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Gain-Scheduled Control of a Fossil-Fired Power Plant Boiler

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Abstract

In this paper the objective is to optimize the control of a coal fired 250 MW power plant boiler. The conventional control system is supplemented with a multivariable optimizing controller operating in parallel with the conventional control system. Due to the strong dependence of the gains and dynamics upon the load, it is beneficial to consider a gain-scheduling control approach. Optimization using complex-μ synthesis results in unstable LTI controllers in some operating points of the boiler. A recent gain-scheduling approach allowing for unstable fixed LTI controllers is applied. Gain-scheduling which interpolates between unstable controllers is not allowed using traditional schemes. The results show that a considerable optimization of the conventional controlled system is obtainable. Also the gain-scheduled optimizing controller is seen to have a superior performance compared to the fixed LTI optimizing controllers operating alone.

Keywords: Gain-Scheduling, Power Plant Control, Unstable Controllers, Transfer Function Interpolation.

1 Introduction

The electric power production units in Denmark can be divided into the following two categories. The units within the first category are not available for load control for the central load dispatch centers. These units are e.g. wind turbines and small combined heat and power plants. The units within the second category are large coal or gas fired power plants which are available for load control. Within the recent years the production rate from the first category has increased. In 1980 the ratio between the categories was 1:4 and in 1990 this ratio had increased to 2:3 and is expected to increase further in the future. Therefore the demand on the load following capability of the units within the second category increases. This category comprises newer gas-fired plants with high efficiency and lower efficiency older coal-fired plants. To achieve a high total efficiency the newer plants normally operate at maximum load implying that the older boilers, mainly 250MW coal-fired Benson boilers, are used for taking care of the load changes. This explains the need for dealing with the improvement of the load following capability of older power plant units.

Experience shows that the conventional control system is a primary limiting factor for the maximum allowable load gradient. One of the inputs to the conventional control system is the load reference which is always given as a piece-wise linear signal. The load gradient is the slope of this reference signal with a typical maximum of 2% of nominal load per minute. A gradient that exceeds the maximum allowable value results in unacceptable steam temperature and pressure variations. These variations occur despite the fact that none of the boiler input signals are saturated indicating that a better control may be achievable. A characteristic of the boiler is that the gains and dynamics are strongly dependent upon the load complicating an optimization of the conventional control system.

For safety reasons it is desirable to retain the conventional control system. An optimizing multivariable controller is coupled in parallel with the conventional control system. The conventional control system allows for a safe commissioning and switching between automatic mode and manual mode. The primary purpose of the optimizing controller is to take care of cross couplings. This architecture has been sug-

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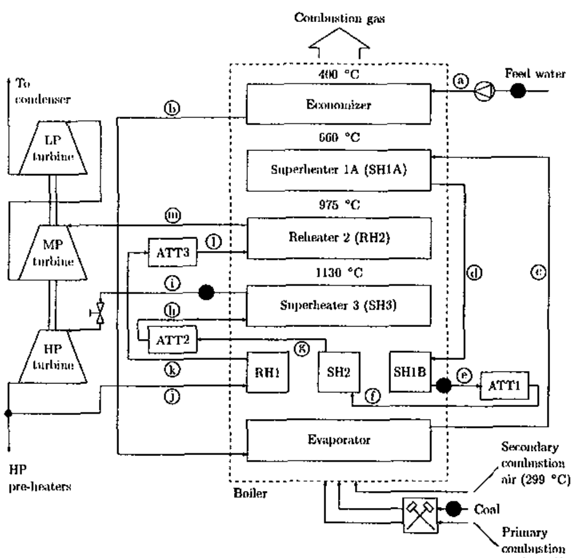
gested and applied in [Han93] and in [NA81] and has furthermore been applied in [Mor97] and [Han98]. The gains and dynamics of the boiler depend upon the operating point suggesting the need for considering a gain-scheduled controller design. In this paper a gain-scheduling approach that allows for internally unstable LTI controllers is applied for the optimization of the conventional control of an existing 250MW fossil-fired Benson boiler.

2 Problem Formulation

The power plant boiler under consideration is the boiler in unit 2 (SVS2) in the power plant I/S SKÆRBÆKVÆRKET situated at Skærbæk, Denmark. SVS2 is a once-through 250MW coal-fired Benson boiler. The feedwater flow is used for controlling the superheater steam temperature T_{sh} and the fuel flow is used for controlling the superheater steam pressure P_{sh}. Figure 1 shows the steam flow and combustion air/gas flow for the SVS2 boiler. The filled circles "●" in the figure shows: At (a): Here the controllable feedwater input enters. At (i): Here P_{sh} is measured. At (e): Here T_{sh} is measured. At the bottom it shows where the controllable fuel input enters. The input-output data, that has been available for building the LTI models used in this paper, are measurements from the SVS2 boiler unit at 187MW and at 240MW.



(a) Temperature: 263 °C , Pressure: 216 bar
(b) Temperature: 360 °C , Pressure: 212 bar
(c) Temperature: 375 °C , Pressure: 198 bar
(d) Temperature: 437 °C , Pressure: 194 bar
(e) Temperature: 462 °C , Pressure: 192 bar
(f) Temperature: 445 °C , Pressure: 191 bar
(g) Temperature: 468 °C , Pressure: 188 bar
(h) Temperature: 458 °C , Pressure: 187 bar
(i) Temperature: 545 °C , Pressure: 185 bar
(j) Temperature: 354 °C , Pressure: 42.4 bar
(k) Temperature: 450 °C , Pressure: 41.2 bar
(l) Temperature: 417 °C , Pressure: 40.8 bar
(m) Temperature: 545 °C , Pressure: 40 bar

Figure 1: The steam flow and combustion air/gas flow. The temperatures and pressures are steady state values, valid at 100% load. (ATT) is a spray attemporator.

2.1 LTI Models

LTI Models have been computed for the operating points 187MW and 240MW. Recall that the optimizing MIMO controller is to be connected in parallel with the conventional SISO controllers. Consequently the models needed as basis for the MIMO controller design describe the conventionally *controlled* plant - that is, both the plant and the conventional control system. As a consequence of this special architecture the control object seen from the optimizing MIMO controller is open-loop stable. The models are 10th order fully parameterized LTI state-space models with 2 controllable inputs (a signal that is added to the feedwater control signal and a signal that is added to the fuel control signal) and a measurable disturbance input (the load). The controlled outputs are the superheater steam pressure error e_{Psh} and the superheater steam temperature error e_{Tsh}. Note that the load acts both as a measurable disturbance and as the gain-scheduling parameter. The model parameters have been computed using the recent subspace identification algorithm N4SID [vOdM94].

2.2 Controller Design Objectives

The critical process variables are the superheater steam pressure P_{sh} and in particular the superheater steam temperature T_{sh}. The controllable inputs are the feedwater and fuel flow and the dominating disturbances occurring in practice are load changes and disturbances on the fuel input primarily due to activating and deactivating coal mills. The objective for the LTI controller design for the two fixed operating points 187MW and 240MW is to *reduce the variations in T_{sh} due to load disturbances and fuel input disturbances without deteriorating the control of P_{sh}*.

Complex μ synthesis using D-K iteration has been applied for computing the LTI controllers at the two fixed operating points. Standard input multiplicative and standard output multiplicative uncertainty specifications were chosen. Experience shows that, as the controllers are tuned towards a good rejection of the load and fuel input disturbances, the controllers become internally unstable. This fact complicates the gain-scheduling problem. Therefore it is necessary to consider a gain-scheduling approach that allows the fixed LTI controllers to be internally unstable.

3 Method

From a gain-scheduling point of view, the present application offers special challenges in the following two respects:

1. The controllers at each operating point have open-loop unstable transfer functions. This means that a convex combination of the controllers will never offer a stable closed loop system in the whole operating range and, hence, a more sophisticated controller architecture is required.
2. The plant models at each operating point are obtained as pure black box models. This means that there is no natural parameterization of the plant parameters which offers a natural link to any gain-scheduling variable.

One approach to tackle these two problems is a new gain-scheduling procedure which has been presented in [SAPH98]. This method takes a behavioral approach to gain-scheduling and interpolates trajectories of the involved differential equations rather than the parameters of these equations. Moreover, the method requires the plant models to be stable (as they are in this paper) but allows for unstable controllers (as is the case here). The method interpolates models for two operating points by interpolating their transfer functions as $P_\alpha(s) = (1-\alpha)P_0(s) + \alpha P_1(s)$, $\alpha \in (0,1)$ where P_i, $i = 0,1$ are the models in two operating points, and α is a gain-scheduling parameter, which in this paper is taken to be the actual load. This approach to interpolation is non-standard but well motivated from a behavioral point of view.

The main idea in [SAPH98] is a model reference like structure which is depicted in Figure 2, which is also the method applied in this paper. The method is based on the following result.

Theorem 1 *Assume that $P_i(s)$, $i = 0,1$ are two (open loop) internally stable systems, and $K_i(s)$, $i = 0,1$ are two (possibly unstable) controllers, such that $K_i(s)$ stabilize $P_i(s)$, $i = 0,1$, and the closed loop systems are well-posed. Consider the following class of systems*

$$P_\alpha(s) = (1-\alpha)P_0(s) + \alpha P_1(s), \quad \alpha \in (0,1)$$

and define

$$M_\alpha(s) = \begin{pmatrix} 0 & (1-\alpha)I & \alpha I \\ I & \left(1-(1-\alpha)^2\right)P_0(s) - \alpha(1-\alpha)P_1(s) & -\alpha(1-\alpha)P_0(s) - \alpha P_1(s) \\ I & -(1-\alpha)^2 P_0(s) - \alpha(1-\alpha)P_1(s) & -\alpha(1-\alpha)P_0(s) + \left(1-\alpha^2\right)P_1(s) \end{pmatrix}$$

and

$$\bar{K}(s) = \begin{pmatrix} K_0(s) & 0 \\ 0 & K_1(s) \end{pmatrix}$$

Then the following controller

$$K_\alpha(s) = \mathcal{F}_\ell(M_\alpha(s), \bar{K}(s))$$

is internally stabilizing for any $P_\alpha(s)$, $\alpha \in (0,1)$.

A possible implementation for $K_\alpha(s)$ is shown in Figure 2.

The method in Theorem 1 is not guaranteed to work under arbitrarily fast transitions between operating points, but for the present application the transition rate is not critical.

4 Results

It was possible to obtain complex μ LTI controllers with good disturbance rejection properties at their respective operating points. The tuning towards good disturbance rejection however led to unstable controllers. For such controllers, the associated plant models are only guaranteed to stabilize the controllers in the respective operating points for which they were designed. When using the gain-scheduling approach described in section 3 the (possibly unstable) controllers are stabilized in the whole operating region by the plant models for which

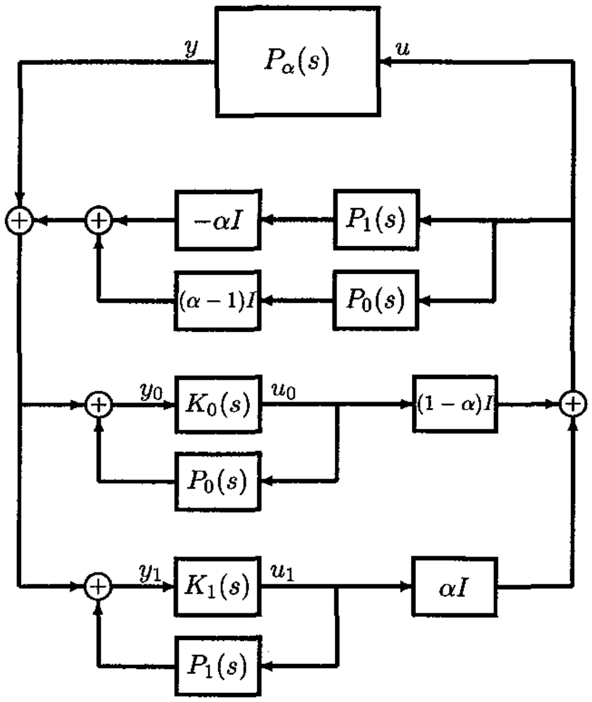


Figure 2: General gain scheduling structure for unstable controllers

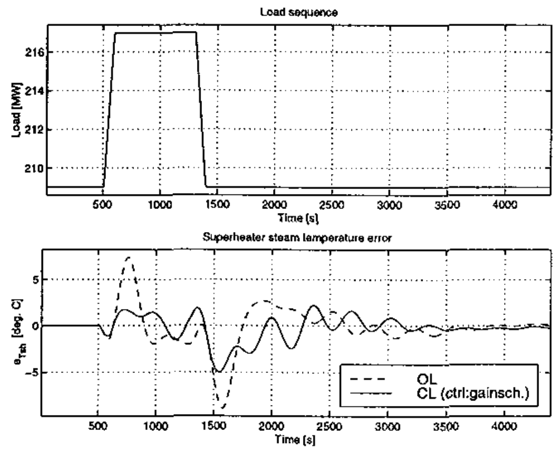


Figure 3: Load sequence and resulting open-loop and gain-scheduled closed-loop temperature errors.

they were designed. In the following it is assumed that the plant model can be approximated as an interpolation between the 187MW and 240MW models as shown above.

In Figure 3 a load sequence in the middle of the scheduling interval is shown together with the resulting errors for T_{sh} in open-loop and in closed-loop using the suggested gain-scheduling controller. It is clearly seen that a significant improvement is obtained using the gain-scheduled controller. Note, that each of the 2 fixed LTI controllers applied alone leads to unstable closed-loop systems in this part of the scheduling interval. As an example of the behavior at the two endpoints Figure 4 shows the situation at the lower end of the scheduling interval. Note, that the closed-loop system resulting from applying the LTI controller designed at 187MW becomes unstable when the load is increased to 195MW. In contrast, the closed-loop system resulting from applying the gain-scheduled controller remains stable and a significant improvement is obtained compared to the open-loop case.

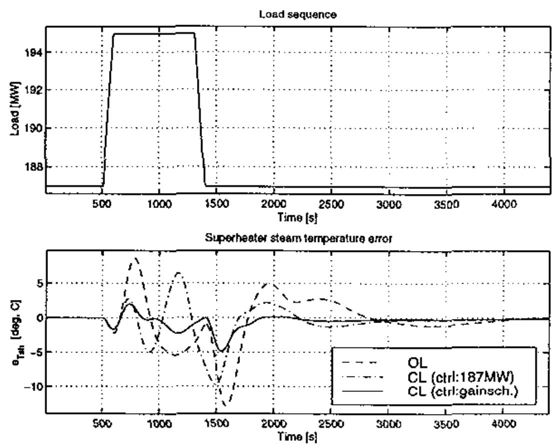


Figure 4: Load sequence and resulting open-loop, fixed (187MW) closed-loop and gain-scheduled closed-loop temperature errors.

5 Conclusions

A safe architecture combining a conventional control system based on SISO controllers with an optimizing multivariable controller was used as basis for the optimization of a 250MW coal-fired power plant boiler. The gains and dynamics of the boiler depend upon the operating point (the load) indicating the need for considering gain-scheduling. A recent approach for gain-scheduling that allows for unstable fixed LTI controllers was applied. Significant improvement of the control of the critical superheater steam temperature were obtained in the examined scheduling interval retaining an acceptable control of the superheater steam pressure (not shown). This paper represents a coherent design strategy that is well-suited for industrial systems with gains and dynamics that depend strongly upon a time-varying parameter.

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