Robust Fault Detection in the Load-Frequency Control of Interconnected Power Systems

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ABSTRACT

This paper presents a robust approach to detecting and identifying a fault in the load-frequency control loop of interconnected power systems. Although the approach is applicable to N-area systems, a two-area example is considered for simplicity. The approach is capable of detecting faults in real time and under real life operating conditions. The detection of faults is robust in that it takes place in the presence of unknown load and other external disturbances, such as plant and sensor noises.

INTRODUCTION

Load-frequency control is essential for successful operation of power systems, especially interconnected power systems [7]. Without it the frequency of power supply may not be able to be controlled within the required limit band. It is therefore very important that when a fault occurs in the control loop it is detected and identified in real time so that a remedial action can be undertaken.

So far detection of faults in power systems, especially transmission systems, has largely been the responsibility of "protection systems", which have over the time proven to be quite effective in providing failure signals and invoking a protection action to safeguard equipment and/or aspects of power system operation. It is well known that protection systems are mainly hardware based and their design requires a fair amount of intricate detail. In addition, they are quite expensive to install, run and maintain. Although the area of protection of transmission and even of distribution systems has matured considerably, its application to the problem of load and frequency control has so far been vary basic.

In this paper, we introduce for the first time a software approach to fault detection and identification in the load-frequency control loops of interconnected power systems. It is shown that the presented scheme is capable of detecting faults in real time under real operating conditions such as the presence of unknown load disturbances, and plant and measurement noise. The paper presents simulation results where faults occur in one or more control loop(s) and in the communication channels which carry the transmitted signals from the sensors to the controller.

POWER SYSTEM MODEL

The linearised power system model considered is shown in Figure (1). In the figure the dotted lines represent the control loops, which in this paper are to be faulted. The disturbance inputs p_{d1}, p_{d2} reflect the change in the load demand in areas 1 and 2, respectively, while various noise sources, shown as $p_{d3}, p_{d4}, p_{d5}, p_{d6}$, are also included to optionally reflect sensor and actuator noise. This model has been the subject of numerous studies in the problem of load-frequency control (see for example [1], [6], [8], [10]). For simplicity, the system is chosen to comprise two interconnected areas with an additional DC link. The system data and parameters are taken to be the same as those first reported in [7], [8].

A state space representation of this system [8] is given as

$$\dot{x} = Ax + Bu + Ed_1 \qquad (1)$$

$$y = Cx + Dd_2 \qquad (2)$$

The state, control, disturbance and output variables are defined as follows:

$$x = \begin{bmatrix} p_{tie} & f_1 & p_{g_1} & p_{v_1} & \int ACE_1 dt & f_2 & p_{g_2} & p_{v_2} & \int ACE_2 dt & p_{dc} \end{bmatrix}^T$$

$$u = \begin{bmatrix} p_{c_1} & p_{c_2} \end{bmatrix}^T ;$$

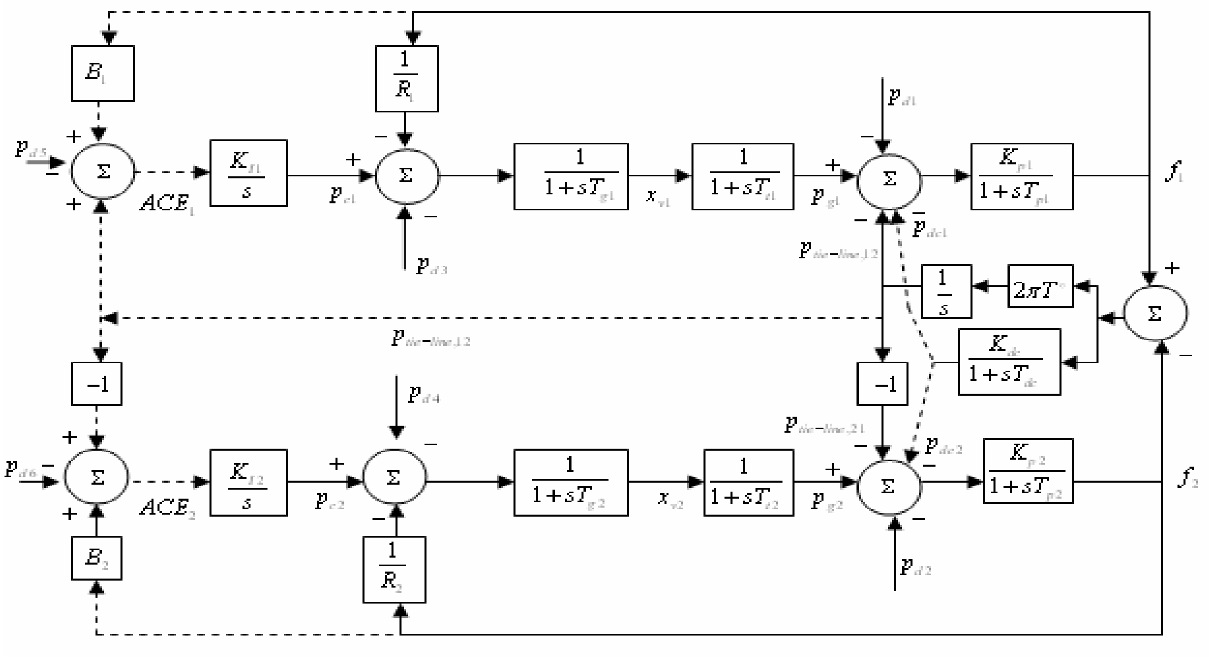

Figure (1) A block-diagram for a Two Area Interconnected Power System for Load-frequency Control Studies

$$d_1 = \begin{bmatrix} p_{d_1} & p_{d_2} \end{bmatrix};$$

$$d_2 = \begin{bmatrix} p_{d_3} & p_{d_4} & p_{d_5} & p_{d_6} & p_{d_7} \end{bmatrix};$$

$$y = \begin{bmatrix} p_{tie} & f_1 & f_2 & \int ACE_1 dt & \int ACE_2 dt \end{bmatrix}^T.$$

DESIGN OF LOAD-FREQUENCY CONTROLLER

An optimal output controller for the system described by equations (1)-(2) has been designed using a two-stage process. The first stage involves the design of an optimal state feedback controller based on the approach reported in [2]. The second stage is projection of the state feedback controller to an output feedback controller using the numerical algorithm of [9] (detailed analysis of optimal output feedback controller design is given in [3]).

In order to achieve zero steady state tie-line power and frequency deviations, an optimal proportional-plus-integral controller structure is adopted (see [4] for further detail on this subject). As a result the following P-I controller has been obtained:

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -\begin{bmatrix} K_{p_1} \\ K_{p_2} \end{bmatrix} y - \begin{bmatrix} K_{I_1} \\ K_{I_2} \end{bmatrix} \int y dt$$

or

$$u = -K_p y - K_I \int y dt \qquad (3)$$

where $K_p \in \Re^{2\times3}$ & $K_I \in \Re^{2\times2}$ and have the following values:

$$K_p = \begin{bmatrix} 0.1791 & 0.3816 & -0.0241 \\ -0.3687 & -0.0071 & 0.2907 \end{bmatrix}$$

$$K_I = \begin{bmatrix} 1.2117 & 0.0497 \\ -0.1581 & 0.6258 \end{bmatrix}.$$

The control law of equation (3) may be explicitly written in terms of the physical outputs, and the area control error (ACE) as

$$u = -K_p \begin{bmatrix} P_{tie} \\ f_1 \\ f_2 \end{bmatrix} - K_I \begin{bmatrix} \int ACE_1 dt \\ \int ACE_2 dt \end{bmatrix} - KDd_2 \qquad (4)$$

where

$ACE_1 \triangleq P_{tie} + B_1 f_1$, $ACE_2 \triangleq -P_{tie} + B_2 f_2$;

$K = \begin{bmatrix} K_p & K_I \end{bmatrix}$.

Equation (4) may be more compactly expressed as:

$$u = -\left(K_p C_p + K_I C_I\right) x + KDd_2 \qquad (5)$$

where

$$C_I = \begin{array}{c} \begin{array}{cccccccccc} & & & & \int ACE_1 dt & & & & & \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\ \begin{array}{cccccccccc} & & & & & & & & \int ACE_2 dt & \end{array} \end{array}$$

CLOSED LOOP SYSTEMS: NOMINAL CONDITIONS

Substituting the control law (5) into the system equation (1)-(2) gives the following closed-loop nominal control system

$$\dot{x} = A_c x + E_d d \quad (6)$$
$$y = Cx + D_d d \quad (7)$$

where $A_c = A_o + BK_p C_p + BK_I C_I ; E_d = \begin{bmatrix} E & -BKD \end{bmatrix};$
$D_d = \begin{bmatrix} 0_{5\times 2} & D \end{bmatrix}; d = \begin{bmatrix} d_1^T & d_2^T \end{bmatrix}^T$.

It is easy to verify that the closed-loop system (6) is stable with the following set of eigenvalues:

$$\lambda = \begin{Bmatrix} \text{-13.5692,-13.9100,-1.6389} \pm j\text{8.2499, -0.9019} \pm j\text{3.5499,} \\ \text{-0.3335,-0.5502,-2.0357} \pm \text{j 0.1771} \end{Bmatrix}$$

CLOSED LOOP SYSTEMS UNDER FAULT CONDITIONS

It is quite common that faults occur in the feedback control loops. Such faults may be attributed to a loss of signal or a communication channel or controller malfunction or a combination of all of these.

In order to model faults in the load-frequency control loop, we adopt the following convention: $\gamma_{p_{tie}} = 0$ implies a fault in the p_{tie} feedback loop (see figure 1) while $\gamma_{p_{tie}} = 1$ implies no fault in the loop. Similarly $\gamma_{f_1} = 0{,}1$ (resp. $\gamma_{f_2} = 0.1$) imply the no fault (resp. fault) conditions in the frequency feedback loops of areas 1 and 2 respectively.

Incorporating faults, the new open-loop system becomes:

$$\dot{x} = A_c x + E_f f + E_d d \quad (8)$$
$$y = Cx + D_d d \quad (9)$$

where f is the fault signal to be estimated and E_f is a fault distribution matrix, the structure of which implies the fault condition.

DESIGN OF FAULT DETECTION FILTER

In the following, we briefly present a robust fault detection filter (RFDF) design technique [11] suitable for the problem outlined above. The technique involves design of an optimal residual generator as the reference residual model. Based on this the fault detection problem is formulated as an H_∞ model matching problem. This is then formulated as an H_∞ model optimisation problem and solved as a linear matrix inequality (LMI) problem. Once a solution is accomplished, a threshold for residual evaluation is obtained.

The output of the residual generator reflects the fault condition of the system. In the absence of faults, for example, the output of the residual generator stays below a threshold value. Otherwise the output breaches the threshold, signifying a faulty operation of the plant.

The development is described in following two steps:

Step 1. Introduction of optimal reference residual model.
Step 2. Minimization of H_∞ norm of the difference between the reference residual model and actual residual generator by formulation of a LMI.

Let us now consider the system described in (8)-(9). The task of fault detection comprises the tasks of residual generation and residual evaluation. For residual generation, the following RFDF is proposed:

$$\dot{\hat{x}} = \left(A_c - HC\right)\hat{x} + Hy \quad (10)$$
$$\hat{y} = C\hat{x} \quad (11)$$
$$r = V(y - \hat{y}) \quad (12)$$

where H is a gain matrix and V is a weighing matrix. Denoting the estimation error as $e = x - \hat{x}$, we obtain the state error dynamics as

$$\dot{e} = \left(A_c - HC\right)e + E_f f + \left(E_d - HE_d\right)d \quad (13)$$
$$r = VCe + VD_d d \quad (14)$$

From equations (13)-(14), it can be deduced that the problem of RFDF design reduces to the determination of H and V such that:

1. $(A_c - HC)$ is asymptotically stable.
2. Generated r is such that it is robust to norm-bounded unknown disturbances and modelling errors and at the same time as sensitive as possible to faults.

DESIGN OF OPTIMAL FAULT DETECTION FILTER

The design of optimal fault detection filter for the generation of reference residual is formulated as the following optimization problem:

$$\min_{H,V} J = \frac{\left\| V\left(D_d + \left(sI - A_c + HC\right)^{-1}\left(E_d - HD_d\right)\right)\right\|_\infty}{\inf_{\omega\in[0,\infty)} \sigma_i\left(V\left(j\omega I - A_c + HC\right)^{-1}\left(E_f\right)\right)} \quad (15)$$

A solution to the minimization problem described by equation (15) is

$$H_{opt} = \left(E_d D_d^T + YC^T\right)Q^{-1} \quad (16)$$
$$V_{opt} = Q^{-1/2} \quad (17)$$

where $Q = D_d D_d^T$ and positive semi-definite matrix Y is obtained as a solution of the following algebraic Ricatti equation (ARE)

$$Y\left(A_c - E_d D_d^T Q^{-1} C\right)^T + \left(A_c - E_d D_d^T Q^{-1} C\right) Y - Y C^T Q^{-1} C Y$$
$$+ E_d \left(I - D_d^T Q^{-1} D_d\right)^2 E_d^T = 0 \qquad (18)$$

Then, the optimal fault detection filter is described by the following set of equations:

$$\dot{x}_{opt} = A_{opt} x_{opt} + E_{optf} f + E_{optd} d \qquad (19)$$
$$r_f = C_{opt} x_{opt} + D_{optd} d \qquad (20)$$

where

$$A_{opt} = \left(A_c - H_{opt} C\right); E_{optf} = E_f;$$
$$E_{optd} = \left(E_d - H_{opt} D_d\right); C_{opt} = V_{opt} C;$$
$$D_{optd} = V_{opt} D_d .$$

Therefore, the overall system dynamics can be described by the following set of equations

$$\dot{\tilde{x}} = \tilde{A}\tilde{x} + \tilde{B}_w w \qquad (21)$$
$$r_e = \tilde{C}\tilde{x} + \tilde{D}_w w \qquad (22)$$

where:

$$\tilde{x} = \begin{bmatrix} e^T & x_{opt}^T & x^T \end{bmatrix}^T, w = \begin{bmatrix} 0 & f^T & d^T \end{bmatrix}^T$$
$$\tilde{A} = diag\left[\left(A_c - HC\right) \quad A_{opt} \quad A_c\right],$$
$$\tilde{B}_d = \begin{bmatrix} E_d - HD_d \\ E_{optd} \\ E_d \end{bmatrix}, \tilde{B}_f = \begin{bmatrix} E_f \\ E_{optf} \\ E_f \end{bmatrix}, \tilde{B}_w = \begin{bmatrix} 0 & \tilde{B}_f & \tilde{B}_d \end{bmatrix}$$
$$\tilde{C} = \begin{bmatrix} VC & -C_{opt} & 0 \end{bmatrix}, \tilde{D}_w = \begin{bmatrix} 0 & 0 & \tilde{D}_d \end{bmatrix}, \tilde{D}_d = VD_d - D_{optd} .$$

DESIGN OF RFDF:

The solution of RFDF design problem, described by the equations (10)-(12), is based upon the application of a well-known bounded real lemma [5]. The design is formulated as an H_∞ model-matching problem and involves the computation of the unknown matrices H and V. This is achieved by the formulation and solution of a LMI as stated in Theorem 1 below.

Theorem1 [11]: Given $\gamma > 0$, if there exist scalars matrices $P_1 > 0,\ P_2 > 0,\ \ P_3 > 0,\ \ Y_1,\ V$ such that the LMI

$$\left[N_{ij}\right] < 0 \qquad (23)$$

in which the submatrices $\left\{N_{ij},\ \ i, j \in 1, 2, \ldots, 7\right\}$ are detailed in [11] holds, then system (21)-(22) is asymptotically stable and the H_∞ performance

$$\left\|r_e\right\|_2 < \gamma \left\|w\right\|_2 \qquad (24)$$

is satisfied. In this case the observer gain matrix is given by

$$H = P_1^{-1} Y_1 \qquad (25)$$

In this example, the matrix $N = \left[N_{ij}\right] \in \Re^{46\times 46}$.

The residual generation is carried out as per equation (14). It is important to note that in this procedure the residual is adaptive so that as the plant conditions vary so too does the threshold. The generated residual tracks the threshold in the fault-free case, and is otherwise different. For evaluation of the generated residual, a threshold, J_{th}, is used. J_{th} is calculated as upper bound on the residual for the fault free case. That is,

$$J_{th} = \left\|r_d(t)\right\|_2 \qquad (26)$$

where $r_d(t) = r(t)\big|_{f=0}$.

Then,

$$\left\|r\right\|_2 > J_{th} \Rightarrow \text{ with faults } \Rightarrow \text{ alarm} \qquad (27)$$
$$\left\|r\right\|_2 \le J_{th} \ \Rightarrow \text{ no faults} \qquad (28)$$

APPLICATION TO TAIPS

The fault detection technique outlined above is tested on the TAIPS described in section 2 by equations (8)-(9) under the PI control law of equation (3).

The test involves the following noise-free scenarios:

Scenario I: The closed-loop power system is disturbed by a 0.01 p.u. change in the load demand in area 1 at time t=0. After 15s, fault occurs in the control loop of area 1, which results in total loss of the control signal $u_1 = K_{p_1} y + K_{I_1} \int y dt$. At time t=16s the fault is cleared and the control loop is closed leading to normal operation of the power system.

Scenario II: The same conditions as in scenario I are repeated but the fault is unable to be cleared and stays in place for the remainder of the simulation study.

The simulation results of the two scenarios are shown in Figures 2 and 3. With respect to scenario I, figures 2a-2c show the responses of the tie-line power change, and the frequencies in areas 1 and 2, respectively. As can be seen from these responses the controller, after some transitional period, is able to affect zero steady state change in these variables whenever an internal or external disturbance takes place, as required.

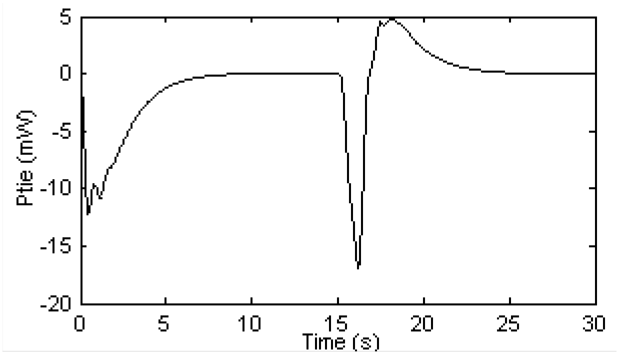

Figure 2 (a). Response of $P_{tie-line}$

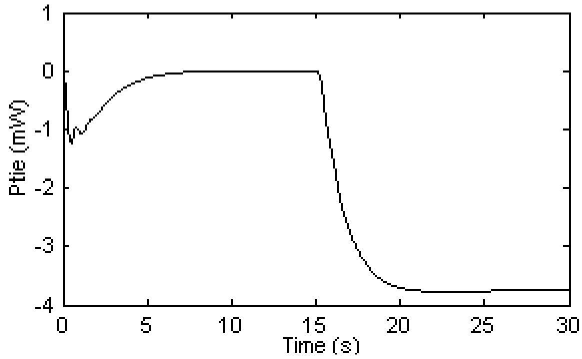

Figure 3(a). Response of $P_{tie-line}$

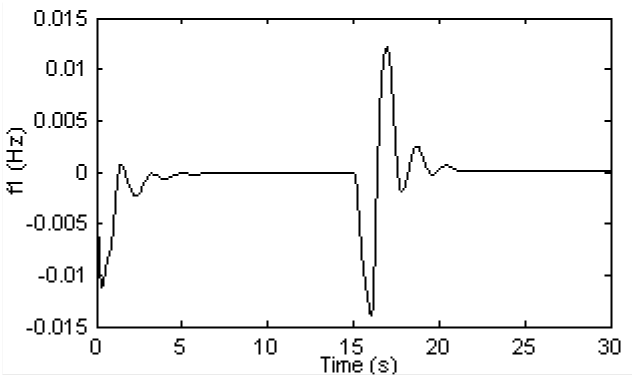

Figure 2(b). Response of f_1

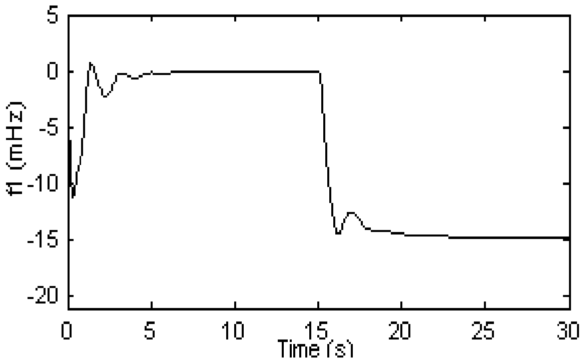

Figure 3(b). Response of f_1

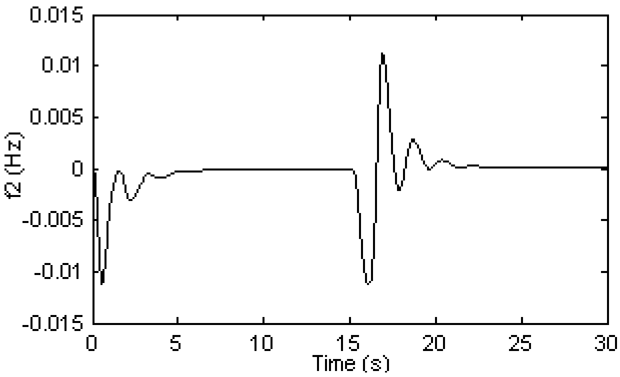

Figure 2(c). Response of f_2

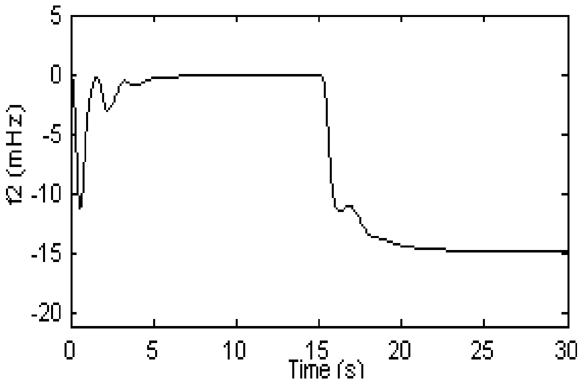

Figure 3 (c) Response of f_2

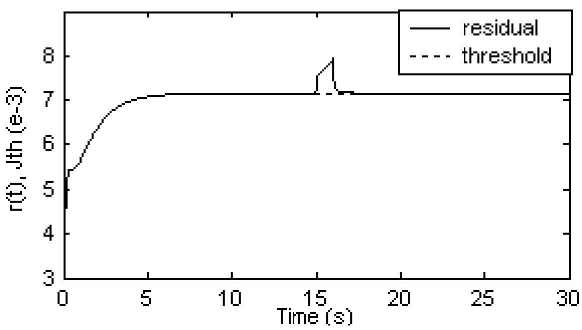

Figure 2 (d). Residual generation

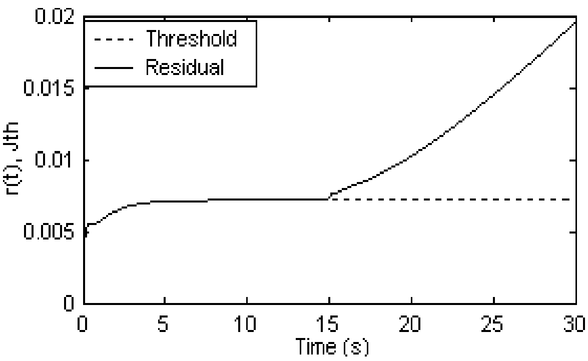

Figure 3 (d) Residual generation

Figure 2(d) demonstrates the generated residual. It can be seen that the residual tracks the threshold for the no fault period and surges above the threshold in the event of the fault. The surge above the threshold line signifies the fact that a fault has taken place in that particular loop.
Figures 3(a)-3(c) illustrate the simulation results of scenario II where the responses of the tie-line power, and the frequencies in areas 1 and 2, respectively, are shown. It is clear from these figures that the tie-line power and frequencies of area 1 and area 2 are not able to return to the required zero steady state change due to the loss of the control loop.
Figure 3(d) shows the response of the residual generator. As expected, the residual instantaneously diverges from the threshold at t = 15 s., signifying the occurrence of fault at that time in the particular control loop.

CONCLUSIONS

In this paper, we present a robust filter based approach for the detection and identification of faults in the load-frequency control loop of two area interconnected power system (TAIPS). A closed loop model of the TAIPS system is obtained by using an optimal output controller. Then, the malfunctioning in the feedback loops is modelled as occurring faults. The robust fault detection filter is employed for fault detection and identification in presence of unknown disturbances and noise. Simulation results have been presented for two fault scenarios. The results conform to the physical and expected behaviour of the system under prescribed conditions.

ACKNOWLEDGEMENTS

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