Fault Tolerant Control of Sensor Faults in Microgrid Inverter Control System

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Abstract. Aiming at sensor drift fault, the design problem of active fault tolerant controller for island-AC microgrid inverter system is studied. The controller has good ability to suppress external finite energy disturbance. Firstly, a closed-loop system state space model is constructed for an isolated AC microgrid inverter system with external finite energy disturbance. Then, when the sensor fault occurs in the control system, the fault information is taken as an auxiliary state vector, and the estimated value of the sensor fault and the system state variable is obtained simultaneously through the proposed extended observer. A fault tolerant controller is designed based on the idea of fault compensation. Finally, the correctness and effectiveness of this method are verified by programming simulation in MATLAB.

1. Introduction
Microgrids utilize many power electronics technologies to form independent systems [1]. It is a power generation form that organically combines various distributed generation (DG), loads, energy storage devices and protection systems [2,3]. Distributed microgrids can operate in connection with large power grids. At the same time, voltage control can also be carried out on the inverter system to achieve island operation [4]. Therefore, taking effective control strategy to ensure the stability of the inverter system is one of the key issues to realize the stable operation of distributed microgrid. Taking LCL inverter system as the control object is a research hotspot in the field of microgrid in recent years.

Due to the complex operating conditions of distributed microgrid, the traditional PID voltage control strategy cannot ensure the robustness of control performance [5]. A large proportion high frequency resonant signal controller was adopted [6]. Although the system controlling the orthogonal cosine model signal successfully realized the system without high frequency static disturbance tracking, the anti-disturbance ability of the control model was affected. The studied a new adaptive high voltage sliding mode AC voltage fluctuation control strategy, which successfully realized the global sliding mode voltage fluctuation and robust control performance of high voltage inverter circuit system under the operation of high voltage island circuit [7]. The studies an adaptive sliding mode voltage control strategy, which achieves the global voltage robustness of the inverter system under island-based operation [8].

However, the actual system is often subject to external disturbances such as environment, magnetic field and power grid fluctuations. Internal components often fail, such as actuator failure, sensor failure, etc. Therefore, in the design of control system, it is very important to study how to maintain stability and superior control performance of the system when failure occurs. Fault-tolerant control system and actuator faults have been concerned by many scholars, but the research on sensor faults is relatively few. In the aspect of designing observer to estimate sensor faults, the literature respectively studied the design problems of several kinds of observer to detect fault information [9]. In the aspect of fault-tolerant design based on fault signals, literature mainly studied several design problems of fault-tolerant controllers based on detected fault information. The problem is even more complicated when the system is affected by external finite energy perturbations, in which case the description of microgrid control has been little explored.

To sum up, this article in view of the island mode the topology of the micro grid inverter system, establish a set of sensor drift fault with the outside world limited energy disturbance in the integration
of the closed loop output feedback state space description, in order to on-line real-time estimation of sensor fault information, design the expansion/fault observer, the fault information is estimated based on the fault observer design based on the fault compensation of fault-tolerant controller in order to ensure the stability of the inverter control system and the disturbance suppression.

2. Problem description

2.1. Main circuit topology of island-based inverter system
The main circuit topology of island-AC microgrid inverter system is shown in Figure 1. The inverter includes a DC input voltage source $U_{dc}$, a fully controlled power device IGBT, an impedance existing in the transmission line, a tiny resistance owned by the switching device and a low-pass filter LCL. $U_{dc}$ is the DC power supply in the microgrid inverter system, including photovoltaic, wind power and other renewable energy; The series resistance of each switching device in the system is equivalent $R_1$. There is also resistance in the process of electric energy from inverter output to AC bus. These low-voltage resistances are equivalent $R_2$. The resistance on the filter LCL in series with the capacitor is $R$. $i_1$ is the current through the inductor $L_1$, $i_2$ is the current through the inductor is $L_2$.

![Figure 1. Main circuit topology of island AC microgrid inverter system.](image)

2.2 Fault model of island inverter
According to the islands of the structure of ac microgrid inverter system topology, assumes that the system is the ideal condition and stable operation, the switching loss and transmission lines in power loss into account, the Clarke transform to eliminate the common mode of three phase, by Kirchoff voltage law, current available island exchange LCL type micro grid inverter of third order mathematical model of continuous.

$$
\begin{align*}
L_1 \frac{di_1}{dt} &= U_0 - u_c - R(i_1 - i_2) - R_1 i_1 \\
L_2 \frac{di_2}{dt} &= u_c + R(i_1 - i_2) - R_2 i_2 \\
C \frac{du_c}{dt} &= i_1 - i_2
\end{align*}
$$

(1)

Where, the current flowing over the inductor $L_1$ is $i_1$; the current flowing over the inductor $L_2$ is $i_2$; the AC voltage through the inverter output is $U_0$; the voltage at both ends of capacitor $C$ is $u_c$. Next, define the state variable as $x(t) = [i_1, i_2, u_c]^{T}$, in this way, the state space expression of the microgrid inverter system can be obtained as follows:
In the actual power system operation, it is often affected by some interference information from outside or inside the system, which affects the normal operation of the system. Therefore, considering that the island-AC microgrid inverter system is disturbed by external finite energy, when the internal sensor fails, the closed-loop model of the system is as follows:

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) + Bw(t) \\
.y(t) &= Cx(t) + Rf(t) \\
\end{align*}
\]

Where, \( A = \begin{bmatrix} -\frac{R+R_1}{L_1} & \frac{R}{L_2} & -\frac{1}{L_4} \\ \frac{R}{L_2} & -\frac{R+R_2}{L_2} & \frac{1}{L_4} \\ \frac{1}{C} & -\frac{1}{C} & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L_4} & 0 & 0 \\ 0 & -\frac{1}{L_2} & 0 \end{bmatrix}, C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, u(t) = \begin{bmatrix} U_0 \\ 0 \end{bmatrix}. \)

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\]

Where, the vector matrix is \( R \) assigned to the fault position on the sensor, \( R=[r_1, r_2, r_3] \), \( f(t) \) represents the fault assignment vector of an unknown point on the sensor, \( f(t) = [f_1(t), f_2(t), f_3(t)]^T \). \( f_1(t) \) indicates that the fault occurred on the sensor that detects the current \( i_1 \), \( f_2(t) \) indicates that the fault occurred on the sensor that detects the current \( i_2 \), \( f_3(t) \) indicates that the fault occurs on the sensor that detects voltage \( U_{in} \). The sensor faults studied in this paper are mainly sensor drift faults, the expression form is \( y_{out} = ky_{in} \) (\( k \) is constant), \( w(t) \) is a finite disturbance of external energy, satisfy the \( \|w(t)\| \leq \beta, \beta > 0 \). The fault estimation and fault-tolerant control system of microgrid sensor designed in this paper is shown in Figure 2.

**Figure 2.** Diagram of a fault estimation and fault tolerant control system using an extended observer.

### 3. Design an extended fault estimation observer

In this paper, the estimated value of the system state variable is obtained together with the fault signal of the sensor failure, so the sensor fault can be regarded as an auxiliary variable of the system state variable, that is, the following definitions are made \( x_i(t) = Rf(t), \bar{x} = [x^T(t) \ x^T_i(t)]^T \), then the closed-loop state space model of the microgrid with sensor failure described in Equation (3) can be transformed into the following system:

\[
\begin{align*}
E\ddot{x}(t) &= \bar{A}\bar{x}(t) + \bar{B}u(t) + \bar{B}w(t) \\
y_f(t) &= \bar{C}\bar{x}(t) \\
\end{align*}
\]
Where, \( E = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, A = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} B \\ 0 \end{bmatrix}, C = [C \ I] \).

For the extended system (4) and (5), the state observer is constructed as follows:

\[
\dot{\zeta} = (\overline{A} - L_p \overline{C})(E + L_D \overline{C})^{-1}(\zeta + L_D y_f) + \overline{B} u + L_p y_f
\]

\[
\dot{\hat{x}} = (E + L_D \overline{C})^{-1}(\zeta + L_D y_f)
\]

In the above equation, \( \zeta \) is the auxiliary vector of the state variable, and the estimated value of the state variable in the extended system represented by equation (4) is used for representation. The proportional gain matrix of the extended observer is defined as \( L_p \), and the differential gain matrix of the fault-tolerant controller is defined as \( L_D \). It is easy to find that the failure observer designed according to the above method does not directly appear the differential term output \( y_f \) in the original system, which means that the designed observer is easier to realize in engineering practice. Note: In order to simplify writing, all the vectors about \( t \) in the formula are abbreviated in the following section. For example, write \( x(t) \) as \( x \). By adding \( L_D y_f \) and \( L_p y_f \) sum to both sides of the equal sign of equation (4), it can be rewritten as follows:

\[
(E + L_D \overline{C})\hat{x} = (\overline{A} - L_p \overline{C})\hat{x} + \overline{B} u + \overline{B} w + L_D y_f + L_p y_f
\]

According to equation (7), it can be obtained \( \zeta = (E + L_D \overline{C})\hat{x} - L_D y_f \), substituting it into equation (6), the following equation can be obtained:

\[
(E + L_D \overline{C})\hat{x} = (\overline{A} - L_p \overline{C})\hat{x} + \overline{B} u + L_D y_f + L_p y_f
\]

The observer state estimation error is defined as \( \hat{e} = \hat{x} - x \), the state estimation error in the original system is \( e \), sensor fault estimation error is \( \hat{e}_s \). Make \( S = (E + L_D \overline{C}) \), the dynamic error equation can be obtained by subtracting Equation (9) from Equation (8) as follows:

\[
\dot{e} = S^{-1}(\overline{A} - L_p \overline{C})e + S^{-1}\overline{B} w
\]

The observer is designed to make the estimated errors \( e \) robust to finite energy perturbations \( w \), and then to estimate the state and fault information of the system. Based on the above analysis, the \( H_\infty \) performance indicators are defined as follows:

\[
\|e\|^2 = \int_0^\infty (e^T e)d\tau < \gamma^2 \int_0^\infty (w^T w)d\tau = \gamma^2 \|w\|^2, \gamma > 0
\]

In order to make the estimated error satisfy the performance index, theorem 1 is given.

Theorem 1: is defined as a positive definite matrix, \( P_i \) is an arbitrary matrix, \( Q_i \) is a normal number, if they exist and satisfy the LMI described in equation (12):

\[
\begin{bmatrix}
\Pi & P_i S^{-1} \overline{B} \\
\overline{B}^T S^{-1} P_i & -\gamma^2 I
\end{bmatrix} < 0
\]

Where, \( \Pi = \overline{A}^T S^{-1} P_i + P_i S^{-1} \overline{A} - \overline{C}^T Q_i^{-1} \overline{C} + I \). In this way, the dynamic equation of fault estimation error (10) can satisfy the \( H_\infty \) performance indicators. In this way, the designed differential gain matrix \( L_D \) and proportional gain matrix \( L_p \) can be calculated as follows:

\[
L_D = [0_{3 \times 1} \ H]^T, \quad L_p = S P_i^{-1} Q_i
\]

\( H \) can be any nonsingular matrix. In order to facilitate calculation, it is chosen as the identity matrix. Proof: Lyapunov equation is chosen as the following form:

\[
V_i = e^T P_i e
\]
Derivation of Lyapunov equation in equation (14):
\[ V = e^T \left[ A^T S^{-T} P_1 + P_1 S^{-1} A - C^T Q^T C - QC - \sigma e^T P_1 S^{-1} B \right] e + 2 e^T P_1 S^{-1} B w \] (15)

In order to satisfy the \( H_{\infty} \) performance indicators expressed in equation (11), the following inequality must be true:
\[ \int_0^\infty (e^T e - \gamma_1^2 w^T w) d\tau < \int_0^\infty (e^T e - \gamma_1^2 w^T w) d\tau + V_1 < 0 \] (16)
The derivative of equation (16) can be obtained as follows:
\[ \dot{V}_1 + e^T e - \gamma_1^2 w^T w < 0 \] (17)
Substituting equation (15) into equation (16), we can get:
\[ \begin{bmatrix} e^T \\ w \end{bmatrix} \begin{bmatrix} \Pi & P_1 S^{-1} B \\ B^T S^{-T} P_1 & -\gamma_1^2 I \end{bmatrix} \begin{bmatrix} e \\ w \end{bmatrix} < 0 \] (18)
Equation (12) in Theorem 1 is equivalent to equation (18). Complete proof.

4. Adjustment of sensor faults
On the basis of the estimated sensor fault values, a sensor fault adjustment method using static output feedback is proposed. The fault information can be estimated from the fault observer designed in the previous section, and the estimated sensor fault items can be expressed as:
\[ \hat{x}_s = \begin{bmatrix} 0_{13} \\ I \end{bmatrix} \hat{x} \] (19)
In order to eliminate the influence of sensor failure in the system measurement output, the sensor estimation term is subtracted from the system output:
\[ y_c = y_f - \hat{x}_s = Cx + \begin{bmatrix} 0_{13} \\ I \end{bmatrix} e \] (20)
According to equation (20), a static output feedback fault-tolerant controller based on fault adjustment can be proposed:
\[ u = Gy_c \] (21)
Where \( G \) is the feedback gain matrix.
Substituting equations (20) and (21) into the original system equation (3), the following closed-loop system can be obtained:
\[ \dot{x} = (A + B G) x + B G \begin{bmatrix} 0_{13} \\ I \end{bmatrix} e + B w \] (22)
\[ y_c = Cx + \begin{bmatrix} 0_{13} \\ I \end{bmatrix} e \] (23)
In order to maintain the stability of the system in the case of sensor failure, give the theorem 2.

Theorem 2: \( P_1 \) is defined as a positive definite matrix, \( Q \) is an arbitrary matrix, \( \gamma_2 \) is a normal number, if they exist and satisfy Equation (24),
\[ \Sigma = A^T P_2 P_2 A - C^T Q_2^T Q_2 C + I \] (24)
\[ Q_2 = P_2 B G \quad G = (B^T B)^{-1} B^T Q_2^T \]
Therefore, an active fault-tolerant controller designed with the idea of output feedback can make the microgrid system (3) asymptotically stable when the sensor fails.

The Lyapunov function is defined as follows:
\[ V = V_s(x) + \sigma V_1(e) = x^T P x + \sigma e^T P_1 e \] (25)
According to Theorem 1, there is a normal number \( \kappa_\sigma \) that satisfies the following inequality:
\[ V_1 < -\kappa_\sigma \| e \|^2 \] (26)
The derivative of Lyapunov function:
\[ \dot{V} \leq x^T \left[ (A + B G)^T P + P(A + B G) \right] x + 2 x^T P B w + 2 x^T P B G \begin{bmatrix} 0 \\ I \end{bmatrix} e - \sigma \kappa_\sigma \| e \|^2 \] (27)
The system can remain asymptotically stable without sensor failure due to the introduction of controller gain matrix $G$ in the paper. The proof process is similar to the proof process in Theorem 1, and the following inequality conditions should be satisfied:

$$x^T((A + BGC)^TP + P(A + BGC))x + 2x^TPBw + x^T - \gamma_2^2w^Tw < 0$$  \hspace{1cm} (28)

Through calculation, it can be seen that the LMI condition described in Theorem 2 is exactly the same as the meaning expressed in the above formula.

When inequality (28) holds, there exists a normal number $\kappa_1$ such that the following inequality holds:

$$x^T((A + BGC)^TP + P(A + BGC))x + 2x^TPBw < -\kappa_1\|x\|^2$$  \hspace{1cm} (29)

Substituting inequality (29) into inequality (27), we get:

$$\dot{V} < -\kappa_1\|x\|^2 + \sigma_e\|x\|\|e\| - \sigma\kappa_0\|e\|^2$$  \hspace{1cm} (30)

There, $\sigma_e = 2\|PBG\|$, when $\sigma > \frac{\sigma^2e}{\kappa_0\kappa_1}$, we get:

$$\dot{V} < -\kappa_1\|x\|^2 + \sqrt{\sigma\kappa_0\|e\|^2} \leq -(\kappa_1/2)\|x\|^2 - (\sigma\kappa_0/2)\|e\|^2 < 0$$  \hspace{1cm} (31)

As can be seen from the above equation, when sensor faults occur, the system is kept asymptotically stable through fault compensation.

5. Simulation example

The linearization model of the island AC microgrid inverter system is set as:

$$A = \begin{bmatrix} -80 & 40 & -2000 \\ 40 & -80 & 2000 \\ 10000 & -10000 & 0 \end{bmatrix}, \ B = \begin{bmatrix} 2000 & 0 \\ 0 & -2000 \\ 0 & 0 \end{bmatrix}, \ C = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}.$$

When there is a bounded energy disturbance, let

$$w(t) = \begin{bmatrix} \cos(2\pi t)\exp(-0.3t) \\ \cos(2\pi t)\exp(-0.3t) \\ [0, 0]^T \end{bmatrix}, \ t \in [5, 10]$$

Based on theorem 1 and theorem 2, the fault observer proportional gain matrix $L_p$ and the controller differential gain matrix $L_0$ can be obtained by using the feas function in Matlab software.

When $\gamma_1 = 94$, the gain matrix of fault observer is obtained through simulation and when $\gamma_2 = 40$, the gain matrix of fault-tolerant controller is obtained through simulation as follows:

$$L_p = \begin{bmatrix} -131.4459 & -139.4607 & 0.6630 & -366.3596 \end{bmatrix}, \ G = \begin{bmatrix} 66.8856, -66.8856 \end{bmatrix}.$$

The simulation diagram of the output voltage and current of the system when the sensor fault does not occur is shown in Figure 3. When the fault occurs on the detected $i_1$ sensor, the simulation diagram of the output voltage and current of the system is shown in Figure 4.

When, $f_i = [f_{i1} \ 0 \ 0]^T$, the fault expression is $f_i = 0.01i_1$. When the sensor used to detect voltage $u_C$ fails, the simulation diagram of the output voltage and current of the system is shown in Figure 5, when, $f_i = [0, 0, f_{i2}]^T$, the fault expression at this time is $f_i = 0.01(i_2 - i_3)$. The simulation diagram of the output voltage and current of the system when all sensors for detecting current $i_1$, and $i_2$ and voltage $u_C$ fail is shown in Figure 6.
The two figures in Figure 3 respectively represent the simulation figures of the output voltage and current of the system when the sensors that detect current and voltage have no faults. In this case, the voltage runs stably, so does the current. Figure 4 ~ Figure 6 show the waveform of voltage and current when different sensors fail. It can be seen that both voltage and current have sudden changes. With the addition of fault tolerant controllers, voltages and currents gradually return to their stable operating values. It can be proved that the fault tolerant controller designed in this paper not only has good disturbance suppression performance, but also has good fault tolerant ability.

Figure 4. Waveforms of output voltage and current when the sensor detecting $i_i$ fails

Figure 5. Waveforms of output voltage and current when the sensor detecting $u_C$ fails
6. Conclusion
In this paper, the active fault-tolerant controller is designed for the AC microgrid inverter system when there is bounded energy disturbance outside the system and when the sensor fails. A sufficient condition for asymptotic stability of the control system is derived by Lyapunov function when the sensor drift fault occurs. Finally, MATLAB software is used to verify that the proposed method has obvious control advantages and improves the safety and reliability of the system.

7. References
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Figure 6. Waveforms of output voltage and current when all sensors for detecting \( i_1 \), \( i_2 \) and \( u_c \) fail