International Journal of Sciences and Techniques of Automatic control & computer engineering
IJ-STA, Volume 10, N°1, Special Issue AND, April 2016, pp 2055–2061.

Fault Detection Identification and Isolation via high-gain observer in a Semi Continuous Stirred Tank Reactor

Amira ABDELKADER[1,2], Moez BOUSSADA[1], Koffi FIATY[2], Hassan HAMMOURI[2] and Ahmed Said NOURI[1]
[1]National Engineering School of Gabes, University of Gabes,
Research unit: Numerical Control of Industrial Process
Gabes 6029, Tunisia, Phone: +216 75 39 21 00
[2] LAGEP, University of Lyon 1, F-69622,Villeurbanne, Lyon, France
CNRS, UMR 5007.
43 boulevard 11 novembre, 69100 Villeurbanne, France
Email:{abdelkader, fiaty, hammouri}@lagep.univ-lyon1.fr, moez.boussada@isimg.rnu.tn, ahmedsaid.nouri@enig.rnu.tn

***Abstract*—This paper deals with Fault Detection Identification and Isolation (FDII) in actuators and system (component) applied to a Semi Continuous Stirred Tank Reactor(SCSTR).**
The proposed FDII is based on high gain observers, for detecting faults of actuators and system component. This algorithm has the advantage of detecting multiple faults simultaneously. The observer is constructed from a sub-model, the number of observers is related by number of actuator or/and system component how we want estimate. The signals used in our study derived from a real system.

***Index Terms*—: Actuator and system fault detection, fault identification and isolation, high gain observer, chemical reactor.**

I. INTRODUCTION

This paper present Fault Detection Identification and Isolation (FDII) in actuators and system component applied to a (SCSTR). The study of FDI for nonlinear systems is very important in practical applications, because many industrial processes are nonlinear nature and consequently have a nonlinear mathematical model.
Among the different methods of FDI, there are two approaches:

- based data analysis: neural networks, fuzzy logic (qualitative methods) and expert system (quantitative method) etc ..
- model-based : for example the fault tree (quantitative method)[10], [17] or else Analytical Redundancy Relations (ARR), filtering and Observers (qualitative methods)[16].

The observer-based FDI is the most extensively studied technique [18], [5], [15], [12], [9], [3], [6], [19], [11] and [7]. Indeed, with this technique, not only the fault can be detected and isolated but also it can be identified.

This paper is organized as follows; in section II, we describe the model of the reactor. In section III, a high gain observer is constructed for estimating the evolution of actuators and/or system component, hence we solve the problem of residual generation. Simulation results are reported throughout. Finally some remarks are given.

II. SYSTEM DESCRIPTION

In the reactor shown in Fig.1, the esterification reaction of the fatty acids presents in the olive oil waste is formulated by equation (1).

$$RCO_2H + C_2H_5OH \rightleftharpoons RCO_2C_2H_5 + H_2O \qquad (1)$$

The model obtained from the material and energy balances is based on the following assumptions:

- the reaction mixture is assumed to be perfectly stirred,
- the thermodynamic equilibrium at the liquid-vapor interface is reached and is described by the Raoult law,
- saturation vapor pressure of the different compounds are described by Antoine equation,

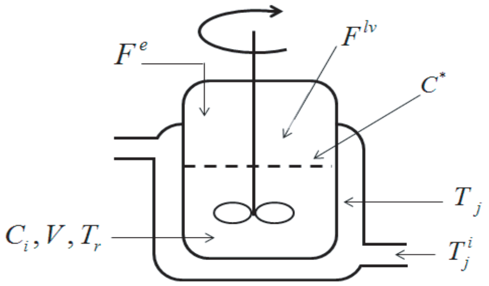


Fig. 1: Schema of the chemical reactor

This paper was recommended for publication in revised form by the Editor Staff.
Edition: CPU of Tunis, Tunisia, ISSN: 1737-7749

The system model is given by [4] :

$$\begin{cases} \frac{dC_i}{dt} = \frac{F^e}{V}(C_i^e - \frac{\rho^e}{\rho}C_i) - \frac{F^{lv}}{V}(C_i^* - \frac{\rho^{lv}}{\rho}C_i) + \upsilon_i r, \quad i = 1..4 \\ \\ \frac{dV}{dt} = \frac{F^e\rho^e}{\rho} - \frac{F^{lv}\rho^{lv}}{\rho} \\ \\ \frac{dT_r}{dt} = \frac{F^e\rho^e}{V\rho C_p}(C_p^e T_r^e - C_p T_r) - F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{VC_p} - r\frac{\Delta_r H}{\rho C_p} \\ \qquad + \frac{UA}{V\rho C_p}(T_j - T_r) \\ \\ \frac{dT_j}{dt} = \frac{F_j}{V_j}(T_j^i - T_j) - \frac{UA}{V_j\rho_j C_p}(T_j - T_r) \end{cases} \tag{2}$$

With C_1, C_2, C_3 and C_4 are respectively the concentration of the fatty acids (oleic acid), ethanol, water and esters, F^e is the input flow rate, F^{lv} is the vaporization flow rate, V is the liquid phase volume in the reactor, T_r is the temperature of the reaction mixture and T_j is the jacket temperature.
The reaction rate is given by [8]:
$r = (a + bC_{cat}) \exp\left(-\frac{E}{RT_r}\right) C_1 C_2$
with a and b are constants.
C_{cat} the catalysor concentration, defined as: $a_{cat} * m_{cat}$, with a_{cat} is its activity and m_{cat} is its mass, with $a = 1.15\ m^3/mol/s$, $b = 0.579\ m^3/mol/s * (1/meqH^+)$, $a_{cat} = 3.2$ and $m_{cat} = 10\ g$.
The concentration of the different components in the liquid film are calculated from the following relations by:

$$C_i^* = y_i^* \frac{\rho^{lv}}{\sum\limits_i y_i^* M_i}$$

with

$$y_i^* = \frac{P_i^0(T_r)}{P}\frac{C_i}{\sum\limits_i C_i} \quad ; \quad \ln\left(P_i^0(T_r)\right) = \alpha_i - \frac{\beta_i}{T_r + \gamma_i}$$

and

$$\rho^{lv} = \sum_i \frac{y_i^* M_i}{\sum\limits_k \frac{y_k^* M_k}{\rho_k}}$$

The coefficients α_i, β_i and γ_i used from [14].

The parameter F^{lv} plays an important role in the plant behavior since it is present in the chemical and thermodynamic aspect, for more details of the parameter synthesis and the experimental validation see [4] and [1].

III. HIGH-GAIN OBSERVER FOR NONLINEAR SYSTEMS FAULT DETECTION AND DIAGNOSIS IN SCSTR

The esterification plant can now be described by the following equations:

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ \\ y = h(x) \end{cases} \tag{3}$$

with $f(x) = \begin{bmatrix} -\frac{F^{lv}}{V}(C_i^* - \frac{\rho^{lv}}{\rho}C_i) + \upsilon_i r \\ -\frac{F^{lv}\rho^{lv}}{\rho} \\ -\frac{F^{lv}\rho^{lv}}{\rho}\frac{\Delta H_v}{VC_p} - r\frac{\Delta_r H}{\rho C_p} + \frac{UA}{V\rho C_p}(T_j - T_r) \\ -\frac{F_j}{\upsilon_j}T_j - \frac{UA}{V_j\rho_j C_p}(T_j - T_r) \end{bmatrix}$,

$$g(x) = \begin{bmatrix} \frac{C_i^e}{V} - \frac{\rho^e}{V\rho}C_i & 0 \\ \frac{\rho^e}{\rho} & 0 \\ \frac{\rho^e}{V\rho C_p}(C_p^e T_r^e - C_p T_r) & 0 \\ 0 & \frac{F_j}{\upsilon_j} \end{bmatrix}$$

The state variables are
x_1, x_2, x_3 and x_4 : Concentrations of fatty acid, alcohol, ester and water (mol/l),
x_5 : Liquid volume in the reactor (l),
x_6 and x_7 : Sensed output temperature of reaction mixture and Jacket (k).
The control variables are
$u_1 = F^e$: Feed flow rate (l/mn),
$u_2 = T_j^i$: Coolant temperature (k).
with
$x \in \Re^n$, state vector x^T=[$C_{1..4}$, V, T_r]
$u \in \Re^m$, control vector u^T=[F^e, T_j^i]
$y \in \Re^p$, output vector y^T=[C_1, V, T_r, T_j]

A. Actuator fault detection and fault estimation

The table below present possible faults that can be brought about in the process.
The fault has to be modeled properly and then included in the model equations.

Fault	Group
$f_{T_j^i}$	Actuator fault
f_{F^e}	Actuator fault
$f_{C_i^e}$	Component fault
f_{F_j}	Component fault
f_{C_1}	Sensor fault
f_V	Sensor fault
f_{T_r}	Sensor fault
f_{T_j}	Sensor fault

TABLE I: possible faults in the process

This work is dedicated to actuator and system (component) fault detection and identification and their isolation.
We present a study of two cases, the first case we will consider only the actuators faults, in the second case we will present an actuator fault and system fault.

Considering the new system (4); two new states were added over the original system, these states are $x_8 = F^e$ and $x_9 = T_j^i$, increasing the model with two actuators, in order to estimate the variations and fluctuations of the control and to detect fault.

$$M_1\begin{cases}\dot{x}_i=-\frac{F^{lv}}{x_5}(x_i^*-\frac{\rho^{lv}}{\rho}x_i)+\nu_i r+(x_i^e-\frac{\rho^e}{\rho}x_i)\frac{u_1}{x_5}, \quad i=1..4\\ \dot{x}_5=-\frac{F^{lv}\rho^{lv}}{\rho}+\frac{\rho^e}{\rho}u_1\\ \dot{x}_6=\frac{UA}{\rho C_p x_5}(x_7-x_6)-F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{C_p x_5}-r\frac{\Delta_r H}{\rho C_p}\\ \qquad +\frac{\rho^e}{\rho C_p x_5}(C_p^e T_r^e-C_P x_6)u_1\\ \dot{x}_7=-\frac{F_j}{V_j}x_7-\frac{UA}{V_j\rho_j C_p}(x_7-x_6)+\frac{F_j}{V_j}u_2\\ \dot{x}_8=\varepsilon_1\\ \dot{x}_9=\varepsilon_2\end{cases} \tag{4}$$

With ε_1 and ε_2 nearly to zero.

The advantage of using diagnosis based observer that the fault will be detected and identified at the same time.
A bank of i high gain observers will be designed for the fault detection and identification. The high gain observer's number is equal to the number of the system actuators, ie: 2 in our example $F^e=u_1$ and $T_j^i=u_2$.
The first sub-model is presented by S_{11} (5) and his observer presented by $\hat{S}_{11}$ (6).

$$S_{11}\begin{cases}\dot{T}_r=\frac{F^e\rho^e}{V\rho C_p}(C_p^e T_r^e-C_p T_r)-F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{VC_p}-r\frac{\Delta_r H}{\rho C_p}\\ \qquad +\frac{UA}{V\rho C_p}(T_j-T_r)\\ \dot{F}^e=0\end{cases} \tag{5}$$

$$\hat{S}_{11}\begin{cases}\dot{\hat{T}}_r=\frac{\hat{F}^e\rho^e}{V\rho C_p}(C_p^e T_r^e-C_p\hat{T}_r)-F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{VC_p}-r\frac{\Delta_r H}{\rho C_p}\\ \qquad +\frac{UA}{V\rho C_p}(T_j-\hat{T}_r)+G_{1\theta_{11}}*(T_r-\hat{T}_r)\\ \dot{\hat{F}}^e=G_{2\theta_{11}}*(T_r-\hat{T}_r)\end{cases} \tag{6}$$

The second sub-model is presented by S_{12} (7) and his observer presented by $\hat{S}_{12}$ (8).

$$S_{12}\begin{cases}\dot{T}_j=\frac{F_j}{V_j}(T_j^i-T_j)-\frac{UA}{V_j\rho_j C_p}(T_j-T_r)\\ \dot{T}_j^i=0\end{cases} \tag{7}$$

$$\hat{S}_{12}\begin{cases}\dot{\hat{T}}_j=\frac{F_j}{V_j}(\hat{T}_j^i-\hat{T}_j)-\frac{UA}{V_j\rho_j C_p}(\hat{T}_j-T_r)+G_{1\theta_{12}}*(T_j-\hat{T}_j)\\ \dot{\hat{T}}_j^i=G_{2\theta_{12}}*(T_j-\hat{T}_j)\end{cases} \tag{8}$$

B. Actuator and system fault detection and fault estimation

We apply the same technique presented above, considering the new system (9); two new states were added over the original system, these states are $x_8=F^e$ and $x_9=F_j$, increasing the model with one actuator and one component system, in order to estimate their variations and to detect fault.

$$M_2\begin{cases}\dot{x}_i=-\frac{F^{lv}}{x_5}(x_i^*-\frac{\rho^{lv}}{\rho}x_i)+\nu_i r+(x_i^e-\frac{\rho^e}{\rho}x_i)\frac{u_1}{x_5}, \quad i=1..4\\ \dot{x}_5=-\frac{F^{lv}\rho^{lv}}{\rho}+\frac{\rho^e}{\rho}u_1\\ \dot{x}_6=\frac{UA}{\rho C_p x_5}(x_7-x_6)-F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{C_p x_5}-r\frac{\Delta_r H}{\rho C_p}\\ \qquad +\frac{\rho^e}{\rho C_p x_5}(C_p^e T_r^e-C_P x_6)u_1\\ \dot{x}_7=\frac{F_j}{V_j}(u_2-x_7)-\frac{UA}{V_j\rho_j C_p}(x_7-x_6)\\ \dot{x}_8=\varepsilon_3\\ \dot{x}_9=\varepsilon_4\end{cases} \tag{9}$$

With ε_3 and ε_4 nearly to zero.

The first sub-model is presented by S_{21} (10) and his observer presented by $\hat{S}_{21}$ (11).

$$S_{21}\begin{cases}\dot{T}_r=\frac{F^e\rho^e}{V\rho C_p}(C_p^e T_r^e-C_p T_r)-F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{VC_p}-r\frac{\Delta_r H}{\rho C_p}\\ \qquad +\frac{UA}{V\rho C_p}(T_j-T_r)\\ \dot{F}^e=0\end{cases} \tag{10}$$

$$\hat{S}_{21}\begin{cases}\dot{\hat{T}}_r=\frac{\hat{F}^e\rho^e}{V\rho C_p}(C_p^e T_r^e-C_p\hat{T}_r)-F^{lv}\frac{\rho^{lv}}{\rho}\frac{\Delta H_v}{VC_p}-r\frac{\Delta_r H}{\rho C_p}\\ \qquad +\frac{UA}{V\rho C_p}(T_j-\hat{T}_r)+G_{1\theta_{21}}*(T_r-\hat{T}_r)\\ \dot{\hat{F}}^e=G_{2\theta_{21}}*(T_r-\hat{T}_r)\end{cases} \tag{11}$$

The second sub-model is presented by S_{22} (12) and his observer presented by $\hat{S}_{22}$ (13).

$$S_{22}\begin{cases}\dot{T}_j=\frac{F_j}{V_j}(T_j^i-T_j)-\frac{UA}{V_j\rho_j C_p}(T_j-T_r)\\ \dot{F}_j=0\end{cases} \tag{12}$$

$$\hat{S}_{22}\begin{cases}\dot{\hat{T}}_j=\frac{\hat{F}_j}{V_j}(T_j^i-\hat{T}_j)-\frac{UA}{V_j\rho_j C_p}(\hat{T}_j-T_r)+G_{1\theta_{22}}*(T_j-\hat{T}_j)\\ \dot{\hat{F}}_j=G_{2\theta_{22}}*(T_j-\hat{T}_j)\end{cases} \tag{13}$$

where $\theta_{nm}>0$ is the tuning parameter of the observer:

$$G_{\theta_{nm}}=\begin{bmatrix}G_{1\theta_{nm}}\\ G_{2\theta_{nm}}\end{bmatrix}=\begin{bmatrix}2\theta_{nm}\\ \theta_{nm}^2\end{bmatrix}, \; for\; n,m=1..2$$

n present the case and m present the sub-model.

C. Residual generator

Fault detection is based on generating a residual comparing the measurements of physical system variables with their estimation provided by the observer, in the first case :

$$R_1=\left|F^e-\hat{F}^e\right| \tag{14}$$

and

$$R_2=\left|T_j^i-\hat{T}_j^i\right| \tag{15}$$

In the second case we present :

$$R_1=\left|F^e-\hat{F}^e\right| \tag{16}$$

and

$$R_2=\left|F_j-\hat{F}_j\right| \tag{17}$$

Once the residual is generated and evaluated, it be compared with the limit value called the threshold. If the residual deviates from the threshold, a fault is declared as detected $R>Th$ else it is a normal behavior.

We are interested only for a fixed threshold and not to an adaptive threshold because the faults are assumed to be deterministic. Assuming that the noise has a zero mean, the residual has a time varying mean contributed entirely by the faults. As the noise is assumed to be stochastic and the faults not, the variance of the residual is due to the failure [13].

IV. RESULT AND DISCUSSION

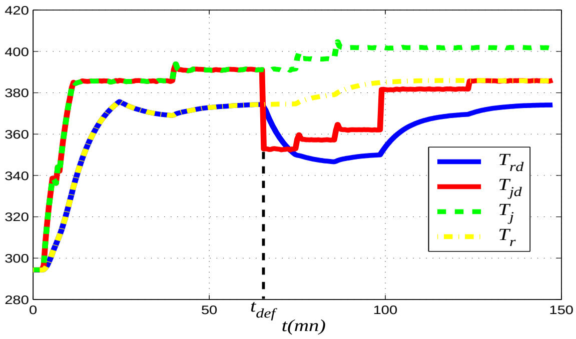
This detection method will be applied to a SCSTR, two case will be presented:

1) 1^{st} case :: *Actuators defaults*

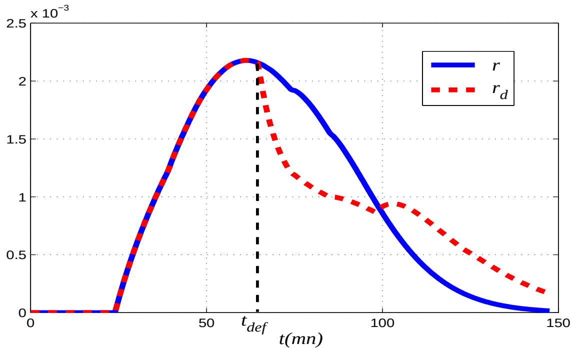
Two scenarios possible is presented in this case [2], in the first introducing only one actuator fault, while in the second we introduce two faults that affects both actuators simultaneously.

The first scenario:

In Fig.2 we present a simple actuator fault that affects $T_j^i = u_2$, which presents the identification of the actuator if the fault exists, in the case of Fig.2b, even in cases where there is no fault (Fig.2a).



(a) Identification of 1^{st} actuator F^e without fault



(b) Identification of 2^{sd} actuator T_j^i with fault and its comparison without fault

Fig. 2: Identification for actuators (single fault)

In Fig.3, the fault detection is presented, here we chose a partial abrupt fault, varies between 40% and 15% and which presents in particular the loss of efficiency of the actuator, at $t_{def} = 66\ min$ the fault can be detected in Fig.3b.

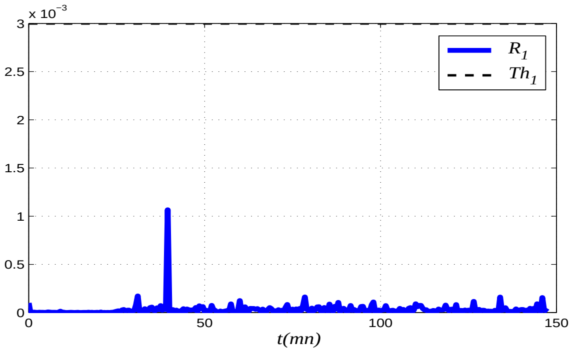
By implementing the bank of observers, it is possible to calculate the different residual sets.

The residues generation is performed simultaneously with the fault identification. It suffices to calculate the residual $R_i = |u_i - \hat{u}_i|$.

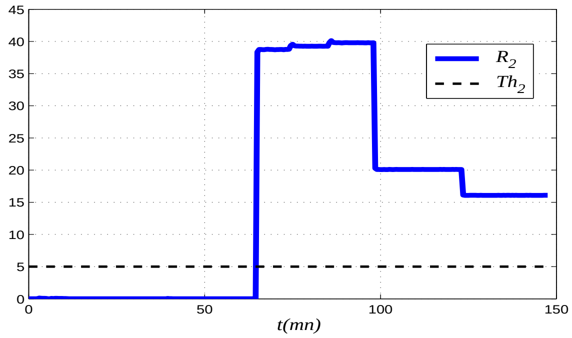
In fact the residue is not zero, and it exceeds the threshold value set in advance and the failure actuator is isolated. While R_1 is almost zero presents a normal behavior (Fig.3a).

For the simulations, the system S_{11} and the observer $\widehat{S}_{11}$, has been considered with initial conditions given by : $T_r = 294\ K$, $F^e = 0\ l/mn$, $\widehat{T}_r = 284\ K$ and $\widehat{F}^e = 0\ l/mn$, also for the system S_{12} and the observer $\widehat{S}_{12}$, we pose $T_j = 294.7\ K$, $T_j^i = 290\ K$, $\widehat{T}_j = 294.7\ K$ and $\widehat{T}_j^i = 290\ K$.

Then, first observer has been tuned with $\theta_{11} = 3$, the second with $\theta_{12} = 25$.



(a) Residual R_1 : normal behavior



(b) Residual R_2:fault detection

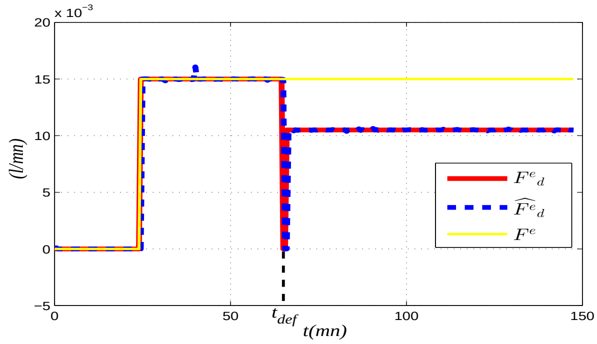
Fig. 3: Residuals evaluation

The second scenario:

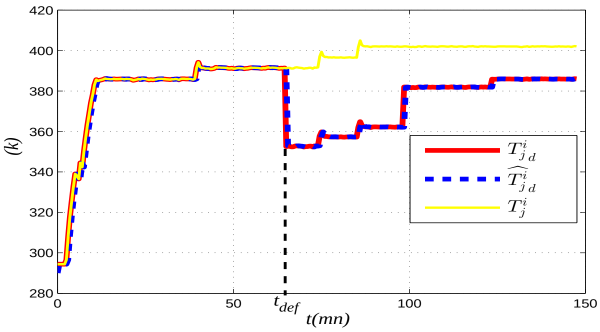
In this case we present a simultaneous faults. Indeed, we will present two actuators faults $F^e = u_1$ the flow rate and $T_j^i = u_2$ coolant temperature, the second fault is the same as the first scenario, the first fault is added, it is a flow rate fault, which is total for one minute (total closing of the valve) and a loss of efficiency that reaches 30%, Fig.4 presents fault detection.

Indeed from $t_{def} = 66\ min$, the two residues leave zero and exceeds the fixed threshold, in Fig.5 the estimation of two faults using the high gain observer is presented.

We present in Fig.6 some fault effect on different states. Indeed, the actuators faults can touch the temperature of the reaction mixture T_r and the jacket temperature T_j. Thus the rate of reaction, so the consumption of the fatty acid C_1 (Fig.6b) and of course the production time of the ester (Fig.6c).

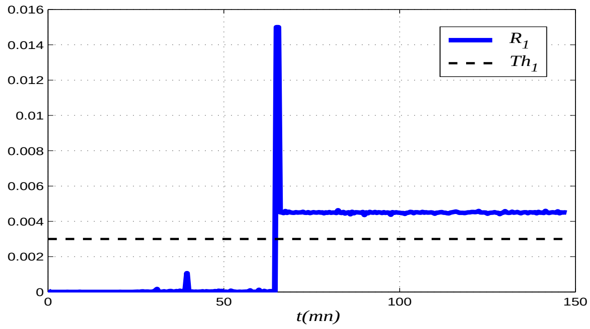


(a) Identification of 1^{st} actuator F^e with fault and its comparison without fault

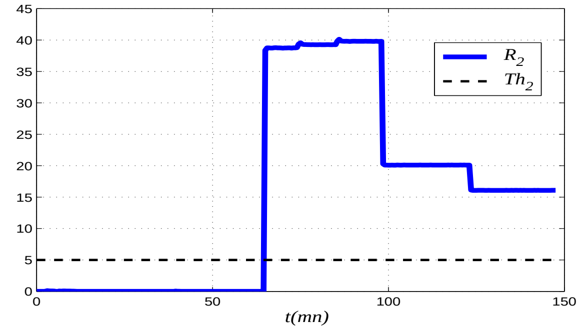


(b) Identification of 2^{sd} actuator T^i_j with fault and its comparison without fault

Fig. 4: Identification for actuators faults (Simultaneous faults)

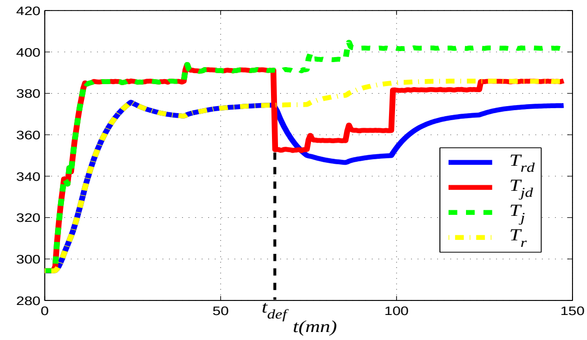


(a) Residual R_1:fault detection

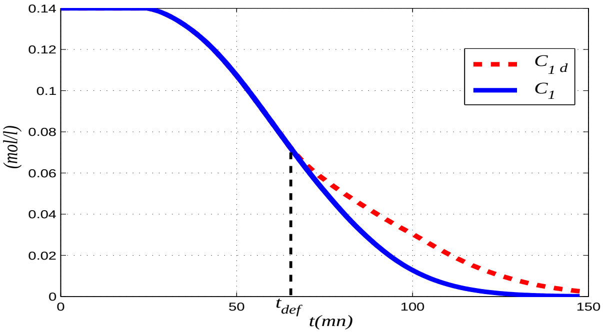


(b) Residual R_2: fault detection

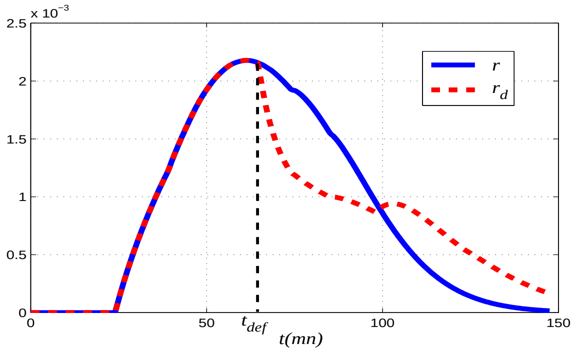
Fig. 5: Residuals evaluation



(a) Temperature evolution without and with fault



(b) Evolution of fatty acid concentration without and with fault



(c) Reaction rate affected by the fault

Fig. 6: Faults effects

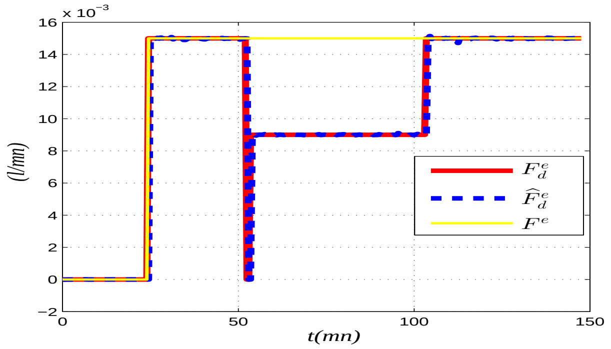
2) 2^{sd} *case ::* Actuator and component system default

In this part we present a simultaneous faults, we will present one actuator fault $F^e = u_1$ the flow rate and one component system fault F_j heat transfer fluid flow.

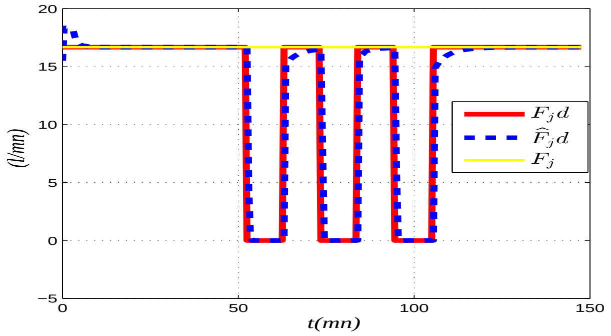
From $t_{def} = 52\ min$ until $t_{def} = 105\ min$ we detect a simultaneous abrupt fault, the first is a flow rate fault, which is total for one minute (total closing of the valve) and a loss of efficiency that reaches 40%, Fig.7a. The second it is a fault from the pump for heat transfer fluid, a closure and a complete opening presented in Fig.7b.

Indeed the two residues leave zero and exceeds the fixed threshold, in Fig.8 the residuals evaluation is presented.

For the simulations, the system S_{21} and the observer $\widehat{S}_{21}$ has been considered with initial conditions given by : $T_r = 294\ K$, $F^e = 0\ l/mn$, $\widehat{T}_r = 289.5\ K$ and $\widehat{F}^e = 0\ l/mn$.
For the system S_{22} and the observer $\widehat{S}_{22}$, we pose $T_j = 294\ K$, $F^j = 16.6\ l/mn$, $\widehat{T}_j = 289.5\ K$ and $\widehat{F}^j = 15.5\ l/mn$.
Then, the first observer has been tuned with $\theta_{21} = 5$, the second with $\theta_{22} = 27$.

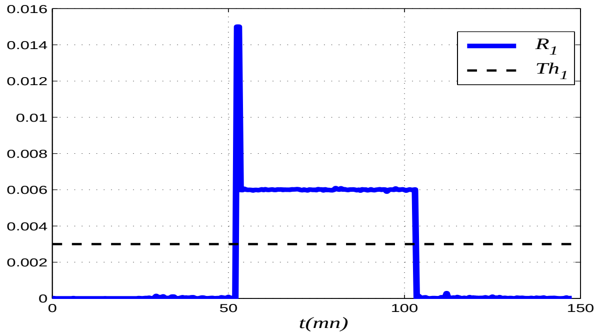


(a) Identification of the actuator F^e with fault and its comparison without fault

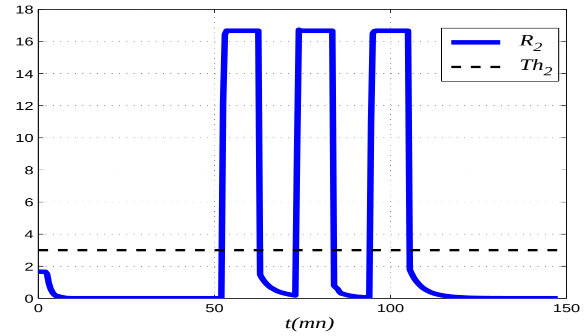


(b) Identification of the component system F_j with fault and its comparison without fault

Fig. 7: Identification for Simultaneous faults



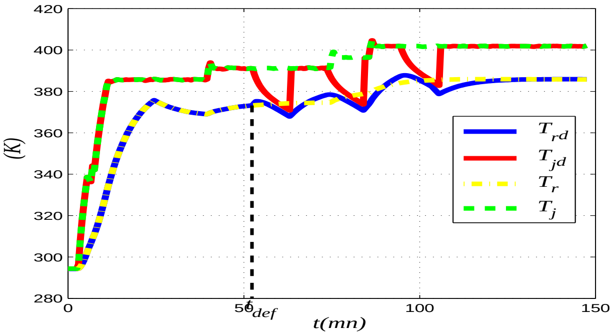
(a) Residual R_1 : fault detection



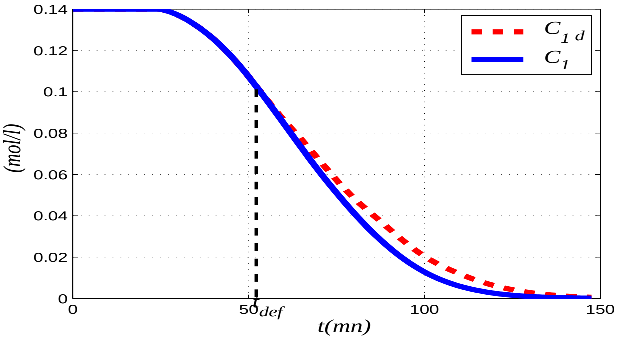
(b) Residual R_2 : fault detection

Fig. 8: Residuals evaluation

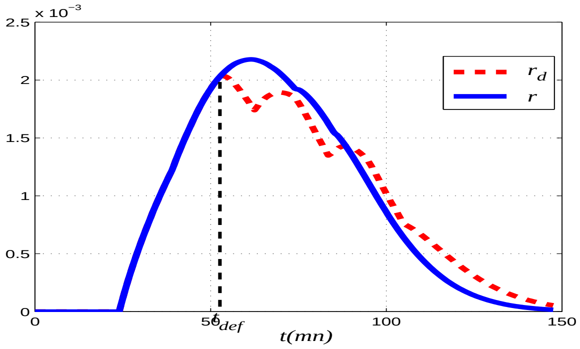
Finally we present in Fig.9 the fault effect on different states of esterification, to show the necessity of diagnosis for this process. Indeed, the actuator and component system can touch the temperature of the reaction mixture T_r and the jacket temperature T_j. Thus the rate of reaction, so the consumption of the fatty acid C_1 and the production time of the ester, Fig.9b and Fig.9c, like the first case, effects are presented in two different ways.



(a) Temperature evolution without and with fault



(b) Evolution of fatty acid concentration without and with fault



(c) Reaction rate affected by the fault

Fig. 9: Faults effects

V. CONCLUSION

A high gain observer designed for fault detection and estimation has been proposed in this paper. The FDII scheme is composed of a bank of high-gain observer, evolution of actuator or component system fault is estimated through each observer. Good results were obtained, at the detection and Identification for the single fault even a simultaneously multi-fault.

ACKNOWLEDGMENT

This work was supported by the Ministry of Higher Education and Scientific Research in Tunisia.

REFERENCES

[1] A. Abdelkader, M. Boussada, A.S. Nouri, H. Hammouri, and K. Fiatty. A nonlinear high gain observer for an olive oil waste esterification in a continuous stirred tank reactor. In *15th international conference on Sciences and Techniques of Automatic control and computer engineering, Tunisia*, pages 1049–1054, 2014.

[2] A. Adelkader, M. Boussada, K. Fiaty, H. Hammouri, and A.S Nouri. Actuator fault detection identification and isolation via high-gain observer for an olive oil waste esterification in a semi continuous stirred tank reactor. In *IEEE 16th international conference on Sciences and Techniques of Automatic control and computer engineering*, pages 312–316, 2015.

[3] G. Besançon. Observer-based approach to fault detection and isolation for nonlinear systems. *Automatica*, 39:1095–1102, 2003.

[4] M. Boussaada, K. Fiaty, and G.Gilles. A moving state estimator of an olive oil waste esterification in a semi-batch reactor: experimental validation. In *ISCRE Hong Kong*, 2002.

[5] J. Chen and R.J; Patton. *Robust model-based fault diagnosisfor dynamic systems*.

[6] Y. Chetouani. Fault detection in a chemical reactor by using the standardized innovation. *Process Safety and Environmental Protection*, 84:27–32, 2006.

[7] K. Emami, T. Fernando, B. Nener, H. Trinh, and Y. Zhang. A functional observer based fault detection technique for dynamical systems. *Journal of the Franklin Institute*, 352:2113–2128, 2015.

[8] M.H. Frikha, M. Benzina, and S. Gabsi. Equation cintique de l'estrification des acides gras libres de l'huile de grignon d'olive par l'thanol au dessus de l'azotrope eau-thanol. *Entropie*, 33:48–54, 1997.

[9] H. Hammouri, M. Kinnaert, and E.H. Elyaagoubi. Observer based approach to fault detection and isolation for nonlinear systems. *IEEE Transaction on Automatic Control*, 44:1879–1884, 1999.

[10] R. Isermann and P. Balle. Trends in the application of model-based fault detection and diagnosis of technical process. *Control Engineering, institute of Automatic Control*, 5:709–719, 1997.

[11] C. Keleris, M. M. Polycarpou, and T. Parisini. A robust nonlinear observer based approach for distributed fault detection of input output interconnected systems. *Automatica*, 53:408–415, 2015.

[12] S. Methnani, F.Lafont, JP. Gauthier, T. Damak, and A. Toumi. Actuator and sensor fault detection, isolation and identification in nonlinear dynamical systems, with an application to a waste water treatment plant. *Journal of Computer Engineering and Informatics*, 1:112–125, 2013.

[13] R. Patton, P. Frank, and R. Clark. *Fault Diagnosis in Dynamic Systems*.

[14] R.C. Reid, J.M. Prausnitz, and B.E. Poling. *The properties of gases and liquids*. Mc Graw-Hill, 4 ed edition, 1988.

[15] A. Sellami S. Dhahri, F. Ben Hmida and M. Gossa. Lmi-based sliding-mode observer design method for reconstruction of actuator and sensor faults. *International Journal on Sciences and Techniques of Automatic control, IJ-STA*, 1:91–207, 2007.

[16] M. Staroswiecki. Quantitative and qualitative models for fault detection and isolation. *Mechanical Systems and Signal Processing*, 14:301–325, 2000.

[17] V. Venkatasubramanian, R. Rengaswamy, K. Yin, and S.N. Kavur. A review of process fault detection and diagnosis : Part 1 : Quantitative model-based methods. *Computers and Chemical Engineering*, 27:293–311, 2003.

[18] A.S. Willsky. A survey of design methods for failure detection in dynamic systems. *Automatica*, 12:601–611, 1976.

[19] Y. Yang, S. X. Ding, and L. Li. On observer-based fault detection for nonlinear systems. *Systems and Control Letters*, 82:18–25, 2015.