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Fault detection of a PEMFC system based on delayed LPV observer☆

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ARTICLE INFO

Article history:
Received 31 July 2018
Received in revised form
6 November 2018
Accepted 12 November 2018
Available online 13 December 2018

Keywords:
LPV system
Time-delay
Fault estimation
Fuel cells
Unknown input observer

ABSTRACT

This work deals with the fault estimation of actuator fault for a polymer electrolyte membrane fuel cell (PEMFC) using descriptor approach. The main contribution of this paper is to consider unknown inputs and time delay in the output. Delay-dependent sufficient conditions for the design of an unknown input observer with time delays are given in terms of linear matrix inequalities (LMIs). For that purpose, an unknown input observer (UIO) for delayed LPV model is designed. Firstly, by considering the faults as auxiliary states, we obtain an augmented LPV system. An algorithm scheme is developed in order to compute the UIO proposed for the augmented system with actuator faults, secondly. Basing on the Lyapunov theory, the convergence and the stability of the UIO are analyzed. Finally and in order to apply the proposed fault diagnosis approach, the time delay is related to the mass flow oxygen in the anode of a PEMFC and actuator faults such as the compressor outlet mass flow rate and the return manifold outlet orifice are designed. Simulation results prove the effectiveness of this approach.

Introduction

During the last decade, a plaintiful research activity has been addressing estimation, control and diagnosis problems in FCS (Fuel Cell Systems) and particularly thanks to PEMFC (Proton Exchange Membrane Fuel Cell) applied to automotive systems [1], autonomous robots [2], power supply sources [3] and buildings [4]. It is known that the PEMFC has many advantages: zero pollution, power density, reliability, flexibility, low operating temperature, etc. A fuel cell combines hydrogen and oxygen to produce electricity, heat and water. Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric vehicles.

Modeling a fuel cell system is not easy. Fuel cell systems include materials science, transport phenomena, electro chemistry and catalysis. Fuel cell models are based on thermodynamic, fluid mechanic, FC dynamic and electrochemical process. For this reason, the energy generation from FCs is so complex. A fuel cell is not working alone. A set of auxiliary components are needed such as: air flow compressor, supply and return manifold, hydrogen tank, mass flow and pressure of hydrogen, current and velocity of compressor, water

☆ Fully documented templates are available in the elsarticle package on CTAN.

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https://doi.org/10.1016/j.ijhydene.2018.11.053

pressure, voltage and temperature of the stack, controllers, etc.) in order to reach the desired operating point. When faults occur in the PEMFC, a Fault Detection and Isolation (FDI), a Fault Detection and Diagnosis (FDD) and Fault Tolerant Control (FTC) have been developed in order to guarantee the safe operation, security and availability. The observer or estimator plays an important role to estimate states and fault signals such as in model-based control [5–7], in model-based for fault detection and diagnosis [8–10] and life prognostic [11,12] and in active FTC [13–15]. Then, the interest of observer for FCS no longer needs to be demonstrated and have received a great importance regarding the number of significant papers in this field. Pukrushpan et al. [16] developed a model including auxiliary components: a compressor, a supply and return manifolds, humidifier, etc. This model is used for the air system controlled by a LQR (Linear Quadratic Regulator) to increase the performance. The weakness of this work is the lack of an observer. In recent years, huge research activity has been addressing the problem of estimation in fuel cell systems. Various estimators have been applied to the state estimation of FCS such as Extended Kalman Filters (EKF) [17,18], Unscented Kalman Filter (UKF) [19,20] and adaptive UKF [21,22]. All those approaches are based on the linearization around the operating points which depend on the conditions such as air flow, humidity and temperature. Luenberger observer was used to estimate the membrane water content in PEMFCs. However, this observer ensures its convergence to a neighborhood of the real system states in the presence of external disturbances Arcak et al. [23] developed an adaptive observer in order to estimate the hydrogen partial pressure based on the fuel cell voltage. This work is based on an electrical model without taking account of the low dynamics such a gaseous phases. Grgn et al. [24] developed an observer which consists of two adaptive observers estimating both partial pressures and the membrane water content in PEMFCs. The weakness of this work is the lack of robustness fuel cell voltage's measurement noise and the parameter uncertainties. A nonlinear observer proposed by [25] for a PEMFC system based on Second Order Sliding Mode techniques. The goal is to estimate the hydrogen partial pressure, using the measurements of stack voltage, stack current, anode pressure and anode inlet pressure. Piffard et al. [26] proposed a Sliding Mode State Observer to manage durability issues and cost for PEMFC in automotive applications. The nitrogen build-up in the anode side (relative humidities in the channels) is estimated by an observer. The lack of this observer is the average nitrogen estimation and relative humidities which are not sufficient precise to be used in FDD. Kim et al. [27] developed a sliding mode observer to estimate the hydrogen and oxygen pressure, the manifold. This method is not suitable for the estimation of hydrogen and oxygen mass flow which are useful for the safety of PEMFC. Consequently, the problem control, observation, diagnosis has been one of the main interests for many researchers during the recent years. All those previous work cited in this article do not take account on the time delays. Time-delay often appears in many control systems such as chemical reactions [28], mechanical systems [29], electrical circuits [30] and many other process control systems [31,32]. This delay is due to various reasons such as transportation, communication protocols, transmission or inertia effects. In many cases, time delay systems are source of instability. The stability issue and the performance of control systems with delay are, therefore, both of theoretical and practical importance. Observer design for time-delay systems appears a stabilization problem since the observation error dynamics must be stabilized using only partial state measurements.Compared with full-state feedback stabilization, the stabilization using partial state is in the general case a quite hard problem. For further results on observation of time-delay systems, we refer the reader to Bhat and Koivo [33], Knap and Carter [34] and Hou et al. [35]. Referring to many results on observation of time-delay systems, conditions under which the observer/filter exists can be classified into two main categories: delay-independent conditions and delay-dependent ones [36]. However, delay-dependent results expose less conservative than delay-independent conditions. Nevertheless, in most cases, a small delay is tolerable to maintain stability by output feedbacks. Karimi and Chadli [37] have developed a Takagi-Sugeno (T-S) fuzzy models with unknown inputs and state delays. Sufficient conditions for the design of an unknown input T-S observer with time delays have been done in terms of linear matrix inequalities (LMIs). Nevertheless, in most cases, a small delay is tolerable to maintain stability by output feedback. For further results on observation of time-delay systems, the reader can refer to Carpace et al. [38]. Some works are related to Time Delay Control (TDC) applied to fuel cells. Wang et al. [39] focused on the accurate but simple control using TDC to prevent oxygen starvation and/or to obtain the maximum efficiency of the PEMFC. Kim [40] proposed a TDC in order to regulate the optimum stoichiometry of oxygen and hydrogen, even when there are dynamical fluctuations of the required PEMFC power.

All those controllers aim to increase the transient performance of PEMFC but they do not take account of the time delay appearing obviously in the PEMFC.

Regarding the estimation of on observation of time delays systems for fuel cell systems, very few work can be found in the literature. Shultze and Horn [41] proposed a state estimation strategy based on the UKF combined with a prediction compensating the significant time delay for the estimated actual system state. A measurement of the cathode exhaust air (ODA) gas mass flow and oxygen content introduced a significant time delay. Following this work, the same authors proposed a state estimation with time delay and state feedback control of cathode exhaust gas mass flow for PEMFCS. The weakness of this method is the linear feedback controller.

The contribution of this paper is the fault diagnosis problem of LPV systems with varying time-delay by using the descriptor approach with the measurement of mass flow oxygen is delayed. The designed observer depends to the time-delay created in the studied system. The existence and the convergence of the UIO are obtained respectively by solving the Linear Matrix inequalities (LMIs) and using the Lyapunov theory. The observer gains are calculated in presence of the delayed measurement.

The paper is organized as follows. The second section develops upon the Fuel Cell model rewritten in the form of delayed LPV system. It is followed by a description of the nonlinear unknown input observer design in the third section.

The stability and the convergence of the observer in presence of the delay systems are showed through results given in this section. Afterwards, in the fourth section, a PEM fuel cell system with the compressor outlet mass flow rate and the return manifold outlet orifice actuators are tested to verify the desired performance. Conclusions are given in the last section.

Description and modeling of fuel cell systems

PEM fuel cell description

The fuel cell system used in this study is shown on Fig. 1. The fuel cell is an electrochemical device that converts electrochemical energy of fuel into electrical energy. It is composed by an electrolyte, an anode (negative electrode) and cathode (positive electrode) and then the electrical current is generated by an electrochemical reaction. For the fuel cell to work, it needs hydrogen which enters the FC in the anode and oxygen which enters at the cathode, usually oxygen is produced by air compressor. There are different types of electrolyte layers. PEMFC can be used for electric vehicles, mobile phones, laptops, and generally small portable electronics. The advantage of PEMFC is regarding the conduction of proton but impermeable to gas. In order to work as shown on Fig. 1, auxiliary devices are necessary: air compressor, hydrogen tank, a supply manifold and a return manifold.

PEM fuel cell model

Pukrushpan et al. [16] have presented the model given by equation (1). The model represents a good behavior of a fuel cell stack and the observer and control community generally accept it.

$$
\begin{aligned}
\dot{p}_{sm}(t) &= \frac{\gamma R_a}{V_{sm}}\left(T_{atm}W_{cp}\left(1+\frac{1}{\eta_{cp}}\right)\left(\frac{p_{sm}(t)}{p_{atm}}\right)^{\frac{\lambda-1}{\gamma}} + k_{sm,out}\left(p_{sm}(t) - \frac{R_{O_2}T_{st}}{V_{ca}}T_{sm}m_{O_2,ca}(t-\tau)\right)\right)\\
\dot{p}_{rm}(t) &= \frac{R_aT_{rm}}{V_{rm}}\left(k_{ca,out}\left(\frac{R_{O_2}T_{st}}{V_{ca}}m_{O_2,ca}(t-\tau) - p_{rm}(t)\right) - k_{rm,out}(p_{rm}(t)-p_{atm}(t))\right)\\
\dot{m}_{O_2,ca}(t) &= k_{sm,out}p_{sm}(t) - (k_{sm,out}+k_{ca,out})\frac{R_{O_2}T_{st}}{V_{ca}}m_{O_2,ca}(t) + k_{ca,out}p_{rm}(t)\\
\dot{m}_{H_2,an}(t) &= K_1\left(K_2p_{sm}(t) - \frac{R_{H_2}T_{st}}{V_{an}}m_{H_2,an}(t)\right)
\end{aligned}
\tag{1}
$$

where the state vector $x(t)$, the input vector $u(t)$ and the output vector $y(t)$ are defined as

$$
\begin{aligned}
x(t) &= \begin{bmatrix} p_{sm} & p_{rm} & m_{O_2,ca} & m_{H_2,an}\end{bmatrix}^T\\
y(t) &= \begin{bmatrix} p_{sm} & p_{rm} & m_{H_2,an}\end{bmatrix}^T\\
u(t) &= \begin{bmatrix} W_{cp} & k_{rm,out}\end{bmatrix}^T
\end{aligned}
$$

Then, the system (1) can be obtained as

$$
\begin{aligned}
\dot{x}(t) &= A_0x(t) + A_1x(t-\tau) + Bu(t)\\
y(t) &= Cx(t)
\end{aligned}
\tag{2}
$$

where

$$
A_0 = \begin{bmatrix} -\frac{\gamma R_a k_{sm,out}T_{sm}}{V_{sm}} & 0 & 0 & 0\\ 0 & -\frac{R_a k_{ca,out}T_{rm}}{V_{rm}} & 0 & 0\\ K_1K_2 & 0 & -\frac{K_1R_{H_2}T_{st}}{V_{an}} & 0\\ k_{sm,out} & k_{ca,out} & 0 & \chi_{44}\end{bmatrix}, A_1 = \begin{bmatrix} 0&0&0&\chi_{14}\\0&0&0&\chi_{24}\\0&0&0&0\\0&0&0&0\end{bmatrix} B = \begin{bmatrix} b_1(p_{sm}) & 0\\ 0 & b_2(p_{sm})\\ 0&0\\0&0\end{bmatrix}, \text{ and } C = \begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\end{bmatrix}
$$

$$
\chi_{14} = \frac{\gamma R_a k_{sm,out}R_{O_2}T_{st}T_{sm}}{V_{ca}V_{sm}},\quad \chi_{24} = \frac{R_a k_{ca,out}R_{O_2}T_{st}T_{sm}}{V_{ca}V_{sm}},\quad \chi_{44} = -\frac{(k_{sm,out}+k_{ca,out})R_{O_2}T_{st}}{V_{ca}}
$$

$$
b_1(p_{sm}) = \frac{\gamma R_aT_{atm}\left(\eta_{cp}+1\right)}{V_{sm}\eta_{cp}},\quad b_2(p_{sm}) = -\frac{R_aT_{rm}}{V_{rm}}(p_{rm}-p_{atm})
$$

The PEM fuel cell system can be rewritten as

$$
\begin{aligned}
\dot{x}(t) &= A_0x(t) + A_1x(t-\tau) + B_iu(t)\\
y(t) &= Cx(t)
\end{aligned}
\tag{3}
$$

where: $x(t)\in\Re^n$ is the state vector, $u(t)\in\Re^c$ is the control input and $y(t)\in\Re^m$ represents the output vector.A_0, $A_1$and C are the matrices with appropriate dimensions. And B_i for $i = 1..r$ is the matrice of the time bounded varying parameter ρsuch that:

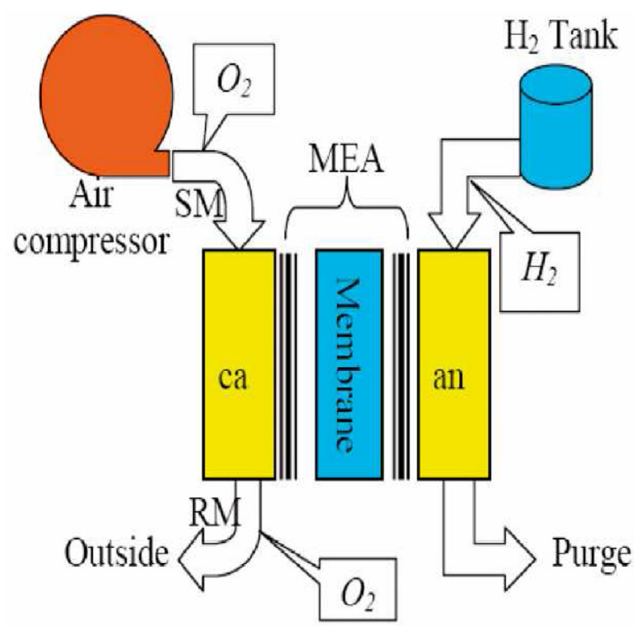

Fig. 1 – PEM fuel cell system with auxiliary components.

$$B(\rho) = \sum_{i=1}^{r} \rho_i B_i \tag{4}$$

ρ_i are weights of the LPV subsystems satisfying:

$$\sum_{i=1}^{r} \rho_i = 1, 0 \le \rho_i \le 1 \tag{5}$$

Considering the actuator fault, the polytopic representation of the system (3) can be as follows

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} A_j x(t - \tau_j(t)) + B_i u(t) + F_i f(t) \right) \\ y(t) = Cx(t) \\ \tau_0 = 0 \\ 0 \le \tau_j \le \tau_m; j = 1..n \\ x(t) = \phi(t) \end{cases} \tag{6}$$

with τ_j for $j = 0..n$ are the delays which τ_m is the delay upper bound and $\tau_0 = 0$. An augmented system is proposed as:

$$\begin{cases} E\dot{\overline{x}}(t) = \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} \overline{A}_j x(t - \tau_j(t)) + \overline{B}_i u(t) \right) \\ y(t) = \overline{C}\overline{x}(t) \\ \tau_0 = 0 \\ 0 \le \tau_j \le \tau_m; j = 1..n \\ \overline{x}(t) = \phi(t) \end{cases} \tag{7}$$

with:

$$\overline{x}(t) = \begin{bmatrix} x(t) \\ f(t) \end{bmatrix}, E = \begin{bmatrix} I_n & 0 \\ 0 & I_p \end{bmatrix}$$
$$\overline{A}_j = \begin{bmatrix} A_j & F_i \\ 0 & I_p \end{bmatrix}, \overline{B}_i = \begin{bmatrix} B_i \\ 0 \end{bmatrix}, \overline{C} = [C \quad 0]$$

Assumptions

- The pair (A_j, C) is observable for $j = 0..n$
- The matrix C is of full row rank.

Lemma1. *Consider two matrices P and Z, P is a positive definite matrix and Z is full column rank, then we have* $ZPZ^T > 0$

Unknown input observer design

We present here a designed unknown input observer for delayed LPV systems. The existence and convergence conditions are formulated as LMIs terms. The observer considered for the system (6) is given by:

$$\begin{cases} \dot{z}(t) = \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} N_j z(t - \tau_j(t)) + L_j y(t - \tau_j(t)) + G_i u(t) \right) \\ \hat{\overline{x}}(t) = z(t) + H_2 y(t) \\ \hat{y}(t) = C\hat{\overline{x}}(t) \\ z(t) = 0, -\tau_m \le t \le 0 \\ r(t) = y(t) + \hat{y}(t) \end{cases} \tag{8}$$

where $\hat{x}(t)$ is the state estimation vector of $x(t)$. H_2, N_j, L_j and G_i are the observer matrices which should be determined. $r(t)$ is called residual vector that is used to detect faults. The state estimation error is:

$$e(t) = \overline{x}(t) - \hat{\overline{x}}(t) \tag{9}$$

$$e(t) = \overline{x}(t) - z(t) - H_2\overline{C}\overline{x}(t) \tag{10}$$

$$e(t) = (I_n - H_2\overline{C})\overline{x}(t) - z(t) \tag{11}$$

If $H_1 \in \Re^{n \times n}$ can be calculated from the following condition:

$$H_1 E = I_n - H_2\overline{C} \tag{12}$$

then,

$$e(t) = H_1 E\overline{x}(t) - z(t) \tag{13}$$

and the error dynamics is given as:

$$\dot{e}(t) = H_1 E\dot{\overline{x}}(t) - \dot{z}(t) \tag{14}$$

After substituting (6) and (8) in (14) results:

$$\begin{aligned} \dot{e}(t) = & \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} H_1 \left(\overline{A}_j x(t - \tau_j(t)) + \overline{B}_i u(t) \right) \right) \\ & - \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} N_j z(t - \tau_j(t)) + L_j y(t - \tau_j(t)) + G_i u(t) \right) \end{aligned} \tag{15}$$

some manipulations result:

$$\begin{aligned} \dot{e}(t) = & \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} N_j e(t - \tau_j(t)) + (H_1 A_j - L_j C - N_j H_1 E) x(t - \tau_j(t)) \right. \\ & \left. + (H_1 B_i - G_i) u(t) \right) \end{aligned} \tag{16}$$

If the following conditions hold,

$$H_1E + H_2C = I_n \tag{17}$$

$$H_1A_j - N_jH_1E = -L_jC \tag{18}$$

$$G_i = H_1B \tag{19}$$

the dynamic error equation becomes

$$\begin{cases} \dot{e}(t) = \sum_{i=1}^{r} \rho_i \left(\sum_{j=0}^{n} N_j e(t-\tau_j(t)) \right) \\ r(t) = \overline{C}e(t) \end{cases} \tag{20}$$

Lemma2. *The delayed LPV system described by (20) is stable if there exist a definite positive symmetric matrices P and Q_j for $j = 1..n$ satisfying*:

$$\begin{bmatrix} PN_0 + N_0^TP + Q_1 + \ldots + Q_n & PN_1 & PN_2 & \ldots & PN_n \\ * & -(1-\alpha_1)Q_1 & 0 & \ldots & 0 \\ * & * & -(1-\alpha_2)Q_2 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ * & * & * & \ldots & -(1-\alpha_n)Q_n \end{bmatrix} < 0 \tag{21}$$

Proof: The Lyapunov-Karasovskii function

$$V(e(t)) = e^T(t)Pe(t) + \sum_{j=1}^{n} \int_{t-\tau_j(t)}^{t} e^T(s)Q_je(s)ds \tag{22}$$

is considered such that P and Q_j for $j = 1..n$ are definite positive symmetric matrices. The time derivative of (22) is:

$$\begin{aligned} \dot{V}(e(t)) &= e^T(t)PN_0e(t) + e^T(t)PN_0^Te(t) \\ &+ \sum_{j=1}^{n} \left(e^T(t)PN_je(t-\tau_j(t)) + e^T(t-\tau_j(t))PN_j^Te(t)\right. \\ &\left.+ e^T(t)Q_je(t) - (1-\dot{\tau}_j(t))e^T(t-\tau_j(t))Q_je(t-\tau_j(t))\right) \end{aligned} \tag{23}$$

Considering that $\dot{\tau}_j \le \alpha_j$ for $j = 1..n$, we obtain

$$\dot{V}(e(t)) \le \sum_{j=0}^{n} \begin{bmatrix} e(t) \\ e(t-\tau_1) \\ e(t-\tau_2) \\ \vdots \\ e(t-\tau_n) \end{bmatrix}^T \xi \begin{bmatrix} e(t) \\ e(t-\tau_1) \\ e(t-\tau_2) \\ \vdots \\ e(t-\tau_n) \end{bmatrix} \tag{24}$$

where

$$\xi = \begin{bmatrix} PN_0 + N_0^TP + Q_1 + \ldots + Q_n & PN_1 & PN_2 & \ldots & PN_n \\ * & -(1-\alpha_1)Q_1 & 0 & \ldots & 0 \\ * & * & -(1-\alpha_2)Q_2 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ * & * & * & \ldots & -(1-\alpha_n)Q_n \end{bmatrix} \tag{25}$$

According to the Lyapunov stability theory, the dynamic error (20) is stable if $\dot{V}(e(t))$ is definite and negative [42].

Steps for computing the UIO

This subsection will focus with the steps for calculating the designed unknown input observer.

$$[H_1 \quad H_2] \begin{bmatrix} E \\ C \end{bmatrix} = I_n \tag{26}$$

The matrix $H = [H_1 \quad H_2]$ is unknown and $Y = \begin{bmatrix} E \\ C \end{bmatrix}$ .If

$$rank(Y) = n \tag{27}$$

Then the solution of (26) is:

$$H = I_nY^+ \tag{28}$$

Where the pseudo inverse matrix Y^+ is of $(n \times (n+m))$ dimension.

$$Y^+ = (Y^TY)^{-1}Y^T \tag{29}$$

Such that $Y_1 \in \Re^{n\times n}, Y_2 \in \Re^{n\times m}$ and $X = I_n - YY^+$, the equation (28) can be rewritten as follow:

$$H = [H_1 \quad H_2] = I_n[Y_1^+ \quad Y_2^+] + K[X_1 \quad X_2] \tag{30}$$

Introducing a variable K_j for $j = 0..n$, where

$$K_j = L_j - N_jH_2 \tag{31}$$

So,

$$N_j = H_1A_j - K_jC \tag{32}$$

After substituting H_1, (32) becomes

$$N_j = H_{10}A_j + KX_1A_j - K_jC \tag{33}$$

where

$$H_{10} = I_nY_1^+ \tag{34}$$

Convergence and stability analysis

Theorem1. *If there exist symmetric positive definite matrices P and Q_j for $j = 1..n$ and matrices M and P_j for$j = 0..n$ such that*

$$\begin{bmatrix} \Delta_0 & \Delta_1 & \Delta_2 & \dots & \Delta_n \\ * & -(1-\alpha_1)Q_1 & 0 & \dots & 0 \\ * & * & -(1-\alpha_2)Q_2 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ * & * & * & \dots & -(1-\alpha_n)Q_n \end{bmatrix} < 0 \tag{35}$$

where

$$\begin{aligned} \Delta_0 &= PH_{10}A_0 + MX_1A_0 - P_0C + (PH_{10}A_0 + MX_1A_0 - P_0C)^T \\ &\quad + Q_1 + \dots + Q_n \\ \Delta_j &= PH_{10}A_j + MX_1A_j - P_jC, j = 1..n \end{aligned} \tag{36}$$

So, the observer (8) exists and the state estimation error converges to a small set.

$$K = P^{-1}M \tag{37}$$

$$K_j = P^{-1}P_j, j = 1..n \tag{38}$$

Proof: Replacing equation (33) in the Lemma2 (21).

Algorithm 1. UIO design

Step 1. Compute $H_10 = I_nY_1^+$ and X_1 from the n first columns of X.
Step 2. Solve LMI (35) in order to obtain the matrices P, M, Q_j for $j = 1..n$ and P_i for $j = 0..n$.
Step 3. Calculate K and K_j for $j = 0..n$ from the equations (37) and (38) respectively.
Step 4. Compute $G_i$for $i = 1..r$, H_2 and N_j for $j = 0..n$ respectively from equations (17), (19) and (33).
Step 5. Compute $L_j$for $j = 0..n$from equation (31).

Numerical simulation

In this section, we test a PEM fuel cell system with actuator fault. Considering the range of the supply and return manifold pressures,$[p_{sm_{min}} \quad p_{sm_{max}}]$ and $[p_{rm_{min}} \quad p_{rm_{max}}]$, the membership function can be selected as

$$\begin{aligned} \rho_1(p_{sm}, p_{rm}) &= \frac{p_{sm_{max}} - p_{sm}}{p_{sm_{max}} - p_{sm_{min}}} \times \frac{p_{rm_{max}} - p_{rm}}{p_{rm_{max}} - p_{rm_{min}}} \\ \rho_2(p_{sm}, p_{rm}) &= \frac{p_{sm_{max}} - p_{sm}}{p_{sm_{max}} - p_{sm_{min}}} \times \frac{p_{rm} - p_{rm_{min}}}{p_{rm_{max}} - p_{rm_{min}}} \\ \rho_3(p_{sm}, p_{rm}) &= \frac{p_{sm} - p_{sm_{max}}}{p_{sm_{max}} - p_{sm_{min}}} \times \frac{p_{rm_{max}} - p_{rm}}{p_{rm_{max}} - p_{rm_{min}}} \\ \rho_4(p_{sm}, p_{rm}) &= \frac{p_{sm} - p_{sm_{max}}}{p_{sm_{max}} - p_{sm_{min}}} \times \frac{p_{rm} - p_{rm_{min}}}{p_{rm_{max}} - p_{rm_{min}}} \end{aligned} \tag{39}$$

The matrices of the model (6) can be calculated using Table 1 as following.

Table 1 – Nomenclature.

Variables	Description	Value
$k_{rm,out}$	The return manifold outlet orifice	$0.3629 \times 10^{-5}(Kg/sa)$
$k_{ca,out}$	cathode outlet orifice constant	0.2177×10^{-5}
$k_{sm,out}$	manifold outlet orifice constant	0.3629×10^{-5}
η_{cp}	Compressor efficiency	0.8
γ	The ratio of specific heats of air	1.4
R_a	The air gas constant	$286.9J/(kgK)$
R_{O_2}	Oxygen gas constant	$256.9J/(kgK)$
R_{H_2}	Hydrogen gas constant	$4124.3J/(kgK)$
M_{H_2}	Hydrogen molar mass	$2.016 \times 10^{-3}kg/mol$
M_{O_2}	Hydrogen molar mass	$32 \times 10^{-3}kg/mol$
k_t	Compressor motor	$0.0153N.m/A$
k_v	Compressor motor constant	$0.0153V.(rad/s)$
K_1	proportional gain	2.1
K_2	nominal pressure drop coefficient	0.94
C_p	specific heat capacity of air	$1004J/(mol.K)$
T_{atm}	atmospheric temperature	298.15K
T_{sm}	supply manifold temperature	300K
T_{rm}	return manifold temperature	300K
T_{st}	stack temperature	350K
V_{ca}	cathode volume	$0.01m^3$
V_{rm}	return manifold volume	$0.005m^3$
V_{an}	anode volume	$0.005m^3$
n	cell number in fuel cell stack	381
F	Faraday constant	96485 coulombs
W_{cp}	compressor outlet mass flow rate	$0.1kg/s$
p_{atm}	atmospheric pressure	$101325Pa$

$$A_0 = \begin{bmatrix} -21.86 & 0 & 0 & 0 \\ 0 & -37.47 & 0 & 0 \\ 1.97 & 0 & -6.06 \times 10^8 & 0 \\ 3.63 \times 10^{-6} & 2.17 \times 10^{-6} & 0 & -52.81 \end{bmatrix},$$

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 1.99 \times 10^8 \\ 0 & 0 & 0 & 3.41 \times 10^8 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} B_1 = \begin{bmatrix} 9.94 \times 10^5 & 0 \\ 0 & -4.94 \times 10^{11} \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$B_2 = \begin{bmatrix} 9.94 \times 10^5 & 0 \\ 0 & -2.06 \times 10^{13} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, B_3 = \begin{bmatrix} 1.45 \times 10^7 & 0 \\ 0 & -4.94 \times 10^{11} \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$B_4 = \begin{bmatrix} 1.45 \times 10^7 & 0 \\ 0 & -2.06 \times 10^{13} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \end{bmatrix}, F = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

The actuator faults such as the compressor outlet mass flow rate (W_{cp}) and the return manifold outlet orifice are designed and fault signals are given as:

$$f_1(t) = \begin{cases} W_{cp} & 10 \le t \le 30 \\ 0, & otherwise \end{cases} f_2(t) = \begin{cases} 10^{-3}(\sin(0.5t) & 40 \le t \le 50 \\ 0, & otherwise \end{cases} \tag{40}$$

Solving the LMIs according to the algorithm steps, the gains of the UIO can be computed as following:

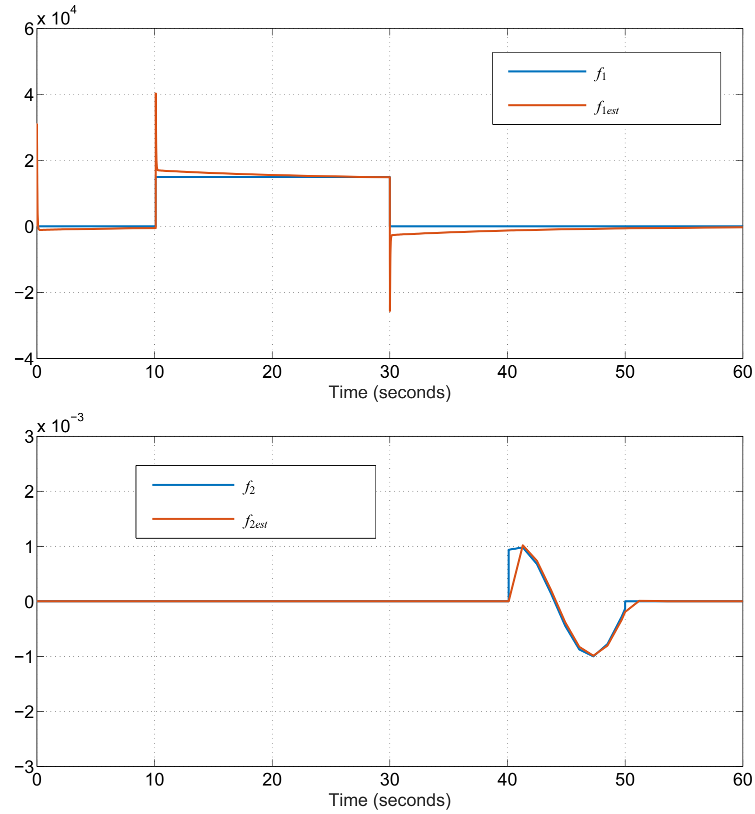

Fig. 2 – The time evolution of real and estimated actuator faults, f_1 and.f_2.

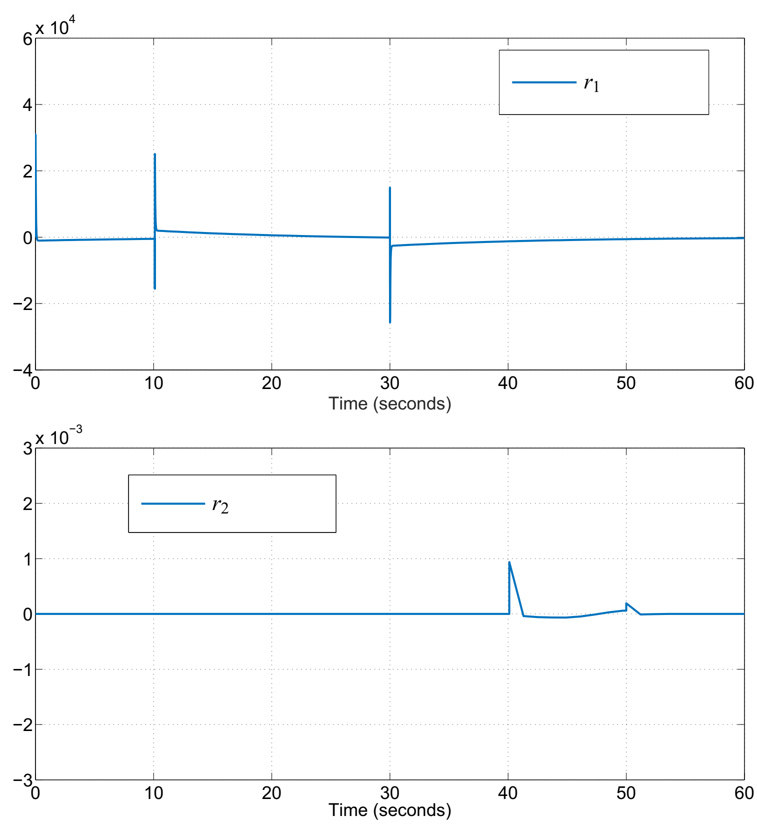

Fig. 3 – Actuator fault estimation errors, r_1 and.r_2.

$$N_0 = 10^8 \times \begin{bmatrix} -0.9301 & -0.5453 & 0.0000 & 0.9944 \\ -1.5942 & -0.9347 & 0.0000 & 1.7045 \\ -0.0000 & 0.0000 & -0.0000 & 0.0000 \\ 0.0000 & 0.0000 & -0.0000 & -0.0000 \end{bmatrix}$$

$$L_0 = 10^8 \times \begin{bmatrix} 0.9301 & 0.0803 & -0.2727 \\ 1.5942 & 0.1376 & -0.4674 \\ 0.0000 & -0.0000 & -3.0314 \\ -0.0000 & -0.0000 & 0.0000 \end{bmatrix}$$

$$G_1 = 10^{11} \times \begin{bmatrix} 0.0000 & 0 \\ 0 & -2.4681 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$G_2 = 10^{13} \times \begin{bmatrix} 0.0000 & 0 \\ 0 & -1.0317 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$G_3 = 10^{11} \times \begin{bmatrix} 0.0001 & 0 \\ 0 & -2.4681 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$G_4 = 10^{13} \times \begin{bmatrix} 0.0000 & 0 \\ 0 & -1.0317 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Other matrices of the observer are computed from the algorithm and the above gains. We note that we have the same outputs gains and the same states gains for $j = 0..4$ because firstly, there is no parameter variation in outputs and states respectively and we consider a constant time delay secondly. Then, we simulate the system during the time of $t = 60$s. Simulation results are illustrated as below:

The simulation results are given in Fig. 2 and Fig. 3. Fig. 2 presents the fault estimates and Fig. 3 shows the corresponding estimation errors. In Fig. 2, f_1 and f_2 are the compressor outlet mass flow rate and the return manifold outlet orifice actuators, respectively. First fault occurs in the period of $10-30$s, this period is called as failure simulation time, and second fault has a sinus form is created between 40 s and 50 s. These faults are successfully detected and estimated basing on the designed unknown input observer with time delay. From the obtained results, we see that the fault can be efficiently estimated with a small error. The estimated actuator faults converge to the real values rapidly, which indicates that the proposed approach is efficient.

Conclusion

In this paper, an actuator fault estimation algorithm for PEM fuel cell system with small time-delay has been investigated. Basing on the descriptor approach, we elaborate an augmented system which introduce the faults as an auxiliary states. Then, we design the unknown input observer for delayed LPV systems and we analyze the convergence of the observer using Lyapunov theory. By solving the LMIs, the performance of this approach is compared in terms of state observation errors and in terms of actuator error estimates. A PEMFC system is used to prove the effectiveness of the proposal approach. Future research might be developed to produce a minimum of conservative time delay dependent conditions and further works will be focused on the fault tolerant control of delayed LPV systems with actuator and/or sensor faults.

Acknowledgment

This work was supported by the Ministry of High Education and Research of Tunisia and with the cooperation of the Center of Research in Informatics, Signal and Automatics of Lille, France (CRIStAL).

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