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Fuzzy Observer Design for PV Conversion System with Fault Effects

Van-Phong Vu*, Van-Thuyen Ngo, Dinh-Nhon Truong
Ho Chi Minh City University of Technology and Education, Vietnam
* Corresponding author. *Email: phongvv@hcmute.edu.vn*

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ABSTRACT

This paper proposes a new approach to design an observer for the Photovoltaic conversion system. Originally, the PV conversion system is modeled under the nonlinear framework that is difficult for designing the observer. Thus, in this work, the original nonlinear form of the PV conversion system will be transformed to the T-S fuzzy model with the existence of the disturbance. Unlike the previous articles, the PV conversion system in this work is affected by the faults, and the fault impacts not only the system but also the output. The observer is designed to estimate the unknown states and the faults of the PV conversion system asymptotically as well as eliminate the impact of the disturbance. The augment technique is employed to modify the PV conversion system. With the aid of the Lyapunov theory and Linear Matrix Inequality (LMI) technique, the conditions for observer design have been proposed in the main theorem. Finally, the simulation results are also provided to prove the success and merit of the proposed method.

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1. Introduction

Recent years, the demand for electric power is highly increasing. That leads to using the fossil fuels such as oil and coal, in power plants also considerably grow up. Unfortunately, using fossil fuels will emit the carbon dioxide (CO2) that causes global warming and air population. Because of this reason, developing renewable energy to replaces fossil fuels is a pressing issue that receives great attention from researchers. Solar energy, nowadays, is becoming one of the most popular renewable energy in the world. This kind of energy source can reduce CO2 emission, be noise-free, and have low- capital investment [1]-[3]. There are plenty of papers paying attention to study the PV conversion system in the past few years [4]-[12]. For example, the intelligent PV module has been developed in [4] to reduce the loss rate when using the PV system. The P&O algorithm was investigated for the Standalone system at high perturbation frequency [5]. In paper [12], the fractional-order PI controller was designed for the PV system in which the flower pollination algorithm (FPA) and water cycle algorithm (WCA were employed to determine the optimal parameters for the PV system and PI controller.

It is noted that the PV conversion system is modeled under the framework of a nonlinear system. Unfortunately, design observer and controller directly for the nonlinear system are always very challenging for the researchers. In past decades, an approach for modeling the nonlinear system called the Takagi-Sugeno model was introduced in [13]-[15]. The T-S fuzzy model, in general, is the combination of the linear sub-system models and “IF-THEN” rules. The advantages of the T-S fuzzy model are that it can model exactly the nonlinear system and the powerful theories of the linear system can be applied for the nonlinear system. Due to these reasons, in this paper, the T-S fuzzy model will be employed to model the PV conversion system. Recently, there exist numerous studies applying the T-S fuzzy model for solving the problems of PV conversion systems [16]-[22]. For instance, Chiu has proposed a method to design the observer-based controller to track the MPP for the PV system with a DC-DC buck converter [16]. The fuzzy state feedback controller based on the H-infinite was designed to track for the Maximum Power Point of the PV conversion system [19]. Fuzzy PI state feedback

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controller was designed to control the PV conversion system for minimizing the tracking error and reduce the effects of the disturbance [20].

In practice, some physical parameters are hard to measure by the sensor, or using sensors will cause to increase in the cost to build the system. Moreover, the sensor is sensitive to noise that leads to obtaining the inaccurate information. To over this challenge, the observer was synthesized to replace sensors for estimating the state variables. Regarding, designing the observer for the PV system, several studies have been investigated in recent years [16], [23]-[25]. For example, the method to design a hybrid observer based on the hybrid dynamical system approach was proposed in [24] to estimate the unknown states of the PV system with a DC-DC buck converter. However, the observer form of paper [24] is nonlinear and seems complicated. The Luenberger observer was designed for PV system to estimate the unknown states [25]. The observer design method in paper [25] applied H-infinite technique to deal with the effects of the disturbance. However, with this technique, it cannot remove completely the influence of disturbance.

Normally, the PV conversion system always operates under rigorous conditions, therefore, the effects of the faults are inevitable. The fault will impact the performance of the system, even cause the PV conversion system to be out of order. However, to our best knowledge, the problem of fault estimation has not been taken into consideration in any previous studies that research about PV system. Therefore, in this paper, we will propose a new method to design the observer for the PV conversion system. It should be noted that this paper merely takes into account the observer design and does not consider the problem of the controller design. The main contributions of this paper are emphasized in the following aspects

i) The PV conversion system is represented in terms of the T-S fuzzy model to help designing observer be easier

ii) The fuzzy observer is synthesized for the PV system with the effects of fault that has not been considered in the previous papers [16], [23]-[25].

iii) The observer in this paper can not only estimate the unknown state variables of the PV conversion system and fault simultaneously but also eliminate the influences of disturbance completely.

iv) The observer is used to replace the sensors that will assist to avoid the effects of measurement noise as well as decrease the cost to build the system.

The rest of this paper is organized as follows. The mathematical model and the problem description will be presented in Section 2. The observer synthesis procedure can be found in Section 3. Section 4 will provide the simulation results and several conclusions are shown in Section 5.

Notations: $A < 0$ ($A > 0$) stands for negative definite (positive definite) matrix A. A^T indicates the transpose of matrix A. A^+ is the Moore-Penrose pseudoinverse of matrix A. I defines the identity matrix.

2. Mathematical Model and Problem Description

2.1. Mathematical Model of PV Conversion System

The structure of the PV conversion System is illustrated in Fig. 1. The system consists of two main parts: the PV module and DC-DC boost converter. The mathematical models of these two components are presented as follows.

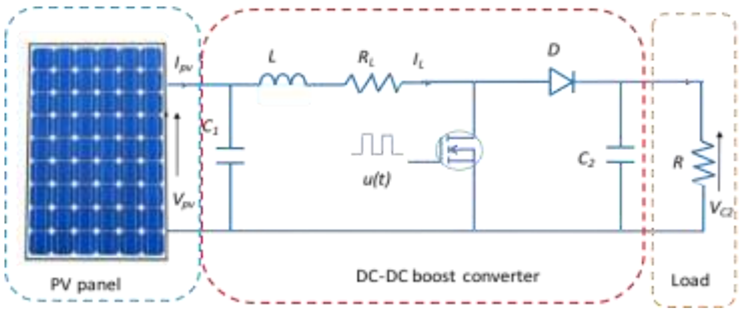

Figure 1. *Structure of the PV conversion system*

2.1.1 Mathematical Model of PV module

The PV module is described in the following equations:

$$I_{pv} = I_{ph} - I_0\left(e^{(\frac{V_{pv}+R_sI_{pv}}{nV_T}} - 1\right) - \left(\frac{V_{pv} + R_sI_{pv}}{R_{sh}}\right)$$
$$V_T = \frac{KT}{q} \quad (1)$$

where V_{pv} and I_{pv} are the output voltage and output current of the PV conversion system. T indicates the cell temperature and $q = 1.6 \times 10^{-19}C$ stands for the electronic charge. $K = 1.3805 \times 10^{-23}J$ is he Boltzmann's constant; n = 1.5 and I_0 are the ideal PN junction characteristic factor and diode's saturation current.

Assume that the shunt resistance R_{sh} is much larger than R_s, therefore, Eq. (1) is rewritten as follows

$$I_{pv} = I_{ph} - I_0\left(e^{(\frac{V_{pv}+R_sI_{pv}}{nV_T}} - 1\right) \quad (2)$$

2.1.2 Mathematical model of the DC-DC boost converter

From Fig. 1, it is seen that the PV conversion system has two models which relied on the state of the switch (ON/OFF). Let us denote the state variables

$$x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} = \begin{bmatrix} V_{pv}(t) \\ I_L(t) \\ V_{c2}(t) \end{bmatrix}, d(t) = I_{pv}(t),$$

Case 1: The switch is ON

When the switch is on, the PV conversion system is modeled by the following state-space equation

$$\dot{x}(t) = Ax(t) + Dd(t) \quad (3)$$

in which

$$A = \begin{bmatrix} 0 & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & -\frac{R_L}{L} & 0 \\ 0 & 0 & -\frac{1}{RC_2} \end{bmatrix}, D = \begin{bmatrix} \frac{1}{C_1} \\ 0 \\ 0 \end{bmatrix}$$

Case 2: The switch is OFF

$$\dot{x}(t) = \bar{A}x(t) + Dd(t) \quad (4)$$
$$\bar{A} = \begin{bmatrix} 0 & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & -\frac{R_L}{L} & -\frac{1}{L} \\ 0 & \frac{1}{C_2} & -\frac{1}{RC_2} \end{bmatrix},$$

Combining (3) and (4), the general model of the PV conversion system is described

$$\dot{x}(t) = [Ax(t) + Dd(t)]u(t) + [\bar{A}x(t) + Dd(t)](1 - u(t)) \quad (5)$$

The equation (5) is rewritten

$$\dot{x}(t) = \bar{A}x(t) + [A - \bar{A}]x(t)u(t) + Dd(t) \quad (6)$$

Let us define

$$B(x(t)) = [A - \bar{A}]x(t)$$

then (6) becomes

$$\dot{x}(t) = \bar{A}x(t) + B(x(t))u(t) + Dd(t) \quad (7)$$

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where

$$B(x(t)) = \begin{bmatrix} 0 \\ \frac{V_{C2}(t)}{L} \\ \frac{I_L(t)}{C_2} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{x_2(t)}{L} \\ \frac{x_3(t)}{C_2} \end{bmatrix},$$ $u(t)$ is the duty ratio of the input signal.

It should be noted that during operation, the DC-DC boost converter is impacted by the fault that maybe the open-circuit fault, short-cirtuit fault and/or fault cause by abnormal failure of the sensors. For the sake of generalization, in this paper, the fault is considered as a external *f(t)* (this method can be seen in book [26]) and it is assumed that the fualt exist in both actuator and output sensors, then the system (7) becomes

$$\begin{cases} \dot{x}(t) = \bar{A}x(t) + B(x(t))u(t) + Dd(t) \\ \qquad +Ef(t) \\ y = Cx(t) + Jf(t) \end{cases} \quad (8)$$

where $f(t)$ is the fault; $E \in \Re^3$ and $J \in \Re^2$ are the fault matrices.

Remark 1: In this paper, $I_{pv}(t)$ is concerned as the disturbance, hence, from Eq. (8), it is seen that the PV system is impacted by both disturbance and faults. The fault will influence the system and sensors simultaneously.

2.1.3 T-S fuzzy system modeling of the PV conversion system

From Eq. (8), it is seen that this is a nonlinear model that includes two nonlinear terms $x_2(t)$ and $x_3(t)$. Designing an observer directly for the nonlinear system is a great challenge. To avoid this difficulty, in this paper, the T-S fuzzy model [13]-[15] is employed to model the PV system (8). The PV system is modeled under the framework of the T-S fuzzy system as the following step.

Let us define the premise variables

$$\theta_1(t) = x_2(t) = V_{C2}(t),$$
$$\theta_1(t) \in [\theta_{1,min} \quad \theta_{1,max}]$$
$$\theta_2(t) = x_3(t) = I_L(t),$$
$$\theta_2(t) \in [\theta_{2,min} \quad \theta_{2,max}]$$

Then the membership functions

$$Q_1(\theta_1(t)) = \frac{\theta_1(t) - \theta_{1,min}}{\theta_{1,max} - \theta_{1,min}}$$
$$Q_2(\theta_1(t)) = 1 - Q_1(\theta_1(t))$$
$$Q_3(\theta_2(t)) = \frac{\theta_2(t) - \theta_{2,min}}{\theta_{2,max} - \theta_{2,min}}$$
$$Q_4(\theta_2(t)) = 1 - Q_3(\theta_3(t))$$

The PV conversion system (8) is represented under the T-S fuzzy model with four rules as follows

Rule 1:

If $\theta_1(t)$ is $Q_1(\theta_1(t))$ and $\theta_2(t)$ is $Q_3(\theta_2(t))$ then

$$\begin{cases} \dot{x}(t) = A_1x(t) + B_1u(t) + Dd(t) + Ef(t) \\ y(t) = Cx(t) + Jf(t) \end{cases}$$

Rule 2:

If $\theta_1(t)$ is $Q_1(\theta_1(t))$ and $\theta_2(t)$ is $Q_4(\theta_2(t))$ then

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$$\begin{cases}\dot{x}(t) = A_2x(t) + B_2u(t) + Dd(t) + Ef(t) \\ y(t) = Cx(t) + Jf(t)\end{cases}$$

Rule 3:

If $\theta_1(t)$ is $Q_2(\theta_1(t))$ and $\theta_2(t)$ is $Q_3(\theta_2(t))$ then

$$\begin{cases}\dot{x}(t) = A_3x(t) + B_3u(t) + Dd(t) + Ef(t) \\ y(t) = Cx(t) + Jf(t)\end{cases}$$

Rule 4:

If $\theta_1(t)$ is $Q_2(\theta_1(t))$ and $\theta_2(t)$ is $Q_4(\theta_2(t))$ then

$$\begin{cases}\dot{x}(t) = A_4x(t) + B_4u(t) + Dd(t) + Ef(t) \\ y(t) = Cx(t) + Jf(t)\end{cases}$$

Overall the T-S fuzzy system is presented in the following form

$$\begin{cases}\dot{x}(t) = \sum_{i=1}^{4}\beta_i(\theta(t))\{A_ix(t) + B_iu(t) \\ \quad +Dd(t) + Ef(t)\} \\ y(t) = Cx(t) + Jf(t)\end{cases} \tag{9}$$

where

$$\theta(t) = [\theta_1(t) \quad \theta_2(t)],$$
$$\beta_1(\theta(t)) = Q_1(\theta_1(t))Q_3(\theta_2(t)),$$
$$\beta_2(\theta(t)) = Q_1(\theta_1(t))Q_4(\theta_2(t))$$
$$\beta_3(\theta(t)) = Q_2(\theta_1(t))Q_3(\theta_2(t)),$$
$$\text{and } \beta_4(\theta(t)) = Q_2(\theta_1(t))Q_4(\theta_2(t))$$

$$A_1 = A_2 = A_3 = A_4 = \bar{A} = \begin{bmatrix} 0 & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & -\frac{R_L}{L} & -\frac{1}{L} \\ 0 & \frac{1}{C_2} & -\frac{1}{RC_2}\end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ \frac{V_{C2,min}}{L} \\ \frac{I_{L,min}}{C_2}\end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ \frac{V_{C2,min}}{L} \\ \frac{I_{L,max}}{C_2}\end{bmatrix}, B_3 = \begin{bmatrix} 0 \\ \frac{V_{C2,max}}{L} \\ \frac{I_{L,min}}{C_2}\end{bmatrix},$$

$$B_4 = \begin{bmatrix} 0 \\ \frac{V_{C2,max}}{L} \\ \frac{I_{L,max}}{C_2}\end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1\end{bmatrix}, J = \begin{bmatrix} 1 \\ 1\end{bmatrix}, E = \begin{bmatrix} 1 \\ 1 \\ 1\end{bmatrix}.$$

From now on, the system (9) will be used for designing observers instead of the system (8)

We reconstruct the system (9) based on the augment technique

$$\begin{cases}\begin{bmatrix}\dot{x}(t) \\ \dot{f}(t)\end{bmatrix} = \sum_{i=1}^{4}\beta_i(\theta(t))\{\begin{bmatrix} A_i & E \\ 0 & 0\end{bmatrix}\begin{bmatrix} x(t) \\ f(t)\end{bmatrix} + \begin{bmatrix} B_i \\ 0\end{bmatrix}u(t) + \begin{bmatrix} D & 0 \\ 0 & I\end{bmatrix}\begin{bmatrix} d(t) \\ \dot{f}(t)\end{bmatrix}\} \\ y(t) = [C \quad J]\begin{bmatrix} x(t) \\ f(t)\end{bmatrix}\end{cases} \tag{10}$$

Let us define

$$X(t) = \begin{bmatrix} x(t) \\ f(t)\end{bmatrix}, \dot{X}(t) = \begin{bmatrix}\dot{x}(t) \\ \dot{f}(t)\end{bmatrix}, \tilde{A}_i = \begin{bmatrix} A_i & E \\ 0 & 0\end{bmatrix}, \tilde{B}_i = \begin{bmatrix} B_i \\ 0\end{bmatrix}, \tilde{C} = [C \quad J], \tilde{D} = \begin{bmatrix} D & 0 \\ 0 & I\end{bmatrix}, \omega(t) = \begin{bmatrix} d(t) \\ \dot{f}(t)\end{bmatrix}$$

Then the system (10) becomes

$$\begin{cases}\dot{X}(t) = \sum_{i=1}^{4}\beta_i(\theta(t))\{\tilde{A}_iX(t) + \tilde{B}_iu(t) + \tilde{D}\omega(t)\} \\ y(t) = \tilde{C}X(t)\end{cases} \tag{11}$$

2.2Problem description

Suppose that the state variables of the PV conversion system (8) are unknown, however, they are necessary for system supervisory and controller design. In addition, the PV system is impacted by the faults and disturbances that will significantly impact the performance of the system, even make the system malfunction. Therefore, estimate the faults are very important for the monitoring system. Due to these reasons, in this paper, the fuzzy observer is designed to estimate the unknown states instead of using the sensors and estimate the information of the faults simultaneously.

3. Fuzzy Observer Design for PV Conversion System

In this section, the observer will be synthesized for the PV conversion system to estimate the unknown states and the fault. The structure of the system is illustrated in Fig. 2. The observer form for the PV system under T-S framework (8) is presented as follows

$$\begin{cases} \dot{s}(t) = \sum_{i=1}^{4} \beta_i\left(\hat{\theta}(t)\right)\{W_i s(t) + Z_i u(t) + H_i y(t)\} \\ \hat{X}(t) = s(t) - Fy(t) \end{cases} \quad (12)$$

where $\hat{X}(t) \in \Re^4$ is the estimation of $X(t)$, $s(t) \in \Re^4$ is state variable vector of the observer. $W_i \in \Re^{4\times 4}$, $Z_i \in \Re^4$, $H_i \in \Re^{4\times 2}$, and $F \in \Re^{4\times 2}$ are the observer gains that need to determine in the next steps.

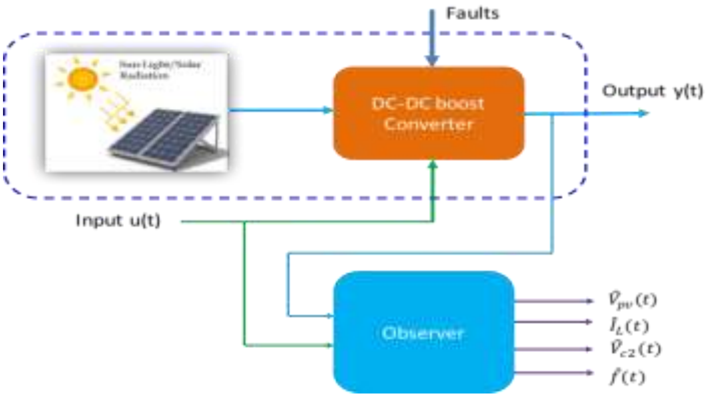

Figure 2. *Structure of the PV conversion system*

Theorem 1: The estimation states approach to real states asymptotically if there exist the matrices W_i, Z_i, H_i, F and the positive symmetric matrix Q such that the following conditions are satisfied.

$$MW_i - M\tilde{A}_i + H_i\tilde{C} = 0 \quad (13)$$

$$Z_i - M\tilde{B}_i = 0 \quad (14)$$

$$M\tilde{D} = 0 \quad (15)$$

$$W_i^T Q + QW_i < 0 \quad (16)$$

Proof: Let us denote the estimation error

$$e(t) = \hat{X}(t) - X(t) \quad (17)$$

Substituting (12) into (17) yields

$$e(t) = s(t) - Fy(t) - X(t) = s(t) - \left(F\tilde{C} + I\right)X(t) \quad (18)$$

Define $M = F\tilde{C} + I$ then (18) becomes

$$e(t) = s(t) - MX(t) \quad (19)$$

Taking the derivative of (19) obtains

$$\dot{e}(t) = \dot{s}(t) - M\dot{X}(t) \quad (20)$$

Substituting (11), (12) into (20), we have

$$\dot{e}(t) = \sum_{i=1}^{4} \beta_i\big(\theta(t)\big)\big\{W_i e(t) + \big[MW_i - M\tilde{A}_i + H_i C\big]x(t) + [Z_i - M\tilde{B}_i]u\big\} - M\tilde{D}\omega(t)\} \quad (21)$$

If the conditions (13) and (15) hold then (21) is rewritten as follows

$$\dot{e}(t) = \sum_{i=1}^{4} \beta_i\big(\theta(t)\big)\{W_i e(t)\} \quad (22)$$

Select the Lyapunov function

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$$V\big(e(t)\big) = e^T(t)Qe(t) \tag{23}$$

Taking the derivative of (23) yields

$$\dot{V}\big(e(t)\big) = \dot{e}^T(t)Qe(t) + e^T(t)Q\dot{e}(t) \tag{24}$$

From (23) and (24), we have

$$\dot{V}\big(e(t)\big) = \sum_{i=1}^{4} \beta_i\big(\theta(t)\big)e^T(t)\{W_i^T Q + QW_i\}\, e(t) \tag{25}$$

If the condition (16) holds, it infers that $\dot{V}\big(e(t)\big) < 0$ and the estimation error $e(t) \to 0$ when $t \to \infty$. The proof is completed.

It is seen that because both W_i and Q are the matrix variables, therfore the term QW_i and $W_i^T Q$ are the nonlinear tearms and the condition (16) is called Bilinear Matrix Inequality (BMI). Owing to the nonlinear terms, solving the BMI (16) become much more challenging. However, regarding solving the Linear Matrix Inequality (LMIs), there exist many algorithms developed in past few years that assist to solve LIM being easier and Matlab software also provides the LMI tool for resovling the LMIs. Due to this reason, in this papers, we have transformed the BMI to LMI and employing the LMI tools of Matlab to obtain the observer gains. The conditions (13)-(15) will be used to transform the BMI (16) to the LMI in the following steps.

From (14), we have

$$(I + F\tilde{C})\tilde{D} = 0 \tag{26}$$

The general solution of (26) is

$$F = \Theta + Y\Xi \tag{27}$$

where $\Theta = -D(\tilde{C}\tilde{D})^+$, $\Xi = \mathrm{I} - (\tilde{C}\tilde{D})(\tilde{C}\tilde{D})^+$ and $(\tilde{C}\tilde{D})^+ = [(\tilde{C}\tilde{D})^T\big(\tilde{C}\tilde{D}\big)]^{-1}(\tilde{C}\tilde{D})^T$

Let us define a slack variable K_i such that

$$K_i = H_i + W_iF \tag{28}$$

Substituting (28) into (13) yields

$$W_i = MA_i - K_i\tilde{C} \tag{29}$$

Combining (29) and (28), one obtains

$$H_i = K_i\big(I + \tilde{C}F\big) - M\tilde{A}_iF \tag{30}$$

Substituting (30) into (29), we have

$$W_i = (I + (\Theta + Y\Xi\,)\tilde{C})\tilde{A}_i - K_i\tilde{C} \tag{31}$$

From (31) and (16), it infers that

$$[(I + (\Theta + Y\Xi\,)\tilde{C})\tilde{A}_i - K_i\tilde{C}]^T Q + Q[(I + (\Theta + Y\Xi\,)\tilde{C})\tilde{A}_i - K_i\tilde{C}] < 0 \tag{32}$$

Rewritten (32), one obtains

$$[(I + \Theta\tilde{C})\tilde{A}_i]^T Q + Q[(I + \Theta\tilde{C})\tilde{A}_i] + (\tilde{C}\tilde{A}_i)^T\Xi^T Y^T Q + QY\Xi\,\tilde{C}\tilde{A}_i - \tilde{C}^T {K_i}^T Q + QK_i\tilde{C} < 0 \tag{33}$$

Let us define $\bar{Y} = QY$ and $\bar{K}_i = QK_i$ then (33) becomes

$$[(I + \Theta\tilde{C})\tilde{A}_i]^T Q + Q[(I + \Theta\tilde{C})\tilde{A}_i] + (\tilde{C}\tilde{A}_i)^T\Xi^T\bar{Y}^T + \bar{Y}\Xi\,\tilde{C}\tilde{A}_i - \tilde{C}^T{\bar{K}_i}^{\,T} + \bar{K}_i\tilde{C} < 0 \tag{34}$$

It is clear that the equation (34) is a LMI therefore, we can conclude that the BMI (16) is transformed to LMI (34) that can be solved easily by Matlab.

The procedure to determine the observer gains are presented as follows

Step 1: Calculate $\Theta = -D(\tilde{C}\tilde{D})^+$ and $\Xi = \mathrm{I} - (\tilde{C}\tilde{D})(\tilde{C}\tilde{D})^+$.
Step 2: Solve (34) by using LMI tools, we obtain $\bar{Y}$ and $\bar{K}_i$.
Step 3: Compute $Y = Q^{-1}\bar{Y}$ and $K_i = Q^{-1}\bar{K}_i$.
Step 4: The observer gains are calculated as follows

$$F = \Theta + Y\Xi\,,\ W_i = M\tilde{A}_i - K_i\tilde{C},\ H_i = K_i\big(I + \tilde{C}F\big) - M\tilde{A}_iF \text{ and } Z_i = M\tilde{B}_i$$

Step 5: The estimation of the state $\hat{x}(t)$ and fault estimation $\hat{f}(t)$ are computed in the following formula

$$\hat{x}(t) = \begin{bmatrix} \hat{V}_{pv}(t) \\ \hat{I}_L(t) \\ \hat{V}_{c2}(t) \end{bmatrix} = [I \quad 0] \times \hat{X}(t), \hat{f}(t) = [0 \quad I] \times \hat{X}(t)$$

4. Simulation Results

In this section, the simulation will be carried out by Matlab and Simulink to show the effectiveness of the proposed observer for estimating both the states of the PV conversion system and the faults. The PV conversion system includes PV model with the parameters in Table 1 and the DC-DC boost with the parameters presented in Table 2. We assume that the system (9) is impacted by the external disturbance and the fault simultaneously. The external disturbance *d(t)* of PV conversion system (9) is the current $i_{pv}(t)$ that is arbitrary signal generated by the PV and the faults exist in both system and output sensors. The mathematical model of the fault is with following form and illusted in Fig.3

$$f(t) = \begin{cases} 0 \quad if \ 0 \le t < 4 \\ -0.2\,t + 1.8 \quad 4 \le t \le 6 \\ 0 \quad if \ t > 6 \end{cases}$$

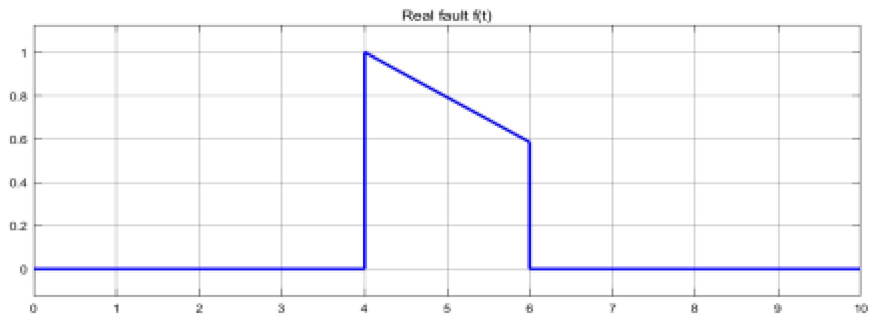

Figure 3. *Time-varying system fault f(t)*

The fault in Fig. 3 is the time-varying fault that happens in the range from 4 second to 6 second. This fault is do not need to satisfy any constraints.

Table 1. *Parameters of PV models*

Symbols	Meaning	Values	Units
P_{pvopt}	Maximum power	60	W
I_{pvopt}	Maximum current	3.5	A
V_{pvopt}	Maximum voltage	17.1	V
I_{ph}	Short circuit current	3.8	A
V_{oc}	Open circuit voltage	21.1	V

Table 2. *Parameters of DC-DC boost Converter*

Symbols	Parameters	Values	Units
C_1	Input Capacitor	500	μF
C_2	Output Capacitor	2200	μF
L	Inductor	5	mH
R_L	Resistance of self-inductance	0.01	Ω
R	Load Resistance	20	Ω

Solving the LMI (34), we obtain the following results

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$$Q=\begin{bmatrix}0.63 & 0.01 & -0.31 & 0.31\\ 0.01 & 4.09 & 0.01 & -0.01\\ -0.31 & 0.01 & 0.63 & 0.31\\ 0.31 & -0.01 & 0.31 & 0.63\end{bmatrix}$$

The observer gains:

$$W_1=\begin{bmatrix}-8.24 & 454.54 & 213.58 & 229.07\\ -0.33 & -2.00 & -0.33 & 0.33\\ -229.07 & 454.54 & -8.24 & -213.58\\ -213.58 & -454.54 & 229.07 & -8.24\end{bmatrix}$$

$$W_2=\begin{bmatrix}-8.24 & 454.54 & 317.76 & 333.24\\ -0.33 & -2.00 & -0.33 & 0.33\\ -333.24 & 454.54 & -8.24 & -317.76\\ -317.76 & -454.54 & 333.24 & -8.24\end{bmatrix}$$

$$W_3=\begin{bmatrix}-8.24 & 454.54 & 192.86 & 208.34\\ -0.33 & -2.00 & -0.33 & 0.33\\ -208.34 & 454.54 & -8.24 & -192.86\\ -192.86 & -454.54 & 208.34 & -8.24\end{bmatrix}, F=\begin{bmatrix}-1 & 1\\ 0 & 0\\ 0 & 0\\ 0 & -1\end{bmatrix}$$

$$W_4=\begin{bmatrix}-8.24 & 454.54 & 215.19 & 230.67\\ -0.33 & -2.00 & -0.33 & 0.33\\ -230.67 & 454.54 & -8.24 & -215.19\\ -215.19 & -454.54 & 230.67 & -8.24\end{bmatrix}, Z_4=10^{-3}\begin{bmatrix}1.5909\\ 7.0000\\ 1.5909\\ -1.5909\end{bmatrix}$$

$$H_1=H_2=H_3=H_4=\begin{bmatrix}0 & 1\\ 200 & -199\\ 0 & 1\\ 0 & -1\end{bmatrix} Z_1=\begin{bmatrix}0\\0\\0\\0\end{bmatrix},$$

$$Z_2=10^{-3}\begin{bmatrix}1.5909\\ 0\\ 1.5909\\ -1.5909\end{bmatrix};\ Z_3=\begin{bmatrix}0\\ 7000\\ 0\\ 0\end{bmatrix}$$

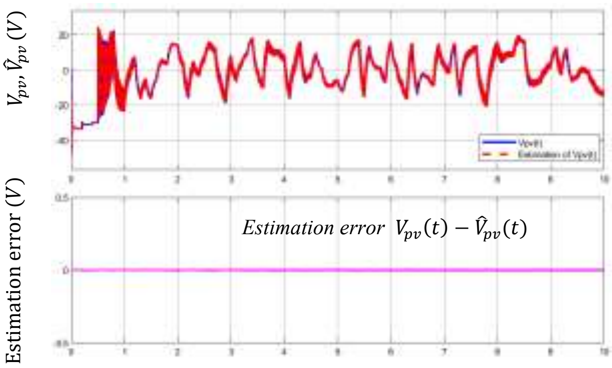

Figure 4. *Real Vpv(t), Estimation* $\hat{V}_{pv}(t)$*, and estimation error* $V_{pv}(t)-\hat{V}_{pv}(t)$

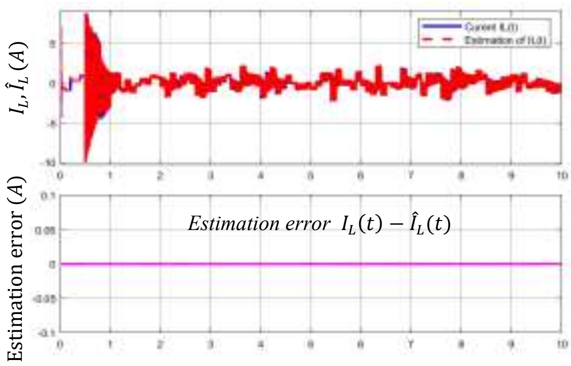

Figure 5. *Real* $I_L(t)$*, Estimation* $\hat{I}_L(t)$*, and estimation error* $I_L(t)-\hat{I}_L(t)$

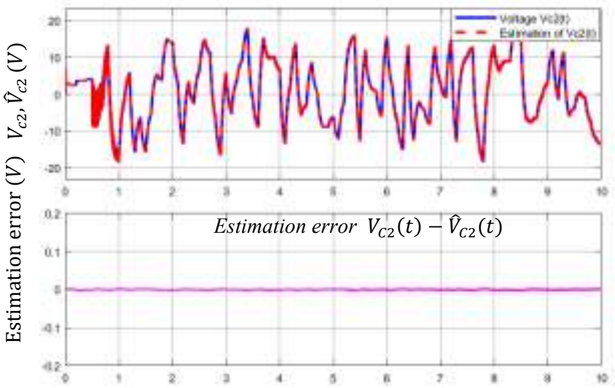

Figure 6. *Real* $V_{c2}(t)$ *estimation*, $\hat{V}_{c2}(t)$, *estimation error* $V_{c2}(t) - \hat{V}_{c2}(t)$

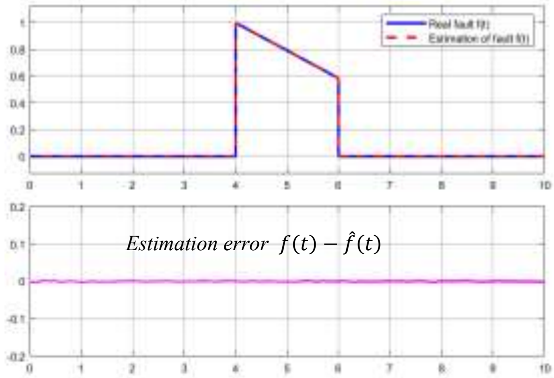

Figure 7. *Real fault f(t), Estimation* $\hat{f}(t)$*, and estimation error* $f(t) - \hat{f}(t)$.

Figs. 4-7 illustrated the simulation results for the PV conversion system (9) with observer form (12). The real values of $V_{pv}(t)$, $I_L(t)$, $V_{c2}(t)$, estimation values of $\hat{V}_{pv}(t)$, $\hat{I}_L(t)$, $\hat{V}_{C2}(t)$, and the estimation errors error $V_{pv}(t) - \hat{V}_{pv}(t)$, $I_L(t) - \hat{I}_L(t)$, *and* $V_{c2}(t) - \hat{V}_{c2}(t)$ are shown in Figs. 4-6, respectively. The Fig. 3 shows that, from second 4 to 6, the fault appears and affects to both the system and the output sensors. From Figs. 4-6, it is seen that estimation states $\hat{V}_{pv}(t)$, $\hat{I}_L(t)$, $\hat{V}_{C2}(t)$ approach to real states $V_{pv}(t)$, $I_L(t)$, $V_{c2}(t)$ asymptotically and all estimation errors $V_{pv}(t) - \hat{V}_{pv}(t)$, $I_L(t) - \hat{I}_L(t)$, *and* $V_{c2}(t) - \hat{V}_{c2}(t)$ are almost zero. The estimation error In Fig. 7, it demonstrated that the estimation of faults can approach a real fault, and the estimation error also converges to zero. Based on these simulation results, it is obvious that, even with the influences of the fault *f(t)*, the proposed observer is still able to eliminate the impact of the fault and successfully estimate the states of the PV conversion system and fault simultaneously.

4. Conclusions

The observer is synthesized for the PV conversion system that is modeled under the T-S fuzzy model framework. The problem of the fault influence has been considered in this paper. The observer can estimate both the unknown states and faults. The observer conditions that presented in term of LMIs are derived in the main theorem. With obtained observer gain, the PV system with the observer is simulated by Matlab and Simulink software. The simulation results have proved the success and merit of the proposed method.

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Van-Phong Vu (Member, IEEE) received the B.S. degree from the Department of Automatic Control, Hanoi University of Sciences and Technology, Hanoi, Vietnam, in 2007, the M.S. degree from the Department of Electrical Engineering, Southern Taiwan University of Sciences and Technology, Tainan, Taiwan, in 2010, and the Ph.D. degree from the Department of Electrical Engineering, National Central University, Jhongli, Taiwan, in 2017. He is currently a Lecturer with the Ho Chi Minh City University of Technology and Education, Ho Chi Minh City. His research interests include the fuzzy systems, intelligent control, observer and controller design for the uncertain systems, polynomial systems, fault estimation, and large-scale systems

Van-Thuyen Ngo received the B.S. degree in Electrical Engineering from Ho Chi Minh City University of Technology and Education, Ho Chi Minh city, Vietnam in 1999; M.S. degree in Electrical Engineering from Ho Chi Minh University of Technology, Ho Chi Minh City, Vietnam in 2003; and the Ph.D. degree in Automation Technology from University of Technology Sydney, Sydney, Australia, in 2008. Dr. Ngo is currently an Associate Professor with the Ho Chi Minh City University of Education and Technology, Ho Chi Minh City. His research interests include the robot planning and control, control system.

Dinh-Nhon Truong received the Ph.D. degree from the Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan, 2013. He is a Senior lecturer at the Department of Automatic Control, Hochiminh City University of Technology and Education, Vietnam. His research interests are Grid-connected wind power systems, Application of FACTS devices and Power system stability.