Controller Design for MIMO Boiler Turbine Process

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Abstract: In present work, a boiler turbine plant is presented as a 2x2 MIMO system with high multivariable interaction having two manipulated variables namely the governor valve position and the fuel flow rate and two control variables namely generated electric power and the steam pressure. The controller for this plant has been designed using conventional PID and MPC technique by first investigating the stability using Niederlinski index and interaction analysis using RGA recommendations for the selected plant. The decoupler is designed and its singular value analysis is performed. Closed loop step response is observed and compared to those of the composite MIMO system.

Key words: Relative gain array, boiler turbine, decoupling, multivariable process, predictive control

1. INTRODUCTION

In boiler turbines, the chemical and thermal energy is transformed to electricity. It is a highly complex, multivariable, time delayed and nonlinear process. In a typical boiler turbine plant a header collects all the steam which is generated from number of boilers which is then distributed to several turbines through header. The steam flow is directly proportional to power generation which is the key parameter to be controlled. The other parameter to be controlled is the drum pressure. The ultimate objective is to meet the load demand of electric power. The schematic diagram of a boiler turbine plant is depicted in Fig. 1.

T. Rajkumar et al. [2] used wide open control strategy with 3 element control system to provide tight control the drum water level in boiler turbine. Three elements indicate 3 variables namely steam flow, feed water flow and drum water level which collectively has effect on feed water valve position. Drum Level

![Figure 1: Schematic diagram of the boiler-turbine unit[1]](image-url)
Control Algorithm was implemented in the Advanced Adaptive PID Controller Block in the FCP270 Field Control Processor.

Quicker response and little overshoot was observed in the response of speed controller for steam turbine using MPC technique as compared to conventional PID controller and fuzzy controller [3]. Omar shahin et al. observed robustness and satisfactory performance of the boiler turbine system employing adaptive wavelet neural network. Discrete Lyapunov stability theorem was used here to determine the learning rates [4].

Speed control of gas turbine system was proved to be outstanding with adaptive fuzzy PID controllers as compared to conventional controllers [5].

2. PLANT MODEL AND ITS MULTIVARIABLE ANALYSIS

The process has two manipulated variables, the governor valve position (GV) and the fuel flow rate (FR). The variables to be controlled are the electric power (EP) and the steam pressure (SP). Equation 1 shows the model of an industrial boiler turbine process [6] that will be used to design the controller.

\[
\begin{bmatrix}
    EP \\
    SP
\end{bmatrix} =
\begin{bmatrix}
    \frac{68.81 e^{-2s}}{984 s^2 + 94 s + 1} & \frac{(-23.58 s - 2.196)e^{-8s}}{372 s^2 + 127 s + 1} \\
    \frac{e^{-2s}}{6889 s^2 + 166 s + 1} & \frac{2.194 e^{-8s}}{6400 s^2 + 160 s + 1}
\end{bmatrix}
\begin{bmatrix}
    GV \\
    FR
\end{bmatrix}
\]

(1)

The open loop step response of this plant model is shown in Fig. 2.

Figure 2: Open loop step response
The open loop step response is clearly indicating that the plant model is physically realizable and BIBO (bounded input-bounded output) stable. Before designing the multiloop controller for the considered plant the suitable pairing between manipulated and control variables is done by determining the relative gain array (RGA)[7].

Consider the steady state model of a 2x2 MIMO plant,

\[
\begin{bmatrix}
    y_1 \\
    y_2
\end{bmatrix} =
\begin{bmatrix}
    K_{11} & K_{12} \\
    K_{21} & K_{22}
\end{bmatrix}
\begin{bmatrix}
    u_1 \\
    u_2
\end{bmatrix}
\]

Where \( u_1, u_2 \) are manipulated variables and \( y_1, y_2 \) are controlled variables. The steady state gain matrix is given by,

\[
[K] =
\begin{bmatrix}
    K_{11} & K_{12} \\
    K_{21} & K_{22}
\end{bmatrix}
\]

Now the RGA is expressed as:

\[
\text{RGA} =
\begin{bmatrix}
    \lambda_{11} & \lambda_{12} \\
    \lambda_{21} & \lambda_{22}
\end{bmatrix}
\]

Mathematically, \( \text{RGA} = K \ast (K^T)^{-1} \)

where the operator \( \ast \) represents element by element multiplication.

If \( \lambda_{12} < \lambda_{11} \) then suitable pairing is \( u_1 - y_1 \) and \( u_2 - y_2 \) else it is \( u_1 - y_2 \) and \( u_2 - y_1 \).

Now, for the considered plant the steady state gain matrix is given below,

\[
[K] =
\begin{bmatrix}
    0.6 & -2.1 \\
    0.1 & 0.9
\end{bmatrix}
\]

Using relations (5) and (6), the RGA for this plant comes out as,

\[
\text{RGA} =
\begin{bmatrix}
    0.985 & 0.015 \\
    0.015 & 0.985
\end{bmatrix}
\]

This RGA suggests that the suitable pairing is \( u_1 - y_1 \) and \( u_2 - y_2 \).

The second parameter is the Niederlinski index[8] which determines the closed loop stability of the control system. It is calculated using the following relation

\[
N = \frac{\text{Det}[[K]]}{K_{11}K_{22}}
\]

The MIMO system will be unstable for all possible values of controller parameters if \( N < 0 \)

Now using relation (8), the Neiderlinski index for this plant is determined as,

\[
N = \frac{68.81 \times -2.196}{68.81 \times 2.194} = 1.01
\]

Hence for this plant \( N > 0 \) which indicates that the system is closed loop stable.
3. MULTILOOP PI CONTROL DESIGN

The SIMULINK model of multiloop PI controller for the considered boiler turbine plant is depicted in Fig. 3 with tuned values $K_p=0.020458$ and $K_i=0.00040917$ for controller1 and $K_p=0.94334$ and $K_i=0.004233$ for controller2. The corresponding electric power and steam pressure responses are presented in Fig. 4 and 5. The characteristic parameters of these responses are specified in Table 1 and 2.

![Simulink model of multiloop PI controller](image)

**Figure 3: Simulink model of multiloop PI controller**

![Electric power response of PI controller](image)

**Figure 4: Electric power response of PI controller**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec)</td>
<td>64</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>254</td>
</tr>
<tr>
<td>Overshoot (%)</td>
<td>10.5</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**Table 1**
Characteristics of electric power response of PI controller
Table 2
Characteristics of steam pressure response of PI controller

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec)</td>
<td>99.4</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>664</td>
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<tr>
<td>Overshoot (%)</td>
<td>4.11</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.04</td>
</tr>
</tbody>
</table>

4. PREDICTIVE CONTROLLER DESIGN

Figure 5: Steam pressure response of PI controller

Figure 6: Simulink model of model predictive controller
The SIMULINK model of MPC (model predictive controller) is shown in Fig. 6. The MPC calculates an objective function [9] based on the prediction of the output samples up to a fixed prediction horizon and then determines the discrete moves of the input manipulated variables in such a way that the objective function is minimized.

The MPC design tuning parameters are enlisted in Table 3. The electric power response of this controller is depicted in Fig. 7.

<table>
<thead>
<tr>
<th>Tuning Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control interval(sec)</td>
<td>1.0</td>
</tr>
<tr>
<td>Prediction horizon</td>
<td>10</td>
</tr>
<tr>
<td>Control horizon</td>
<td>2</td>
</tr>
<tr>
<td>Rate weight for GV</td>
<td>0.1</td>
</tr>
<tr>
<td>Rate weight for FR</td>
<td>0.1</td>
</tr>
<tr>
<td>Weight for EP</td>
<td>1</td>
</tr>
<tr>
<td>Weight for SP</td>
<td>0</td>
</tr>
<tr>
<td>Duration(seconds)</td>
<td>50</td>
</tr>
<tr>
<td>Robustness</td>
<td>0.8</td>
</tr>
</tbody>
</table>

This response has settling time of around 12 seconds which is very small as compared to the response in case of PI controller. Moreover the PI controller response has a significantly larger overshoot than MPC response.

5. DECOUPLER DESIGN

The MIMO systems have severe loop interactions which degrades the set point tracking performance of the control system. In order to avoid loop interactions decoupling of the system is done. To check the possibility of decoupling usually condition number investigation is done by singular value analysis [10]. It is a matrix technique that determines if a system is able to be decoupled. First of all the eigen values $\lambda_1$ and $\lambda_2$ of matrix $(K^T K)$ are determined. Then the singular values $s_1$ and $s_2$ are determined by taking square root of $\lambda_1$ and $\lambda_2$ respectively.

Now, let’s introduce a parameter called condition number (CN) which is defined as,

$$CN = \frac{s_1}{s_2}; \text{ if } s_1 \geq s_2$$ (10)
As a thumb rule, if CN is greater than 50 then it is impossible to decouple the given MIMO system.

The eigen values of the matrix $K^TK$ for the considered boiler turbine process comes out to be $\lambda_1 = 4.9$ and $\lambda_2 = 4740.5$. The corresponding singular values are $s_1 = 2.2136$ and $s_2 = 68.8513$.

Hence the condition number (CN) using relation (11) is,

$$CN = \frac{s_2}{s_1} = 31.1,$$

showing that decoupling is possible.

Now let $G(s)$ be the transfer matrix of a $2\times2$ MIMO system.

$$[G(s)] = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{12}$$

Then, the interaction compensator matrix for achieving decoupling is given below [16],

$$[G_f(s)] = \begin{bmatrix} 1 & g_{11}(s) \\ g_{12}(s) & 1 \end{bmatrix} \tag{13}$$

Where,

$$g_{11}(s) = \frac{-g_{12}(s)}{g_{11}(s)} \tag{14}$$

$$g_{12}(s) = \frac{-g_{21}(s)}{g_{22}(s)} \tag{15}$$

Here $g_{11}(s)$ and $g_{12}(s)$ are the gains of the interaction compensators for loop 1 and loop 2 respectively.

Now, the modified simulink model incorporating the two interaction compensators (decouplers) using relations (14) and (15) is shown in the figure 8.

The following relations hold good for the model in Fig. 8.

$$\begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} = [G_f(s)] \begin{bmatrix} v_1(s) \\ v_2(s) \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = [G(s)] \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{17}$$

Here $v_1(s)$ and $v_2(s)$ are the outputs of the two PI controllers of Fig. 8.

Combining relations (16) and (17) we get,

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = [G(s)][G_f(s)] \begin{bmatrix} v_1(s) \\ v_2(s) \end{bmatrix} \tag{18}$$

Which gives the following results,

$$y_{1(s)} = \left[ g_{11}(s) - \frac{g_{12}(s)g_{21}(s)}{g_{22}(s)} \right] v_1(s) \tag{19}$$
Thus we get two independent decoupled SISO systems $v_1-y_1$ (decoupled SISO1) and $v_2-y_2$ (decoupled SISO2) with gains $G_1(s)$ and $G_2(s)$. The expressions for $G_1(s)$ and $G_2(s)$ determined using relations (19) and (20) are given in relations (21) and (22).

\[
G_1(s) = \left[ g_{22}(s) - \frac{g_{12}(s)g_{22}(s)}{g_{11}(s)} \right] v_2(s) \quad (20)
\]

\[
(1.485 \times 10^8 s^5 + 4.186 \times 10^8 s^4 + 1.436 \times 10^8 s^3 + 4.334 \times 10^6 s^2 + 4.482 \times 10^4 s + 153.2)e^{-2s} \quad (21)
\]

\[
(1.485 \times 10^8 s^6 + 4.186 \times 10^8 s^4 + 1.436 \times 10^8 s^3 + 4.334 \times 10^6 s^2 + 4.482 \times 10^4 s + 153.2) e^{-2s} \quad (22)
\]
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Table 4
Closed loop step response characteristics of decoupled SISO 1 system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec)</td>
<td>53.7</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>221</td>
</tr>
<tr>
<td>Overshoot (%)</td>
<td>10.5</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Figure 10: Setpoint tracking response of steam pressure with decoupler

Table 5
Closed loop step response characteristics of decoupled SISO 2 system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec)</td>
<td>99</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>628</td>
</tr>
<tr>
<td>Overshoot (%)</td>
<td>4.2</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Figure 11: Electric power response for MIMO and decoupled system
6. CONCLUSION

In the present work the multivariable analysis of a 2x2 boiler turbine plant has been done by determining RGA which suggested the suitable loop pairing for designing controller. The calculated value of Niederlinski index indicated that this system has good closed loop stability.

The multiloop controller has been designed using PI and MPC technique. The performance of MPC comes out to be much better than conventional PI technique. An excellent setpoint tracking performance has been observed after decoupling of the composite plant.

References


