Bevrani, Hassan (1999) Robust load frequency controller in a deregulated environment: a mu-Synthesis approach. In *Proceedings 1999 IEEE lnternational Conference on Control Applications* 1, pages pp. 616-621, Hawaii, USA.

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Proceedings of the 1999 IEEE
International Conference on Control Applications
Kohala Coast-Island of Hawai'i, Hawai'i, USA • August 22-27, 1999

ROBUST LOAD FREQUENCY CONTROLLER IN A DEREGULATED ENVIRONMENT: A μ-SYNTHESIS APPROACH

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Abstract

An approach based on μ-synthesis tools is proposed for the design of robust load frequency controller for electric power system in deregulated environment.

In this paper, we consider the system (area) as a collection of independent generation, transmission and distribution companies and Connections between this area and the rest of the system are taken as disturbances.

An example is given to illustrate the proposed approach. The resulting controller is shown to minimize the effect of disturbances and achieve acceptable frequency regulation.

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 load frequency control is tracking of load variation while maintaining system frequency and tie line power interchanges close to specified values.

The classical load frequency controllers are designed and tuned for a particular operating point of power system. Closed-loop stability and acceptable performance is only achieved for slight deviations from the nominal operating point.

To overcome the problem of parameter variations and disturbances, a new robust load frequency controller for the new structure of power systems is proposed. In this paper, we consider the system as a collection of independent generation, transmission and distribution companies.

In the new structure, each control area has its own generation and transmission network and is responsible for tracking its own load and honoring tie-line power exchange contracts with its neighbors.

The paper addresses the design of robust load frequency controller based on μ-synthesis technique developed by doyle, [1-2], for interconnected large-scale electric power systems for a possible structure in the new deregulated open-access environment.

Under current organizations, several notable approaches based on classical, optimal, H^∞ and other control theorems have already been proposed [3-12].

In section 2, the main points of μ-theory is given. In section 3 a model for a distribution company is given which is used in section 4 to design a robust μ controller.

2 μ-Analysis and Synthesis

For the sake of completeness, in this section, we will highlight the main points of the μ-theory. For deeper insights into the theory, the interested reader is referred to [1] and [2].

To begin, we consider the feedback control system shown in Figure 1, with the generalized plant G(s), the controller K(s), and the uncertainty block $\Delta(s)$. Here, ω is the exogenous input vector, z is the error output vector, y is the measured output vector, and u is the control input vector to the generalized plant. Given the setup in Figure 1, our goal is to design a controller K(s) that internally stabilizes every perturbed plant in the family and achieves a desired performance criteria by minimizing the upper bound on the norm of z over unit norm disturbances ω; i.e., we stabilize the plant family and satisfy the condition

$$\| T_{z\omega} \|_\infty = \sup_{\omega \in R} \overline{\sigma}(T_{z\omega}(j\omega)) < 1 \qquad (1)$$

where $T_{z\omega}(j\omega)$ is the transfer function matrix from disturbance input ω to the error output z. Note that $\overline{\sigma}(.)$ denotes the maximum singular value of a matrix.

To accomplish our goal using the μ- synthesis technique, we need to present an overview of existing results in the μ-theory. To proceed, consider a square complex matrix M, and the set $\mathbf{B}\Delta$ of complex uncertainties; i.e.,

$$\Delta = \left\{ \mathrm{diag}\left[\delta_1, \dots, \delta_m, \Delta_1, \dots, \Delta_n\right] : \delta_i \in C,\ \Delta_j \in C^{k \times k} \right\}; \quad (2)$$

and $\mathbf{B}\Delta = \{\Delta \in \Delta : \overline{\sigma}(\Delta) \le 1\}$.

Define $\mu_\Delta^{-1}(M)$ as smallest $\overline{\sigma}(\Delta)$ when Δ ranges over $\mathbf{B}\Delta$ and $d=\det[I - M\Delta] = 0$.

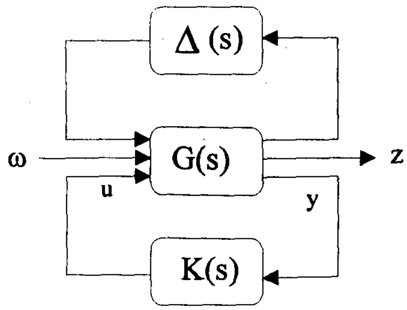


Figure 1: Perturbed feedback control system

Furthermore, let

$$\| M \|_{\mu} = \sup_{\omega \in R} (\mu_{\Delta}(M(j\omega)) \tag{3}$$

and consider the feedback configuration shown in Figure 2. To design a controller that achieves both robust stability and robust performance, we need to perform the following steps:

- Isolate the uncertainty from the nominal model and generate the Δ_{υ} block. Then, perform a lower linear fractional transformation, resulting in the system of Figure 2 with Δ replaced by Δ_{υ}.

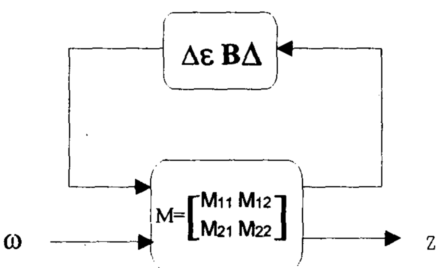


Figure 2: M-Δ Feedback Configuration

Note that the block labeled M, consists of the nominal plant, a controller, the weighting function and scale factor so that $\Delta_{\upsilon} \in \mathbf{B}\Delta$. Under these conditions, the closed-loop system remains stable for all possible perturbations $\Delta_{\upsilon} \in \mathbf{B}\Delta$ if and only if the nominal closed-loop system is stable and

$$\|M_{11}\|_{\mu} < 1. \tag{4}$$

- Formulate the performance criteria in terms of a standard H^{∞} problem. That is interpret the performance specifications in terms of suitable frequency dependent weighting functions in the generalized plant. Then, the nominal performance is assured if

$$\|M_{22}\|_{\infty} < 1. \tag{5}$$

Moreover, in presence of the uncertainty Δ_{υ}, the robust performance is assured if

$$\left\|M_{22} + M_{21}\Delta_U(I - M_{11}\Delta_U)^{-1}M_{12}\right\|_{\infty} < 1. \tag{6}$$

- Include the fictitious performance uncertainty block Δ_P, and redraw the system in the standard " M-Δ" configuration where

$$\Delta(S) = \begin{bmatrix} \Delta_U(s) & 0 \\ 0 & \Delta_P(s) \end{bmatrix} \tag{7}$$

- Based on the μ-theory, the robust performance holds for the generalized uncertainty structure Δ(s), if and only if

$$\|M\|_{\mu} < 1. \tag{8}$$

At this stage, using the performance robustness condition and the well-known upper bound for μ, the robust synthesis problem reduces to solving the following problem: Determine

$$\min_{K} \inf_{D} \sup_{\omega} \bar{\sigma}(D\, M(K) D^{-1}). \tag{9}$$

Equivalently, $\min_{K,D} \| D\, M(K) D^{-1} \|_{\infty}$ (10)

by iteratively solving for D and K. Here D is any positive definite symmetric matrix with appropriate dimension.

- Continue this process until the $\sup_{\omega} \bar{\sigma}(DM(K)D^{-1})$ no longer diminishes.
- Finally, reduce the order of the controller, if possible, by utilizing the standard model reduction techniques.

In Section 4, we shall apply this procedure to design a robust load-frequency controller. Before this can be done, however, we need to have mathematical description of a distribution company.

3 Model Description

Let us consider a simple distribution company and its suppliers as shown in Figure 3, [10]. In this example the distribution company (DISCO) buys firm power from one generation company (GENCO 2) and enough power from other generation company (GENCO 1) to supply its load and support the LFC task. Transmission company (TRANSCO 1) delivers power from GENCO 1. TRANSCO 1 is also contracted to deliver power associated with the LFC problem.

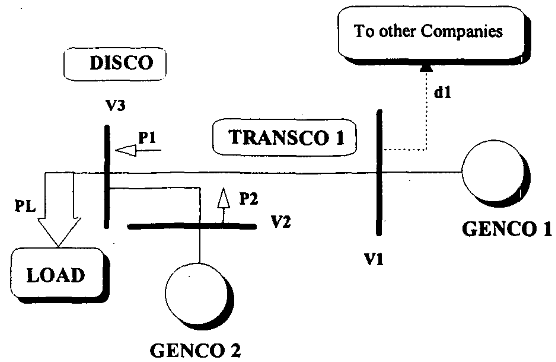


Figure 3: A distribution company and its Suppliers

In the structure proposed the DISCO are to be responsible for tracking the load and hence performing the load frequency control task by securing as much transmission and generation capacity as needed. Connections of the DISCO to other companies are considered as disturbances.

For simplicity assume that GENCOs 1 and 2 have one generator each. The state space realization of the distribution area is given by :

$$\dot{x} = Ax + Bu + Dw \tag{11}$$

where:

$$x^T = [\Delta f_1 \quad \Delta P_{M1} \quad \Delta P_{V1} \quad \Delta\delta_1 - \Delta\delta_2 \quad \Delta f_2 \quad \Delta P_{M2} \quad \Delta P_{V2}]$$
$$w^T = [\Delta P_L \quad d_1] \; ; \; u = \Delta P_{ref1}$$

$$A = \begin{bmatrix} -\frac{D_1}{T_{P1}} & \frac{1}{T_{P1}} & 0 & -\frac{\alpha}{T_{P1}} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{M1}} & \frac{K_{M1}}{T_{M1}} & 0 & 0 & 0 & 0 \\ -\frac{K_{H1}}{R_1 T_{H1}} & 0 & -\frac{1}{T_{H1}} & 0 & 0 & 0 & 0 \\ 2\pi & 0 & 0 & 0 & -2\pi & 0 & 0 \\ 0 & 0 & 0 & \frac{\alpha}{T_{P2}} & -\frac{D_2}{T_{P2}} & \frac{1}{T_{P2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{M2}} & \frac{K_{M2}}{T_{M2}} \\ 0 & 0 & 0 & 0 & -\frac{K_{H2}}{R_2 T_{H2}} & 0 & -\frac{1}{T_{H2}} \end{bmatrix}$$

$$\alpha = \frac{T_1 T_2}{(T_1 + T_2)}, T_{Pi} = \frac{2H_i}{f_0}$$

$$B^T = \begin{bmatrix} 0 & 0 & \frac{K_{H1}}{T_{H1}} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$D^T = \begin{bmatrix} -\frac{T_1}{(T_1+T_2)T_{P1}} & 0 & 0 & 0 & -\frac{T_2}{(T_1+T_2)T_{P2}} & 0 & 0 \\ -\frac{1}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and,

Δ : deviation from nominal value
H_i : constant of inertia
D_i : Damping
f_o : nominal frequency
f_i : frequency
δ_i : rotor angle
P_M : turbine (mechanical) power
d_i : disturbance (power quantity).
P_V : steam valve power
R_i : droop characterisict
P_{refi} : reference setpoint (control input)
T_i : synchronizing power coefficient
T_M and T_H: time constants of turbine and governor
K_M and K_H: gains of turbine and governor

As an example, consider a distribution company as depicted in figure 3. Data is given in Table 1, [10].

Table 1: Data for the simulation

Quantity	GENCO1	GENCO2
Rating (MW)	1000	800
Constant of Inertia: H(sec)	5	5
Damping: D(puMW/Hz)	0.02	0.015
Droop characteristic: R(%)	4	5
Generator's: $T_p = 2H / f_o$	0.2	0.2
Turbine's Time Constant: T_M	0.5	0.5
Governor's Time Constant: T_H	0.2	0.1
Gains: K_M, K_H	1	1
Synchronizing coefficients: T_i	0.2	0.1

4 Design Methodology

The objective is to formulate the LFC problem as an μ-control design problem [2]. The state-space model is based on equation (11), and, let the output variables be given by the Area Control Error (ACE).

We now proceed to design a robust controller using the μ-synthesis approach. The objective is to design a controller that will result in a stable closed-loop system and minimize

5 Simulation Results

Having setup our robust synthesis problem in terms of the standard μ-theory, we use the μ-analysis and synthesis toolbox, [13], to obtain a solution. The controller K(s) is found at the end of the third D-K iteration yielding the value of about 0.9843 on the upperbound on μ. The state space realization of the reduced order controller has the following form :

$$\begin{aligned} \dot{\hat{x}} &= \hat{A}\hat{x} + \hat{B}y \\ u &= \hat{C}\hat{x} + \hat{D}y \end{aligned} \tag{13}$$

The figures below show the simulation results following a 10% load increase in the distribution system. Figure 7 and 8 campare the closed-loop and open-loop frequency deviations at both GENCOs. At steady-state the frequency is back to its nominal value. These figures demonstrate the effectiveness of the proposed design.

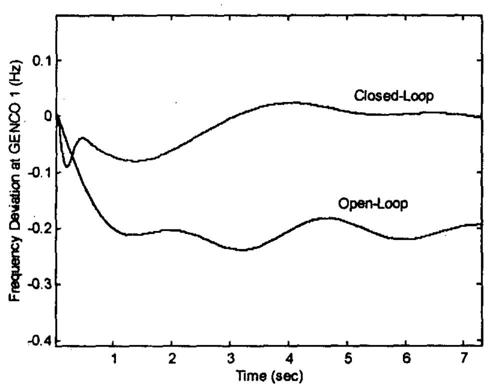


Figure 7: Frequency deviation at GENCO 1 following a 10% load increase.

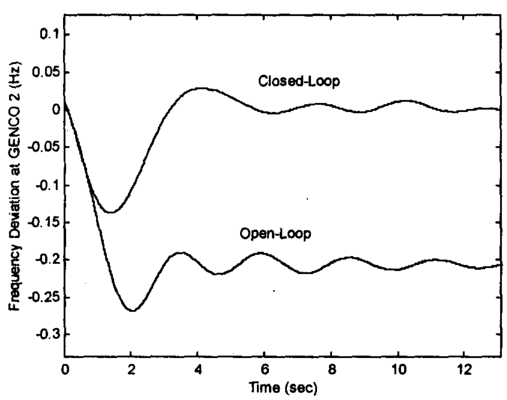


Figure 8: Frequency deviation at GENCO 2 following a 10% load increase.

Figure 9, shows the control signal proposed that it represents the changes in the setpoint of GENCO 1.

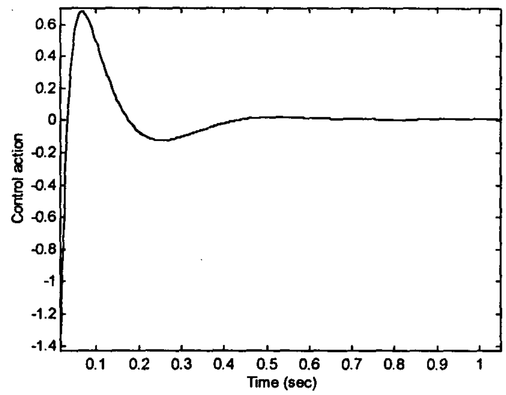


Figure 9: GENCO 1 Controller Following a 10% load increase

Changes in power coming to the distribution company from GENCO 1 and GENCO 2, shows that power is Initially coming from both units to respond to the load increase which will result in a frequency drop that is sensed by the speed governors of both machines. But at steady-state the additional power is coming from GENCO 1 only and GENCO 2 does not contribute to the LFC problem solution.

An important issue concerning the structure of the resulting compensator is its high order; i.e., it is tenth order even after model reduction techniques were employed. This is expected in view our tight design objectives in corporating several simultaneous uncertainties and wide range of input disturbances. Indeed, most robust controllers obtained via this approach display this feature. Note that after reducing the order of result controller (to tenth order) by model reduction techniques, however, the upper bound on μ remains less than one, but it effects on output response. For example, figure 10 shows this fact, following a 2% load Increase in the distribution system.

6 Conclusion

An approach to robust load frequency controller for electric power system for a possible structure in a deregulated environment is proposed using the μ-synthesis tools. The system is modeled as a collection of independent companies with an open access policy.

A simple test system is given to demonstrate the effectiveness of the proposed approach. Based on extensive simulation results, it is verified that all proposed design objectives are met.

the effects of the worst disturbances or exogenous inputs w on the output variables. To meet our objective, we consider the closed-loop interconnection system as shown in figure 4.

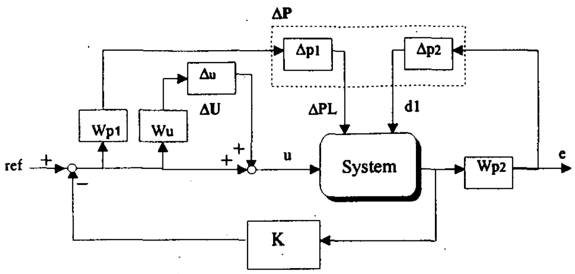


Figure 4: The block diagram for μ-synthesis

Note that there are three uncertainty blocks and associated weighting functions. The block Δ_u model the multiplicatiive uncertainty while the blocks Δ_{pl} and Δ_{p2} are the fictitious uncertainties added to assure robust performance. The robust controller K(s) must be computed to meet design objectives. An important issue in regard to selection of the weights is the degree to which they can guarantee the satisfaction of design objectives. For the problem at hand a suitable set of weighting functions is:

$$w_{pl}(s) = \frac{2\times10^{-5}s}{2\times10^{-7}s+1};\ w_{p2}(s) = \frac{s+0.2}{40(s+0.001)} \qquad (12)$$
$$w_u(s) = \frac{2.5(s+315)}{(s+1000)};$$

In order to keep the complexity of the controller reasonably low, we will cover all multiplicative uncertainties due to parameter variations and unmodelled dynamics with the above first order $w_u(s)$ weight. We choose the weighting function $w_u(s)$ to offset the effect of error incurred in the modelling process, i.e., linearization method. This error starts to become significant at frequencies above 300 rad/sec, and grows large at frequencies above 1000 rad/sec.

To achieve the control objectives, we also need to choose the performance weights $w_{pl}(s)$ and $w_{p2}(s)$, which are associated with the control effort and tracking/regulation error respectively. The selection of $w_{pl}(s)$ and $w_{p2}(s)$ entails a tradeoff among different performance requirements, particularly good regulation versus peak control action. The weight on the control input $w_{pl}(s)$ chosen close to a differntiator to penalize fast change and large overshoot in the control input. The weight on the error $w_{p2}(s)$ was chosen close to an integrator at low frequencies in order to get zero steady-state error and good tracking.

Finally, we know that to reject disturbances and to track command signal property, it is required that singular value of sensitivity function be reduced at low frequencies, $w_{pl}(s)$ and $w_{p2}(s)$ be such select that this condition saticfied.

Figure 5 shows the magnitude Bode plot of the weighting functions $w_u(s)$ and inverse of $w_{pl}(s)$, $w_{p2}(s)$. Our next task is to isolate the uncertainties from the nominal plant model and redraw the system in the standard M-Δ block from shown in figure 6.

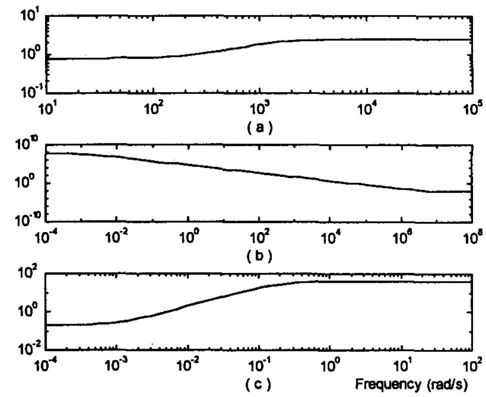


Figure 5: Magnitude plot of the a) Multiplicative uncertainty weighting function $w_u(s)$, b) Inverse of performance weighting function $w_{pl}(s)$, c) Inverse of performance weighting function $w_{p2}(s)$.

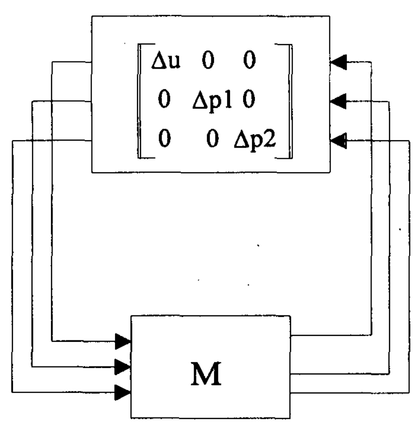
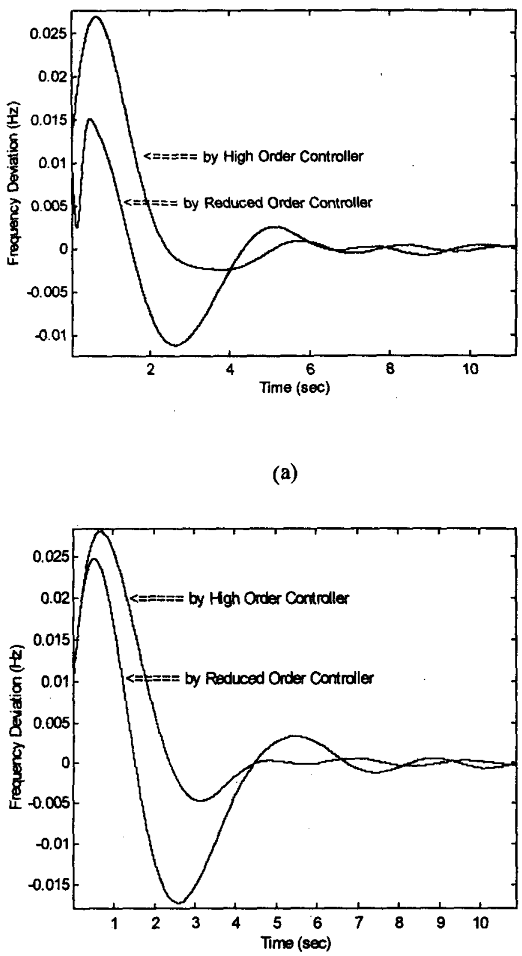


Figure 6: Standard M-Δ block



(a)

(b)

Figure 10: Frequency deviation at a) GENCO1, and b) GENCO2, following a 2% load increase.

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