoid the phase transition position problem. Parameter identification for the model structure was completed using operational data from a 1000 MW ultra-supercritical OTB. The model was determined to be reasonable by comparison tests between computed data and measured data for both steady and dynamic states. The simplified model is verified to have appropriate fidelity in control system design to achieve effective and economic operation of the unit.

1. Introduction

Shortage of energy sources and pollution of the environment have increased the interest in developing power generation units with high efficiency and low emissions. Large capacity, high temperature and pressure tolerance (up to 600 °C and 28 MPa) are essential characteristics of those power units [1]. Therefore, OTB (once-through boiler units), which are ideally matched to very high temperature and pressure requirements, are widely adopted. However, the design and debugging technique of coordinated control system in many ultra-supercritical OTBunits is still immature, and the characteristics of the unit haven't been grasped. So in the practical operation, some of the parameters deviate from the design value and many primary facilities are not running in the optimal state. These lead to some serious drawbacks, such as loss of unit energy, waste in coal and decrease of equipment life. When these drawbacks have no influence on safety operation, they are usually ignored by operators. Therefore, analyzing the unit characteristics, establishing appropriate dynamic model, and developing optimal control system based on the model are the premises of ultra-supercritical unit performance improvement.

A model used for controller design is expected to have a tractable mathematical structure and reflect the essential overall dynamic and nonlinear characteristics of the unit. It should strike a balance between complexity and accuracy. In this regard, it is of prime importance to find out the meaningful process inputs, outputs and internal state variables, and to capture and reproduce the nonlinear and interaction effects in close resemblance to the physical process. A classical model for drum boiler turbine units (DBT) was presented by Åström and Bell [2], and a detailed mathematical analysis was presented in 2000 [3]. The equations of the model were developed on the basis of a combination of fundamental physical laws, heuristic knowledge of boiler behavior, and a data fit via numerical identification. This model has been widely used in DBT modeling research and provides method reference for OBT modeling. So far a substantial number of lumped mathematical model for the OTB have been presented in the technical literatures. In the early research the lumped model was derived by dividing the OTB into 14 compartments [4]. However, this model is overly concerned with physical accuracy that results in too many expressions and state variables to be practical for the control design. Considering this restriction, a simplified third-order state space model for the supercritical OTB has been built [5]. Although this model meets the simplification requirements, it does not describe dynamics of throttle pressure. Therefore, it is inappropriate to

* Corresponding author. Tel.: +86 18500556173; fax: +86 010 61772849.
E-mail address: ncepu_hu@yahoo.com (Y. Hu).

http://dx.doi.org/10.1016/j.energy.2015.10.077
0360-5442/

Nomenclature

u_B	fuel flow rate command (kg/s)
r'_B	mass flow rate of fuel to the mill (kg/s)
τ	delay time of pulverizing process (s)
r_B	mass flow rate of fuel to the furnace (kg/s)
M	amount of coal in the mill (kg)
c_0	pulverizing inertia time (s)
c_B	output coefficient of the mill
f_H	correction coefficient of coal grind ability
f_W	correction coefficient of the moisture content of coal
f_R	correction coefficient of coal fineness
p	steam pressure
ρ	density (kg/m^3)
u	specific internal energy (kJ/kg)
D	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
T	temperature (°C)
H_n	heat removed by circulating water (kJ/s)
v_t	total working fluid volume in the boiler (m^3)
Q	heat transferred from tubes to fluid in the boiler (kJ/s)
Q_0	heat transferred from tubes to steam in the superheater (kJ/s)
k_0	gain of coal calorific value (kJ/kg)
ε	drag coefficient
u_t	throttle valve opening ($0 \le u_t \le 1$)
η	energy conversion rate of turbine
N_e	active power

Subscripts

a	average parameter of flow in the boiler
fw	feed water flow
s	steam flow out of the superheater
sw	spray flow
st	throttle steam flow
m	steam flow in the separator

Abbreviations

OTB	once-through boiler unit
DBT	drum boiler-turbine unit
Matlab	Matrix Laboratory

perform analysis that is required by the controller design. Some work has been carried out to obtain a lumped model of the OTB with consideration for the change of phase transition position [1,6]. Again these models cannot be applied to the controller design because of their complexity. There also has been an application of the intelligence method in OTB modeling in recent years, such as genetic algorithm [7], fuzzy clustering [8] and neural network [9]. Compared with the analytical method, the data-driven method is more practical and flexible, but these models are excessively dependent on the sample data and have no clear general structure. Currently there is no general simplified model for controller design of the OTB. In this regard, the objective of this study is to establish a descriptive nonlinear control model that exhibits a simple form and a general structure, which can be applied in model reduction analysis, model linear processing, and control design for different units with different parameters.

Being primarily focused on the overarching structure and dominant dynamics of the OTB, the work in this paper is a combination of simplifications, mechanism analysis, data analysis and identification techniques. Through reasonable simplifications and data analysis, the whole boiler is considered as one compartment and parameters of steam in the separator are chosen as the lumped parameters to avoid phase transition position problem. Then a lumped parameter model structure is generated by mechanism analysis and simplification. The input variables of the model structure are fuel command, feed water mass flow rate and throttle valve opening. The output variables are throttle pressure, active power and separator enthalpy. Parameters in the model structure are identified by operational data from a 1000 MW ultra-supercritical OTB. Comparison tests with the actual unit were performed using Matrix Laboratory (Matlab) to validate the model.

2. Model description

2.1. Pulverizing system

Before being fed into a furnace, coal needs to be ground in a coal mill. This leads to inertia and delay in the dynamics of coal in pulverizing system [10]. The delay time is composed of the coal transmission time, the accumulation time on the mill and the delivery time in the primary air pipe. The delay section can be written as

$$r'_B = u_B\, e^{-\tau s} \tag{1}$$

The inertia of the pulverizing system is caused by the mill and the coal separator. The mass balance equation in the mill is

$$\frac{dM}{dt} = r'_B - r_B \tag{2}$$

According to the characteristics of the mill, mass flow rate of fuel to the furnace can be expressed as:

$$r_B = c_B M f_H f_W f_R = \frac{1}{c_0} M \tag{3}$$

All of the coefficients above can be treated as the inverse of a constant c_0, called pulverizing inertia time. Combining Eqs. (1), (2) with (3) gives the transfer function description of the pulverizing system.

$$r_B = \frac{e^{-\tau s}}{c_0 s + 1} u_B \tag{4}$$

2.2. Boiler-turbine system

2.2.1. Simplification illustration

From an analysis of previous studies, it is clear that dividing the boiler into several compartments according to either the phase state of the working substance or the physical position and then developing models for each compartment will increase the difficulty of modeling and complexity of the model. This defeats the original intentions of the model. Thus, to develop a simple model, we regarded the heating exchangers, i.e. the economizer, the water walls and the superheaters, as a heating tube, and only concerned with the state changes of the inlet point, the outlet point, and the representative point of the boiler.

Spray attemperators are used for regulation of steam temperature, so they should be addressed in the modeling process. However the importing of multilevel attemperators will deal the superheater into several distinct parts and increase the complexity