DYNAMIC BEHAVIOR OF A COMMERCIAL CFB UNIT – MEASUREMENTS AND RELATED STUDIES

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Abstract – The dynamic test series needed to determine the dynamic characteristics of the plant and validate the model consist of three different tests: a) thermal inertia test, b) storage capacity test and c) load ramp test. The first leads to determine the time response of the combustion and steam generation system, the second one gives an idea on the steam pressure behavior while the third test validates the capacity of the boiler. The first part of the suggested paper introduces the modelling procedure including necessary dynamic tests. It summarizes the results of the test campaign of a coal fired CFB unit, including thermal inertia, storage capacity and load ramp tests. The second part of the proposed paper describes the control design which involves the following two steps: a) determining the best possible operation in response to load change demand via nonlinear model-based optimization and then b) the realization of it based on conventional (feedback, feedforward) control solutions.

INTRODUCTION

The operation of power plants has to face the continuously tightening regulations and satisfy more and more demanding performance requirements; either it is defined by a single customer or an electric grid operator. These extended operation modes involve: a) capability to change load level frequently and in a fast manner within as wide range of load level as possible b) increased operational range by safely (without risking boiler or turbine trip) decreasing the minimum achievable load level, and c) meanwhile satisfying emissions limitations at steady-state operation and during the transient response, too. Circulating fluidized bed (CFB) boilers, see in Figure 1, can play a great role due to their inherent fuel flexibility combusting large variety of fuels and fuel mixtures and the very effective emission reduction possibilities inside the bed. CFB boilers can be incorporated with both drum or once through steam generators allowing high efficiency power generation. (Kovács et al. 2015).

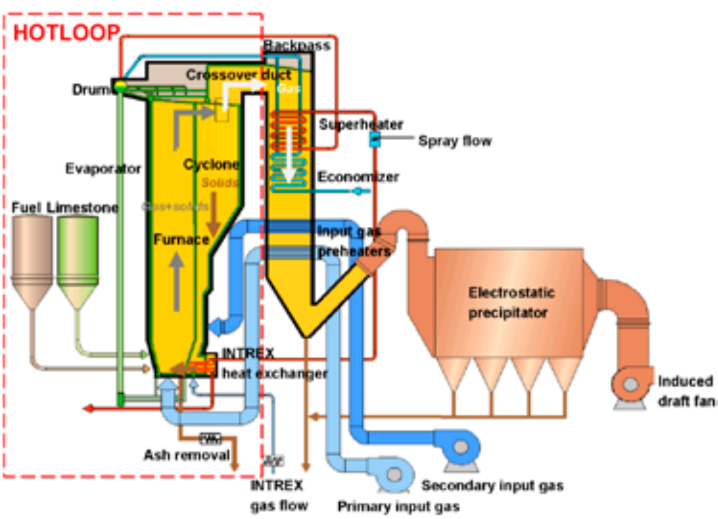

Figure 1 Operation schematic of a CFB boiler.

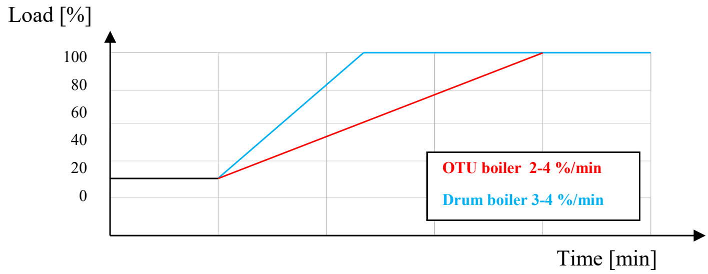

Figure 2 Typical load change capability of different CFB boilers and turbine.

The possible load demand scenario vary in a large scale. Usual load ramps are in the range of 2-4 %MCR/min (percentage of the maximum continuous rate per time period), see Figure 2. However, the requirements are continuously tightening, demand of 10% within 10 sec and maintain it of 30 minutes is frequently seen.

In order to address the abovementioned challenges, the dynamic response of the power plants has to be improved either by design modifications or maximizing the operational potential. Besides satisfying the required generated power, the main steam quality – its temperature and pressure – has to be maintained. It requires solid understanding of the dynamic characteristics of the plant and it has to be taken into account during the design phase. There are several factors determining – as well as limiting – the feasible ramp rate, including:

a) the size of firing system: thermal inertia including heat transfer and energy storage of metals, the minimum and maximum firing power, the rate of change in heating power, fuel quality, furnace size,

b) the size of the steam generation process either drum or once through boiler: energy and steam storage capacity of the evaporator and the drum,

c) the size of the superheater system: storage capacity of the superheater system,

d) the capacity of the water spray system,

e) the capacity of the main steam valve,

f) the dynamics of the turbine-generator (including possible reheating stages) unit,

d) the operation mode – constant or sliding pressure unit, subcritical or supercritical boiler – has also a large influence.

Although the abovementioned properties inherently define the performance boundaries (e.g. the maximum achievable load change ramp, or disturbance rejection), it is not obvious how to achieve those. A proper unit master and local control design is required. The selection of the master control (e.g. boiler- and/or turbine following), the general control philosophy (feedback or feed forward), the utilized process knowledge (conventional PID or model-based control) may help to achieve the limits but can also limit the performance. In order to evaluate the performance quality of the designed control structure, the definition of "best possible controlled performance (BPCP)" is required. The BPCP automatically defines the upper limit of the feasible performance demand; forcing better performance may lead to performance degradation due to hitting hard constraints. It is clear that a firm model of the plant is required.

The current paper summarizes the experience of the Amec Foster Wheeler improving load change performance of the CFB boilers as well as introduces the current control engineering research activities in co-operation with the University of Oulu. The first part of this paper introduces the modelling procedure including necessary dynamic tests. It summarizes the results of the test campaign of a coal fired CFB unit, including thermal inertia, storage capacity and load ramp tests. The second part of the paper describes the control design which involves the following steps: a) determining the best possible operation in response to load change demand via nonlinear model-based optimization and then b) the realization of it based on conventional (feedback, feedforward) control solutions.

DYNAMIC MODELLING

Amec Foster Wheeler Energia Oy utilizes two approaches simulating the performance of steam boilers: a phenomenological modelling and a simplified block- and goal-oriented modelling. Utilizing full construction data, description of all the chemical reactions, thermo-, hydro- and momentum balance equations and the automation system leads to a very accurate but complex model. The model, which is built in Apros simulation environment and extended with an in-house hot-loop model, can be tailored to a specific steam generator. Extending the model with the turbine-generator unit, the balance of plant (BOP) and the unit master control systems, the performance of the complete power plant can be evaluated in various operation cases. Besides normal (steady-state and transient, i.e. load change) operations, different trip and run-back situations can be easily and safely demonstrated. The detailed model also enables to develop and test different control scenarios. The main advantage of such a model is the inherent full static and dynamical features of the plant. The main disadvantage is its complexity, the tremendous data, time and tuning effort needed.

When the goal of modelling is reduced and strictly specified, simple, block-oriented models can be developed. In this systems engineering approach, the process is described by those properties which determine the performance to be analyzed. In case of evaluating specific transient behavior (e.g. planned load changes, response to grid frequency control), those properties are related to thermal inertia and mass-/energy storage capacities. The model can be built around the simplified representation of the dynamic relationship of a steam generator, defined by the 3508 VDI/VDE guideline (VDI 2003), see Figure 3. The model comprises the following relationship: fuel power – steam generation (thermal inertia), steam storage – steam pressure (storage capacity), dynamics of turbo-generator unit (time constants). Those parameters can be approximated from constructional data, from simulation studies of the complex model or by dynamic measurement of existing power plants.

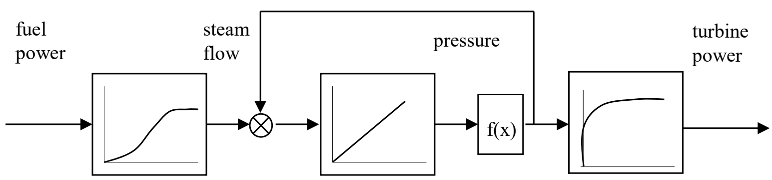

Figure 3 Simplified representation of the dynamic relationships in boiler/turbine process.

DYNAMIC TESTS

The dynamic tests supporting simple block-oriented model development are demonstrated here. The presented data were collected from tests performed in a (sub)bituminous-coal fired CFB drum boiler (equipped with INTREX heat exchanger). The time-schedule for the two standard tests, thermal inertia and storage capacity tests, are illustrated in Figure 4. The thermal inertia tests were completed as step load changes in the thermal load range of 50-100%. The boiler load steps were introduced manually while the main steam pressure and temperature were in auto control mode. The step change ended when main steam mass flow reached new steady-state.

At low-, mid- and high load levels, steam storage capacity tests were additionally performed. A typical scenario is shown in Figure 5; a small change in the main steam pressure was introduced by the steam valve while the combustion rate was kept constant guaranteeing unchanged steady-state values of the steam mass flow. The storage capacity is calculated from the integrated deviation of the steam mass flow.

CONTROL DESIGN

The obtained block-oriented dynamical model (based on VDI/VDE approach) is considered as the basis for further control design. It has two major manipulated variables (MV), the combustion rate and the steam valve position, and two controlled variables (CV), the main steam pressure and the generated turbine/generator load. Performance demands (in form of set point tracking/regulation) against generated power and steam pressure are defined; constraints exist for steam pressure (maximum and minimum limits) and for combustion rate (min/max and ramp rate). The control design has two steps: 1) defining the best possible control performance (BPCP) and 2) its approximation by standard master control structure. The BPCP will be determined as follows:

first it is evaluated whether the load requirement can be satisfied within the performance limitations (hard constraints) and if solution is found the steam pressure performance will be further tuned in order to minimize its deviation from the set point.

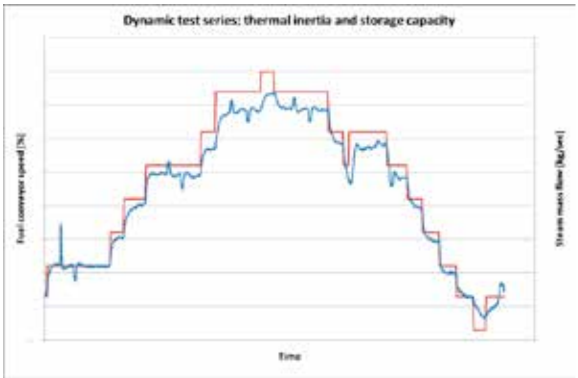

Figure 4 Dynamic test series.

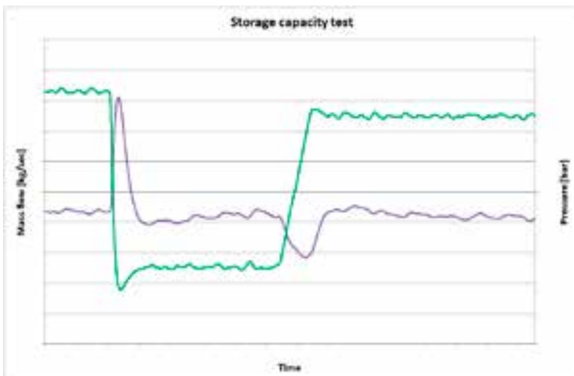

Figure 5 Storage capacity test.

BPCP PROBLEM FORMULATION

The discrete time mathematical model of the system has the following form

$$\begin{aligned} x_{k+1} &= f(x_k, u_k) \\ y_k &= C x_k \end{aligned}, \quad k = 0,1,\ldots \tag{1}$$

subject to

$$\begin{aligned} &A_0\, u_k \le b_0 \\ &A_1\, u_k + A_2 u_{k-1} \le b_2 \\ &A_{3,k}\, y_k \le b_{3,k} \end{aligned} \tag{2}$$

where $x_k \in R^n$ is the system's state vector, $u_k \in R^2$ denotes the vector of manipulated inputs and $y_k \in R^2$ is the output at time instant k. The state is augmented by a subsystem describing a transport delay related to system inputs. Consequently the dimension of the state n depends on the time discretization.

Given the system model, initial condition x_0 and operational constraints, find an input trajectory $\{ u_0, u_1, \ldots \}$ such that the system's output $\{ y_1, y_2, \ldots \}$ tracks a reference trajectory $\{ r_1, r_2, \ldots \}$.

BPCP PROBLEM SOLUTION

The outlined problem requires trajectory tracking in a two dimensions. In such case a highly nontrivial problem related to the qualification of tracking performance is encountered. Given an input trajectory, the tracking performance aims to measure how well the corresponding output trajectory approaches the reference trajectory usually by quantifying the "distance" between the two trajectories. The tracking performance makes it possible to distinguish between the input trajectories and to formulate a meaningful optimization problem seeking for an input which provides the minimal distance between the corresponding output and reference trajectories.

The development of such a distance measure is a nontrivial task originating from the fact that in many cases it is not easy to express the exact physical requirements by parametric functions. To overcome the difficulties here the method of preference ordering is used. Preference ordering is based on the requirement that regarding tracking performance some components of the output have higher importance than the others. In our particular case the observed output is two dimensional which leads to a two level approach considering prioritization. First, level one aims to maximize the tracking performance related to the first component of the output vector $y_{1,k}$ which is going to be referred to as preferred output while in level two the tracking performance of the second component $y_{2,k}$ (marked as non-preferred output) is optimized subject to a tracking performance constraint given by level one. In both levels finite horizon optimization problems (formulated as quadratic programs) are solved using N step lookahead. Using this, the two level approach is as follows:

Level one: choose N, define the tracking time horizon T. At each time instant k

1. Linearize the system dynamics (1) around $(x_k, 0)$ giving the linearized dynamics $x_{\tau+1} = A_k x_\tau + B_k u_\tau + w_k$, $y_\tau = C x_\tau$.
2. Compute $\{u_\tau^\star, u_{\tau+1}^\star, \dots, u_N^\star\} = \arg\min \sum_{\tau=k}^{k+N} \left(y_{1,\tau+1} - r_{1,\tau+1}\right)^2$ subject to $x_{\tau+1} = A_k x_\tau + B_k u_\tau + w_\tau$, $y_\tau = C x_\tau$ and constraint system (2).
3. Apply the control action $\bar{u}_k = u_\tau^\star$ to the (nonlinear) system (1).

Level one provides the input trajectory $\{\bar{u}_0, \bar{u}_1, \dots, \bar{u}_T\}$ which minimizes the tracking error between the preferred output and its reference trajectory in a least squares sense under the outlined approximation scheme. Let $\{\bar{y}_{1,1}, \bar{y}_{1,2}, \dots, \bar{y}_{1,T+1}\}$ denote the corresponding trajectory of the preferred output. As level one revealed there exists an input trajectory which is "optimal" considering the reference tracking of the preferred output. Using this level two aims to improve the tracking of the non-preferred output so that the tracking of the preferred output is kept "optimal". With that said, the following algorithm is implemented:

Level two: At each time instant k

1. Linearize the system dynamics (1) around $(x_k, 0)$ giving the linearized dynamics $x_{\tau+1} = A_k x_\tau + B_k u_\tau + w_k$, $y_\tau = C\, x_\tau$.
2. Compute $\{u_\tau^\star, u_{\tau+1}^\star, \dots, u_N^\star\} = \arg\min \sum_{\tau=k}^{k+N} \left(y_{2,\tau+1} - r_{2,\tau+1}\right)^2$ subject to $x_{\tau+1} = A_k x_\tau + B_k u_\tau + w_\tau$, $y_\tau = C x_\tau$, $y_{1,\tau+1} = \bar{y}_{1,\tau+1}$ and constraint system (2).
3. Apply the control action $\tilde{u}_k = u_\tau^\star$ to the (nonlinear) system (1).

As a result the "optimal" control sequence $\{\tilde{u}_0, \tilde{u}_1, \dots, \bar{u}_T\}$ is obtained which is considered as the solution to the tracking problem under the outlined approximation scheme. Further development of the method is presented in Selek (2017).

LOAD RAMP SIMULATION

The load change performance of the CFB plant is demonstrated here. The BPCP is calculated for a 40% load change from 50% to 90% MCR with a ramp of 4%MCR/min. Boiler following control mode is selected; the MV-CV pairs are the boiler load – steam pressure and the valve position – turbine load. Both the turbine load and the boiler load are defined by the accompanying steam mass flow. The BCPC is shown in Figure 6 and its approximation with feedback PID controllers in Figure 7. The MIMO (multi-input-multi-output) PID controlled process performed rather similarly as it was predicted by the BPCP.

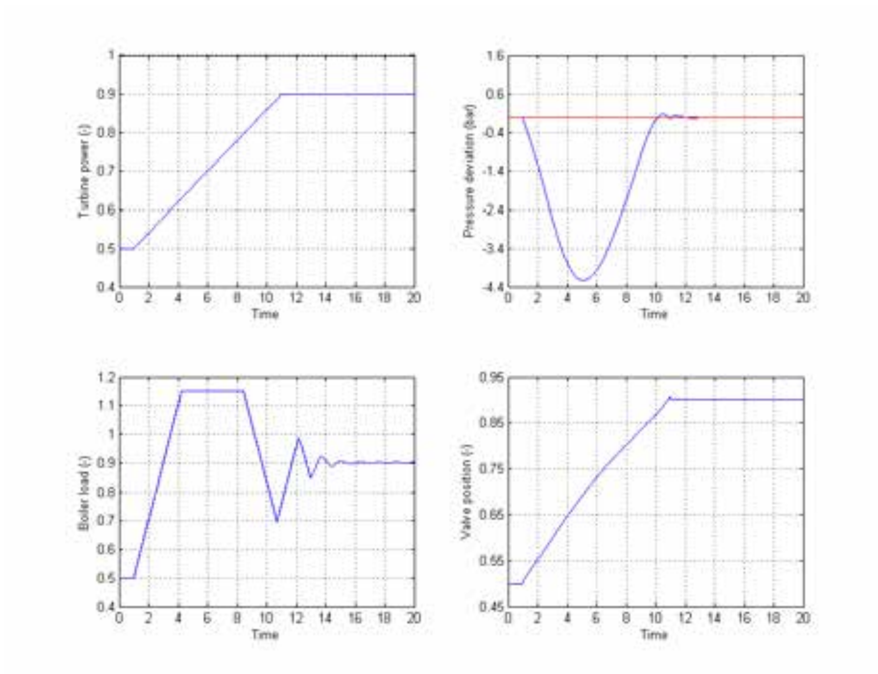

Figure 6 BPCP with optimized main steam pressure behavior.

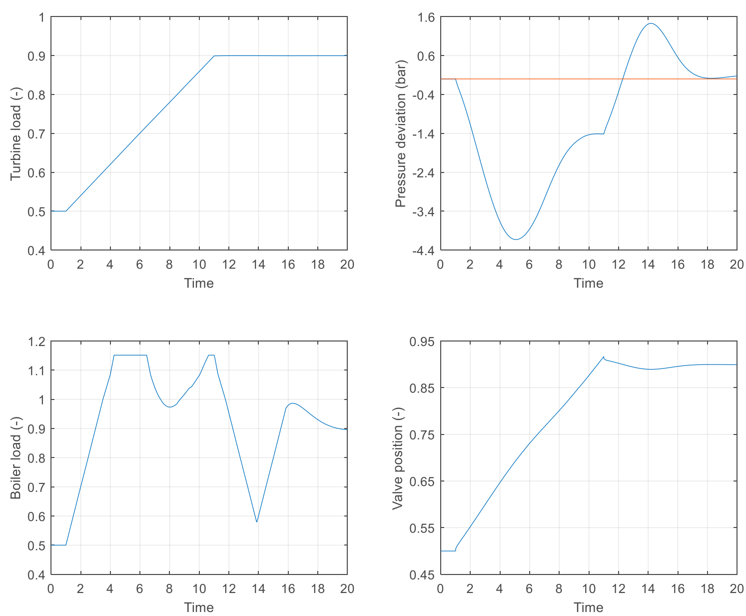

Figure 7 Approximation of the BPCP with two PID feedback controllers.

CONCLUSION

The paper summarized several dynamic modelling, -testing and control design related design topics. These tasks shall be performed in an iterative manner in order to improve the model applicable to next new design and to enable even tighter control design and thus performance. A new element was introduced into this chain, the BPCP evaluation. The main advantage of utilizing the BPCP approach is that it can declare in a fast manner whether the required set point trajectory (here turbine load ramp) is feasible without any effort to tune the MIMO PID controlled process. Further, in case of feasible load ramp, it defines the best possible performance for the pressure. In the given example, the turbine load demand was very strict, no error was allowed during ramping. The definition of demands and constraints are very flexible in the BPCP optimization routine. Also, the optimization engine inside BPCP approach can be applied to any other control task. At unit master level, better balance between the boiler and turbine sections can be achieved providing background for increasing ramp rates and more accurate pressure control.

REFERENCES

Kovács, J., Kettunen, A., Ikonen, E., Hultgren, M., Niva, L. 2015 Addressing the challenge of fast load change requirements, 22nd International Conference on Fluidised Bed Conversion, Turku, Finland.

Selek, I., Kovács, J. 2017. A robust tube MPC approach for the analysis of load response of power plants. 9th European Nonlinear Dynamics Conference. 25-30 June, Budapest, Hungary

VDI-Standard 2003. VDI/VDE 3508. Unit Control of Thermal Power Stations. The Association of German Engineers.