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ROBUST SENSOR FAULT DETECTION AND ISOLATION IN LOAD FREQUENCY CONTROL BY UNKNOWN INPUT OBSERVERS

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ABSTRACT
In this paper, a robust sensor fault detection and isolation in load frequency control loop of interconnected power systems based on Unknown Input Observers (UIO) is designed and applied. The disturbances are assumed as unknown inputs to the UIO and the UIO is robust to disturbances. Simulations are performed for the dynamical model of a power control system composed of two areas. The proposed scheme is able to detect and isolate sensor faults. By using residuals, the designed "Fault Detection and Isolation Logic" system shows the operator which sensor is faulty. Hence the faulty sensor can be replaced by a healthy one for a more reliable operation.

KEY WORDS
Fault diagnosis, power system operation, load frequency control

1. Introduction

In an interconnected power system, which is composed of two or more areas, area-wise decentralized Load Frequency Control (LFC) is an effective method of maintaining system's frequency and power interchanges. Since a failure in the execution of a properly designed LFC may result in undesired deviations in the system's frequency and power interchanges, the detection and isolation of any fault occurring in the load frequency loops is of importance.

Aldeen and Sharma [1] have introduced, for the first time, a software approach to fault detection and identification in the LFC loops of interconnected power systems. Their approach is based on the failure detection filter. In this study, an Unknown Input Observer (UIO) and its application to a LFC for sensor Fault Detection and Isolation (FDI) are scrutinized. In order to establish a robust FDI, the UIOs are organized in the structure of the Generalized Observer Scheme (GOS).

The problem of designing an observer for a linear system with both known and unknown inputs has been studied for over two decades [2]-[10]. In real problems, there are many situations where disturbances are present. Disturbances are assumed as unknown inputs to the Unknown Input Observer (UIO). Aldeen and Crusca have proposed a fault detection procedure based on the UIO to detect transmission network faults and to isolate their exact locations [11]. In this paper, UIOs are designed to detect and isolate the sensor faults in a LFC system.

In the paper, simulations are performed for the ninth-order dynamical model of a power control system composed of two areas. By using residuals, the designed "Fault Detection and Isolation Logic" system shows the operator which sensor is faulty. Thus, the sensor faults are isolated straightforwardly. The simulation results show that sensor faults can be effectively detected and isolated.

2. Robust Unknown Input Observer (UIO) Design

Consider the dynamical system subject to sensor faults as:

$$\begin{aligned} \dot{x} &= Ax + Bu + Ed \\ y &= Cx + f_s, \end{aligned} \tag{1}$$

where $x \in R^n$ is the state vector, $u \in R^q$ is the input vector, $d \in R^q$ is unknown input vector, $y \in R^p$ is the measurable output vector, $f_s \in R^m$ is an immeasurable vector considered as an additive bias resulting from sensor failures. The matrices A, B, E, and C have appropriate dimensions.

An observer is defined as an unknown input observer for the system described by (1). The main task in robust fault detection is to generate a residual signal that is insensitive to the system disturbance. The system nonlinearities can be assumed as an additive unknown disturbance term in the dynamic system equation.

The block diagram of a full-order UIO is given in Fig. 1. The equations for this full-order UIO is described as

$$\begin{aligned} \dot{z} &= Fz = TBu + Ky \\ \hat{x} &= z + Hy, \end{aligned} \tag{2}$$

where $\hat{x} \in R^n$ is the estimated state vector and $z \in R^n$ is the state of the full-order observer, and F, T, K, H are matrices to be designed for achieving unknown input de-

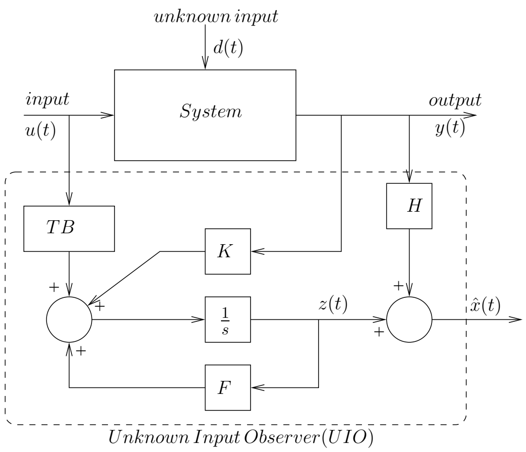

Figure 1. The structure of a full-order UIO

coupling and other design requirements [9] as

$$K = K_1 + K_2 \quad (3)$$
$$(HC - I)E = 0 \quad (4)$$
$$T = I - HC \quad (5)$$
$$F = A - HCA - K_1C \quad (6)$$
$$K_2 = FH \quad (7)$$

If the above requirements are satisfied, then the dynamics of the state estimation error $e = x - \hat{x}$ will be

$$\dot{e} = Fe. \quad (8)$$

The UIO given by (2) is designed such that the state estimation error approaches zero asymptotically, regardless of the presence of the unknown input . The equations (3)-(7) should be met to design the UIO provided that all eigenvalues of the matrix F are stable. Note that K_1 is assigned such that F will be Hurwitz. Two assumptions should be made in this approach:

Assumption I: rank(CE)=rank(E)

Assumption II: (C, A_1) is detectable pair

$$\begin{aligned} A_1 &= A - E[(CE)^T CE]^{-1}(CE)^T CA \\ A_1 &= A - HCA \end{aligned} \quad (9)$$

From the above analysis, it can be seen that K_1 is a free matrix of parameters in the design of an UIO. After K_1 is determined, other parameter matrices in the UIO can be computed. The matrix K_1, which stabilizes the matrix F, is not unique due to the multivariable nature of the problem. That is to say there is still some design freedom left in the choice of K_1, after unknown input disturbance conditions have been satisfied. The freedom of the parameters of K_1 allows one to guarantee the matrix F to be stable. During the design, the matrix F is first chosen as a stable matrix and then the matrix K_1 is calculated from (6).

The Unknown Input Observer (UIO) Design Procedure is given below: [9]

1. Check the rank condition for E and CE: If $rank(CE) \neq rank(E)$, an UIO does not exist, go to 10.
2. Compute H, T, and A_1:
$$\begin{aligned} H &= E[(CE)^T(CE)]^{-1}(CE)^T \\ T &= I - HC \\ A_1 &= TA \end{aligned}$$
3. Check the observability: If the pair (C, A_1) is observable, an UIO exists and K_1 can be computed using pole placement, go to 9.
4. If the pair (C, A_1) is not observable construct a transformation matrix P for the observable canonical decomposition to select independent $n_1 = rank(W_0)$ (W_0 is the observability matrix of (C, A_1)) row vector $p_1^T, \ldots, p_{n_1}^T$ from W_0, together other $n - n_1$ row vector to construct a non-singular matrix.
5. Perform an observable canonical decomposition on (C, A_1):
$$PA_1P^{-1} = \begin{bmatrix} A_{11} & 0 \\ A_{12} & A_{22} \end{bmatrix} \qquad CP^{-1} = \begin{bmatrix} C^* & 0 \end{bmatrix}$$
6. Check the detectability of (C, A_1). If A_{22} is not Hurwitz, an UIO does not exist and go to 10.
7. Select n_1 desirable eigenvalues and assign them to $A_{11} - K_p^1 C^*$ using pole placement.
8. Compute
$$K_1 = P^{-1}KP = P^{-1} \begin{bmatrix} (K_p^1)^T & (K_p^2)^T \end{bmatrix}^T$$
where K_p^2 can be any $(n - n_1) \times m$ matrix.
9. Compute F and K: $F = A_1 - K_1C, K = K_1 + K_2 = K_1 + FH$.
10. STOP.

3. Power Control System Model

Within a power system area, as the dynamics between the generators are neglected and the coherency among them is assumed, the collective dynamic performance of all generators in each area can be represented by an equivalent generating unit model that is composed of a generator, turbine and governor.

The block diagram of a two-area system with an area-wise decentralized LFC is given in Fig. 2. In addition to the primary regulation by speed governors acting on generators, the supplementary control is supplied by feedback loops that integrate the Area Control Errors, which are the deviations in frequencies and power interchanges. A dynamic model of a multi-area power system is summarized as follows:

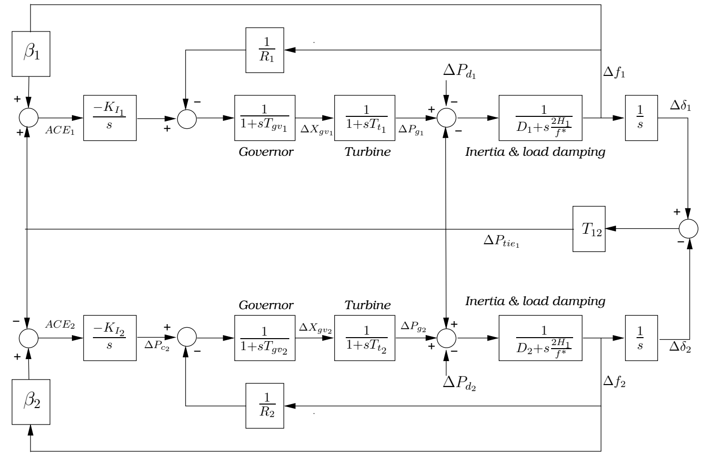

Figure 2. Block diagram of LFC applied to a two-area system

For a multi-area power system, each area i is represented by an equivalent generating unit. The state variables Δf_i, ΔP_{g_i} and ΔX_{gv_i} are the deviations in the frequency, generation and governor valve position of area i, respectively. The generator dynamics is as follows:

$$\dot{f}_i = \frac{f^*}{2H_i}(\Delta P_{g_i} - \Delta P_{d_i} - \Delta P_{tie_i} - D_i \Delta f_i - \Delta f_i),$$

where f^* is the nominal frequency, H_i and D_i are the inertia and damping constants, and ΔP_{d_i} and ΔP_{tie_i} represent the deviations in the load demand and interchange power, respectively.

$$\Delta \dot{P}_{g_i} = -\frac{1}{T_{t_1}}\Delta P_{g_i} + \frac{1}{T_{t_i}}\Delta X_{gv_i}$$

$$\Delta \dot{X}_{gv_i} = -\frac{1}{T_{gv_i}}\Delta X_{gv_i} - \frac{1}{T_{gv_i}R_i}\Delta f_i + \frac{1}{T_{gv_i}}\Delta P_{c_i}$$

where T_{t_i} and T_{gv_i} are the time constants of turbine and governor respectively. R_i is the regulation constant and ΔP_{c_i} is deviation in speed changer position of the governor.

For a power system having n areas, the deviation in the tie-line power of area i,

$$\Delta P_{tie_i} = \sum_{j=1}^{n} T_{ij}\left(\int \Delta f_i dt - \int \Delta f_j dt\right),$$

where T_{ij} is the synchronizing power coefficient between area i and j. For each control area, Area Control Error (ACE) is de□ned as

$$ACE_i = \Delta P_{tie_i} - \beta_i \Delta f_i,$$

where β_i is the frequency bias. The closed-loop control is provided by

$$\Delta P_{c_i} = -K_{I_i}\int ACE_i dt,$$

where K_{I_i} is the integral gain.

A state-space representation of the two-area model is as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu + Ed \\ y &= Cx. \end{aligned} \qquad (10)$$

The state vector,

$$x = \begin{bmatrix} \int \Delta P_{tie_1} dt & x_1 & x_2 \end{bmatrix}^T,$$

where

$$x_i = \begin{bmatrix} \int \Delta f_i dt & \Delta f_i & \Delta P_{g_i} & \Delta X_{gv_i} \end{bmatrix}.$$

The input vector, $u = \begin{bmatrix} \Delta P_{c_1} & \Delta P_{c_2} \end{bmatrix}^T$. E is called the disturbance distribution matrix and $E = \begin{bmatrix} \Delta P_{d_1} & \Delta P_{d_2} \end{bmatrix}^T$. The output vector,

$$y = [\Delta f_1 \quad \Delta f_2 \quad \Delta P_{tie_1} \quad \Delta P_{g_1} \quad \Delta P_{g_2} \quad \int \Delta f_1 dt \quad \int \Delta f_2 dt \quad \int \Delta P_{tie_1} dt]^T.$$

As an example, using the parameters given in [12], the matrices in (10) are computed as follows:

$$A = \begin{bmatrix} 0 & .55 & 0 & 0 & 0 & -.55 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -3.27 & -.05 & 6 & 0 & 3.27 & 0 & 0 & 0 \\ 0 & 0 & 0 & -3.3 & 3.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & -5.2 & 0 & -12.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -3.27 & 0 & 0 & 0 & -3.27 & -.05 & 6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -3.3 & 3.3 \\ 0 & 0 & 0 & 0 & 0 & 0 & -5.2 & 0 & -12.5 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 12.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12.5 \end{bmatrix}^T$$

$$E = \begin{bmatrix} 0 & 0 & -6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \end{bmatrix}^T$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & .545 & 0 & 0 & 0 & -.545 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$K = \begin{bmatrix} 1 & .425 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & .425 & 0 & 0 & 0 \end{bmatrix}$$

4. Unknown Input Observer for the Power System

Let us design the Unknown Input Observer for the power system. First check the rank condition for E and CE: If $rank(CE) = rank(E)$, an UIO exists. Indeed, $rank(CE) = rank(E) = 2$. Check the observability: If (C, A_1) observable, an UIO exists and K_1 can be computed using pole placement. Since $rank(obsv(A_1, C)) = 9$,

(C, A_1) is observable, an UIO exists and K_1 can be computed. Compute F and K : $F = A_1 - K_1 C, K = K_1 + K_2 = K_1 + FH$. The structure for the full-order observer described in (2) is as follows:

$$\dot{z} = -30\ I\ z + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 12.5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5 \\ 0 & 0 \end{bmatrix} u$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.54 & -0.54 & 30 \\ 0.81 & 0.18 & 0.34 & 0 & 0 & 30 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 26.66 & 0 & 0 & 0 & 0 \\ -4.23 & -0.97 & -1.78 & 0 & 0 & -5.31 & 0 & -12.5 \\ 0.18 & 0.81 & -0.34 & 0 & 0 & 0 & 30 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 26.66 & 0 & 0 & 0 \\ -0.97 & -4.23 & 1.78 & 0 & 0 & 0 & -5.31 & 12.5 \end{bmatrix} y$$

$$\hat{x} = z + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.81 & 0.18 & 0.34 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.18 & 0.81 & -0.34 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} y$$

As an example, the errors between the actual values of the first four outputs and their estimated values are given in Fig. 3.

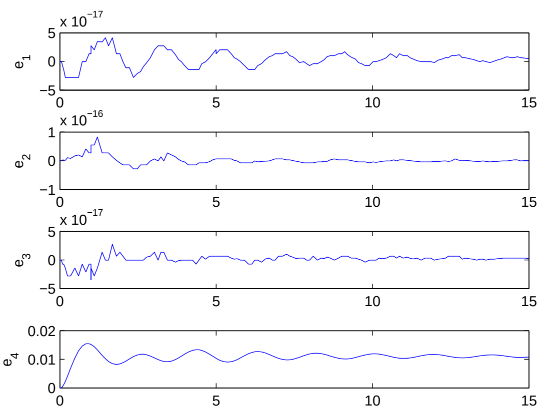

Figure 3. Errors between the actual outputs and the estimated outputs

5. Robust Sensor Fault Detection and Isolation Scheme Based on UIOs

The fault isolation problem is to locate the fault or to determine which sensor has failed. In this study, a structured residual set [9], in which each residual is sensitive to certain group of faults and insensitive to others, is designed for fault isolation. A Generalized Observer Scheme (GOS) [9], which is a commonly accepted robust and UIO-based sensor fault isolation scheme (Fig. 4), is applied.

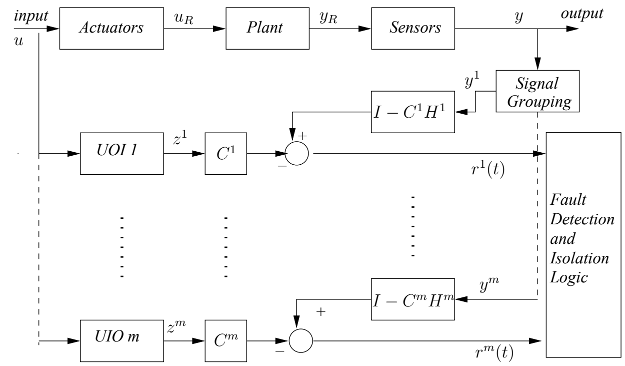

Figure 4. A robust sensor fault isolation scheme

Assuming that all actuators are fault-free, the system equations [9] are as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu + Ed \\ y^j &= C^j x + f_s^j \\ y_j &= c_j x + f_{sj} \end{aligned} \qquad (11)$$

where $c_j \in R^{1\times n}$ is the jth row of the matrix C, $C^j \in R^{(m-1)\times n}$ is obtained from C by deleting jth row c_j, $y_j \in R^{1\times m}$ is the jth component y_j. Then, m UIO-based residual generator is constructed as:

$$\begin{aligned} \dot{z^j} &= F^j z^j + T^j Bu + K^j y^j \\ r^j &= (I - C^j H^j) y^j + C^j z^j \qquad for \quad j = 1, 2, \dots m \end{aligned} \qquad (12)$$

Each residual generator is driven by all inputs and all outputs except one output. When all actuators are fault-free and a fault occurs in the jth sensor, the residual will satisfy the following isolation logic:

$$\begin{aligned} \|r^j\| &< T^j_{SFI} \\ \|r^k\| &\geq T^k_{SFI} \qquad for \quad k = 1, \dots j-1, j+1, \dots m \end{aligned}$$

where T^j_{SFI}'s are isolation thresholds and $\|r^j\|$'s are the Euclidean norms of the residuals.

6. Fault Detection and Isolation Logic Design

A fault indicator logic system is designed to determine which sensor is faulty. This system is based on the comparison of the threshold exceeds. The GOS method allows one to detect the faulty sensor by checking if the residuals have exceeded the thresholds. In the design, threshold exceeds are indicated as "logic 1" and otherwise "logic 0". For example, if a fault occurs in "Sensor 1" the "Residual 1" doesn't exceed the threshold and indicated as "logic 0" and other residuals exceed the thresholds and are indicated as “logic 1”. As an example, the designed ”Sensor Fault Indicator Logic Block” is shown in Fig. 5 for a system with three sensors. The interior constitution of the “Sensor Fault Indicator Logic” subsystem can be seen in figure 6.

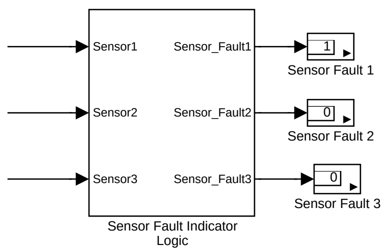

Figure 5. Sensor fault indicator logic when a fault occurs in Sensor 1.

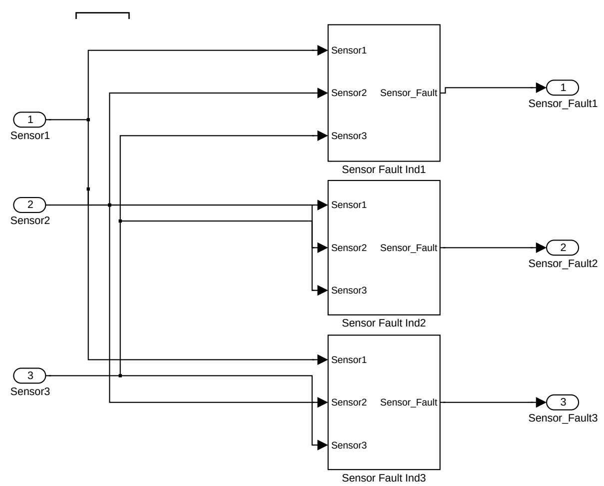

Figure 6. Interior constitution of the sensor fault indicator logic subsystem

7. Simulation Results of the Sensor Fault Detection and Isolation for LFC

The designed system can be modelled with Simulink as in Fig 8. The correct measurements and feedback signals of frequency and power interchanges are very important for the effectiveness of LFC. Therefore, in the simulation, as an example, a failure in Sensor 1 (measuring f_1: the frequency of area 1) is assumed to have occurred. Simulation results are presented for Sensor 1 failure occurring at 5 s. Figure 7 shows the squared residuals when a fault has occurred in Sensor 1.

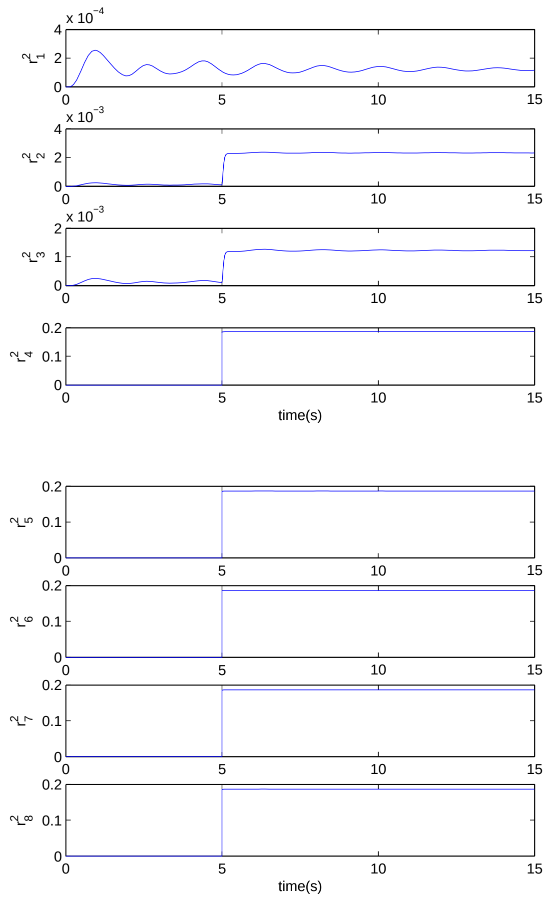

Figure 7. Squared residuals when a fault occurs in Sensor 1.

8. Conclusion

In this paper, a robust sensor fault detection and isolation in load frequency control in power systems by unknown input observers has been designed and applied. Simulations have been performed for the dynamical model of a power control system composed of two areas. By using residuals, the designed “Fault Detection and Isolation Logic” system shows the operator which sensor is faulty. The proposed scheme is able to detect and isolate sensor faults. In future work, the scheme will be extended to detect and isolate the actuator faults as well.

References

[1] Aldeen M, and Sharma R, Robust detection fault in frequency control loops *IEEE Trans. On Power Systems*, 22 (1), 2007, 413-422.

[2] Guan, Y, and Saif M, A New Approach to Robust Fault Detection and Identification *IEEE Transactions on Aerospace and Electronic Systems*, 29, 1993, 685-695.

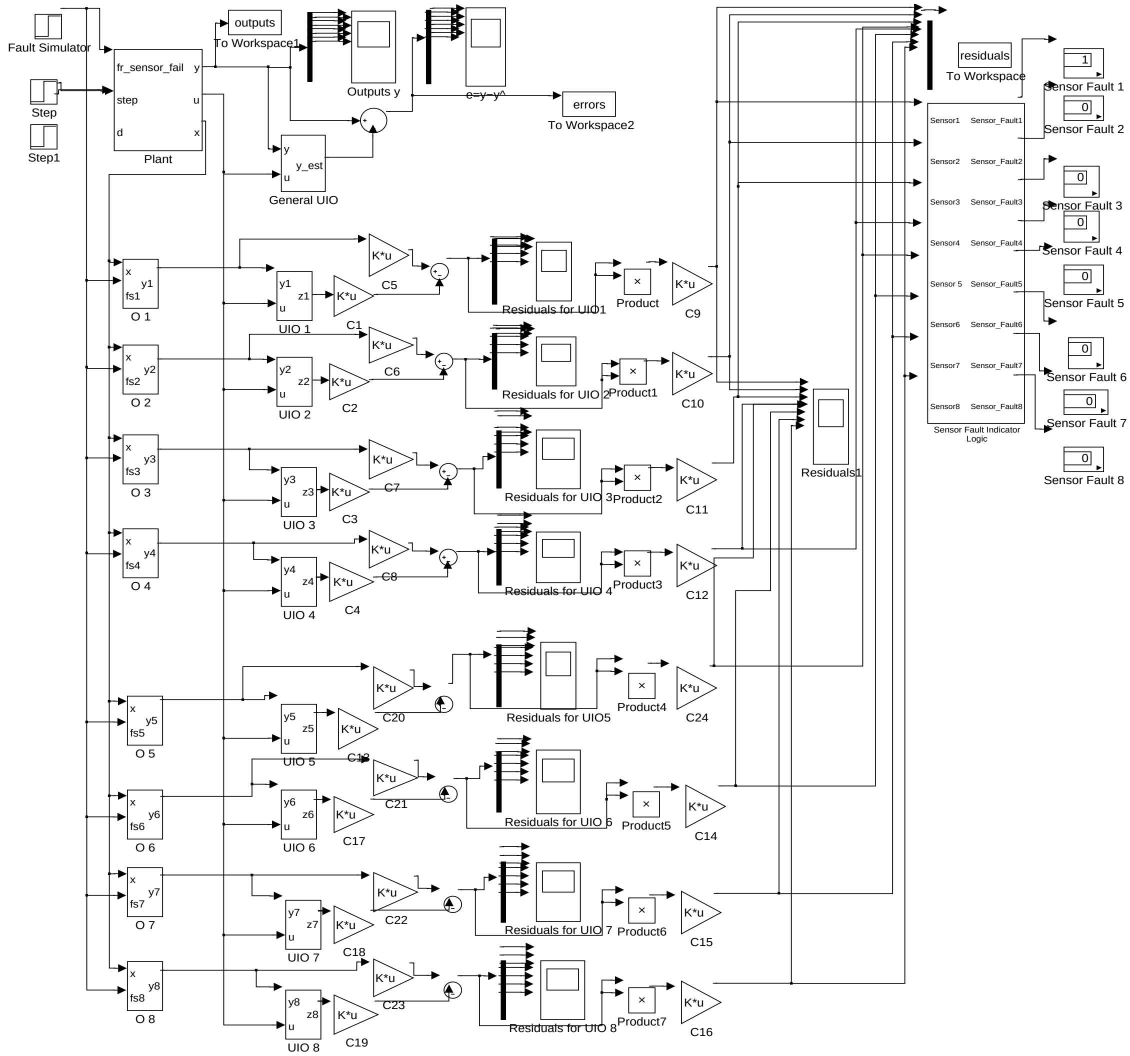

Figure 8. The designed system with sensor isolation schemes together

[3] Guan Y, and Saif M, A novel approach to the design of unknown input observers, *IEEE Transactions on Automatic Control*, 36, 1993, 632-635.

[4] Guan, Y, and Saif M, Robust Fault Detection in Systems with Uncertainties, *IEEE Transactions on Automatic Control*, 33, 1991,570-576.

[5] Hou M, and Müller P C, Design of Observers for Linear Systems with Unknown Inputs, *IEEE Trans. on Automatic Control*, 37, 1992, 871-875.

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

[7] Yang F, and Wilde R W, Observers for linear systems with unknown inputs *IEEE Trans. on Automatic Control*, 33, 1998, 677-681.

[8] Kudva P, Viswanadham N, and Ramakrisna A, Observers for linear systems with unknown inputs, *IEEE Transactions on Automatic Control*, 25, 1980, 113-115.

[9] Chen J, Patton R J, *Robust model-based fault diagnosis for dynamic systems*, Kluwer Academic Publisher, 68-84, 1999.

[10] Tsui C C, A New Design Approach to unknown Input Observers, *IEEE Transactions on Automatic Control*, 41, 1996, 632-635.

[11] Aldeen M, Crusca F, Observer-based fault detection and identification scheme for power systems, *IEE Proc.-Gener. Transm. Distrib* 153 (1), 2006, 71-79.

[12] Elgerd O I, Fosha C E, Optimum Megawatt-Frequency Control of Multiarea Electric Energy Systems, *IEEE Trans. on Power Apparatus and Systems*, 89(4), 1970, 556-563.