Observer Output Feedback Load Frequency Control for a Two-Area Interconnected Power System

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Abstract. *This paper presents an observer output-feedback load frequency control for power systems with uncertain parameters and time delays in communication networks. First, an observer-based controller is designed dependent on only the observer output. Therefore, the conservatism is reduced and the robustness is enhanced. It also both save computing time and make the control method simpler. Second, the stability of both the observer error system and closed-loop control system is proven via the Lyapunov direct method. Moreover, simulation results show that the proposed observer output-feedback load frequency controller results in shortening the frequency's transient response, maintaining required control quality in the wider operating range, and being more robust to uncertainties as compared to some existing control methods.*

Key Words: load frequency control, interconnected power systems, observer output.

I. INTRODUCTION

In a power system, both active and reactive power demands are never steady and they continually change with the rising or falling trend. Steam input to turbo-generators or water input to hydro-generators must, therefore, be continuously regulated to match the active power demand, failing which the machine speed will vary with consequent change in frequency and it may be highly undesirable. Therefore, it is necessary to design a load frequency control (LFC) system, which deals with the control of loading of the generator depending on the frequency.

Frequency control is constructed by three levels: primary, secondary, and tertiary control [1]. The objective of primary control is to re-establish a balance between generation and demand within the synchronous area at a frequency different from the nominal value. Primary control responds within few seconds. Under normal operation, the primary control can reduce small frequency deviation, but for larger deviation, secondary control is required. Secondary control is used to steer frequency deviation to zero. Following a serious situation, if the frequency is rapidly dropped to a critical value, tertiary control may be required to reestablish the nominal frequency.

In the literature, the load frequency controllers commonly used in the industry are a proportional–integral (PI) type or a PI–differential (PID) type [2]–[4]. This is because of their simple structure and possibility of their online tuning based on trial-and error approaches. Recently developed approaches in LFC have been proven to be more robust using some new control techniques. Robust control [5]–[10], pole shifting [11]-[13], model predictive algorithms control [14] [15], genetic algorithms [16] [17], robust linear matrix inequality control [18]-[20], active disturbance rejection control [21]-[23]. The above approaches are achieved under that power system is operated with all the parameters on their nominal values without considering parameter uncertainties. In real power system, parameter uncertainties always exist because of the variations of internal and external conditions. In order to solve this problem, the LFC of power system with parameter uncertainties using sliding mode control technique is developed in [24]-[28]. The solutions proposed in previous studies necessarily require that all state variables are available for measurements. However, in many interconnected power system, the state variables are not accessible for direct measurement or the number of measuring devices is limited. In this situation, there are two approaches in designing the load frequency controllers for interconnected power system. One is to use state observers to provide an estimate of the unmeasured states [29]-[31]. The other is to utilize the output-based controllers, such as static gain and dynamic compensator types [20], [32]. However, these approaches given in [29]-[32] can not be applied for the interconnected power system with time delayed and parametric uncertainties. Motivated by the previous works, in this paper, a new observer output-feedback load frequency controller is proposed in order to control the frequency of a two-area interconnected power system with time delayed and parametric uncertainties. The observer and integral control are employed to improve power-system performance. The main contributions of this paper are as follows.

- The proposed controller design is dependent on only the observer output $(u = -K\hat{y}(t))$. Therefore, the conservatism is reduced and the robustness is enhanced. It also both save computing time and make the control method simpler.
- The stability of both the observer error system and closed-loop control system is proven via the Lyapunov direct method.
- Simulation results show that the proposed observer output-feedback load frequency controller results in shortening the frequency's transient response, maintaining required control quality in the wider operating range, and being more robust to uncertainties as compared to some existing control methods.

II. TWO-AREA INTERCONNECTED POWER SYSTEM

The load frequency control (LFC) system investigated is composed of an interconnection of a two-area power system[24]-[26]. The control block diagram of the linearized system model is shown in Fig. 1. For the sake of convenience, each control area can be represented by an equivalent turbine, generator and governor system. The tie line power must be accounted for the incremental power balance equation of each area. The balance between connected control areas is achieved by detecting the frequency and tie-line power deviations in order to generate the area control error (ACE). Under this circumstance, three levels of frequency control attempt to remove the frequency and tie-line power deviations. The ACE for each control area can be expressed as a linear combination of tie-line power change and frequency deviation:

$$ACE_1 = -\Delta P_{tie} - B_1 \Delta f_1 \tag{1}$$

and

$$ACE_2 = -\Delta P_{tie} - B_2 \Delta f_2 \tag{2}$$

The dynamic equations of two area of a multi-area power system are as follows:

$$\begin{aligned}\Delta \dot{X}_{G1} = \frac{-1}{T_{g1}} \Delta X_{g1} + \frac{-1}{R_1 T_{g1}} \Delta f_1 \\ + \frac{1}{T_{g1}} \Delta E_1 + \frac{1}{T_{g1}} u_1\end{aligned} \tag{3}$$

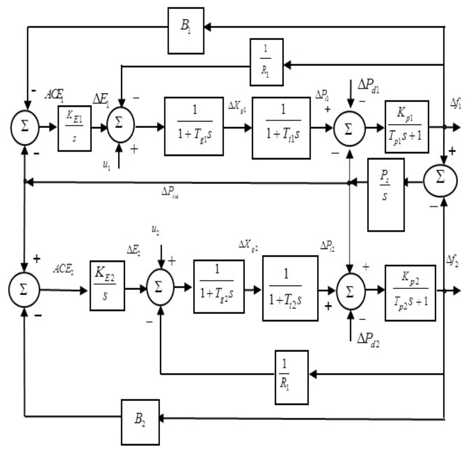

Fig. 1: Two control areas interconnected through a single tie line

$$\Delta\dot{P}_{T1} = \frac{1}{T_{t1}}\Delta X_{g1} + \frac{-1}{T_{t1}}\Delta P_{t1}$$

$$\Delta\dot{f}_1 = \frac{K_{P1}}{T_{p1}}\Delta P_{t1} + \frac{-1}{T_{p1}}\Delta f_1 - \frac{K_{P1}}{T_{p1}}\Delta P_{tie} - \frac{K_{P1}}{Tp1}\Delta P_{d1}$$

$$\Delta\dot{P}_{tie} = P_s(\Delta f_1 - \Delta f_2)$$

$$\Delta\dot{X}_{g2} = \frac{-1}{T_{g2}}\Delta X_{g2} + \frac{-1}{R_2 T_{g2}}\Delta f_2 + \frac{1}{T_{g2}}\Delta E_2 + \frac{1}{T_{g2}}u_2$$

$$\Delta\dot{P}_{T2} = \frac{1}{T_{t2}}\Delta X_{g2} + \frac{-1}{T_{t2}}\Delta P_{t2}$$

$$\Delta\dot{f}_2 = \frac{K_{P2}}{T_{p2}}\Delta P_{t2} + \frac{-1}{T_{p2}}\Delta f_2 + \frac{K_{P2}}{T_{p2}}\Delta P_{tie} - \frac{K_{P2}}{Tp2}\Delta P_{d2}$$

$$\Delta\dot{E}_1 = -K_{E1}[B_1\Delta f_1 + \Delta P_{tie}]$$

$$\Delta\dot{E}_2 = -K_{E2}[B_2\Delta f_2 + \Delta P_{tie}]$$

where $\Delta f_i(t)$ is the incremental change in frequency for ith area subsystem (Hz), $\Delta P_{ti}(t)$ is the incremental change in generator output power for the ith area subsystem (p.u.MW), $\Delta X_{gi}(t)$ is the incremental change in governor valve position for the ith area subsystem (p.u.MW), $\Delta P_{di}(t)$ is the incremental change in load demand for the ith area, $\Delta P_{tie}(t)$ is tie-line power deviation, $\Delta E_i(t)$ is the integral control, T_{ti} is the governor time constant for the ith area subsystem (s), T_{ti} is the turbine time constant for the ith area subsystem (s), T_{Pi} is the plant model time constant for the ith area subsystem (s), P_s is the synchronizing coefficient between the ith and jth area subsystem (p.u.MW), K_{Pi} is the plant gain for the ith area subsystem, K_{Ei} is the integral control gain, B_i is the bias constant for the ith area, R_i is the speed regulation due to governor action for the ith area subsystem (Hz p.u. MW^{-1}), ACE_i is the area control error of the ith area. The two-area power system can be written in state-space form as follows:

$$\dot{x} = \bar{A}x + \bar{B}u + Fd$$

where $x=[\Delta X_{g1}\ \Delta P_{t1}\ \Delta f_1\ \Delta P_{tie}\ \Delta X_{g2}\ \Delta P_{t2}\ \Delta f_2\ \Delta E_1\ \Delta E_2]^T$ is the state variables, $u=[u_1\ u_2]^T$ is the control input. The system matrices for the two-area interconnected power system are given as below (equations (4)-(5)), and $\Delta P=[\Delta P_{d1}\ \Delta P_{d2}]^T$.

The matrix form of system dynamic model with parameter uncertainties is as

$$\dot{x}(t) = (A + \Delta A)x(t) + Bu(t) + F\Delta P \quad (6)$$

and

$$y(t) = Cx(t) = \begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} \quad (7)$$

where $A\in R^{m\times n}$ and $B\in R^{n\times m}$ are matrices of the nominal parameters; ΔA represent parametric uncertainties; y(t) is output and

$$C = \begin{bmatrix} 0 & 0 & -B_1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & -B_2 & 0 & 0 \end{bmatrix}.$$

To guarantee the asymptotic stability of overall system, the observer output-feedback controller is designed based on the following assumptions.
Assumption 1: Assuming that the incremental

$$\bar{A}=\begin{bmatrix} \frac{-1}{T_{g1}} & 0 & \frac{-1}{T_{g1}R_1} & 0 & 0 & 0 & 0 & \frac{1}{T_{g1}} & 0 \\ \frac{1}{T_{t1}} & \frac{-1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{K_{p1}}{T_{p1}} & \frac{-1}{T_{p1}} & \frac{-K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & P_s & 0 & 0 & 0 & -P_s & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{g2}} & 0 & \frac{-1}{T_{g2}R_2} & 0 & \frac{1}{T_{g2}} \\ 0 & 0 & 0 & 0 & \frac{1}{T_{t2}} & \frac{-1}{T_{t2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{K_{p2}}{T_{p2}} & 0 & \frac{K_{p2}}{T_{p2}} & \frac{-1}{T_{p2}} & 0 & 0 \\ 0 & 0 & -B_1K_{E1} & -K_{E1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{E2} & 0 & 0 & -B_2K_{E2} & 0 & 0 \end{bmatrix}, \tag{4}$$

$$\bar{B}=\begin{bmatrix} \frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{T_{g2}} & 0 & 0 & 0 & 0 \end{bmatrix}^T, F=\begin{bmatrix} 0 & 0 & \frac{-K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_{p2}}{T_{p2}} & 0 & 0 \end{bmatrix}^T \tag{5}$$

change in load demand ΔP is bounded and there exist a constant $\epsilon>0$ such that

$$\left\|\Delta P\right\| \le \varepsilon \tag{8}$$

Assumption 2: Assuming that parametric uncertainties ΔA satisfy the following condition

$$\Delta A = MH(t)N, \left\|\Delta H(t)\right\| \le 1$$

where M and N are known constant real matrices with appropriate dimensions; *H(t)* is a norm-bounded unknown matrix.

The main objective of this paper is to develop an observer output-feedback controller such that the stability of both the observer error system and closed-loop control system is asymptotically stable in spite of the existence of the parametric uncertainties.

III.DESIGNING OBSERVER OUTPUT FEEDBACK LOAD FREQUENCY CONTROLLER

In practice, the load frequency control (LFC) controller structure is traditionally a PI type controller using the ACE as its input. In this section, the output-feedback control design algorithm for such a load–frequency controller using the observer technique is presented. The proposed design is to minimize the frequency deviations and the tie-line power exchanges. A suitable dynamic observer-based control for the system (6)- (7) is given by

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L[t(t) - \hat{y}(t)] \tag{9}$$
$$\hat{y}(t) = C\hat{x}(t) \tag{10}$$
$$u(t) = -KC\hat{x}(t) = -K\hat{y}(t) \tag{11}$$

where $\hat{x}\in\mathrm{R}^n$ is the estimation of $x(t)$, $\hat{y}(t)\in\mathrm{R}^p$ is the observer output, $K\in\mathrm{R}^{m\times n}$ is the controller gain, and $L\in\mathrm{R}^{n\times p}$ is the observer gain. By equations (9)-(11), equation (6) can be rewritten as

$$\dot{x}(t) = (A - BKC)x(t) + \Delta Ax(t) + BKCe(t) + F\Delta P \tag{12}$$

and

$$\dot{e}(t) = \dot{x}(t) - \dot{\hat{x}}(t) = (A - LC)e(t) + \Delta Ax(t) + F\Delta P \tag{13}$$

where *e(t)=x(t)-$\hat{x}$(t)* is the estimated error of system. From equation (12)-(13) and we have

$$\begin{bmatrix}\dot{x}(t)\\ \dot{e}(t)\end{bmatrix} = \begin{bmatrix} A - BKC + \Delta A & BKC \\ \Delta A & A - LC\end{bmatrix}\begin{bmatrix}x(t)\\ e(t)\end{bmatrix} + \begin{bmatrix}F\Delta P\\ F\Delta P\end{bmatrix}$$

Now we are in position to derive sufficient conditions in terms of linear matrix inequalities (LMI) such that the two-area interconnected power system (6) is robustly stabilizable. Let us begin with considering the following LMI:

$$\begin{bmatrix} \Omega + \alpha_5 N^T N & P_1 BKC \\ (BKC)^T P_1 & \Xi \end{bmatrix} < 0 \quad (14)$$

where $P_1 \in R^{n\times n} > 0$, $P_2 \in R^{n\times n} > 0$,
$\Omega = P_1(A - BKC) + (A\text{-}BKC)^T + \alpha_4 P_1 F F^T P_1 + \alpha_2 P_1 M M^T P_1$,
$\Xi = P_2(A - LC) + (A - LC)^T P_2 + \alpha_3 P_2 F F^T P_2 + \alpha_1 P_2 M M^T P_2$
the scalar $\alpha_1>0$, $\alpha_2>0$, $\alpha_3>0$ and $\alpha_4>0$. Then, we can establish the following theorem.

Theorem 1: The system is bounded stable by the observer output-feedback controller - provided that there exist some positive constants $\alpha_1>0$, $\alpha_2>0$, $\alpha_3>0$ and $\alpha_4>0$, two positive definite symmetric matrices $P_1 \in R^{n\times n}$, $P_2 \in R^{n\times n}$ and matrices $K \in R^{m\times n}$, $L \in R^{n\times p}$ such that

$$\begin{bmatrix} \Omega + \alpha_5 N^T N & P_1 BKC \\ (BKC)^T P_1 & \Xi \end{bmatrix} < 0$$

where
$\Omega = P_1(A - BKC) + (A\text{-}BKC)^T + \alpha_4 P_1 F F^T P_1 + \alpha_2 P_1 M M^T P_1$,
$\Xi = P_2(A - LC) + (A - LC)^T P_2 + \alpha_3 P_2 F F^T P_2 + \alpha_1 P_2 M M^T P_2$
Before proving Theorem 1, we recall the following Lemmas:
Lemma 1 [34]: Let X and Y are real matrices of suitable dimension then, for any scalar $\varphi>0$, the following matrix inequality holds:

$$XY + Y^T X^T \leq \varphi^{-1} X X^T + \varphi Y^T Y.$$

Lemma 2 [34]: Let X, Y and F be matrices of compatible dimension then

$$XH(t)Y + Y^T H^(T)(t) X^T \leq \varphi^{-1} X X^T + \varphi Y^T Y.$$

for any *H(t)* satisfying ||H(t)|| and a scalar $\varphi>0$.
Proof Theorem 1: Let us choose the Lyapunov functional as

$$V(x(t), e(t)) = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \quad (15)$$

where $P_1 \in R^{n\times n} > 0$ and $P_2 \in R^{n\times n} > 0$. Then, we have

$$\begin{aligned}
\dot{V}(x(t), e(t)) = & \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \\
& \left\{ \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} A - BKC + \Delta A & BKC \\ \Delta A & A - LC \end{bmatrix} \right. \\
& + \left. \begin{bmatrix} A - BKC + \Delta A & BKC \\ \Delta A & A - LC \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \right\} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\
& + \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} F\Delta P \\ F\Delta P \end{bmatrix} + \begin{bmatrix} F\Delta P \\ F\Delta P \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\
& + \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \left\{ \begin{bmatrix} 0 \\ P_2 M \end{bmatrix} H(t) \begin{bmatrix} N & 0 \end{bmatrix} + \begin{bmatrix} N^T \\ 0 \end{bmatrix} H^T(t) \begin{bmatrix} 0 & M^T P_2 \end{bmatrix} \right. \\
& + \left. \begin{bmatrix} P_1 M \\ 0 \end{bmatrix} H(t) \begin{bmatrix} N & 0 \end{bmatrix} + \begin{bmatrix} N^T \\ 0 \end{bmatrix} H^T(t) \begin{bmatrix} M^T P_1 & 0 \end{bmatrix} \right\} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\
& + \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_1 F\Delta P \\ P_2 F\Delta P \end{bmatrix} + \begin{bmatrix} (F\Delta P)^T P_1 & (F\Delta P)^T P_2 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\
= & \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_1(A - BKC) + (A - BKC)^T P_1 & P_1 BKC \\ (BKC)^T P_1 & P_2(A - LC) + (A - LC)^T P_2 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\
& + \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \left\{ \begin{bmatrix} 0 \\ P_2 M \end{bmatrix} H(t) \begin{bmatrix} N & 0 \end{bmatrix} + \begin{bmatrix} N^T \\ 0 \end{bmatrix} H^T(t) \begin{bmatrix} 0 & M^T P_2 \end{bmatrix} \right. \\
& + \left. \begin{bmatrix} P_1 M \\ 0 \end{bmatrix} H(t) \begin{bmatrix} N & 0 \end{bmatrix} + \begin{bmatrix} N^T \\ 0 \end{bmatrix} H^T(t) \begin{bmatrix} M^T P_1 & 0 \end{bmatrix} \right\} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\
& + e^T(t) P_2 F \Delta P + \Delta P^T F^T P_2 e(t) + x^T(t) P_1 F \Delta P \\
& + \Delta P^T F^T P_1 x(t). \quad (16)
\end{aligned}$$

Applying Lemma 1 and Lemma 2 to equation (16), we obtain

$$\begin{aligned}
\dot{V}(x(t), e(t)) \leqslant & \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \left\{ \alpha_1 \begin{bmatrix} 0 \\ P_2 M \end{bmatrix} \begin{bmatrix} 0 & M^T P_2 \end{bmatrix} \right. \\
& + \alpha_2 \begin{bmatrix} P_1 M \\ 0 \end{bmatrix} \begin{bmatrix} M^T P_1 & 0 \end{bmatrix} + \alpha_5 \begin{bmatrix} N^T \\ 0 \end{bmatrix} \begin{bmatrix} N & 0 \end{bmatrix}
\end{aligned}$$

$$+\begin{bmatrix} P_1(A-BKC)+(A-BKC)^TP_1 & P_1BKC \\ (BKC)^TP_1 & P_2(A-LC)+(A-LC)^TP_2 \end{bmatrix}\Bigg\} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$

$$+\alpha_3 e^T(t)P_2FF^TP_2e(t)+\alpha_4 x^TP_1FF^TP_1x$$
$$+\tau\Delta P\Delta P^T$$
$$=\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} \Omega+\alpha_5N^TN & P_1BKC \\ (BKC)^TP_1 & \Xi \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+\tau\|\Delta P\|^2. \tag{17}$$

where τ=$\alpha_3{}^{-1}$+$\alpha_4{}^{-1}$, α^5=$\alpha_1{}^{-1}$+$\alpha_2{}^{-1}$
Ω = P_1(A - BKC) + (A-BKC)^T + $\alpha_4 P_1 FF^T P_1$ + $\alpha_2 P_1 MM^T P_1$,
and
Ξ = P_2(A - LC) + (A - LC)$^T P_2$ + $\alpha_3 P_2 FF^T P_2$ + $\alpha_1 P_2 MM^T P_2$
Letting

$$\Pi=-\begin{bmatrix} \Omega+\alpha_5N^TN_1 & P_1BKC \\ (BKC)^TP_1 & \Xi \end{bmatrix}>0,$$

the equation (17) yields

$$\dot{V}(x(t),e(t)) \le -\lambda_{min}(\Pi)\left\|\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}\right\|^2+\mu$$

where the constant value μ=$\varepsilon^2\tau$ and the eigenvalue $\mu_{min}(\Pi)$>0. Using the results of [23], [28], we have $\dot{V}(x(t),e(t))<0$ with

$$\left\|\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}\right\| > \sqrt{\frac{\mu}{\lambda_{min}(\Pi)}}$$

Hence, the system is bounded stable.

Remark 1: The observer based load frequency control for interconnected power system can be seen in [21]-[23] and [26]-[27]. However, these approaches only considered the estimation error of the observer based full state feedback control, which increases the computation of burden due to the associated closed-loop system, possessing a dynamical order double that of the actual systems.

Remark 2: In this approach, we use the output estimate to substitute the original state to construct a direct output feedback controller to solve the load frequency control of power system. Therefore, the conservatism is reduced and the robustness is enhanced. It also both save computing time and make the control method simpler.

IV. EXTENSION ON DESIGNING OBSERVER OUTPUT FOR LOAD FREQUENCY CONTROL WITH COMMUNICATION DELAYS

The linearized model of the governor valve position of a two-area power system with time delayed would be as [19], [28], [33]

$$\Delta\dot{X}_{G1}(t)=\frac{-\Delta X_{g1}(t)}{T_{g1}}+\frac{-\Delta f_1(t)}{R_1T_{g1}} +\frac{\Delta E_1(t-d)}{T_{g1}}+\frac{u_1(t)}{T_{g1}}$$

and

$$\Delta\dot{X}_{g2}(t)=\frac{-\Delta X_{g2}(t)}{T_{g2}}+\frac{-\Delta f_2(t)}{R_2T_{g2}} +\frac{\Delta E_2(t-d)}{T_{g2}}+\frac{u_2(t)}{T_{g2}}$$

The governor gets a delayed ACE signal, and the third term represents the impact of the former state. Thus, the matrix form of system dynamic model with communication delays can be rewritten as

$$\dot{x}(t)=(A+\Delta A)x(t)+A_dx(t-d) + Bu+F\Delta P \tag{18}$$

and

$$y(t)=Cx(t)=\begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} \tag{19}$$

where the term $x(t{-}d)$ represents delayed states. The known function $d=d(t)$ is the time-varying delay which is assumed to be continuous, non-negative and bounded in $\mathbb{R}^+$, that is, $\bar{d}=sup_{t\in\mathbb{R}^+}d(t)<\infty$. The initial conditions for the system is given by $x(t)=\phi(t)$, $(t\in[-\bar{d},0])$ where $\phi(t)$ are continuous in $[-\bar{d},0]$ and the delayed matrix

$$A_d = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{g1}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{g2}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

A dynamic observer-based output feedback control for the delayed system (18)-(19) is given by

$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + A_d\hat{x}(t-d) \\ &\quad + Bu(t) + L[y(t) - \hat{y}(t)] \quad (20) \\ \hat{y}(t) &= C\hat{x}(t) \quad (21) \\ u(t) &= -KC\hat{x}(t) = -K\hat{y}(t) \quad (22) \end{aligned}$$

where $\hat{x}(t-d) \in R^n$ is the estimation of $x(t-d)$, $\hat{y}(t) \in R^p$ is the observer output, $K \in R^{m\times n}$ is the controller gain, and $L \in R^{n\times p}$ is the observer gain. According to equations (20)-(22), equation (18) can be rewritten as

$$\begin{aligned} \dot{x}(t) =&(A - BKC)x(t) + \Delta Ax + A_d x(t-d) \\ &+ BKCe(t) + D\Delta P \quad (23) \end{aligned}$$

and

$$\begin{aligned} \dot{e}(t) =&\dot{x}(t) - \dot{\hat{x}}(t) \\ &= (A - LC)e(t) + A_d e(t-d) \\ &+ \Delta Ax + F\Delta P \quad (24) \end{aligned}$$

where $e(t) = x(t) - \hat{x}(t)$ is the estimated error of system. Using equations (23)-(24) and we obtain

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A - BKC + \Delta A & BKC \\ \Delta A & A - LC \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} A_d & 0 \\ 0 & A_d \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix} + \begin{bmatrix} F\Delta P \\ F\Delta P \end{bmatrix} \quad (25)$$

Then, we can establish the following theorem.

Theorem 2: The delayed system is bounded stable by the observer-based output feedback controller (20)-(22) provided that there exist some positive constants $\alpha_1>0$, $\alpha_2>0$, $\alpha_3>0$ and $\alpha_4>0$, four positive definite symmetric matrices $P_3 \in R^{\times n}$, $P_4 \in R^{n\times n}$, $P_5 \in R^{n\times n}$, $P_6 \in R^{n\times n}$ and matrices , $K \in R^{m\times n}$, and $L \in R^{n\times p}$ such that

$$\begin{bmatrix} \begin{bmatrix} \Omega & P_3BKC \\ (BKC)^T P_3 & \Xi_2 \end{bmatrix} & \begin{bmatrix} P_3A_d & 0 \\ 0 & P_4A_d \end{bmatrix} \\ \begin{bmatrix} A_d^T P_3 & 0 \\ 0 & A_d^T P_4 \end{bmatrix} & -\begin{bmatrix} P_5 & 0 \\ 0 & P_6 \end{bmatrix} \end{bmatrix} < 0$$

where

$$\begin{aligned} \Omega =&P_3(A - BKC) + (A - BKC)^T P_3 \\ &+ \alpha_4 P_3 F F^T P_3 + \alpha_5 N^T N \\ &+ \alpha_2 P_3 M M^T P_3 + P_5 \end{aligned}$$

and

$$\begin{aligned} \Xi =&P_4(A - LC) + (A - LC)^T P_4 + \\ &\alpha_3 P_4 F F^T P_4 + \alpha_1 P_4 M M^T P_4 + P_6 \end{aligned}$$

Proof Theorem 2: We first construct the following the Lyapunov functional candidate

$$V(x(t), e(t)) = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_3 & 0 \\ 0 & P_4 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \int_{t-\tau}^{t} \begin{bmatrix} x(s) \\ e(s) \end{bmatrix}^T \begin{bmatrix} P_5 & 0 \\ 0 & P_6 \end{bmatrix} \begin{bmatrix} x(s) \\ e(s) \end{bmatrix} ds$$

where $P_3 \in R^{\times n} > 0, P_4 \in R^{n\times n} > 0, P_5 \in R^{n\times n} > 0, P_6 \in R^{n\times n} > 0$. Then, we get

$$\begin{aligned} \dot{V}(x, e) =& \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_3 & 0 \\ 0 & P_4 \end{bmatrix} \begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} \\ &+ \begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix}^T \begin{bmatrix} P_3 & 0 \\ 0 & P_4 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\ &+ \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_5 & 0 \\ 0 & P_6 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \\ &- \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}^T \begin{bmatrix} P_5 & 0 \\ 0 & P_6 \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix} \end{aligned}$$

$$= \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \left\{ \begin{bmatrix} P_3(A - BKC) + (A - BKC)^T P_3 & P_3BKC \\ (BKC)^T P_3 & P_4(A - LC) + (A - LC)^T P_4 \end{bmatrix} \right.$$

$$+ \begin{bmatrix} 0 \\ P_4 M \end{bmatrix} H(t) \left[N \; 0\right] + \begin{bmatrix} N^T \\ 0 \end{bmatrix} H^T(t) \left[0 \; M^T P_4\right]$$

$$+\begin{bmatrix} P_3M \\ 0 \end{bmatrix} H(t)\,[N\ 0] + \begin{bmatrix} N^T \\ 0 \end{bmatrix} H^T(t)\,\left[M^T P_3\ 0\right]\Bigg\} \tag{26}$$

$$\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_3A_d\ 0 \\ 0\ PA_d \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}$$
$$+\begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}^T \begin{bmatrix} A_d^TP_3\ 0 \\ 0\ A_d^TP \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_5\ 0 \\ 0\ P_6 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$-\begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}^T \begin{bmatrix} P_5\ 0 \\ 0\ P_6 \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}$$
$$+e^T(t)P_2F\Delta P + \Delta P^TF^TP_2e(t)$$
$$+x^TP_1F\Delta P + \Delta P^TF^TP_1x. \tag{27}$$

Applying Lemma 1 and Lemma 2 to equation (27), we achieve

$$\dot V(x(t),e(t)) \leqslant \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \Bigg\{\varepsilon_1 \begin{bmatrix} 0 \\ P_4M \end{bmatrix} \left[0\ M^TP_4\right]$$
$$+\varepsilon_5 \begin{bmatrix} N^T \\ 0 \end{bmatrix} [N\ 0] + \varepsilon_2 \begin{bmatrix} P_3M \\ 0 \end{bmatrix} \left[M^TP_3\ 0\right]$$
$$+\begin{bmatrix} P_3(A-BKC)+(A-BKC)^TP_3\ P_3BKC \\ (BKC)^TP_3\ P_4(A-LC)+(A-LC)^TP_4 \end{bmatrix}\Bigg\}$$
$$\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_3A_d\ 0 \\ 0\ P_4A_d \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}$$
$$+\begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}^T \begin{bmatrix} A_d^TP_3\ 0 \\ 0\ A_d^TP_4 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+\alpha_3e^T(t)P_4FF^TP_4e(t)$$
$$+\alpha_4x^TP_3FF^TP_3x + \tau\Delta P\Delta P^T$$
$$+\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} P_5\ 0 \\ 0\ P_6 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$-\begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}^T \begin{bmatrix} P_5\ 0 \\ 0\ P_6 \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}$$

$$=\chi(t)^T \begin{bmatrix} \begin{bmatrix} \Omega\ P_3BKC \\ (BKC)^TP_3\ \Xi_2 \end{bmatrix} & \begin{bmatrix} P_3A_d\ 0 \\ 0\ P_4A_d \end{bmatrix} \\ \begin{bmatrix} A_d^TP_3\ 0 \\ 0\ A_d^TP_4 \end{bmatrix} & \text{-} \begin{bmatrix} P_5\ 0 \\ 0\ P_6 \end{bmatrix} \end{bmatrix} \chi(t)$$
$$+\tau\|\Delta P\|^2, \tag{28}$$

where

$$\chi(t) = \left[x^T(t)e^T(t)x^T(t-d)e^T(t-d)\right]^T$$
$$\tau = \alpha_3^{-1} + \alpha_4^{-1}, \alpha_5 = \alpha_1^{-1} + \alpha_2^{-1}$$
$$\Omega = P_3(A-BKC) + (A-BKC)^TP_3$$
$$+\alpha_4P_3FF^TP_3 + \alpha_5N^TN$$
$$+\alpha_2P_3MM^TP_3 + P_5$$

and

$$\Xi = P_4(A-LC) + (A-LC)^TP_4$$
$$+\alpha_3P_4FF^TP_4$$
$$+\alpha_1P_4MM^TP_4 + P_6$$

Letting $\Pi =$

$$-\begin{bmatrix} \begin{bmatrix} \Omega & P_3BKC \\ (BKC)^TP_3 & \Xi \end{bmatrix} & \begin{bmatrix} P_3A_d & 0 \\ 0 & P_4A_d \end{bmatrix} \\ \begin{bmatrix} A_d^TP_3 & 0 \\ 0 & A_d^TP_4 \end{bmatrix} & -\begin{bmatrix} P_5 & 0 \\ 0 & P_6 \end{bmatrix} \end{bmatrix} > 0,$$

the equation (28) yields

$$V(x(t),e(t)) \leq -\lambda_{min}(\Pi)\left\|\chi(t)\right\|^2 + \mu$$

where the constant value $\mu = \varepsilon^2\tau$ and the eigenvalue $\lambda_{min}(\Pi) > 0$. Using the results of [23], [28], we have $\dot V(x(t),e(t)) < 0$ with

$$||\chi(t)|| > \sqrt{\frac{\mu}{\lambda_{min}(\Pi)}}.$$

Hence, the delayed system is bounded stable.

Remark 3: LMI-based load frequency control for power systems with communication delays can be seen in papers [18]-[20]. However, the approaches given in [18]-[19] need to find the solution of two LMI equations. In papers [20] the number of matrix variables in LMI equations are seven and the number of LMI equations are two. Thus, the proposed approach offers less number of matrix variables in LMI equations making it easier to find a feasible solution.

Remark 4: Output feedback load frequency control for power systems can be seen in papers [29]-[32]. Unlike the previous approaches, this study can be applied for the interconnected power system with time delayed and parametric uncertainties.

V. SIMULATION RESULTS

In order to evaluate the performance of the proposed observer output-feedback controller, the simulation results are compared with those of methods given in [10] and [35]. The investigated system parameters are given as follows [10] and [35]: speed regulation $R_1=0.05$ and $R_2=0.0625$; Frequency-sensitive load coefficient $D_1=0.6$ and $D_2=0.9$; Frequency bias factors $B_1=20.6$ and $B_2=16.9$; Inertia constant $H_1=5$ and $H_2=4$; Governor time constant $T_{g1}=0.2$sec and $T_{g2}=0.3$sec; Turbine time constant $T_{t1}=0.5$sec and $T_{t2}=0.6$sec; Integral control gain $K_{E1}=K_{E2}=0.3$; the synchronizing coefficient between two areas $P_s=2$. The nominal plant models for the two areas are as follows:

Case 1: In order to test the robustness of the proposed observer output-feedback controller, the system with nominal parameters is used (ΔA=MH(t)N=0) and the step load disturbances are applied as + 0.015 p.u. for area 1 at 5 s, +0.015 p.u. for area 2 at 5 s. By solving LMI it is easy to verify that conditions in Theorem 1 are satisfied with positive matrices (see Equations (29)-(31)) and the scalars α_3=0.1 and α_4=1.1.

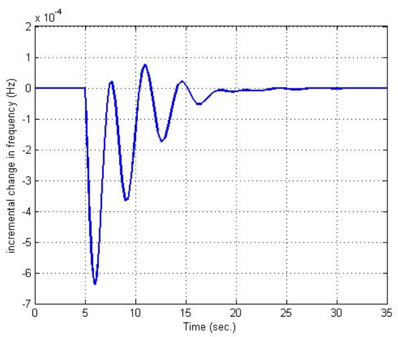

Fig. 2: Frequency deviation of area-1 (Case 1)

The simulation results of $\Delta f_1(t)$, $\Delta P_{tie}(t)$, $\Delta f_2(t)$, ACE_1 and ACE_2 using the proposed controller are shown in Fig. 2 to Fig. 6. It is observed that the frequency deviation, the tie-line power deviation and the area control error converge to zero. The simulation results indicate that the controller given in [10], [35] results in considerably larger oscillating overshoots and larger transient frequency deviation in both area 1 and area 2, comparing with the results from the proposed observer output-feedback controller.

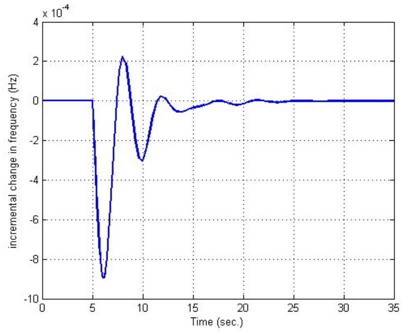

Fig. 3: Frequency deviation of area-1 (Case 1)

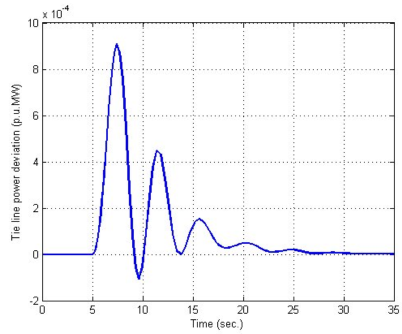

Fig. 4: Tie-line power deviation (Case 1)

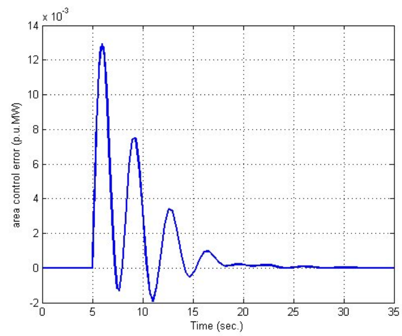

Fig. 5: ACE in control area 1 (Case 1)

$$A = \begin{bmatrix} -5 & 0 & -100 & 0 & 0 & 0 & 0 & 5 & 0 \\ 2 & -2 & 0 & 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0.1 & -0.06 & -0.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 & -2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -3.33 & 0 & -53.33 & 0 & -3.33 \\ 0 & 0 & 0 & 0 & 1.667 & -1.667 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.125 & 0 & 0.125 & -0.115 & 0 & 0 \\ 0 & 0 & 6.18 & -0.3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.3 & 0 & 0 & -5.7 & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 3.333 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, F = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -0.1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -0.125 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -20.6 & 0 \\ -1 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & -16,9 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}^T.$$

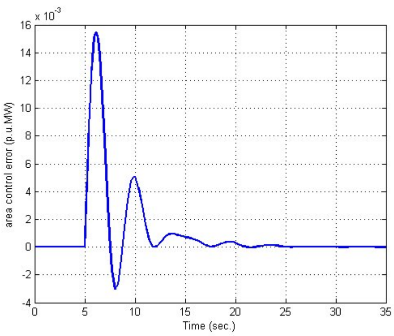

Fig. 6: ACE in control area 2 (Case 1)

Case 2: In Case 1, the two-area power system is operated with all the parameters on their nominal values without considering parameter uncertainties. In real power system, parameter uncertainties always exist because of the variations of internal and external conditions. In this case, we study the LFC problem of the two-area power system with load changes and parameter uncertainties by using the proposed observer output-feedback controller. The uncertain parameters in the two-area power system are assumed to satisfy $\Delta A = MH(t)N$ with $M = I$, $H(t) = sin(t)$ and $N = 0.5I$. The step load disturbances are applied as + 0.03 p.u. for area 1 at 5 s, -0.03 p.u. for area 2 at 10 s. By solving LMI it is easy to verify that conditions in Theorem 1 are satisfied with positive matrices (see Equations (32)-(34)) and the scalars α_1=5, α_2=5, α_3=0.1, α_4=1.1 and α_5=0.4.

The simulation results of $\Delta f_1(t)$, $\Delta P_{tie}(t)$,

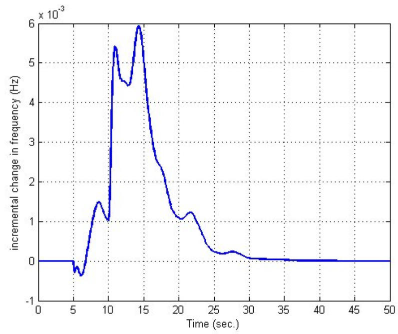

Fig. 7: Frequency deviation of area-1 (Case 2)

$\Delta f_2(t)$, ACE_1 and ACE_2 using the proposed controller are shown in Fig. 7 to Fig. 11. From Fig. 7 to Fig. 11, it can be found that the designed observer output-feedback controller stabilizes the LFC system even when the uncertainties exist, which shows the robustness

$$P_1 = \begin{bmatrix} 1.02 & -0.26 & 11.8 & -0.04 & -0.88 & 0.48 & -4.41 & -0.96 & 0.31 \\ -0.26 & 1.04 & 2.11 & 1.67 & 0.05 & -0.73 & -0.8 & -1.09 & 0.21 \\ 11.8 & 2.11 & 239 & 1.33 & -6.18 & -2.17 & -10.0 & -22.5 & 6.73 \\ -0.04 & 1.6 & 1.33 & 39.4 & -0.16 & -2.66 & 1.18 & 9.31 & -8.6 \\ -0.88 & 0.05 & -6.18 & -0.16 & 2.13 & -1.10 & 17.4 & 0.75 & -1.19 \\ 0.48 & -0.73 & -2.17 & -2.66 & -1.1 & 2.24 & -6.23 & 0.48 & -1.45 \\ -4.41 & -0.8 & -10.0 & 1.18 & 17.4 & -6.23 & 194 & 4.87 & -17.9 \\ -0.96 & -1.09 & -22.5 & 9.31 & 0.75 & -0.48 & 4.87 & 9.17 & -1.39 \\ 0.31 & 0.21 & 6.73 & -8.63 & -1.19 & -1.45 & -17.9 & -1.39 & 9.99 \end{bmatrix}, \quad (29)$$

$$P_2 = \begin{bmatrix} 100 & -38.7 & -8.88 & -27,6 & 20.5 & 8.14 & -0.43 & -6.11 & -29.3 \\ -38.7 & 250 & 15.1 & -169 & 18.3 & 47.8 & -8.47 & -210 & -63.5 \\ -8.88 & 15.1 & 980 & 37.3 & 6.12 & -10.8 & -118 & -30.8 & 11.1 \\ -27.6 & -169 & 37.3 & 414 & 52.6 & 113 & -23.9 & 202 & -190 \\ 20.5 & 18.3 & 6.12 & 52.6 & 127 & -30.4 & -5.73 & -38.3 & -96.7 \\ 8.14 & 47.8 & -10.8 & 113 & -30.4 & 176 & 26.4 & -50.6 & -166 \\ -0.42 & -8.47 & -118 & -23.9 & -5.73 & 26.4 & 986 & 11.4 & -58.5 \\ -61.1 & -210 & -30.8 & 202 & -38.3 & -50.6 & 11.4 & 272 & 84.8 \\ -29.3 & -63.5 & 11.1 & -190 & -96.7 & -166 & -58.5 & 84.8 & 291 \end{bmatrix} \quad (30)$$

$$L = 10^3 \begin{bmatrix} 0.6543 & -1.5006 \\ 0.7380 & -1.6966 \\ -0.0345 & 0.0771 \\ 0.7146 & -1.5866 \\ -0.6277 & 1.3789 \\ -0.7390 & 1.6221 \\ 0.0424 & -0.0949 \\ -0.0753 & 0.1093 \\ 0.0955 & -0.2298 \end{bmatrix}, K = \begin{bmatrix} 0.000001 & -0.07 \\ -0.061 & 0.00001 \end{bmatrix} \quad (31)$$

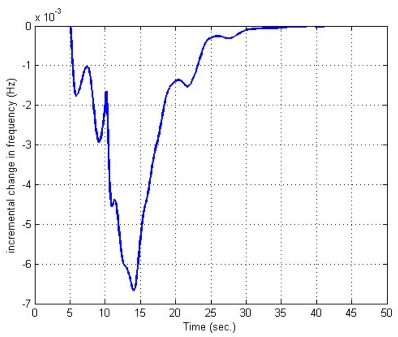

Fig. 8: Frequency deviation of area-2 (Case 2)

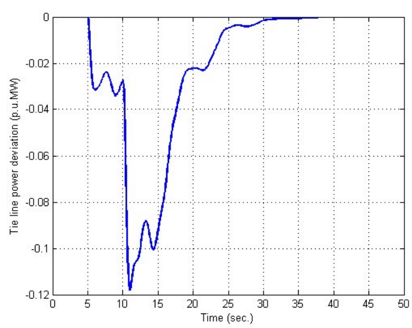

Fig. 9: Tie-line power deviation (Case 2)

of controller against parameter uncertainties.

Case 3: As the time delay will degrade the dynamic performance and cause instability of augmented power system. In this case, we analyze the stability of two-area LFC schemes with time delays using the proposed observer output-feedback controller. The delayed time

$$P_1 = \begin{bmatrix} 0.90 & -0.46 & 10.5 & -0.17 & -0.56 & 0.36 & -1.74 & -0.51 & 0.20 \\ -0.42 & 0.36 & -4.4 & 0.12 & 0.15 & -0.2 & -0.39 & -0.03 & 0.04 \\ 10.5 & -4.4 & 146.3 & -2.03 & -3.86 & 1.64 & 6.89 & -7.62 & 2.21 \\ -0.17 & 0.12 & -2.03 & 2.52 & 0.14 & -0.15 & 0.92 & 0.7 & -0.78 \\ -0.56 & 0.15 & -3.86 & 0.14 & 1.14 & -0.71 & 9.08 & 0.42 & -0.5 \\ 0.36 & -0.20 & -1.64 & -0.15 & -0.71 & 0.72 & -5.06 & -0.20 & -0.16 \\ -1.74 & -039 & 6.89 & 0.92 & 9.08 & -5.06 & 93.04 & 2.18 & -5.75 \\ -0.51 & -0.03 & -7.62 & 0.7 & 0.42 & -0.20 & 2.18 & 1.41 & -0.18 \\ 0.20 & 0.04 & 2.21 & -0.77 & -0.50 & -0.16 & -5.75 & -0.18 & 91.83 \end{bmatrix}, \quad (32)$$

$$P_2 = \begin{bmatrix} 73.7 & -19.8 & 2.77 & 43.3 & 12.2 & -3.21 & -2.86 & -54.0 & -9.05 \\ -19.8 & 19.3 & -2.02 & 3.11 & -0.42 & 4.78 & 0.15 & 0.59 & -4.30 \\ 2.77 & -2.02 & 408 & 20.3 & -7.99 & 4.29 & -71.4 & -2.0 & 4.09 \\ -43.3 & 3.11 & 20.3 & 65.0 & 21.9 & -0.2 & -27.9 & 40.1 & -21.5 \\ 12.24 & -0.42 & -7.99 & 21.9 & 46.0 & -10.0 & 9.50 & -11.8 & -35.3 \\ -3.21 & 4.78 & 4.29 & -0.2 & -10.0 & 9.71 & -8.16 & -1.40 & -0.19 \\ -2.86 & 0.15 & -71.4 & -27.9 & -9.5 & -8.16 & 467.4 & 3.1 & -3.76 \\ -54.0 & 0.59 & -2.0 & 40.1 & -11.8 & -1.40 & 3.16 & 53.4 & 13.2 \\ -9.05 & -4.3 & 4.09 & -21.5 & -35.3 & -0.19 & -3.79 & 13.2 & 35.7 \end{bmatrix} \quad (33)$$

$$L = 10^3 \begin{bmatrix} 0.6543 & -1.5006 \\ 0.7380 & -1.6966 \\ -0.0345 & 0.0771 \\ 0.7146 & -1.5866 \\ -0.6277 & 1.3789 \\ -0.7390 & 1.6221 \\ 0.0424 & -0.0949 \\ -0.0753 & 0.1093 \\ 0.0955 & -0.2298 \end{bmatrix}, K = \begin{bmatrix} 0.000001 & -0.07 \\ -0.061 & 0.00001 \end{bmatrix} \quad (34)$$

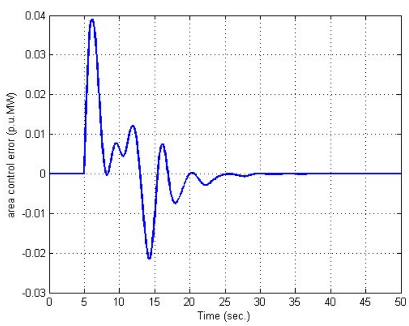

Fig. 10: ACE in control area 1 (Case 2)

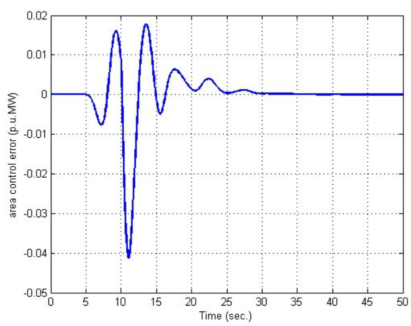

Fig. 11: ACE in control area 2 (Case 2)

is chosen to be as *d=d(t)=0.1s*. The step load disturbances are applied as + 0.02 p.u. for area 1 at 5 s, +0.02 p.u. for area 2 at 10 s. The uncertain parameters in the two-area power system are the same with Case 2.

From Fig. 12 to Fig. 16, it is obvious that time delays have effected the closed-loop system performance, however, in spite of this, the

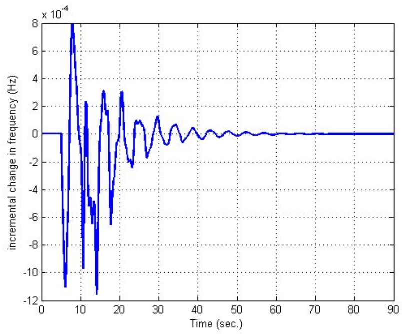

Fig. 12: Frequency deviation of area-1 (Case 3)

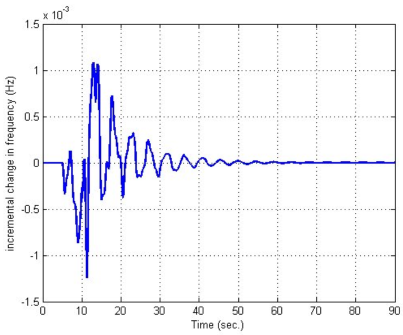

Fig. 13: Frequency deviation of area-2 (Case 3)

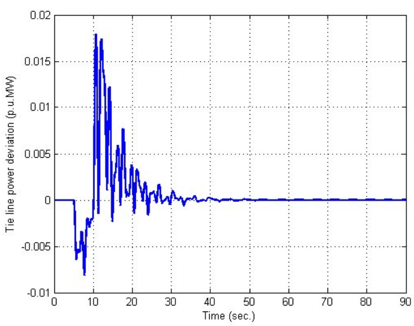

Fig. 14: Tie-line power deviation (Case 3)

system is still stable and that the steady-state values of frequency deviation and tie-line power deviation still converge to zero. Remark 5: The proposed observer output-feedback load frequency controller results in shortening the frequency's transient response, maintaining required control quality in the wider operating range, and being more robust to uncertainties as compared to the methods given in [10] and [35].

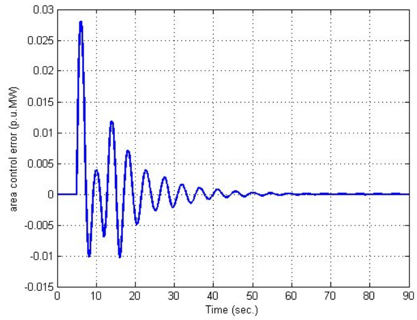

Fig. 15: ACE in control area 1 (Case 3)

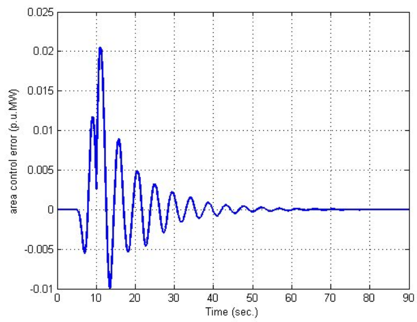

Fig. 16: ACE in control area 2 (Case 3)

VI. CONCLUSION

In this paper, the observer output-feedback controller is proposed in order to control the frequency of a two-area interconnected power system. The observer and integral control are employed to improve power-system performance. The proposed controller design is dependent on only the observer output. Therefore, the conservatism is reduced and the robustness is enhanced. It also both save computing time and make the control method simpler. Moreover, simulation results show that the proposed controller ensures better disturbance rejection, maintains required control quality in the wide range of operating conditions, shortens the frequency's transient response avoiding the overshoot and is more robust to system uncertainties.

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Appendix A: Transfer function model of two-area time-delay power system [19], [28], [33]