FEASIBILITY ANALYSIS OF CONTROL-LOOP INTERACTION COMPENSATION FOR A FOSSIL-FUEL POWER PLANT

Raul Garduno-Ramirez
Electrical Research Institute
Division of Control Systems, GCI
Cuernavaca, Mor. 62490 Mexico

Kwang Y. Lee
The Pennsylvania State University
Department of Electrical Engineering
University Park, PA 16802 USA

Abstract: Fossil-fuel power plants are complex systems currently being required to take on load-following duties with full-range variations in power generation. Most of their control systems consist of decentralized PI control loop configurations supplemented with ad-hoc compensation schemes, intended to minimize the effects of interaction among the control loops caused by the non-linear coupled process dynamics. This paper analyses the viability of an inverse decoupling compensation scheme to lessen control loop interaction to ease wide-range power generation control throughout the power plant operating space. The proposed compensator introduces compensation factors among the control signals, which can be systematically determined from an equivalent process gain matrix that conveys all required information about control loop interaction. Copyright © 2003 IFAC

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1. INTRODUCTION

Late years have witnessed increased participation of fossil-fuel power plants in load-following duties to satisfy the large load demand changes imposed by market conditions. This practice demands wide-range capability in both, power generation and power rate of change, from any power unit. Variations from the minimum to the maximum generation level in short time periods are not rare anymore. This conceptually simple requirement imposes high physical demands on power unit equipments, and leads to conflicting operational and control situations.

Most control systems at fossil-fuel power plants consist of decentralized control configurations based on conventional PI controllers. These schemes were designed under the assumption that the plant might be separated into several single-input-single-output processes. This assumption is only valid during normal operation at base load, where the process characteristics are nearly constant, linear, and non-interacting. Conversely, these conditions do not hold for wide-range load-following operation regimes, where traditional control schemes, designed and tuned for regulation and disturbance rejection, but set-point tracking, may decrease process performance due to the nonlinear and coupled plant dynamics, which change with the point of operation.

Decentralized control schemes have been enhanced with many different compensation schemes to reduce, or to eliminate, the effects of control loop interaction to enhance power plant operation (Taft, 1987; Dimeo and Lee, 1995). Current compensation schemes have been developed through various decades of research and practical experience; most designs are industrial property of power plant manufacturers. With a few exceptions (Ray and Majumder, 1985), the design of most compensation schemes is an ad-hoc process that strongly relies on the designer’s experience, nor the resulting schemes are good for wide-range operation.

This paper analyses the feasibility of a compensation scheme to diminish control loop interaction to ease wide-range power generation control throughout the power plant operating space. The structure of the proposed interaction compensator is derived from the multivariable case for disturbance rejection through feedforward control, which is equivalent to a simple inverted decoupling scheme. Compensation factors are introduced among the control signals, preserving the direct control paths of the original uncompensated decentralized control scheme. These factors can be systematically determined from an equivalent process gain matrix that conveys all required information about control loop interaction, as established by the relative gain array (RGA)-based interaction analysis technique (McAvoy, 1983). Section 2 presents the
control loop interaction compensator as an inverted decoupler obtained from a feedforward disturbance compensator. Section 3 introduces the control loop interaction compensator for a power plant. Section 4 examines the realization feasibility of the interaction compensator throughout the power plant operating space. Finally, Section 5 concludes this paper.

2. INVERTED DECOUPLING

2.1 Single Loop Disturbance Compensation

A basic feedback control loop is typically represented as in Fig. 1, with transfer function:

\[ Y = [1 + GG_i]^{-1} [GG_i R + G W] \]  

(1)

where \( R \), \( W \), and \( Y \) are the Laplace transform of the reference, disturbance, and output signals, in that order, and \( G \), \( G_i \), and \( G_c \) are the plant, controller, and disturbance transfer functions, respectively.

Fig. 1. Feedback control loop.

It can be shown that this control structure does not provide the means for load disturbance rejection. It only provides compensation of model uncertainties through the design of \( G_c \). The fundamental control loop can be extended through feedforward control to achieve load disturbance rejection as shown in Fig. 2, with transfer function:

\[ Y = [1 + GG_i]^{-1} [(GG_i R + G_i + GG_i W)] \]  

(2)

where \( G_d \) is the disturbance feedforward control transfer function. Feedforward control action makes faster corrections than feedback control, acting before any deviation of the measured variable takes place. Theoretically, \( G_d \) can be designed to suppress the effect of load disturbances as:

\[ G_d = -G^{-1}G_i \]  

(3)

Fig. 2. Feedforward-feedback control.

2.2 Multiple Loop Disturbance Compensation

In industrial control systems, most load disturbances consist of loop interaction due to the process coupled dynamics. The single feedforward-feedback control loop scheme can be extended to compensate for any number of loop interaction effects in a multivariable process. Thus, transfer function (2) becomes:

\[ Y_k = [1 + G_k G_{ik}]^{-1} \left[ \sum_{j=1}^{m} (G_j G_{jk}) R_j + \sum_{j=1}^{m} (G_j + i G_{jk}) U_j \right] \]  

(4)

where \( j = 1, \ldots, k, \ldots, m \) is the control loop number. The transforms \( Y \), \( R \), and \( U \) correspond to the output, reference, and control signals, respectively. \( G_i \) is the process transfer function in loop \( k \), \( G_{ik} \) is the controller transfer function in loop \( k \). \( G_{jk} \) and \( G_{jk} \) are the interaction, and disturbance feedforward transfer functions from loop \( j \) to loop \( k \), respectively.

All control loops with the form in (4) can be arranged in a scheme as shown in Fig. 3 for a two-input-two-output (TITO) system, where the transfer functions for feedforward disturbance compensation form the control loop interaction compensator.

Fig. 3. TITO control loop interaction compensation.

2.3 Inverted Decoupling

Decoupling of multivariable processes includes three schemes: ideal, simplified and inverted (Luyben, 1970), which augment the plant dynamics to appear as a set of independent plants that can be individually controlled. The feedforward interaction compensator is structurally equivalent to an inverted decoupler. However, it should be kept in mind that the objective of the interaction compensator is not to accomplish perfect decoupling, but to decrease the interaction among control loops to lessen the control workload on the feedback controllers, so that the originally decentralized control scheme will effectively perform throughout the plant operating space.

As a basis to design the interaction compensator for a fossil fuel power plant, the inverted decoupler is first explained for the TITO linear plant defined by:

\[
\begin{align*}
y_1 &= P_{11}u_1 + P_{12}u_2 \\
y_2 &= P_{21}u_1 + P_{22}u_2
\end{align*}
\]  

(5)

where \( y_1 \) and \( y_2 \) are the plant outputs, \( u_1 \) and \( u_2 \) are the inputs, and \( P_{11} = G_1, P_{12} = G_{12}, P_{21} = G_{21}, \) and \( P_{22} = G_2 \) are the plant input-output transfer functions. In the inverted decoupler structure (Fig. 3), the plant inputs,
\[ u_1 \text{ and } u_2 \text{ are related to the controller outputs, } v_1 \text{ and } v_2, \text{ through:} \]

\[ u_1 = v_1 + D_{12}u_2, \quad u_2 = v_2 + D_{11}u_1 \quad (6) \]

where \( D_{12} = G_{B2} \) and \( D_{11} = G_{B1} \) are the decoupler transfer functions, which are to be designed in such a way that the apparent plant (decoupler and plant) appears as two independent systems of the form:

\[ y_1 = P_1v_1, \quad y_2 = P_2v_2 \quad (7) \]

Substituting (6) in (5), taking (7) into account, and solving for the compensator transfer functions yields:

\[ D_{22} = \frac{P_2}{P_1}, \quad D_{21} = \frac{P_1}{P_2} \quad (8) \]

In the inverted decoupling case, both the decoupler transfer functions (8) and the apparent plant transfer functions (7) have the simplest expressions.

### 3. Interaction Compensator Design

According to the inverted decoupler design in Section 2, the design of the interaction compensator is based on the mathematical model of a fossil-fuel power plant. The essential dynamics of a 160 MW oil-fired drum-type power plant, for wide-range simulations, has been remarkably captured through a third order nonlinear model (Bell and Aström, 1987):

\[
\begin{align*}
\frac{dE}{dt} &= \left(0.73u_2 - 0.16\right)P^{n/8} - E \Big/ 10 \\
\frac{dP}{dt} &= 0.9t_i - 0.0018u_i P^{n/8} - 0.15u_3 \\
\frac{dP}{dt} &= (141t_1 - (1.04)P) / V_i \\
\end{align*}
\]

where the inputs are the positions of valve actuators that control the mass flow rates of fuel (\( u_1 \) in per unit), steam to the turbine (\( u_2 \) in per unit), and feedwater to the drum (\( u_3 \) in per unit). The three outputs are electric power (\( E \) in MW), drum steam pressure (\( P \) in kg/cm\(^2\)), and drum water level deviation (\( L \) in m). The three state variables are electric power, drum steam pressure, and steam-water density (\( \rho_s \)), \( \alpha_s \) is the steam quality, and \( q_e \) is the evaporation rate (kg/sec). A linear state-space model can be obtained at any suitable operating point defined by \( x_0 = [E, P, \rho_s] \), \( u_0 = [u_1, u_2, u_3] \) and \( y_0 = [E, P, L] \) (Garduno and Lee, 2002):

\[
\begin{align*}
\dot{x} &= A\dot{x} + B\dot{u} \\
\dot{y} &= C\dot{x} + D\dot{u} \quad (10)
\end{align*}
\]

where \( \dot{x} = x - x_0, \dot{u} = u - u_0, \) and \( \dot{y} = y - y_0 \) are the state, input, and output vector deviations, in that order. The required transfer matrix model can be obtained from the linear state-space model (10) as:

\[ \hat{\gamma} = T \quad \hat{u} = \left[ C(sI - A)^{-1}B + D \right] \hat{u} \quad (11) \]

where \( \hat{\gamma} \) and \( \hat{u} \) are the Laplace transform of the output deviation, \( \gamma \), and the input deviation, \( u \), \( s \) is the Laplace complex variable, and \( T \) stands for the system transfer matrix. The elements of the transfer function matrix are found to be:

\[ T_{11} = \frac{A_{11}B_{21}}{s}, \quad T_{12} = \frac{[B_{12}s^2 + (A_{12}B_{22} - A_{22}B_{12})s]}{d}, \quad T_{13} = \frac{A_{12}B_{32}}{d}s \]

where \( A_{ij} \) are the elements of the plant transfer functions (7) and the apparent plant transfer functions (8). The interaction compensator is designed as a static inverted decoupler that uses the steady-state gains of the plant transfer functions instead of the dynamic plant transfer functions in (12):

\[ K = \lim_{s \to 0} T(s) \quad (14) \]

From (14) and (12), the elements of matrix \( K \) are:

\[ \begin{align*}
K_{11} &= \lim_{s \to 0} T_{11}(s) = \frac{A_{11}B_{21}}{A_{12}} \\
K_{12} &= \lim_{s \to 0} T_{12}(s) = \frac{A_{12}B_{22} - A_{22}B_{12}}{A_{11}A_{22}} \\
K_{13} &= \lim_{s \to 0} T_{13}(s) = \frac{A_{12}B_{32}}{A_{11}} \\
K_{21} &= \lim_{s \to 0} T_{21}(s) = -\frac{B_{13}}{A_{22}} \\
K_{22} &= \lim_{s \to 0} T_{22}(s) = \frac{B_{22}}{A_{22}} \\
K_{23} &= \lim_{s \to 0} T_{23}(s) = -\frac{B_{23}}{A_{22}} \\
K_{31} &= \lim_{s \to 0} \left(\frac{A_{22}B_{33}}{A_{22}}\right) \quad \lim_{s \to 0} \frac{y_{31}}{s} \quad (15)
\end{align*} \]
\[ K_{32} = \lim_{s \to 0} \left( \frac{A_{32}B_{13}C_{33} - A_{32}B_{23}C_{33}}{s^4} \right) = \lim_{s \to 0} \frac{\gamma_{32}}{s} \]

\[ K_{33} = \lim_{s \to 0} \left( \frac{A_{32}B_{13}C_{33} - A_{32}B_{23}C_{33}}{s^4} \right) = \lim_{s \to 0} \frac{\gamma_{33}}{s} \]

where \( \gamma_{31}, \gamma_{32}, \) and \( \gamma_{33}, \) are appropriately defined for the equalities to hold. The steady-state matrix \( K \) is undetermined because of \( K_{31}, K_{32}, \) and \( K_{33}, \) which reflect the integrative process dynamics of the drum water level control loop, necessary to achieve wide-range operation. This problem makes it difficult to directly quantify the control loop interaction based on the relative gain array (RGA) method (McAvoy, 1983), as would be desired, using the Hadamard product (element by element) of matrix \( K \):

\[ \Lambda = \left( K^{-1} \right)^T \otimes K \]  

(16)

Fortunately, interaction analysis based on the RGA shows that, in these cases, the interaction information provided by the process steady-state gain matrix can also be retrieved from an equivalent gain matrix, which can also be used to design the compensator. Matrix \( K \) may be written as:

\[ K = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ \frac{\gamma_{11}}{s} & \frac{\gamma_{12}}{s} & \frac{\gamma_{13}}{s} \end{bmatrix} \]  

(17)

then,

\[ K^{-1} = \begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ \frac{L_{31}}{s} & \frac{L_{32}}{s} & \frac{L_{33}}{s} \end{bmatrix} \]  

(18)

with matrix \( L \) appropriately defined. Then, the RGA is obtained from (17) and (18) taking the Hadamard product, canceling \( s \), and taking the limit:

\[ \Lambda = \begin{bmatrix} L_{11}K_{11} & L_{12}K_{12} & L_{13}K_{13} \\ L_{12}K_{21} & L_{22}K_{22} & L_{23}K_{23} \\ \frac{L_{31}}{s} \gamma_{31} & \frac{L_{32}}{s} \gamma_{32} & \frac{L_{33}}{s} \gamma_{33} \end{bmatrix} \]  

(19)

that would be calculated the same with the equivalent steady-state gain matrix, given as:

\[ K = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ \frac{\gamma_{11}}{s} & \frac{\gamma_{12}}{s} & \frac{\gamma_{13}}{s} \end{bmatrix} \]  

(20)

3.2 **Compensator Design**

The control loop interaction compensator design procedure for the fossil-fuel power plant requires that the product of the equivalent steady-state gain matrix \( K \) and the inverted decoupling matrix \( D \) be equal to a decoupled steady-state gain matrix \( M \):

\[ M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{bmatrix} \]

\[ D = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} \]  

(21)

where \( D_{ij}, i=1,2,3, j=1,2,3, \) are the decoupling factors, or interaction compensation factors, to be designed, and \( M_{1}, M_{2}, \) and \( M_{3} \) are the decoupled steady-state gains for the power, pressure, and level control loops, respectively. The interaction compensator is shown in Fig. 4 (Garduno and Lee, 2000).

![Fig. 4. Control-loop interaction compensator.](image)

Carrying out the product on the right hand side of (21), equating to zero the off-diagonal elements, and solving the resulting system of equations yields the desired interaction compensation factors:

\[ D_{31} = \frac{k_{31} \gamma_{31} - k_{32} \gamma_{31} - k_{33} \gamma_{31}}{k_{33} \gamma_{31} - k_{32} \gamma_{31}} \]

\[ D_{32} = \frac{k_{32} \gamma_{32} - k_{22} \gamma_{32}}{k_{22} \gamma_{32} - k_{23} \gamma_{32}} \]

\[ D_{33} = \frac{k_{33} \gamma_{33} - k_{23} \gamma_{33}}{k_{23} \gamma_{33} - k_{22} \gamma_{33}} \]  

(22)

Therefore, in steady-state the apparent power plant will appear as three decoupled processes with gains \( M_{1}, M_{2}, \) and \( M_{3} \):

\[ E = M_{1}v_{1} = K_{11}v_{1} \]

\[ P = M_{2}v_{2} = K_{22}v_{2} \]

\[ L = M_{3}v_{3} = \gamma_{33}v_{3} \]  

(23)

4. **COMPENSATOR FEASIBILITY**

The procedure outlined in Section 3 calculates the compensation factors at the point of operation where the state-space and the transfer matrix models in (10) and (11) were found. Wide-range operation requires knowledge of the compensation factors along any
predefined power-pressure operating policy in the power plant operating space, defined by the set of all feasible points of operation. These points lie between the upper and lower pressure limits shown in Fig. 5, which also shows a constant-pressure and a variable-pressure operating policy.

![Diagram showing constant and variable pressure limits](image)

Fig. 5. Power plant operating space.

Operation above the constant pressure policy is not used because of low process efficiency. Therefore, the zone of interest for investigation is that between the constant pressure and the lower limit policies. Tables 1 and 2 present the decoupling factors along the \((E, P)\) constant pressure and lower limit policies, found with (23). This shows that the compensation factors can be calculated without any trouble in the operating zone of interest. In the next two sections, the degeneracy and sensitivity of the equivalent plant gain matrix is demonstrated (Garduno and Lee, 2002).

| Table 1. Constant pressure compensator factors |
|---|---|---|---|---|---|---|
| \(E\) | \(P\) | \(D_{13}\) | \(D_{13}\) | \(D_{21}\) | \(D_{23}\) | \(D_{31}\) |
| 20 | 140 | -1.13 | 0.17 | 1.42 | 0.0 | 1.56 | -0.31 |
| 40 | 140 | -0.55 | 0.17 | 1.42 | 0.0 | 1.56 | -0.09 |
| 60 | 140 | -0.36 | 0.17 | 1.42 | 0.0 | 1.56 | -0.02 |
| 80 | 140 | -0.27 | 0.17 | 1.42 | 0.0 | 1.56 | 0.01 |
| 100 | 140 | -0.21 | 0.17 | 1.42 | 0.0 | 1.56 | 0.03 |
| 120 | 140 | -0.17 | 0.17 | 1.42 | 0.0 | 1.56 | 0.05 |
| 140 | 140 | -0.14 | 0.17 | 1.42 | 0.0 | 1.56 | 0.06 |
| 160 | 140 | -0.12 | 0.17 | 1.42 | 0.0 | 1.56 | 0.07 |
| 180 | 140 | -0.11 | 0.17 | 1.42 | 0.0 | 1.56 | 0.07 |

| Table 2. Lower limit compensator factors |
|---|---|---|---|---|---|---|
| \(E\) | \(P\) | \(D_{12}\) | \(D_{13}\) | \(D_{21}\) | \(D_{23}\) | \(D_{31}\) |
| 20 | 32 | -0.04 | 0.17 | 7.13 | 0.0 | 1.78 | 0.01 |
| 40 | 36 | -0.02 | 0.17 | 6.20 | 0.0 | 1.76 | 0.02 |
| 60 | 52 | -0.03 | 0.17 | 4.19 | 0.0 | 1.70 | 0.03 |
| 80 | 67 | -0.04 | 0.17 | 3.17 | 0.0 | 1.66 | 0.03 |
| 100 | 82 | -0.06 | 0.17 | 2.55 | 0.0 | 1.63 | 0.04 |
| 120 | 96 | -0.07 | 0.17 | 2.14 | 0.0 | 1.61 | 0.05 |
| 140 | 110 | -0.08 | 0.17 | 1.84 | 0.0 | 1.59 | 0.06 |
| 160 | 124 | -0.09 | 0.17 | 1.62 | 0.0 | 1.57 | 0.07 |
| 180 | 138 | -0.10 | 0.17 | 1.44 | 0.0 | 1.56 | 0.07 |

4.1 Numerical Feasibility

Designing the interaction compensator is equivalent to solve the system of linear equations:

\[
y = Ku = Mv
\]  

for the process input vector, \(u\), in terms of the control signal vector, \(v\):

\[
u = K^{-1}Mv = Dv
\]  

Clearly, if \(K\) is degenerate, decoupling could be very difficult to achieve, and if \(K\) is not full-rank decoupling can not be achieved. Degeneracy of the equivalent plant gain matrix \(K\) can be assessed through its condition number, which is defined as the ratio of the largest to the smallest singular value of the equivalent plant gain matrix:

\[
\text{cn} = \frac{\sigma(\max)(K)}{\sigma(\min)(K)}
\]  

The larger the condition number (>100), the poorer the numerical conditioning of matrix \(K\), that is, the larger its degeneracy. Fig. 6 shows the condition number along the constant pressure and lower limit policies. Clearly, it can be seen that the gain matrix has no degeneracy problems.
The output error $\Delta y$ is inversely proportional to the determinant of the gain matrix, $|K|$. Fig. 7 shows $|K|$ along the constant pressure and lower limit policies. Clearly, it can be seen that $|K|$ is large enough to produce very small output deviations due to modeling errors.

![Graph](image)

Fig. 7. Determinant of equivalent gain matrix.

4.4 Interaction Compensation Simulations

Simulation experiments were carried out to evaluate the response of the power unit. Fig. 8 shows the unit response to a wide-range unit load demand ramp for both compensated and uncompensated cases. The ramp goes from 50% (80 MW) through 100% (160 MW) base load, with a 5%/min (8 MW/min) load rate, which is a rather fast loading according to American standards. Power and pressure responses are both good. However, a meaningful improvement is obtained in the compensated level response throughout the ramp transition, which means the compensator is effectively reducing the interaction among the control loops, thus helping the controllers to achieve their proposed goals.

![Graph](image)

Fig. 8. Response to load ramp. Reference (dotted), uncompensated (dashed), compensated (solid).

Although not shown, it should be mentioned that both the control signals calculated by the controllers ($v_1$, $v_2$, and $v_3$) and those coming out from the interaction compensator ($u_1$, $u_2$, and $u_3$) take allowable values, confirming the feasibility of the approach.

5. SUMMARY AND CONCLUSIONS

This paper presented the feasibility analysis of a compensator to diminish control loop interaction in decentralized control systems to ease wide-range power generation control throughout the power plant operating space. The structure of the proposed interaction compensator was derived from the multivariable case of a feedforward control scheme for disturbance rejection, obtaining a simple inverted decoupling scheme.

The interaction compensator was found to be numerically well-conditioned. The proposed design procedure is a systematic design approach that does not require the solution of an optimization problem, nor years of design experience. Furthermore, its structure provides the compensator with the versatility and necessary characteristics for practical application. Also, the fact that control loops with integrative dynamics can be included in the design without any further complication adds for the generality of the approach. It should be emphasized that this kind of process dynamics are normally avoided by other control strategies such as predictive control. Simulation results demonstrated that inclusion of the control-loop interaction compensator effectively reduced interaction among the feedback control loops, easing their job and improving their effectiveness throughout the power plant operating space.

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7. REFERENCES


