Bilateral-based LFC Analysis Using a Modified Conventional Model

H. Bevrani[*] and T. Hiyama
Dept. of Electrical and Computer Eng., Kumamoto University, Japan
[*] bevrani@st.eecs.kumamoto-u.ac.jp

Abstract: *This paper addresses a modified dynamical model to analysis of load-frequency control (LFC) in a bilateral-based restructured power system. In a new environment, vertically integrated utilities no longer exist, however the common objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area are remained.*

It is assumed that each distribution company (Disco) is responsible for tracking its own load and honoring tie-line power exchange contracts with its neighbors by securing as much transmission and generation capacity as needed. Therefore the overall power system structure can be considered as a collection of distribution areas as separate control areas interconnected through high voltage transmission lines or tie-lines. A three control areas power system example with possible contract scenarios and load changes is given to illustrate the generalized model.

Keywords: LFC, restructured power system, bilateral contracts, modeling.

1 Introduction

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. In a deregulated environment, load-frequency control (LFC) acquires a fundamental role to enable power exchanges and to provide better conditions for the electricity trading. LFC is treated as an ancillary service essential for maintaining the electrical system reliability at an adequate level.

In an open energy market, generation companies (Gencos) may or may not participate in LFC task. In other hand a distribution company (Disco) may contract individually with a Genco or independent power producers (IPPs) for power in its area or other areas. Currently these transactions are done under the supervision of the independent system operator (ISO), independent contract administrator (ICA) or other responsible organizations.

This paper attempts to give a modified model to adapt well-tested classical LFC scheme to the changing environment of power system operation under deregulation. The main advantage of this strategy is in using the basic concepts of traditional framework and avoid of using the impractical or untested LFC models. 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, Gencos 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 model and efficient control strategies to maintain the reliability and eliminates the frequency error. Here, we introduce a modified dynamical model for traditional LFC model by taken into account the effect of bilateral contracts on the dynamics, following the ideas presented in [1], [2] and [3]. In [1], a traditional-based dynamical model is proposed for two-control area in deregulated environment. We have generalized this idea for a multi-area power system. The new LFC model includes all the information required in a vertically operated utility industry plus the contract data information.

This paper is organized as follows. Section 2 describes the modified traditional LFC structure and proposed dynamical model versus new environment. In order to demonstrate the effectiveness of proposed LFC model, some simulation results for a set of various contract scenarios are given in section 3.

2 Modified Traditional LFC Structure

2.1 Traditional Structure

The traditional LFC is well discussed in [4-5]. In a traditional power system structure, the generation, transmission and distribution is owned by a single entity called vertically integrated utility (VIU) which supplies power to the customers at regulated rates. Usually the definition of a control area is determined by the physical boundaries of a VIU. All such control areas are interconnected by tie lines. In the classical LFC system, the balance between connected areas is achieved by detecting the frequency and tie line power deviations to generate the area control error (ACE) signal which is turn utilized in a simple control strategy *K(s)* such as proportional-integral (PI) as shown in the Fig. 1.

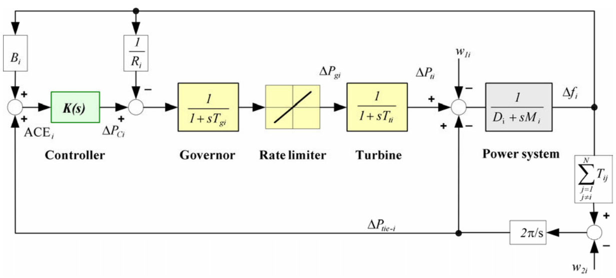

Figure 1: A control area: traditional structure

where,
Δf_i : frequency deviation, ΔP_{gi} : governor valve position, ΔP_{ci} : governor load setpoint, ΔP_{ti} : turbine power, ΔP_{tie-i} : net tie-line power flow, ΔP_{di} : area load disturbance, M_i : equivalent inertia constant, D_i : equivalent damping coefficient, T_{gi} : governor time constant, T_{ti} : turbine time constant, T_{ij} : tie-line synchronizing coefficient between area i & j, B_i : frequency bias, and R_i : drooping characteristic.

In Fig. 1, w_{1i} and w_{2i} can be defined as follow.

$$w_{1i} = \Delta P_{di} \tag{1}$$

$$w_{2i} = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} \Delta f_j \tag{2}$$

Considering these input signals as two disturbance channels will be useful in view point of decentralized controller design. A load disturbance within an area causes the frequency deviation in that area, then the feedback mechanism comes into play and generates appropriate rise/lower signal to the turbine to make generation track the load variation. In the steady state, the generation is matched with the load, driving the tie-line power and frequency deviations to zero. This control structure has well worked in the past.

2.2 Modified Structure

In the restructured power systems, VIU no longer exist, however the common objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area are remained. 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, Gencos 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 modeling strategies to describe the dynamical behaviors of new environment. In [1], a traditional-based dynamical model is proposed for two-control area in deregulated environment. We have generalized this idea for a multi-area power system. The generalized LFC model uses all the information required in a vertically operated utility industry plus the contract data information.

The new power system structure includes separate generation, transmission and distribution companies with an open access policy. Based on bilateral transactions, a Disco has the freedom to contract with any available Genco in its own or another control area. Therefore the concept of physical control area is replaced by virtual control area. The boundary of the VCA is flexible and encloses the Gencos and the Disco associated with the contract.

For simplicity, analogously to the traditional LFC structure, the physical control area boundaries are assumed for each Disco, its distribution area and local Gencos as before. But the Disco may have a contract with a Genco in out of its distribution area boundaries, in another control area. Similar to [6], the general theme in our work is that the loads (the Discos) are responsible for purchasing the services they require. Therefore the overall power system structure can be considered as a collection of distribution areas (Discos) as separate control areas interconnected through high voltage transmission lines or tie-lines. Each control area has its own LFC and is responsible for tracking its own load and honoring tie-line power exchange contracts with its neighbors. All the transactions have to be cleared by the ISO or other responsible organizations. There can be various combinations of contracts between each

Disco and available Gencos. On the other hand each Genco can contract with various Discos. Similar to the Disco participation matrix in [1], let define the "generation participation matrix (*GPM*)" concept to conveniently visualize of these bilateral contracts in the generalized model.

GPM shows the participation factor of each Genco in the considered control areas and each control area is determined by a Disco. The rows of a *GPM* correspond to Gencos and columns to control areas which contract power. For example, for a large scale power system with m control area (Discos) and n Gencos, the GPM will have the following structure. Where gpf_{ij} refers to "generation participation factor" and shows the participation factor of Genco i in the load following of area j (based on a specified bilateral contract).

$$GPM = \begin{bmatrix} gpf_{11} & gpf_{12} & \cdots & gpf_{1(m-1)} & gpf_{1m} \\ gpf_{21} & gpf_{22} & \cdots & gpf_{2(m-1)} & gpf_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ gpf_{(n-1)1} & gpf_{(n-1)2} & \cdots & gpf_{(n-1)(m-1)} & gpf_{(n-1)m} \\ gpf_{n1} & gpf_{n2} & \cdots & gpf_{n(m-1)} & gpf_{nm} \end{bmatrix} \quad (3)$$

The sum of all the entries in a column in this matrix is unity, e. g.

$$\sum_{i=1}^{n} gpf_{ij} = 1 \quad (4)$$

Any entry in a *GPM* that corresponds to a contracted load by a Disco, demanded from the corresponding Genco, must be reflected to the control area system. This introduces new information signals which were absent in the traditional structure [1]. These signals identify which Genco has to follow a load demanded by which Disco. The scheduled track over the tie lines must be adjusted by demand signals of those distribution control areas having a contract with Gencos out of its boundaries. The difference between scheduled and current (actual) tie-line power flows gives a tie-line power error which is used to perform area control error (ACE) signal.

Based on above explanations, the modified LFC block diagram for control area i can be obtained in a deregulated environment as shown in Fig. 2. New information signals due to possible various contracts between Disco i and other Discos and Gencos are shown as dashed-line inputs. Where,

$$\sum_{k=1}^{n} \alpha_{ki} = 1 \quad ; \quad 0 \le \alpha_{ki} \le 1 \quad (5)$$

$$w_{1i} = \Delta P_{Loc\text{-}i} + \Delta P_{di} \quad (6)$$

The input w_{2i} is defined as traditional form (2). We can consider the scheduled ΔP_{tie-i} (w_{3i}) for a N-control area power system as follow.

$$\begin{aligned} w_{3i} &= \sum (Total\ export\ power - Total\ import\ power) \\ &= \sum_{\substack{j=1 \\ j\neq i}}^{N} (\sum_{k=1}^{n} gpf_{kj})\Delta P_{Lj} - \sum_{k=1}^{n} (\sum_{\substack{j=1 \\ j\neq i}}^{N} gpf_{jk})\Delta P_{Li} \end{aligned} \quad (7)$$

According to Fig. 1, we can write

$$\Delta P_{tie\text{-}i,error} = \Delta P_{tie\text{-}i,actual} - w_{3i} \quad (8)$$

and the elements of vector w_{4i} can be expressed as,

$$\begin{aligned} w_{4i\text{-}1} &= \sum_{j=1}^{N} gpf_{1j}\Delta P_{Lj} \\ &\vdots \\ w_{4i\text{-}n} &= \sum_{j=1}^{N} gpf_{nj}\Delta P_{Lj} \end{aligned} \quad (9)$$

where,
α : ACE participation factor, N: number of control areas, ΔP_j : pu demand of area j, ΔP_{Loc-i} : contracted local demand, w_{3i} : scheduled ΔP_{tie-i} ($\Delta P_{tie\text{-}i,scheduled}$), and $\Delta P_{tie\text{-}i,actual}$: actual ΔP_{tie-i} .

The generation of each Genco must track the contracted demands of Discos in steady state. The desired total power generation of a Genco i in terms of GPM entries can be calculated as

$$\Delta P_{mi} = \sum_{j=1}^{N} gpf_{ij}\Delta P_{Lj} \quad (10)$$

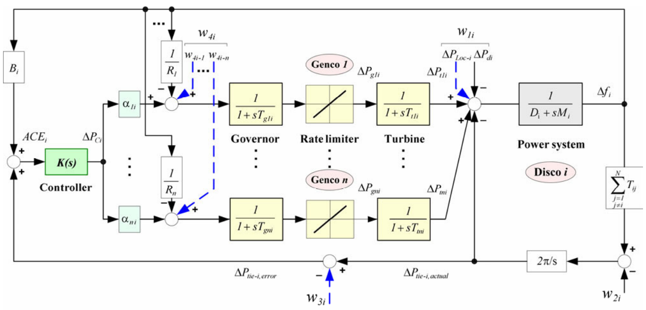

Figure 2: Modified control area in a deregulated environment

In order to taken account the contract violation cases, as like as [3], the excess demand by a distribution area (Disco) is not contracted out to any Genco and the load change in appears only in terms of its ACE and its shared by all the Gencos of the area (in which the contract violation occurs). The validity of above model will be cleared using some simulations cases in the next section.

2.3 State-space Dynamic Model

According to Fig. 2, the state space model for control area i can be obtained as

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_i u_i + F_i w_i \\ y_i &= C_i x_i + D_i w_i \end{aligned} \tag{11}$$

x_i is the state variable vector, w_i is the disturbance input vector and y_i is the measured output vector. Where,

$$x_i^T = \begin{bmatrix} \Delta f_i & \Delta P_{tie-i} & x_{ti} & x_{gi} \end{bmatrix} \tag{12}$$

$$x_{ti} = \begin{bmatrix} \Delta P_{t1i} & \Delta P_{t2i} & \cdots & \Delta P_{tni} \end{bmatrix} \tag{13}$$

$$x_{gi} = \begin{bmatrix} \Delta P_{g1i} & \Delta P_{g2i} & \cdots & \Delta P_{gni} \end{bmatrix} \tag{14}$$

$$u_i = \Delta P_{Ci}\,,\; w_i^{\mathrm{T}} = \begin{bmatrix} w_{1i} & w_{2i} & w_{3i} & w_{4i} \end{bmatrix} \tag{15}$$

$$w_{4i}^{\mathrm{T}} = \begin{bmatrix} w_{4i-1} & w_{4i-2} & \cdots & w_{4i-n} \end{bmatrix} \tag{16}$$

and,

$$A_i = \begin{bmatrix} A_{i11} & A_{i12} & A_{i13} \\ A_{i21} & A_{i22} & A_{i23} \\ A_{i31} & A_{i32} & A_{i33} \end{bmatrix},\; B_i = \begin{bmatrix} B_{i1} \\ B_{i2} \\ B_{i3} \end{bmatrix},\; F_i = \begin{bmatrix} F_{i11} & F_{i12} \\ F_{i21} & F_{i22} \\ F_{i31} & F_{i32} \end{bmatrix}$$

$$A_{i11} = \begin{bmatrix} -D_i/M_i & -1/M_i \\ 2\pi \sum\limits_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 \end{bmatrix},\; A_{i12} = \begin{bmatrix} 1/M_i & \cdots & 1/M_i \\ 0 & \cdots & 0 \end{bmatrix}_{2\times n}$$

$$A_{i22} = -A_{i23} = diag\begin{bmatrix} -1/T_{t1i} & -1/T_{t2i} & \cdots & -1/T_{tni} \end{bmatrix}$$

$$A_{i33} = diag\begin{bmatrix} -1/T_{g1i} & -1/T_{g2i} & \cdots & -1/T_{gni} \end{bmatrix}$$

$$A_{i31} = \begin{bmatrix} -1/(T_{g1i}R_{1i}) & 0 & 0 \\ \vdots & \vdots & \vdots \\ -1/(T_{gni}R_{ni}) & 0 & 0 \end{bmatrix}$$

$$A_{i13} = A_{i21}^{\mathrm{T}} = 0_{2\times n}\,,\; A_{i32} = 0_{n\times n}$$

$$F_{i11} = \begin{bmatrix} -1/M_i & 0 & 0 \\ 0 & -2\pi & 0 \end{bmatrix},$$

$$F_{i21} = F_{i31} = 0_{n\times 2}\,,\; F_{i12} = 0_{2\times n}\,,\; F_{i22} = 0_{n\times n}$$

$$F_{i32} = diag\begin{bmatrix} 1/T_{g1i} & 1/T_{g2i} & \cdots & 1/T_{gni} \end{bmatrix}$$

$$B_{i1} = 0_{2\times 1}\,, B_{i2} = 0_{n\times 1}\,,$$

$$B_{i3}^{\,T} = \begin{bmatrix} \alpha_{1i}/T_{g1i} & \alpha_{2i}/T_{g2i} & \cdots & \alpha_{ni}/T_{gni} \end{bmatrix}$$

The determining of measured output vector y_i and the corresponded matrices C_i and D_i is depend to the designer and it may vary depending to the problem formulation. The above dynamical model will be very useful for LFC synthesis (especially decentralized approaches) under bilateral market organization. In comparison of traditional model (Fig. 1), the complexity of modified LFC structure, mainly because of introducing the new input disturbance channels, is increased. These disturbance channels display the effects of various bilateral contracts.

3 Case Study and Simulation Results

3.1 Case Study

To illustrate the effectiveness of modeling strategy, a three control area power system shown in Fig. 3, is considered as a test system. It is assumed that each control area includes two Gencos and one Disco. The power system parameters are considered the same as given in [9].

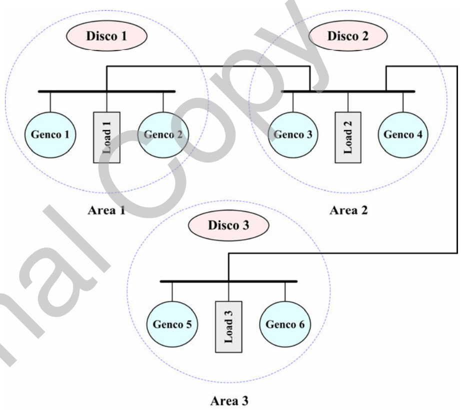

Figure 3: 3-control area power system

3.2 Simulation Results

In order to demonstrate the effectiveness of the generalized LFC model, some simulations were carried out. In these simulations, the following set of pre-tuned simple proportional-integral (PI) controllers were applied to the three control area power system described in Fig. 3. A robust approach for controller synthesis using proposed LFC structure is given in [7].

$$\begin{aligned} K_1(s) &= -0.0025 - 0.0041 \\ K_2(s) &= -0.0012 - 0.0040 \\ K_3(s) &= -0.2915 - 0.0053 \end{aligned} \tag{17}$$

In this section, the validity of modeling is tested for the various possible scenarios of bilateral contracts and load disturbances.

Scenario 1:

A large load disturbance (a step increase in demand) is applied to each area:

$$\Delta P_{L1} = 100\ MW,\; \Delta P_{L2} = 70\ MW,\; \Delta P_{L3} = 60\ MW$$

Assume each Disco demand is sent to its local

Gencos only, based on following GPM.

$$GPM = \begin{bmatrix} 0.5 & 0 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0.5 \\ 0 & 0 & 0.5 \end{bmatrix}$$

Frequency deviation (Δf), power changes (ΔPm) and area control error (ACE) of closed-loop system for areas 1 and 3 are shown in Fig. 4 and Fig. 5. The area control error and frequency deviation of all areas are quickly driven back to zero, the generated power and tie-line power are properly convergence to specified values. As shown in these figures, the actual generated powers of Gencos, according to Equation (10), reach the desired values in the steady state.

$$\Delta P_{m1} = gpf_{11}\Delta P_{L1} + gpf_{12}\Delta P_{L2} + gpf_{13}\Delta P_{L3} \\ = 0.5(0.1) + 0 + 0 = 0.05 \ pu$$

and,

$$\Delta P_{m2} = 0.05, \Delta P_{m3} = \Delta P_{m4} = 0.035, \Delta P_{m5} = \Delta P_{m6} = 0.03 \ pu.$$

Since there are no contracts between areas, the scheduled steady state power flows (Equation (7)) over the tie lines are zero. The actual tie-line powers are shown in Fig. 6.

Scenario 2:

Consider larger demands by Disco 2 and Disco 3 as follows.

$$\Delta P_{L1} = 100 \ MW, \ \Delta P_{L2} = 100 \ MW, \ \Delta P_{L3} = 100 \ MW$$

And assume Discos contract with the available Gencos in other areas, according to the following GPM,

$$GPM = \begin{bmatrix} 0.25 & 0.25 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.25 & 0.75 \\ 0.25 & 0.25 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.25 \end{bmatrix}$$

The closed-loop responses for control area 1 and 2 are shown in Fig. 7 to Fig. 8. According to Equation (10), the actual generated powers of Gencos for this scenario can be obtained as

$$\Delta P_{m1} = 0.25(0.1) + 0.25(0.1) + 0 = 0.05 \ pu \ ,$$

and

$$\Delta P_{m2} = 0.05, \Delta P_{m3} = 0.1 \ , \Delta P_{m4} = 0.05, \Delta P_{m5} = \Delta P_{m6} = 0.025 \ pu.$$

Also, the simulation results show the same values in steady state. The scheduled power tie-lines in the directions from area 1 to area 2 and area 2 to area 3, using Equation (7) are obtained as

$$\Delta P_{tie,1\text{-}2} = (gpf_{12} + gpf_{22})\Delta P_{L2} - (gpf_{31} + gpf_{41})\Delta P_{L1} \\ = (0.25 + 0)0.1 - (0 + 0.25)0.1 = 0 \ pu$$

$$\Delta P_{tie,2\text{-}3} = (0.75 + 0)0.1 - (0.25 + 0)0.1 = 0.05 \ pu$$

Fig. 9 shows actual tie-line powers and they reach to above values at steady state.

Scenario 3:

In this scenario, we simulate the effect of contract violation problem. Consider the scenario 2 again, but assume the Disco 1 demand 50 MW more power than that specified in the contract. As it is mentioned in section 2, this excess power must be reflected as an uncontracted local demand of area 1 and must be supplied by local Gencos, only.

Fig. 10 shows the excess load is taken up by Genco 1 and Genco 2 only, according to their AGC participation factors, and Gencos in other distribution areas do not participate to compensate it. Since GPM is the same as in scenario 2, the generated power of Gencos in area 2 and area 3 is the same as in scenario 2 in steady state.

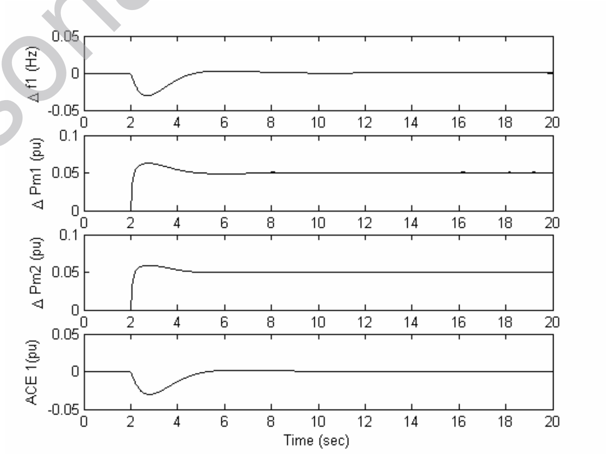

Figure 4: Area-1 responses to scenario 1

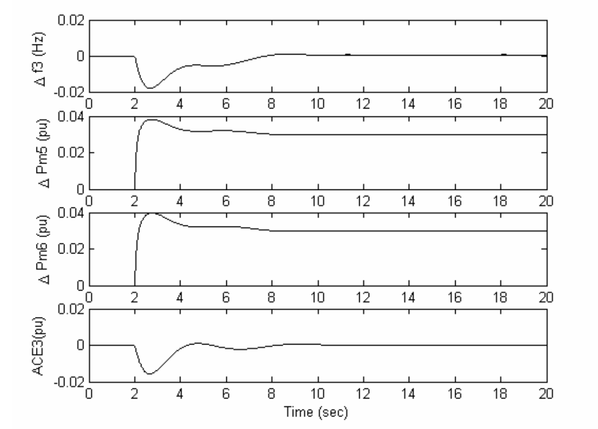

Figure 5: Area-3 responses to scenario 1

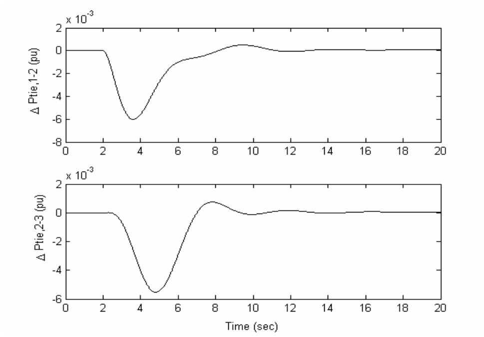

Figure 6: Power tie-line responses to scenario 1

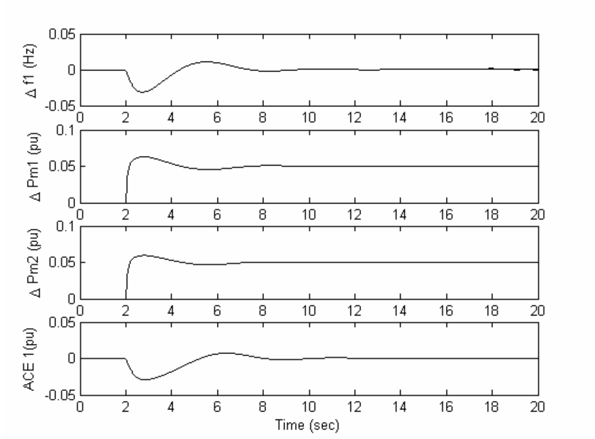

Figure 7: Area-1 responses to scenario 2

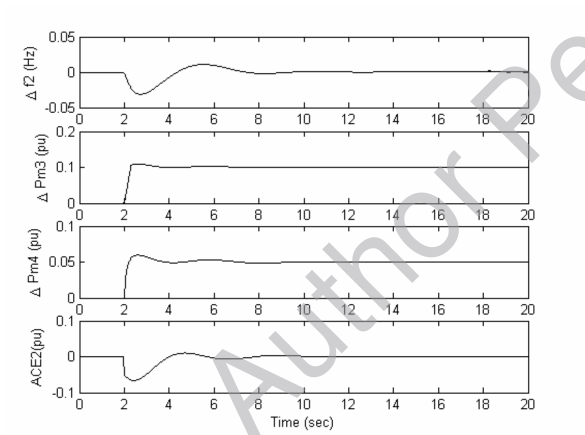

Figure 8: Area-2 responses to scenario 2

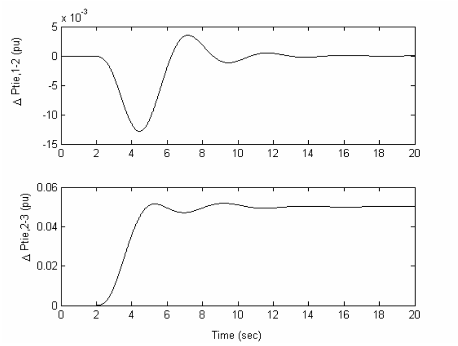

Figure 9: Power tie-line responses to scenario 2

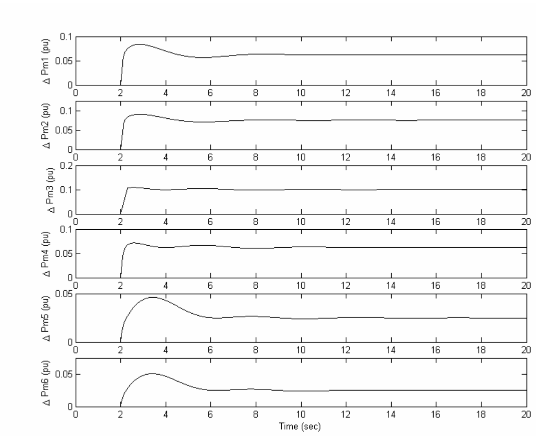

Figure 10: Generated power in responses to scenario 3

4 Conclusion

In this paper, a modeling methodology based on traditional LFC structure is introduced to obtain a more suitable dynamical model for LFC systems in bilateral-based large scale power systems. In order to demonstrate the effectiveness of the generalized model, some simulations were carried out. The proposed model could be useful for both LFC analysis and synthesis purposes.

Acknowledgements

This work is supported in part by Japan Society for the Promotion of Science (JSPS) under grant P04346. Special thanks go to Prof. Y. Mitani from Kyushu Inst. of Technology, Japan and K. Tsuji from Osaka University, Japan for their kind helps and valuable discussion.

References

[1] V. Donde, M. A. Pai and I. A. Hiskens, "Simulation and optimization in a AGC system after deregulation," *IEEE Trans. Power Systems*, vol. 16, no. 3, pp. 481-489, 2001.

[2] J. Kumar, NG. K. Hoe and G. B. Sheble, "AGC simulator for price-based operation, Part 1: A model," *IEEE Trans. Power Systems*, vol.2, no.12, pp. 527-532, 1997.

[3] J. Kumar, NG. K. Hoe and G. B. Sheble, "AGC simulator for price-based operation, case study results," *IEEE Trans. Power Systems*, vol.2, no.12, pp. 533-538, 1997.

[4] O. I. Elgerd, C. Fosha, "Optimum megawatt-frequency control of multiarea electric energy systems," *IEEE Trans. Power Apparatus & Systems*, vol. PAS-89, no. 4, pp. 556-563, 1970

[5] C. Fosha, O. I. Elgerd, "The megawatt-frequency control problem: a new approach via optimal control," *IEEE Trans. Power Apparatus & Systems*, vol. PAS-89, no. 4, pp. 563-577, 1970.

[6] R. D. Chritie, A. Bose, "Load Frequency Control Issues in Power System Operation after Deregulation," *IEEE Trans. Power Systems*, vol.11, no.3, pp. 1191-1200, 1996.

[7] H. Bevrani, Y. Mitani and K. Tsuji, "Robust decentralized LFC design in a deregulation environment," 2nd Int. Conf. on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT), Hong Kong, 2004.

[8] H. Bevrani, Y. Mitani and K. Tsuji, "Robust AGC: Traditional structure versus restructured scheme," IEEJ Trans. On Power and Energy, vol. 124, no. 5, 2004.