New Diagnosis Method by Luenberger Observer Using Bond Graph Approach

Abderrahmène SALLAMI, Nadia ZAZOURI, Mekki KSOURI

Abstract—The paper concerns the design of a new methodology for diagnosis by Luneberger Observer using the Bond Graph. The observer design provides a state estimated from the model and inputs and outputs measurements. Furthermore, we have exploited the architectural of the Bond Graph to generate the diagnostic condition based on Luenberger observers. Furthermore, the performance of the proposed diagnosis system is studied by these residuals to the certainties and faults. The research results have been applied to an industrial process RODS (Reverse Osmosis Desalination System) of Research and Technology Center of Energy Borj Cedria. In this context, the proposed method was operated from the modeling step to the diagnosis system step.

Index Terms—Diagnosis, Lunberger Observer, Bond Graph, Reverse Osmosis Desalination System.

I. INTRODUCTION

The diagnostic system is primarily intended to issue alarms which aims to attract the attention of the operator on monitoring the occurrence of one or more events that could affect the operation of the installation [1], [2], [3] and [4].. Given the complexity of the processes, the generation of alarms is the most used way to alert the operator of the occurrence of an "abnormal" event. Alarms are related to malfunctions that may appear on the production system. It is important to clarify the meaning given to the words used to evoke malfunctions that may occur in the system. We retain, for this, the definitions in [5], [6] and [7]. Nowadays engineering sciences rely heavily on the estimate of the state of the systems. Indeed, the complete knowledge of the state of a system is often necessary to develop a control law or the establishment of a monitoring or diagnostic strategy. In practice, the state of a system is not always available and the input and output signals are the only accessible measurement quantities. The most common solution to overcome this problem is to couple the system another auxiliary system, called estimator or state observer. The Observer provides an estimate of the system state from his model and measures its inputs and outputs.

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The observer conventionally used in the context of linear systems, said proportional gain or Luenberger [4]. In recent years the diagnosis observer is used to estimate the faults of shareholders and sensor faults [8] and [9]. These industrial systems are governed by a number of physical phenomena and various technology components, so the Bond Graph approach based on an energy analysis and multi-physics, is well suited. The Bond Graph modeling tool was defined by Henry Paynter [10]. This energy approach allows to highlight the analogies between the different areas of physics (mechanics, electricity, hydraulics, thermodynamics, acoustics, etc ...) and to represent in a uniform multidisciplinary physical system [11], [12], [13] and [14].

The method for making the diagnosis is to generate residue analytical redundancy relations calling from linear mono power bond graph model are studied in Tagina [15] by following the causal paths. At the junction structure (junctions 0, 1, TF and GY), many relationships between different flows and stress can be established. The method is interesting but remains limited and complicate in the presence of a large system size and also the lack of instrumentation for the most part real systems leaves the state is not accessible to measurement. This lack imposes the synthesis of observers whose role is to estimate all or part of the state. Structural analysis can be performed directly from bond graph model [16]. You can determine the order of the model, the rank of the state matrix and conditions of observability and controllability of an industrial system.

The tool bond graph was used for the synthesis of the observer Luenberger in the case of linear systems [17], [18] and [19]. The originality of this work lies in the fact that the bond graph was used both for the construction of the observer's model for calculating gains. We chose to present the case the simplest and most common, namely the observer Luenberger complete order.

In this paper, we proposed a new method for the diagnosis of industrial systems. The originality of this work lies in the exploitation of the architectural appearance of the bond graph representation of industrial systems in the diagnostic condition based on Luenberger observers. The generation of waste (regardless of the size of the industrial system) is determined from the relationship of the output estimate. To detect and locate faults, we have developed and proposed a diagnostic technique by observers Bank (BG-DOS/ BG-GOS). For the calculation of the gain of the observer bond graph is based on the theorem Rahmani [20].

II. DIAGNOSISI BY OBSERVER

A. Observer Diagnosis using the analytical model

The principle of diagnosis is to estimate, with appropriate techniques, all components of the state vector or, more generally, the process output and, using the estimation error as residual [21]. This is ensured by means of a proportional observer. The block diagram of such a method is given in figure. 1.

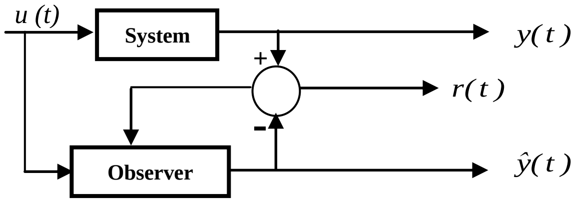

Fig. 1 Diagnosis by observer

Residual equations are defined as follows:

- Residual of state estimation:

$$r_x = \tilde{X} = x - \hat{x} \qquad (1)$$

- Residual of output estimate:

$$r_y = \tilde{Y} = y - \hat{y} = C(x - \hat{x}) \qquad (2)$$

B. *Diagnosis by observer using the bond graph model*

To build the observers, check the observability of the system. On the bond graph perspective, proposed by [22], a system modeled by bond graph is structurally observable if the following two conditions are met:

First condition: There are at least causal paths linking a sensor each dynamic element *I* or *C* in integral causality when placed bond graph model preferred integral causality.

Second condition: All I or C elements derived assuming causality when placed bond graph model in derivative causality, and that the sensors dualized. Figures 2 and 3 present respectively the Luenberger observer using the bond graph for items *I* and *C* [23], [24], [25], [26], [27], [28] and [29].

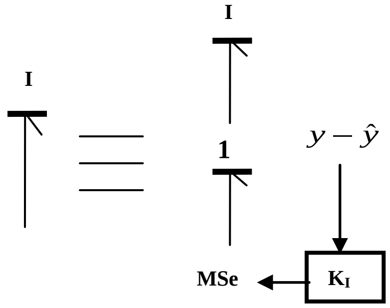

Fig. 2 Construction of Luenberger observer if an element I

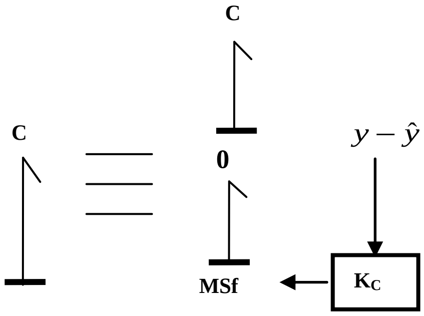

Fig. 3 Construction of Luenberger observer if an element C

The Observer provides an estimate of the system state from his model and measures its inputs and outputs. The observer conventionally used in the context of linear systems, is said to gain Proportional (P) or Luenberger. Either a continuous system described by the equation of state using the bond graph shown in Figure 4:

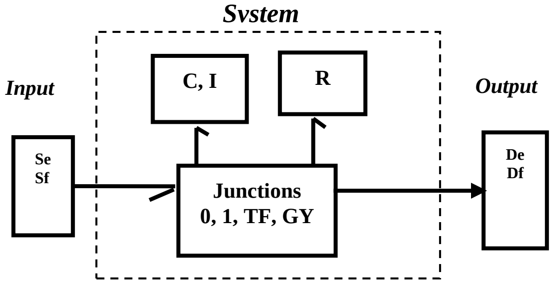

Fig. 4 Diagram of the continuous system described by bond graph

The observer of proportional type state is represented by Figure 5. The equation of state is of the following form:

$$\begin{cases} \dot{\hat{x}}(t) = \begin{pmatrix} \dot{\hat{p}}_I \\ \dot{\hat{q}}_c \end{pmatrix} = A\begin{pmatrix} p_L \\ q_C \end{pmatrix} + Bu(t) + K(y(t) - \hat{y}(t)) \\ \hat{y} = C\begin{pmatrix} \hat{p}_L \\ \hat{q}_C \end{pmatrix} \end{cases} \qquad (3)$$

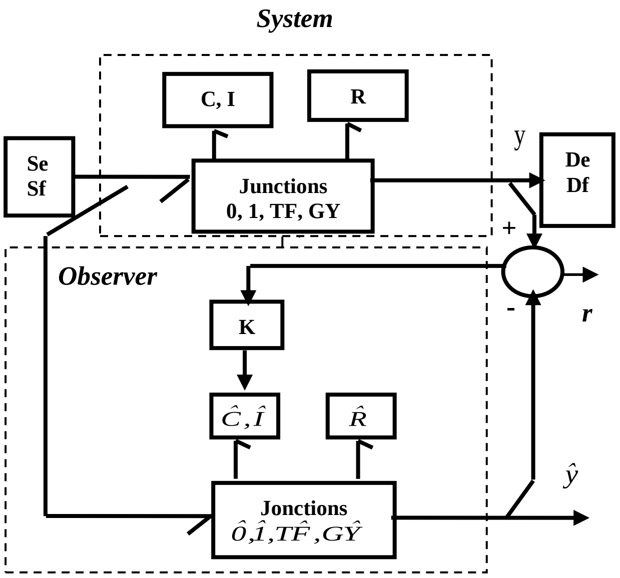

Fig. 5 Structure of an observer Luenberger using bond graph

C. *Generating residues*

Waste generation from a proportional observer using the bond graph model is summarized by the following steps:

1st step: Verify that the bond graph model of the system is structurally observable if yes, then continue the following steps;

2nd step: Construction of the observer using the bond graph;

3rd stage: The residue of symbolic expression is derived from the following equation:

$$r = y - \hat{y} \qquad (4)$$

4th stage: After calculations made, the residual is in the form:

$$r : \Phi(R, I, C, TF, GY) \qquad (5)$$

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III. EXPEREMENTAL OF REVERSE OSMOSIS

The desalination system of reverse osmosis water is a process that provides fresh water (drinking or, more rarely because of cost, usable for irrigation) from brackish or salt water (water Sea particular).

In the first part we will present the test bench that exists and Research Centre for Energy Technology (CRTEn). Thereafter, we will give the bond graph model word of this test bench (it gathers the energy source, an adaptation module and desalination unit). Then we will introduce the bond graph model of reverse osmosis. At the end of this first part, we will expose the simulated and experimental results.

In the second part, we will provide the definite diagnosis by Luenberger observer using the analytical model and the bond graph model of reverse osmosis. Then we will determine the gain of the observer Luenberger by the analytical model and the bond graph model. After, we will formulate the uncertain diagnosis Luenberger observer using the bond graph model of this reverse osmosis. At the end of this second part, we will determine the index of sensitivity and detectability index of reverse osmosis.

A. Description of test bench

The test bench (RO1500) is composed of:

- A photovoltaic generator (PV) composed of a module array (PV) connected in series and parallel to produce the desired current and the voltage for the power supply to all of rechargeable batteries.
- A power adjustment module composed of two DC/DC converters and DC/AC ensuring the supply of the desalination unit.
- A reverse osmosis desalination unit is composed of two reverse osmosis modules. Each module consists of a membrane consisting of a composite end of polyamide film, able to purify the water salinity of less than 3g/L. Figure 3 shows the experimental system of the desalination unit.

Fig. 6 Experimental reverse osmosis desalination unit system

B. Principle of reverse osmosis

Osmosis is the transfer solvent through a membrane under the influence of a concentration gradient. If one considers a system with two compartments separated by a semi-selective membrane and containing two solutions of different concentrations, the osmosis resulting in a water flow directed from the dilute solution to the concentrated solution.
Applying a pressure on the concentrated solution, the quantity of water transferred by osmosis will decrease. With a sufficiently high pressure, the water flow will even cancel: this pressure is called the osmotic pressure P (assuming that the diluted solution is pure water). If it exceeds the value of the osmotic pressure, there is a water flow directed in opposite direction of the osmotic flow: this is the phenomenon of reverse osmosis.
The osmotic pressure of the electrolyte is given by the following relationship:
This relation is valid for dilute solutions, with :

- i: The number of ion species constituting the solute,
- C: molar concentration of the solute (mol.m-3),
- T: temperature (K)
- A: The ideal gas constant (8.31 J.mol-1.K-1)
- Π: The osmotic pressure of electrolytes (Pascals).

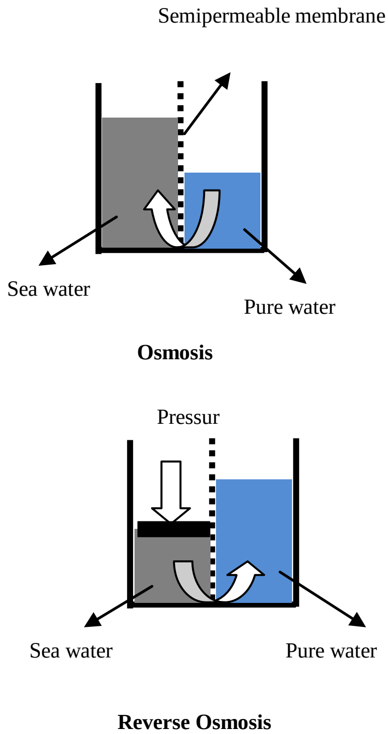

Fig. 7 Reverse osmosis system

C. Bond graph of reverse osmosis

From figure 7, we propose a bond graph model for reverse osmosis desalination unit figure 3. The most important parameters that must be controlled are the pressure (*P*) and flow rates of the water produced (*Qp*) and release water (*Qr*). The model of the reverse osmosis desalination system (IO) is equivalent to a storage element of a hydraulic inlet (feed) and two outputs (product water and reject). It will therefore be represented in the bond graph model with a storage element (*C: Cm*). The flow of the salt water is represented by a stream source Sf (*Sf: Qe*) and the line connecting the pump with reverse osmosis is represented by a type of restrictor R (*R: Rc*). The membrane is represented by a type of restrictor *R* (*R: Rm*), it changes its value depending on the hydraulic characteristics of the membrane. The control valve is modeled by a variable resistance element (*R: MR*) since any change in its position causes a variation in the supply pressure and the tanks are represented by type storage elements *C* (*Cp*: Storing the amount of water produced, *Cr*: Storing the amount of water discharge).

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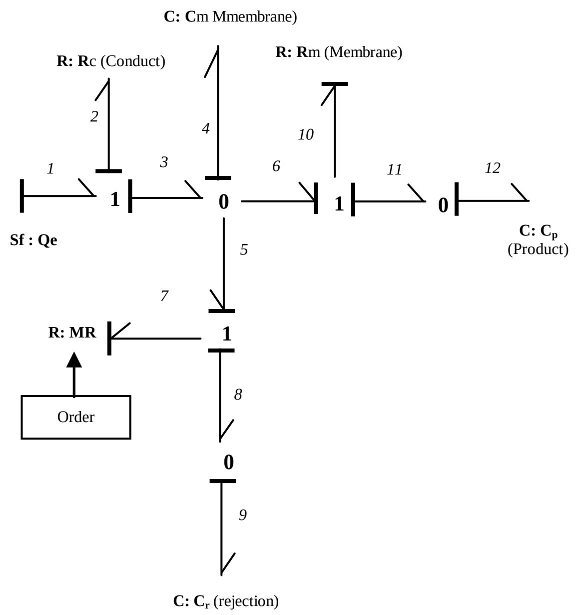

Fig. 8 Bond graph model of reverse osmosis

Figure 4 shown below illustrates the variations of the input pressure (*P*) of the flow of product water (*Qp*) and rejection rate (*Qr*) as a function of each position of the control valve (*MR*). We find that when the control valve (waste) is opened between 0s instants 50s and the supply pressure and the flow rate of water produced have very low values. While when it is closed for times greater than 100s, the flow rate of water produced increases as the flow rate of water release decreased.

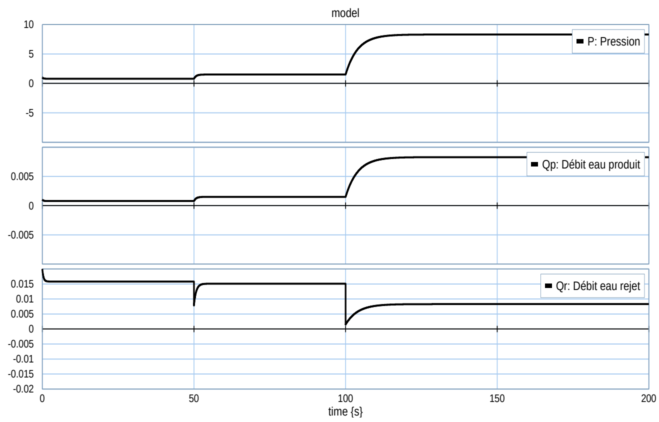

Fig. 9 Variations (*P*), (*Q p*) and (*Qr*) as a function of the position of the control valve and for n = 1500 rev / min

D. Experimental Results

The experimental model has three sensors for measuring the pressure (*Pa*) of water from the product flow (*Qp*) and the flow rate of water discharge (*Qr*). For each measurement series, is manipulated so that only one parameter (pump speed, discharge valve position) or variable, while the other is kept constant.

Table 1 shown below illustrates the different values of the pressure as a function of output rates for each position of the control valve and for a = speed of rotation of the pump 1500tr n / min and for a salinété Ce = 0.8g / l .

Table. 1 Variations (Q) and (Q p) for each variation (P)

P (KPa)	*Qp* (m^3/s) (Experimental)	*Qp* (m^3/s) (Simulated)	*Qr* (m^3/s) (Experimental)	*Qr* (m^3/s) (Simulated)
1	0.0018	0.0018	0.10	0.012
14	0.0025	0.0023	0.0185	0.0183
38	0.0035	0.0032	0.0175	0.0170

The shapes showed in figures 10 and 11 shows that when the feed pressure varies with the control valve, the product water flows and discharge water will vary proportionally to a constant speed of rotation of the pump.

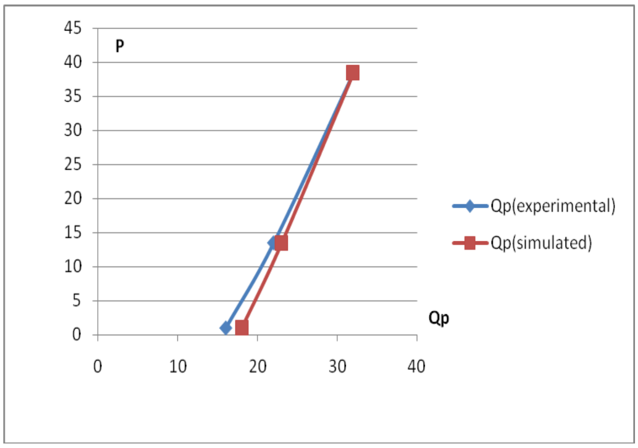

Fig. 10 Variations the product water (*Qp*) for each variation of pressure (*P*)

We remark that the flow (Qp) of clean water increases with the difference pressure side of the membrane. The experimental result is similar to the simulated one.

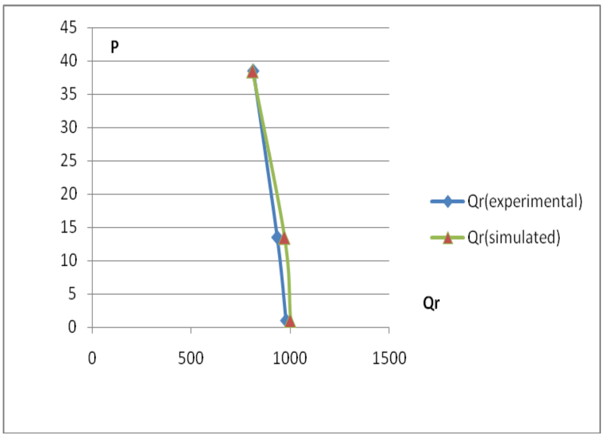

Fig. 11 Variations the outflow of rejected water (*Qr*) for each variation of pressure (*P*)

We notice from figure 8 that the rejected flow (Q_r) decreases. This confirms the obtained results.

IV. DIAGNOSIS OF REVERSE OSMOSIS

A. Diagnostic Luenberger observer based on bond graph model

According to the bond graph model represented by figure 3, we can determine the equation of state:

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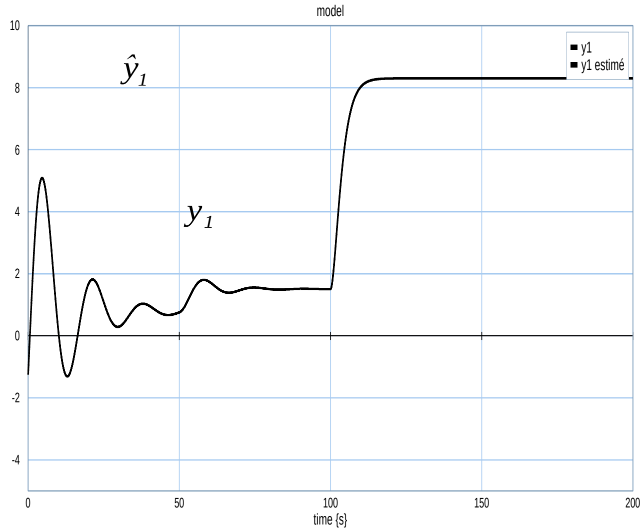
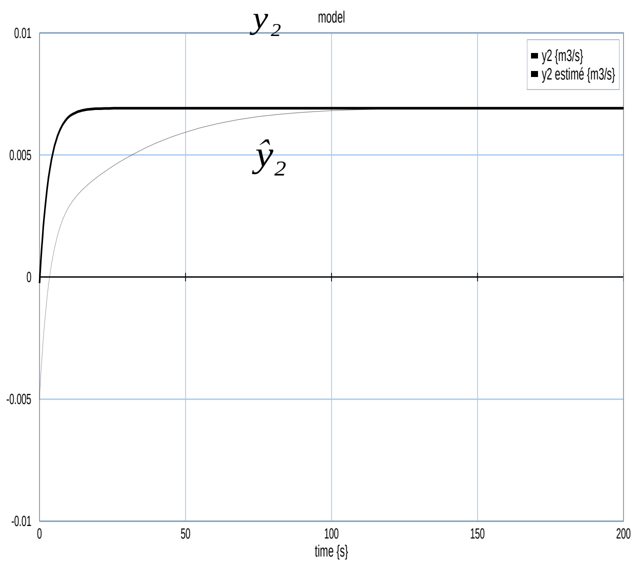
$$\begin{cases} \begin{pmatrix} \dot{q}_4 \\ \dot{q}_9 \\ \dot{q}_{12} \end{pmatrix} = \begin{bmatrix} -\frac{1}{C_m}(\frac{1}{R_m}+\frac{1}{MR}) & \frac{1}{C_r MR} & \frac{1}{C_p R_m} \\ \frac{1}{C_m MR} & -\frac{1}{C_r MR} & 0 \\ \frac{1}{C_m R_m} & 0 & -\frac{1}{C_p R_m} \end{bmatrix} \begin{pmatrix} q_4 \\ q_9 \\ q_{12} \end{pmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} Qe \\ y = \begin{bmatrix} \frac{1}{C_m} & 0 & 0 \\ \frac{1}{C_m MR} & -\frac{1}{C_r MR} & 0 \\ \frac{1}{C_m R_m} & 0 & -\frac{1}{C_p R_m} \end{bmatrix} \begin{pmatrix} q_4 \\ q_9 \\ q_{12} \end{pmatrix} \end{cases} \quad (6)$$

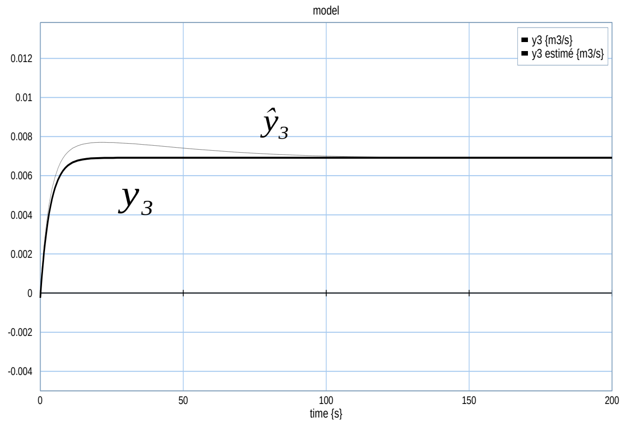
We simulated the system with 20 sim. Figure 13 represents the evolution of the variables of the system outputs.



(a)



(b)



(c)

Fig. 13 Estimated outputs, a) : Output Variables y_1 et $\hat{y}_1$, b) : Output Variables y_2 et $\hat{y}_2$, c) : Output Variables y_3 et $\hat{y}_3$

To make the diagnosis, calculate residues. From the BG model in figure 13, one can deduce the residuals $r_1(t)$, $r_2(t)$ and $r_3(t)$.

- Residual r_1: $e_4 - e_{\hat{4}} = 0$

$$\frac{K_{12}}{C_r} r_1(t) + MR \frac{dr_2(t)}{dt} + [K_{22} - 1] \frac{1}{C_r} r_2(t) + \frac{K_{32}}{C_r} r_3(t) = 0$$

- Residual r_2: $f_7 - f_{\hat{7}} = 0$

$$(C_m + C_p) \frac{dr_1(t)}{dt} + C_p R_m \frac{dr_3(t)}{dt} \quad (K_{11} + K_{13}) r_1(t)$$
$$(K_{21} + K_{23}) r_2(t) \quad (K_{31} + K_{33}) r_3(t) = 0$$

- Residual r_3: $f_{10} - f_{1\hat{0}} = 0$

$$(C_m + C_r) \frac{dr_1(t)}{dt} + C_r MR \frac{dr_2(t)}{dt} \quad (K_{11} + K_{12}) r_1(t)$$
$$(K_{21} + K_{22}) r_2(t) \quad (K_{31} + K_{32}) r_3(t) = 0$$

Figure 14 show that the residuals converge to zero

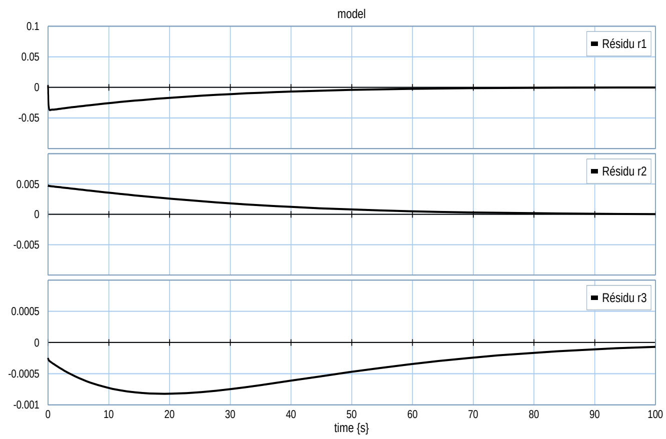


**Fig. 14 a) Residual $r_1(t)$ in the case of normal operation,
b) Residue $r_2(t)$ in the case of normal operation,
c) Residue $r_3(t)$ in the case of normal operation.**

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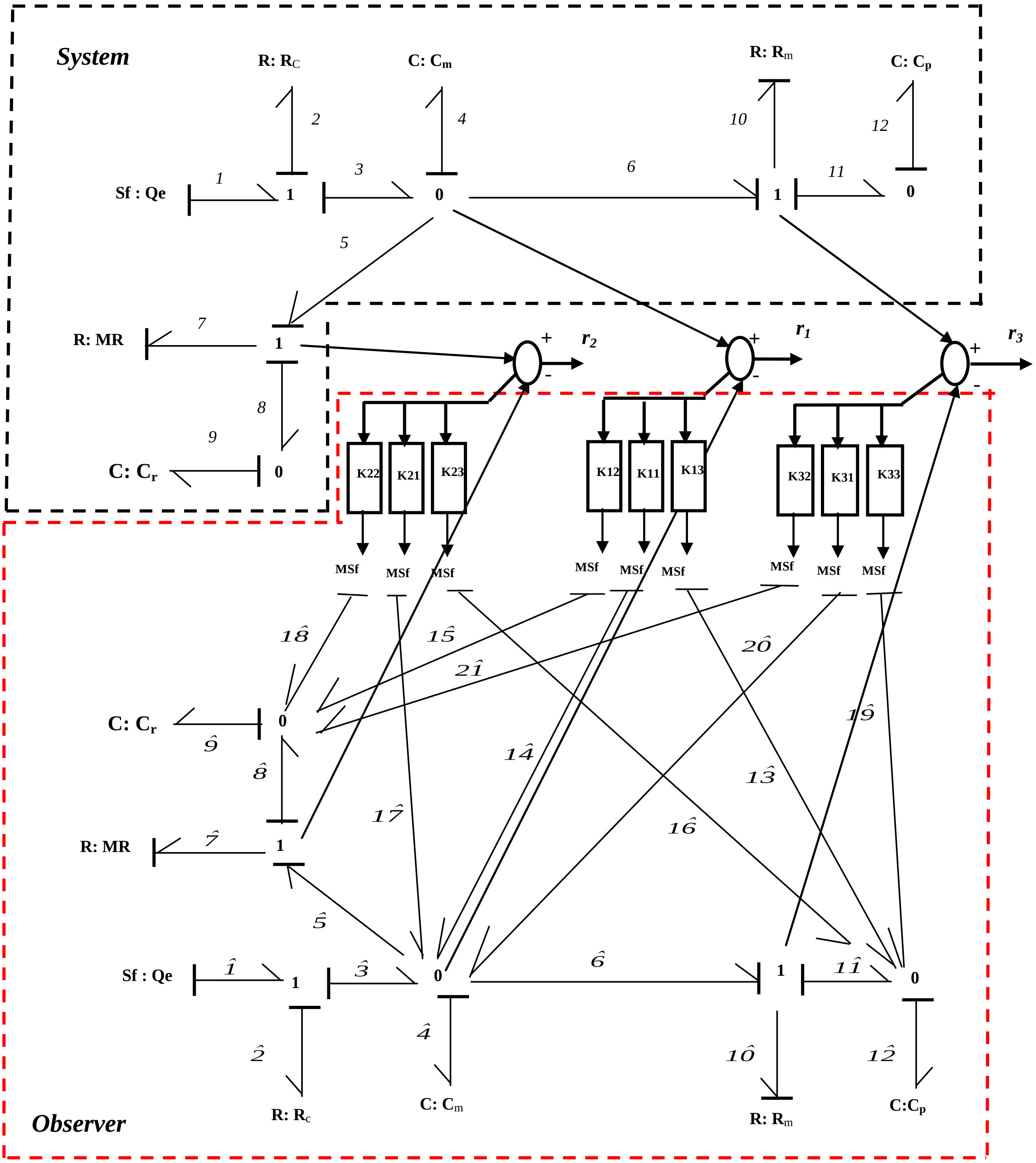

Fig. 12 Luenberger observer of reverse osmosis

B. Generation of residue defects with sensors

Within the sensor, Df_1 and Df_2 are affected by defects respectively (Fc_1, Fc_2 and Fc_3), then:

- Residual r_1: $(e_4 + F_{C1}) - e_{\hat{4}} = 0$

$$\frac{K_{12}}{C_r} r_1(t) + MR\frac{dr_2(t)}{dt} + [K_{22} \quad 1]\frac{1}{C_r} r_2(t) + \frac{K_{32}}{C_r} r_3(t) + \frac{dF_{C1}(t)}{dt} \quad MR\frac{dF_{C2}(t)}{dt} \quad \frac{1}{C_r} F_{C2}(t) = 0$$

- Residual r_2: $(f_7 + F_{C2}) - f_{\hat{7}} = 0$

$$K_{11} r_1(t) \quad C_m \frac{dr_1(t)}{dt} \quad K_{21} r_2(t) \quad (1 + K_{31}) r_3(t) \quad F_{C1}(t) + F_{C2}(t) \quad F_{C3}(t) = 0$$

- Residual r_3: $(f_{10} + F_{C3}) - f_{\hat{10}} = 0$

$$K_{11} r_1(t) \quad C_m \frac{dr_1(t)}{dt} \quad (K_{21}(+1) r_2(t) \quad K_{31} r_3(t) \quad F_{C1}(t) \quad F_{C2}(t) + F_{C3}(t) = 0 \quad 8$$

The equations 8, 9 and 10 show that $r_1(t)$, r_2 *(t) and* r_3 *(t)* are responsive to defects of the sensors. Figure 15 confirms that

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these residues are sensitive to defects of the sensors *De*, Df_1 and Df_2.

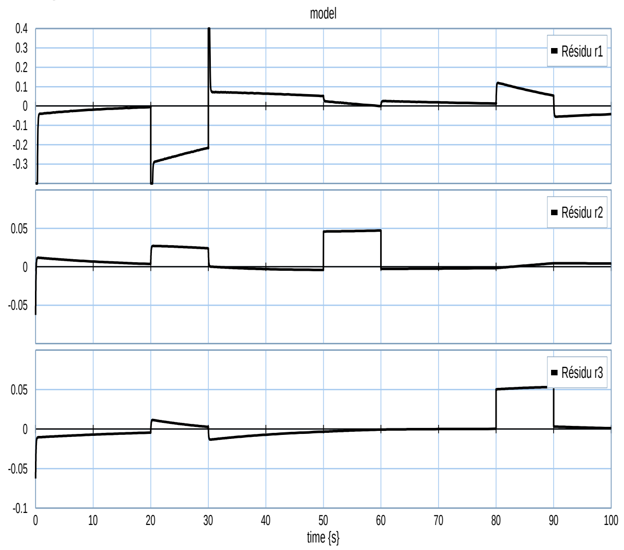

Fig.15 a) Residual r_1 *(t)* with faulty sensors *De*, Df_1 and Df_2, b) Residual $r_2(t)$ with faulty sensor *De*, Df_1 and Df_2, c) Residual $r_3(t)$ with faulty sensor *De*, Df_1 and Df_2

C. Detection and localization of sensor faults

Figure 16 shows the evolution of residuals r_1 *(t)*, r_2 *(t)* and r_3 *(t)* using the BG-DOS structures. The residual r_1 *(t)* is sensitive to the fault occurred on the sensor De and insensitive to faults on the other sensors (Df_1 and Df_2), the residual r2 (t) is sensitive to the fault appeared on the Df_1 sensor and insensitive to faults on other sensors (*De* and Df_2), the residual $r_3(t)$ is responsive to the fault occurred on the sensor Df_2 and insensitive to faults in other sensor (*De* and Df_1).

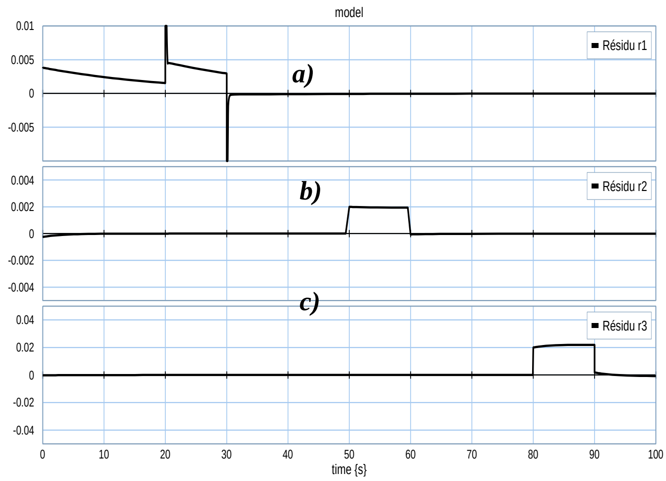

Fig. 16 Residuals $r_1(t)$, $r_2(t)$ and $r_3(t)$ of reverse osmosis for the DOS structure

Figure 17 shows the evolution of residuals $r_1(t)$, $r_2(t)$ and $r_3(t)$ using the BG-GOS structures. The residue $r_1(t)$ is insensitive to fault occurred on the sensor De and sensitive to defects on the other sensors (Df_1 and Df_2), the residual r_2 *(t)* is insensitive to the fault appeared on the Df_1 and sensor sensitive to defects on other sensors (De and Df_2), the residue $r_3(t)$ is insensitive to the fault occurred on the Df_2 and sensitive sensor faults on other sensors (*De* and Df_1).

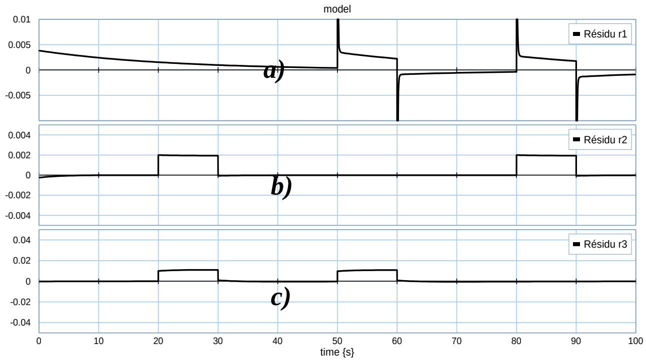

Fig. 17 Residuals $r_1(t)$, r_2 *(t)* and $r_3(t)$ of reverse osmosis for the GOS structure

Tables 2. a) and 2. b) Represent the binary signatures of defects for DOS structures and GOS deducted to perfectly isolate faults.

	De	Df_1	Df_2
r_1	1	0	0
r_2	0	1	0
r_3	0	0	1

a) Structure

	De	Df_1	Df_2
r_1	0	1	1
r_2	1	0	1
r_3	1	1	0

b) Structure

V. CONCLUSION

In this paper, we proposed a new methodology for monitoring of industrial systems. Our contribution is the development of a supervision strategy based on the proportional observer (Luenberger) for linear systems using the bond graph model. The first model, the bond graph model is used for modeling and the determination of residues Luenberger observer. Indeed, the complete knowledge of the state of a system is often necessary to develop a control law or the establishment of a monitoring or diagnostic strategy. Or the state of a system is generally only partially available and the input and output signals are in practice the only variables available by measurement. The most common solution to overcome this problem is to couple the existing system an auxiliary system, called estimator or state observer. The Observer provides an estimate of the system state from his model and measures its inputs and outputs. Furthermore, we have exploited the architectural appearance of the bond graph representation of industrial systems in the diagnostic condition based Luenberger observers. In this paper, we showed how to use a bond graph approach for modeling, state estimation, fault detection and simulation of dynamic systems. The addition of 20-sim [30] software in our work, as it allowed us to physically see each component and also the process of

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building a simple way the observer Luenberger for system monitoring.

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