A scenario on Load-Frequency Controller Design
In a Deregulated Power System

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Abstract: An approach based on μ-synthesis and analysis theory is proposed for the design of load frequency controller in response to the new technical control demand for power system in a deregulated environment. In this approach the power system is considered as a collection of separate control areas and each control area can buy electric power from some generation companies to supply the area-load.

The proposed technical scenario is illustrated with application to the design of load-frequency controller for a typical control area. The resulting controller is shown to minimize the effect of disturbances and achieve acceptable frequency regulation in presence of uncertainties and load variation.

Keywords: Load frequency control, Robust control, μ-synthesis, Deregulated power system.

1. Introduction

Any power system has a fundamental control problem of matching real power generation to load plus losses, a problem called Load Frequency Control (LFC) or frequency regulation. The purpose of LFC is tracking of load variation while maintaining system frequency and tie line power interchanges close to specified values.

Currently, the electric power industry is in transition from large, vertically integrated utilities providing power at regulated rates to an industry that will incorporate competitive companies selling unbundled power at lower rates. These changes introduce a set of significant uncertainties in power system control and operation, especially on LFC problem solution.

In vertically integrated power system structure, it is assumed that each bulk generator unit is equipped with secondary control and frequency regulation requirements, but in an open energy market, generation companies may or may not participate in LFC problem. Therefore, in a control area including numerous distributed generators with an open access policy and a few LFC participators, comes the need for novel control strategies to maintain the reliability and eliminates the frequency error.

Under deregulated environment, several notable solutions have already been proposed. ⁶⁻⁹ have reported strategies to adapt well-tested classical LFC schemes to the changing environment of power system operation under deregulation. The H²-based method for a distribution area with two generation units is given in ⁹. ⁹ has proposed the μ-based load frequency controller for the same example. ¹⁰⁻¹¹ discuss on some general issues for solution of LFC problem for power system after deregulation. ¹² has introduced the participation matrix concept to generalized the classic LFC scheme in a deregulated environment.

This paper focuses on technical issues associated with LFC in a restructured power system and addresses the new design of robust load frequency controller based on μ-theory with a possible structure in the competitive environment. The power system structure is considered as a collection of control areas interconnected through high voltage transmission lines or tie-lines. Each control area has its own load frequency controller and is responsible for tracking its own load and honoring tie-line power exchange contracts with its neighbors.

This paper is organized as follows. Section 2 describes the control area modeling. The synthesis methodology and application to a typical distribution control area is given in section 3. Finally some simulation results are given in section 4 to demonstrate the effectiveness of the proposed method.

2. Control area modeling

Consider a typical distribution control area includes 4 Generation companies (Genco) that supply the area-load directly or through the Transmission companies (Transco) as shown in Fig. 1. Without loss of generality, assume Genco1 can be able to generate enough power to satisfy
minimum necessary participation factor to tracking the load and performing the LFC task, and Genco 2, Genco 3
and Genco 4 are the main supplier for area-load. In other word the control-area delivers enough power from Genco
1 and firm power from other Gencos to supply its load and support the LFC task. Connections of this area to other
areas are considered as disturbances (d).

Fig. 1 A control area power system

The state space model of control area can be obtained as

\[ \dot{x} = Ax + Bu + Fw \]

where:

\[ x^T = [x_1 \ x_2 \ x_3 \ x_4 \ x_5] \quad w^T = [\Delta P \ d] \quad u = \Delta P_{ref} \]

\( d \) is the disturbance vector and,

\[ X_i = [\delta_1 \ \delta_2 \ \delta_3 \ \delta_4] ; \quad i = 1, 2, 3, 4 \]

\[ X_s = [\delta_1 \ \delta_2 \ \delta_3 \ \delta_4] \]

where,

\( \delta_1 \): rotor angle, \( \delta_2 \): \( \delta_3 \) = \( \delta_1 \) - \( \delta_3 \)

\( \Delta P \): turbine (mechanical) power, \( f_1 \): frequency,

\( \Delta P \): disturbance (power quantity), \( P_r \): steam valve power,

\( P_{ref} \): reference set-point, \( P_s \): area load.

Analogously to the traditional area control error (ACE), let define the output system variable as follow:

\[ y = Cx + Ew \]

where

\[ C = [C_1 \ C_2 \ \ldots \ C_N \ C_{N+1}] \quad E = [1 \ 0] \]

and,

\[ C_1 = \begin{bmatrix} \beta_1 & 0 & 0 \end{bmatrix} \quad C_{N+1} = \begin{bmatrix} 1 \ \ldots \ 1 \end{bmatrix} \quad i = 1, \ldots, N \]

\( \beta_1 \) is a properly setup coefficient of the secondary regulator and \( \theta \) is a zero vector with the same size of \( d \).

The objective is supplying power to area load at a nominal frequency. Therefore in case of a load disturbance, Genco 1 must adjust its output accordingly to track the load changes and maintain the energy balance.

3. Proposed strategy

3.1 Synthesis framework

To achieve our objectives and according to \( \mu \)-synthesis requirements we have proposed the control strategy applicable for control area shown in Fig. 2. The \( \Delta U \) models the structured uncertainty set in the form of multiplicative type and \( W_U \) includes the associated weighting functions.

![Fig. 2 The controller synthesis framework](image)

According to requirement performance and practical constraint on control action, three fictitious uncertainties \( W_{ref} \), \( W_{r} \) and \( W_{f} \) are added to power system model. The \( W_{ref} \) on the control input sets a limit on the allowed control signal to penalize fast change and large overshoot in the control action. This is necessary in order to guarantee implement ability of the resulting controller. The weights \( W_{ref} \) and \( W_{f} \) at the output set the performance goal e.t. tracking/ regulation on the output area control signal. \( \Delta \) is a diagonal matrix includes \( \Delta P_1 \), \( \Delta P_2 \) and \( \Delta P_3 \), the uncertainty blocks associated with \( W_{ref} \), \( W_{r} \) and \( W_{f} \), respectively.

The synthesis starts with setting the desired level of stability and performance and chosen uncertainties to achieve robust performance. In order to maintain adequate performance in the face of uncertainty and disturbances, the appropriate weighting functions must be used. Actually the inclusion of uncertainties is adequately allow for maximum flexibility in designing the closed loop system characteristics and the demands placed on the controller will increase. We can redraw the Fig. 2 as a standard M-\( \Delta \) configuration, which is shown in Fig. 3.

![Fig. 3 M-\( \Delta \) configuration](image)

\( G \) includes the nominal model of control area (power system), associated weighting functions and scaling factors.
The block labeled M, consists of G and controller K. Now, the synthesis problem is designing the robust controller K. Based on the μ-synthesis, the robust stability and performance holds for a given M-Δ configuration (Fig. 3), if and only if:

\[ \inf_{\omega \in \mathbb{R}} \sup_{\omega} \| M(j\omega) \| < 1. \] (3)

Using the performance robustness condition and the well-known upper bound for μ, the robust synthesis problem reduces to determine

\[ \min_{K, D} \inf_{\omega} \sup_{\omega} \| D M(j\omega) D^{-1} \|, \] or equivalently

\[ \min_{K, D} \| D M(G, K)(j\omega) D^{-1} \|_{\infty}, \]

by iteratively solving for D and K (D-K iteration algorithm) \(^{(4)}\). Here D is any positive definite symmetric matrix with appropriate dimension and \( \min_{\omega} \) denotes the maximum singular value of a matrix. For deeper insights into the theory, the interested reader is referred to \(^{(13-16)}\).

The controller found by this procedure is typically of a high order. In order to decrease the complexity of computation, appropriated model reduction techniques might be applied to the obtained controller model. The proposed strategy guarantees the robust performance and robust stability for closed-loop system. In summary, the proposed method consists of the following steps:

**Step 1:** Identify the uncertainty blocks and associated weighting functions for the given area, according to dynamic model, practical limits and performance requirements, as shown in Fig. 2.

**Step 2:** Isolate the uncertainties from nominal model, generate \( \Delta P_1, \Delta P_2, \Delta P_3 \) and \( \Delta u \) blocks, and performing M-Δ feedback configuration (formulate the robust stability and performance).

**Step 3:** Start the D-K iteration using μ-synthesis toolbox to obtain the optimal controller.

**Step 4:** Reduce the order of result controller by utilizing the standard model reduction techniques and apply μ-analysis to closed loop system with reduced controller to check whether or not upper bound of μ remains less than one.

### 3.2 Design objectives

The nominal open-loop system is stable with one oscillation mode, but simulation results show that the open-loop system performance is affected by changes of per unit inertia constants of Genco 1 and Genco 3 (\( H_1 \) and \( H_2 \)), more significant than changes of other control area parameters within a reasonable range. Eigenvalue analysis shows that the considerable change in these parameters may lead the power system to instability situation. Therefore, here in viewpoint of uncertainty, our focus is concentrated on variation of \( H_1 \) and \( H_2 \) parameters which is important parameter from control issue and it is a source of uncertainty associated with area power system model.

Following we will model this uncertainties as an unstructured multiplicative uncertainty block that containing all the information available about \( H_1 \) and \( H_2 \) variations. It is notable that there isn’t any obligate to consider the uncertainty in the few parameters, only. Considering the more complete model by including additional uncertainties is possible and causes less conservative in synthesis. However the complexity of computations and the order of result controller will increase.

For the problem at hand (Fig. 1), we have set our objectives to control area frequency regulation and assuring the robust stability and performance in presence of specified uncertainties, disturbances and load variation as follow:

1. Holding stability and robust performance in presence of 75% uncertainty for \( H_1 \) and \( H_2 \).
2. Maintaining acceptable overshoot and settling time on frequency deviation and power changing at Gencos' terminals.
3. Minimizing the effectiveness of input step disturbance from outside area (d).
4. Set reasonable limit on control action signal in change speed and amplitude viewpoint.

### 3.3 Selection of weighting functions

**Uncertainty weight selection:** As it is mentioned in previous section, we can consider the specified uncertainty in power system area as a multiplicative uncertainty (\( M_0 \)) associated with nominal model \( G_0(s) \).

Corresponding to a variable parameter, let \( G_0(s) \) denotes the transfer function from the control input \( u \) to control output \( y \) at operating points other than nominal point. Following a practice common in robust control, we will represent this transfer function as

\[ \hat{G}(s) = G_0(s)(1 + \Delta_u(s) W_u(s)) \]

\( \Delta_u(s) \) shows the uncertainty block corresponding to variable parameter and \( W_u(s) \) is the associated weighting function. Then the multiplicative uncertainty block can be expressed as

\[ \| \Delta_u(s) W_u(s) \| = \| \hat{G}(s) - G_0(s) \| G_0(s)^{-1} \| ; \quad G_0(s) \neq 0 \]

\( W_u(s) \) is fixed weighting function containing all the information available about the frequency distribution of the uncertainty, and where \( \Delta_u(s) \) is stable transfer function representing model uncertainty. Furthermore, without loss of generality (by absorbing any scaling factor into \( W_u(s) \) if necessary), it can be assumed that

\[ \| \Delta_u(s) W_u(s) \|_{\infty} = \sup_s |\Delta_u(s)| \leq 1 \]

Thus, \( W_u(s) \) is such that its respective magnitude Bode plot covers the Bode plot of all possible plants. Some sample uncertainties corresponding to different values of \( H_1 \) and \( H_2 \) are shown in Fig. 4. This figure shows the frequency responses of both parametric uncertainties are close to each other. To keep the complexity of obtained controller low, according to above result we can model...
uncertainties due to $H_1$ and $H_2$, variation by using a single, norm bonded, multiplicative uncertainty to cover all possible plants as follows:

$$w(s) = -10(s + 0.04) \frac{s + 15}{s + 1}$$

(7)

The frequency responses of $W_s(s)$ is also shown in Fig. 4. This figure clearly show that attempting to cover the uncertainties at all frequencies and finding a tighter fit using higher order transfer function will result in high-order controller. The weight (7) used in our design provides a conservative design at high frequency but it gives a good tradeoff between robustness and controller complexity.

**Performance weight selection** As we discussed in section 3, in order to guarantee robust performance we need to add to this structure a fictitious uncertainty block $\Delta_p$, along with the corresponding performance weights $W_{p1}$, $W_{p2}$ and $W_{p3}$, associated with the area control error minimization and control effort. In fact an important issue in regard to selection of these weights is the degree to which they can guarantee the satisfaction of design performance objectives.

Based on following discussion, for the problem at hand a suitable set of performance weighting functions that offering a good compromise among all the conflicting time-domain specifications, is:

$$W_{p1}(s) = \frac{0.1s}{0.01s+1}, \quad W_{p2}(s) = \frac{0.005s+1}{35.7s+0.04}, \quad W_{p3}(s) = \frac{0.9s+0.9}{100s+1}$$

(8)

The selection of $W_{p1}$, $W_{p2}$ and $W_{p3}$ entails a tradeoff among different performance requirements. The weight on the control input $W_{p2}$ was chosen close to a differentiator to penalize fast change and large overshoot in the control input. The weights on input disturbance from other areas ($W_{p1}$) and output error ($W_{p3}$) were chosen close to an integrator at low frequencies in order to get disturbance rejection, good tracking and zero steady-state error. Additionally as pointed out in previous section the order of the selected weights should be kept low in order to keep the controller complexity low.

Finally, we know that to reject disturbances and to track command signal properly, it is required that singular value of sensitivity function be reduced at low frequencies, $W_{p1}$ and $W_{p2}$ be such select that this condition satisfied. Fig. 5 shows the inverse magnitude Bode plot of the performance weighting functions $W_{p1}$, $W_{p2}$ and $W_{p3}$.

Our next task is to isolate the uncertainties from the nominal plant model and redraw the system in the standard $\mathcal{M}$-$\Delta$ configuration which is shown in Fig. 6.

As it is mentioned above, the blocks $\Delta_{p1}$, $\Delta_{p2}$ and $\Delta_{p3}$ are the fictitious uncertainties added to assure robust performance, while the block $\Delta$ models the multiplicative uncertainty associated with area model. By using the uncertainty description and performance weights developed in above, we get an uncertainty structure $\Delta$ with a scalar block (corresponding to the uncertainty) and a 3x3 block (corresponding to the performance). Having setup our robust synthesis problem in terms of the standard $\mu$-theory, we used the $\mu$-analysis and synthesis toolbox to obtain a solution.

The controller $K(s)$ is found at the end of the Three D-K
iteration yielding the value of about 0.994 on the upper bound on $\mu$, thus guaranteeing robust performance. The resulting controller has a high order (29th). The controller is reduced to a 6th order with no performance degradation (Fig. 7), using the standard Hankel Norm reduction. The Bode plots of the full-order controller and the reduced-order controller are shown in Fig. 8.

![Bode plot](image)

**Fig. 7** The $\mu$ plot of closed-loop system including reduced controller

![Bode plot](image)

**Fig. 8** Bode plots of original and the reduced-order controller.

### 4. Simulation Results

In order to demonstrate the effectiveness of the proposed method, some simulations were carried out. In these simulations, the proposed load frequency controller was applied to the power system (control area) described in Fig. 1. For simplicity it is assumed that each Genco has one generator unit. The power system parameters are given in Table 1.

![Figure 9](image)

**Fig. 9** Frequency deviation at Gunits, following a 10% load increase.

![Figure 10](image)

**Fig. 10** Change in power supplied to area following a 10% load increase.

Figures 9 and 10 show the frequency deviation and power change signals at Gencos, following a 10% increase in the area-load. In Fig. 9 $\Delta f_1$, ..., $\Delta f_4$ are corresponded to $\Delta f_1$, ..., $\Delta f_4$ at Genco 1, ..., Genco 4, respectively. At steady-state the frequency is back to its nominal value.

![Table 1](image)

**Table 1. Applied data for simulation**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Genco 1</th>
<th>Genco 2</th>
<th>Genco 3</th>
<th>Genco 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating (MW)</td>
<td>1600</td>
<td>600</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Constant of inertia, $H_{\text{c}}$ (sec)</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Damping, $D$ (pu MW/sec)</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.015</td>
</tr>
<tr>
<td>Droop Characteristic %</td>
<td>4.2</td>
<td>5.2</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Generator's $J$, $2H/J$,</td>
<td>0.167</td>
<td>0.134</td>
<td>0.134</td>
<td>0.167</td>
</tr>
<tr>
<td>Turbine's Time Constant, $\tau_d$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Governor's Time Constant, $\tau_g$</td>
<td>0.2</td>
<td>0.1</td>
<td>0.12</td>
<td>0.1</td>
</tr>
<tr>
<td>Gain $K_m, K_m$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Synchronizing coefficient $T_s$</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 11 demonstrates the outside disturbance rejection property of closed loop system. This figure shows the frequency deviation at Gunits following a step disturbance.
of $d=0.01$ pu to area from other area at $t=17$s. Power system is started up with a 10% area-load increase, already.

$\Delta P_L = +10\% ; \ t \in [0 \ 40]s$

d = 0.01 pu ; \ t \in [17 \ 40]s

Fig. 11 Frequency deviation at Gunits if:

$\Delta P_L = +10\% ; \ t \in [0 \ 40]s$ and $d = 0.01$ pu ; $t \in [17 \ 40]s$

Finally, Fig. 12 presents the robustness of closed loop power system in presence of $H_1$ and $H_2$ variation (for worst case) and area-load change, simultaneously. This figure shows the frequency deviation at Gunits for:

$H_1 = H_{\text{min}} , H_2 = H_{\text{max}}, \Delta P_L = +10\% ; \ t \in [0 \ 25]s$

Fig. 12 Frequency deviation at Gunits for

$H_1 = H_{\text{min}} , H_2 = H_{\text{max}}, \Delta P_L = +10\% ; \ t \in [0 \ 25]s$

5 Conclusions

In this paper a new method for robust load frequency controllers using $\mu$-synthesis in a multi-machine power system has been proposed. Design strategy includes enough flexibility to setting the desired level of stability and performance, and, considering the practical constraint by introducing appropriate uncertainties.

The proposed method was applied to a typical multimachine power system including four generator units. Simulation results demonstrated the effectiveness of methodology. It was shown that the designed controller is capable to guarantee the robust stability and robust performance such as precise reference frequency tracking and disturbance attenuation under a wide range of parameter variation and area-load conditions.

References