Unknown Input Observer Based Robust Actuator Fault Detection and Isolation in Interconnected Power Systems

V. M. I. GENC and F. CALISKAN

***Abstract*— In this paper, the performance degradation of a generating unit in a multi-area power system regulated by an area-wise decentralized load frequency control is detected and isolated via a scheme of unknown input observers. This scheme is robust to the changes in the load demand, which are considered as the unknown inputs. The actuator faults studied in this work are meant to be the performance degradations in generating units under load frequency control. Both stuck and non-stuck actuator faults are analyzed and the performances of the proposed method in both cases are tested through computer simulations on a two-area power system composed of five generating units. The results show that a performance degradation in any generating unit can be detected and isolated successfully provided that the faults in the sensors measuring generator outputs are absent.**

Index Terms— **actuator fault, fault diagnosis, fault detection and isolation, interconnected power systems, load frequency control, power generation control**

I. INTRODUCTION

LOAD Frequency Control (LFC) is a widely used method for maintaining the nominal frequency in an interconnected power system while keeping the net active power interchanges as scheduled between its control areas. As in any feedback control system, faults related to the actuators, sensors or controllers used in the LFC loops can result in unexpected and undesired operations. These types of faults occurring in the LFC system can cause abnormal steady-state deviations in the system's frequency as well as in the power interchanges and the loadings of the generating units. Therefore, it is crucial to detect and isolate (identify) these faults in a short time to prevent a sustained undesired LFC operation caused by them.

In a model based Fault Detection and Isolation (FDI) technique, faults are detected and isolated based on a comparison between the system's available measurements and its mathematical model. Specifically, Unknown Input Observers (UIOs), which are insensitive to disturbances or unknown inputs, are extensively used for a robust FDI [1]-[6]. In recent years, the studies about the application of FDI in power system dynamics and control have greatly increased. For instance, a software approach to fault detection and identification in the LFC loops of interconnected power systems is introduced in [7], where the faults occurring in the load frequency control loops and the communication channels are detected using a failure detection filter. The transmission network faults are detected and their exact locations are found in [8] using UIOs, where the faults are modeled as unknown inputs decoupled from the state and output measurements.

A new approach for fault detection in a power system based on independent component analysis is proposed in [9], and tested on a typical power system's simulated data and compared with the approaches available in literature. In [10], the fault diagnosis problem for power systems is solved using two nonlinear observers for generating the fault signals for comparison: an extended Kalman estimator and a new extended Kalman filter with moving horizon.

A fault-tolerant controller for linear time-invariant (LTI) systems with multiple actuators, including a fault tolerant speed governor, is designed in [11] so that the closed-loop system satisfies the following two properties: stability under all permissible sets of faults, and better performance after clearing every subset of the existing faults in the system. A robust load frequency control is proposed in [12] for multi-area power systems with stochastic disturbances induced by the integration of large number of renewable energy resources.

In [13], an FDI method in electrical energy systems based on techniques developed in the context of invertibility of switched systems is proposed. The existence of unknown input observers for networks of interconnected second-order linear time invariant systems is studied in [14] and a bank of unknown input observers is used for detecting and isolating faults in the network.

In [15], a robust FDI procedure to detect and isolate sensor and controller faults occurring in the LFC loops is proposed. In [16], the FDI scheme developed in [15] is also applied to power systems including electric vehicles and renewable

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energy sources to detect and isolate sensor faults within the control system. A sensor fault tolerant control system is proposed in [17] for distributed energy resource units in a microgrid.

Although improper actions of controllers fed by the Area Control Error (ACE) signals are treated in [15] as faults, the performance degradation caused by the actuator faults in the generating units are more likely to occur in an LFC system. Therefore, unlike the study in [15], in this paper, governors are characterized as actuators, and the detection and isolation of a performance degradation in a generating unit is studied by means of a robust actuator FDI scheme. This approach necessitates a distinct modeling approach from the LFC system studied in [15].

Both stuck and non-stuck faults are studied in this paper. Since stuck faults in the governors can lead more severe misoperations, UIOs are designed to detect and isolate the stuck governor faults besides non-stuck governor faults, whereas, in [15], only the non-stuck faults in the integral controllers of the LFC system have been considered. A stuck fault in a governor of a generating unit under LFC may easily lead to an unscheduled generation dispatch as well as a drastic degradation in the transient response of the LFC system. A non-stuck fault, on the other hand, can be less severe and could only affect the transient response. Both types of faults can be detected and isolated with the proposed scheme in this paper. The implications caused by them can be avoided by replacing the faulty components that are identified (isolated) by the method.

Simulations are performed for a benchmark model of a power system composed of two areas. The effectiveness of the FDI scheme for detection and isolation of a performance degradation in a generating unit has been demonstrated. The applicability of the proposed scheme in the presence of sensor faults is also studied, simulated and the results are analyzed. A preliminary work considering only the non-stuck governor faults neglecting the possibility of sensor faults is given in [18].

II. DESIGN OF ACTUATOR FDI ALGORITHM ROBUST TO UNKNOWN INPUTS

A state space representation of a dynamical system with actuator faults can be expressed as follows:

$$\dot{x} = Ax + B^i u^i + B^i f_a^i + b_i(u_i + f_{ai}) + Ed$$

$$\dot{x} = Ax + B^i u^i + B^i f_a^i + \begin{bmatrix} E & b_i \end{bmatrix} \begin{bmatrix} d \\ u_i + f_{ai} \end{bmatrix}, \quad i = 1,2,\dots.r$$

$$\dot{x} = Ax + B^i u^i + B^i f_a^i + E^i d^i$$

$$y = Cx \quad , \tag{1}$$

where $b_i \in R^{nx1}$ is the i-th column of the matrix B, $B^i \in R^{nx(r-1)}$ is obtained from B by discarding the i-th column b_i, $u_i \in R^{1x1}$ is the i-th element of u, $u^i \in R^{(r-1)x1}$ is obtained from u by discarding the i-th element, u_i, $f_{ai} \in R^{1x1}$ is the i-th element of f_a, $f_a^i \in R^{(r-1)x1}$ is obtained from f_a by deleting the i-th element f_{ai}, $y \in R^m$ is the output (measurement) vector. E^i and d^i respectively are

$$E^i = \begin{bmatrix} E & b_i \end{bmatrix}, d^i = \begin{bmatrix} d \\ u_i + f_{ai} \end{bmatrix}, \; i = 1,2,\dots.r \; . \tag{2}$$

Moreover, the dynamic equations of the unknown input observer UIO_i to be used for detection and isolation of an actuator fault i are given as

$$\dot{z}^i = F^i z^i + T^i B^i u^i + K^i y \tag{3}$$

$$\hat{x} = z^i + H^i y \qquad i = 1,2,\dots.r \; , \tag{4}$$

where $\hat{x} \in R^n$ is the estimated state vector and $z^i \in R^n$ is the state of the full-order observer [3]. F^i, T^i, K^i, and H^i are the design parameter matrices to be determined such that the FDI design based on UIOs is robust to unknown inputs (disturbances).

The error dynamics, where state estimation error $e = x - \hat{x}$ can be obtained as

$$\begin{aligned} \dot{e} = & \left[(I - H^i C)A - K_1^i C\right]e + \\ & \left[F^i - (I - H^i C)A - K_1^i C\right]z^i - \\ & \left[K_2^i - ((I - H^i C)A - K_1^i C)H^i\right]y - \\ & \left[T^i - (I - H^i C)\right]B^i u^i - (H^i C - I)E^i d^i \end{aligned} \tag{5}$$

where

$$K^i = K_1^i + K_2^i. \tag{6}$$

Followed by the equalities,

$$\begin{aligned} & H^i C E^i = E^i \\ & T^i = I - H^i C \\ & F^i = T^i A - K_1^i C \text{ must be Hurwitz} \\ & K_2^i = F^i H^i , \end{aligned} \tag{7}$$

the error dynamics becomes

$$\dot{e} = F^i e . \tag{8}$$

If all eigenvalues of F^i have negative real parts, the error asymptotically approaches zero.

The necessary and sufficient existence conditions [4] for the UIO_i are :

(i) $rank(CE^i) = rank(E^i)$ (9)

(ii) (C, A_1) is a detectable pair, where

$$A_1 = A - E^i\left[(CE^i)^T CE^i\right]^{-1}(CE^i)^T CA \cdot \tag{10}$$

Since the residual $r = Ce$, it can be rewritten as

$$r = y - C\hat{x} = (I - CH^i)y - Cz^i,\, i = 1,2,\ldots r \ \cdot \tag{11}$$

UIO_i is driven by all outputs and all inputs but input i (see, Fig.1). If the actuator i fails, then the norms of the residual vectors meet the following inequalities:

$$\left\|r^i\right\| < T^i_{AFI} \ \ and \left\|r^k\right\| \geq T^k_{AFI} \ \ for\ k = 1,..i-1, i+1,\ldots r \,, \tag{12}$$

where T^i_{AFI} s are predefined isolation threshold values, which are determined based on the comparison between fault-free and faulty operations for the specific system under study. Since the residuals differ greatly for the two opposing cases, the proper threshold values can easily be selected in such a way that any false alarm is not produced nor does the scheme miss any fault.

A robust and UIO-based actuator fault detection and isolation scheme, which consists of a bank of UIO's is depicted in Fig. 1.

III. FDI Application to a Two-Area Power System under LFC

A two-area power system with an area-wise decentralized LFC is given in the block diagram in Fig.2. The areas are modeled with a number of coherent generating units, each of which is represented by a turbine-speed governor system. Area 1 is represented by a group of three generating units while Area 2 is assumed to be composed of two generating units. In Fig. 2, inertia and load damping constants of area j are denoted by H_j and D_j, respectively, where f_o is the nominal frequency. In each area j, the turbine and governor time constants of any generating unit k are represented by T_{tjk} and T_{gvjk}, respectively, whereas R_{jk} is the regulator droop constant. The area control error ACE_j is obtained using the bias setting β_j and the synchronizing torque coefficient T_{12} and fed back to each area control center through an integral controller with the constant K_{Ij} . Distribution coefficient for the loading of unit k in area j is denoted by α_{jk} . In order to analyze and develop a FDI scheme for the actuator faults, the actuator and plant dynamics have to be separated. Assuming that the system is subject to actuator faults, the dynamics of the plant involving the turbines and generators can be expressed as

$$\dot{x} = Ax + Bu_R + Ed \ \ y = Cx \cdot \tag{13}$$

The state vector,

$$\begin{aligned} x = \big[\textstyle\int \Delta P_{tie} \quad \int \Delta f_1 \quad \Delta f_1 \quad \Delta P_{g11} \quad \Delta P_{g12} \\ \Delta P_{g13} \quad \int \Delta f_2 \quad \Delta f_2 \quad \Delta P_{g21} \quad \Delta P_{g22} \big] \end{aligned} \tag{14}$$

where Δf_j is the frequency deviation in area j and ΔP_{gjk} is the deviation in the generation at the k-th unit of area j and ΔP_{tie} is the tie-line power flow deviation. The disturbance vector,

$$d = \left[\Delta d_1 \quad \Delta d_2\right], \tag{15}$$

where the change in the load demand of area is represented by Δd_j .

$$A = \begin{bmatrix} 0 & T_{12} & 0 & 0 & 0 & 0 & -T_{12} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{fT_{12}}{2H_1} & -\frac{fD_1}{2H_1} & \frac{f}{2H_1} & \frac{f}{2H_1} & \frac{f}{2H_1} & \frac{fT_{12}}{2H_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{t11}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{t12}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{t13}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \frac{fT_{12}}{2H_2} & 0 & 0 & 0 & 0 & -\frac{fT_{12}}{2H_2} & -\frac{fD_2}{2H_2} & \frac{f}{2H_2} & \frac{f}{2H_2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{t21}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{t22}} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{T_{t11}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{T_{t12}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{t13}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{t21}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{t22}} \end{bmatrix}^T$$

$$E = \begin{bmatrix} 0 & 0 & -\frac{f}{2H_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{f}{2H_2} & 0 & 0 \end{bmatrix}^T$$

The control input vector, which is composed of actuator outputs,

$$u_R = \left[\Delta X_{gv11} \quad \Delta X_{gv12} \quad \Delta X_{gv13} \quad \Delta X_{gv21} \quad \Delta X_{gv22}\right], \tag{16}$$

where ΔX_{gvjk} is the deviation in the governor valve or gate position of the k-th unit in area j.

The dynamics of the actuators involving governors with the LFC system can be represented as

$$\begin{aligned} \dot{x} &= A_R x_R + B_R u_c + F_R x \\ u_R &= C_R x_R = x_R\,, \end{aligned} \tag{17}$$

where

$$u_c = -Kx = \left[\Delta P_{c11} \quad \Delta P_{c12} \quad \Delta P_{c13} \quad \Delta P_{c21} \quad \Delta P_{c22}\right] \tag{18}$$

comprises the deviations in the speed governor changer positions ΔP_{cjk} of the k-th unit in area j.

$$A_R = B_R = diag\left[-\frac{1}{T_{g11}} \quad -\frac{1}{T_{g12}} \quad -\frac{1}{T_{g13}} \quad -\frac{1}{T_{g21}} \quad -\frac{1}{T_{g22}}\right]$$

$$F_R = \begin{bmatrix} 0 & 0 & -\frac{1}{T_{g11}R_{11}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{g12}R_{12}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{g13}R_{13}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{g21}R_{21}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{g22}R_{22}} & 0 & 0 \end{bmatrix}$$

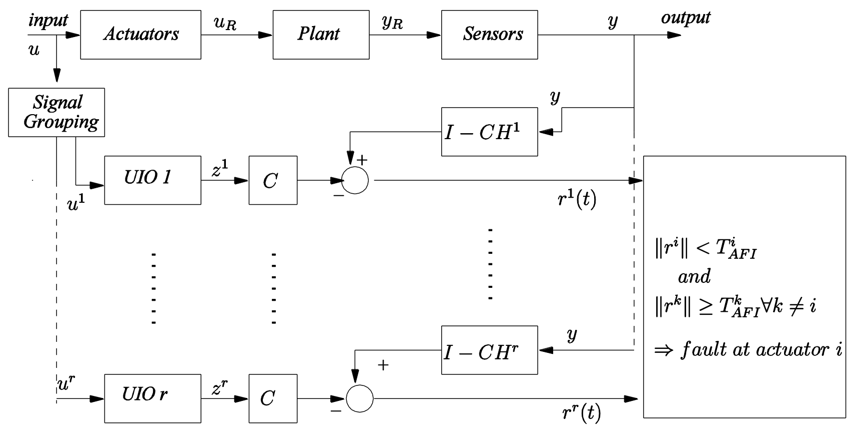

Fig. 1 A robust actuator fault isolation scheme.

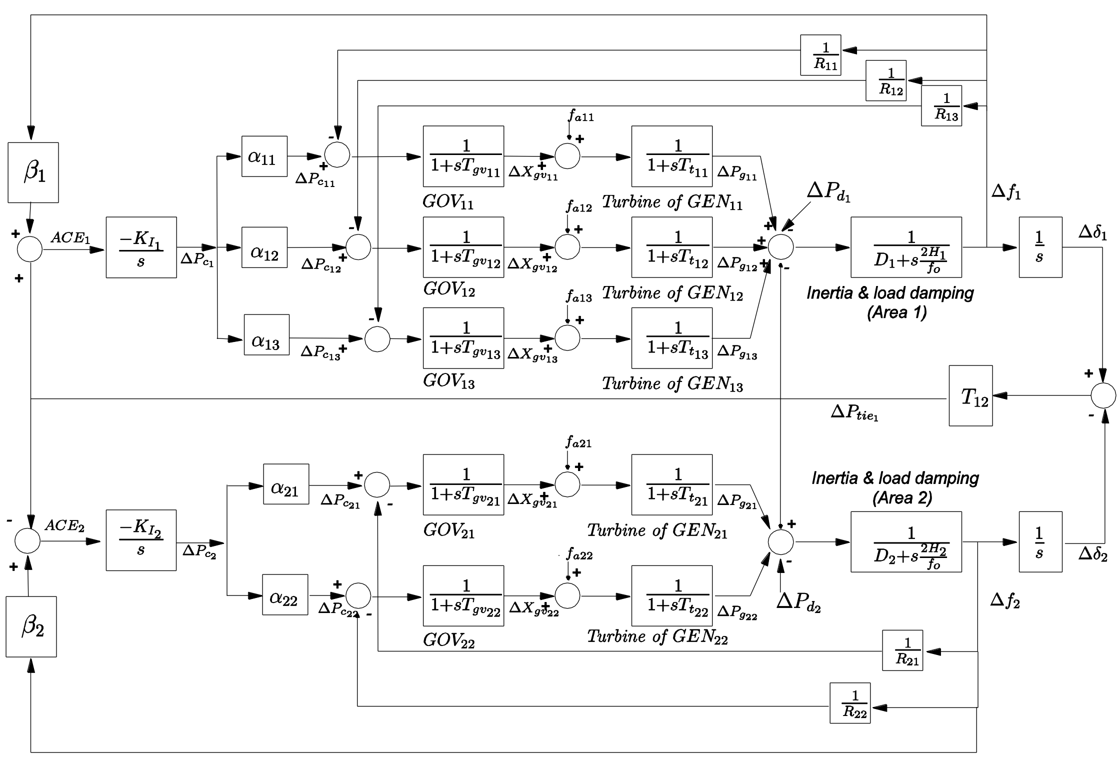

Fig. 2. Block diagram of LFC applied to a two-area system.

IV. SIMULATION RESULTS

In this section, we provide the simulation results to demonstrate the performance of the proposed FDI algorithm which successfully detects and isolates the governor faults in a two-area load frequency controlled power system described in the previous section with the parameters given in Table I. Two types of actuator faults are considered: stuck faults and non-stuck faults.

TABLE I
PARAMETERS OF THE LFC SYSTEM

Symbol	Quantity
H_j	5 s
D_j	0.0083pu MW/Hz
Tt_{jk}	0.3 s
Tgv_{jk}	0.08 s
R_{jk}	2.4 Hz/pu MW
T_{12}	0.545puMW
β_j	0.425puMW/Hz
f	60 Hz
$\alpha_{11} = \alpha_{12}$	0.3
α_{13}	0.4
α_{21}	0.2
α_{22}	0.8
K_{Ij}	1

A. Case I (Stuck faults)

If any governor does not respond to the changes in the load demand due to a fault where the valve or gate positions are stuck, an undesired generation dispatch as well as a degraded transient response of the LFC system can be observed.

The bank of UIOs generates the residuals such that the detection and isolation of the faults in the actuators can be performed. The successful design for the UIOs is robust to the unknown disturbances, which are the changes in the load demand in power system control areas.

In the simulations, we assume only a single governor fault at a time in one of the generating units belonging to an area. The existence of the UIOs and the success in the operation of the proposed FDI method are strongly dependent on the selected set of observed variables. Due to the necessary and sufficient condition in (9), $rank(CE^i) = rank(E^i)$. Since the matrix B is as given in Section III, $rank(CE^i) = rank(E^i) = n_A + 1 = 3$, where $n_A = 2$ is the number of areas. This condition implies that in order to design the full set of UIOs, the vector of measured variables, y, must include all the frequency measurements Δf_j and the actuator outputs ΔP_{gjk} as follows:

$$y = [\Delta f_1 \quad \Delta P_{g11} \quad \Delta P_{g12} \quad \Delta P_{g13} \quad \Delta f_2 \quad \Delta P_{g21} \quad \Delta P_{g22}]$$

The following simulation results show that this selection of the measured variables based on the necessary and sufficient condition above leads to successful detection and isolation of the actuator faults in the power system model under study.

As an example, in the two area test system, we assume that the governor GOV_{11} is stuck while the generating units controlled by the other governors are attempting to maintain the generation-load balance. Fig. 3 illustrates the output of the generating unit GEN_{11} as the governor GOV_{11} is stuck with a deviation in its output by 0.01 pu after an increase in the load demand of 0.1 pu in Area 1 at t=0.2 s. The stuck fault in (1) can be characterized as

$$f_{a1} = \begin{cases} 0 & 0 < t < t_f \\ 0.01 & t \geq t_f \end{cases} \quad and\ u_1(t) = 0\ for\ t \geq t_f ,$$

where the output of the generating unit reaches 0.01 pu at the instant of fault occurrence $t = t_f$, i.e. $\Delta P_{g11}(t_f) = 0.01pu$.

The effect of this fault on the transient response in the frequency of Area 1 is given in Fig. 4.

The undesired dispatch of generation due to the stuck fault can be seen, as the Fig. 5 and Fig. 6, which depict the change in generator outputs for fault free and stuck fault cases, are compared.

The FDI method described in Section II is applied for detecting and isolating the stuck actuator fault through the computation of the residuals. The comparison of the squared norms residuals given in Fig. 7 reveals the occurrence of the fault in GOV_{11} as all the residuals except for r_{11} change significantly.

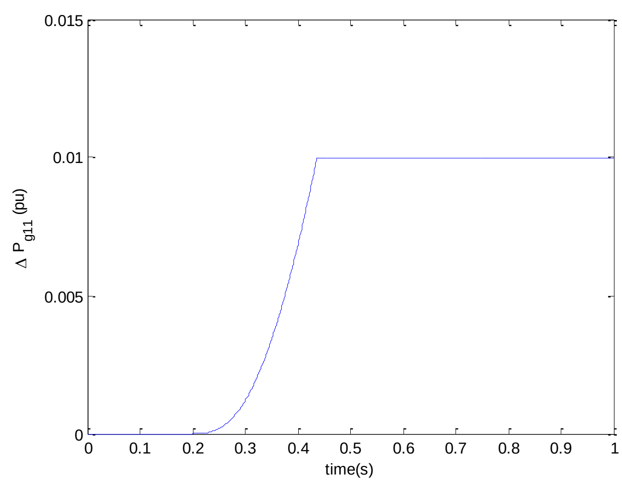

Fig. 3 The output of generating unit GEN_{11} in case of a stuck actuator fault.

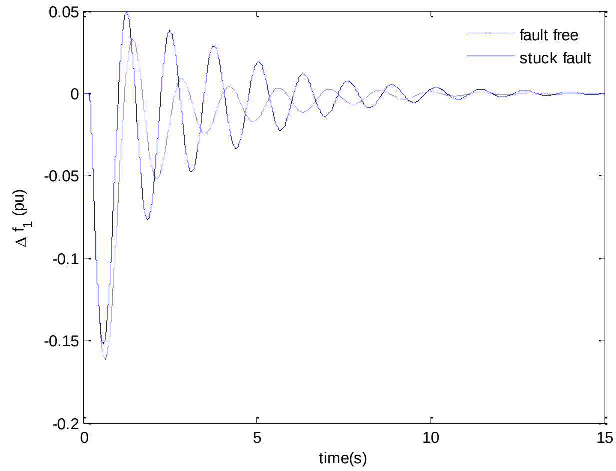

Fig. 4 The change in frequency in Area 1 in case of no fault and in case of stuck fault.

B. Case II (Non-Stuck faults)

In this case, a non-stuck actuator fault in GOV_{11} causing a degradation in the transient response of the system is assumed. In this case study, the fault occurs at GOV_{11} at t=1.5 s after a change in the load demand 0.1 pu at t=0.2 s. The non-stuck fault in (1) can be characterized as

$$f_{a1} = \begin{cases} 0 & 0 < t < 1.5s \\ 0.01 & t \geq 1.5s \end{cases}$$

Although the non-stuck fault does not result in any undesired dispatch of generation and the LFC corrects all the steady-state deviations, the fault, depending on its magnitude, may cause a deviation in the transient response of the system from its nominal behavior.

The deviation in the output of the generating unit GEN_{11} and the deviation in the frequency of area 1 are given in Fig. 8 and Fig. 9, respectively.

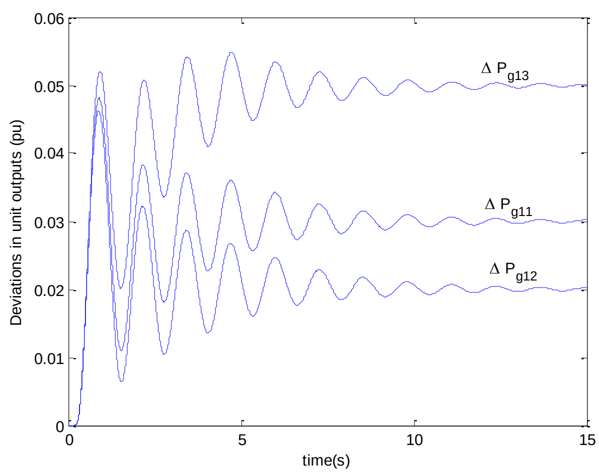

Fig. 5 Deviations in generating unit outputs in Area 1 in case of no fault.

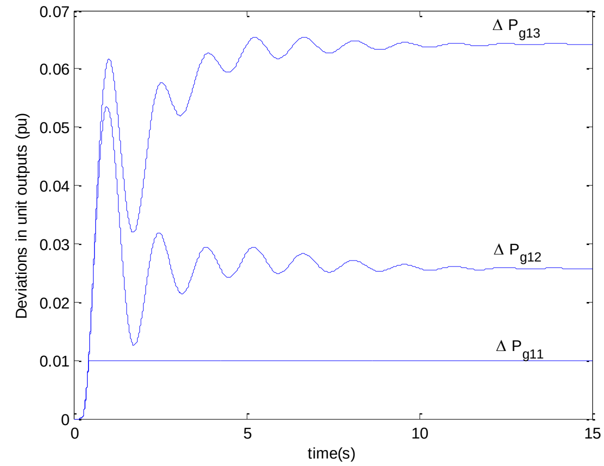

Fig. 6 Deviations in generating unit outputs in Area 1 when there is a stuck fault at GOV_{11}.

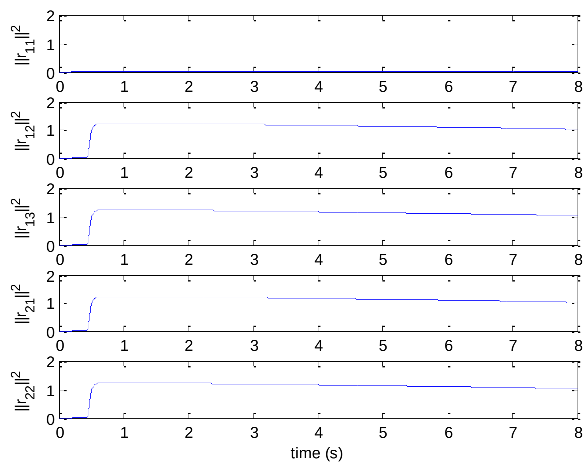

Fig. 7 Squared norms of residuals indicating the stuck actuator fault at GOV_{11}.

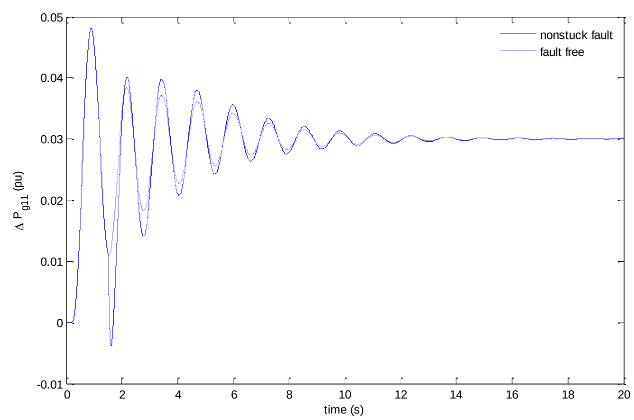

Fig. 8 Deviation in generating unit output GEN_{11} in case of no fault and in case of non-stuck fault.

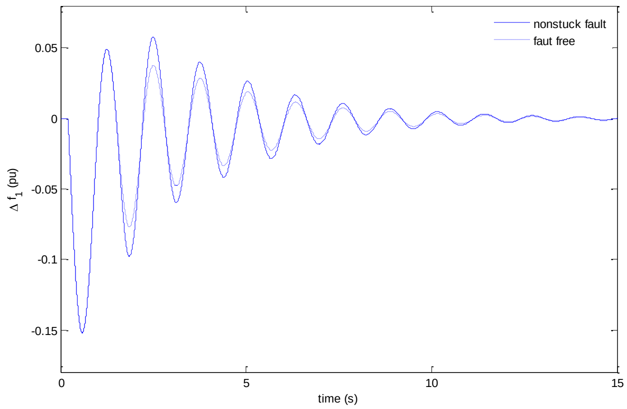

Fig. 9 Change in frequency in area 1 in case of no fault and in case of non-stuck fault.

Fig. 10 illustrates the squared norms of the residuals. Through the observation of the residuals, the fault in GOV_{11} can be detected and isolated clearly since only the residual r_{11} is insensitive to the fault whereas the rest of the residuals are sensitive.

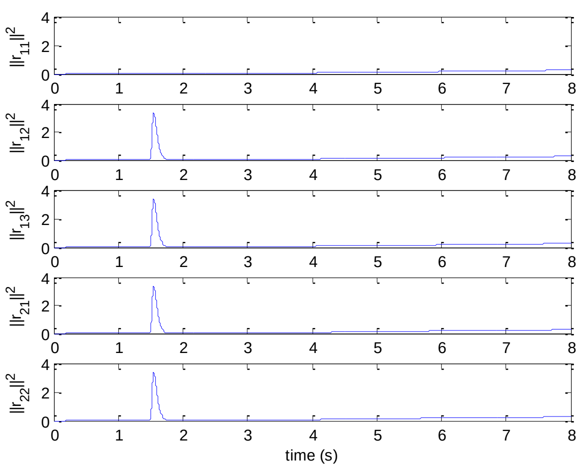

Fig. 10 Squared norms of residuals indicating the non-stuck actuator fault at GOV_{11}.

Stuck faults cause nonzero residuals whereas the residuals fall to zero rapidly when non-stuck faults occur, see Fig. 7 and Fig. 10. Thus, the two cases can be differentiated by simply observing this characteristic of the residuals.

If inclusion of sensor faults is assumed, UIOs for isolating the sensor faults can be designed as in [15], (in which isolation of sensor faults including only the ones measuring the frequencies and the tie-line power flow is studied and successfully implemented.) This requires an extension of the output vector (inclusion of $\Delta f_1 + \Delta f_2$) since the existence of UIOs is not maintained with the output vector chosen previously. This results in selecting the vector of measured variables as

$$y = \lfloor \Delta f_1 \quad \Delta P_{g11} \quad \Delta P_{g12} \quad \Delta P_{g13} \quad \Delta f_2 \quad \Delta P_{g21} \quad \Delta P_{g22} \quad \Delta P_{tie} \quad \Delta f_1 + \Delta f_2 \rfloor$$

However, even if the condition for the existence of UIOs is satisfied, the algorithm fails to differentiate the sensor and actuator faults from each other. Fig. 11 illustrates the residual norms that falsely indicate a sensor fault at GOV_{11} despite of a non-stuck actuator fault occurrence that can be isolated by means of the residuals given in Fig. 10. Similarly, in case of a fault at a sensor measuring an actuator output, it is not possible to distinguish it from a fault occurring at the same actuator. This is illustrated in Fig. 12 and Fig. 13, in which a fault that takes place only at the sensor measuring P_{g11} is assumed.

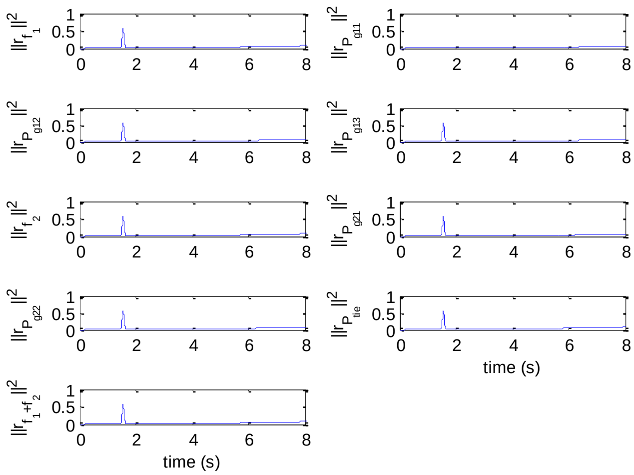

Fig. 11 Squared norms of residuals indicating a false sensor fault at GOV_{11}.

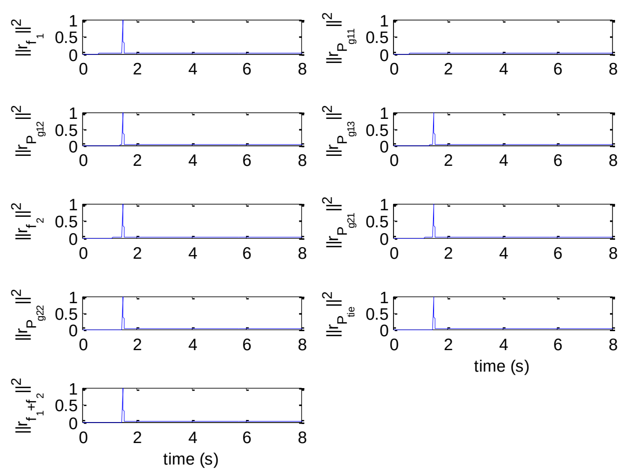

Fig. 12 Squared norms of residuals indicating a sensor fault at GOV_{11}.

If no fault occurs in the sensors measuring the actuator outputs, the actuator faults can be easily distinguished from the faults in the sensors measuring the frequencies and tie-line power flow. For example, in case of a sensor fault in measuring Δf_1, the squared norms of residuals given in Fig. 14, show that no actuator faults is detected or isolated whereas Fig. 15 shows an existence of a sensor fault. With the chosen measurement vector, the faults in the sensors measuring Δf_1 and Δf_2 cannot be isolated although they can be detected. The successful isolation of the sensor fault can be achieved by the inclusion of the governor output measurements as shown in [15].

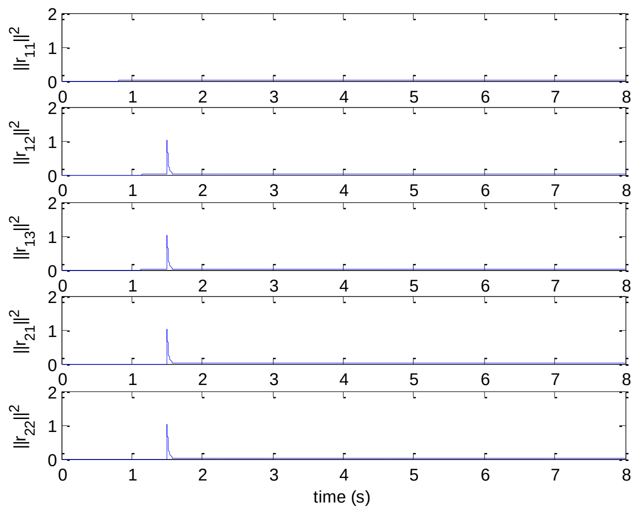

Fig. 13 Squared norms of residuals indicating a false actuator fault at GOV_{11}.

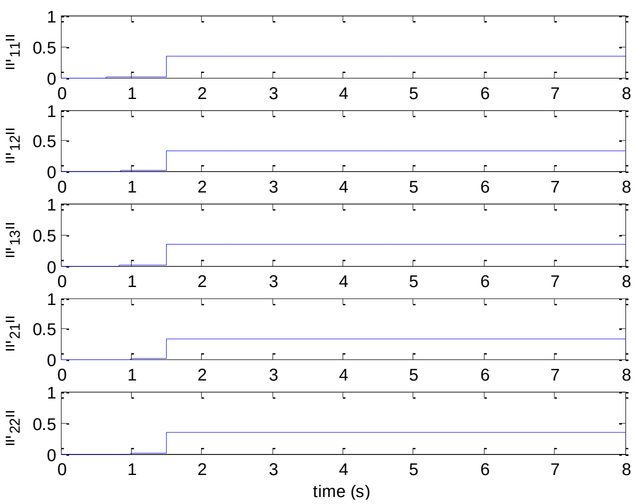

Fig. 14 Squared norms of residuals indicating no actuator fault.

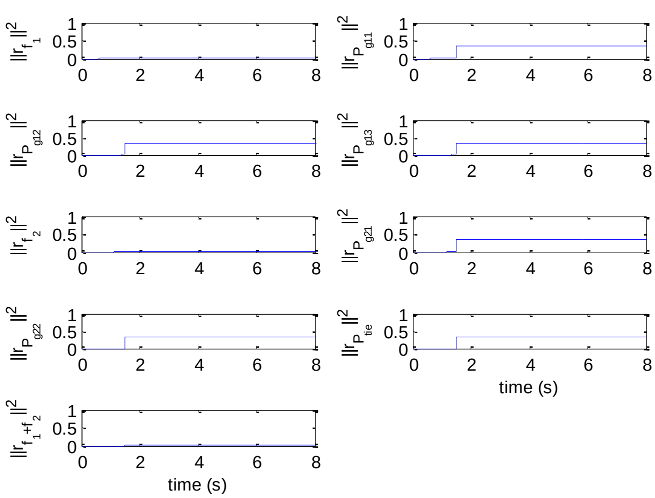

Fig. 15 Squared norms of residuals indicating an existence of a sensor fault.

V. CONCLUSION

In this paper, it has been shown that governor faults can be detected and isolated successfully in an interconnected power system with LFC by means of an elaborately designed bank of unknown input observers and treating these faults as actuator faults in the proposed method. This is achieved by a proper and feasible selection of observed variables that satisfies the condition for existence of the unknown input observers.

Both stuck and non-stuck faults have been explored. As a stuck fault in a governor is detected and isolated, an undesired generation dispatch as well as degradation in the transient behavior of the system can be avoided by replacing the faulty component. Non-stuck faults, which are less severe and affecting only the transient response, can also be detected and isolated through the same design.

The proposed method assumes no fault occurrence in sensors measuring the governor outputs and fails to distinguish the actuator faults from these sensor faults. The method is demonstrated on an example of a two-area power system model and can be easily applied to a more extensive power system having larger number of areas and generating unit models of higher order. The simulation results have shown the actuator fault detection and isolation can be carried out in real-time.

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