Decentralized Load Frequency Control Using Local Sliding Mode Observers with Unknown Inputs

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***Abstract*—This paper presents a new load frequency control (LFC) design in a multi area power system by using local observers. Firstly, sliding mode observers with unknown inputs are designed for each area to estimate the state variables locally. In this stage interconnections and load variations are assumed as unknown inputs. Then, local state feedback and output integral are used to attenuate the effect of load variations in each area. Analysis and simulation results for a three-area interconnected power system show improvements on closed loop performance in comparisons with other existing methods.**

***Index Terms*—LFC; decentralized control; PI; Sliding mode observer with unknown inputs.**

I. Introduction

Frequency unchanging against load variations is an important control problem in the dynamical operation of interconnected power systems. The LFC is to drives the frequency deviation and the inter-area power flow through tie-lines to zero by manipulating the load reference setpoint [1]. Actually, this task can be theoretically described as a disturbances attenuation problem of large-scale systems with several interconnected subsystems or control areas. Each area has its own generator and it is responsible for its own load and scheduled power interchanges with neighboring areas [2].

In [3], [4] two recent overviews of control strategies as well as of their current use in the field of LFC problems were provided. Based on these, decentralized LFC scheme is more practical than the centralized one because it only uses the local area state information to attenuate the frequency deviation [5]. But to design the decentralized controllers it is important to note that the large-scale controlled system becomes stable under local control. It has been neglected in many papers [6]. To overcome this problem, in this paper we use local state feedback. But using state feedback may require many measurements which is impossible or extensive. So we design local observer for each subsystems to estimate the state variables. But according to interconnection terms and load changes which are unknown or immeasurable in each control area, we design sliding mode observer with unknown inputs. Sliding mode observers are robust, insensitive and very fast [7] so the estimation of the state vector could be used instead of the state vector itself.

Also, PI controller is widely used as the local controller with different parameters tuning methods: adaptive PI [8], fuzzy PI [9], robust PI [10], PI with adaptation GA tuning algorithm [11], PI with PSO tuning algorithm [12], PI design based on internal model control [13], PI design with respect to coefficient diagram method [14], sliding mode PI control [15] and etc. This is because of the inherent PI character: eliminating the steady state error to step disturbances. In this paper we use integral control to decrease the load changes effects. So the local controller is constructed by the state estimation feedback and integrator.

This paper is organized as follows. In Section 2, multi area power system is described and the LFC dynamic with problem statement is presented. The sliding mode observer design with unknown input is considered and the control idea of design the controller based on sliding mode in section 3 is discussed. In Section 4, for a three area power system, the simulation results are obtained and compared with other recent control approaches. Finally, concluding remarks are given in Section5.

2. MULTI AREA POWER SYSTEM

A large multi area power system consist of a number of control areas that are interconnected through some tie-lines. Each control area of a multi area interconnected power system has the structure shown in Fig.1: Foe each i and j $(i \neq j)$, ith control area is interconnected to the jth control area through a tie line. The model for the ith area of a multi area power system with a generator unit in each area is described in [5].By considering power system parameters in table1, the overall generator-load dynamic relationship between the incremental mismatch power $\Delta P_{mech_i} - \Delta P_{L_i}$ and the frequency deviation $\Delta\omega_i$ can be expressed as

$$\Delta\dot{\omega}_i = \frac{1}{M_i^a}\Delta P_{mech_i} - \frac{1}{M_i^a}\Delta P_{L_i} - \frac{1}{M_i^a}D_i\Delta\,\omega_i - \frac{1}{M_i^a}\Delta P_{tie,i} \qquad (1)$$

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Manuscript received August 20, 2016; accepted September 18, 2016

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$$\Delta\dot{P}_{mech_i} = \frac{1}{T_{CH_i}}\Delta P_{\upsilon_i} - \frac{1}{T_{CH_i}}\Delta P_{mech_i} \tag{2}$$

$$\Delta\dot{P}_{\upsilon_i} = \frac{1}{T_{G_i}}\Delta P_{ref_i} - \frac{1}{R_i^f T_{G_i}}\Delta\omega_i - \frac{1}{T_{G_i}}\Delta P_{\upsilon_i} \tag{3}$$

The relationship between areas i and j of the tie-line power flow is:

$$\Delta\dot{P}_{tie}^{ij} = T_{ij}\Delta\omega_i - T_{ij}\Delta\omega_j, \qquad \Delta P_{tie}^{ij} = -\Delta P_{tie}^{ji} \tag{4}$$

and the total tie-line power flow between multi area is defined by the following equation:

$$\Delta\dot{P}_{tie,i} = \sum_{\substack{j=1\\ j\neq i}}^{M}\Delta\dot{P}_{tie}^{ij} = \sum_{\substack{j=1\\ j\neq i}}^{M}T_{ij}\Delta\omega_i - \sum_{\substack{j=1\\ j\neq i}}^{M}T_{ij}\Delta\omega_j \tag{5}$$

The area control error (ACE) can be defined by an appropriate combination of frequency deviation $\Delta\omega_i$ and tie-line power variation $\Delta P_{tie.i}$ for ith area. Therefore, if B_i is a bias factor, then:

$$ACE_i = B_i\Delta\omega_i + \Delta P_{tie.i} \tag{6}$$

With a set of state variables $x_i = [\Delta\omega_i, \Delta P_{mech_i}, \Delta P_{\upsilon_i}, \Delta P_{tie.i}]^T$, control input $u_i = \Delta P_{ref,i}$, disturbance input $w_i = \Delta P_{Li}$ and output ACE_i, the interconnected power system described by (1)-(4) can be represented as the following state space model

$$\begin{aligned}\dot{x}_i(t) &= A_{ii}x_i(t) + B_{ii}u_i(t) + E_{ii}w_i(t) + \sum_{j\neq i}F_{ij}x_{1,j}(t)\\ y_i &= C_{ii}x_i(t)\end{aligned} \tag{7}$$

with

$$A_{ii} = \begin{bmatrix} -\frac{D_i}{M_i^a} & \frac{1}{M_i^a} & 0 & -\frac{1}{M_i^a}\\ 0 & -\frac{1}{T_{CH_i}} & \frac{1}{T_{CH_i}} & 0\\ -\frac{1}{R_i^f T_{G_i}} & 0 & -\frac{1}{T_{G_i}} & 0\\ \sum_{j\neq i}T_{ij} & 0 & 0 & 0\end{bmatrix},$$

$$B_{ii} = \begin{bmatrix}0\\0\\ \frac{1}{T_{G_i}}\\0\end{bmatrix}, E_{ii} = \begin{bmatrix}-\frac{1}{M_i^a}\\0\\0\\0\end{bmatrix}, F_{ij} = \begin{bmatrix}0\\0\\0\\ -\sum_{j\neq i}T_{ij}\end{bmatrix}, C_{ii}^T = \begin{bmatrix}B_i\\0\\0\\1\end{bmatrix}$$

3. CONTROLLER STRUCTURE AND DESIGN

One of the most important problems of system (7) is instability which is happened because of the imported interference of one control area from other areas. To stabilize the system, we use the pole placement with state feedback as a controller. All state variables of the system should be available in all control areas, which is not possible, since data transfer density and measurements increases the cost. Also, it is not reasonable to eliminate interference.

Here, we design a local observer for each area. The effect of power flow through the-tie lines (interconnections) assumed to be unknown input. So we propose local sliding mode observer with unknown input structure to estimate the state variables by eliminating interconnections effect. Then by applying local state estimation feedback, each control area is stabilized. Finally, integral controller is added to remove the step changes in load.

3.1 Sliding mode observer with unknown input

Consider the following linear observable system

$$\begin{aligned}\dot{x} &= Ax + Bu + R\bar{u}\\ y &= Cx\end{aligned} \tag{8}$$

where u is known input, $\bar{u}$ is unknown input bounded by $\rho(t)$ i.e $\|\bar{u}(t)\| \leq \rho(t)$, x is the state variables vector and y is the output. Matrices A, B, R and C are known with appropriate dimensions. The proposed sliding mode observer is

$$\begin{aligned}\dot{\hat{x}} &= A\hat{x} + Bu - L(\hat{y} - y) + v\\ \hat{y} &= C\hat{x}\end{aligned} \tag{9}$$

where the observer gain L and sliding based input v must be determined such that the error signal $e = \hat{x} - x$ goes to zero asymptotically. To do this, let us find the error dynamics as

$$\begin{aligned}\dot{e} &= (A - LC)e + v - R\bar{u}\\ e_y &= Ce\end{aligned} \tag{10}$$

Due to observability of the system (8), there always exists an observar gain L such that $A - LC$ becomes Horwitz. So one can find symmetric positive definte matrices P and Q satisfying

$$(A - LC)^T P + P(A - LC) = -Q \tag{11}$$

Therefore, we have the following theorem

Theorem 1. System (10) with Lyapanov equation (11), becomes exponentially stable if

i) There exists matrix F such that $R^T P = FC$;

ii) $$v = \begin{cases} \dfrac{-P^{-1}C^T F^T Fe_y}{\|Fe_y\|}\rho(t) & Fe_y \neq 0\\ 0 & Fe_y \equiv 0\end{cases}$$

Proof: Consider the following Lyapunov function:

$$V(e) = e^T Pe \geq 0 \tag{12}$$

where P is obtained by (11). By differentiating $V(e)$ along the error dynamic (10), we get:

$$\dot{V}(e) = e^T P((A-LC)e + v - R\bar{u}) + ((A-LC)e + v - R\bar{u})^T Pe \triangleright$$
$$= -e^T Qe + (e^T Pv + v^T Pe) - (e^T PR\bar{u} + \bar{u}^T R^T Pe) \quad (13)$$

By substituting the assumptions i and ii in (13) we have:

$$\dot{V}(e) = -e^T Q e - 2e^T \frac{C^T F^T F e_y}{\|F e_y\|} \rho(t) - 2(e^T C^T F^T \bar{u} + \bar{u} F C e)$$
$$\dot{V}(e) = -e^T Q e - 2\|F e_y\| \rho(t) - 2\bar{u} F e_y \quad (14)$$
$$\dot{V}(e) \le -e^T Q e - 2\|F e_y\|(\rho(t) - \|u\|) \le -e^T Q e$$

which implies that the error dynamic (10) is exponentially stable. This completes the proof.

3.2 Controller design

Now we are ready to design the controller based on sliding mode observer discussed in previous subsection. To design local observer for each control area let us rewrite the local state space model (7) as follows

$$\dot{x}_i(t) = A_{ii}x_i(t) + B_{ii}u_i(t) + R_{ii}\bar{u}_i(t)$$
$$y_i = C_{ii}x_i(t) \quad (15)$$

where A_{ii}, B_{ii}, C_{ii} are the same as defined in (7) and

$$R_{ii} = \left[E_{ii}, F_{i1}, \cdots, F_{\substack{ij \\ j\ne i}}, \cdots, F_{iM}\right], \quad \bar{u}_i(t) = \left[w_i, x_{11}, \cdots, x_{\substack{1j \\ j\ne i}}, \cdots, x_{1M}\right]^T$$

Clearly if all state variables become stable, then x_{1j} will be bounded. Also, the load changes w_i is bounded which implies $\bar{u}_i$ is bounded or simply the norm of the unknown input $\bar{u}_i$ is finite. Hence we can design a sliding mode observer based on the method proposed subsection 3.1 as

$$\dot{\hat{x}}_i(t) = A_{ii}\hat{x}_i(t) + B_{ii}u_i(t) - L_{ii}(\hat{y}_i - y_i) + v_i \quad (16)$$

where L_{ii}, v_i are obtained as in (9). The control input $u_i(t)$ must contain a stabilizing such as state feedback or feedback of estimation of state variables. Also, it concludes an integral part to overcome the effect of step changes in load. So the control structure is selected as

$$u_i(t) = -K_{pi}\hat{x}_i - k_{ii}\int y_i \quad (17)$$

where K_{pi} (feedback gain) and k_{ii} (integrator gain) must be determined. The feedback gain K_{pi} is chosen such $A_{ii} - B_{ii}K_{pi}$ is Hurwitz which can be done by any pole placement method [7]. To determine the integrator gain, we rewrite the closed loop model (15) under the control input (17).

$$\frac{d}{dt}\begin{bmatrix} x_i \\ \int y_i \\ e_i \end{bmatrix} = \bar{A}_{ii}\begin{bmatrix} x_i \\ \int y_i \\ e_i \end{bmatrix} + \begin{bmatrix} R_{ii} \\ 0 \\ -R_{ii} \end{bmatrix}\bar{u}_i + \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} v \quad (18)$$

with

$$\bar{A}_{ii} = \begin{bmatrix} A_{ii} - B_{ii}K_{pi} & -B_{ii}k_{ii} & -B_{ii}K_{pi} \\ C_i & 0 & 0 \\ 0 & 0 & A_{ii} - L_{ii}C_{ii} \end{bmatrix}$$

So the integrator gain must be selected such that $\bar{A}_{ii}$ be Hurwitz or simply the following matrix

$$\begin{bmatrix} A_{ii} - B_{ii}K_{pi} & -B_{ii}k_{ii} \\ C_i & 0 \end{bmatrix}$$

becomes Hurwitz.

4. SIMULATION RESULTS

Simulations have been carried out in order to validate the effectiveness of the proposed scheme. The Matlab software package has been used for this purpose. Here a three-area power system is considered which is described in [5]. The nominal parameters are listed in Table 2. The control parameters are obtained as

$$F_1 = \begin{bmatrix} -0.0031 \\ -0.0011 \end{bmatrix}, \quad F_2 = \begin{bmatrix} 0.00006456 \\ 0.00001812 \end{bmatrix}, \quad F_3 = \begin{bmatrix} -0.0021 \\ -0.0006 \end{bmatrix}$$

$$P_1 = \begin{bmatrix} 0.0179 & 0.0406 & 0.3544 & 0.0113 \\ 0.0406 & 1.4555 & 27.0963 & 0.0064 \\ 0.3544 & 27.0963 & 650.4512 & -0.4169 \\ 0.0113 & 0.0064 & -0.4169 & 0.0107 \end{bmatrix}$$

$$P_2 = \begin{bmatrix} 0.0175 & 0.0398 & 0.0755 & 0.0113 \\ 0.0398 & 1.7154 & 6.7464 & 0.0033 \\ 0.0755 & 6.7464 & 32.1555 & -0.0982 \\ 0.0113 & 0.0033 & -0.0982 & 0.0111 \end{bmatrix}$$

$$P_3 = \begin{bmatrix} 0.0169 & 0.0431 & 0.2638 & 0.0113 \\ 0.0431 & 1.7204 & 21.3461 & 0.0066 \\ 0.2638 & 21.3461 & 339.0396 & -0.3197 \\ 0.0113 & 0.0066 & -0.3197 & 0.0117 \end{bmatrix}$$

$$L_{11} = \begin{bmatrix} 1.653 \\ 10.933 \\ 264.9381 \\ 7.731 \end{bmatrix}, \quad L_{22} = \begin{bmatrix} 1.564 \\ 11.690 \\ 58.370 \\ 7.608 \end{bmatrix}, \quad L_{33} = \begin{bmatrix} 1.894 \\ 11.857 \\ 191.233 \\ 7.404 \end{bmatrix}$$

$$K_{11} = [-34.985 \quad 50.26 \quad 0.375 \quad -39.468]$$
$$K_{22} = [-2.183 \quad 5.977 \quad 0.229 \quad -4.616]$$
$$K_{33} = [271.374 \quad 35.108 \quad 0.3 \quad 41.991],$$

In order to simulate the disturbance of the system, we consider two cases:

Case 1. A large disturbance in load 0.1pu (10%) in area 1 at t=10s.

Case 2. Simultaneous 0.03pu (3%) load changing in area 2 and area 3 at t=5s.

Fig. 2 shows the frequency deviations $\Delta\omega_i (i=1,2,3)$ in case 1. In Fig 3 $\Delta P_{ref,i} (i=1,2,3)$ are plotted. The generator output power deviation rate $\Delta \dot{P}_{mech,i} (i=1,2,3)$ are plotted in Fig 4.These results are comparable to those studied in [5]. It is noteworthy that with the controller (17) the system is more stable and fast (with settling time about 20s) as compared with Distributed Model Predictive Control was proposed in [5](with 60s settling time). In Fig.5, the area control errors are plotted to show the effect of loads changing in area 2 and 3. Simultaneously, it indicates fast disturbance rejection in all areas with settling time 45s. In Fig.6 $\Delta P_{ref,i}$ are plotted which shows a

suitable control effort, where $\max\limits_{i=1,2,3} \left|\Delta P_{ref,i}\right| \le 0.32$

Table1. Power systems parameters	
ω	*Angular frequency of rotating mass*
δ	*Phase angle of rotating mass*
D	$\dfrac{\text{percent change in load}}{\text{percent change in frequency}}$
M^a	*Angular momentum*
P_{mech}	*Mechanical power*
P_L	*Nonfrequency sensitive load*
T_{CH}	*Charging time constat (prime mover)*
T_G	*Governor time constant*
R^f	$\dfrac{\text{percent change in frequency}}{\text{percent change in unit output}}$
P_v	*Steam valve position*
P_{ref}	*Load reference set point*
T_{ij}	*Tie – line (between areas i and j) stiffness coefficient*
P_{tie}^{ij}	*Tie – line power flow between areas i and j*
$P_{tie,i}$	*Total tie – line power flow between areas – i and others*

Table2. Model parameters values for simulation		
$D_1 = 2$	$D_2 = 2.75$	$D_3 = 2.4$
$R_1^f = 0.03$	$R_2^f = 0.07$	$R_3^f = 0.05$
$M_1^a = 3.5$	$M_2^a = 4.0$	$M_3^a = 3.75$
$T_{CH1} = 50$	$T_{CH_2} = 10$	$T_{CH_3} = 30$
$T_{G1} = 40$	$T_{G_2} = 25$	$T_{G_3} = 32$
$R_1 = 1$	$R_2 = 1$	$R_3 = 1$
$B_1 = 1$	$B_2 = 1$	$B_3 = 1$
$T_{12} = T_{13} = 7.54$	$T_{21} = T_{23} = 7.54$	$T_{31} = T_{32} = 7.54$

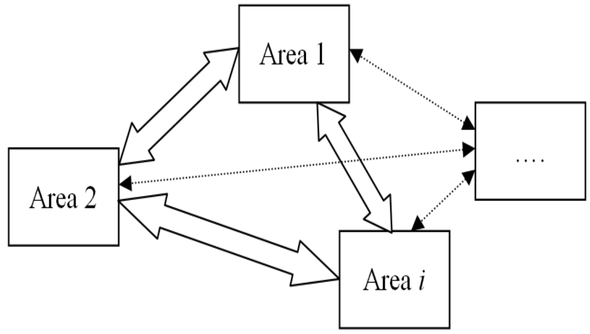

Fig. 1. Block diagram of interconnected power system

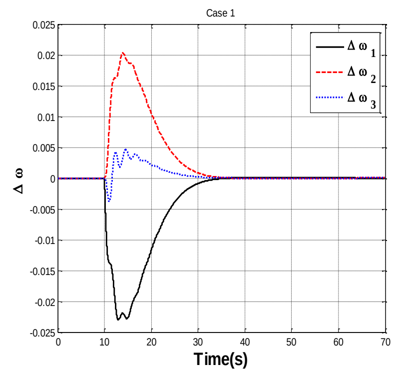

Fig. 2. Power system responses to case 1 frequency deviation in all areas with respect to 10% load change in area 1.

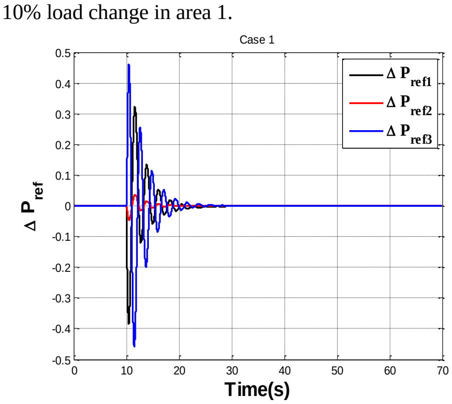

Fig. 3. Deviation of control input $\Delta P_{ref,i}$ in case 1 : $|\Delta P_{ref,i}| \le 0.45$.

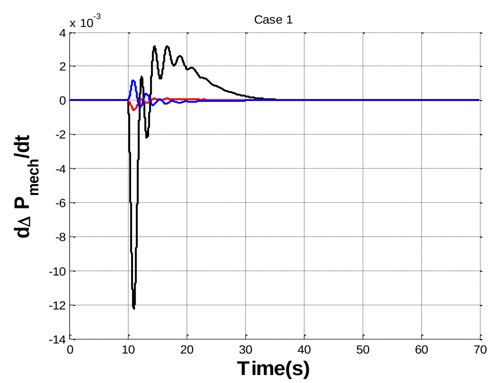

Fig. 4. The generator output power deviation rate $\Delta \dot{P}_{mech,i} (i=1,2,3)$ in case: $|\Delta \dot{P}_{mech,i}| \le 0.0012$.

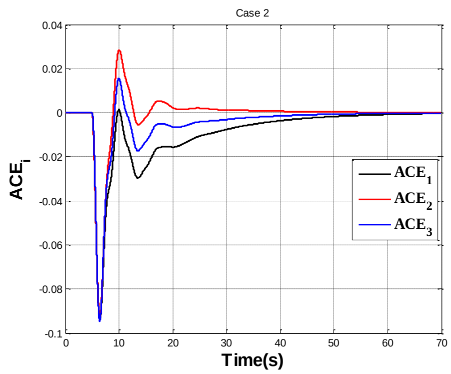

Fig. 5. The area control error $ACE_i\ (i=1,2,3)$ in case 2.

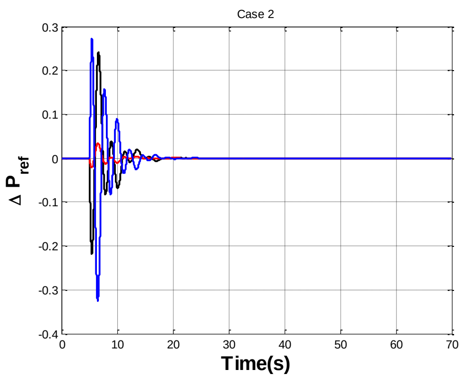

Fig. 6. The governors reference inputs $\Delta P_{ref,i}\ (i=1,2,3)$ in case 2: $|\Delta P_{ref,i}| \leq 0.32$.

5. Conclusion

In this paper, we introduce a novel process Design and application of sliding mode observer has been used in multi area load frequency control in this paper. Local sliding mode observers with unknown inputs have been employed to estimate the local state variables. The local load changes and tie-line effect was assumed as unknown bounded inputs. Then, state feedback and integrator were simultaneously designed. To investigate the effectiveness of the proposed controller, time-based simulations were performed on the three-area power system. Simulation results reveal that the proposed approach provided satisfactory closed loop performance with low oscillation and settling time. The main reasons for the superiority and attribute of the proposed approach are: local design to control of multi input multi output system with reliable global stability, and fast disturbance rejection.

6. References

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