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Decentralized Sensor Fault Detection and Isolation Using Robust Observer for a DC Microgrid

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ABSTRACT

Sensor faults are common problems in an islanded DC Microgrid, which significantly compromise the performance and operational integrity of the Microgrid. Aiming to detect and isolate sensor faults in islanded DC Microgrids, this paper proposes a robust fault detection and isolation scheme for an islanded DC Microgrid with uncertainties. Therein, a model considering the converter uncertainties is established and utilized to design the observer. Then, a residual-based function is generated that utilizes the estimation error of the observers to detect and identify faults. Model uncertainties are minimized on the estimation error by incorporating an H_∞ *uncertainty attenuation in to the observer design. The sufficient condition for stability is derived and expressed as Linear Matrix inequality (LMI). Simulation using Matlab/Simscape results are presented validating the accurate fault detection and identification.*

Keywords - *DC Microgrid, Sensor fault, Fault detection, Fault isolation,* H_∞ *observer*

1. INTRODUCTION

Over the last few years, restrictions on fossil fuel sources have pushed towards distributed generation units that are easily integrated through microgrids in a grid-connected or islanded fashion [1] [2]. With the development of power electronics, DC Microgrids have been gaining popularity, manifested in their widespread applications in electric vehicles, naval ships, aircrafts, spacecrafts, submarines, and telecom systems, due to their advantages compared to the conventional counterpart AC Microgrids [3] [4] [5]. Generally islanded DC Microgrids contains distributed generation units (DGUs) feeding some loads interconnected to a common DC-bus. Each DGU consists of a DC voltage source, often generated by a renewable energy resource and a controllable DC-DC converter. The main goal of control in the islanded DC Microgrid is to achieve power-sharing and regulate the output voltages of each DGU for a safe and reliable operation [6] [7]. Typically, droop-based control is intended to rapidly stabilize the voltage of DC Microgrids and to facilitate accurate current sharing. In this, the voltage and current sensors are essential in the operation of the control systems, as they offer the necessary feedback for control and monitoring. However, these sensors are not ideal and are subjected to faults and noise. Faulty readings from malfunctioning sensors can cause several issues, such as the loss of reference tracking and accidental triggering of safety mechanisms. Given the critical applications of DC Microgrids, scholars have begun to focus on fault detection and fault identification of DC Microgrids. In [8], a bank of adaptive high-gain state observers was designed to detect sensor faults for a line regulating converter in the DC Microgrid. In [9], a dual-extended Kalman filter was proposed to reconstruct sensor faults. An unknown input observer-based fault detection approach for sensor faults in DC Microgrids was introduced in [10]. In [11], a sensor fusion approach based on an Unscented Kalman filter was proposed to detect and identify sensor faults in a centralized DC microgrid. Hence, this paper proposes a decentralized H_∞ observer to detect and isolate sensor faults taking into consideration the parametric uncertainties of the DGU power converter.

The rest of the paper is organized as follows. Section II briefly presents the modeling of the DC Microgrid. Section III is composed of two parts, including the design and stability analysis of the observer, and the fault detection and isolation algorithm. Simulation results are provided in section IV. Finally conclusions are given in section V.

2. DC-MICROGRID MODELING

The considered islanded Microgrid interconnecting *N* DGUs to a common DC-bus is depicted in Fig. 1. Each DGU is composed of a DC voltage source and buck converter. The different units are connected in parallel through the DC-bus to a constant power load and constant resistive load. This structure is widely adopted in more electric aircraft, more electric ships, and other areas [12] [13].

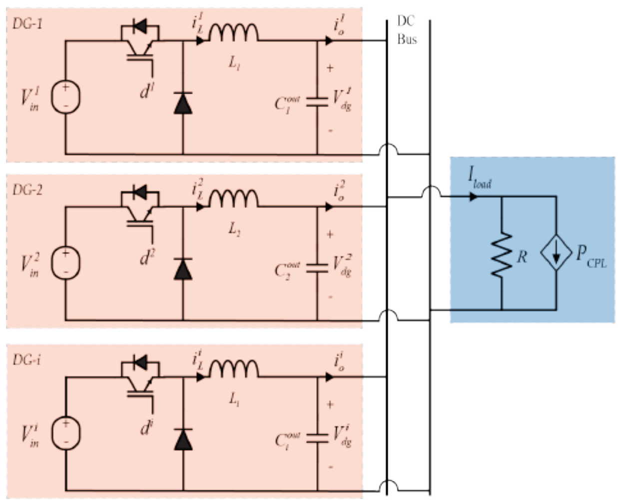

Figure 1. Structure of the adopted DC MG system.

According to Fig. 1, DG-i converters can be modeled using the following average state space model as:

$$\begin{aligned} \frac{dV_{dg}^{i}(t)}{dt} &= \frac{i_L^i(t)}{C_i^{out}} - \frac{1}{C_i^{out}} i_o^i(t) \\ \frac{di_L^i(t)}{dt} &= \frac{V_{in}^i}{L_i} d^i(t) - \frac{V_{dg}^i(t)}{L_i} \end{aligned} \tag{1}$$

where C_i^{out}, L_i and V_{in}^i are the converter parameters, V_{dg}^i and $i_L^i(t)$ are state variables of the system, $d^i(t)$ is the duty cycle, i_o^i is the output current of the converter.

The equation (1) describes the nominal model of the converter in which the parametric uncertainties of the inductor and output capacitor are neglected. In practical situations precise values my not be available, so the capacitor and inductor values can be expressed as:

$$\begin{aligned} \tilde{L}_i &= L_i + \Delta L_i \\ \tilde{C}_i^{out} &= C_i^{out} + \Delta C_i^{out} \end{aligned} \tag{2}$$

In this context, L_i and C_i^{out} represent the nominal values, while ΔL_i and ΔC_i^{out} denote the parametric uncertainties. Thus, the uncertain system of the converter can be written as:

$$\begin{aligned} \frac{dV_{out}^i(t)}{dt} &= \frac{i_L^i(t)}{C_{out}^i} - \frac{1}{C_{out}^i} i_o^i(t) + d_1 \\ \frac{di_L^i(t)}{dt} &= \frac{V_{in}^i}{L^i} d^i(t) - \frac{V_{out}^i(t)}{L^i} + d_2 \end{aligned} \tag{3}$$

Where:

$$\begin{aligned} d_1 &= \frac{\Delta C_{out}^i}{C_{out}^i (C_{out}^i + \Delta C_{out}^i)} (i_o^i(t) - i_L^i(t)) \\ d_2 &= \frac{\Delta L^i}{L^i (L^i + \Delta L^i)} (V_{dg}^i(t) - V_{in}^i d_i(t)) \end{aligned} \tag{4}$$

For notational compactness, the dynamics of converters (4) can be expressed as state space representation as follows:

$$\dot{x}^i(t) = \bar{A}^i x^i(t) + \bar{B}^i u^i(t) + d \tag{5}$$

Where $x^i(t) = \begin{bmatrix} V_{dg}^i(t) & i_L^i(t) \end{bmatrix}$ and $A = \begin{bmatrix} 0 & \frac{1}{C_{dg}^i} \\ -\frac{1}{L^i} & 0 \end{bmatrix}, B = \begin{bmatrix} -\frac{1}{C_{dg}^i} & 0 \\ 0 & \frac{V_{in}^i}{L} \end{bmatrix}, u^i(t) = \begin{bmatrix} i_o^i(t) \\ d_i(t) \end{bmatrix}, d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$

(6)

The objective of this paper is to isolate output voltage and inductor current sensor fault in in each DG-i unit at the primary level of control. To that end, two robust H_∞ observers that take into consideration the model uncertainties will be designed in the next section each of which will use one measured state to estimate the other state.

3. SENSOR FAULT ISOLATION

The fault isolation involves two parts: one is a sensor fault-free state estimation using two observers, and the second is a fault detection and isolation. These parts will be discussed in the following.

2.1 Design of H_∞ observers

In order to detect and isolate fault in a DG-i a fault-free state estimation is required. To this end, two observer are employed each will be dedicated to estimate one state by using the other one as presented in Fig 2. The observer is expressed as follows:

$$\begin{aligned} \dot{\hat{x}}_i(t) &= A_i \hat{x}_i(t) + B_i u(t) + \Gamma_i (y_i(t) - \hat{y}_i(t)) \\ \hat{y}_i(t) &= C_i \hat{x}_i(t) \end{aligned} \tag{7}$$

Where Γ_i is the proportional gain of the observer.

The state estimation error e_i is defined as follows:

$$e_i = x_i(t) - x_i(t) \tag{8}$$

Using (7) and (5), the dynamics of the estimation error is:

$$\dot{e}_i = \dot{x}_i(t) - \dot{\hat{x}}_i(t) = (A_i - \Gamma_i C_i)e_i + d \tag{9}$$

Take the following Lyapunov candidate for error dynamic system:

$$V(e_i) = e_i^T(t)Pe_i(t) \tag{10}$$

Using (10) and (9), one can write:

$$\begin{aligned}\dot{V}(e_i) &= \dot{e}_i^T(t)Pe_i(t) + e_i^T(t)P\dot{e}_i(t) \\ &= e_i^T(t)\left(A_i^T P + PA_i - C_i^T \Gamma_i^T P - P\Gamma_i C_i\right)e_i(t) + 2e_i^T(t)Pd\end{aligned} \tag{11}$$

Note that if d=0, one can obtain:

$$\dot{V}(e_i) < 0 \text{ if } A_i^T P + PA_i - C_i^T \Gamma_i^T P - P\Gamma_i C_i < 0 \tag{12}$$

implying that the error dynamics in (9) is asymptotically stable. The main objective of robust H_∞ is to minimize the effect of disturbances i.e. $d \neq 0$, on the state estimation error, which can be expressed as [14]:

$$\|H\|_\infty = \sup \frac{\|e_i\|_2}{\|d\|_2} \leq \gamma \tag{13}$$

The sufficient stability for the H_∞ observer and the disturbance attenuation objective (13) can only be achieved if the following condition is satisfied:

$$\dot{V}(e_i) + e_i^T C_i^T C_i e_i - \gamma^2 d^T d \leq 0 \tag{14}$$

Thus using (11), the left side of (14) can be expressed as:

$$\begin{bmatrix} e_i^T & d^T \end{bmatrix} \underbrace{\left(\begin{bmatrix} \Xi & * \\ P^T & 0 \end{bmatrix} + \begin{bmatrix} C_i^T & * \\ 0 & -\gamma I \end{bmatrix} \right)}_{\Sigma} \begin{bmatrix} e_i \\ d \end{bmatrix} \leq 0 \tag{15}$$

In which, $\Xi = A_i^T P + PA_i - C_i^T \Gamma_i^T P - P\Gamma_i C_i$

Using shur-complement and after some mathematical manipulation Σ can be transformed to:

$$\Sigma = \begin{bmatrix} \Omega & * & * \\ P & -\gamma I & * \\ C_i & 0 & -I \end{bmatrix} \tag{16}$$

where $\Omega = A_i^T P + PA_i - C_i^T Q_i^T - Q_i C_i$, $Q_i = P\Gamma_i$

If $\Sigma \leq 0$ then the condition (15) is satisfied and $\dot{V}(e_i) \leq 0$. Hence, the stability of the observer is proved. The gain of gain of the observer $\Gamma_i = P^{-1}Q_i$ is obtained by solving the Linear Matrix inequality (15) determine using Matlab Toolbox to find to the variable Q_i and P . Once these gains of the two observers are determined, the observers can be implemented for online operation.

2.2 Fault detection and identification

Fault identification is achieved by using the two observers (analytical redundancy) estimates and comparing each one with its respective measurement. Since the loading conditions of the DG-i unit may varies, a norm based evaluation function of the observed errors norm is adopted to generate the residuals of the inductor current r_i and output voltage r_v

$$\Upsilon_i(t)=\int_{t-T_W}^{t}\|r_i\|d\tau \;,\; \Upsilon_v(t)=\int_{t-T_W}^{t}\|r_v\|d\tau \tag{17}$$

where $r_i = i_L^i - \hat{i}_L^i, r_v = V_{dg}^i - \hat{V}_{dg}^i$, and T_w is the window size.

Faults detection and identification are achieved using the following logic:

$$\begin{cases}\Upsilon_v(t)\geq\Delta_v\rightarrow fault\\ \Upsilon_v(t)\leq\Delta_v\rightarrow no-fault\end{cases} \quad \begin{cases}\Upsilon_i(t)\geq\Delta_i\rightarrow fault\\ \Upsilon_i(t)\leq\Delta_i\rightarrow no-fault\end{cases} \tag{18}$$

where Δ_i and Δ_v are the constant thresholds for the current and voltage residual functions, respectively.

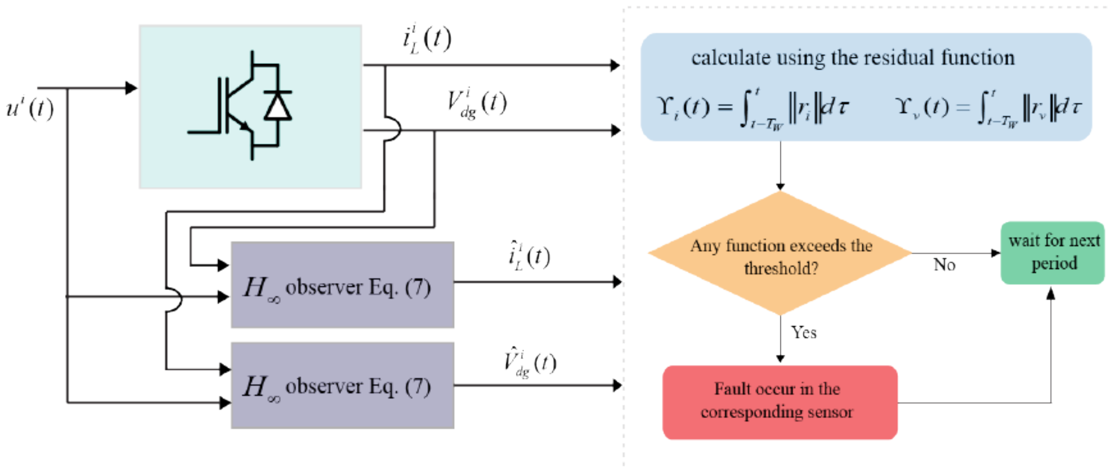

Figure 2. Flowchart of the sensor fault identification.

4. SIMULAITON RESULTS

The simulation model of the islanded DC Microgrid depicted in Fig.1 with 3 DGUs has been developed in *MATLAB/Simscape*. The fault identification scheme is validated using the parameters listed in Table I. the two observers parameter matrix are obtained by LMI (15) and motivated by [15]. The regional pole placement method is introduced to assign the poles and improve the system performance. With $D(2211100,100100)$ regional pole, we obtained optima H_∞ attenuation level of $\gamma = 0,00001$ and:

$$\Gamma_1 = 1.0e5\begin{bmatrix}0.6976\\1.8429\end{bmatrix};\Gamma_1 = 1.0e5\begin{bmatrix}-9.2487\\0.5265\end{bmatrix}$$

Table I : Microgrid parameters

V_{in}^i	$V_{in}^1 = 100V\ V_{in}^2 = 80V\ V_{in}^3 = 120V$
L_i	7mH
C_i^{out}	$355\mu F$

Nominal voltage	40V
Switching frequency	30kHz
P_{cpl}	80W
R_{load}	5Ω

The sensitivity of the fault identification scheme to the variable load operation is tested. Indeed, a 100 % increment and decrement of the P_{cpl} load is considered at instants *t= {0.3; 0.7} s*, respectively. An intermittent bias sensor fault is set to occur in the current sensor in *t= {0.1; 0.4} s* of *DG-1*, afterward an intermittent bias fault occur in the voltage sensor in *t= {0.5; 0.9} s* of DG-1.

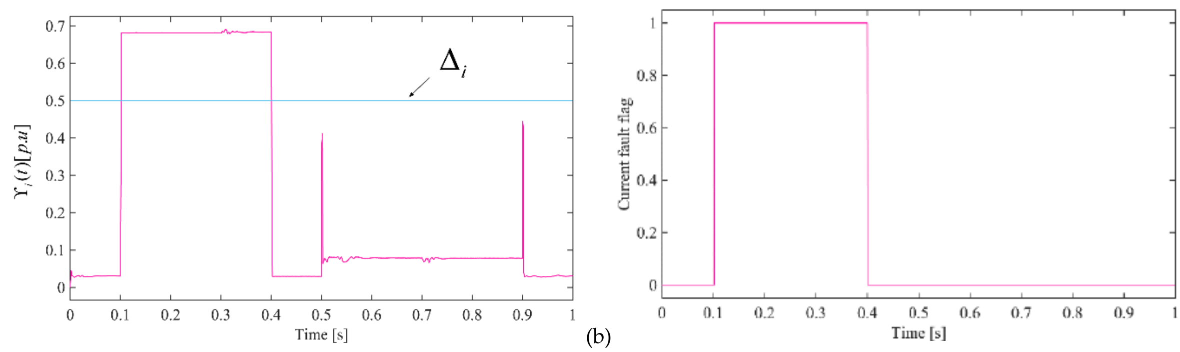

Figure 3: Simulation results of the islanded DC Microgrid under sensors faults: (a) Current residual evaluation function, (b) Current fault detection flag.

The current residual evaluation function is presented in Fig. 3(a), where the function $\Upsilon_i(t)$ is continuously checked and compared with its respective threshold. At *t=0.1s* the evaluation function $\Upsilon_i(t)$ exceeds Δ_i which is detected in *2ms* raising a fault flag as seen in Fig. 3(b).

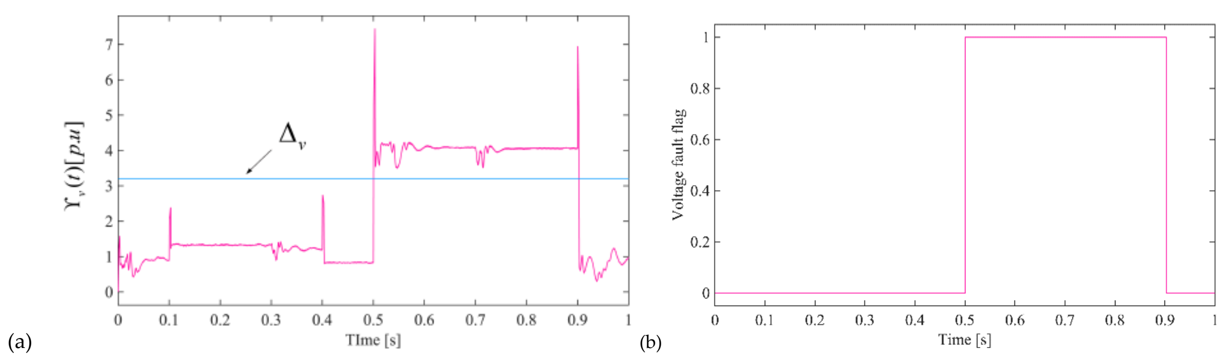

Figure .4 Simulation results of the islanded DC Microgrid under sensors faults: (a) Voltage residual evaluation function (a) Voltage fault detection flag (b).

Similarly, Fig .4(a) depicts the voltage residual evaluation function $\Upsilon_v(t)$, which is being constantly compared to its respective threshold Δ_v. According to Fig .4(b), at *t=0.5s* a fault is detected and isolated in *4ms* when the evaluation function exceeds the threshold Δ_v. The fault flag is rest once the fault is cleared. This demonstrates the ability of the proposed scheme to detect and isolate sensor faults in few milliseconds. This time scale is sufficient given the dynamics of the power converter within the DC Microgrids.

5. CONCLUSION

In this paper, a fault detection and isolation method based on an observer with prescribed H_∞ performance index is proposed for an islanded DC Microgrid. Firstly, a DGU model incorporating uncertainties is established to design an H_∞ observer to generate accurate fault free-state estimation. Next, a residual based function uses the estimation error of the observer to detect and isolate sensor faults. Model uncertainties affecting the estimation accuracy are reduced by integrating uncertainties H_∞ attenuation level to the observer design. The stability condition is expressed as linear matrix inequality. Finally, simulation results validate the effectiveness of the proposed fault detection scheme.

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