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Sensor and Actuator Fault Tolerant Control of Grid-Tied Microgrid

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***Abstract*—The rising penetration of the deployed renewable energy resources (DERs) in the electrical grid introduces new challenges in terms of grid's reliable operation. DERs are bonded to the backbone system at a Point of Common Coupling (PCC) at the distribution level, possibly via a micro grid. Micro grids generally operates in grid-tied and islanded modes. In islanded mode, the reactive and active power ought to reach balance with the load demand., while in the grid-tied mode, the active and active powers must be desired criteria defined by the distribution system operator. Therefore, in both cases, proper control is vital to the microgrid's operation and its DERs. In this article, a fault tolerant control (FTC) method bottomed on H_∞ observer is advised for a DER supplying a grid-tied microgrid to make it resilient against sensor and actuator faults and guarantee its reliable operation.**

***Index Terms*—Distributed energy resources, fault tolerant control, microgrid, sensor and actuator faults.**

I. Introduction

Traditional power generation in electrical grids is dependent on fossil fuels, which are known to release carbon dioxide. Because of the increasing demand for power, electrical networks must contend with a substantial amount of power loss, voltage fluctuation, and feeder blockage. Integration of effective power electronic converters with distributed energy sources (DERs) [1]- [2] through the use of microgrids in the distribution grid is a potential approach that may be taken to solve the problem. DERs are distributed energy resources that are typically based on renewable energy sources (such as fuel cells, solar, or wind) and are put in close proximity to areas where customers obtain their electricity. When a DER is deployed, load dependability is improved, and in the event that there is an interruption in power supply, the load demand can be satisfied by operating DERs in an isolated mode. However, the main drawbacks of distributed energy resources (DERs) include the unpredictability of their power output as well as the inherent intermittent nature of renewable energy sources [3]. The solution is controllers for the power electronic interfaces of DERs that are resistant to the failure of sensors and actuators and can regulate DER output power to the desired level. It has been determined that this resolution is effective.

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Conventional power generation in electrical grids relies on the fossil fuels emitting CO_2. Also, electrical grids have to deal with the considerable power loss, voltage fluctuation, and feeder blockage because of rising load requisition. Combining DERs with high-performance power electronic converters is a realistic solution. [1]- [2] through the microgrid in the distribution grid. DERs are primarily based on renewable energie sources (such as fuel cell , solar, wind) and are installed near electricity consumers.Deploying a DER also improve load dependable in case of the power interruption, the load demand can be met by operating of DERs in islanded mode. However, uncertainty of power output and inherent intermittency of renewable energy sources are often seen as DERs' most significant drawbacks. [3]. The problem can be fixed by using DER power electrical interface controllers, which are resilient in the face of malfunctioning sensors and actuators that regulate the DER's power output.

Although the researchers have been studied the microgrid and distribution network fault detection and protection, studies on the sensor or actuator fault tolerant control(FTC) of microgrid is restricted. There are seveeral approaches to detection sensor fault in power systems [4]–[11]: in [4], two observer-basis sensor failure perception approaches are proposed beacuse of control loops of power system load frequency ; in [5], [6], an obscure input observer-established sensor failure determined method purpose of load frequency control loop of interdependent power system is discussed; Kalman filter and chi-squared test used in [7] to define failures or cyber offensive on the phasors-measurement unit (PMU); in [8], an observer-based FTC approcah for the grid-tied microgrid is investigated; a virtual actuator based FTC approach for the power systems is proposed in [9]; in [12], For a wind energy system with a doubly fed induction generator (DFIG) coupled to a microgrid, a new FTC approach is proposed to enable ride through in any voltage sag scenarios, even deep sags. In spite of the researches done so far, there is a lack of sufficient studies on fault tolerant control of the voltage source converter (VSC) coupled DERs in microgrid. Moreover, there is no studies to address the simultaneous sensor and actuator FTC. In addition, researchers and scientists from a wide range of disciplines are interested in studying FTC strategies for sensor and actuator faults [10], [11], [13]–[15].

In this research, an observed-based FTC for the VSC-coupled DER with sensor or/and actuator failures is suggested. The motivation for this paper comes from the aforementioned issues for the reliable operation of microgrids, as well as the paucity of studies on FTC for sensor and actuator faults. In contrast to the study that came before it, the observer that is being offered in this paper is intended to give simultaneous estimation of the system state, flaws in the sensor or actuator, and it consists of the two processes that are outlined below. The accuracy of the observations is improved by first implementing a virtual observer, and then, because the virtual observer takes into account quantities that cannot be measured directly, a real observer is constructed with the assistance of the virtual observer. An observer-based FTC is designed to be implemented in the second step of the process in order to remove the impact that failures and discomforts have on the performance of the DER that is linked to the grid-tied microgrid.

This article is structured as : The Section II, presents the state-space model of microgrid ; The Section III, displays an observer for evaluating controller feedback amplification as well as system states and faluts; the proposed FTC is applied to the mesh microgrid in the Section IV, and its performance is evaluated using several simulataed events; and finally, the article end is in the Section VI.

II. Grid-Tied Microgrid Model

We consider the microgrid as a linear time invariant (LTI) system which is modeled as follows:

$$\Sigma : \begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + D\epsilon(t) \\ y(t) = Cx(t), \end{cases} \tag{1}$$

where $x(t) = (x_1, x_2, x_3, ..., x_n)^T \in \mathbb{R}^n$ is the state vector of the system, $u(t) = (u_1, u_2, x_3, ..., u_m)^T \in \mathbb{R}^m$ is the control vector, $y(t) = (y_1, y_2, y_3, ..., y_q)^T \in \mathbb{R}^q$ is the output vector of the system, and $\epsilon(t) = (\epsilon_1, \epsilon_2, \epsilon_3, ..., \epsilon_p)^T \in \mathbb{R}^p$ is the external disturbance. Also, $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{q\times n}$, and $D \in \mathbb{R}^{n\times p}$ are the known system matrices. The following set of equations is used to obtain the state space model of a DER in a grid-tied microgrid.

$$\begin{aligned}
\dot{i}_{1d} &= -\frac{R_1}{L_1} i_{1d} + \omega i_{1q} - \frac{v_{cfd}}{L_1} + \frac{v_{dc}}{2L_1} m_d \\
\dot{i}_{1q} &= -\omega i_{1d} - \frac{R_1}{L_1} i_{1q} - \frac{v_{cfq}}{L_1} + \frac{v_{dc}}{2L_1} m_q \\
\dot{i}_{2d} &= \frac{1}{L_2}(v_{cfd} - v_{sd}) + \omega i_{2q} \\
\dot{i}_{2q} &= \frac{1}{L_2}(v_{cfq} - v_{sq}) - \omega i_{2d} \\
\dot{v}_{cfd} &= \frac{1}{C_f}(i_{1d} - i_{2d}) + \omega v_{cfq} \\
\dot{v}_{cfq} &= \frac{1}{C_f}(i_{1q} - i_{2q}) - \omega v_{cfd},
\end{aligned} \tag{2}$$

v means the voltage and i means current, d , q denote the dq components, t and f show the DER's terminal and filter parameters, R_1 is the DER-side resistance, and C_f is the capacitor and L_1 is the inductance of DER-side of the LCL filter. The angular frequency is $\omega = 2\pi f$, the grid frequency is f. m_d and m_q shows, modulation indexes and they regulate the DER's output voltage as follows:

$$v_{td} = m_d \frac{v_{dc}}{2}, \; v_{tq} = m_q \frac{v_{dc}}{2}. \tag{3}$$

According to (2) and (3), the state, input, and disturbance vectors in (1) are obtained as follows: the state vector is $x = [i_{1q} \quad i_{1q} \quad i_{2d} \quad i_{2q} \quad v_{cfd} \quad v_{cfq}]^T \in \mathbb{R}^{n=6}$; the input vector is $u = [m_d \quad m_q]^T \in \mathbb{R}^{m=2}$; and $\epsilon = [v_{sd} \quad v_{sq}]^T \in \mathbb{R}^{m=2}$ is known as disturbance vector. The matrices of the DER state space model (1) are as follow:

$$A = \begin{bmatrix} -\frac{R}{L_1} & \omega & 0 & 0 & -\frac{1}{L_1} & 0 \\ -\omega & -\frac{R}{L_1} & 0 & 0 & 0 & -\frac{1}{L_1} \\ 0 & 0 & -\frac{R}{L_2} & \omega & -\frac{1}{L_2} & 0 \\ 0 & 0 & -\omega & -\frac{R}{L_2} & 0 & -\frac{1}{L_2} \\ \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix}$$

$$B = \frac{V_{dc}}{2} \begin{bmatrix} \frac{1}{L_1} & 0 \\ 0 & \frac{1}{L_1} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -\frac{1}{L_2} & 0 \\ 0 & -\frac{1}{L_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}.$$

The active and reactive powers delivered to the grid by DER at the point of common coupling (PCC) are obtained by:

$$\begin{aligned} P_s &= \frac{3}{2}(v_{sd} i_{2d} + v_{sq} i_{2q}) \\ Q_s &= \frac{3}{2}(-v_{sd} i_{2q} + v_{sq} i_{2d}). \end{aligned} \tag{4}$$

As the phase locked loop (PLL) provides that $v_{sd} = |V_s|$ and $v_{sq} = 0$, where $|V_s|$ is the voltage magnitude, we can write:

$$\begin{aligned} P_s &= \frac{3}{2}|V_s| i_{2d} \\ Q_s &= -\frac{3}{2}|V_s| i_{2q}. \end{aligned} \tag{5}$$

The objective of the DER's controller is to generate the PWM signals so that i_{2d} and i_{2q} track their corresponding reference values obtained by the desired active ($P_{s_{ref}}$) and reactive powers ($Q_{s_{ref}}$) as the following [16].

$$\begin{aligned} P_{s_{ref}} &= \frac{3}{2}|V_s| i_{2d_{ref}} \\ Q_{s_{ref}} &= -\frac{3}{2}|V_s| i_{2q_{ref}}. \end{aligned} \tag{6}$$

III. Fault-Tolerant Control Design

In the content of this article, we contemplate sensors and actuators failures. whenever sensors failure happens, the actual reading of the system output described as

$$y^F(t) = Cx(t) + f_s(t), \tag{7}$$

where $f_s \in \mathbb{R}^q$ is the sensor failure. Additionally, whenever an actuators failure happen, the control input described as

$$u(t) = u_F(t) + f_a(t), \tag{8}$$

where $f_a \in \mathbb{R}^m$ is the actuator failure, and $u_F(t)$ is the control signal.

To derive the observer and control law, the following assumptions and definition must be considered.

Assumption 1: A and B matrices are controllable, A and C are observable.

Assumption 2: f_a is the element of $\mathcal{L}_2\,[0,\infty)$

Definition 1: A stable system with $\mathcal{H}_\infty$ performance must satisfy the following conditions:

1) The system must be stable with zero disturbance.
2) For an arbitrary positive constant γ with zero initial condition, the following condition must be hold:
$$\int_0^\infty x^T(t)x(t)dt < \gamma^2 \int_0^\infty \epsilon^T(t)\epsilon(t)dt.$$

Three failure scenarios are considered, sensor failure, actuator failure , and simultaneous actuators and sensors failures. All scenarios proceed as follows. Initial, an observer is offered to evaluate system states (1) and the faults. Later, an observer-based controller was developed.

A. Sensor Fault

We contrived the below observer for the system (1) with sensor failure (7):

$$\begin{cases} \dot{\psi}(t) = \mathcal{A}\psi(t) + \mathcal{B}u(t) + \mathcal{L}y^F(t) \\ r_F(t) = \psi(t) + \mathcal{C}y^F(t), \end{cases} \tag{9}$$

where $\psi(t)$ is an ancillary variant, matrixes $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{L}$ are parameters of observer , $r_F(t)$ is the prediction for $x(t)$ and $f_s(t)$.

To contrive the observer for both system, $x(t)$, sensor failure, $f_s(t)$, system (1) with sensor failure (7) reobtained as ;

$$\begin{cases} F_1\dot{r}(t) = A_0 r(t) + Bu(t) + D(t) \\ y_F(t) = F_2 r(t), \end{cases} \tag{10}$$

where $r(t) = \left[\begin{smallmatrix} x(t) \\ f_s(t) \end{smallmatrix}\right]$, $A_0 = [A \quad 0_{n\times q}]$, $F_1 = [I_n \quad 0_{n\times q}]$, $F_2 = [C \quad I_q]$. It is clear that $rank\left(\left[\begin{smallmatrix} F_1 \\ F_2 \end{smallmatrix}\right]\right) = n+q$, which means it is full rank and its inverse exists.

Let $E_1 = \left[\begin{smallmatrix} I_n \\ -C \end{smallmatrix}\right]$ and $E_2 = \left[\begin{smallmatrix} 0_{n\times q} \\ I_q \end{smallmatrix}\right]$, following calculate can be done easily:

$$\begin{cases} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} [E_1 \quad E_2] = I_{n+q} \\ [E_1 \quad E_2] \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = I_{n+q}, \end{cases} \tag{11}$$

which means $\left[\begin{smallmatrix} F_1 \\ F_2 \end{smallmatrix}\right]^{-1} = [E_1 \quad E_2]$. Multiplying E_1 by the both sides of (10) yields:

$$E_1F_1\dot{r}(t) = E_1A_0r(t) + E_1Bu(t) + E_1D\epsilon(t), \tag{12}$$

and using (11), i.e., $E_1F_1 + E_2F_2 = I_{n+q}$, we have:

$$\dot{r}(t) = E_1A_0r(t) + E_1Bu(t) + E_1D\epsilon(t) + E_2F_2\dot{r}_F(t). \tag{13}$$

Now, think of the below conjectural observer:

$$\begin{aligned} \dot{r}_F(t) =& E_1A_0r_F(t) + E_1Bu(t) + E_1D\epsilon(t) + E_2F_2\dot{r}_F(t) \\ &+ L(y^F(t) - F_2r_F(t)), \end{aligned} \tag{14}$$

An observer gain matrix denoted by L. Error dynamics are achieved by defining the estimating error as $\eta(t) = r(t) - r_F(t)$.

$$\dot{\eta}(t) = (E_1A_0 - LF_2)\eta(t) + E_1D\epsilon(t). \tag{15}$$

For an arbitrary positive stable δ, fault (15) will be asymptotically constant with the inconvenience emaciation level δ, if a positive matrix $P \in \mathbb{R}^{(n+q)\times(n+q)}$ exists , any matrix $H \in \mathbb{R}^{(n+q)\times q}$ satisfies the below linear matrix inequality (LMI):

$$\Pi = \begin{bmatrix} \Delta & PE_1D \\ * & -\delta^2 I \end{bmatrix} < 0, \tag{16}$$

where $\Delta = PE_1A_0 + A_0^TE_1^TP - HF_2 - F_2^TH^T + I$. The parameters of observer (9) are obtained as follows.

$$\begin{aligned} &\mathcal{A} = E_1A_0 - LF_2, \quad \mathcal{B} = E_1B, \quad \mathcal{C} = E_2 \\ &\mathcal{L} = L - (E_1A_0 - LF_2)E_2, \quad L = P^{-1}H. \end{aligned} \tag{17}$$

Contrived an H_∞ observer for system (1), acquired $r_F(t)$ as the conjectural value for $x(t)$ and $f_s(t)$. Acquired the observer controller is ready. $u(t) = KF_1r_F(t)$, The observer-based control input is of the form, where K is the control gain. This results in a rewrite of the system (1) as:

$$\begin{aligned} \dot{x}(t) =& Ax(t) + BKF_1r_F(t) + D\epsilon(t) \\ =& (A+BK)x(t) - BKF_1\eta(t) + D\epsilon(t) \\ =& (A+BK)x(t) - Bd(t) + D\epsilon(t), \end{aligned} \tag{18}$$

where $d(t) = KF_1\eta(t)$.

For an arbitrary positive stable α , designed observer (9) with parameters (17) with sensor fault (7) will be asymptotically constant with the inconvenience emaciation level γ, if a positive matrix $S \in \mathbb{R}^{n\times n}$ and any matrix $G \in \mathbb{R}^{m\times n}$ fulfil the below LMI:

$$\begin{bmatrix} \overline{\Delta} & S & -B & D \\ * & -I & 0 & 0 \\ * & * - \alpha I & 0 & \\ * & * & * & \delta^2 I \end{bmatrix} < 0, \tag{19}$$

where $\overline{\Delta} = AS + SA^T + BG + G^TB^T$. The control gain K and disturbance attenuation level γ can be calculated as follow:

$K = GS^{-1}$
$\gamma = \sqrt{(\alpha\lambda_{max}(K^TK) + 1)\delta^2}.$

B. Actuator Fault

To get an idea of the state of the system (1), $x(t)$, actuator fault, $f_a(t)$, Planned below observer:

$$\begin{cases} \dot{\bar{\psi}}(t) = \bar{\mathcal{A}}\bar{\psi}(t) + \bar{\mathcal{B}}u_F(t) + \bar{\mathcal{L}}y(t) \\ \bar{r}_F(t) = \bar{\psi}(t) + \bar{\mathcal{C}}y(t), \end{cases} \tag{20}$$

where $\bar{\psi}(t)$ is an ancillary variant, matrixes $\bar{\mathcal{A}}$, $\bar{\mathcal{B}}$, $\bar{\mathcal{C}}$, and $\bar{\mathcal{L}}$ are the observer parameters, $\bar{r}_F(t)$ is the prediction of $x(t)$, $f_a(t)$.

Whenever an actuator failure happen, system (1) reformulated :

$$\begin{cases}\bar{E}_1\dot{\bar{r}}(t) = A_1 r(t) + Bu_F(t) + D\epsilon(t) \\ y(t) = \bar{E}_3 r(t),\end{cases} \tag{21}$$

where $\bar{r}(t) = \begin{bmatrix} x(t) \\ f_a(t)\end{bmatrix}$, $A_1 = [A \quad B]$, $\bar{E}_1 = [I_n \quad 0_{n\times m}]$, $\bar{E}_3 = [C \quad 0_{q\times m}]$. Defining $\bar{E}_2 = [B_1 C \quad I_m]$ where $B_1 \in \mathbb{R}^{m\times q}$ is a full column rank (if $m > q$) or row rank (if $m < q$) matrix, it is clear that $rank\left(\begin{bmatrix}\bar{E}_1 \\ \bar{E}_2\end{bmatrix}\right) = n + m$ that means it is full rank, therefore its reverse consists.

Let $\bar{F}_1 = \begin{bmatrix} I_n \\ -B_1 C\end{bmatrix}$ and $\bar{F}_2 = \begin{bmatrix} 0_{n\times m} \\ I_m\end{bmatrix}$, following calculate can be done easily:

$$\begin{cases}\begin{bmatrix}\bar{E}_1 \\ \bar{E}_2\end{bmatrix}\begin{bmatrix}\bar{F}_1 & \bar{F}_2\end{bmatrix} = I_{n+m} \\ \begin{bmatrix}\bar{F}_1 & \bar{F}_2\end{bmatrix}\begin{bmatrix}\bar{E}_1 \\ \bar{E}_2\end{bmatrix} = I_{n+m},\end{cases} \tag{22}$$

which means $\begin{bmatrix}\bar{E}_1 \\ \bar{E}_2\end{bmatrix}^{-1} = \begin{bmatrix}\bar{F}_1 & \bar{F}_2\end{bmatrix}$. Multiplying $\bar{F}_1$ by the both sides of (21) and using (22) yields:

$$\dot{\bar{r}}(t) = \bar{F}_1 A_1 \bar{r}(t) + \bar{F}_1 B u_F(t) + \bar{F}_1 D\epsilon(t) + \bar{F}_2\bar{E}_2\dot{\bar{r}}(t). \tag{23}$$

Now, consider the following virtual observer:

$$\begin{aligned}\dot{\bar{r}}_F(t) =& \bar{F}_1 A_1 \bar{r}_F(t) + \bar{F}_1 B u_F(t) + E_1 D\epsilon(t) + \bar{F}_2\bar{E}_2\dot{\bar{r}}(t) \\ &+ \bar{L}\big(y^F(t) - \bar{E}_3\bar{r}_F(t)\big),\end{aligned} \tag{24}$$

An observer gain matrix denoted by L. Error dynamics are achieved by defining the estimating error as $\eta(t) = r(t) - r_F(t)$.

$$\dot{\bar{\eta}}(t) = \big(\bar{F}_1 A_1 - \bar{L}\bar{E}_3\big)\bar{\eta}(t) + \bar{F}_D D\epsilon(t), \tag{25}$$

where $\bar{\epsilon}(t) = \begin{bmatrix}\epsilon(t) \\ f_a(t)\end{bmatrix}$, $\bar{F}_D = \begin{bmatrix}\bar{F}_1 D & \bar{F}_2\end{bmatrix}$.

For an optional positive stable $\overline{\delta}$, fault (25) will be asymptotically constant with inconvenience emaciation level δ, if a positive matrix $\overline{P} \in \mathbb{R}^{(n+q)\times(n+q)}$ exists and any matrix $\overline{H} \in \mathbb{R}^{(n+q)xq}$ below LMI:

$$\overline{\Pi} = \begin{bmatrix}\$ & \overline{PF}_D \\ * & -\overline{\delta}^2 I\end{bmatrix} < 0, \tag{26}$$

where $\$ = \overline{PF}_1 A_1 + A_1^T\overline{F}_1^T\overline{P} - \overline{HE}_3 - \overline{H}_3^T\overline{H}^T + I$. The parameters of observer (20) are as follows.

$$\begin{aligned}&\overline{\mathcal{A}} = \overline{F}_1 A_1 - \overline{LE}_2, \quad \overline{\mathcal{B}} = \overline{F}_1 B, \quad \overline{\mathcal{C}} = B_1\overline{F}_2 \\ &\overline{\mathcal{L}} = \overline{L} - (\overline{F}_1 A_1 - \overline{LE}_3)\overline{F}_2 B_1, \quad \overline{L} = \overline{P}^{-1}H.\end{aligned} \tag{27}$$

Now, we can reproduce the observer-based controller utilization by $r_F(t)$, which is acquired from the created H_∞ observer (20) with parameters (27) convincing LMI (26) and inconvenience emaciation level $\overline{\delta}$.

The following form is the input for the observer-based controller.

$$u_F(t) = (\overline{KE}_1 - \overline{E}_4)\overline{r}_F(t), \tag{28}$$

where $\overline{E}_4 = [0_{m\times n} \quad I_m]$, and $\overline{K}$ means the control gain. Then we can obtain system (1) with actuator fault (8) as below.

$$\begin{aligned}\dot{x}(t) =& Ax(t) + B((\overline{KE}_1 - \overline{E}_4)\overline{r}_F(t) + f_a(t)) + D\epsilon(t) \\ =& (A + B\overline{K})x(t) - B(\overline{KE}_1 + \overline{E}_4)\overline{\eta}(t) + D\epsilon(t) \\ =& (A + B\overline{K})x(t) - B\overline{d}_1(t) + B\overline{d}_2(t) + \overline{D}\overline{\epsilon}(t),\end{aligned} \tag{29}$$

where $\overline{D} = [D \quad 0]$, $\overline{d}_1(t) = \overline{KE}_1\overline{\eta}(t)$, and $\overline{d}_2(t) = \overline{E}_4\overline{\eta}(t)$.

For an arbitrary positive stable $\overline{\alpha}$ and $\overline{\beta}$ created observer (19) with parameters (27) compensate LMI (26). The system (1) with actuator fault (8) will be asymptotically constant with inconvenience emaciation level $\overline{\gamma}$, if a positive matrix $\overline{S} \in \mathbb{R}^{n\times n}$ and any matrix $\overline{G} \in \mathbb{R}^{m\times n}$ compensates the below LMI:

$$\begin{bmatrix}\overline{\$} & \overline{S} & -B & B & D \\ * & -I & 0 & 0 & 0 \\ * & * & -\overline{\alpha}I & 0 & 0 \\ * & * & * & -\overline{\beta}I & 0 \\ * & * & * & * & -\overline{\delta}^2\end{bmatrix} < 0, \tag{30}$$

where $\overline{\$} = A\overline{S} + \overline{S}A^T + B\overline{G} + \overline{G}^T B^T$. The control gain K and disturbance attenuation level γ can be calculated as follows:

$$\overline{K} = \overline{GS}^{-1}$$
$$\overline{\gamma} = \sqrt{(\overline{\alpha}\lambda_{max}(\overline{K}^T\overline{K}) + 1)\overline{\delta}^2}.$$

C. Sensor and Actuator Faults

Content of this subsection ; sensors and actuators failures are contemplated. For that purpose initial contemplate the below observer by us :

$$\begin{cases}\dot{\hat{\psi}}(t) = \hat{\mathcal{A}}\hat{\psi}(t) + \hat{\mathcal{B}}u_F(t) + \hat{\mathcal{L}}y^F(t) \\ \hat{r}_F(t) = \hat{\psi}(t) + \hat{\mathcal{C}}y^F(t),\end{cases} \tag{31}$$

where $\hat{\psi}(t)$ is an ancillary variant, matrixes $\hat{\mathcal{A}}$, $\hat{\mathcal{B}}$, $\hat{\mathcal{C}}$, and $\hat{\mathcal{L}}$ are the observer parameters, and $\hat{r}_F(t)$ is the estimation of $x(t)$, $f_s(t)$, $f_a(t)$.

Considering the similar prosess of the preceding subsections, system (1) with sensors failure (7) and actuators failure (8) presented as follow:

$$\begin{cases}\begin{aligned}\dot{\widehat{r}}(t) =& \widehat{F}_1 A_2\widehat{r}(t) + \widehat{F}_1 B u_F(t) + \widehat{F}_1 D\epsilon(t) \\ &+ (\widehat{F}_2\widehat{E}_2 + \widehat{F}_3\widehat{E}_3)\dot{\widehat{r}}(t)\end{aligned} \\ y^F(t) = \widehat{E}_2\widehat{r}(t),\end{cases} \tag{32}$$

where $\widehat{r} = \begin{bmatrix}x^T(t) & f_s^T(t) & f_a^T(t)\end{bmatrix}^T$, $A_2 = [A \quad 0_{n\times q} \quad B]$, and

$$\widehat{E} = \begin{bmatrix}\widehat{E}_1 \\ \hline \widehat{E}_2 \\ \hline \widehat{E}_3\end{bmatrix} = \left[\begin{array}{ccc} I_n & 0_{n\times q} & 0_{m\times q} \\ \hline C & I_q & 0_{q\times m} \\ \hline B_1 C & B_1 & I_m\end{array}\right]$$

$$\widehat{F} = \left[\begin{array}{c|c|c}\widehat{F}_1 & \widehat{F}_2 & \widehat{F}_3\end{array}\right] = \left[\begin{array}{c|c|c} I_n & 0_{n\times q} & 0_{n\times m} \\ -C & I_q & 0_{q\times m} \\ 0_{m\times n} & -B_1 & I_m\end{array}\right]$$

where $\widehat{E}$ is a full rank matrix with an reverse matrix is $\widehat{E}^{-1} = \widehat{F}$. Then, virtual observer design as follow:

$$\begin{aligned}\dot{\hat{r}}_F(t) =& \hat{F}_1 A_2 \hat{r}_F(t) + \hat{F}_1 B u_F(t) + \\ & \big(\hat{F}_2 D \epsilon(t) + \hat{F}_3 B 1_1\big)\hat{E}_2 \dot{\hat{r}}(t) + \hat{L}\big(y^F(t) - \hat{E}_2 \hat{r}_F(t)\big),\end{aligned} \tag{33}$$

An observer gain matrix denoted by L. Error dynamics are achieved by defining the estimating error as $\eta(t) = r(t) - r_F(t)$.

$$\dot{\hat{\eta}}(t) = (\hat{F}_1 A_2 - \hat{L}\hat{E}_2)\hat{\eta}(t) + \hat{D}\hat{\epsilon}(t), \tag{34}$$

where $\hat{\epsilon}(t) = \left[\begin{smallmatrix}\epsilon(t)\\ f_a(t)\end{smallmatrix}\right]$, and $\hat{D} = \left[\begin{smallmatrix}D & 0\\ -CD & I\end{smallmatrix}\right]$.

For an arbitrary positive constant $\widehat{\delta}$, error (34) will be asymptotically constant with inconvenience emaciation level $\widehat{\delta}$, if a positive matrix $\widehat{P} \in \mathbb{R}^{(n+m+q)\times(n+m+q)}$ exists, any matrix $\widehat{H} \in \mathbb{R}^{(n+m+q)\times q}$ satisfies below LMI:

$$\widehat{\Pi} = \begin{bmatrix}\Xi & \widehat{P}\widehat{D}\\ * & -\widehat{\delta}^2 I\end{bmatrix} < 0, \tag{35}$$

where $\Xi = \widehat{P}\widehat{F}_1 A_2 + A_2^T \widehat{F}_1^T \widehat{P} - \widehat{H}\widehat{E}_2 - \widehat{E}_2^T \widehat{H}^T + I$. The parameters of observer (31) are as follows.

$$\widehat{\mathcal{A}} = \widehat{F}_1 A_2 - \widehat{L}\widehat{E}_2 \quad \widehat{\mathcal{B}} = \widehat{F}_1 B \quad \widehat{\mathcal{C}} = \widehat{F}_4 \quad \widehat{L} = \widehat{P}^{-1}\widehat{H}$$
$$\widehat{\mathcal{L}} = \widehat{L} - (\widehat{F}_1 A_2 - \widehat{L}\widehat{E}_2)\widehat{F}_4 B_1 \quad \widehat{F}_4 = \begin{bmatrix}0_{n\times q}\\ I_q\\ 0_{m\times q}\end{bmatrix}. \tag{36}$$

The observer-based control input ;

$$u_F(t) = (\hat{K}\hat{E}_1 - \hat{E}_4) r_F(t), \tag{37}$$

where $\hat{E}_4 = [0_{m\times n} \quad 0_{m\times q} \quad I_m]$, and $\hat{K}$ is the control gain. System (1) with both sensor failure (7) and actuator failure (8) happen

$$\begin{aligned}\dot{x}(t) =& Ax(t) + B((\hat{K}\hat{E}_1 - \hat{E}_4)\hat{r}_F(t) + f_a(t)) + D\epsilon(t)\\ =& (A + B\hat{K})x(t) - B(\hat{K}\hat{E}_1 + \hat{E}_4)\hat{\eta}(t) + D\epsilon(t)\\ =& (A + B\hat{K})x(t) - B\hat{d}_1(t) + B\hat{d}_2(t) + \overline{D}\overline{\epsilon}(t),\end{aligned} \tag{38}$$

Where $\hat{d}_1(t) = \hat{K}\hat{E}_1\hat{\eta}(t)$, $\hat{d}_2(t) = \hat{E}_4\hat{\eta}(t)$, $\overline{D}$ is defined (33).

For an arbitrary positive stable $\widehat{\alpha}$ and $\widehat{\beta}$ designed observer (31) with parameters (36)satisfy LMI (35). The system (1)with sensor failure (7) , with actuator failure (8) is asymptotically constant with inconvenience emaciation level $\widehat{\gamma}$, if a positive matrix $\widehat{S} \in \mathbb{R}^{n\times n}$, any matrix $\widehat{G} \in \mathbb{R}^{m\times n}$ satisfies following LMI:

$$\begin{bmatrix}\widehat{\Xi} & \widehat{S} & -B & B & \overline{D}\\ * & -I & 0 & 0 & 0\\ * & * & -\widehat{\alpha}I & 0 & 0\\ * & * & * & -\widehat{\beta}I & 0\\ * & * & * & * & -\widehat{\delta}^2\end{bmatrix} < 0, \tag{39}$$

where $\widehat{\Xi} = A\widehat{S} + \widehat{S}A^T + B\widehat{G} + \widehat{G}^T B^T$. The control gain K and disturbance attenuation level $\widehat{\gamma}$ can be calculated as follow:

$$\widehat{K} = \widehat{G}\widehat{S}^{-1}$$
$$\widehat{\gamma} = \sqrt{(\widehat{\alpha}\lambda_{max}(\widehat{K}^T\widehat{K}) + 1)\widehat{\delta}^2}.$$

IV. Numerical Simulation

As discussed, the main objective of the FTC method is to make the grid-tied microgrid resilient against the impact of failures and inconveniences. The cases considered for the simulation are sensor failure, actuator failure and simultaneous sensor and actuator failuress. The simulated microgrid, which is related to the distribution grid, in Fig. 1. The DER connected to the microgrid is controlled by the designed observer-based FTC which its diagram is shown in Fig. 2

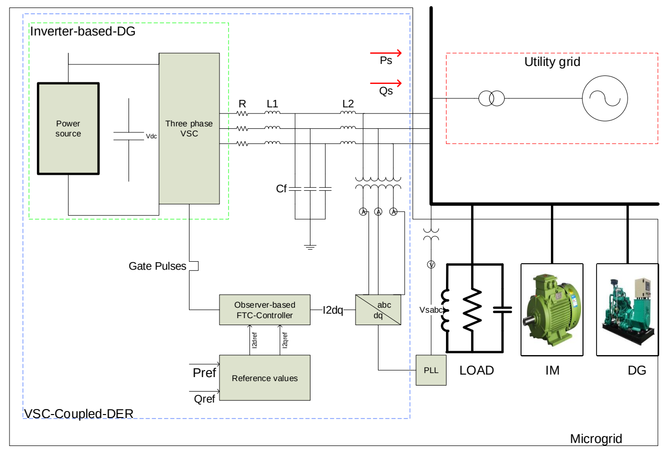

Fig. 1. The simulated grid-tied microgrid.

The simulated distribution grid symbolizes a part of the Canadian reference dispersion system [17]. The microgird consists of an inverter-based DER, a diesel-based synchronous dispersion generator (DG), an induction motor load, and an RLC load. A diesel engine regulator and an IEEE ST1A excitation system are combined to construct the synchronous DG unit. The inverter-based DER, which is related to the distribution grid at PCC through an LCL filter, consists of a three-phase VSC based on IGBT controlled by space-vector PWM. The data of the excitation system, the synchronous DG unit, the diesel engine regulator and the parameters of the induction motor are taken from [17]. The parameters of the

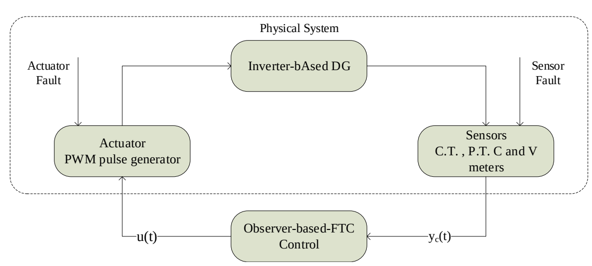

Fig. 2. FTC diagram of the VSC-coupled DER.

simulated microgrid are as follows: L= 100 H; R= 0.75 Ω; the line to line rms voltage 480 V; the AC system frequency $\omega = 377$ rad/s.

To assess the efficiency of the intended FTC, the following events are executed in the microgrid: at t = 0.2 s, $P_{s_{ref}} = 0$ and $Q_{s_{ref}} = 0$ where $P_{s_{ref}}$ and $Q_{s_{ref}}$ are the reference reactive and active powers; at t = 0.25 s, $P_{s_{ref}}$ is subjected to a step change from 0.0 MW to 3.0 MW; at t = 0.40 s, $P_{s_{ref}}$ has a step change from 2.3 MW to -3.3 MW; and finally, at t= 0.4 s, $Q_{s_{ref}}$ has a step change from 0.0 MVAr to 1.5 MVAr.

The sensor and fault estimation is investigated by LMI which is achieved through two step. The first stage involves using a virtual observer to increase the precision of the observations. As the virtual observer does not include any quantifiable values, the real observer design is also included at this stage. In the second step, based on the real observer, FTC is constructed. The obtained results are based on the current on the q-frame. Fig.3, Fig. 4 and Fig. 5 show actuator, sensor and simultaneous fault cases, respectively.

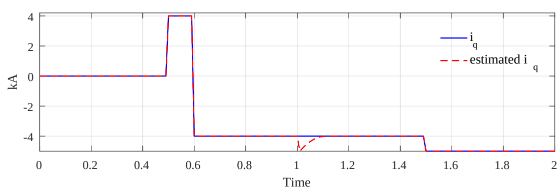

Fig. 3. FTC response for actuator fault on q-frame current.

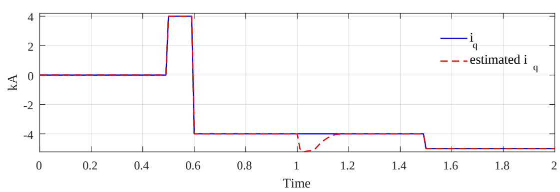

Fig. 4. FTC response for sensor faults on q-frame current.

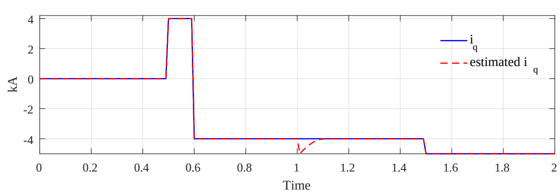

Fig. 5. FTC response for Sensor and actuator faults on q-frame current.

V. Experimental Verification

The fault-tolerant control algorithm proposed in this study has been experimentally validated for a grid-connected DER. The experimental setup is shown in Figure 6. The dSpace 1103 card was used as the control card in the experiment. Other components used in the experimental setup are shown in Figure 6 with their connections. The DER unit is represented as a DC source as shown in figure 6 and is connected to the mains via a transformer through an LC filter.

Figure 7 and figure 8 show actuator fault without FTC and actuator fault with FTC, respectively. As shown in Figure 8, the proposed fault tolerance algorithm accurately detects and tolerates actuator faults and sets it to the reference value.

On the other hand, sensor faults without FTC and sensor faults with FTC are shown in Figure 9 and Figure 10, respectively. As shown in Figure 10, the proposed fault tolerance algorithm accurately detects and tolerates sensor faults and sets it to the reference value.

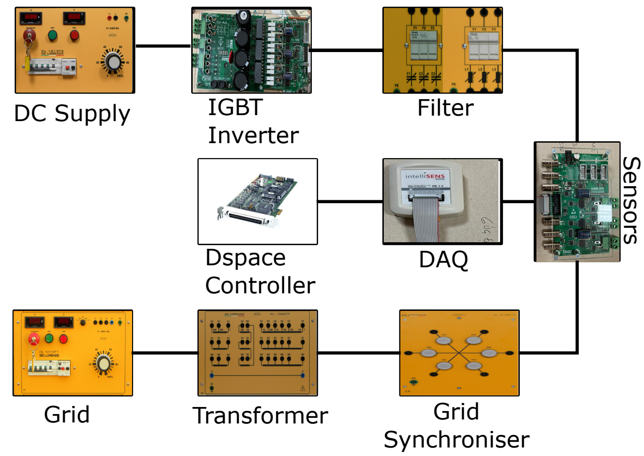

Fig. 6. Experimental Setup.

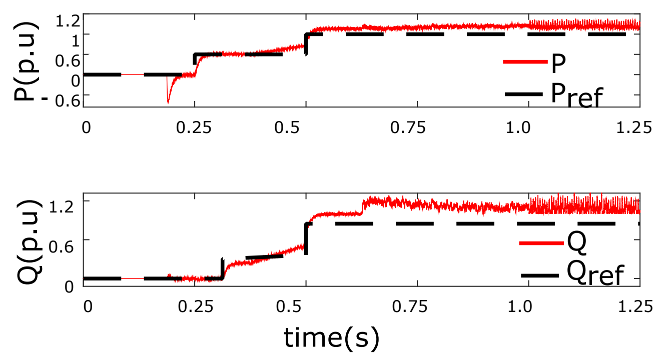

Fig. 7. Actuator faults without FTC.

VI. Conclusion

An observer-based FTC was created for a VSC-coupled DER in this article. The VSC-coupled DER is connected to the distribution grid through a microgrid. The proposed FTC design was accomplished through the following two steps: first, a H_∞ observer was designed to estimate the system state and sensor/actuator fault; second, the estimated fault

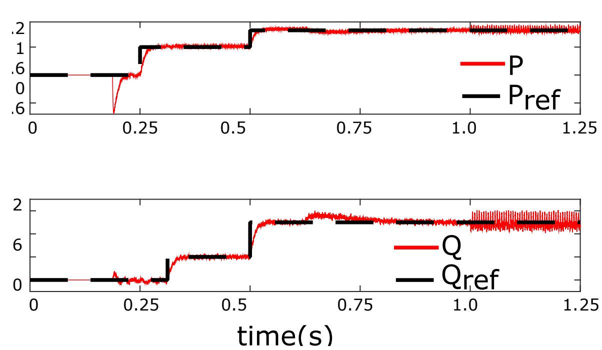

Fig. 8. Actuator faults with FTC.

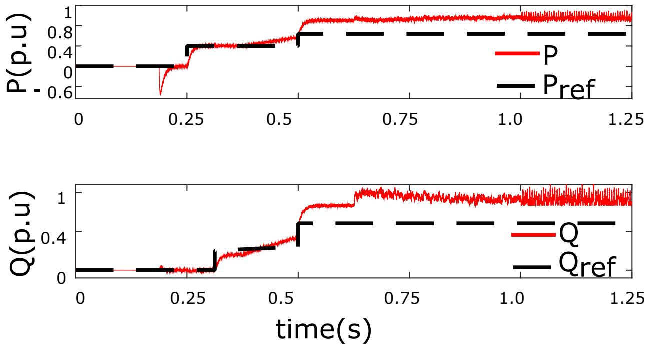

Fig. 9. Sensor faults without FTC.

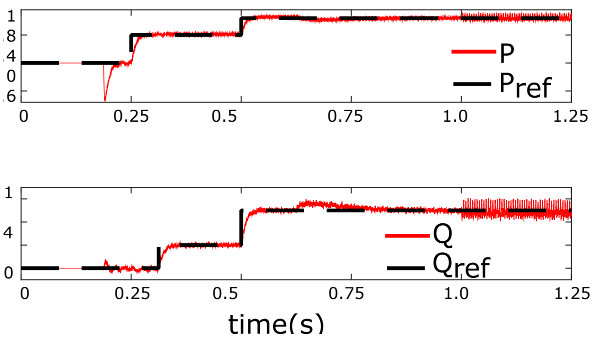

Fig. 10. Sensor faults with FTC.

obtained by the observer was used to calculate the feedback control gain in a manner that satisfies the defined LMI and the disturbance attenuation level; and third, the proposed FTC design was implemented. Both theoretical modeling and actual experimentation have been used to validate the functionality of the proposed FTC. The suggested FTC was able to manage the DER in such a way that its output powers followed the values that were required by carrying out many step adjustments in the reference active and reactive powers when there was a failure in either the sensor or the actuator.

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