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RESEARCH ARTICLE

Robust Fault Detection Scheme for Synchronous Generator Having Nonlinear Uncertain Measurements Along With Perturbation

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ABSTRACT Accurate and fast detection of faults is one of the main concerns of power systems for their operation and productivity. In this paper, a robust dynamic fault detection filter is presented for a synchronous generator (SG) characterized by a highly non-linear model, having uncertainties and perturbations both in state and measurements. The filter is so designed that the residual signal is robust against model uncertainties, process disturbances on the one hand and sensitive to faults on the other hand. To this end, a so-called mixed $\mathscr{H}_{-}/\mathscr{H}_{\infty}$ optimization is used to design the filter. The norm-based threshold is design which guarantee no false alarm. The effectiveness of the proposed approach is demonstrated by introducing synchronous generators in IEEE 9 and IEEE 39 Bus system, and considering different types of faults.

INDEX TERMS Fault detection filter, nonlinear system, power system, synchronous generator, uncertain measurements.

To meet the stringent quality standards, the degree of complexity in industrial processes has increased over. Consequently, vulnerability to faults within the processes has been increased. If a fault is not detected in a timely manner, it can cause performance degradation and catastrophic damage to both the components and the persons working there [1], [2]. Detection of faults, is therefore important for safe and reliable operation of industrial processes.

Among different industrial processes, power system is an important industrial process, and early detection of faults in power systems is highly desirable for smooth and continuous operation. Modern power systems, which are also very complex industrial processes are more prone to faults due to their complex nature arising from the penetration of communication and advance control systems in power networks [3]. Moreover decentralization of power systems has also contributed towards the increased complexity [4], [5]. Faults in power systems cause unwanted effects such as, discontinuity in supply, unbalance in the system, economic losses, component damage and blackout. Therefore, early detection of faults, both on operational and economical fronts [6], [7] is highly desirable for their smooth and continuous operation. Power systems consist of generation system, transmission and distribution system [8]. In generation subsystem, synchronous generators (SGs) are the critical components. Any fault or abnormality in SG, results in the performance degradation of the transmission and distribution

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subsystem connected to it. In order to keep a power system working as per desire, timely detection of faults in SG is very important. The generator faults are classified as *actuator faults*, *three phase faults*, and *sensor faults*. *Actuator faults* includes faults in excitation system, and prime mover, and overexcited limiter failure, whereas *sensor faults* are due to malfunctioning of current transformer, potential transformer, frequency sensors and phasor measuring unit [9].

It is important to detect faults as early as possible to avoid considerable damage to power systems components [10], [11]. Different fault detection (FD) schemes have been reported in the literature that can detect faults at the earlier stages in power systems, [12], [13], [14], [15]. Both linear and nonlinear models have been studied towards the development of fault detection systems [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26].

In power system, observer based FD is proposed in [18]. The authors therein presented the mathematical model of the power systems from generation, transmission, and distribution. A more generalized model is presented. This study lacks the information of uncertainties and unknown inputs which are the major cause of false alarms. A similar problem can be observed in [19], [20], [21], [22], wherein uncertainties, and process disturbances are not considered in the design of FD scheme.

In [23] internal fault detection scheme for synchronous generator has been considered. The proposed scheme discriminates between internal and external faults and abnormal conditions. This work considers only winding faults; Other faults like prime over failure, excitation failure to list a few have not been considered.

The work in [24] addresses fault detection filter design to detect the fault in power systems. This study is based on the idea of decoupling faults from states. In this work faults have also been modeled as unknown inputs.

The work in [25] presents interesting results on designing time varying observer based FD scheme for the detection of faults in synchronous machines. The authors therein have studied three phase faults, faults in mechanical torques and in excitation systems. The work is based on adopting the linearized version of nonlinear model at every time step. An associated issue is the increased computation time. Recently, the authors in [26] presented a comprehensive study on fault detection of synchronous generators wherein, an observer based fault detection scheme is designed. The salient features of the scheme include mathematical model of faults in SG, and the design of threshold in order to differentiate between faults, disturbances and measurement noises. While the authors consider linear measurements. In practice, the measurements obtained from sensors are nonlinear and uncertain in nature. Thus any FD system design considering the nonlinear and uncertain measurements will lead to better performance in fault detection. Driven by this motivation, a nonlinear optimal FD filter (FDF) for fault detection in synchronous generators in power systems is proposed in this paper, which has following salient features:

- A nonlinear Lipschitz model for output measurements is proposed in this paper.
- It is robust against model uncertainties and disturbances.
- It can differentiate between faults and uncertainties.
- Design of such a fault detection scheme for nonlinear Lipschitz equivalent model having nonlinearities both in state and output is novel.

The remaining of the manuscript is categorized as, Section *I*, synchronous generator dynamic model along with Lipschitz constant consideration is described. In Section *II*, an optimal FDF is proposed, which is robust against perturbation. In Section *III*, simulation results are presented, which shows the effectiveness of proposed FDF against faults.

I. PROBLEM FORMULATION

We describe system, model modification and problem statement in this section.

A. SYSTEM MODEL

Considered the following state space model that describes the dynamics of the system under consideration

$$\begin{aligned} \dot{x} &= A_o x + \mathscr{T}(x,u) + B_o u + E_{do} d \\ y &= F_{do} d + \mathscr{H}(x,u) + D_0 u \end{aligned} \tag{1}$$

where $x \in \mathbb{R}^{n_x}$ is the state, $u \in \mathbb{R}^{n_u}$ is the control input, $d \in \mathbb{R}^{n_d}$ is disturbance and $y \in \mathbb{R}^{n_y}$ is output of the system. A_o and B_o are the state and input matrix respectively. $\mathscr{T}(x,u)$ and $\mathscr{H}(x,u)$ represents nonlinearities in state and output respectively.

B. MODEL MODIFICATION

The nonlinear relation between $x(t)$ and $y(t)$ is through $\mathscr{H}(x,u)$. In order to design optimal FDF the work in [27] inspired us. The function $\mathscr{H}_1(.)$ is described as

$$\mathscr{H}_1(.) = -C_0 x + \mathscr{H}(x,u) \tag{2}$$

Since $\mathscr{H}(.)$ is Lipschitz locally having Lipschitz constant $\eta_{\mathscr{H}}$, from (2) it follows that $\mathscr{H}_1(.)$ is Lipschitz locally having Lipschitz constant η_m where

$$\eta_m = \eta_{\mathscr{H}} + \|C_0\|_2 .$$

where matrix C_0 will be any matrix having appropriate dimensions and pair (A_0, C_0) should be detectable, this condition is necessary for observer design. Matrices C_0 and D_0 are derived by linearising the $\mathscr{H}(.)$ around operating point this results in to detectable pair of (A_0, C_0), so (1) can be written as

$$\begin{aligned} \dot{x} &= A_0 x + B_0 u + \mathscr{T}(x,u) + E_{d0} \\ y &= C_0 x + D_0 u + F_{d0} d + \mathscr{H}_1(x,u) \end{aligned} \tag{3}$$

Now considering the fault and uncertainties, the above equations can be written as

$$\begin{aligned} \dot{x} &= \bar{A}x + \bar{E}_d d + E_{f0} f + \bar{B}u + \mathscr{T}(x,u) \\ y &= \bar{C}x + \bar{D}u + \bar{F}_d d + F_{f0} f + \mathscr{H}_1(x,u) \end{aligned} \tag{4}$$

$f \in R^{kf}$ represents unknown faults. Where E_{fo}, F_{fo} are known fault matrices. The matrices $\bar{A}$, $\bar{C}$, $\bar{B}$, $\bar{E_d}$, $\bar{D}$, and $\bar{F_d}$ are uncertain matrices and can be written as

$$\bar{A} = \delta A_0 + A_0, \quad \bar{C} = \delta C_0 + C_0, \bar{B} = \delta B_0 + B_0,$$
$$\bar{D} = \delta D_0 + D_0, \quad \bar{F_d} = \tilde{F_{d0}} + F_{d0}, \quad \bar{E_d} = \delta E_{d0} + E_{d0}$$

where model uncertainties $\delta A_0, \delta B_0, \delta C_0, \delta D_0, \delta E_{d0}$ and δF_{d0} belong to the poly-topic type and are represented as

$$\begin{bmatrix} \delta A_0 & \delta B_0 & \delta E_0 \\ \delta C_0 & \delta D_0 & \delta F_0 \end{bmatrix} = \sum_{k=1}^{l} \omega_j \begin{bmatrix} A_{0k} & B_{0k} & E_{0k} \\ C_{0k} & D_{0k} & F_{0k} \end{bmatrix},$$
$$\sum_{j=1}^{l} \omega_j = 1, \ \omega_k \geq 0$$

where the matrices $A_{0k}, B_{0k}, C_{0k}, D_{0k}, E_{0k}$ and F_{ok}, $\forall k = 1, 2 \ldots . l$ are known and are of compatible dimensions [28], [29] . Lipschitz conditions for the functions $\mathscr{T}(.)$ and $\mathscr{H}(.)$ are given as

$$\left\| \mathscr{T}(x, u) - \mathscr{T}(\hat{x}, u) \right\|_2 \leq \eta_{\mathscr{T}} \left\| x - \hat{x} \right\|_2$$
$$\left\| \mathscr{H}_1(x, u) - \mathscr{H}_1(\hat{x}, u) \right\|_2 \leq \eta_{\mathscr{H}} \left\| x - \hat{x} \right\|_2$$

where $\eta_{\mathscr{T}}$ and $\eta_{\mathscr{H}}$ are the Lipschitz constant.

Methods of computation of Lipschitz constant are described in detail in [30].

C. ERROR DYNAMICS

Consider the following nonlinear observer-based FDF

$$\begin{aligned} \dot{\hat{x}} &= A_o\hat{x} + L(y - \bar{C}_o\hat{x} - D_o u - \mathscr{H}_1(\hat{x}, u)) + B_o u \\ &\quad + \mathscr{T}(\hat{x}, u) \\ r &= (y - \hat{y}) \end{aligned} \tag{5}$$

Define $e = x - \hat{x}$, then the error dynamics can be written as follows

$$\begin{aligned} \dot{e} &= (A_o - LC_o)e + (\bar{E}_d - L\bar{F}_d)d + (B_{oi} - LD_{oi}) \\ &\quad + L(\mathscr{H}_1(x, u) - \mathscr{H}_1(\hat{x}, u)) + (E_{fo} - LF_{fo})f \\ &\quad + (A_{oi} - LC_{oi})x + \mathscr{T}(x, u) - \mathscr{T}(\hat{x}, u) \\ r &= C_o e + C_{oi}x + D_{oi}u + \bar{F}_d d + F_{fo}f \\ &\quad + (\mathscr{H}_1(x, u) - \mathscr{H}_1(\hat{x}, u)) \end{aligned} \tag{6}$$

The dynamics of residual generator for error dynamics (6) and system (4) in compact form can be written as

$$\begin{aligned} \dot{e_0} &= A_N e_0 + \phi_N + E_N d_0 + E_{N,f} f + L\phi_2 \\ r &= C_N e_0 + F_N d_0 + F_{N,f} f + \phi_2 \end{aligned} \tag{7}$$

wher

$$e_0 = \begin{bmatrix} x \\ e \end{bmatrix}, \quad d_o = \begin{bmatrix} u \\ d \end{bmatrix}, \quad \phi_N = \begin{bmatrix} \mathscr{T}(x, u) \\ \mathscr{T}(x, u) - \mathscr{T}(\hat{x}, u) \end{bmatrix}$$
$$A_N = \tilde{A} - \tilde{L}\tilde{C}, \quad E_N = \tilde{E_d} - \tilde{L}\tilde{F_d}, \quad C_N = \tilde{C},$$
$$F_N = \tilde{F_d}, \quad E_{N,f} = \tilde{E_f} - \tilde{L}F_{N,f}, \quad F_{N,f} = F_{fo},$$
$$\phi_2 = (\mathscr{H}_1(x, u) - \mathscr{H}_1(\hat{x}, u)),$$

$$\tilde{A} = \begin{bmatrix} A_0 + A_{0k} & o \\ A_{0k} & A_0 \end{bmatrix}, \quad \tilde{L} = \begin{bmatrix} 0 \\ L \end{bmatrix},$$
$$\tilde{C} = \begin{bmatrix} C_{0k} & C_0 \end{bmatrix}, \tilde{E_d} = \begin{bmatrix} B_0 + B_{0k} & E_{d0} + E_{d0k} \\ B_{0k} & E_{d0} \end{bmatrix},$$
$$\tilde{F_d} = \begin{bmatrix} D_{0k} & F_{d0} + F_{d0k} \end{bmatrix}$$

D. PROBLEM STATEMENT

Our objective is to design an FDF for nonlinear uncertain system. such that system in (7) is stable asymptotically and the index $\mathscr{H}_-/\mathscr{H}_\infty$ is minimized. The $\mathscr{H}_-/\mathscr{H}_\infty$ performance index is defined as

$$\|r\|_2 \leq \beta \|d\|_2 \tag{8}$$
$$\|r\|_2 \geq \gamma \|f\|_2 \tag{9}$$

where β is the attenuation level of the disturbance and γ is the sensitivity level of the fault.

II. ROBUST DYNAMIC FDF DESIGN

The proposed design of robust dynamic FDF is presented in this section. The sufficient condition for the $\mathscr{H}_-/\mathscr{H}_\infty$ induced norm based optimal FDF is proved by the following theorem.

Theorem 1: Consider the system in (4)*, the residual generator in* (6) *and the fault detection filter in* (5)*, if there exist* Q_i*,* P_i *symmetric matrices, which are also positive semi-definite and non-negative constants* λ_g ($g = 1, 2, 3 \ldots 10, 31, 41$)*, then the observer gain* L *can be computed by solving the following optimization problem*:

$$\min_{\beta,\gamma,\lambda_1,\ldots\lambda_{10},\lambda_{31},\lambda_{41},P_i,Y_i,Q_i} Z_1\gamma - Z_2\zeta$$

subject to (4), (6) *and*

$$\begin{bmatrix} \upsilon_1 & P_k\tilde{E_d} - Y_k\tilde{F_d} + \tilde{C}^T\tilde{F_d} & P_k & P_k \\ \upsilon_{21} & \lambda_{41}\tilde{F_d}^T\tilde{F_d} - \beta^2 I & 0 & 0 \\ P_k & 0 & -\lambda_1 I & 0 \\ P_k & 0 & 0 & -\lambda_2 \end{bmatrix} \leq 0 \tag{10}$$

$$\begin{bmatrix} \upsilon_2 & Q_k\tilde{E_f} - Y_kF_{fo} - \tilde{C}^TF_{fo} & Q_k & Q_k \\ \upsilon_{22} & -\lambda_6 F_f^T F_f + \gamma^2 I & 0 & 0 \\ Q_k & 0 & -\lambda_7 I & 0 \\ Q_k & 0 & 0 & -\lambda_8 \end{bmatrix} \leq 0 \tag{11}$$

where

$$\begin{aligned} \upsilon_1 &= \tilde{A}^T P_k + P\tilde{A} - \tilde{C}^T Y_k^T - Y_k\tilde{C} + S\eta_{\mathscr{H}}^2 + \lambda_3\eta_{\mathscr{H}}^2 \\ &\quad + \lambda_4\eta_{\mathscr{H}}^2 + \lambda_1\eta_{\mathscr{T}}^2 + \lambda_{31}\tilde{C}^T\tilde{C} + \eta_{\mathscr{H}}^2 \\ \upsilon_2 &= \tilde{A}^T Q_k + Q_k\tilde{A} - \tilde{C}^T Y_k^T - Y_k\tilde{C} + S\eta_{\mathscr{H}}^2 - \lambda_9\eta_{\mathscr{H}}^2 \\ &\quad - \lambda_{10}\eta_{\mathscr{H}}^2 + \lambda_7\eta_{\mathscr{T}}^2 - \lambda_5 C^T C - \eta_{\mathscr{H}}^2 \\ \upsilon_{21} &= \tilde{F_d}^T\tilde{C} + \tilde{E_d}^T P_i - \tilde{F_d}^T Y_i^T, \quad \upsilon_{22} = -F_{fo}^T\tilde{C} + \tilde{E_f}Q_i \\ &\quad - F_{fo}^T Y_i^T \end{aligned}$$

The objective function weights are represented by Z_1 *and* Z_2.

The gain of proposed FDF will be calculated as

$$\tilde{L} = \bar{P}^{-1}\bar{Y}, \quad \bar{Y} = \sum_{k=1}^{l} w_k Y_k, \quad \bar{P} = \sum_{k=1}^{l} w_k P_k \tag{12}$$

Proof:

Consider the dynamics of the residual generator in (7)

$$\begin{aligned} \dot{e}_0 &= A_N e_0 + \phi_N + E_N d_0 + E_{N,f} f + L\phi_2 \\ r &= C_N e_0 + F_N d_0 + F_{N,f} f + \phi_2 \end{aligned} \tag{13}$$

Due to existence of fault and perturbation the error signal can be written as

$$\dot{e}_0 = \dot{e}_d + \dot{e}_f \tag{14}$$

e_d indicate the error in the existence of perturbation and e_f indicate the error in the existence of fault, and can be written as

$$\begin{aligned} \dot{e}_d &= A_N e_d + \phi_{Nd} + E_N d + L\phi_{2d} \\ r_d &= C_N e_d + F_N d + \phi_{2d} \end{aligned} \tag{15}$$

$$\begin{aligned} \dot{e}_f &= A_N e_f + \phi_{Nf} + E_{N,f} f + L\phi_{2f} \\ r_f &= C_N e_f + F_{N,f} f + \phi_{2f} \end{aligned} \tag{16}$$

In order to prove the sub system (15) internal stability, we consider the Lyapunov function

$$V = e_d^T P_k e_d, P_k = \begin{bmatrix} P_{1k} & 0 \\ 0 & P_{4k} \end{bmatrix} > 0$$

Differentiating the Lyapunov function along the residual generator (15)

$$\begin{aligned} \dot{V} &= e_d^T (A_N^T P_k + P_k A_N) e_d + e_d^T P_k E_N d + d^T E_N^T P e_d \\ &\quad + \phi_{Nd}^T P_k e_d + e_d^T P_k \phi_{Nd} + \phi_{2d}^T L^T P_k e_d + e_d^T P_k L \phi_{2d} \end{aligned} \tag{17}$$

Bound on the nonlinear terms by using Lemma [31], can be written as follows

$$\phi_{Nd}^T P_k e_d + e_d^T P_k \phi_{Nd} \le e_d^T \frac{1}{\lambda_1} P_k P_k e_d + \lambda_1 \phi_{Nd}^T \phi_{Nd}$$

Now by using Caushy-Schwarz inequality, Where $\lambda_1 > 0$, the inequality presented above
can be written as

$$\phi_{Nd}^T P_k e_d + e_d^T P_k \phi_{Nd} \le e_d^T \frac{1}{\lambda_1} P_k P_k e_d + \lambda_1 \eta_{\mathscr{T}}^2 e_d^T e_d \tag{18}$$

Using (18), (17) can be written as

$$\begin{aligned} \dot{V} &= e_d^T (A_N^T P_k + P_k A_N + \frac{1}{\lambda_1} PP + \lambda_1 \eta_{\mathscr{T}}^2) e_d \\ &\quad + e_d^T P_k E_N d + d^T E_N^T P_k e_d + \underbrace{2 e_d^T P_i L \phi_{2d}} \end{aligned} \tag{19}$$

Now applying Lemma [32] to under braces term the above equation can be written as

$$\begin{aligned} \dot{V} &= e_d^T (A_N^T P_k + P_k A_N + \frac{1}{\lambda_1} P_k P_k + \lambda_1 \eta_{\mathscr{T}}^2) e_d + e_d^T P_k E_N d \\ &\quad + d^T E_N^T P_k e_d + \lambda_2 \phi_{2d}^T L^T L \phi_{2d} + \frac{1}{\lambda_2} e_d^T P_k P_k e_d \end{aligned} \tag{20}$$

Now considering

$$\begin{aligned} \lambda_2 \phi_{2d}^T L^T L \phi_{2d} &\le \|L\phi_{2d}\| \\ &\le \|L\| \|\phi_{2d}\| \\ &\le \|L\| \eta_{\mathscr{H}}^2 e_d^T e_d \\ &\le \underbrace{L^T L \eta_{\mathscr{H}}^2} e_d^T e_d \\ &\le S \eta_{\mathscr{H}}^2 e_d^T e_d \end{aligned}$$

The above equation can be written as

$$\dot{V} \le \begin{bmatrix} e_d \\ d \end{bmatrix}^T \begin{bmatrix} M_1 & P_k E_N \\ E_N^T P_k & 0 \end{bmatrix} \begin{bmatrix} e_d \\ d \end{bmatrix} \le 0 \tag{21}$$

where $M_1 = A_c^T P_k + S\eta_{\mathscr{H}}^2 + P_k A_c + \frac{1}{\lambda_1} P_k P_k + \lambda_1 \eta_{\mathscr{T}}^2 I + \frac{1}{\lambda_2} P_k P_k$. The system will be internally stable if

$$\begin{bmatrix} M_1 & P_k E_N \\ E_N^T P_k & 0 \end{bmatrix} \le 0$$

Now considering the $\mathscr{H}_\infty$ performance index in (8)

$$r_d^T r_d - \beta^2 d^T d + \dot{V} \tag{22}$$

First, we consider

$$r_d^T r_d - \beta^2 d^T d \tag{23}$$

By substituting the values in (23), the above equation can be written as

$$(C_N e_d + \phi_{2d} + F_N d)^T (C_N e_d + \phi_{2d} + F_N d) - \beta^2 d^T d \tag{24}$$

Above equation can be written as

$$\begin{aligned} & e_d^T C_N^T C_N e_d + d^T F_N^T C_N e_d + d^T F_N^T F_N d - \beta^2 d^T d \\ &\quad + \underbrace{\phi_{2d}^T C_N e_d + e_d^T C_N^T \phi_{2d}} + \underbrace{\phi_{2d}^T F_N d + d^T F_N^T \phi_{2d}} \\ &\quad + \underbrace{\phi_{2d}^T \phi_{2d}} + e_d^T C_N^T F_N d \end{aligned} \tag{25}$$

Now by applying Lemma [32] and using Caushy-Schwarz Lipschitz condition on under the braces term and by putting the values in (22), we obtain

$$\begin{bmatrix} e_d \\ d \end{bmatrix}^T \begin{bmatrix} M_2 & P_k E_N + C_N^T F_N \\ F_N^T C_N + E_N^T P_k & F_N^T F_d - \beta^2 I + \frac{1}{\lambda_4} F_N^T F_N \end{bmatrix} \begin{bmatrix} e_d \\ d \end{bmatrix} \tag{26}$$

where $M_2 = A_N^T P_k + P_k A_N + S\eta_{\mathscr{H}}^2 + \lambda_3 \eta_{\mathscr{H}}^2 + \lambda_4 \eta_{\mathscr{H}}^2 + \lambda_1 \eta_{\mathscr{T}}^2 + \frac{1}{\lambda_1} P_k P_k + C_N^T C_N$
$+ \eta_{\mathscr{H}}^2 + \frac{1}{\lambda_3} C_N^T C_N + \frac{1}{\lambda_2} P_k P_k$,

$$r_d^T r_d - \beta^2 d^T d + \dot{V} = \zeta_d^T \tilde{\phi} \beta_d$$

where $\zeta_d = \begin{bmatrix} e_d \\ d \end{bmatrix}$. Now by Congrance Transformation $\tilde{\phi} < 0$

$$\begin{bmatrix} M2 & P_i E_N + C^T F_N \\ F_N^T C_N + E_N^T P_i & F_N^T F_N - \beta^2 I + \frac{1}{\lambda_4} F_N^T F_N \end{bmatrix} < 0$$

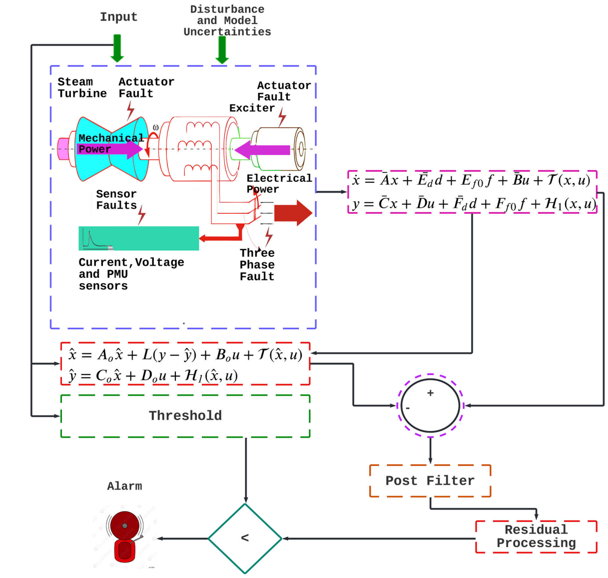

FIGURE 1. Fault detection in synchronous generator using observer.

Thus, $r_d^T r_d - d^T d + \dot{V} < 0$
This implies

$$\int_0^\infty r_d^T r_d - \int_0^\infty \beta^2 d^T d + \int_0^\infty \dot{V} < 0$$

$$\|r_d\|_2 \leq \beta^2 \|d\|_2 + V(0) - V(\infty)$$

By applying Schur complement and along with some mathematical manipulations, the inequality presented above can be written as

$$\begin{bmatrix} \upsilon_1 & P_k\tilde{E_d} - Y_k\tilde{F_d} + \tilde{C}^T\tilde{F_d} & P_k & P_k \\ \upsilon_{21} & \lambda_{41}\tilde{F_d}^T\tilde{F_d} - \beta^2 I & 0 & 0 \\ P_k & 0 & -\lambda_1 I & 0 \\ P_k & 0 & 0 & -\lambda_2 \end{bmatrix} \leq 0 \quad (27)$$

In a similar way the subsystem (16) internal stability can be prove. Consider the Lyapunov function

$$\mathscr{Y} = e_f^T Q_i e_f, Q_k = \begin{bmatrix} Q_{1k} & 0 \\ 0 & Q_{4k} \end{bmatrix} > 0 \quad (28)$$

Now consider the performance index (9). Working on similar lines as above this will yield (11)

$$\begin{bmatrix} \upsilon_2 & Q_k\tilde{E_f} - Y_kF_{fo} - \tilde{C}^T F_{fo} & Q_k & Q_k \\ \upsilon_{22} & -\lambda_6 F_f^T F_f + \gamma^2 I & 0 & 0 \\ Q_k & 0 & -\lambda_7 I & 0 \\ Q_k & 0 & 0 & -\lambda_8 \end{bmatrix} \leq 0 \quad (29)$$

Complete block diagram of proposed FD scheme is shown in Fig. 1

III. APPLICATION AND RESULTS

Considered the synchronous generator model which is transient in nature connected to the transformer, detail of which

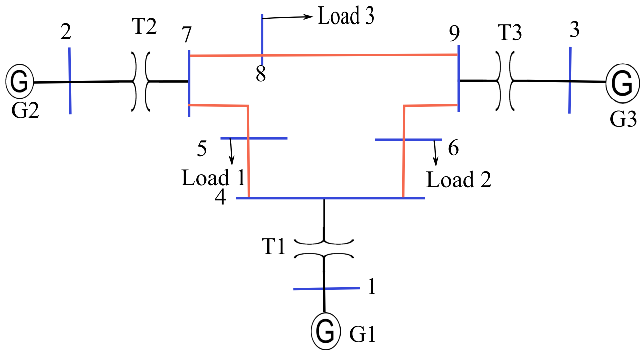

FIGURE 2. Single line, 3-machine, 9-bus system.

Algorithm 1 Procedure for the design of optimal FDF is written below.

1) *compute the Lipschitz constants*
2) *Solve the multi-objective problem in Theorem 1 for non-negative constants* λ_g $(g = 1, 2, 3, \ldots 10, 31, 41)$, *and matrices* P_i *and* Q_i. *Such that* γ *should be maximized and* β *should be minimized.*
3) *After solving the LMIs, the gain of proposed FDF can be calculated by* (12)
4) *Compute norm-based constant threshold, which guarantees no false alarm* [32].

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can be found in [25]. The matrices A_o and B_o are written as

$$A_o = \begin{bmatrix} 0 & w_B & 0 & 0 & 0 \\ 0 & \frac{D_r}{M} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{q0}} & 0 & \frac{1}{T_{q0}} \\ 0 & 0 & 0 & \frac{1}{T_{d0}} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_A} \end{bmatrix}$$

$$B_o = \begin{bmatrix} 0 & 0 & 0 & w_B \\ \frac{T_m}{M} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{K_A}{T_A} & 0 & 0 \end{bmatrix}$$

where $w_B, D_r, M, T_{d0}, T_{q0}, T_A, T_m,$ and K_A represent base speed of rotor, rotor damping constant, moment of inertia, d-axis time constant, q-axis time constant, mechanical torque and voltage gain of automatic voltage regulator respectively. The function $\mathscr{T}(x,u) = [\mathscr{T}_1(x,u)\ \mathscr{T}_2(x,u)\ \mathscr{T}_3(x,u)\ \mathscr{T}_4(x,u)\ \mathscr{T}_5(x,u)]^T$ is written as follows.

$$\mathscr{T}_1(x,u) = 0,\ \mathscr{T}_2(x,u) = \frac{-T_e}{M},\ \mathscr{T}_3(x,u) = \frac{1}{T_{qo}}(X_d i_d - X_d' i_d)$$

$$\mathscr{T}_4(x,u) = \frac{1}{T_{do}}(-X_q i_q + X_q' i_q),\quad \mathscr{T}_5(x,u) = \frac{1}{T_A}[K_A(-V_t)]$$

where T_e, X_d, X_q, i_d, i_q and V_t represent electrical torque, d-axis synchronous reactance, q-axis synchronous reactance, d-axis current, q-axis current, and magnitude of

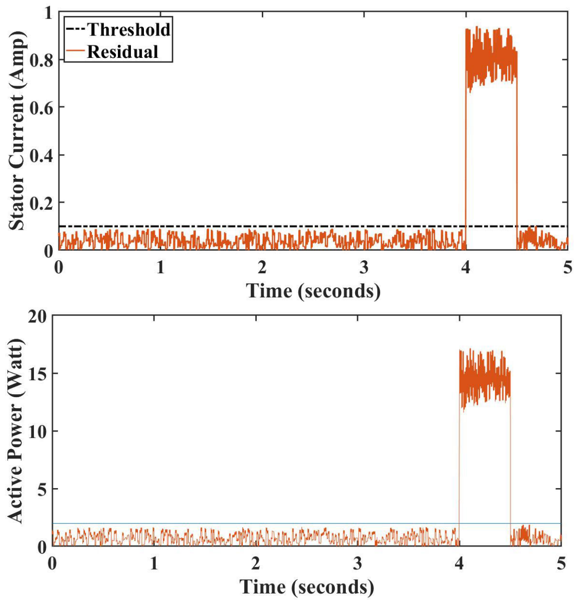

FIGURE 3. Three-phase fault detection (Generator 1).

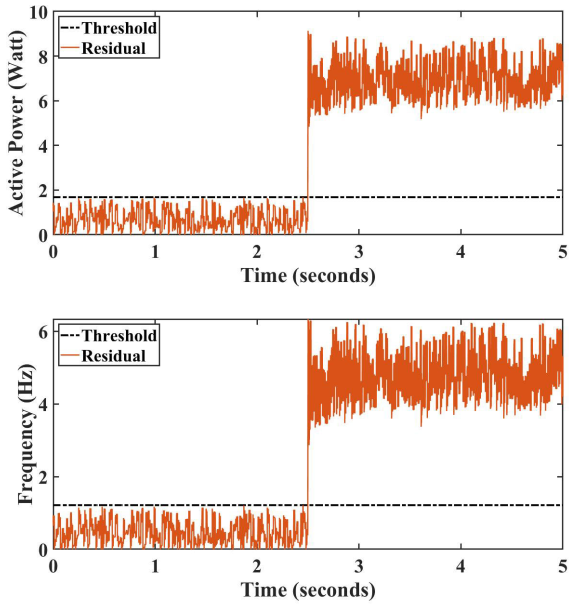

FIGURE 4. Actuator fault detection (Generator 1).

stator voltage respectively The functions $\mathscr{H}_1(x,u) = [_{11}(x,u)\ \mathscr{H}_2(x,u)\ \mathscr{H}_3(x,u)\ \mathscr{H}_4(x,u)\ \mathscr{H}_5(x,u)]^T$ is given as follows.

$$\mathscr{H}_{11}(x,u) = \bar{n}\sqrt{i_q^2 + 1_d^2},\quad \mathscr{H}_2(x,u) = x_1 \arctan(\frac{i_d}{i_q})$$
$$\mathscr{H}_3(x,u) = e_d i_d + e_q i_q - (i_d^2 + i_q^2)(R_s + \bar{n}^2 R_T)$$
$$\mathscr{H}_4(x,u) = e_d i_q - e_q i_d - (X_q'' + \bar{n}^2 X_T) i_q^2 - (X_d'' + \bar{n}^2 X_T) i_d^2,$$
$$\mathscr{H}_5(x,u) = x_2$$

where $\bar{n}, e_d, e_q, R_s, R_T, X_q'', X_d''$, and X_T represent d-axis emf, q-axis emf transformer armatue resistance, transformer winding resistance, d-axis sub transient reactanvce, q-axis sub transient reactance and transformer leakage reactance respectively.

The effectiveness of proposed filter is demonstrated through IEEE 9-bus system as shown in Fig. 2. Perturbations are modeled as $\bar{F_d} = \bar{D}$ and $\bar{E_d} = \bar{B}$, Sensor faults are modeled as $E_f = 0$ and $F_f = I$, where actuator faults are modeled as $F_f = D$ and $E_f = B$. Fig.1 shows synchronous generator along with actuator, sensor and three-phase faults.

1) Case 1: In this case, different types of faults for generator 1, connecting to bus 4 are considered. First three-phase fault occur at time t = 4 second for 0.5 second as shown in Fig. 3 is considered. The line between bus 4 and 6 is tripped. The fault is detected successfully by the proposed scheme. Secondly, the generator 1 experienced an actuator fault at t= 2.5 seconds. Bus 4 is used for measurement monitoring. It is seen from Fig. 4, that proposed FDF detect the fault successfully.
2) Case 2:In this case, we considered the faults related to generator 2, connected at bus 7. At time t=2.5 second, an actuator fault occurred, which is detected by the proposed filter successfully as shown in Fig. 5.
Secondly sensor fault at generator 2 occurred at t=2.2 seconds and detected successfully as shown in Fig. 6
3) Case 3:In this case generator 3 connecting to bus 9 is considered, sensor fault occurred at t=2.5 second, which is detected successfully as shown in Fig. 7. Similarly, Fig. 8 effectiveness of FDF against three phase which remains for 0.5 second.

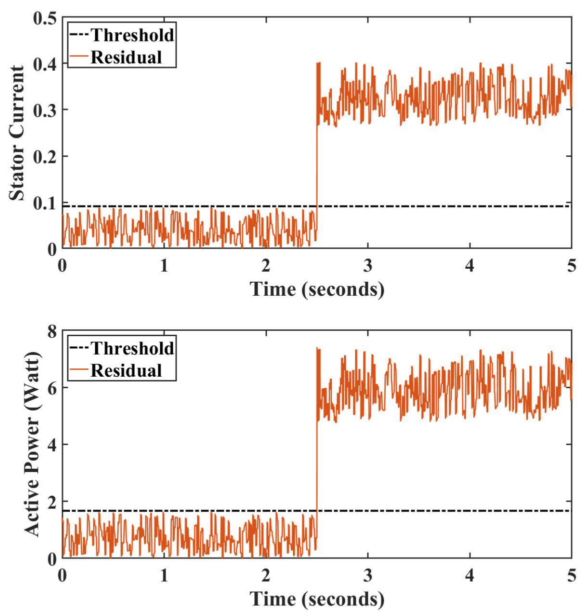

FIGURE 5. Actuator fault detection (Generator 2).

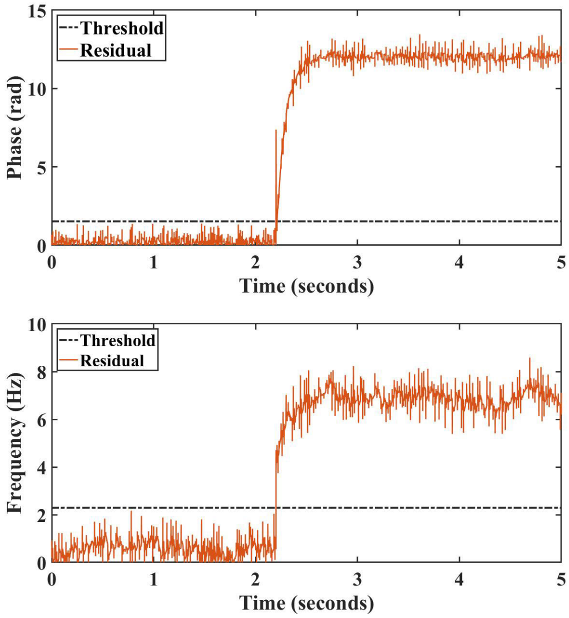

FIGURE 6. Sensor fault detection (Generator 2).

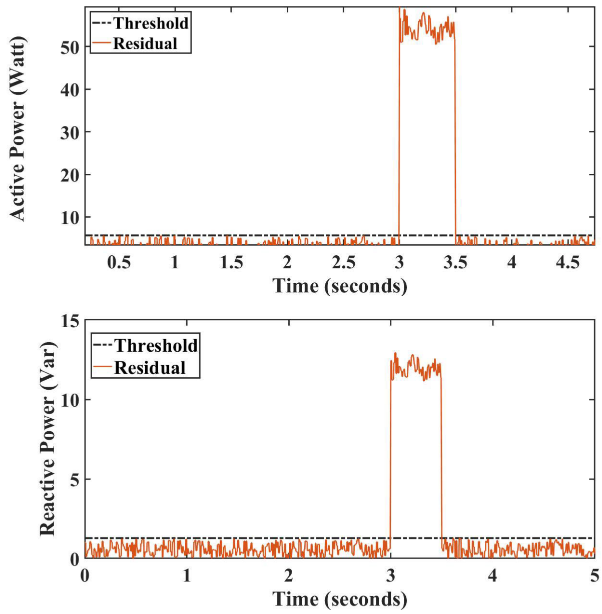

FIGURE 8. 3-phase fault detection (Generator 3).

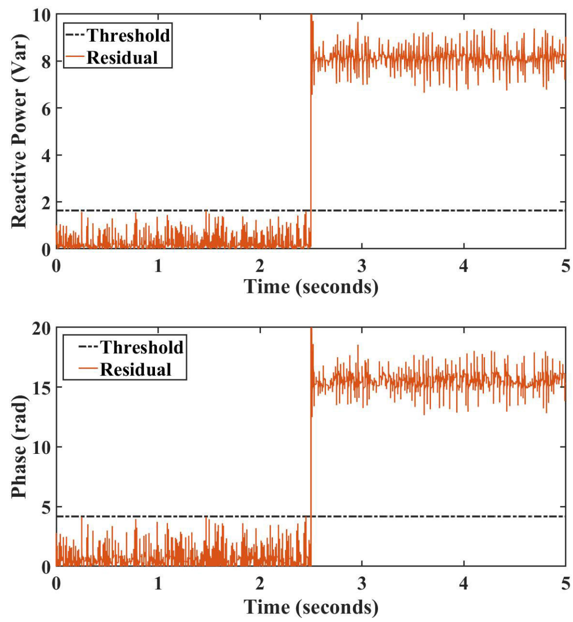

FIGURE 7. Sensor fault detection (Generator 3).

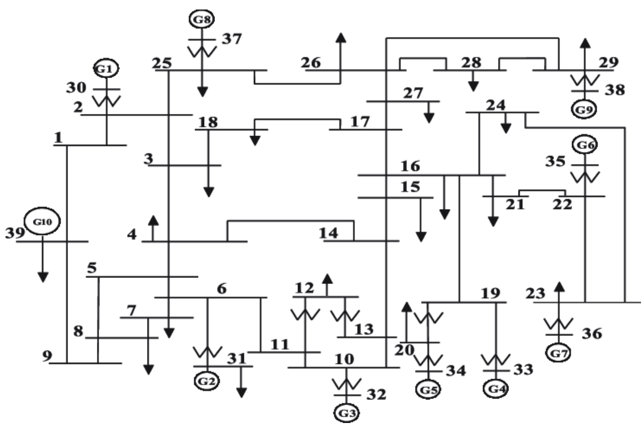

FIGURE 9. IEEE 39 Bus System.

4) Case 4:Now we considered IEEE-39 bus system as shown in fig. 9. Detail of which can be found in [33] and [34]. Sensor fault occurred at generator 7 connecting to bus 23 at t=3 seconds. Fig. 10 shows that proposed scheme successfully detects the sensor fault.
5) Case 5: In this case we considered the generator 4 connecting to bus 19 in IEEE 39 bus system. Three phase fault occurred at t=2 seconds and remains for 0.5 seconds. Fig. 11 shows that proposed scheme successfully detects that faults

It is clearly seen that proposed FD scheme precisely detect the fault in early stage even in the existence perturbation. Which is crucial for power system reliability and continuity of power supply.

Recently a work for anomaly of synchronous generators has been reported in [25]. In this work authors presented time varying observer-based anomaly detection scheme for power system monitoring. In this authors have to linearize the system which increase the computational burden while in our proposed scheme there is no need of linearization at each time step. Secondly they did not considered fault model and model uncertainties in their proposed work while we considered fault model and model uncertainties in this manuscript. Thirdly the scheme presented in this study is more sensitive towards faults as compared to scheme presented in [25] as shown in fig. 12. From simulation result it is clearly seen that for same magnitude and type of fault scheme proposed

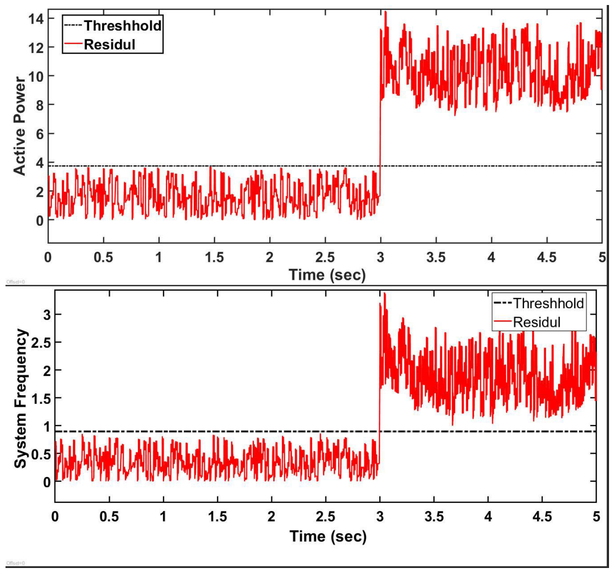

FIGURE 10. Sensor fault detection (Generator 7).

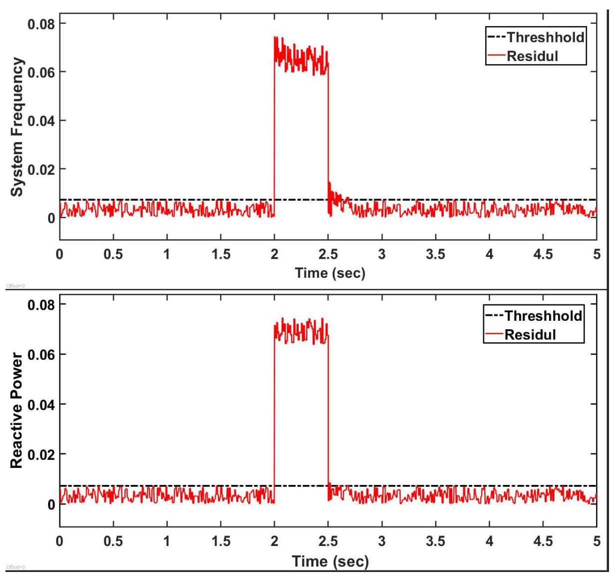

FIGURE 11. Three phase fault detection (Generator 4).

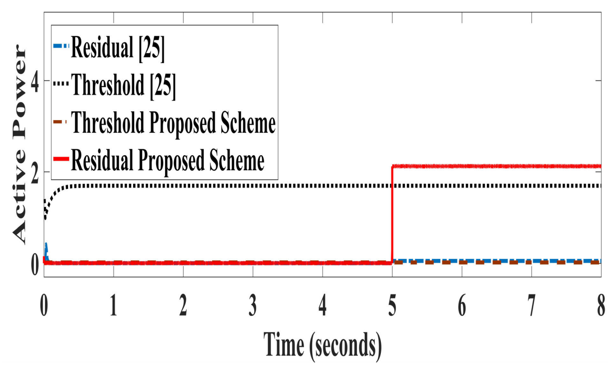

FIGURE 12. Comparison with [25] .

in this paper successfully detects the fault while the scheme presented in [25] is not able to detect the fault.

IV. CONCLUSION

In this paper, the design of an optimal FDF has been presented, which accurately detects the faults. A highly nonlinear model of a synchronous generator has been considered along with its equivalent Lipschitz model. Model uncertainties and disturbances both in state and measurements have been considered which makes our system to more resemble like a real system. To guarantee no false alarm norm-based threshold has been computed.

In future, presented work would be extended further considering the network effect such as time delay, communication failure, packet drop-out in the system. The effect of bounded uncertainties along with fault isolation will also be considered in future work.

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