Modeling Large Modern Fossil-Fueled Steam-Electric Power Plant and Its Coordinated Control System for Power System Dynamic Analysis

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Abstract — Fossil-fueled steam-electric power plants have many outstanding advantages and are still one of the main power types in the world especially for non-European countries. The classic mathematic models are designed for traditional hydraulic governing steam turbine units. Single turbine and its control system models are used wildly for dynamic analysis in power system. Digital electro-hydraulic (DEH) control systems and coordinated control systems (CCS) are used in most of the modern large power boiler-turbine units. They are key elements in the operation of the power station and have great impact on the system responses to the frequency or load disturbances. But seldom researches are available for modern generation unit models with both CCS and boiler control systems.

A general model of power plant with CCS control system is built for power system dynamic analysis. The proposed model is compared with the classic ones under given disturbance inputs. The simulated results show the CCS should be considered in power plant modeling for power system dynamic analysis.

Index Terms—coordinated control system, dynamic model, parameter identification, power plant

I. INTRODUCTION

More and more boiler-steam turbine generation units are used in the power system especially for non-Europe countries for some special features of fossil-fueled power plants. When a load disturbance occurred in the system, a frequency variation will cause a primary regulation action on generation units. The units will automatically adjust their outputs to fit for the new load demand. Variation of the governing valve position may exceed to the outlet pressure of the related boiler but boiler often has a long control time cycle after the pressure error was observed. Coordinated Control System (CCS) is usually used to speed up the regulation procedure of boiler and to improve the stability of the steam parameters upstream of steam turbine.

Many researchers [1-7] have studied the mathematic models of power plant for power system dynamic analysis. According to their research, low order models for turbine units are more popular for power system dynamic analysis. According to huge test experiences, single turbine model is not enough without a consideration of a main steam pressure variation. A boiler model is also needed for some circumstances. Control system of boiler and the CCS acting on both the boiler and turbine systems will have great impact on the pressure stability even output power of turbine units. But these control systems are not well considered in relative research [8].

In this paper, a fossil-fuel power plant model is presented with CCS for power system analysis. The model parameters are identified for a 600MW turbine coal fired generation unit. The model responses are compared to the model without a CCS model to evaluate the impact of CCS model on system frequency stability.

II. STABILITY, AND FINALLY DRAW SOME USEFUL CONCLUSIONS

POWER PLANT MODEL STRUCTURE

A general dynamic model structure of fossil-fueled steam-electric power plant and its CCS is presented in this chapter. The whole model is divided into three parts as steam turbine, boiler and control system. In order to avoid the frequent input of the steady-state values in a simulation, the variable parameters are all relative variations in this paper. The variables are defined as the error between the actual value and the steady-state value divided by its rated value. An equation is shown as (1) for a clearly understand of the variables used in many simulation analyses.

$$\nu = \frac{V_{\text{local}} - V_{\text{steady}}}{V_{\text{rated}}}$$

Almost all the simulation analyses are based on a prior steady state. By using such a kind of variables, the initial value and the derivatives of a variable will always be zero. The initialization of integral components or many steady equations are avoided for different operation conditions or even different simulation objects.

A. Steam turbine

Modern generation steam turbines are mostly large power reheat units. There are multi low pressure cylinders and even multi intermediate pressure cylinders for some units. All the low pressure cylinders or the intermediate pressure cylinders
can be considered as one for power system dynamic analysis due to their similar dynamics during governing process.

A classic steam turbine model is used wildly for decades. Its relative variation form is adopted in this paper as shown in fig. 1. Steam flow entered into steam turbine, which is proportional to sum of the product of governing valve position variation \( \Delta GVP \) and steam pressure variation of superheater \( P_s \) and two variations themselves. \( T_H, T_R \) and \( T_L \) are time constants of three equivalent steam volume as high pressure volume, reheater volume and crossover volume, and \( p_s, p_r, p_l \) are average steam pressures of three volumes. Output power is a sum of output by three kinds of turbine cylinder. Power of each cylinder is considered to be proportion to its inlet steam pressure due to high pressure ratio. Relative with the rated output power the output portions of three cylinders are \( K_H, K_R \) and \( K_L \) respectively.

\[
\frac{1}{T_s + 1} \Delta P_s = \frac{1}{T_r + 1} \Delta T_r + \frac{1}{T_l + 1} \Delta T_l
\]

\( K = \frac{1}{T_s + 1} \Delta P_s \)

\( \Delta P_s = g_o \Delta \Delta GVP \)

\( \Delta P_r = g_r \Delta P_g \)

where \( g_s, g_r, g_o \) are the flow rate variation discharge from the superheater and the water wall respectively, while \( T_s \) and \( T_r \) are their relative time constants.

The dynamic process of the fuel feed and burring system and water walls are both considered as first-order inertia and pure delay.

The effect on reheater pressure of fuel feed variation is ignored. According to the mathematic models shown before, the whole boiler system can be merged as a model of transfer functions shown in fig.3.

Pressure in the equivalent storage volume is generally proportional to the integral of the mass flow difference between its input and output interfaces. Their equations can be written as (3) and (4).

\[
\frac{dP_o}{dt} = g_o - g_w
\]

\[
\frac{dP_s}{dt} = g_s - g_o
\]

where \( g_s, g_w \) are the flow rate variation discharge from the superheater and the water wall respectively, while \( T_s \) and \( T_r \) are their relative time constants.

Control systems are the key part of whole system dynamics. A simplified unit control system model with CCS shown in fig. 4.

Generally steam turbine and boiler has their own control systems as shown in fig. 4. The boiler control system will control the supply pressure of steam within an acceptable
range around the reference pressure $p_{ref}$. The reference pressure $p_{ref}$ will be const for a constant pressure operation case or a function of load demand for a sliding pressure operation case. The turbine governing system mainly controls the positions of governing valves to maintain the frequency or the spin speed of the generation unit close to the nominal value. Its governing amount depends on the droop $\delta$ of primary frequency regulation framework.

When a load disturbance occurred in the power system, frequency will be changed due to unbalanced power between generations and consumers demands. Then, the turbine governing system will adjust the governing valve positions to change the output power of the turbine. It may also change the outlet flow rate of the superheater and then the steam pressure $p_s$. The variation of superheat steam pressure may counteract part of the governing functions and will result in further actions of turbine governing system. Boiler control system found the pressure deviation and change the firing command to improve the parameter stability but the huge time lag of the process cycle made it hard to stop a large pressure variation $p_s$ which may harmful to the security of the devices.

CCSs are used wildly for boiler-turbine units. They will adjust the firing commands when the frequency exceeds given deadbands or when the turbine control system change the flow rate entered into the turbine. That will speed up the boiler governing process rather than wait for the main steam pressure variation beyond a marked range.

III. MODEL PARAMETER IDENTIFICATION

Model parameters are also critical to the precision of the model simulation. Selection by experience may useful for qualitative research but not enough for power system stability analyses, in which small deviation may cause opposite judgments of stability.

Model parameter identification is one of the most reliable tools to estimate the model parameters. The object system should be excited sufficiently in a test procedure. Then, kinds of parameter identification methods can be used to estimate the parameters from the test records, such as least square method (LSM), spectrum analysis (SA), genetic algorithm (GA), particle swarm optimization method (PSO), and so on. The last two methods can be used for nonlinear models and a method $\text{[9, 10]}$ based on GA is adopted in this paper.

An experiment can be carried out on an object generation unit by modifying its reference frequency and measured relative variables until a new balance state is formed.

**A. Boiler**

In the boiler model as fig. 3, the firing command $P_f$, fuel flow rate $g_f$ and main steam pressure are easy to be measured rather than main steam flow rate $g_s$, so governing valve model are also considered in the identification model of boiler as shown in fig. 5.

![Identification method of boiler model](image)

**Fig. 5 Identification method of boiler model**

The parameters $T_w$, $T_D$, $T_s$ and $K$ can be estimated together with the test data of two input signals $P_f$ and $P_{ef}$ and one output signal $p_s$.

A 600MW steam turbine unit was test for the identification procedure. The identified model responses are compared to the test output signals as shown in fig. 6. The identified model parameters are shown in table I.

![Identified model output and its comparison to the measured data in boiler model](image)

**Fig. 6 Identified model output and its comparison to the measured data in boiler model**

<table>
<thead>
<tr>
<th>IDENTIFIED PARAMETER FOR A BOILER MODEL</th>
<th>Identified value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_w$</td>
<td>22.3s</td>
</tr>
<tr>
<td>$T_D$</td>
<td>46.1s</td>
</tr>
<tr>
<td>$T_s$</td>
<td>0.9s</td>
</tr>
<tr>
<td>$K$</td>
<td>1.8</td>
</tr>
<tr>
<td>$T_f$</td>
<td>1.2s</td>
</tr>
<tr>
<td>$\tau$</td>
<td>2.2s</td>
</tr>
</tbody>
</table>

The fuel feed system parameter $T_f$ and $\tau$ can be estimated from a simple one-input-one-output identification procedure for first-order inertia with pure delay model. The results are also shown in table I.
B. Turbine

Steam pressure after the governing stage, outlet of reheater and outlet of intermediate cylinder are measured for steam pressure \( p_g \), \( p_r \), and \( p_c \) in three volumes. Then all the model parameters can be easily estimated by simple identification procedures. The test data referred in the last section are identified. The results are shown as fig. 8 and Table II.

C. Control system

Most parameters in the control systems can be found from the local engineering station and do not need an identification procedure except for the parameters of servo motor. The time constant can also be easily estimated by simple identification procedures. The results are also shown in fig. 8 and Table II.

IV. RESULTS AND DISCUSSION

The CCS model is copied from the local engineering station and its simplified model was added to the identified model shown in the last chapter. To verify the presented model, another test case was carried out. The stepped reference frequency was inputted to the presented model. The simulated responses are compared to the test data as shown in fig. 9.

Fig. 7 Identified model output and its comparison to the measured data in fuel feed model

Fig. 8 Identified model output and its comparison to the measured data in turbine model and control system model

Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Identified value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{H} )</td>
<td>0.26s</td>
</tr>
<tr>
<td>( T_{R} )</td>
<td>18.5s</td>
</tr>
<tr>
<td>( T_{L} )</td>
<td>0.69s</td>
</tr>
<tr>
<td>( T_{I} )</td>
<td>0.26s</td>
</tr>
</tbody>
</table>

Fig. 9 Model verification

The impact of a CCS is also evaluated according to the identified model. The generation unit model is assumed to be island operation. A 5% load drop is simulated on 4 models. The frequency variations are shown in fig. 10 where the first line shows the outputs of the presented full model, the second line shows the outputs of a model without CCS, the third line shows the outputs of a model without CCS and boiler control system models, and the last line shows the outputs of only the turbine and its control system model.

It can be seen from fig. 10 that only the turbine and its control system model get an obvious low overshoot than other three models. Its steady state frequency deviations are also lower than that of a no-CCS case. It means that the single model of turbine and its control system may lead to a safe condition during power system stability analysis. Boiler automatically adjust its fuel feed will improve the stability relative to that without a pressure control logic. The uses of CCS further reduced the dynamic deviations of system frequency as shown as line 1 in fig. 10. The modeling of boiler, boiler control system and CCS will all improved the accuracy relative to the single turbine and its control system model. They should be considered for some dynamic analyses sensitive to the model accuracy.

Fig. 10 Frequency stability based on different models
V. CONCLUSION

In this paper a power plant model with CCS is presented for power system dynamic analysis. Parameters of the model are identified based on test data of a 600 MW coal fired power plant. The simulation results show good accordance with the measurement records. Simulation results on different models show that the single turbine and its control system model is not accurate enough for some purposes. It may lead over-safe stability during a power system frequency analysis. Boiler pressure control system and CCS both will improved the stability of a power system. The models with boiler control system or with both the boiler control system and CCS have obvious dynamic response characters with each other. All the subsystem models should be considered for cases sensitive to the model accuracy.

VI. REFERENCES


VII. BIOGRAPHIES

Lin Gao was born in Liaoning Province in 1981. He is working for his Doctor degree in Xi’an Jiaotong University.

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