DECENTRALIZED ESTIMATION FOR AGC OF POWER SYSTEMS

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Abstract: A decentralized state estimation method for automatic generation control (AGC) of interconnected power systems is proposed in this paper. Based on the Inclusion Principle for linear stochastic systems, the state space model of the system is decomposed as a group of pair-wise subsystem models. The overlapping decentralized estimators and fully decentralized estimators are designed for each pair subsystems in the framework of LQG control schemes. Two types of estimators are considered for the cases of full and reduced measurement sets in the framework of system closed-loop operations. Simulation results show a high quality of the AGC scheme based on dynamic controllers with the proposed state estimators.

1 INTRODUCTION

Generally speaking, in power system models, an overall system with a longitudinal or a loop or a radial or a network structure can be divided into a lot of overlapping interconnected subsystems. Tie line powers, i.e. the sine of the voltage phase angle differences at the two ends of tie lines connected with areas, are the interconnections of the subsystems. It has been found that the decentralized controllers could be designed based only on local measurements, especially, the tie line power between each pair of areas and the frequency in each area (Chen, 1994; Ohtsuka and Morioka, 1997; Stankovic *et al.*, 1999). Although the decentralized control for overlapping interconnected power systems has attracted considerable attention of researchers (Chen, 1994; Chen and Stankovic, 1996; Ikeda *et al.*, 1981; Malik and Hope, 1984/1985; Ohtsuka and Morioka, 1997; Park and Lee, 1984; Siljak, 1978 and 1991; Stankovic *et al.*, 1999), the decentralized state estimation has been treated mostly within the framework of the dynamic controllers. The estimators of Kalman filter type are discussed in (Hodzic and Siljak, 1986), while in (Ikeda and Siljak, 1986) deterministic systems and their observers are considered in the case of the contractibility of dynamic controllers. The inclusion of observers for deterministic systems has been considered in (lftar, 1993). Luenberger observers are considered in (Park and Lee, 1984) separately with the near optimal decentralized control, since the tie-line power flow deviations are treated as the interconnecting states noted as relatively slow. However, from the practical feasibility point of view, the area autonomy and decentralized estimator design of the power system has not been mature.

First of all in this paper, a kind of multi-overlapping interconnected power system model is decomposed as a group of pair-wise areas and/or subsystems (Chen *et al.*, 2002) with only one overlapping interconnection (the tie-line power) between the two subsystems. Then, the inclusion of Kalman filter type estimators is formulated for the subsystem AGC. Finally, starting from a pair of electric power subsystems, overlapping and fully decentralized estimators based on full and reduced

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measurement sets are formulated. The fully decentralized scheme used only local area measurements is based on a separate tie-line power estimator. Experimental results illustrate the main features of the proposed estimators applied to AGC.

2 SYSTEM MODEL STRUCTURES

Consider a power system with multi- overlapping interconnected structures (Siljak, 1978), described by the linear stochastic continuous-time dynamic model as follows:

$$\begin{cases} \dot{x}_i = A_i x_i + B_i u_i + \Gamma_i \xi_i + \sum_{j=1, j\neq i}^{N} A_{ij} x_j, \\ y_i = C_i x_i + \eta_i, \end{cases}$$

$$i = 1, 2, \ldots, N, \tag{1}$$

where,

$$A_i = \begin{bmatrix} A_{ii} & 0 & a_{ti} \\ d_i^T & 0 & 1 \\ \alpha_{1i} \sum_{j=1, j\neq i}^{N} m_{ij}^T & 0 & 0 \end{bmatrix},$$

$$A_{ij} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\alpha_{1i} m_{ji}^T & 0 & 0 \end{bmatrix},$$

$$B_i = \begin{bmatrix} b_i^{\mathrm{T}} & 0 & 0 \end{bmatrix}^{\mathrm{T}},$$

$$\Gamma_i = \begin{bmatrix} f_i^{\mathrm{T}} & 0 & 0 \end{bmatrix}^{\mathrm{T}},$$

$$C_i = diag\begin{bmatrix} C_{ii} & 1 & 1 \end{bmatrix}, \tag{2}$$

the vector x_i is the state deviations of the i-th area consisting of 10 components: a_T, the valve opening variation of the steam turbine; P_{t1}, P_{t2} and P_{t3}, the high, intermediate and low pressure output variations of steam turbine, respectively; a_H, the gate opening variation of hydro turbine; v_H, dashpot position variation; q, water flow variation of the hydro-turbine; f, frequency variation; v_i, the deviation of the integral area control error (ACE) (Calovic, 1972; Malik and Hope, 1984/1985); P_{ei}, the deviation of the tie-line power exchange variations between the i-th and other areas; while u_i is the deviation of the scalar area control input and ξ_i is immeasurable variation of the area load; $y_i = [P_T, P_H, f, v, P_e]_i^{\mathrm{T}}$ defined as a vector of the local output deviations, where P_T is the output variation of the steam turbine and P_H is the one of the hydro unit; η_i represents the measurement noise vector corresponding to y_i. The parameters and matrices, such as A_{ii}, b_i, C_{ii}, f_i, a_{ti}, d_i, m_{ij} and m_{ji}, are constant and with proper dimensions.

It is obvious that the system (1) constructed by N interconnected subsystems has the multi-overlapping interconnections represented by the tie line power deviations, appearing at the last equation of the state description:

$$\dot{P}_{ei} = \alpha_{1i} \sum_{j=1, j\neq i}^{N} (m_{ij}^T x_{ii} - m_{ji}^T x_{jj}),$$

$$i = 1, 2, \ldots\ldots, N, \tag{3}$$

where, $\alpha_{1i} = P_{10} / P_{i0}$ is a steady load normalization factor based on area 1, that is $\alpha_{11} = 1$. The first item of the sum in (3) is related to the block-diagonal matrix A_i, representing N-1 times overlapping interconnection of state x_{ii} (a part of x_i); while the coefficients of the second item is spread around the non-block-diagonal matrix A_{ij}, j=1,2,...,N, $j \neq i$, representing the interconnections between the i-th and the j-th area. Because of power mutual exchanges, the gross tie line power change deviations in each area have the following relation as:

$$\sum_{i=1}^{N} P_{ei} / \alpha_{1i} = 0 \cdot \tag{4}$$

Decompose the system (1) as a group of pair-wise subsystems (Chen *et al.*, 2002), i.e. only consider the i-th subsystem state space model coherent with the j-th subsystem; therefore, the $N(N$-1)/2 pair subsystems can be represented by

$$\begin{cases} \dot{x}_i = A_i x_i + B_i u_i + \Gamma_i \xi_i + A_{ij} x_j \\ y_i = C_i x_i + \eta_i \end{cases} \tag{5}$$

Where

$$A_i = \begin{bmatrix} A_{ii} & 0 & a_{ti} \\ d_i^T & 0 & 1 \\ \alpha_{1i} m_{ij}^T & 0 & 0 \end{bmatrix},$$

$$A_{ij} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\alpha_{1i} m_{ji}^T & 0 & 0 \end{bmatrix},$$

$$i = 1, 2, \ldots, N\text{-}1,$$

$$j = i+1,\, i+2, \ldots, N \qquad (6)$$

and the other matrices as in (2). Since the tie line power equations between the i-th and the j-th subsystems are of linearly dependent according to (4), the overlapping interconnected power subsystem S_{ij} in pairs can be rewritten by

$$\begin{bmatrix} \dot{x}_{ii} \\ \dot{v}_i \\ \dot{P}_{ei} \\ \dot{v}_j \\ \dot{x}_{jj} \end{bmatrix} = \begin{bmatrix} A_{ii} & 0 & a_{ti} & 0 & 0 \\ d_i^T & 0 & 1 & 0 & 0 \\ \alpha_{1i} m_{ij}^T & 0 & 0 & 0 & -\alpha_{1i} m_{ji}^T \\ 0 & 0 & -\alpha_{1j}/\alpha_{1i} & 0 & d_j^T \\ 0 & 0 & -\alpha_{1j} a_{tj}/\alpha_{1i} & 0 & A_{jj} \end{bmatrix} \begin{bmatrix} x_{ii} \\ v_i \\ P_{ei} \\ v_j \\ x_{jj} \end{bmatrix}$$

$$+ \begin{bmatrix} b_i & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & b_j \end{bmatrix} \begin{bmatrix} u_i \\ u_j \end{bmatrix} + \begin{bmatrix} f_i & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & f_j \end{bmatrix} \begin{bmatrix} \xi_i \\ \xi_j \end{bmatrix}$$

$$\begin{bmatrix} y_{ii} \\ y_{vi} \\ y_{ei} \\ y_{vj} \\ y_{jj} \end{bmatrix} = \begin{bmatrix} C_{ii} & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & C_{jj} \end{bmatrix} \begin{bmatrix} x_{ii} \\ v_i \\ P_{ei} \\ v_j \\ x_{jj} \end{bmatrix} + \begin{bmatrix} \eta_{ii} \\ \eta_{vi} \\ \eta_{ei} \\ \eta_{vj} \\ \eta_{jj} \end{bmatrix},$$

$$i = 1, 2, \ldots, N\text{-}1,$$

$$j = i+1,\, i+2, \ldots, N. \qquad (7)$$

where, dotted lines show the two area models with a overlapping interconnected part. Thus, the power system, decomposed from a multi-overlapping interconnected structure to a group of pair-wise subsystems (Chen *et al.*, 2002), preserves inherent interconnected features.

3 INCLUSION OF ESTIMATORS

The centralized design of AGC is typically faced with both conceptual and computational difficulties, since the necessary information for control has to be acquired from power areas and generating plants spread over large geographic territories. It has been found that the inclusion principle is a suitable tool for coping with the problem of decentralized AGC design. However, the problem has been treated almost exclusively within the framework of deterministic models and static state or output feedback (Siljak, 1991). In this section, we shall present the inclusion of state estimators for a pair of subsystem S_{ij}, based on the stochastic system inclusion principle.

For a decentralized state estimation of power systems, the system (1) can first be decomposed as a pairs of subsystems (5) or (7). Then, in the case of (7), consider corresponding estimators E_{ij} for S_{ij}, in the Kalman filter form:

$$E_{ij}\!:\ \dot{\hat{x}} = A\hat{x} + Bu + L[y - C\hat{x}]. \qquad (8)$$

Where $\hat{x}$ is the estimations of state vector $x^T = [x_{ii}^T \;\; v_i \;\; P_{ei} \;\; v_j \;\; x_{jj}^T]^T$ of S_{ij}, L is an estimation gain matrix, other vectors and matrices are corresponding to S_{ij}. Suppose there is a pair expansion $(\tilde{S}_{ij}, \tilde{E}_{ij})$ for the pair (S_{ij}, E_{ij}) in the framework of the input/state/output inclusion, we state the following:

Definition 1. The pair $(\tilde{S}_{ij}, \tilde{E}_{ij})$ includes the pair (S_{ij}, E_{ij}) if there exist two pairs of full rank matrices (U, V), satisfying $UV = I_{19}$ and full rank matrix R and S, such that for any given initial state vector $[x_0^T, \hat{x}_0^T]^T$ and input $u(t)$ the conditions $[\tilde{x}_0^T, \hat{\tilde{x}}_0^T]^T = E_w\{[x_0^T, \hat{x}_0^T]^T; \operatorname{diag}[V,V]\}$ and $\tilde{u}(t) = E_s\{u(t);R\}$ imply both $[x^T(t), \hat{x}^T(t)]^T = C_w\{[\tilde{x}^T(t), \hat{\tilde{x}}^T(t)]^T; \operatorname{diag}[U,U]\}$ and $y(t) = C_w\{\tilde{y}(t); S\}$ ($\forall t \geq t_0$ t), where $E_s\{\cdot\}$ and E_w $\{\cdot\}$ means strict and weak expansions and $C_w\{\cdot\}$ represents weak contraction (see reference Stankovic *et al.*, 1999).

Theorem 2. The system $\tilde{S}_{ij}$ includes the system S_{ij}, in the sense of Definition 1 if and only if

$$A^i = U\tilde{A}^i V,$$

$$A^i B = U\tilde{A}^i \tilde{B} R,$$

$$CA^i = S\tilde{C}\tilde{A}^i V,$$

$$A^i B = S\tilde{C}\tilde{A}^i \tilde{B} R,$$

$$V\Gamma R_\xi \Gamma^T V^T = \tilde{\Gamma} R_{\tilde{\xi}} \tilde{\Gamma}^T,$$

$$R_\eta = S R_{\tilde{\eta}} S^T,$$

$$i = 0, 1, 2, \ldots. \qquad (9)$$

There are two special cases of inclusions, i.e. restriction and aggregation.

Theorem 3. The estimator E_{ij} is a restriction of the estimator $\tilde{E}_{ij}$ if the system S_{ij} is a restriction of the system $\tilde{S}_{ij}$ and

$$(VLC = \tilde{L}\tilde{C}V) \cap (VLR_\eta L^T V^{\mathrm{T}} = \tilde{L}R_{\tilde{\eta}}\tilde{L}^{\mathrm{T}}),$$

together with one of the followings:

(a) $(VB = \tilde{B}R) \cap (VL = \tilde{L}T)$,

(b) $(VBQ = \tilde{B}) \cap (VL = \tilde{L}T)$,

(c) $(VB = \tilde{B}R) \cap (VLS = \tilde{L})$,

(d) $(VBQ = \tilde{B}) \cap (VLS = \tilde{L})$,

where Q and T are full rank matrices.

Theorem 4. The estimator E_{ij} is an aggregation of the estimator $\tilde{E}_{ij}$ if the system S_{ij} is an aggregation of the system $\tilde{S}_{ij}$ and

$$(LCU = U\tilde{L}\tilde{C}) \cap (LR_\eta L^T = U\tilde{L}R_{\tilde{\eta}}\tilde{L}^{\mathrm{T}}U^{\mathrm{T}}),$$

together with one of the followings:

(a) $(BQ = U\tilde{B}) \cap (LS = U\tilde{L})$,

(b) $(B = U\tilde{B}R) \cap (LS = U\tilde{L})$,

(c) $(BQ = U\tilde{B}) \cap (L = U\tilde{L}T)$,

(d) $(B = U\tilde{B}R) \cap (L = U\tilde{L}T)$,

where Q and T are full rank matrices.

4 DECENTRALIZED ESTIMATION FOR AGC

4.1 Overlapping Decentralized Estimation

The problem of overlapping structures in the pairs of subsystems should be solved, *i.e.* the deviation of the tie-line power variation of subsystems P_{ei} is decoupled for each subsystem. The algorithm to expand a pair of subsystem S_{ij} and to get corresponding estimators E_{ij} is that, by imposing the conditions of inclusion principle presented in the above, a group of expanding matrices can properly be chosen, aimed at decomposition of overlapping part represented by dotted lines in (7), such as:

$$V = \text{block-diag}[I_9, (1\ 1)^{\mathrm{T}}, I_9],$$

$$T = \text{block-diag}[I_4, (1\ 1)^{\mathrm{T}}, I_4],$$

$$U = \text{block-diag}\{I_9, [\beta\ (1-\beta)], I_9\},$$

$$S = \text{block-diag}\{I_4, [\beta\ (1-\beta)], I_4\}, \qquad (10)$$

where, β is a scalar satisfying $0<\beta<1$; the appropriate complementary matrices M_A, M_B, M_C and M_L correspond to the matrices in (7), (8) and satisfy the equations

$$\tilde{A} = VAU + M_A,\ \tilde{B} = VB + M_B,$$

$$\tilde{C} = TCU + M_C,\ \tilde{L} = VLS + M_L, \qquad (11)$$

such that $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ and $\tilde{L}$ include the corresponding matrices of a pair of subsystems and their estimations, respectively. Although the system S_{ij} can become (5) after expanded and modified by using (10) and (11), it is important to know that the transform matrices (10) are needed for contractions to original spaces of each pair subsystems to show their interconnected relations when the decentralized estimations and controls are designed.

To formulate overlapping decentralized state estimation in the framework of LQG control for the pair subsystems in (7), the non-block diagonal matrices, such as, A_{ij}, $j = 1,2,...,N$, $j \neq i$, as byproducts to be considered after local estimation and control is established, are neglected. The local estimation are given by

$$\dot{\hat{x}}_k = A_k\hat{x}_k + B_k u_k + L_k[y_k - C_k\hat{x}_k],$$

$$k = i, j, \qquad (12)$$

where, $\hat{x}_k$ denotes the state estimate vector. Constructing the estimate gain matrices in the block diagonal form for the pair of decoupled subsystems as

$$\tilde{L}_D = diag[L_i, L_j], \qquad (13)$$

and in order to satisfy the estimator restriction and aggregation conditions for contractions, we modify the estimator gain matrix from $\tilde{L}_D$ to $\tilde{L}_M$ by adding $\Delta\tilde{L}$ relative to A_{ij}, $j = 1,2,...,N$, $j \neq i$, to the equation (13) and obtain

$$\tilde{L}_M = \begin{bmatrix} L^i_{9\times4} & L^i_{9\times1} & 0 & 0 \\ L^i_{1\times4} & L^i_{1\times1} & L_m & L^j_{1\times4} \\ L^i_{1\times4} & L_m + L^i_{1\times1} - L^j_{1\times1} & L^j_{1\times1} & L^j_{1\times4} \\ 0 & 0 & L^j_{9\times1} & L^j_{9\times4} \end{bmatrix}. \qquad (14)$$

Overlapping decentralized state estimator L_S can be implemented in the pair subsystems S_{ij} by $L_S = U\widetilde{L}_M T$ directly, or by $L_S S = U\widetilde{L}_M$, $VL_S = \widetilde{L}_M T$ indirectly, based on the Theorem 3 and Theorem 4.

4.2 Fully Decentralized Estimation

Although the estimators described above have been designed in a decentralized way, they are, essentially, centralized. The desired features for an efficient decentralized AGC require that each decentralized dynamic controller and/or estimator should be applied to its subsystem, using the measurements only accessible to its own area (Calovic, 1972 and 1984). In order to comply with these requirements, a modification of the overlapping decentralized methodology has been done, leading to a fully decentralized estimator.

The tie-line power variations depend, essentially, on the states in both the i-th and the j-th areas. According to (3) and (8), fully decentralized estimators can be designed, starting from the estimator of tie-line power variations defined by

$$\dot{\hat{P}}_e = L_m(P_e - \hat{P}_e) \tag{15}$$

where, L_m is an properly chosen constant, adapted to both dynamics of the tie-line power variations and the measurement noise. It is obvious that this estimator is completely autonomous, independent of the remaining parts of the state vector, having in mind that the estimators for the remaining parts of the local state vectors become completely decoupled. The estimator gain matrix is now modified from (14) to

$$\widetilde{L}_M = \begin{bmatrix} L^i_{9\times4} & L^i_{9\times1} & 0 & 0 \\ 0 & L_m & 0 & 0 \\ 0 & L_m - L^j_{1\times1} & L^j_{1\times1} & 0 \\ 0 & 0 & L^j_{9\times1} & L^j_{9\times4} \end{bmatrix}. \tag{16}$$

As far as the types of expansion are concerned, fully decentralized estimator schemes are designed in parallel with the overlapping decentralized ones.

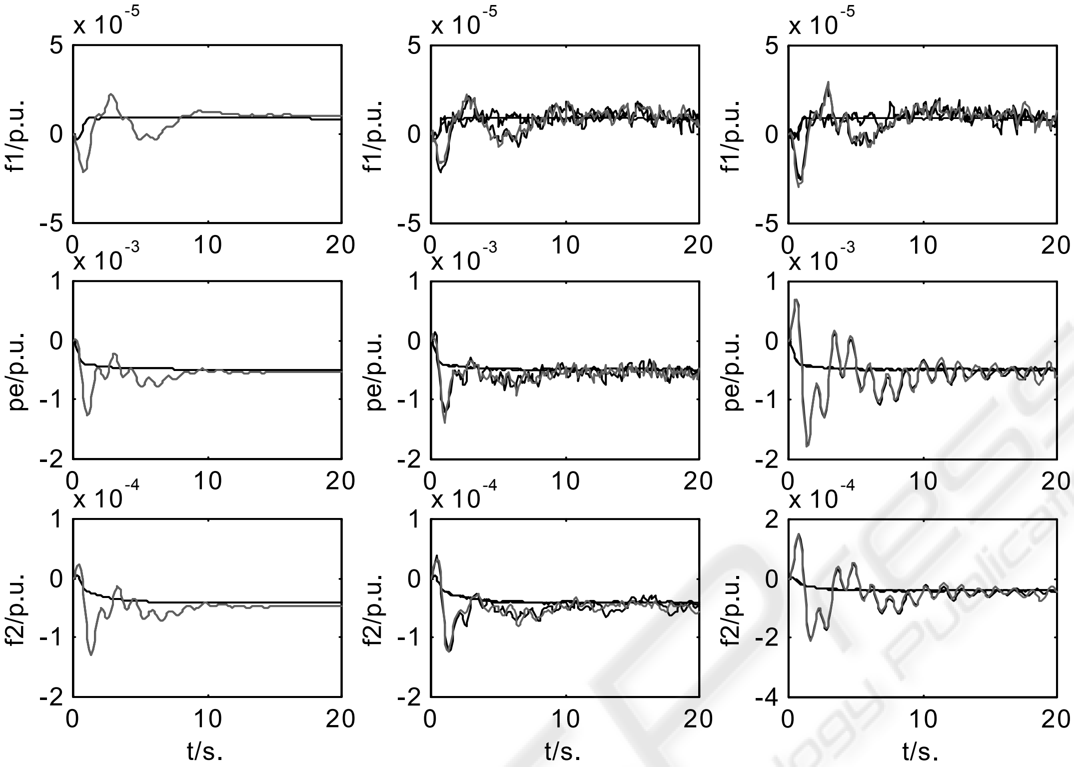
5 EXPERIMENTAL RESULTS

The efficiency of the described estimation schemes applied to AGC has been tested by simulation. All the experiments have been done in the case that the estimators have been implemented together with the corresponding gain matrices mapping the state estimates to the control signals. These gain matrices have been obtained by using the methodology (Stankovic *et al.*, 1999), based on expansion, decomposition to subsystems and the local application of the LQG optimal design. In order to get a better practical feeling about the quality of different estimators, responses to a step load disturbance in area i have been analyzed.

For the pair of subsystems S_{ij}, without losing generality, assume $i = 1$, $j = 2$, let the parameters of the system matrices in (7) correspond to the references (Chen, 1994; Calovic, 1984; Stankovic *et al.*, 1999), and have expanding matrices be (10). Consider the non-balance case of area 1 and area 2, that is a steady load normalization factor $\alpha_{12} = P_{10} / P_{20} = 10$. Therefore, choose $\beta = 0.1$ and step disturbance is 0.01 with 5% white noises in ξ_1. When $y_i = [P_T, P_H, f, v, P_e]_i^T$, $i = 1, 2$, the estimators are designed for full measurement sets; while $y_i = [f, v, P_e]_i^T$, i=1,2, the estimators for reduced measurement sets. The following notation has been adopted for estimator designs: (1) Overlapping decentralized (OD) scheme, full measurement sets (FMS); (2) OD scheme, reduced measurement sets (RMS); (3) Fully decentralized (FD) scheme, FMS; (4) FD scheme, RMS. In the case of OD scheme, L_m=0; and L_m=120 for FD.

In Figure 1 (a), differences between the globally optimal estimation errors (obtained by implementing the globally optimal LQG regulator for the entire model (7)) and the estimation errors obtained by the proposed estimators are depicted for f_1, P_e and f_2, all the noise terms are set to zero, in order to provide a better insight into the corresponding dynamics. Smooth overlapped curves are for the cases of 1 and 2, whereas fluctuant overlapped ones for 3 and 4. Obviously, FD schemes are only slightly inferior to OD schemes; the number of measurements does not influence the estimation accuracy significantly. Figure 1 (b) corresponding to the general situation, when the stochastic effects are present. It is interesting to observe that the estimator decentralization does not degrade the noise immunity significantly; however, the reduction of the number of measurements leads in both OD and FD cases to a visible increase of the estimation error. This estimator parameter L_m plays an important role in achieving the desired overall system performance. Figure 1 (c) shows the estimation error differences when L_m = 20 for FD schemes, corresponding to Figure 1 (b). Obviously, the estimation quality is deteriorated.

In Figure 2 (a) and Figure 2 (b), the true states are represented, together with their estimates, for OD scheme / FMS case and FD scheme / RMS case. The estimation accuracy is obvious; the bias, especially pronounced in f_1, represents a



(a) (b) (c)

Figure 1: Differences of estimation errors.

consequence of the step disturbance, and cannot be eliminated, since it is viewed as a structural change, which does not affect the steady-state control error as the integral action is incorporated into the system model. The estimates P_e appear to be very good, although they are obtained by simple low-pass filtering. In order to illustrate the performance of the overall dynamic AGC controllers incorporating the proposed estimators, The Figure 2 (c) contains the responses to the step disturbance obtained by the globally LQG optimal regulator and FD scheme / FMS case with $L_m = 120$.

6 CONCLUSION

In this paper a decentralized state estimator design methodology is proposed for AGC of the overlapping interconnected power system. Overlapping and fully decentralized estimations for the system is considered from the point of view of obtaining possibilities for direct contraction from the expanded to the original space. The design of the local estimators is based only on the models of the corresponding areas and the associated tie lines. The presented experimental results show a very low performance degradation caused by decentralization.

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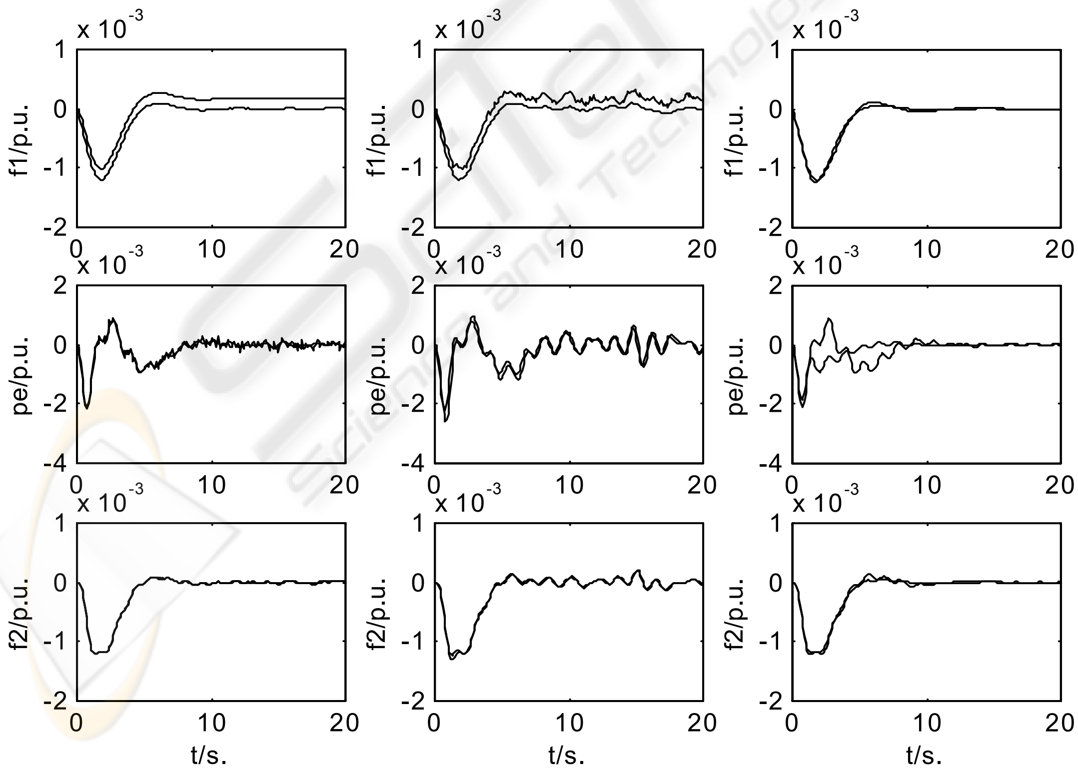

(a) (b) (c)

Figure 2: Estimations and responses.