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

MUHAMMAD ASIM SHOAIB, ABDUL QAYYUM KHAN, (Senior Member, IEEE), GHULAM MUSTAFA, (Senior Member, IEEE), OWAIS KHAN, NASIMULLAH, (Member, IEEE), MUHAMMAD ABID, MUHAMMAD ARIF, SUFI TABASSUM GUL, LUKAS PROKOP, VOJTECH BLAZEK, AND STANISLAV MISAK

1Department of Electrical Engineering, Pakistan Institute of Engineering and Applied Sciences, Islamabad 45650, Pakistan
2Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia
3ENET Center, VSB-Technical University of Ostrava, 70800 Ostrava, Czech Republic

Corresponding author: Muhammad Asim Shoaib (asim_930@yahoo.com)

This work was supported in part by the Higher Education Commission of Pakistan through Indigenous Grant; and in part by the Doctoral Grant competition VSB-Technical University of Ostrava, under Grant cz.02.2.69/0.0/0/19-073/0016945 within the Operational Programme Research, Development and Education "Partial Discharge Detection in Insulation Systems" under Project DGS/TEAM/2020-015 and the National Center of Energy, under Project TN01000007.

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 $\mathcal{H}_2/\mathcal{H}_\infty$ 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...
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

\[
\dot{x} = A_0x + \mathcal{T}(x, u) + B_0u + E_{do}d \\
y = F_{do}d + \mathcal{H}(x, u) + D_0u
\]

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. \(A_0, B_0, E_{do}\) are the state and input matrix respectively. \(\mathcal{T}(x, u)\) and \(\mathcal{H}(x, u)\) represents nonlinearities in state and output respectively.

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

\[
\mathcal{H}(\cdot) = -C_0x + \mathcal{H}(x, u)
\]

Since \(\mathcal{H}(\cdot)\) is Lipschitz locally having Lipschitz constant \(\eta_{m'f}\), from (2) it follows that \(\mathcal{H}(\cdot)\) is Lipschitz locally having Lipschitz constant \(\eta_m\) where

\[
\eta_m = \eta_{m'} + \|C_0\|_2.
\]

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 \(\mathcal{H}(\cdot)\) around operating point this results in to detectable pair of \((A_0, C_0)\), so (1) can be written as

\[
\dot{x} = A_0x + B_0u + \mathcal{T}(x, u) + E_{do}d \\
y = C_0x + D_0u + F_{do}d + \mathcal{H}(x, u)
\]

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

\[
\dot{x} = \tilde{A}x + \tilde{E}_{d}d + E_{f0f} + \tilde{B}u + \mathcal{T}(x, u) \\
y = \tilde{C}x + \tilde{D}u + \tilde{F}_{d}d + F_{f0f} + \mathcal{H}(x, u)
\]
f ∈ $R^d$ represents unknown faults. Where $E_{fo}$, $F_{fo}$ are known fault matrices. The matrices $\bar{A}$, $\bar{C}$, $\bar{B}$, $\bar{E}_d$, $\tilde{F}_d$ and $\tilde{F}_d$ are uncertain matrices and can be written as

$$\bar{A} = \delta A_0 + A_0, \quad \bar{C} = \delta C_0 + C_0, \quad \bar{B} = \delta B_0 + B_0, \quad \tilde{F}_d = F_{d0} + F_{d0}, \quad \tilde{E}_d = E_{d0} + E_{d0}$$

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

$$\begin{bmatrix} \delta A_0 & \delta B_0 & \delta E_{d0} \\ \delta C_0 & \delta D_0 & \delta F_{d0} \end{bmatrix} = \sum_{k=1}^{l} \omega_k \begin{bmatrix} A_{0k} & B_{0k} & E_{d0k} \\ C_{0k} & D_{0k} & F_{d0k} \end{bmatrix}$$

$$\sum_{k=1}^{l} \omega_k = 1, \quad \omega_k \geq 0$$

where the matrices $A_{0k}, B_{0k}, C_{0k}, D_{0k}, E_{d0k}$ and $F_{d0k}$, $\forall k = 1, 2 \ldots l$ are known and are of compatible dimensions [28], [29]. Lipschitz conditions for the functions $\mathcal{F}(\cdot)$ and $\mathcal{H}(\cdot)$ are given as

$$\| \mathcal{F}(x, u) - \mathcal{F}(\hat{x}, \hat{u}) \|_2 \leq \eta_{\mathcal{F}} \| x - \hat{x} \|_2$$

$$\| \mathcal{H}(x, u) - \mathcal{H}(\hat{x}, \hat{u}) \|_2 \leq \eta_{\mathcal{H}} \| x - \hat{x} \|_2$$

where $\eta_{\mathcal{F}}$ and $\eta_{\mathcal{H}}$ 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

$$\begin{align*}
\dot{x} &= A_0 \dot{x} + L(y - \dot{C}_0 \dot{x} - D_0 u - \mathcal{H}_1(\dot{x}, u)) + B_0 u \\
r &= (y - \hat{y})
\end{align*}$$

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

$$\begin{align*}
\dot{e} &= (A_0 - LC_0)e + (\tilde{E}_d - L\tilde{F}_d)d + (B_0i - LD_0i) \\
&+ L(\mathcal{H}_1(x, u) - \mathcal{H}_1(\hat{x}, \hat{u})) + (E_{fo} - LF_{fo})f \\
&+ (A_0 - LC_0)x + \mathcal{F}(x, u) - \mathcal{F}(\hat{x}, \hat{u}) \\
r &= C_0 e + C_0ix + D_0 u + \tilde{F}_d d + F_{fo}f \\
&+ (\mathcal{H}_1(x, u) - \mathcal{H}_1(\hat{x}, \hat{u}))
\end{align*}$$

(6)

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

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

where

$$\begin{align*}
e_0 &= \begin{bmatrix} x \\ e \end{bmatrix}, \\
d_0 &= \begin{bmatrix} u \\ d \end{bmatrix}, \\
\phi_N &= \begin{bmatrix} \mathcal{F}(x, u) - \mathcal{F}(\hat{x}, \hat{u}) \end{bmatrix} \\
A_N &= \bar{A} - \bar{L} \bar{C}, \\
E_N &= \bar{E}_d - \bar{L} \bar{F}_d, \\
C_N &= \bar{C}, \\
F_N &= \bar{F}_d, \\
\phi_2 &= (\mathcal{H}_1(x, u) - \mathcal{H}_1(\hat{x}, \hat{u}))
\end{align*}$$

**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 $\mathcal{H}_- / \mathcal{H}_{\infty}$ is minimized. The $\mathcal{H}_- / \mathcal{H}_{\infty}$ performance index is defined as

$$\| r \|_2 \leq \beta \| d \|_2$$

$$\| r \|_2 \geq \gamma \| f \|_2$$

where $\beta$ is the attenuation level of the disturbance and $\gamma$ 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 $\mathcal{H}_- / \mathcal{H}_{\infty}$ 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 $\lambda_k$ ($k = 1, 2, 3 \ldots 10, 31, 41$), then the observer gain $L$ can be computed by solving the following optimization problem:

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

subject to (4), (6) and

$$\begin{bmatrix}
u_1 & P_k \dot{E}_d - Y_k \dot{F}_d + \tilde{C}_T \dot{F}_d & P_k & P_k \\
\nu_2 & \lambda_{41} \dot{F}_d^T \dot{F}_d - \beta^2 I & 0 & 0 \\
P_k & 0 & -\lambda_7 I & 0 \\
0 & 0 & -\lambda_8 & 0
\end{bmatrix} \leq 0$$

$$\begin{bmatrix}
u_1 \dot{Q}_k \dot{E}_f - Y_k \dot{F}_f - \tilde{C}_T \dot{F}_f & Q_k \\
\nu_2 & -\lambda_6 \dot{F}_f^T \dot{F}_f + \gamma^2 I & 0 & 0 \\
Q_k & 0 & -\lambda_7 I & 0 \\
Q_k & 0 & 0 & -\lambda_8
\end{bmatrix} \leq 0$$

subject to (10) and (11)

where

$$\begin{align*}
\nu_1 &= \dot{A}^T P_k + P \dot{A} - \tilde{C} \tilde{Y}_k^T - \dot{Y}_k \tilde{C} + S \eta_{\mathcal{H}}^2 + \lambda_3 \eta_{\mathcal{H}}^2 \\
&+ \lambda_4 \eta_{\mathcal{H}}^2 \tilde{C} + \gamma^2 \eta_{\mathcal{H}}^2 \\
\nu_2 &= \dot{A}^T Q_k + Q_k \dot{A} - \tilde{C} \tilde{Y}_k^T - \dot{Y}_k \tilde{C} + S \eta_{\mathcal{H}}^2 - \lambda_9 \eta_{\mathcal{H}}^2 \\
&- \lambda_1 \eta_{\mathcal{H}}^2 \tilde{C} + \gamma^2 \eta_{\mathcal{H}}^2 \\
\nu_2 &= \dot{E}_d^T \ddot{C} + E_d^T P_i - \dot{E}_d^T Y_i, \quad \nu_{22} = -F_{fo} \dot{C} + E_f Q_i \\
&- F_{fo} Y_i^T
\end{align*}$$

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

130534
The gain of proposed FDF will be calculated as

\[ \tilde{L} = \tilde{P}^{-1} \tilde{Y}, \quad \tilde{Y} = \sum_{k=1}^{l} w_k Y_k, \quad \tilde{P} = \sum_{k=1}^{l} w_k P_k \quad (12) \]

**Proof:**
Consider the dynamics of the residual generator in (7)

\[ \begin{align*}
    &d_0 = A_N e_N + \phi_N + E_N d_0 + E_N f f + L \phi_2 \\
    &r = C_N e_0 + F_N d_0 + F_N f f + \phi_2
\end{align*} \quad (13) \]

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

\[ \dot{e}_0 = \dot{e}_d + \dot{e}_f \quad (14) \]

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

\[ \begin{align*}
    &\dot{e}_d = A_N e_d + \phi_{Nd} + E_N d + L \phi_{2d} \\
    &r_d = C_N e_d + F_N d + \phi_{2d} \\
    &\dot{e}_f = A_N e_f + \phi_{Nf} + E_N f f + L \phi_{2f} \\
    &r_f = C_N e_f + F_N f f + \phi_{2f}
\end{align*} \quad (15) \]

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

\[ V = e_d^T P_k e_d, \quad P_k = \begin{bmatrix} P_{1k} & 0 \\ 0 & P_{2k} \end{bmatrix} > 0 \]

Differentiating the Lyapunov function along the residual generator (15)

\[ \dot{V} = e_d^T (A_N^T P_k + \overline{P_k A_N}) e_d + e_d^T P_k E_N d + d^T E_N^T P_k e_d + \phi_{Nd}^T P_k e_d + e_d^T P_k \phi_{Nd} + \phi_{2d}^T L T_1 \phi_{2d} + e_d^T \phi_{2d} \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]

\[ \]
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}
u_1 & P_k E_d - Y_k F_{d0} + \tilde{C}^T F_{d0} & P_k & P_k \\

\nu_2 & \lambda_{d1} E_d - \beta^2 I & 0 & 0 \\
P_k & 0 & -\lambda_{d1} I & 0 \\
P_k & 0 & 0 & -\lambda_{d2}
\end{bmatrix}
\leq 0 \quad (27)
\]

In a similar way the subsystem (16) internal stability can be prove. Consider the Lyapunov function
\[
\mathcal{V} = \phi^T e t \phi f, Q_k = \begin{bmatrix} Q_{ik} & 0 & 0 \\

0 & Q_{ik} & 0 \\
0 & 0 & Q_{ik}
\end{bmatrix} > 0 \quad (28)
\]

Now consider the performance index (9). Working on similar lines as above this will yield (11)
\[
\begin{bmatrix}
u_2 & Q_k E_f - Y_k F_{f0} - \tilde{C}^T F_{f0} & Q_k & Q_k \\

\nu_2 & -\lambda_{d} F_{f} + \gamma^2 I & 0 & 0 \\
Q_k & 0 & -\lambda_{d1} I & 0 \\
Q_k & 0 & 0 & -\lambda_{d2}
\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 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 & D_r & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{T_d0} & 0 & \frac{1}{T_d0} \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix} \quad (31)
\]
\[
B_o = \begin{bmatrix} 0 & 0 & 0 & 0 & w_g \\

\frac{T_m}{M} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix} \quad (32)
\]

where \( w_B, D_r, M, T_d0, T_d0, T_A, T_m, \) 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 \( \mathcal{F}(x, u) = [\mathcal{F}_1(x, u) \mathcal{F}_2(x, u) \mathcal{F}_3(x, u) \mathcal{F}_4(x, u) \mathcal{F}_5(x, u)] \) is written as follows.
\[
\mathcal{F}_1(x, u) = 0, \quad \mathcal{F}_2(x, u) = \frac{-T_e}{M}, \quad \mathcal{F}_3(x, u) = \frac{1}{T_d0}(X_{d} i_d - X_{q} i_d) \\
\mathcal{F}_4(x, u) = \frac{1}{T_d0}(-X_{q} i_q + X_{d} i_q), \quad \mathcal{F}_5(x, u) = \frac{1}{T_A} [K_A (-V_t)]
\]

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).

FIGURE 5. Actuator fault detection (Generator 2).

The effectiveness of proposed filter is demonstrated through IEEE 9-bus system as shown in Fig. 2. Perturbations are modeled as \( F_d = \bar{D} \) and \( E_d = \bar{B} \). Sensor faults are modeled as \( F_f = 0 \) and \( F_f = 1 \), 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. Similarly, Fig. 8 effectiveness of FDF against three phase which remains for 0.5 second.

3) Case 3: In this case generator 3 connecting to bus 9 is considered, sensor fault occurred at \( t = 2.2 \) seconds and detected successfully as shown in Fig. 6.
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 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
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 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.

REFERENCES

[1] Y. Wei, J. Qiu, and H. R. Karimi, “Notice of violation of IEEE publication principles: Reliable output feedback control of discrete-time fuzzy affine systems with actuator faults,” IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 64, no. 1, pp. 170–181, Jan. 2017.

[2] M. T. Raza, A. Q. Khan, G. Mustafa, and M. Abid, “Design of fault detection and isolation filter for switched control systems under asynchronous switching,” IEEE Trans. Control Syst. Technol., vol. 24, no. 1, pp. 13–23, Jan. 2016.

[3] R. Javed, G. Mustafa, A. Q. Khan, and M. Abid, “Networked control of a power system: A non-uniform sampling approach,” Electr. Power Syst. Res., vol. 161, pp. 224–235, Aug. 2018.

[4] J. Zhao, G. Zhang, K. Das, G. N. Korres, N. M. Manousakis, A. K. Sinha, and Z. He, “Power system real-time monitoring by using PMU-based robust state estimation method,” IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 300–309, Jan. 2016.

[5] P. Zhang, F. Li, and N. Bhatt, “Next-generation monitoring, analysis, and control for the future smart control center,” IEEE Trans. Smart Grid, vol. 1, no. 2, pp. 186–192, Sep. 2010.

[6] J. Zhao and L. Milic, “A decentralized H-infinity unscented Kalman filter for dynamic state estimation against uncertainties,” IEEE Trans. Smart Grid, vol. 10, no. 5, pp. 4870–4880, Sep. 2018.

[7] B. M. Ebrahimi, M. J. Roshkhar, J. Faiz, and S. V. Khatami, “Advanced eccentricity fault recognition in permanent magnet synchronous motors using stator current signature analysis,” IEEE Trans. Ind. Electron., vol. 61, no. 4, pp. 2041–2052, Apr. 2014.

[8] N. Yadaiah and N. Ravi, “Fault detection in synchronous generators based on independent component analysis,” in Proc. Int. Conf. Frontiers Intell. Comput., Theory Appl. (FICTA). Cham, Switzerland: Springer, 2013, pp. 285–292.

[9] R. Gopinath, C. S. Kumar, and K. Ramachandran, “Scalable fault models for diagnosis of synchronous generators,” Int. J. Intell. Syst. Technol. Appl., vol. 15, no. 1, pp. 35–51, 2016.

[10] I. Hwang, S. Kim, Y. Kim, and C. E. Sear, “A survey of fault detection, isolation, and reconfiguration methods,” IEEE Trans. Control Syst. Technol., vol. 18, no. 3, pp. 636–653, May 2010.

[11] J. Zhang, W. Ma, J. Lin, L. Ma, and X. Jia, “Fault diagnosis approach for rotating machinery based on dynamic model and computational intelligence,” Measurement, vol. 59, pp. 73–87, Aug. 2015.

[12] S. Yin, X. Zhu, and O. Kaynak, “Improved PLS focused on key-performance-indicator-related fault diagnosis,” IEEE Trans. Ind. Electron., vol. 62, no. 3, pp. 1651–1658, Mar. 2015.

[13] M. F. Tariq, A. Q. Khan, M. Abid, and G. Mustafa, “Data-driven robust fault detection and isolation of three-phase induction motor,” IEEE Trans. Ind. Electron., vol. 66, no. 6, pp. 4707–4715, Jun. 2019.

[14] H. Ehya, A. Nysveen, and J. A. Antonino-Daviu, “Advanced fault detection of synchronous generators using stray magnetic field,” IEEE Trans. Ind. Electron., vol. 69, no. 11, pp. 11675–11685, Nov. 2022.

[15] M. Mostafaei and J. Faiz, “An overview of various faults detection methods in synchronous generators,” IET Electr. Power Appl., vol. 15, no. 4, pp. 391–404, 2021.

[16] Y. Tan, H. Zhang, and Y. Zhou, “Fault detection method for permanent magnet synchronous generator wind energy converters using correlation features among three-phase currents,” J. Mod. Power Syst. Clean Energy, vol. 8, no. 1, pp. 168–178, 2020.
S. R. Prasad and M. G. Naik, “Unit commitment using particle swarm optimization,” in IEEE Access, vol. 9, pp. 163697–163706, 2021.

A. Ali, A. Q. Khan, B. Hussain, M. T. Raza, and M. Arif, “Fault modelling and detection in power generation, transmission and distribution systems,” IEE Gener. Transmiss. Distrib., vol. 9, no. 16, pp. 2782–2791, Dec. 2015.

S. M. Hashemi, M. Sanaye-Pasand, and M. Shahidehpour, “Fault detection during power swings using the properties of fundamental frequency phasors,” IEEE Trans. Smart Grid, vol. 10, no. 2, pp. 1385–1394, Mar. 2019.

E. Bernardi and E. J. Adam, “Observer-based fault detection and diagnosis strategy for industrial processes,” J. Franklin Inst., vol. 357, no. 14, pp. 10054–10081, 2020.

P. Jain, L. Jian, J. Poon, C. Spanos, S. R. Sanders, J.-X. Xu, and S. K. Panda, “A Luenberger observer-based fault detection and identification scheme for photovoltaic DC–DC converters,” in Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc., Oct. 2017, pp. 5015–5020.

Y. Hu, J. Zhang, S. Xu, and J. Hang, “Extended state observer based fault detection and location method for modular multilevel converters,” in Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc., Oct. 2016, pp. 2166–2171.

A. Doorwar, B. Bhalja, and O. P. Malik, “A new internal fault detection and classification technique for synchronous generator,” IEEE Trans. Power Del., vol. 34, no. 2, pp. 739–749, Apr. 2019.

M. Aldien and F. Crusca, “Observer-based fault detection and identification scheme for power systems,” IEEE Proc.-Gener. Transmiss. Distrib., vol. 153, no. 1, pp. 71–79, Jan. 2006.

G. Anagnostou, F. Boem, S. Kuenzel, B. C. Pal, and T. Parisini, “Observer-based anomaly detection of synchronous generators for power systems monitoring,” IEEE Trans. Power Syst., vol. 33, no. 4, pp. 4226–4237, Jul. 2018.

M. A. Shoaib, A. Q. Khan, G. Mustafa, S. T. Gul, O. Khan, and A. S. Khan, “A framework for observer-based robust fault detection in nonlinear systems with application to synchronous generators in power systems,” IEEE Trans. Power Syst., vol. 37, no. 2, pp. 1044–1053, Mar. 2022.

S. A. Nugroho, A. F. Taha, and J. Qi, “Robust dynamic state estimation of synchronous machines with asymptotic state estimation error performance guarantees,” IEEE Trans. Power Syst., vol. 35, no. 3, pp. 1923–1935, May 2020.

O. Khan, G. Mustafa, A. Q. Khan, and M. Abid, “Robust observer-based model predictive control of non-uniformly sampled systems,” ISA Trans., vol. 98, pp. 37–46, Mar. 2020.

O. Khan, G. Mustafa, A. Q. Khan, M. Abid, and M. Ali, “Fault-tolerant robust model-predictive control of uncertain time-delay systems subject to disturbances,” IEEE Trans. Ind. Electron., vol. 68, no. 11, pp. 11400–11408, Nov. 2021.

S. A. Nugroho, A. F. Taha, and J. Qi, “Characterizing the nonlinearity of power system generator models,” in Proc. Amer. Control Conf. (ACC), Jul. 2019, pp. 1936–1941.

A. Q. Khan and S. X. Ding, “Threshold computation for fault detection in a class of discrete-time nonlinear systems,” Int. J. Adapt. Control Signal Process., vol. 25, no. 5, pp. 407–429, 2011.

A. Q. Khan and S. X. Ding, “Threshold computation for robust fault detection in a class of continuous-time nonlinear systems,” in Proc. Eur. Control Conf. (ECC), Aug. 2009, pp. 3088–3093.

S. R. Prasad and M. G. Naik, “Unit commitment using particle swarm optimization on IEEE 39 bus system,” in Proc. 4th Int. Conf. Recent Trends Comput. Sci. Technol. (ICRT CST), Feb. 2022, pp. 273–277.

P. Demetriou, M. Asproi, J. Quiroz-Tortos, and E. Kyriakides, “Dynamic IEEE test systems for transient analysis,” IEEE Syst. J., vol. 11, no. 4, pp. 2108–2117, Dec. 2015.

MUHAMMAD ASIM SHOAIB received the B.Sc. degree in electrical engineering from Bahauddin Zakariya University, Multan, Pakistan, in 2001, and the M.Sc. degree in electrical engineering with specialization in power systems from the University of Engineering and Technology, Taxila, Pakistan, in 2015. He is currently pursuing the Ph.D. degree in electrical engineering program with the Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad, Pakistan. His research interests include fault diagnosis of power systems, optimization, artificial intelligence, state estimation, and design of a robust fault detection filter for uncertain nonlinear systems.

ABDUL QAYYUM KHAN (Senior Member, IEEE) received the B.Sc. degree (Hons.) in electrical engineering from the University of Engineering and Technology (UET), Peshawar, Pakistan, in 2001, the M.Sc. degree in systems engineering from the Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad, Pakistan, in 2004, and the Ph.D. degree in electrical engineering from the University of Duisburg-Essen, Duisburg, Germany, in 2010. He is currently a Professor and the Head of the Department of Electrical Engineering, PIEAS. His research interests include fault diagnosis in technical processes, linear and nonlinear observer design, robust control of nonlinear systems, and LMI based optimal design. He was the Chair of the Technical Committee of the IEEE International Conference on Recent Advances in Electrical Engineering, in 2015, 2017, 2018, and 2019, and the IEEE International Conference on Emerging Technologies, in 2016. He is the Chair of the IEEE Control System Society Karachi-Lahore-Islamabad Joint Chapter.

GHULAM MUSTAFA (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the University of Engineering and Technology (UET), Lahore, Pakistan, in 2002, the M.Sc. degree in systems engineering from the Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad, Pakistan, in 2004, and the Ph.D. degree in control systems from the University of Alberta, Edmonton, AB, Canada, in 2012. He is currently a Professor with the Department of Electrical Engineering (DEE), PIEAS. His current research interests include sampled-data control, robust control, and networked control systems and applications. He is also a Life Member of the Pakistan Engineering Council and the Golden Key International Honors Society and the Chair of the IEEE Control Systems Society’s Lahore-Karachi-Islamabad Joint Chapter.

OWAIS KHAN received the B.Sc. degree in electronics engineering from the University of Engineering and Technology (UET), Peshawar, Pakistan, in 2011, the M.Sc. degree in electrical engineering with specialization in control systems from COMSATS University, Islamabad, Pakistan, in 2016, and the Ph.D. degree in electrical engineering with specialization in control systems from the Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad, Pakistan, in 2020. His research interests include robust model predictive control, fault diagnosis, LMI-based optimal control, state estimation, and design of a robust controller for uncertain systems.

NASIMULLAH (Member, IEEE) received the Ph.D. degree in mechatronics engineering from Beihang University, Beijing, China, in 2013. From September 2006 to September 2010, he was a Senior Design Engineer with the Institute of Industrial Control Systems (ICS), Pakistan. He is currently working as a Full Professor of electrical engineering with Taif University, Saudi Arabia. His research interests include renewable energy, flight control systems, integer and fractional order modeling of dynamic systems, integer/fractional order adaptive robust control methods, fuzzy/NN, hydraulic and electrical servos, and epidemic and vaccination control strategies.
MUHAMMAD ABID received the M.Sc. degree in systems engineering from the Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad, Pakistan, in 2004, and the Ph.D. degree in electrical engineering from the Institute of Automatic Control and Complex Systems, University of Duisburg–Essen, Duisburg, Germany, in 2010. He is currently an Associate Professor with PIEAS. His research interests include model-based fault detection in nonlinear systems and robust and optimal control.

MUHAMMAD ARIF received the B.S. degree in electrical power engineering from the University of Engineering and Technology (UET), Lahore, Pakistan, the M.S. degree in systems engineering from Quaid-i-Azam University (QAU), Pakistan, and the Ph.D. degree in control systems from the Huazhong University of Science and Technology (HUST), China. He is currently an Associate Professor with the Department of Electrical Engineering, Pakistan Institute of Engineering and Applied Sciences, Islamabad, Pakistan. His research interest includes renewable energy resources.

SUFI TABASSUM GUL received the B.Sc. degree (Hons.) in electrical engineering from the University of Engineering and Technology (UET), Taxila, Pakistan, in 1999, the M.Sc. degree (Hons.) in systems engineering from the Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad, Pakistan, in 2001, the master’s degree in STIC embedded systems (M2R) from the Ecole Polytechnique de l’Université de Nice-Sophia Antipolis, Biot, France, in 2006, and the Ph.D. degree (Hons.) in electrical engineering with specialization in signal processing and telecommunications from the École Supérieure d’Électricité (Supéléc)/Université de Rennes-I, Rennes, France, in 2009. He is currently an Associate Professor with the Department of Electrical Engineering (DEE), PIEAS. His research interests include fault detection and classification, cognitive or software-defined radios, and signal processing.

LUKAS PROKOP received the Ing. degree in electrical power engineering from the Faculty of Electrical Engineering and Communication, Brno University of Technology. He is currently an Associate Professor with the Faculty of Electrical Engineering and Computer Science, VSB-Technical University of Ostrava. He is also engaged in renewable energy sources, modern technologies, and methods in electrical power engineering and electrical measurements. He is a research team member of the Czech and international research projects. He serves as the Deputy Head of the ENET Research Center.

VOJTECH BLAZEK was born in Czech Republic, in 1991. He received the Ing. degree from the Department of Electrical Engineering, VSB-Technical University of Ostrava, in 2016, where he is currently pursuing the internal Ph.D. degree. He is also a Junior Researcher with the ENET-Research Centre of Energy Units for Utilization of Non-Traditional Energy Sources, VSB-Technical University of Ostrava. His current research interest includes developing modern and green technologies in off-grid systems with vehicle to home technologies.

STANISLAV MISAK was born in Czech Republic, in 1978. He received the Ing. and Ph.D. degrees from the Department of Electrical Engineering, VSB-Technical University of Ostrava, in 2003 and 2007, respectively. He is currently a Professor and the CEO of the ENET Research Centre and the Centre for Energy and Environmental Technologies, VSB-Technical University of Ostrava. He holds a patent for a fault detector for medium voltage power lines. His current research interest includes implementation of smart grid technologies using prediction models and bio-inspired methods.

* * *