Design of Decentralized Neuron Based LFC in a Deregulated Power System

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Abstract: - This paper presents a new decentralized Artificial Neural Network (ANN) controller based on the mixed H_2/H_∞ control technique for Load Frequency Control (LFC) in a deregulated power system. To achieve decentralization, the effects of possible contracted scenarios and interfaces between control areas are treated as a set of new input disturbance signals. In order to account modeling uncertainties, cover practical constraints on control action and minimize the effects of area load disturbances, the idea of mixed H_2/H_∞ control technique is being used for training ANN based controller. This newly developed design strategy combines advantage of the ANN and mixed H_2/H_∞ control techniques for improving robust performance and leads to a flexible controller with simple structure, which can be useful in real world complex power systems. The proposed method is tested on a two-area power system to demonstrate its robust performance with possible contracted scenarios under large load demands and modeling uncertainties. The results of proposed controller are compared with mixed H_2/H_∞ and PI controllers in the presence of Generation Rate Constraints (GRC).

Key-Words: LFC, Decentralized Control, Deregulated Power System, ANN, Mixed H_2/H_∞ control, Robust Control.

1 Introduction

In the restructured power system, Load Frequency Control (LFC) will serve as ancillary service and acquires a principal role to enable power exchanges and to provide better condition for electricity trading [1]. In an open energy market a DISCO has the freedom to have a contract with any GENCO for power transaction in its area or other areas. Currently, all transactions have to be cleared through Independent System Operator (ISO) or other responsible organizations.

In a real world deregulated power system, each control area contains different kinds of uncertainties and various disturbances due to increasing the complexity, system modeling errors and changing power system structure. As a result, a fixed controller based on classical theory is certainly not suitable for LFC problem. Thus, it is required that a flexible controller is developed. Recently, several optimal and robust control strategies have been developed for LFC synthesis according to change of environment in power system operation under deregulation [2-6]. The proposed methods show good dynamical response, but robustness in the presence of modeling uncertainties and system nonlinearities were not considered. Also, some authors suggest complex state feedback or high order dynamical controllers, which are not practical for industry practices.

In this paper, a new decentralized Artificial Neural Network (ANN) controller is developed based on the mixed H_2/H_∞ control technique for LFC problem in an open energy market. Following the idea presented in Ref. [7] a generalized model for LFC scheme is developed based on the possible contracted scenarios in deregulated environments. To achieve decentralization, the effects of possible contracted scenarios and interface between areas is treated as a set of new input disturbance signals in each control area. LFC goals, i.e. frequency regulation and tracking the load demands, maintaining the tie-line power interchanges to specified values in the presence of model uncertainties and Generation Rate Constraints (GRC) determines the LFC synthesis as a multi-objective optimization problem. Thus, first the LFC problem is formulated as a multi objective optimization problem via a mixed H_2/H_∞ control technique and solved by linear Matrix Inequalities (LMI) approach to obtain optimal controllers. Then, these controllers are reconstructed by using learning capability of neural networks to obtain the desired level of robust performance in different operating conditions. The main feature of ANN based controller is that it provides a non-model based control system and do not require the accurate model of the plant. The proposed strategy is tested on a two-area power system for two scenarios in the presence of model uncertainties and GRC under various load changes. The results show that the proposed method guarantees the robust performance for various operating conditions and superior to the mixed H_2/H_∞ and conventional PI controllers.

2 Generalized LFC Scheme Model

The deregulated power system consists of three companies, GENCOs, TRANCOs and DISCOs with an open access policy. In this environment, GENCOs may or may not participate in the LFC task and DISCOs have the liberty to contract with any available GENCOs in their own or other areas. This makes various combinations of possible contracted scenarios between DISCOs and GENCOs.

All the transactions have to be cleared by the ISO or the other responsible organizations. Thus, it is desirable that a new model for LFC scheme is developed in order to account effects of possible contracts on dynamics. Here, we introduce the concept of an '*Augmented Generation Participation Matrix*' (AGPM) to express these possible contracts following the idea presented in Ref. [7]. The AGPM shows the participation factor of a GENCO in the load following contract with a DISCO. The rows and columns of AGPM matrix is equal with the total number of GENCOs and DISCOs in the overall power system, respectively. Consider the number of GENCOs and DISCOs in area i be n_i and m_i in a large scale power system with N control area. The structure of AGPM is given by:

$$AGPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix} \tag{1}$$

where,

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

$$s_i = \sum_{k=1}^{i-1} n_i \,,\; z_j = \sum_{k=1}^{j-1} m_j \,, \quad i, j = 2,\cdots,N \quad \& \quad s_1 = z_1 = 0$$

Which in gpf_{ij} refer to '*generation participation factor*' and shows the participation factor GENCO i in total load following requirement of DISCO j based on the possible contract. The sum of all entries in each column of AGPM is unity. The diagonal sub-matrices of AGPM correspond to local demands and off-diagonal sub-matrices correspond to demands of DISCOs in one area to GENCOs in another area. Fig. 1 shows the block diagram of generalized LFC scheme for control area i in a restructured structure. The nomenclature used is given in Appendix A. Dashed-dot lines show interfaces between areas and the demand signals based on the possible contracts. These new information signals were absent in the traditional LFC scheme. As there are many GENCOs in each area, ACE signal has to be distributed among them according to their ACE participation factor in the LFC task and $\sum_{j=1}^{n_i} apf_{ji} = 1$.

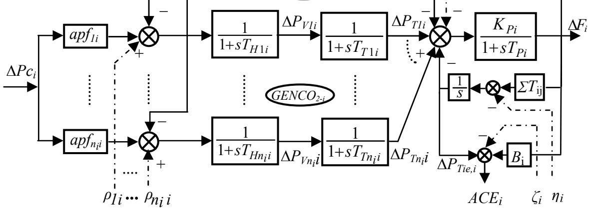

Fig. 1. Generalized LFC scheme for area i in the deregulated environment

From Fig.1, it can see that d_i, ζ_i, η_i and ρ_i as four input disturbance channels are considered for decentralized LFC design and defined as follows:

$$d_i = \Delta P_{Loc,i} + \Delta P_{di} \quad , \quad \Delta P_{Loc,i} = \sum\nolimits_{j=1}^{m_i} (\Delta P_{Lj-i} + \Delta P_{ULj-i}) \tag{2}$$

$$\eta_i = \sum_{j=1 \,\&\, j \neq i}^{N} T_{ij} \Delta f_j \tag{3}$$

$$\zeta_i = \sum_{k=1 \,\&\, k \neq i}^{N} \Delta P_{tie,ik,sch} \tag{4}$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n_i} \sum_{t=1}^{m_k} apf_{(s_i+j)(z_k+t)} \Delta P_{L(z_k+t)-k} - \sum_{t=1}^{n_k} \sum_{j=1}^{m_i} apf_{(s_k+t)(z_i+j)} \Delta P_{L(z_i+j)-i} \tag{5}$$

$$\Delta P_{tie,i-error} = \Delta P_{tie,i-actual} - \zeta_i \tag{6}$$

$$\rho_i = [\rho_{1i} \ldots \rho_{ki} \ldots \rho_{n_i i}]^T \,, \quad \rho_{ki} = \Delta P_{m,k-i} \tag{7}$$

$$\Delta P_{m,k-i} = \sum_{j=1}^{z_{N+1}} gpf_{(s_i+k)j} \Delta P_{Lj-i} + apf_{ki} \sum_{j=1}^{m_i} \Delta P_{ULj-i} \quad , k = 1,2,\cdots,n_i \tag{8}$$

$\Delta P_{m,k-I}$ is the desired total power generation of a GENCO k in area i and must track the demand of the DISCOs in contract with it in the steady state. Due to Fig.1, the state space model for area i can be obtained as:

$$\begin{aligned} \dot{\boldsymbol{x}}_i &= \boldsymbol{A}_i \boldsymbol{x}_i + \boldsymbol{B}_{iu} \boldsymbol{u} + \boldsymbol{B}_{iw} \boldsymbol{w}_i' \\ \boldsymbol{y}_i &= \boldsymbol{C}_i \boldsymbol{x}_i + \boldsymbol{D}_{iw} \boldsymbol{w}_i' \end{aligned} \tag{9}$$

where,

$$x_i^T = [x_{ai} \; x_{1i} \ldots x_{ki} \ldots x_{n_i i}], \; x_{ai} = [\Delta f_i \; \Delta P_{tie,i}]$$

$$x_{ki} = [\Delta P_{Tki} \; \Delta P_{Vki}], \; k = 1,\ldots,n_i \,,\, u_i = \Delta P_{ci} \,,\, y_i = ACE_i$$

$$w_i' = [d_i \quad \eta_i \quad \xi_i \quad \rho_i]^T \,, \rho_i = [\rho_{1i} \ldots \rho_{ki} \ldots \rho_{n_i i}]$$

$$A_i = \begin{bmatrix} A_{11i} & A_{12i} \\ A_{21i} & A_{22i} \end{bmatrix}, \; A_{11i} = \begin{bmatrix} 1/T_{Pi} & -K_{Pi}/T_{Pi} \\ \sum_{j=1\&j\neq i}^{N} Tji & 0 \end{bmatrix}, A_{12i} = \Bigg[\underbrace{\begin{pmatrix} K_{Pi}/T_{Pi} & 0 \\ 0 & 0 \end{pmatrix} \cdots \begin{pmatrix} K_{Pi}/T_{Pi} & 0 \\ 0 & 0 \end{pmatrix}}_{n_i \, blocks} \Bigg]$$

$$A_{21i} = [DP_{1i}^T \ldots DP_{ki}^T \ldots DP_{n_i i}^T], \; A_{22i} = diag(TG_{1i}, \ldots, TG_{ki}, \ldots, TG_{n_i i})$$

$$DP_{ki} = \begin{bmatrix} 0 & 0 \\ -1/(R_{ki} T_{Hki}) & 0 \end{bmatrix}, TG_{ki} = \begin{bmatrix} -1/T_{Tki} & 1/T_{Tki} \\ 0 & -1/T_{Hki} \end{bmatrix}$$

$$B_{iu}^T = [0_{2\times 1}^T \quad B_{1iu}^T \ldots B_{kiu}^T \ldots B_{n_i iu}^T], \; B_{kiu} = [0 \quad apf_{ki}/T_{Hki}]^T, B_{iw}^T = [B_{aiw}^T \quad B_{1iw}^T \ldots B_{kiw}^T \ldots B_{n_i iw}^T]$$

$$B_{aiw} = \begin{bmatrix} -K_{Pi}/T_{Pi} & 0 & 0_{1\times(n_i+1)} \\ 0 & -1 & 0_{1\times(n_i+1)} \end{bmatrix}, B_{kiw} = \begin{bmatrix} 0_{1\times 3} & 0 \ldots 0 \ldots 0 \\ 0_{1\times 3} & b_{1i} \ldots b_{ki} \ldots b_{n_i i} \end{bmatrix}, \; b_{ji} = \begin{cases} -1/T_{Hki} & j = k \\ 0 & j \neq i \end{cases}$$

$$C_i = [C_{ai} \quad 0_{1\times 2n_i}], C_{ai} = [B_i \quad 1], D_{wi} = [0_{1\times 2} \quad -1 \quad 0_{1\times n_i}]$$

3 Mixed H_2/H_∞ Based LFC Formulation

In the real world LFC problem, we are simultaneously following multi objectives such as stability, disturbance attention and reference tracking under model uncertainties and practical constraints. Meeting all LFC design objectives by single control approach due to increasing the complexity and change of the power system structure is difficult. Thus, the idea of mixed H_2/H_∞ control technique is being used to solve of LFC problem, which gives a powerful multi-objectives design addressed by the LMI techniques [8]. Fig. 2 shows the main synthesis framework for formulation LFC problem as a mixed H_2/H_∞ control design for a given control area (Fig. 1).

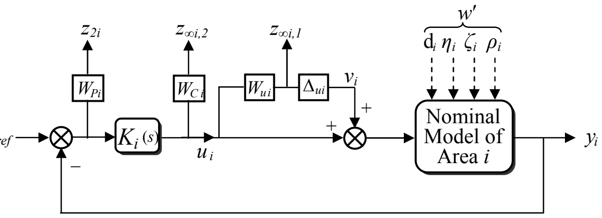

Fig. 2. The proposed synthesis framework

In restructured power systems, each control area contains different kinds of uncertainties because of plant parameter variations, load changes and system modeling errors due to some approximations in model linearization and unmodeled dynamics. Usually, the uncertainties in power system can be modeled as multiplicative and/or additive uncertainties [9]. In Fig. 2 the Δu_i block models the structured uncertainties as a multiplicative type and Wu_i is the associated weighting function.

The output channels $z_{\infty i,1}$ and $z_{\infty i,2}$ are associated with H_∞ performance. The first channel is used to meet robustness against uncertainties and reduce their impacts on close loop system performance. In the second channel ($z_{\infty i,2}$) W_{Ci} sets a limit on the allowed control signal to penalize fast change and large overshoot in the control action signal with regard to practical constraints. The output channel z_{2i} is associated with the H_2 performance and W_{pi} sets the performance goal i.e. zero tracking error and minimizing the effects of disturbances on the area control error (ACE$_i$). We can redraw the Fig. 2 as a mixed H_2/H_∞ general framework synthesis as shown in Fig. 3, where $P_{oi}(s)$ and $K_i(s)$ denote the nominal area model as given by Eq. (9) and controller, respectively. Also, y_i is the measured output (performed by ACE$_i$), u_i is the control output and w_i includes the perturbed, disturbance and reference signals in the control area.

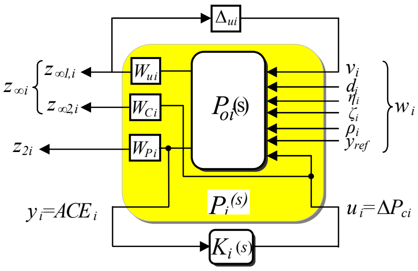

Fig. 3. The formulation of mixed H_2/H_∞ based control design problem

In Fig. 3, $P_i(s)$ is the augmented plant (AP) that includes nominal model of control area i and associated weighting functions. The state-space model of AP can be obtained as:

$$\begin{aligned} \dot{x}_{APi} &= A_{APi}x_{APi} + B_{1i}w_i + B_{2i}u_i \\ z_{\infty i} &= C_{\infty i}x_{APi} + D_{\infty 1i}w_i + D_{\infty 2i}u_i \\ z_{2i} &= C_{2i}x_{APi} + D_{21i}w_i + D_{22i}u_i \\ y_i &= c_{yi}x_{APi} + D_{y1i}w_i \end{aligned} \tag{10}$$

where,

$w_i^T = [v_i \quad d_i \quad \eta_i \quad \zeta_i \quad \rho_i \quad y_{ref}]$, $z_{\infty i}^T = [z_{\infty 1i} \quad z_{\infty 2i}]$

Now, due to Fig. 3 the synthesis problem can be expressed by the following optimization problem: design a controller $K_i(s)$ that minimize a trade off criterion of the form:

$$\gamma_1 \|T_{\infty i}(s)\|^2 + \gamma_2 \|T_{2i}(s)\|^2 \qquad (\gamma_1 \,\&\, \gamma_2 \geq 0) \tag{11}$$

Where $T_{\infty i}(s)$ and $T_{2i}(s)$ are the transfer functions from w_i to $z_{\infty i}$ and z_{2i}. An efficient algorithm for solving this problem is available in LMI control toolbox of MATLAB [10].

4 ANN Based Controller Design

Nowadays artificial neural networks with their massive parallelism and ability to learn any type of nonlinearity are widely used in different branches of science and industry, especially in designing of the very practical control problems [16]. Here, we address a new ANN controller based on the mixed H_2/H_∞ control technique for solution LFC problem. This new hybrid structure is being used to take both the advantages of neural networks and mixed H_2/H_∞ control technique. Fig. 4 shows the main framework formulation of the ANN design problem for a given control area.

The ANN controller architecture employed here is a Multi Layer Perceptron (MLP) neural network, which is a three layer perceptorn with two inputs, 5 neurons in the hidden layer and one output. This architecture provides best performance and has chosen after a series of trial-error and modifications. The ACE$_i$ and the rate of change of ACE$_i$ are chosen as the ANN-based controller inputs. The controller output is the control signal and applies to the governor load set point in each area. The main advantages of this controller are: providing a model free description of control system and not requiring an accurate model of the plant. Thus, it is very suitable to control of the deregulated power systems which their models are unknown or have uncertainties.

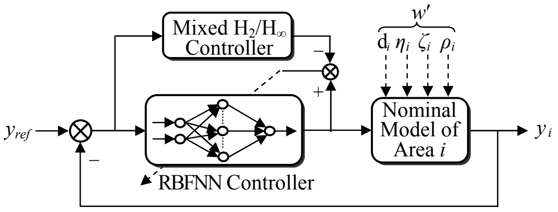

Fig. 4. The proposed ANN based LFC design problem

For training the proposed controller, first the LFC problem is formulated as a decentralized mixed H_2/H_∞ optimization control problem and designed in different operation conditions. Then, the training and test data are obtained with applying these controllers to power system in the presence of GRC in different operating conditions under possible contracts and various load changes. The back propagation algorithm and root mean square (RMS) error criterion are being used for training the proposed network and to evaluate the learning performance. In summary, the designing steps of the ANN controllers are follows as:

Step 1: Formulation LFC problem as a decentralized mixed H_2/H_∞ optimization control problem and designing mixed H_2/H_∞ controllers in different operating conditions.

Step 2: Applying mixed H_2/H_∞ controllers to real power system for obtaining training and test data in the presence of GRC in different operating points.

Step 3: Training the neural networks by using BPP algorithms due to Fig. 4 and testing it.

The design strategy includes enough flexibility to set the desired robust performance and gives flexible controller with simple structure. Due to its practical merit, the proposed method is a decentralized LFC scheme and requires only the ACE. Thus, its construction and implementation are fairly easy and can be used in the real world power systems.

5 Case Study

A two control area power system, shown in Fig. 5 is considered as a test system to illustrate effectiveness of the proposed control strategy. It is assumed that each control area includes two GENCOs and DISCOs. The power systems parameters are considered the same as Ref. [6].

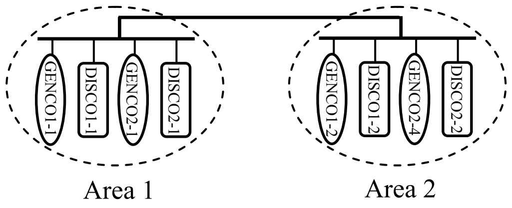

Fig. 5. Two area power system

Uncertainty weights selection: simulation results and eigenvalue analysis show that the open loop system performance is affected by changing in the K_{pi}, T_{pi}, B_i and T_{jj} more significantly than changes of other parameters. Thus, it is assumed that these parameters have uncertain values in each area and variation range is considered as ±50%. These uncertainties are modeled as an unstructured multiplicative uncertainty (Wu_i) block (Fig. 2) that contains all the information available about the K_{pi}, T_{pi}, B_i and T_{jj} variations. Let $\hat{P}_i(s)$ denote the transfer function from the control input u_i to control output y_i at operating points other than the nominal point. Following a practice common in robust control, we will represent this transfer function as:

$$|\Delta u_i(s)W_i(s)| = |(\hat{P}_i(s) - P_{oi}(s))/P_{oi}(s)|; \quad P_{oi}(s) \neq 0 \tag{12}$$

$$\|\Delta u_i(s)\|_\infty = \sup|\Delta u_i(s)| \leq 1$$

$\Delta u_i(s)$ shows the uncertainty block corresponding to the uncertain parameters and $P_{oi}(s)$ is the nominal transfer function model. Thus, $W_{ui}(s)$ is such that its respective magnitude Bode plot covers the Bode plot of all possible plants. Using Eq. (12) some sample uncertainties corresponding to different values of K_{pi}, T_{pi}, B_i and T_{jj} are shown in Fig. 6 for one area. Based on this figure, the following multiplicative uncertainty weight was chosen for control design:

$$W_{u1} = \frac{5.35s^2 + 36.32s + 2.87}{s^2 + 0.57s + 45.40} \tag{13}$$

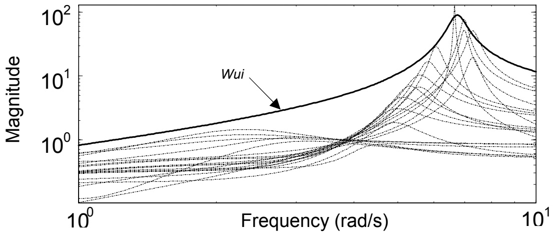

Fig. 6. Uncertainty plot due to change of K_{pi}, T_{pi}, B_i and T_{jj} and $W_{ui}(s)$

Using the same method the weighting function of area 2 is obtained which is identical with area 1.

Performance weights selection: The selection of performance weights W_{Ci} and W_{Pi} entails a trade off among different performance requirements, particularly good area control error minimization versus peak control action. The W_{Ci} must be chosen close to a differentiator to penalize fast change and large overshoots in the control input due to corresponding practical constraints and the W_{Pi} must be chosen close to an integrator at low frequency in order to get disturbance rejection and zero steady state error. Based on the above discussion, a suitable set of performance weighting functions for each two areas is chosen as:

$$W_{Ci} = \frac{0.3s + 1}{s + 10}, \quad W_{Pi} = \frac{0.03s + 0.75}{250s + 1} \tag{14}$$

Mixed H_2/H_∞ based control design: according to the problem formulation and synthesis methodologies as given in Sec. 3, a set of two decentralized robust controller is designed using the *hinfmix* function in the LMI control toolbox with optimization problem Eq. (11) which in γ_1 and γ_2 is fixed in unity. The resulting controllers are dynamic type and whose orders are the same as the size of the AP model (here 8). It should be noted, although via the mixed H_2/H_∞ technique the uncertainty and performance objectives can be introduce in the control synthesis, but due to large model order of real world power systems, these methods yield complex controllers whose size will be very large in general.

As the next step, according to the synthesis procedure described in Sec. 4, a set of two decentralized ANN controller based on the mixed H_2/H_∞ technique designed. This control strategy that has modern adaptive control structure is simple and suitable for LFC applications. The main feature of the proposed method is to use the learning capability and advantage of mixed H_2/H_∞ control technique for achieving robust performance against uncertainties and disturbances.

6 Simulation Result

In the simulation study, the linear model of a turbine $\Delta P_{VKi}/\Delta P_{TKi}$ in Fig. 1 is replaced by a nonlinear model of Fig. 7 (with ±0.015 limit). This is to take GRC into account, i.e. the practical limit on the rate of change in the generating power of each GENCO. Simulations are carried out for two scenarios of possible contracts under uncertainties and large load demands. The performance of proposed ANN-based controllers is compared with the mixed H_2/H_∞ and conventional PI controllers which is widely used for LFC system in practical industry.

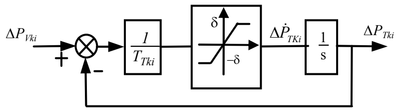

Fig. 7. A nonlinear turbine model with GRC

Scenario 1: Combination of Poolco Based and Bilateral Transactions

In this case, DISCOs have the freedom to have a contract with any GENCO in their and other areas. It is assumed that each DISCO demands 0.1 puMw power from GENCOs and ACE participation factor of each GENCO in LFC is defined as follows: $apf_1= 0.75$, $apf_2=0.25$, $apf_3=0.5$, $apf_4=0.5$. Consider the all the DISCOs contract with the available GENCOs for power as per the following AGPM:

$$AGPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 025 & 0 & 0 \end{bmatrix}$$

The power system responses are shown in Fig. 8, whereas the uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} in each area increase 50% from nominal values. Using the proposed method the frequency deviation of two areas are quickly driven back to zero and the tie-line power flow properly converge to the specified value Eq. (5) in the steady state. i.e.: $\Delta P_{tie,12,sch}=-0.05pu$ The actual generated powers of GENCOs reach the desired values in the steady state as given by Eq. (8). i.e.:

$$\Delta P_{m,1\text{-}1}=0.105,\ \Delta P_{m,2\text{-}1}=0.095,\ pu\ MW$$
$$\Delta P_{m,1\text{-}2}=0.195,\ \Delta P_{m,2\text{-}2}=0.055,\ pu\ MW$$

Scenario 2: Contract Violation

In this case, it may happen that a DISCO violates a contract by demanding more power than that specified in the contract. This excess power must be reflected as a local load of the area but not as the contract demand and taken up by the GENCOs in the same area. Consider scenario 2 again with a modification that DISCO 1 of area 1 demands 0.1 pu MW of excess power. Due to Eq. (2), the total local load in areas 1 and 2 is computed as:

$$\Delta P_{Loc,1}=\Delta P_{L1\text{-}1}+\Delta P_{L2\text{-}1}+\Delta P_{U1\text{-}1}+\Delta P_{U2\text{-}1}= 0.1+0.1+0.1+0= 0.3\,pu\ \mathrm{MW}$$
$$\Delta P_{Loc,2}=\Delta P_{L1\text{-}2}+\Delta P_{L2\text{-}2}+\Delta P_{U1\text{-}2}+\Delta P_{U2\text{-}2}= 0.1+0.1+0+0= 0.2\,pu\ \mathrm{MW}$$

The power system responses in this case are depicted in Fig. 9, whereas the uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} in each area increase 50% from nominal values. Using the proposed method, the frequency deviation of area 1 is quickly driven back to zero and the tie-line power flow properly converges to the specified value Eq. (5) in the steady state. i.e.: $\Delta P_{tie,12,sch}=-0.05pu$.

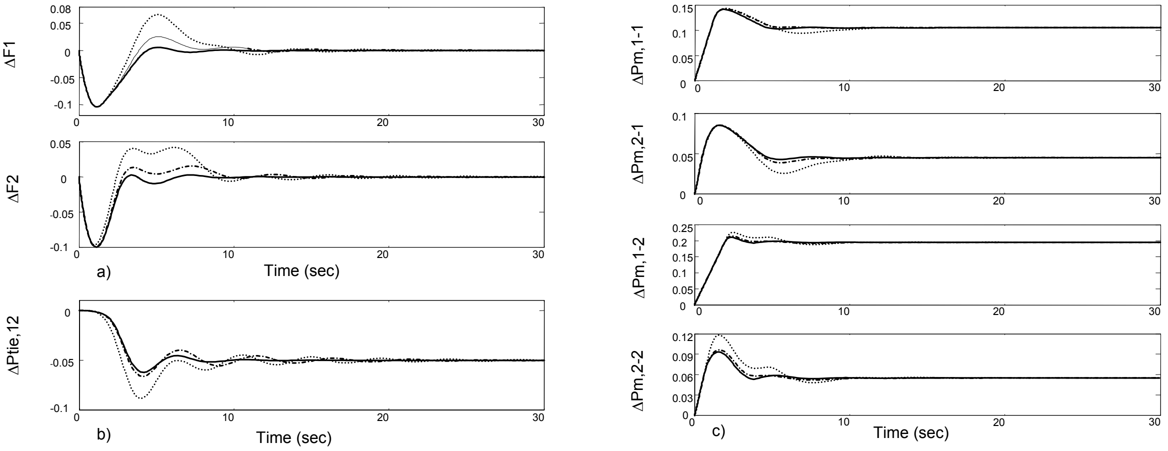

Fig. 8. Power system responses to scenario 1: Soiled (ANN), Dashed-dotted (H_2/H_∞) and Dotted (PI)
a) Frequency deviation b) Tie line power deviation c) GENCOs Power

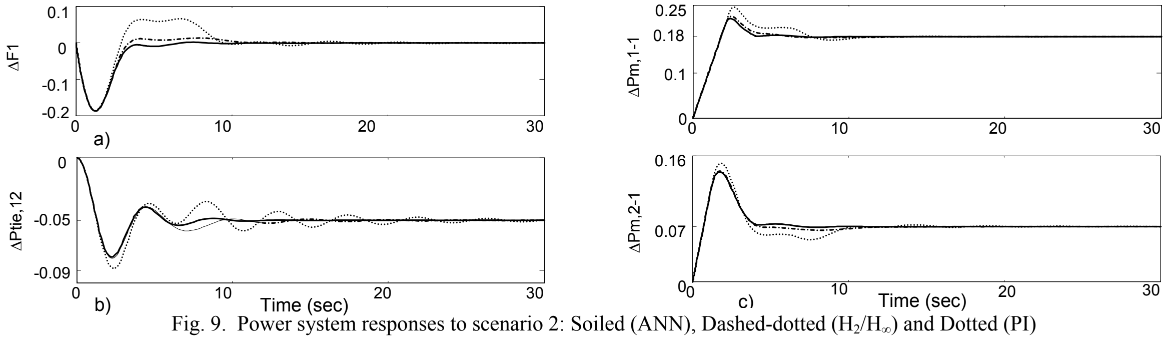

Fig. 9. Power system responses to scenario 2: Soiled (ANN), Dashed-dotted (H_2/H_∞) and Dotted (PI)
a) Frequency deviation in area 1 b) Tie line power deviation c) GENCOs Power in area 1

As AGPM is the same as in scenario 2 and the excess power is taken up by the GENCOs in the same area, the tie-line power is the same as in scenario 2 in the steady state (Fig. 9-b). Also, the generated power of GENCOs in area 2 is not affected by the excess load of $DISCO_{1-1}$ (refer to scenario 2). The un-contracted load of $DISCO_{1-1}$ is taken up by the GENCOs in area 1 according to ACE participation factors in the steady state. Due to Eq. (8) the actual generated powers of GENCOs in area 1 are given by:

$$\Delta P_{m,1-1}=0.18,\ \Delta P_{m,2-1}=0.07\ pu\ MW$$

Fig. 9-c shows the actual generated powers of GENCOs in area 1 properly reach the desired values using the proposed strategy.

7 Conclusion

In this paper, a new decentralized ANN based controller has been proposed based on the robust mixed H_2/H_∞ control technique for LFC in a deregulated power system. This control strategy was chosen in order to account for large parametric uncertainties, system nonlinearities and because of large model order and complexity real world power systems. It uses both the learning capability of ANN and advantage of mixed H_2/H_∞ control technique for achieving the desired level of robust performance. The robustness of the proposed method has been tested on a two area power system and results compared with the mixed and PI controllers for possible contracts under large load demands and specified uncertainties. The simulation results show that it is effective and gives good robust performance against parametric uncertainties and load disturbances even in the presence of GRC. Moreover, it dose not require an accurate model of the LFC problem and has relatively simple structure. Thus its construction and implementation are fairly easy, which can be useful in real world deregulated power system.

Appendix A: Nomenclature

F	area frequency
P_{Tie}	net tie-line power flow turbine power
P_T	turbine power
P_V	governor valve position
P_C	governor set point
ACE	area control error
apf	ACE participation factor
Δ	deviation from nominal value
K_P	subsystem equivalent gain
T_P	subsystem equivalent time constant
T_T	turbine time constant
T_H	governor time constant
R	droop characteristic
B	frequency bias
T_{ij}	tie line synchronizing coefficient between area i and j
P_d	area load disturbance
P_{Lj-i}	contracted demand of Disco j in area i
P_{ULj-i}	un-contracted demand of Disco j in area i
$P_{m,j-i}$	power generation of GENCO j in area i
P_{Loc}	total local demand
η	area interface
ζ	scheduled tie line power flow deviation

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