Robust Actuator Fault Detection and Isolation in a Multi-Area Interconnected Power System

Istemihan Genc, and Fikret Caliskan*

***Abstract*— A robust actuator fault detection and isolation method is proposed to detect and isolate the governor faults in a multi-area power system in which the frequency is regulated by an area-wise decentralized load frequency control system. A bank of unknown input observers that are robust to the changes in the load demand is used while each unknown input observer is sensitive to all actuator faults but one. Each unknown input observer, as a residual generator, is driven by all outputs and all inputs but one. The proposed scheme is tested on a two-area power system composed of 5 generating units through simulation studies which show that the governor faults can be detected and isolated successfully.**

***Index Terms*—power systems, fault detection and isolation, unknown input observer, load frequency control**

I. Introduction

LOAD Frequency Control (LFC) is a well-known method of maintaining frequency and power interchanges of interconnected power systems. Any fault in the actuators, controllers or sensors in the LFC loops may cause unexpected deviations in the system's frequency, power interchanges and loadings of generating units. Therefore, the faults occurring during implementation of LFC need to be detected and isolated.

Model based Fault Detection and Isolation (FDI) has been extensively used for detecting, isolating and identifying the faults in a system based on the comparison between the system's available measurements and its mathematical model [8]. Specifically, Unknown Input Observers (UIOs) have been used for robust FDI in which the observers are insensitive to disturbances [1]-[9]. The application of FDI in power system dynamics and control has recently been studied by some researchers. Aldeen and Sharma [10] have introduced a software approach to fault detection and identification in the LFC loops of interconnected power systems. Through their approach, which is based on the failure detection filter, faults occurring in the load frequency control loops and in the communication channels have been studied. In [11], Aldeen and Crusca have proposed a fault detection procedure based on the UIOs to detect transmission network faults and to isolate their exact locations. They modeled the faults as unknown inputs decoupled from the state and output measurements.

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Recently, by means of UIOs, a robust FDI procedure to detect and isolate sensor and controller faults occurring in the LFC loops has been applied in [12] by the authors.

Normally, in a LFC system, the governor and turbine units or controllers can be characterized as the actuators. In [12], only the faults in the integral controllers of the LFC system have been considered and treated as the actuator faults that may occur in the system, whereas, in this paper, UIOs are designed to detect and isolate the governor faults.

Simulations have been performed for a simplified model of a power system composed of two areas. The effectiveness of UIOs in detection and isolation of the governor faults has been demonstrated.

II. Robust Actuator FDI Scheme Based on UIOs

A dynamical system subject to actuator faults can be expressed as

$$\dot{x} = Ax + Bu + Ed + Bf_a \qquad y = Cx, \tag{1}$$

where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^r$ is the input vector, $d \in \mathbb{R}^q$ is the unknown input (disturbance) vector, $y \in \mathbb{R}^m$ is the output vector and $f_a \in \mathbb{R}^r$ is the actuator fault vector. The equations for a full-order UIO for the system above can be defined as

$$\dot{z} = Fz + TBu + Ky \qquad \hat{x} = z + Hy, \tag{2}$$

where $\hat{x} \in \mathbb{R}^n$ is the estimated state vector and $z \in \mathbb{R}^n$ is the state of the full-order observer [8]. The matrices *F*, *T*, *K*, *H*, which are the design parameters, are selected such that the unknown input is decoupled from the residual,

$$r = y - C\hat{x} = (I - CH)y - Cz. \tag{3}$$

The necessary and sufficient conditions for an UIO are given below [9]:

(i) rank(CE)=rank(E)

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

$$A_1 = A - E[(CE)^T CE]^{-1}(CE)^T CA \tag{4}$$

To design a robust actuator FDI scheme, the dynamical system (1) can be rewritten [8] as

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

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

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

$$y = Cx, \qquad (5)$$

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}. E^i and d^i are defined as

$$E^i = [E \quad b_i], \quad d^i = \begin{bmatrix} d \\ u_i + f_{ai} \end{bmatrix} for\ i = 1,2, \dots r \qquad (6)$$

The residual generator can be stated as

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

$$r^i = (I - CH^i)y + Cz^i \quad for\ i = 1,2, \dots .r \qquad (7)$$

In order to design robust UIOs for actuator FDI, the following equations must be satisfied:

z

$$H^i C E^i = E^i$$
$$T^i = I - H^i C$$
$$F^i = T^i A - K_1^i C \quad \text{must be Hurwitz}$$
$$K_2^i = F^i H^i$$
$$K^i = K_1^i + K_2^i \qquad (8)$$

Each unknown input observer is driven by all outputs and all inputs but one (see, Fig.1). When a fault occurs in one of the actuators, e.g. i-th actuator, each norm of the residual vectors will satisfy the following:

$$\|r^i\| < T_{AFI}^i\ and\ \|r^k\| \geq T_{AFI}^k\ for\ k = 1, .. i-1, i+1, .. r$$

where T_{AFI}^i's are isolation thresholds. 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 as a supplementary control for frequency regulation can be represented as in the block diagram given in Fig.2.

In one area of the test system, three generating units, whereas on the other area, two generating units are assumed.

In order to analyze and develop a FDI scheme for the actuator faults, the actuator and plant dynamics can be distinguished as follows:

Assuming that the system is subject to actuator faults, the dynamics of the plant involving the turbines and generators can be expressed as

$$\dot{x} = Ax + Bu_R + Ed$$
$$y = Cx \qquad (9)$$

The state vector

$$x = [\int \Delta P_{tie} \quad \int \Delta f_1 \quad \Delta f_1 \quad \Delta P_{g11} \quad \Delta P_{g12} \quad \Delta P_{g13} \quad \int \Delta f_2 \quad \Delta f_2 \quad \Delta P_{g21} \quad \Delta P_{g22}], \qquad (10)$$

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

$$d = [\Delta d_1 \quad \Delta d_2], \qquad (11)$$

where Δd_j is the change in the load demand of area j. The control input vector, which is composed of actuator outputs,

$$u_R = [\Delta X_{gv11} \quad \Delta X_{gv12} \quad \Delta X_{gv13} \quad \Delta X_{gv21} \quad \Delta X_{gv22}] \qquad (12)$$

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

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

$$\dot{x}_R = A_R x_R + B_R u_c + F_R x$$

$$u_R = C_R x_R = x_R \qquad (13)$$

where

$$u_c = -Kx = [\Delta P_{c11} \quad \Delta P_{c12} \quad \Delta P_{c13} \quad \Delta P_{c21} \quad \Delta P_{c22}] \qquad (14)$$

comprises the deviations in the speed governor changer positions ΔP_{cjl}.

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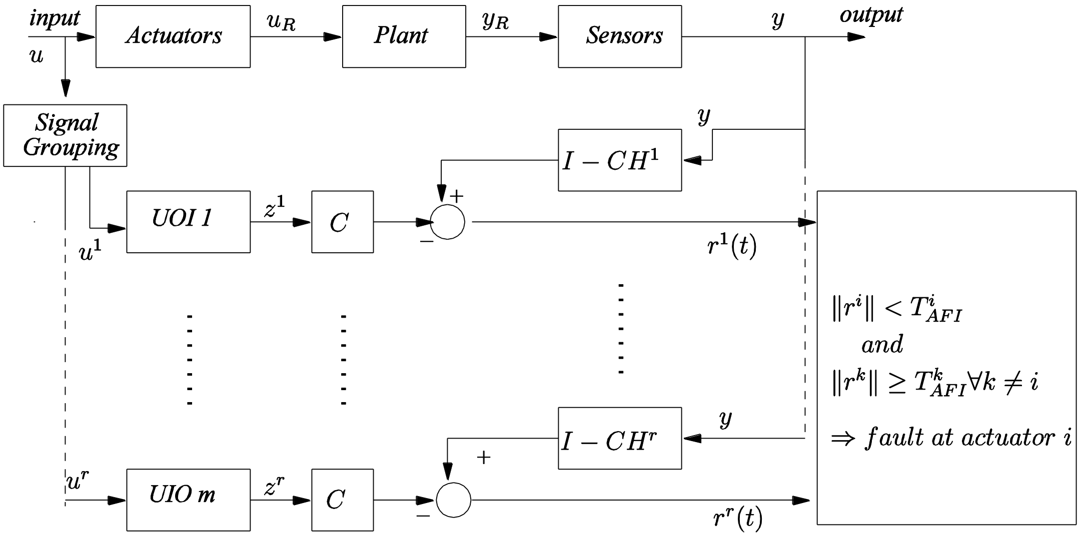

Fig. 1 A robust actuator fault isolation scheme

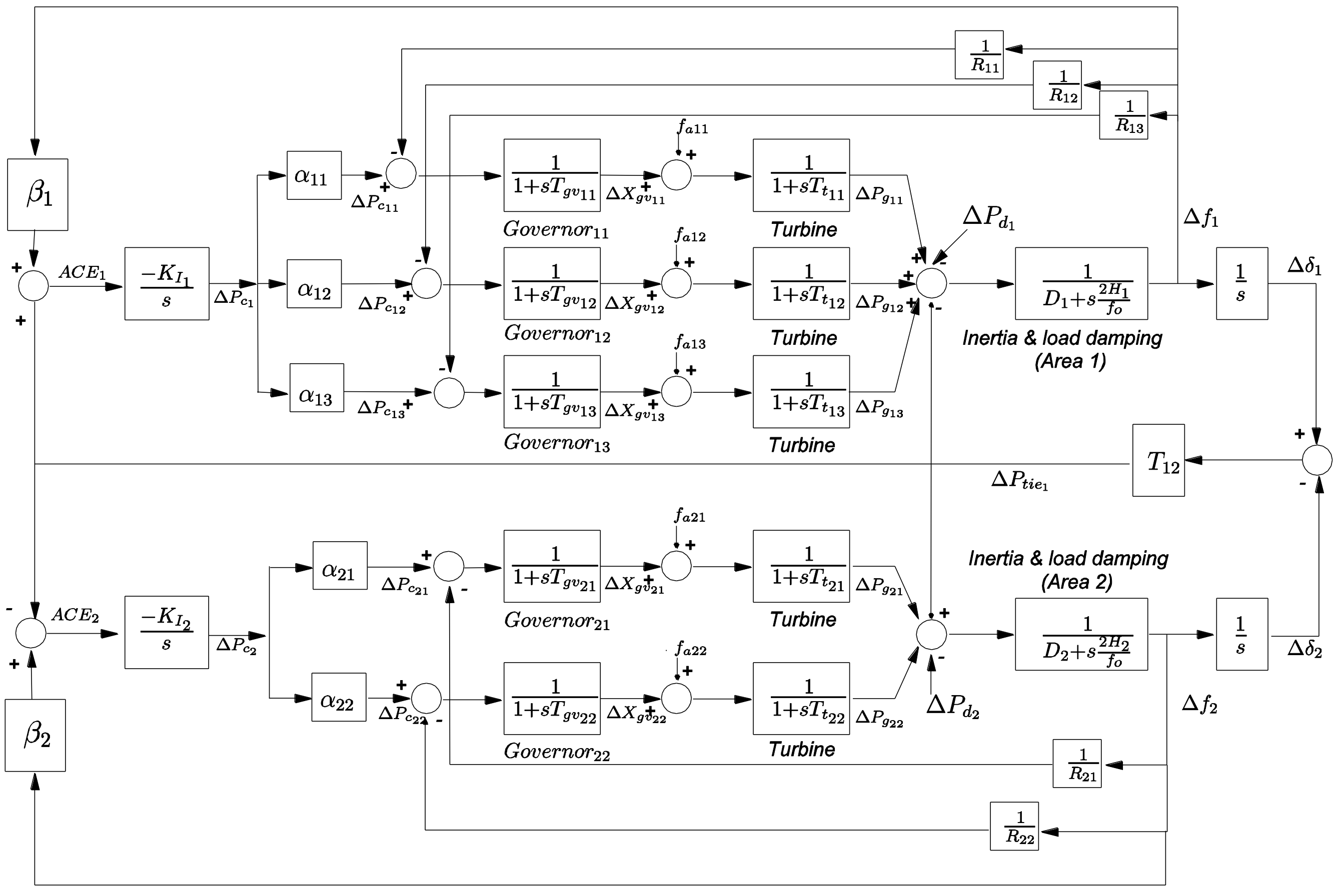

Fig. 2. Block diagram of LFC applied to a two-area system.

IV. Simulation Results

The actuator fault detection and isolation method is demonstrated through simulations performed for the two-area test system described in the previous section. Here we investigate only the actuator faults, where the governors are considered to be the actuators in the system.

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

In the simulations, we assume only one governor fault at a time in one of the generating units belonging to an area. A change in the load demand is simulated to be a step input at time $t = 5s$ whereas the actuator fault occurs at time $t = 7s$.

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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. In order to design the full set of UIOs, the vector of measured variables, y, is selected as follows:

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

The squared norm of the residuals for the no actuator fault case and a case in which $GOV_{I\text{-}3}$ is faulty are given in Fig. 3 and Fig. 4, respectively. As we compare the residuals in both cases, since only the residual corresponding to $GOV_{I\text{-}3}$ is insensitive to the fault, the actuator fault of interest can easily be distinguished.

Time-domain simulations regarding the changes in the frequencies of areas for the cases when the governor fault is assumed and when no fault exists in the system are given in Fig. 5 and Fig. 6. The governor fault considerably affects the transient response of the frequencies with an increase in the overshoot and the settling time.

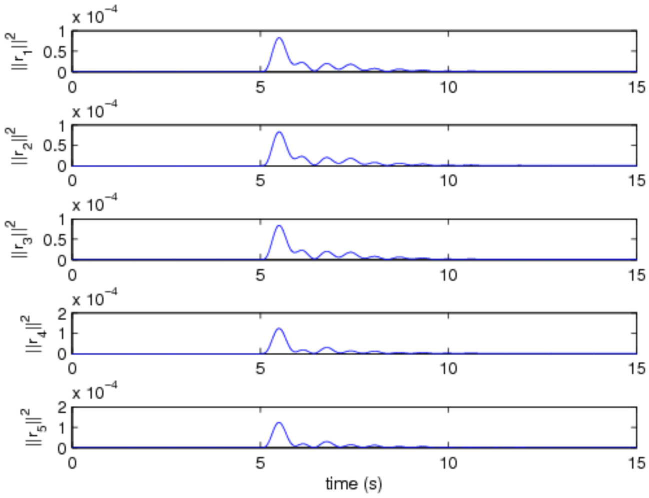

Fig. 3. Norm of residuals when no actuator fault exists.

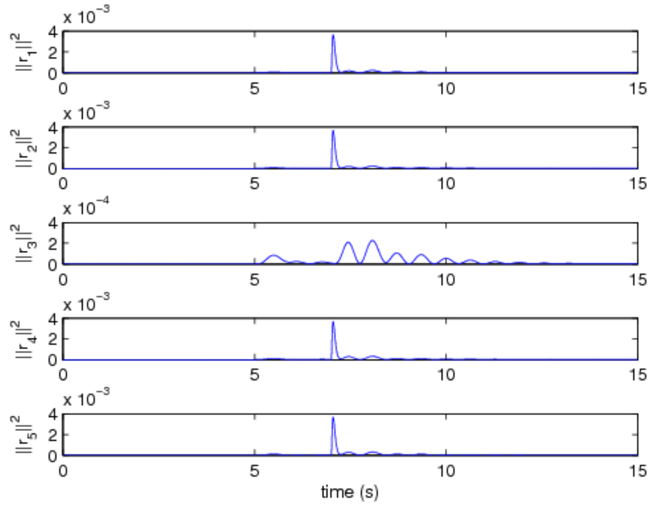

Fig.4. Norm of residuals when $GOV_{I\text{-}3}$ fault exists.

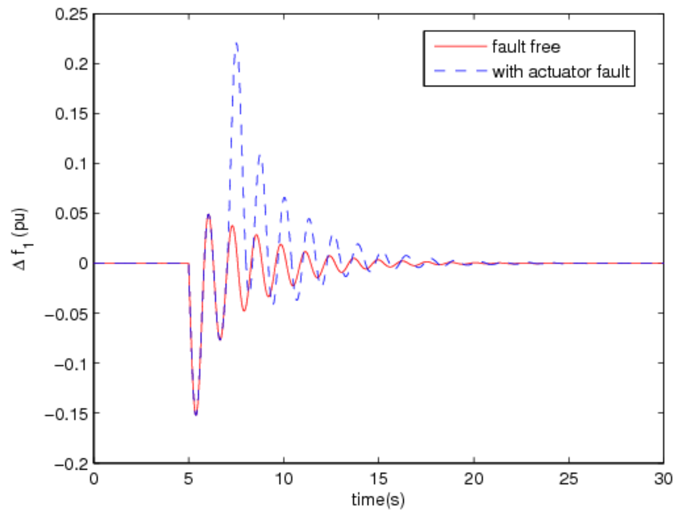

Fig. 5. Frequency deviation in area I.

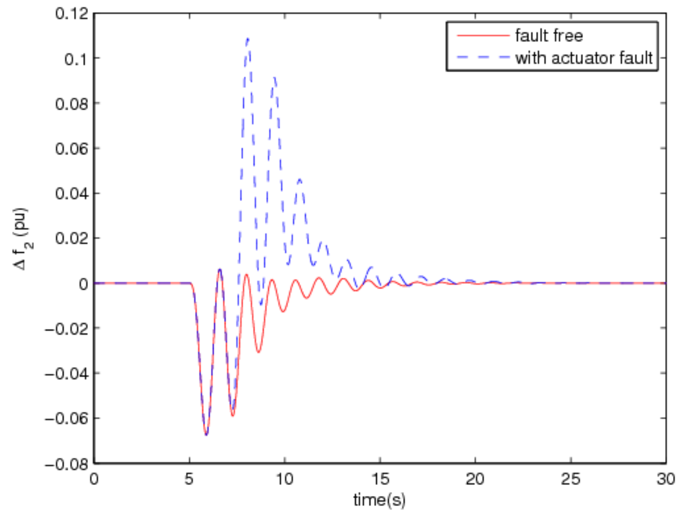

Fig. 6. Frequency deviation in area II.

V. Conclusion

In this paper, a robust actuator fault detection and isolation method has been adapted to isolate the governor faults in the interconnected power systems with LFC. In the method, unknown input observers have been designed and utilized in a power system composed of two areas.

It has been presented that the proposed scheme is able to detect and isolate actuator faults, which are the faults in the governors, by a proper and feasible selection of observed variables. The proposed method shows the operator which actuator is faulty, thus the faulty actuator can be replaced with a healthy one for a more reliable operation of the interconnected power system. The method and its results can easily be generalized to a multi-area power system network.

References

[1] Y. Guan and M. A. Saif, "A new approach to robust fault detection and identification", *IEEE Transactions on Aerospace and Electronic Systems*, vol. 29, no. 3, pp. 685-695, 1993.

[2] Y. Guan and M. Saif, "A novel approach to the design of unknown input observers", *IEEE Transactions on Automatic Control*, vol. 36, no. 5, pp. 632-635, 1991.

[3] Y. Guan and M. Saif, "Robust fault detection in systems with uncertainties", *Proc. of 5th IEEE International Symposium on Intelligent Control*, vol. 1, pp. 570-576, 1990.

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

[4] M. Hou and P. C. Müller, "Design of observers for linear systems with unknown inputs", *IEEE Trans. on Automatic Contro*l, vol. 37, no. 6, pp. 871-875, 1992.

[5] S. Krzeminski and T. Kaczorek, "Perfect reduced-order unknown-input observer for standart systems", *Bulletin of the Polish Academy of Sciences Technical Science*s, 50, pp. 103-107, 2004.

[6] F. Yang, and R. W. Wilde, "Observers for linear systems with unknown inputs", *IEEE Trans. on Automatic Contro*l, vol. 33, no. 7, pp. 677-681, 1998.

[7] P. Kudva, N. Viswanadham and A. Ramakrisna, "Observers for linear systems with unknown inputs", *IEEE Transactions on Automatic Contro*l, vo. 25, no. 1, pp. 113-115, 1980.

[8] J. Chen and R. J. Patton, *Robust model-based fault diagnosis for dynamic system*s, Kluwer Academic Publisher, pp. 68-84, 1999.

[9] C. C. Tsui, "A new design approach to unknown input observers", *IEEE Transactions on Automatic Contro*l, vol. 41, no. 3, pp. 464-468, 1996.

[10] M. Aldeen and R. Sharma, "Robust detection fault in frequency control loops" *IEEE Trans. On Power System*s, vol. 22, no. 1, pp. 413-422, 2007.

[11] M. Aldeen and F. Crusca, "Observer-based fault detection and identification scheme for power systems", *IEE Proc. of Gener. Transm.Distrib*., vol. 153, no. 1, pp. 71-79, 2006.

[12] F. Caliskan, I. Genc, "A Robust Fault Detection and Isolation Method in Load Frequency Control Loops", *IEEE Transactions on Power Systems,* vol. 23, no. 4, pp. 1756-1767, 2008.