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OPTIMIZATION OF BOILER CONTROL TO IMPROVE THE LOAD-FOLLOWING CAPABILITY OF POWER-PLANT UNITS

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Abstract: The capability to perform fast load changes has been an important issue in the power market, and will become increasingly more so due to the incresing commercialisation of the European power market. An optimizing control system for improving the load-following capability of power-plant units has therefore been developed. The system is implemented as a complement, producing control signals to be added to those of the existing boiler control system, a concept which has various practical advantages in terms of implementation and commissioning. The optimizing control system takes account of the multivariable and load-dependent nonlinear characteristics of the boiler process, as a scheduled LQG controller with feedforward action is utilized. The LQG controller improves the control of critical process variables, making it possible to increase the load-following capability of a specific plant. Field tests on a 265 MW coal-fired power-plant unit reveals that the maximum allowable load gradient that can be imposed on the plant, can be increased from 4 MW/min. to 8 MW/min.

Keywords: Multivariable control, LQG control, feedforward control, feedback control, scheduling algorithms, optimization, power-station control, boilers.

1. INTRODUCTION

In Denmark during recent years, the number of production units such as wind turbines and small combined heat and power plants has taken a climb upwards. However, the electric power produced by these units is not available for load control by the central load dispatch centre. In the western part of Denmark, supplied by ELSAM, the ratio between the electric power produced by units available for the central load dispatch centre and units that are not available was about 4:1 in 1980. In 1990 this ratio had decreased to 3:2, and a further decrease is expected in the future. This means that, for instance in the case of forced power-plant outages or significant changes in wind-turbine production, there is an increased demand on the load-following capability of the other units.

Recently, Denmark's neighbouring countries' electricity sectors in Norway, Sweden, Finland and Great Britain have gone from a monopoly setting to an open-market situation. In the not too distant future Denmark is expected to undergo the same development, which will most likely turn the load-following capability into a commercial commodity.

These issues are the reasons for developing an optimizing boiler-control system, with the objective of improving the load-following capability of power-plant units.

For the last 20-30 years, control-system manufacturers of power-plant applications have carried out extensive developments, thus typically contributing to an improved load-following capability for recent power-plant units of about 4%/min. (% of full load power production) of coal-fired units, and about 8%/min. for oil- and gas-fired units, whereas the rates of power-plant units from the 1970s are somewhat lower. The newer units will mostly be operated at full load because of their heigher efficiency, whereas the older ones will often be left to handle the load-following demand. This explains the need to address the problem of improving the load-following capability of the older power-plant units.

The boiler will often pose a limit on the load-following capability in a fossil-fired power plant because - compared to the turbine and generator system - it exhibits slow dynamics. The boiler itself is characterized as being multivariable, since most of the inputs interact with most of the outputs, and as being nonlinear, for instance in the sense that the dynamics are influenced by the actual operating point.

Traditionally, a boiler-control system is based on a number of SISO (single/input, single/output) control loops, utilizing traditional gain-scheduling techniques in order to cope with the nonlinear dynamics. Designing and tuning the SISO control loops of a multivariable process will often be tedious tasks, since the control loops interact with one another, leading to a suboptimal result. Multivariable nonlinear control offers a way of reaching the goal referred to above.

This paper discusses how to design a control system that is able to improve the load-following capabilty of older power-plant units by taking account for the characteristics mentioned above. In order to cope with the multivariability, an LQG controller (Linear Quadratic Gaussian) was chosen. To take account of the nonlinear dynamics, the LQG controller was scheduled according to the boiler load demand. Further feedforward action from the boiler load demand was included in the LQG controller, since it was desired to reduce the disturbances to this demand.

Important work in this field has been reported by Nakamura *et al.* (1989), where an approach of using multivariable control techniques to improve the load-following capability of a power-plant unit has been demonstrated. In (Borsi *et al.,* 1978) decoupling control has successfully been used to improve temperature/pressure interaction for once-through boilers. Other related work has been treated in (Pedersen *et al.,* 1996) and (Nomura *et al.,* 1988).

2. DEVELOPMENT AND VALIDATION OF A DYNAMIC SIMULATION MODEL

The control concept is intended for a typical Danish 250 MW coal-fired power plant unit from the 1970s in the ELSAM area. SKÆRBÆKVÆRKET Unit 2 (SVS2) is a representative unit of this kind, and was therefore used as a test case.

The boiler is a once-through boiler with the heating surfaces arranged as illustrated in Fig. 1.

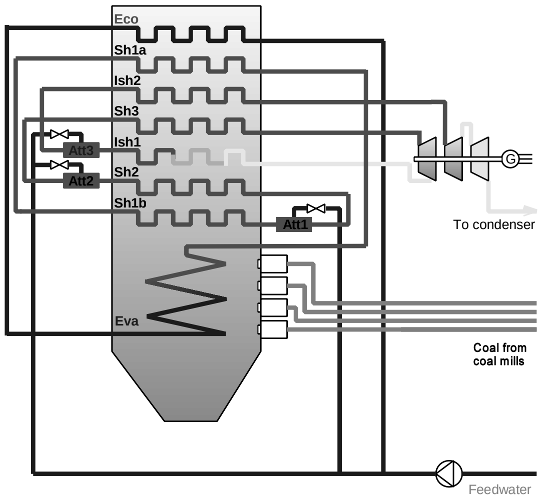

Fig. 1. Once-through boiler, turbines and adjoining components at SVS2.

The existing boiler-control system is designed so that the steam temperature before attemperator 1 is feedback controlled by the feedwater pumps. The live steam pressure is in the boiler-following-turbine operational mode feedback controlled by the firing rate, and with the electrical output feedback controlled by the turbine governor. Furthermore, there is a decoupling from the steam pressure to the feedwater pumps, letting the feedwater pumps help retain the main steam pressure. The superheater steam temperature control is a model-based concept. Feedforward compensation is present from the boiler load demand to the feedwater and fuel flow, and to the turbine governor.

For the purpose of facilitating the development of the optimizing control system, a dynamic simulation model has been developed. The dynamic simulation model of the relevant part of SVS2 (SVS2 Simulator), shown in Fig. 1, has been developed using Framatome Technology's Modular Modelling System (MMS) - a simulation tool designed for the dynamic simulation of nuclear and fossil-fired power plants. The numerical solutions are found using the Advanced Continuous Simulation Language (ACSL).

The SVS2 Simulator has been extensively validated, including static validation, open-loop validation (controllers in manual mode), closed-loop validation (controllers in automatic mode) and through comparisons between simulation results and actual plant data. Examples of the latter, where the responses of the live steam pressure, p_{sh3}, and the steam temperature at the outlet of superheater 1b, T_{sh1b}, are compared, are shown in Fig. 2 and 3. In this comparison, a step change is added to the fuel flow. It can be seen that the responses from the SVS2 Simulator reflect the process dynamics quite well, although the real process is disturbed by minor oscilations that are not present in the simulations.

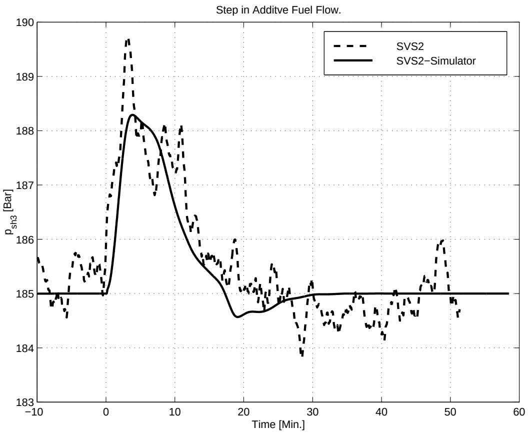

Fig. 2. Comparison between live steam pressure, p_{sh3}, from SVS2 and SVS2 Simulator for a step in additive fuel flow.

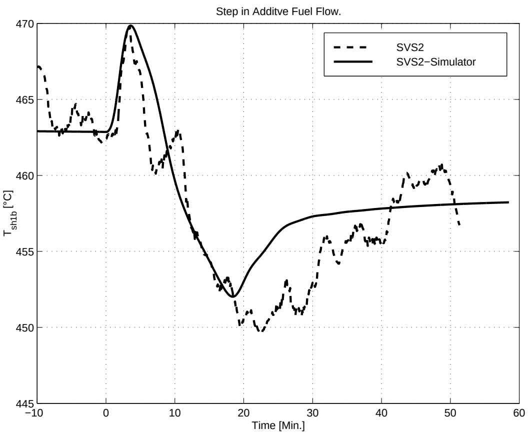

Fig. 3. Comparison between steam temperature T_{sh1b} from SVS2 and SVS2 Simulator for a step in additive fuel flow.

From the validations, it has been concluded that the SVS2 Simulator reflects the process dynamics in a satisfactory manner, so that the initial control concept development can be performed on the dynamic simulation model.

For further information about the SVS2 Simulator refer to (Mortensen, 1997) and (Mortensen *et al.*, (1997).

3. CONTROL STRATEGY

Firstly, the general control strategy will be addressed. Then the LQG controller and the extension to include feedforward action is described. Further, the scheduling of the LQG controller is addressed, and finally, the more specific control strategy for SVS2 is discussed.

3.1. General control strategy

The objective was to improve the load-following capability of existing power-plant units. During fast load changes, the major problem is to keep certain critical variables (e.g., steam temperatures and steam pressure) within predefined limits, as too-large deviations will seriously affect the lifetime of the components. One way of improving the load-following capability of power plants is to improve the control of these critical variables.

In order to increase the robustness and facilitate commissioning and switching between automatic and manual modes, the control system has been designed as a complement to the existing boiler-control system. Fig. 4 shows how the optimizing LQG controller is connected to the existing process.

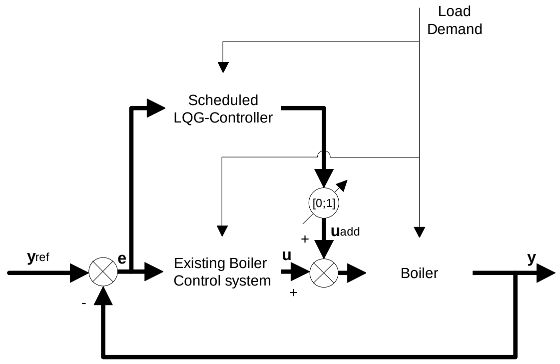

Fig. 4. Scheduled LQG controller with feedforward action from load-demand signal, as a complement to an existing boiler control system.

It can be seen from the figure that the optimizing LQG controller calculates an additive control signal from the control errors, $\boldsymbol{e}$, and from the load demand, which is added to the control signal from the existing boiler-control system. The process to be controlled by the optimizing controller comprises the boiler as well as the existing boiler-control system. The additive control signal, $\boldsymbol{u}_{add}$, can be weighted between 0 and 100%, which facilitates commissioning and switching between the automatic and manual operating modes. When the control error is $\boldsymbol{0}$ and the load demand is constant, the additive control signal is $\boldsymbol{0}$, because no integral action is included in the optimizing controller (this is normally present in the existing boiler control system). When a control error exists, or when a load change is imposed on the boiler, the optimizing controller will be active.

3.2 LQG Controller

The problem of finding the control law of a linear state-space system, where the states are directly measurable, can be solved by formulating a performance index to be minimized. This is done by means of a weighted quadratic function of the states and the control signal. Minimizing this function results in an optimal linear controller known as the Linear Quadratic Regulator (LQR). When stochastic perturbations are considered, the Linear Quadratic Gaussian Regulator (LQG) is obtained. In this case the states must also be estimated.

The state-space model of the system to be controlled is:

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{w}(k) \\ \boldsymbol{y}(k) &= \boldsymbol{C}\boldsymbol{x}(k) + \boldsymbol{v}(k) \end{aligned} \tag{1}$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{u}$ the input vector and $\boldsymbol{y}$ the output vector. The process noise $\boldsymbol{w}$(k) and the measurement noise $\boldsymbol{v}$(k) are assumed to be sequences of independent random variables with zero mean values and covariances:

$$\begin{aligned} &E[\boldsymbol{w}(k)] = \boldsymbol{0}, \qquad E[\boldsymbol{w}(k)\boldsymbol{w}^T(k)] = \boldsymbol{R}_w, \\ &E[\boldsymbol{v}(k)] = \boldsymbol{0}, \qquad E[\boldsymbol{v}(k)\boldsymbol{v}^T(k)] = \boldsymbol{R}_v, \\ &\qquad\qquad\qquad\quad E[\boldsymbol{w}(k)\boldsymbol{v}^T(k)] = \boldsymbol{0}. \end{aligned} \tag{2}$$

According to the separation theorem (cf. (Isermann 1989)) the design of the LQG controller can be divided into two parts, one concerned with an optimal control problem, and one concerned with an optimal filtering problem. These two issues will be described below.

Optimal control. The performance index in the optimal control problem is defined as:

$$I = E[\sum_{k=0}^{N} \boldsymbol{x}^T(k)\boldsymbol{Q}_1\boldsymbol{x}(k) + \boldsymbol{u}^T(k)\boldsymbol{Q}_2\boldsymbol{u}(k)] \tag{3}$$

where $\boldsymbol{Q}_{1,}$ which is positive definite, and $\boldsymbol{Q}_{2,}$ which is positive semidefinite, are the weight matrices used for tuning the controller.

The linear state feedback controller given by:

$$\boldsymbol{u}(k) = -\boldsymbol{L}\boldsymbol{x}(k) \tag{4}$$

which minimizes the performance index. This is calculated by (Isermann 1989):

$$\boldsymbol{L} = (\boldsymbol{Q}_2 + \boldsymbol{B}^T\boldsymbol{S}\boldsymbol{B})^{-1}\boldsymbol{B}^T\boldsymbol{S}\boldsymbol{A} \tag{5}$$

where $\boldsymbol{S}$ is given as the stationary solution to the discrete Riccati matrix equation:

$$\boldsymbol{S} = \boldsymbol{Q}_1 + \boldsymbol{A}^T\boldsymbol{S}\boldsymbol{A} - \boldsymbol{A}^T\boldsymbol{S}\boldsymbol{B}(\boldsymbol{Q}_2 + \boldsymbol{B}^T\boldsymbol{S}\boldsymbol{B})^{-1}\boldsymbol{B}^T\boldsymbol{S}\boldsymbol{A}. \tag{6}$$

Optimal filtering. The optimal filtering problem can be solved using the Kalman filter:

$$\begin{aligned} \hat{\boldsymbol{x}}(k+1) &= \boldsymbol{A}\hat{\boldsymbol{x}}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{K}(y(k) - \boldsymbol{C}\hat{\boldsymbol{x}}(k)) \\ \hat{y}(k) &= \boldsymbol{C}\hat{\boldsymbol{x}}(k) \end{aligned} \tag{7}$$

where $\hat{\boldsymbol{x}}$ is the estimated state and $\boldsymbol{K}$ the Kalman gain. The Kalman gain $\boldsymbol{K}$ can be calculated as (Söderström 1994):

$$\boldsymbol{K} = \boldsymbol{A}\boldsymbol{P}\boldsymbol{C}^T(\boldsymbol{C}\boldsymbol{P}\boldsymbol{C}^T + \boldsymbol{R}_v)^{-1} \tag{8}$$

where $\boldsymbol{P}$ is the stationary solution to the discrete Riccati matrix equation:

$$\boldsymbol{P} = \boldsymbol{R}_w + \boldsymbol{A}\boldsymbol{P}\boldsymbol{A}^T - \boldsymbol{A}\boldsymbol{P}\boldsymbol{C}^T(\boldsymbol{C}\boldsymbol{P}\boldsymbol{C}^T + \boldsymbol{R}_v)^{-1}\boldsymbol{C}\boldsymbol{P}\boldsymbol{A}^T. \tag{9}$$

According to the separation theorem, the state estimate $\hat{\boldsymbol{x}}$ can be used in the control law given in eq. (4).

Another approach is to identify a model in the directly parameterized innovations form, where the Kalman gain is estimated together with the model parameters in the system identification:

$$\begin{aligned} \hat{\boldsymbol{x}}(k+1) &= \boldsymbol{A}\hat{\boldsymbol{x}}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{K}\boldsymbol{e}(k) \\ \boldsymbol{y}(k) &= \boldsymbol{C}\hat{\boldsymbol{x}}(k) + \boldsymbol{e}(k). \end{aligned} \tag{10}$$

It can be shown that (1) and (10) are statistically equivalent descriptions (Van Overschee *et al* (1996)). Since there is often no available knowledge about the covariances in eq. (2), this method is a good alternative.

3.3 Feedforward action with an LQG controller

A state-space model of the system to be controlled including a measurable disturbance $\boldsymbol{d}(k)$, is:

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{B}_d\boldsymbol{d}(k) + \boldsymbol{w}(k) \\ \boldsymbol{y}(k) &= \boldsymbol{C}\boldsymbol{x}(k) + \boldsymbol{v}(k). \end{aligned} \tag{11}$$

A typical disturbance signal $\boldsymbol{d}(k)$ for the plant can be described by the autonomous (no inputs) state-space model:

$$\begin{aligned} \boldsymbol{x}_d(k+1) &= \boldsymbol{A}_d\boldsymbol{x}_d(k) \\ \boldsymbol{d}(k) &= \boldsymbol{C}_d\boldsymbol{x}_d(k). \end{aligned} \tag{12}$$

Combining eq. (11) and eq. (12), the following extended state-space model is obtained:

$$\begin{aligned} \begin{bmatrix} \boldsymbol{x}_d(k+1) \\ \boldsymbol{x}(k+1) \end{bmatrix} &= \begin{bmatrix} \boldsymbol{A}_d & \boldsymbol{0} \\ \boldsymbol{B}_d\boldsymbol{C}_d & \boldsymbol{A} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{x}_d(k) \\ \boldsymbol{x}(k) \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{B} \end{bmatrix} \cdot \boldsymbol{u}(k) + \boldsymbol{w}'(k) \\ \boldsymbol{y}(k) &= \begin{bmatrix} \boldsymbol{0} & \boldsymbol{C} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{x}_d(k) \\ \boldsymbol{x}(k) \end{bmatrix} + \boldsymbol{v}(k) \end{aligned} \tag{13}$$

which is on the standard form (1). Applying the controller synthesis in eq. (5) and eq. (6) results in the following state feedback law:

$$\boldsymbol{u}(k) = -\begin{bmatrix} \boldsymbol{L}_d & \boldsymbol{L} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{x}_d(k) \\ \hat{\boldsymbol{x}}(k) \end{bmatrix} \tag{14}$$

with the state estimator:

$$\begin{aligned} \begin{bmatrix} \boldsymbol{x}_d(k+1) \\ \hat{\boldsymbol{x}}(k+1) \end{bmatrix} &= \begin{bmatrix} \boldsymbol{A}_d & \boldsymbol{0} \\ \boldsymbol{B}_d\boldsymbol{C}_d & \boldsymbol{A} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{x}_d(k) \\ \hat{\boldsymbol{x}}(k) \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{B} \end{bmatrix} \cdot \boldsymbol{u}(k) + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{K} \end{bmatrix} \cdot (y(k) - \hat{y}(k)) \\ \hat{y}(k) &= \begin{bmatrix} \boldsymbol{0} & \boldsymbol{C} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{x}_d(k) \\ \hat{\boldsymbol{x}}(k) \end{bmatrix} \end{aligned} \tag{15}$$

where $\boldsymbol{x}_d(k)$ is measurable and $\hat{\boldsymbol{x}}(k)$ is estimated by the closed-loop state estimator.

The structure of the LQG controller with integrated feedforward action is shown in Fig. 5.

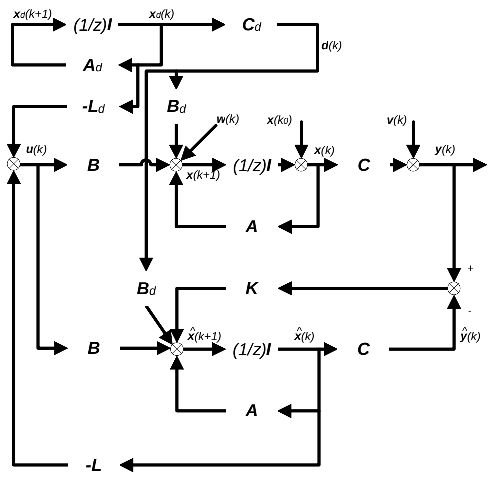

Fig. 5. LQG controller with integrated feedforward action.

A controller of this type is characterized by being relatively simple, with simultaneous tuning of the feedforward part and the feedback part.

As an alternative to this, the feedforward part and the feedback part can be separated, giving the possibility of tuning the two parts individually, at the expense of a more complex structure.

The feedforward controller is given as:

$$\boldsymbol{u}_{ff}(k) = -\begin{bmatrix}\boldsymbol{L}_{ff,d} & \boldsymbol{L}_{ff}\end{bmatrix}\cdot\begin{bmatrix}\boldsymbol{x}_d(k)\\ \hat{\boldsymbol{x}}_{ff}(k)\end{bmatrix} \tag{16}$$

with:

$$\begin{bmatrix}\boldsymbol{x}_d(k+1)\\ \hat{\boldsymbol{x}}_{ff}(k+1)\end{bmatrix} = \begin{bmatrix}\boldsymbol{A}_d & \boldsymbol{0}\\ \boldsymbol{B}_d\boldsymbol{C}_d & \boldsymbol{A}\end{bmatrix}\cdot\begin{bmatrix}\boldsymbol{x}_d(k)\\ \hat{\boldsymbol{x}}_{ff}(k)\end{bmatrix} + \begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{B}\end{bmatrix}\cdot\boldsymbol{u}_{ff}(k), \tag{17}$$

where $\boldsymbol{x}_d(k)$ is measurable and $\hat{\boldsymbol{x}}_{ff}(k)$ is estimated by the open-loop state estimator.

The feedback controller is given as

$$\boldsymbol{u}_{fb}(k) = -\boldsymbol{L}_{fb}\hat{\boldsymbol{x}}_{fb}(k) \tag{18}$$

with the closed-loop state estimator:

$$\begin{aligned}\hat{\boldsymbol{x}}_{fb}(k+1) &= \boldsymbol{A}\hat{\boldsymbol{x}}_{fb}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{B}_d\boldsymbol{d}(k) + \boldsymbol{K}\left(\boldsymbol{y}(k) - \hat{\boldsymbol{y}}_{fb}(k)\right)\\ \hat{\boldsymbol{y}}_{fb}(k) &= \boldsymbol{C}\hat{\boldsymbol{x}}_{fb}(k)\end{aligned} \tag{19}$$

where $\boldsymbol{u}(k) = \boldsymbol{u}_{fb}(k) + \boldsymbol{u}_{ff}(k)$.

The structure of the LQG controller with coordinated feedforward action is shown in Fig. 6.

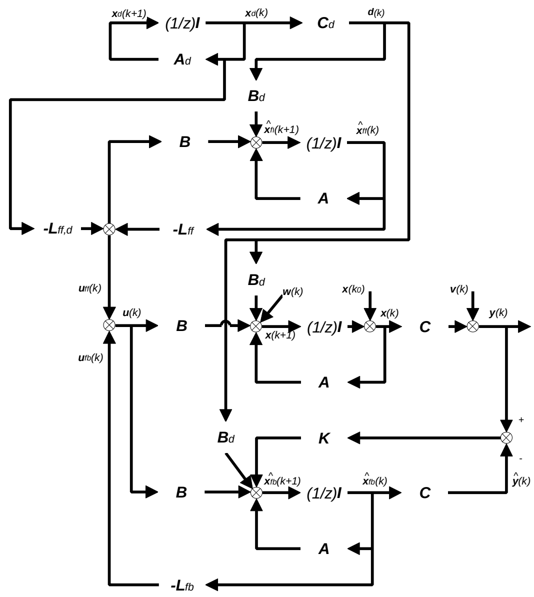

Fig. 6. LQG controller with coordinated feedforward action.

3.4 Scheduling an LQG controller

If it is known how the dynamics of a process change with the operating conditions of the process, it is possible to change the controller parameters accordingly, known as gain-scheduling.

A measurable process variable, which is descriptive of the operating condition and used to adjust the controller parameters, is known as a scheduling variable α, and is in this context assumed to be a scalar. A set $J=\{\alpha_1,\ldots,\alpha_m\}$, containing m values of the scheduling variable is chosen and arranged according to: $\alpha_i > \alpha_j$ for $i>j$. For each value of α in the set J a linear model ($\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{K}$) is given and for each model the state feedback matrix $\boldsymbol{L}$ is designed according to eqs. (5) and (6).

The LQG controller ($\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{K}$, $\boldsymbol{L}$) can be scheduled between the frozen operating points according to linear interpolation:

$$\boldsymbol{X}(\alpha) = \boldsymbol{X}(\alpha_l) + \frac{\boldsymbol{X}(\alpha_{l+1}) - \boldsymbol{X}(\alpha_l)}{\alpha_{l+1} - \alpha_l}(\alpha - \alpha_l) \tag{20}$$

where: $l = 1,\ldots, m-1$.

A disadvantage of this method is that no security of the placement of the closed-loop poles is given between the frozen operating points in J.

An alternative is to schedule the control signals directly:

$$\boldsymbol{u}(\alpha) = \boldsymbol{u}(\alpha_l) + \frac{\boldsymbol{u}(\alpha_{l+1}) - \boldsymbol{u}(\alpha_l)}{\alpha_{l+1} - \alpha_l}(\alpha - \alpha_l) \tag{21}$$

where: $l = 1,\ldots, m-1$.

3.5. *Specific control strategy for the SVS2 unit*

Load changes performed on SVS2 from 40% to 100% at a gradient of 8 MW/min. (regarded as the maximum allowable, only performed in critical situations) result in set-point deviations of about +25°C and -35°C of the steam temperature at the outlet of superheater 1b (T_{sh1b}). Set point deviations of the outlet steam pressure (p_{sh3}) and the high pressure and low-pressure outlet steam temperatures are within acceptable limits.

The deviations of T_{sh1b} are considered as the limiting factor for the load-following capability of the boiler and hence of the unit as a whole. Improvement of the control of T_{sh1b} at load changes is therefore expected to improve the load-following capability of the unit.

In the optimizing control system, the following control inputs are used:

- Additive control signal to fuel flow, $\dot{m}_{fuel,add}$.
- Additive control signal to feedwater flow, $\dot{m}_{fw,add}$.

The following controlled output variables are used:

- Control error on outlet steam pressure, $p_{sh3,err}$.
- Control error on steam temperature after superheater 1b, $T_{sh1b,err}$.
- Evaporator temperature, T_{eva}.

Feedforward and scheduling are introduced from the boiler load demand P_B.

The design goal is hence, during load changes, to decrease the deviations in $T_{sh1b,err}$ without degrading the control of $p_{sh3,err}$.

4. DESIGN AND TEST OF THE LQG CONTROLLER ON THE SVS2 SIMULATOR

Eighth-order linear state-space models of the form:

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{B}_d\boldsymbol{d}(k) + \boldsymbol{K}\boldsymbol{e}(k) \\ \boldsymbol{y}(k) &= \boldsymbol{C}\boldsymbol{x}(k) + \boldsymbol{e}(k). \end{aligned} \tag{22}$$

for the operating points J_{simu}=*{159 MW, 199 MW, 239 MW}={60%, 75%, 90%}* were estimated from SVS2 Simulator data using the N4SID, subspace system-identification method, cf. (Van Overschee *et al.*, 1994) and (MathWorks 1995).

An LQG-controller with integrated feedforward action was designed for each operating point in J_{simu}. The state feedback is calculated from the controllable part of eq. (22), rewritten to the form of eq. (13), with $d(k)$ given as a step disturbance, and hence with the state feedback matrix of the form (14). The LQG controller for $P_B \in I_{simu}$=*[60%, 90%]* is obtained by scheduling the LQG-controllers designed for the operating points P_B belonging to the set J_{simu} according to eq. (20). Outside the interval I_{simu} the LQG-controller for the closest α_l is used.

Fig. 7 shows the responses of $p_{sh3,err}$ and $T_{sh1b,err}$. A reduction in the first peak of $T_{sh1sl,err}$ of about 75% was obtained, while the second almost disappeared. A minor improvement in $p_{sh3,\,err}$ was obtained as well.

Fig. 8 shows the corresponding additive control signals in fuel and feedwater. The action taken by the LQG controller can be explained as follows: since the steam temperature becomes too high, additional feedwater is given (note that the control error is defined as the reference value minus the measured value), which results in lower steam temperature and higher pressure. The higher pressure is compensated for by less fuel, which also results in a lower steam temperature. It was found that the feedforward part of the LQG controller is important because of the significant lag from the control inputs to T_{sh1b}.

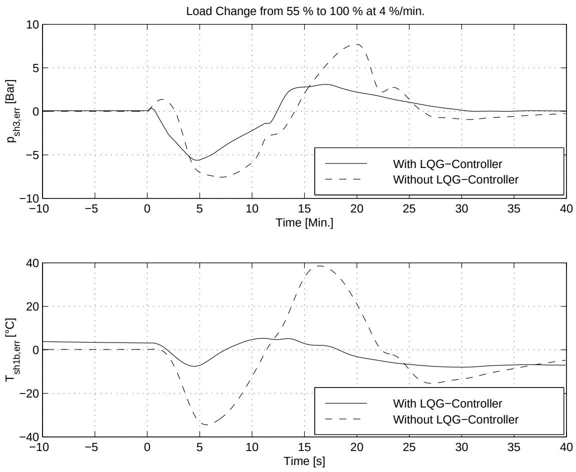

Fig. 7. Load change from 55% load to 100% at 4%/min. Response for $p_{sh3,err}$ and $T_{oh1,err}$.

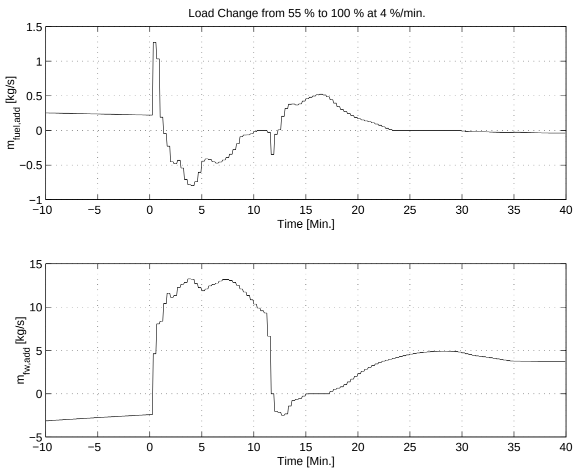

Fig. 8. Load change from 55% load to 100% at 4%/min. Additive control signals.

5. DESIGN AND TEST OF THE LQG CONTROLLER ON THE SVS2 UNIT

Based on the promising results obtained on the SVS2-Simulator using an LQG controller with integrated feedforward action, this controller type is the basis for the test on the real plant.

5.1 LQG controller with integrated feedforward action

Similar to the SVS2-simulator case, 8[th]-order models of the form (22) are estimated for the operating points in J_{SVS2} = *{115 MW, 130 MW, 187 MW, 240 MW}* = *{43.4%, 49.1%, 70.6%, 90.6%}*. J_{SVS2} is chosen in order not to coincide with starting/stopping of the coal mills, and to take account of the characteristics of the modified sliding-pressure operation. LQG controllers with integrated feedforward action are designed as described in Section 4.

From the testing of these controllers in their respective load points, i.e. no scheduling is performed, the following conclusion can be drawn: the integrated design is not appropriate, since the limitation on the bandwidth in the feedback loop (for stability reasons) also limits the performance of the feedforward part.

In practice it is therefore not possible to obtain the same results as on the SVS2 simulator. To overcome this limitation, the LQG controller with coordinated feedforward action described in Section 3.3 has been developed.

5.2 LQG controller with coordinated feedforward action

The LQG controller with coordinated feedforward action overcomes the problems described above, since it allows separate tuning of the feedforward and feedback parts of the controller.

Feedforward part

Feedforward controllers of the form (16) are designed for each operating point in J_{SVS2}, and where the open-loop observer is given by eq. (17).

The sensitivity function from the load disturbance P_B to the outputs $p_{sh3,err}$ and $T_{sh1b,err}$ is shown in Fig. 9 for the 187 MW operating point. This plot reveals that the impact of the load change on $p_{sh3,err}$ and $T_{sh1b,err}$ is significantly reduced.

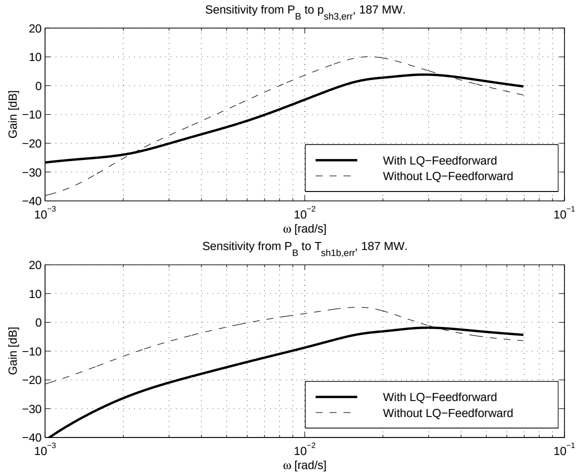

Fig. 9. Sensitivities from P_B to $p_{sh3,err}$ and $T_{sh1b,err}$ for the 187 MW operating point.

Fig. 10 shows the responses for a load change from 200 MW to 180 MW at a gradient of 4 MW/min. for the two cases with and without the LQ-feedforward controller active. Fig. 11 shows the corresponding additive control signals.

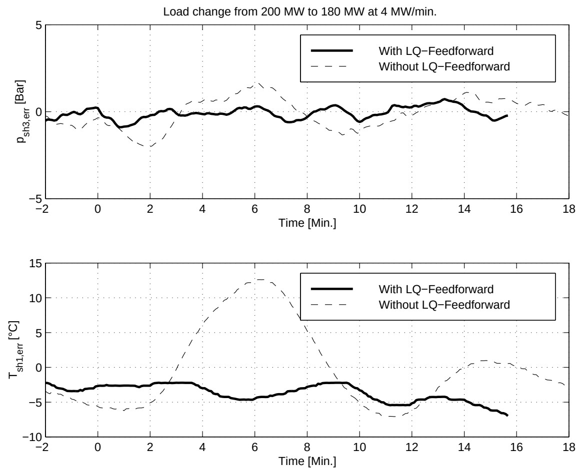

Fig. 10. Comparison between $p_{sh3,err}$ and $T_{sh1b,err}$ for the two cases, with and without LQ feedforward control at a load change from 200 MW to 180 MW.

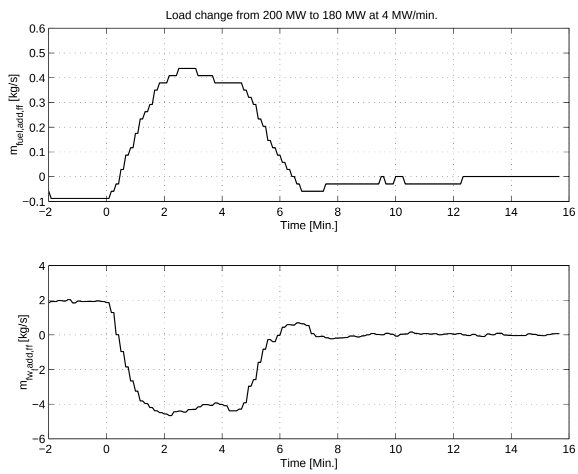

Fig. 11. Additive control signals.

The field test results reveal that an improvement close to that calculated theoretically and given in Fig. 9 is obtained. The action of the LQ feedforward controller can be interpreted as follows: the decrease in steam temperature (note that the control error is defined as the reference value minus the measured value) is compensated for by increasing the fuel rate and decreasing the feedwater rate, which both result in an increased steam temperature. These two actions have a mutually opposite impact on the steam pressure, which altogether results in a reduced steam-pressure deviation.

Similar improvements have been obtained for all operating points in J_{SVS2}. For the 115 MW operating point the improvements shown in Fig. 12 have been obtained by the additive control signals shown in Fig. 13. In this comparison, four identical load changes have been performed, two with and two without LQ feedforward, in order to indicate the consistency of the obtained results.

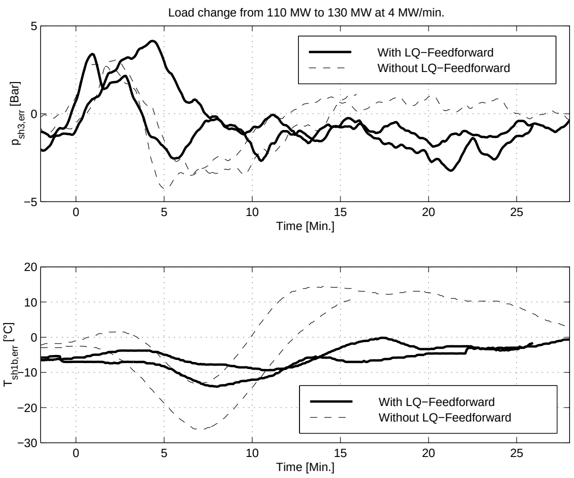

Fig. 12. Comparisons between $p_{sh3,err}$ and $T_{sh1b,err}$ for the two cases, with and without feedforward control, at a load change from 110 MW to 130 MW.

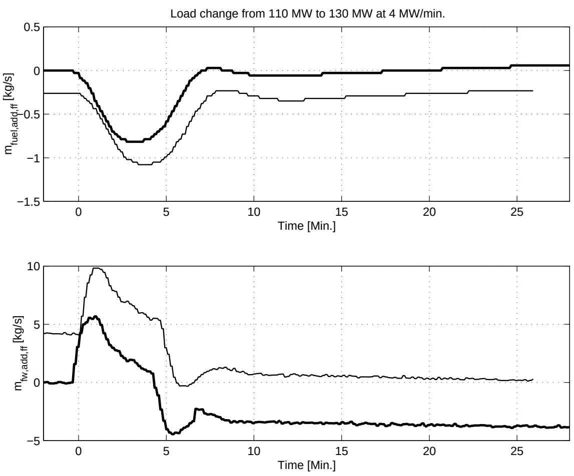

Fig. 13. Additive control signals.

It can be seen that similar results are obtained in the control of $T_{sh1b,err}$, while the control of $p_{sh3,err}$ is as in the status quo.

The LQ feedforward controller for $P_B \in I_{SVS2}=[115\ MW, 240\ MW]$ is obtained by scheduling the operating-point specific LQ feedforward controllers designed for the operating points P_B belonging to the set J_{SVS2} according to eq. (21). Scheduling according to eq. (20) resulted in an unstable LQ feedforward controller for certain intervals of P_B, due to the lack of control of the LQ feedforward controller poles. For a further discussion of the two scheduling methods, refer to *Mortensen, J.H (1997)*.

Improved control of the critical process variable during load changes results in the possibility of increasing the maximum allowable load gradient without stressing the plant further. Practical experiments have examined the extent to which the LQ feedforward controller results in an improved load-following capability. The criterion for determining the new allowable maximum load gradient has been that deviations in $T_{sh1b,err}$ may not increase, either in amplitude or in gradient, and the gradient of T_{eva} may not exceed 8°C/min.

Fig. 14 to 16 show the responses in the main variables for load changes between 170 MW and 200 MW at 8 MW/min. The deviations in $T_{sh1b,err}$, T_{eva} and $p_{sh3,err}$ are kept within acceptable limits, giving the possibility of performing shorter 8 MW/min. load changes in the daily operation. It can, however, also be seen that the control of $T_{sh1b,err}$ is degraded with respect to the 20 MW, 4 MW/min. load changes. Deviations in $T_{sh1b,err}$ are kept to a minimum inside the first 10 min., after which an increase/decrease can be observed. This phenomenon is connected to a change in the dynamics of the $T_{sh1b,err}$ during faster load changes caused by the existing boiler control system. It is expected that the feedback part will reduce this disturbance.

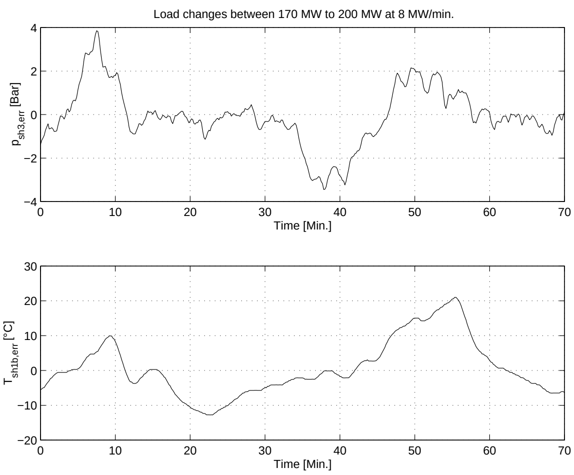

Fig. 14. Response of $p_{sh3,err}$ and $T_{sh1b,err}$ for two load changes between 170 MW and 200 MW at 8 MW/min.

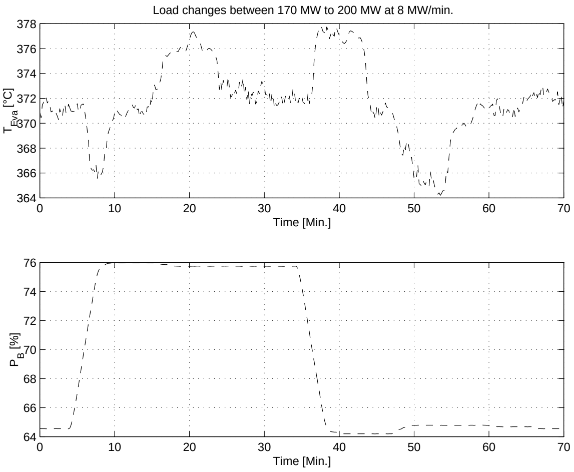

Fig. 15. Evaporator steam temperature, T_{eva}, and boiler load demand, P_B, for two load changes between 170 MW and 200 MW at 8 MW/min.

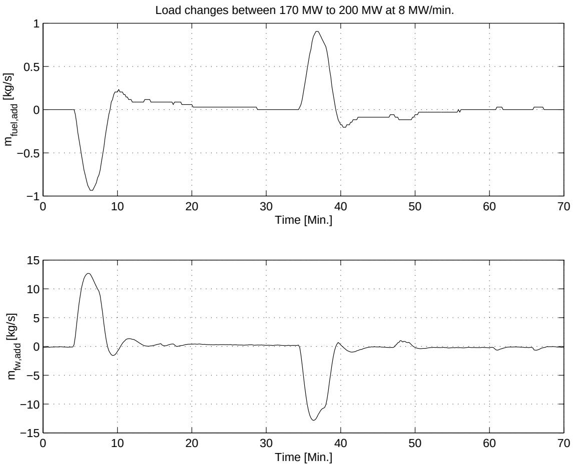

Fig. 16. Additive control signals for two load changes between 170 MW and 200 MW at 8 MW/min.

Feedback part

The purpose of the feedback part of the LQG controller with coordinated feedforward action, is defined as a general improvement of the stability of the boiler, and specifically to reduce the impact of starting/stopping the coal mills on the controlled variables since this event occurs during load changes. Starting/stopping of coal mills introduces significant transient disturbances in the furnace, in the form of a temporary change in coal and combustion air flow, which affect steam temperatures and the steam pressure. It is intended, by designing the LQG controller given by eqs. (18) and (19), to reject disturbances entering from the furnace. LQG controllers for a single load point have been tuned and tested, and have been found to reduce the mentioned disturbance by about 37%. Further research is currently being performed in order to improve the performance of the feedback part, which is expected to increase the load-following capability beyond what has already been obtained by the LQ feedforward part.

6. CONCLUSION

For the purpose of improving the load-following capability of existing power-plant units, a control concept based on a scheduled LQG controller with coordinated feedforward from the boiler load demand has been developed and tested. The concept has been designed as a complement to the existing boiler-control system, in order to give priority to robustness and to facilitate commissioning. This means that no changes are made to the existing boiler-control system and that it is always active.

According to the real plant results, significant improvements in the control of critical process variables are obtained during load changes. Real plant experiments reveal that the maximum allowable load gradient can be increased from 4 MW/min. to 8 MW/min. without further plant stress.

Due to the universal nature of the concept, a similar system could be applied to other power-plant units to the benefit of the competitiveness and reliability in a future, liberalised electricity market.

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