

Efficiency of bond graph and external model integration for alarm processing of a central air conditioning system

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Article Info

Article history:

Received May 31, 2020

Revised Jun 7, 2020

Accepted Jul 3, 2020

Keywords:

Bond graph model

Central air conditioning system

External model

Industrial process

Supervision system

ABSTRACT

The design of a supervision system based on the external model by structuring the industrial process according to several modes of operation (degraded and normal). The disadvantage of this model is that it describes the industrial process components as functions regardless of their dynamics without going into detail. Hence the interest of the bond graph model to fill the external model limits. The performance of the proposed supervisory system using both models lies in the detection and location of faults for each mode of operation. The bond graph model enriched by the concept of causality and thanks to these structural properties can clearly display the elements of the physical system taking into account their dynamics in normal and abnormal operation. The results of our research have been applied to central air conditioning system; the development of the proposed project has proceeded from the modeling stage to the reconfiguration stage of the system.

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1. INTRODUCTION

In order to cope with the need of the industrial market and the increasingly severe economic competition, industrialists tend increasingly to expand their facilities and make them more complex. Indeed, this complexity makes the control systems of industrial systems more difficult and specially to reduce safety and increase the risk of breakdowns [1-4]. In addition, supervisory systems use intelligent systems that provide the user with assistance in managing their urgent alarm tasks in order to increase the reliability and dependability of processes [5-10]. However, the improvement of the dependability of the systems is essentially based on fault detection and isolation algorithms [11-19], these algorithms have the role of comparing the actual behavior of the system wither ferrous behaviors describing the normal operation. The degradation of the performance of diagnostic algorithms is mainly due to the imperfect knowledge of the parametric values of the models and to their random variations [20]. Our research in this paper consists in using a new methodology for the supervision of industrial systems using the external model and the bond graph model. Supervision from the external model point of view considered an industrial system for an operator as an entity offering services, which manipulate variables and use a set of resources [21-24]. The execution of a service is triggered by the verification of an activation condition, and requires the availability of a certain number of resources. At a given moment, this process is in a given mode of exploitation. Only the services belonging to this mode can be executed, from where each mode of operation

must comprise a specific service of change of mode. However, we cannot join any mode from another for reasons of security and consistency of operation. The problem to solve is to use a unifying tool to integrate the functional and structural models for the design of the supervision system (monitoring and reconfiguration). The bond graph tool is well suited for this task [25-30]. From a monitoring point of view, the causal and structural properties of the bond graph are used for the detection and isolation of faults affecting actuators, sensors or the physical components of the system. Thus, the availability of services, necessary for the accomplishment of a mission, will be provided by the monitoring algorithm to the operating mode management graph. Also, these services defined by functions can be generically to bond graph elements. From a reconfiguration point of view, the graphic properties will be exploited to be able to develop the means of reconfiguration of the system.

2. SUPERVISION INDUSTRIAL PROCESS BY EXTERNAL AND BOND GRAPH MODELS

2.1. External model

External models structure the industrial process, according to several modes of operation (gradients and normal). Switching from one mode to another operating mode is described by a diagram called a management diagram of the mode of use. It represents the human-machine interface system. Industrial systems consist of a set of equipment interconnected with each other. A hardware failure of one or more of these elements may dare to drive some of the purposes for which the system was designed, and then its hold alert users to generate alarms. The last must be sufficiently synthetic to clearly express to the operator the nature of the failure and its consequences. The external model that is proposed by [31] is considered here. This model is based on concepts of services, missions and operation modes.

The industrial systems consist of a set of equipment (heat exchanger, motor pump ...), which are organized so that the systems can achieve the objectives for which they were designed:

- The low level: These are the basic services; they are directly interfaced with the process (pumps, valves, sensors ...).
- High level: These are composite services; they are composed of basic services (cooling, boiler ...).

All services S , that are offered by equipment is defined:

$$S_i = \{i \in 1 \dots n\}.$$

Basic services (low level) are associated with each other in defining compound services and perform a mission (Figure 1). A hardware failure means the unavailability of some basic services.

S_i : service i

- Mission M_1 : S_1, S_4, S_5, S_6 .
- Mission M_2 : S_2, S_4, S_7, S_8 .
- Mission M_3 : $S_3, S_4, S_6, S_7, S_9, S_{10}$.
- Mission M_4 : S_1, S_4 .

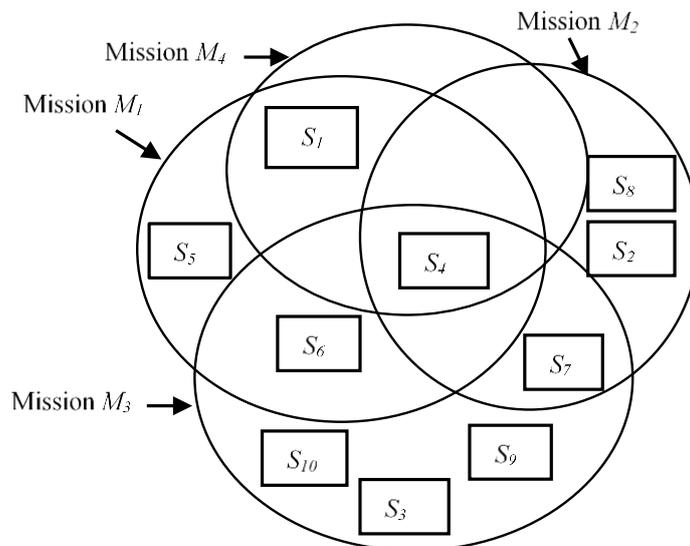


Figure 1. Services and missions

In this example we find ten (10) services and four (4) missions. Each mission has several services and the S4 service is in all four missions. The missions direct and manage the systems in accordance with the specifications. But at some point, only a subset of these missions is needed to achieve the goals. Each of these subsystems is called a mode of operation or operation. An operating mode (OM_i) is a set of services represented by the following relation: $OM_i = (S_{1n}, S_{2n}, \dots S_{mn})$. The operation modes are given by a general classification of the operating modes of the industrial devices: off-farm, configuration, manual or automatic mode, nominal ... etc.

The supervision of industrial processes with the external model is determined by the management of the modes of operations, these modes of operations are interconnected to perform a well-defined function. The request to switch from one mode to another mode must be placed for security reasons because the system may fail on an OM_j mode of use when some services are not available. The switch over is represented by a boolean variable b_{ij} . The set of operating modes and the b_{ij} switching conditions are described by a graph named operation mode management (Figure 2).

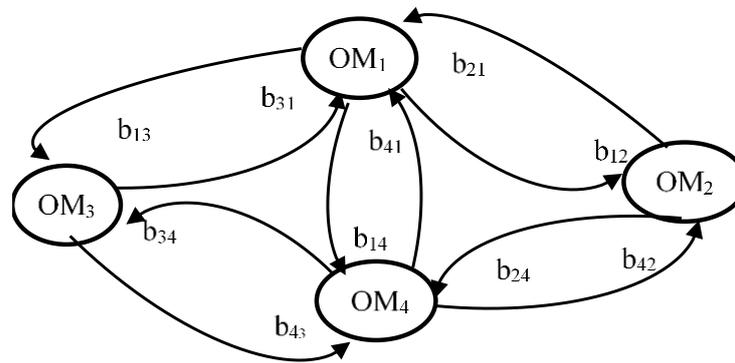


Figure 2. Management of operating mode by external model

2.2. Integration of bond graph and external models

The integration of the bond graph model with the external model for the supervision of industrial processes is proposed by Ould Bouamama [32], this combination will be linked to the services, missions and modes of operation.

The services as defined in the external models are represented by elements of the bond graph are the services offered by the power source equipment (mechanical: motor), (thermal: heat resistance) and (hydraulic pump) water). The services offered by the functional role of the equipment (storage, processing, transport, etc.) are represented in the bond graph by the basic elements respectively (the capacity C for the potential storage, the restriction R for the processing of air or water, transformer TF for transforming electrical voltages or mechanical torques). It should be noted, however, that the services in jump graph can be quantified by constitutive equations deduced from the bond graph model. Missions represented by sets of services are intended to meet all the objectives set by the specifications, so in the sense of bond graph are the set of basic elements that provide a well-defined mission according to the objectives set the industrial process.

The Modes of operations determined by the external model ME_i are the same modes that will be represented by the MBG_i model, from which each mode of operation OM_i corresponds to a mode of operation must be modeled by a model graph bond $MBG_i: OM_i$. At a given time, the method operates in a nominal mode of operation represented by the external model ME_{fn} corresponds to a model bond graph corresponds MBG_{fn} . Let b_{ij} denote the requirement to move from MBG_i to MBG_j (Figure 3).

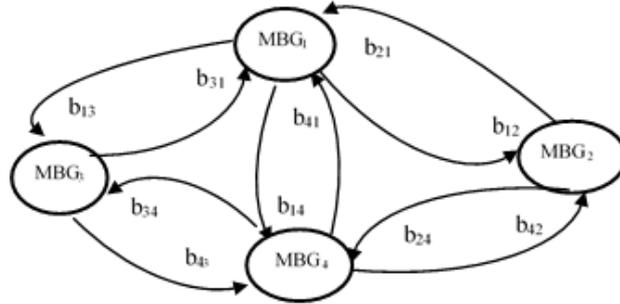


Figure 3. Management of operating mode by bond graph mode

3. SUPERVISION OF A CENTRAL AIR CONDITIONING SYSTEM BY EXTERNAL AND BOND GRAPH MODELS

3.1. Description central air conditioning system

The central air conditioning system (CACs) provides refrigeration for room auxiliaries for medical experiments in a hospital by circulating a liquid whose temperature is maintained at “10°C”. The circulation of this cooled liquid is ensured by a valve (VC) (see Figure 4).

The water is cooled by the three heat exchangers supplied in parallel (CACs₁, CACs₂ and CACs₃), the temperature of the refrigerant is measured at the inlet and the outlet of the exchangers by the sensors T_{Inp} and T_{Outp} .

The valve (VH) is used to modulate the flow of water according to which one, two or three exchangers are in service. Maintaining the temperature at 10°C is provided by the exchanger valves (V₁₂, V₂₂ and V₃₂) connected in series with each exchanger. The valves (V₁₁, V₂₁ and V₃₁) are used to supply the cooling systems under normal operating conditions (two cooling systems, on operation (three cooling systems) or reduced operation (one cooling system)).

In normal operation, the circuit is provided by two exchangers in use. During the summer can we add third exchanger. While during the winter only one exchanger can accomplish the operation and also to have gains in the level of electrical energy consumption.

After a total stop (maintenance of the circuit, emptying ...), the restart will be done in a progressive way, that is to say so as to catch the minimum temperature of 10°C.

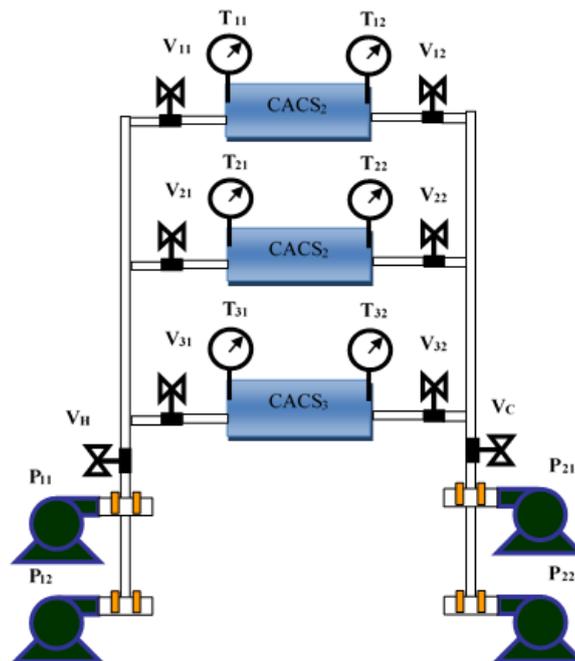


Figure 4. Schematic diagram of central air conditioning system

3.2. System analysis by external and bond graph model in normal function

The central air conditioning system consists of a set of equipment (exchangers, tarpaulins ...) that are organized in such a way that the system can meet the objectives for which it was designed.

This equipment is arranged in two ways:

- Single component: they are directly interfaced with the process (pumps, valves, sensors).
- Complex component: they are composed services; they are composed by basic services (cooling circuits, water booster unit).

According to this principle, it is possible to give a pyramidal decomposition of the cooling system (Figure 5).

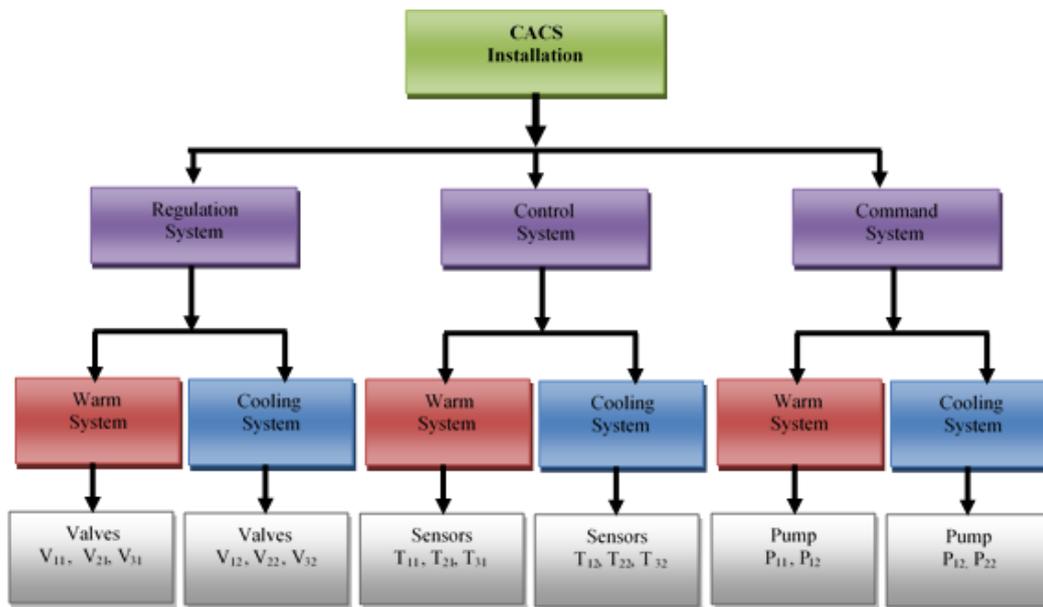


Figure 5. Decomposition of the central air conditioning system

The highest-level services are called missions. They must make it possible to satisfy all the objectives set by the specifications. The various missions of the CACS system are as follows:

- Mission M_1 : Put the water in the circuit CACS;
- Mission M_2 : Check the performances of the devices;
- Mission M_3 : Set the bypass of the CS circuit (valves V_{12} , V_{22} and V_{32});
- Mission M_4 : Reach the set temperature 10°C ;
- Mission M_5 : Ensure the cooling of the auxiliaries by using the pumps (input by one pump P_{11} and one output by one pump P_{21}) operating at 100%;
- Mission M_6 : Ensure the cooling of the auxiliaries by using the pumps (input by tow pumps P_{11} and P_{12} , output by tow pumps P_{21} and P_{22}) operating at 150%, optimally on very hot days;
- Mission M_7 : Ensure the cooling of the auxiliaries by using the pumps (input by one pump P_{11} and output by one pump P_{21}) operating at “50%” according to the required configuration;
- Mission M_8 : Ensure minimal cooling when the unit is shut down;
- Mission M_9 : Maintain the circuit;
- Mission M_{10} : emptying the whole system.

The missions of the cooling system are the ones responsible for leading and managing the system in accordance with the objectives of the specifications. But at a given moment, only a subset of these missions is necessary to meet the objectives set. Each of these subsets is called the operating mode.

For this cooling system, seven operating modes can be distinguished are (Figure 6):

- Preparation mode (ME_1): The circuit is put in water and a set of tests must be executed;
- Start mode (ME_2): The water temperature is gradually brought to the set temperature.
- Nominal operating mode (ME_3): Refrigeration is provided by two central air conditioning system and one pump operating at 100%;

- Reduced operating mode (*ME4*): Refrigeration is provided by one central air conditioning system and a one pump operating at 50%;
- Operating mode (*ME5*): Operation with three refrigeration systems and two pumps operating at 150%;
- Normal shutdown mode (*ME6*): The slice is stopped but the set temperature is maintained by a minimum circulation;
- Full stop mode (*ME7*): Coolant circulation is stopped and draining can be ensured.

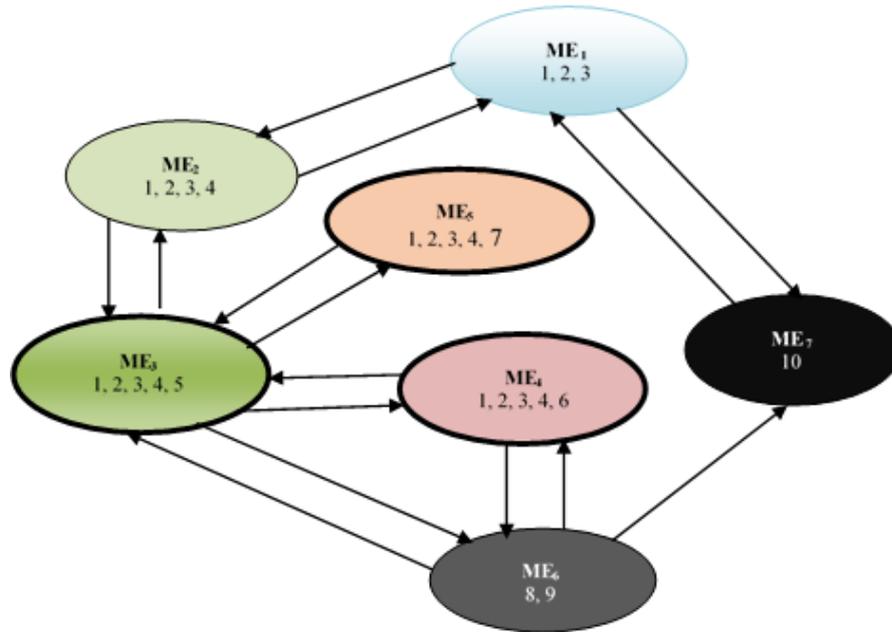


Figure 6. Management of operating mode by external model for central air conditioning system

In this mode of operation (*ME5: MBG5*), the refrigeration of auxiliaries is ensured by the circulation of the liquid through two pumps (input by tow pumps P_{11} and P_{12} , output by tow pumps P_{21} and P_{22}) operating at 150%. The bond graph model is given in Figure 7, this model presented clearly shows the physical phenomena that take place there with three cooling systems ($CACS_1$, $CACS_2$ and $CACS_3$).

In this mode of operation (*ME3: MBG3*), the refrigeration of the auxiliaries is ensured by the circulation of the liquid thanks to one pump operating at 100%. The bond graph model is given by Figure 8, this model presented clearly shows the physical phenomena that take place there with two cooling systems ($CacS_1$ and $CacS_2$).

In this mode of operation (*ME4: MBG4*), operation with one pump operating at 50% and an exchanger in service are allowed. The bond graph model is given in Figure 9.

To determine the analysis of any indstrial systems we must calculate the residuals, in our case the residues are as follows:

a. Residue r_1 :

$$r_1 = \frac{1}{R_{C1}} \cdot (MSe \ De_1) \ C_{F1} \cdot \frac{dDe_1}{dt} \ \frac{1}{R_{W1}} \cdot (De_1 \ De_3) \ \frac{1}{R_{P1}} \cdot (De_2 \ De_1) \tag{1}$$

b. Rsidue r_2 :

$$r_2 = \frac{1}{R_{E1}} \cdot (Se_{ext} \ De_2) \ C_{P1} \cdot \frac{dDe_2}{dt} \ \frac{1}{R_{P1}} \cdot (De_2 \ De_1) \ \frac{1}{R_{P1}} \cdot (De_2 \ De_1) \tag{2}$$

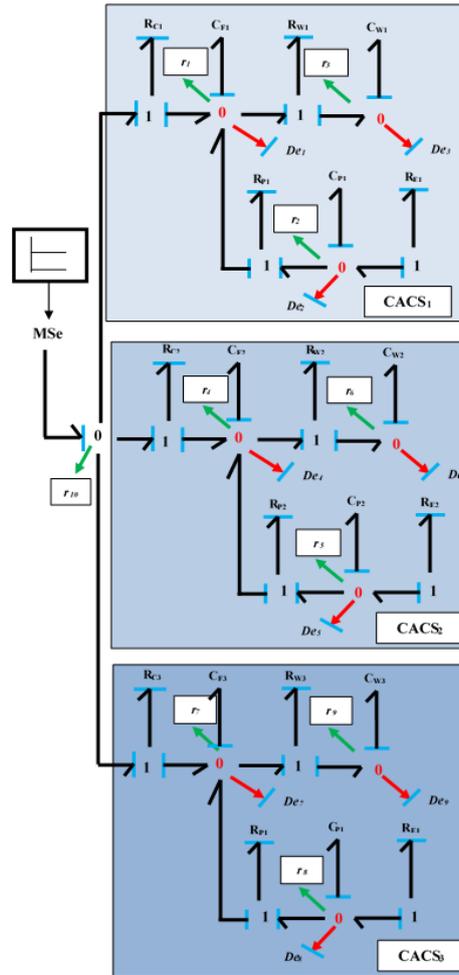


Figure 7. Bond graph of central air conditioning system for over normal function mode MBG_5

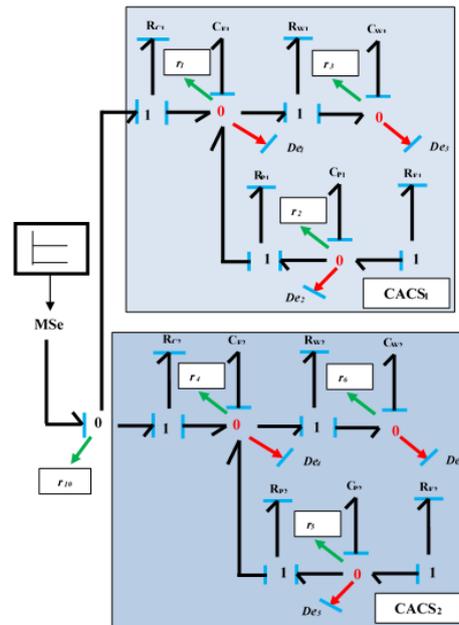


Figure 8. Bond graph of central air conditioning system for normal mode MBG_3

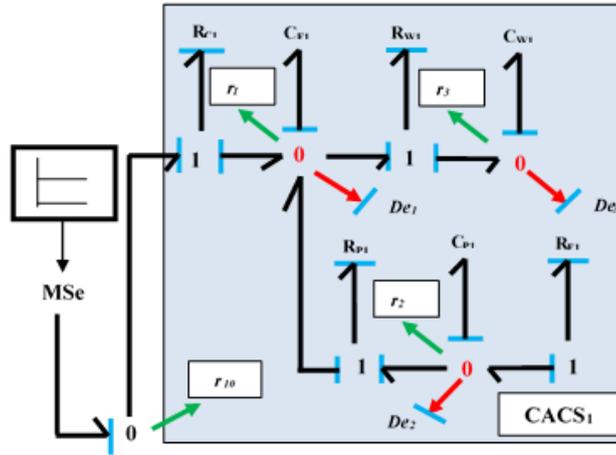


Figure 9. Bond graph of central air conditioning system for reduced operating mode MBG_4

c. Residue r_3 :

$$r_3 = \frac{1}{R_{W1}} \cdot (De_1 - De_2) - C_{W1} \cdot \frac{dDe_3}{dt} - \frac{1}{R_{P1}} \cdot (De_2 - De_1) \tag{3}$$

d. Residue r_4 :

$$r_4 = \frac{1}{R_{C2}} \cdot (MSe - De_4) - C_{F2} \cdot \frac{dDe_4}{dt} - \frac{1}{R_{W2}} \cdot (De_4 - De_6) - \frac{1}{R_{P2}} \cdot (De_5 - De_2) \tag{4}$$

e. Residue r_5 :

$$r_5 = \frac{1}{R_{E2}} \cdot (Se_{ext} - De_5) - C_{P2} \cdot \frac{dDe_5}{dt} - \frac{1}{R_{P2}} \cdot (De_5 - De_4) - \frac{1}{R_{P2}} \cdot (De_5 - De_4) \tag{5}$$

f. Residue r_6 :

$$r_6 = \frac{1}{R_2} \cdot (De_4 - De_5) - C_{W2} \cdot \frac{dDe_6}{dt} - \frac{1}{R_{P2}} \cdot (De_5 - De_4) \tag{6}$$

g. Residue r_7 :

$$r_7 = \frac{1}{R_{C1}} \cdot (MSe - De_1) - C_{F1} \cdot \frac{dDe_1}{dt} - \frac{1}{R_{W1}} \cdot (De_1 - De_3) - \frac{1}{R_{P1}} \cdot (De_2 - De_1) \tag{7}$$

h. Residue r_8 :

$$r_8 = \frac{1}{R_{E1}} \cdot (Se_{ext} - De_8) - C_{P3} \cdot \frac{dDe_8}{dt} - \frac{1}{R_{P3}} \cdot (De_8 - De_7) - \frac{1}{R_{P3}} \cdot (De_8 - De_7) \tag{8}$$

i. Residue r_9 :

$$r_9 = \frac{1}{R_{W3}} \cdot (De_7 - De_8) - C_{W3} \cdot \frac{dDe_9}{dt} - \frac{1}{R_{P3}} \cdot (De_8 - De_7) \tag{9}$$

j. Residue r_{10} :

$$r_{10} = \frac{1}{R_{C1}} \cdot (MSe - De_1) - \frac{1}{R_2} \cdot (MSe - De_3) - \frac{1}{R_{C3}} \cdot (MSe - De_7) \tag{10}$$

3.3. System analysis by external model in abnormal function

If there is a material failure, the cooling system becomes unable to continue part of the missions for which it was designed, the operators of driving and maintenance must be informed. The manufacturers of

the cooling system associate nine (09) alarms with the cooling system, they are illustrated in Table 1 and this table gives for each defect a list of services and missions.

Alarm 01A: this fault is associated with the cooling system ($CACS_1$), the missions affected are missions 1, 2, 3, 4, 5 and the operating mode is threatened ME_3 .

- a. Mission 1: we find this mission in the operating mode in preparation, the absence of this mission makes the mode in preparation unavailable. If the mode of preparation is the current mode, in the presence of a fault, the automatic transition to another mode must be considered. For this case we find two possibilities:
 - Start mode: switching to this mode is impossible since it is not available.
 - Total stop mode: switching to this mode is possible since it is available.
- b. Missions 2, 3, 4: these missions are found in the startup mode, the absence of this mission makes the start mode unavailable. If the start mode is the current mode, in the presence of a fault, the automatic transition to another mode must be considered. For this case we find two possibilities:
 - Nominal operating mode: switching to this mode is impossible since it is not available.
 - Operating mode in preparation: switching to this mode is possible since it is available.
- c. Mission 5: this mission is found in the operating mode nominal operation; the absence of this mission makes this mode unavailable. If the nominal operating mode is the current mode, in the presence of a fault, the automatic transition to another mode can be considered, for this case we find two possibilities:
 - Reduced operation: the transition to this mode is impossible since it is not available.
 - Normal stop operation: switching to this mode is possible since it is available.
- d. Mission 8: we find this mission in the operating mode normal stop, the absence of this mission makes this mode is unavailable. If the nominal operating mode is the current mode, in the presence of a fault, the automatic transition to another mode can be considered, for this case we find two possibilities:
 - Reduced operation: the transition to this mode is impossible since it is not available;
 - Normal stop operation: switching to this mode is possible since it is available.

Table 1. Availability of services and missions in the presence of defects

Alarms	Defaults	Services	Missions
01A	$CACS_1$ exchanger leak	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 5
02A	$CACS_2$ exchanger leak	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 7
03A	$CACS_3$ exchanger leak	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 6
04A	blocked valve V_{11} closed	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 5
	blocked valve V_{11} open	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 5
05A	blocked valve V_{12} closed	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 7
	blocked valve V_{12} open	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 7
06A	blocked valve V_{21} closed	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 6
	blocked valve V_{21} open	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 6
07A	blocked valve V_{22} closed	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 5
	blocked valve V_{22} open	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 5
08A	blocked valve V_{31} closed	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 7
	blocked valve V_{31} open	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 7
09A	blocked valve V_{32} closed	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 6
	blocked valve V_{32} open	Regulation_temp_max Regulation_temp_min	1, 2, 3, 4, 6

3.4. System analysis by bond graph model in abnormal function

The alarm 01 corresponding to a fault (leak) at the cooling system (CAS_1), this fault causes a decrease in the amount of water cooled. These phenomena are readable on the bond graph model and can be quantified by the equations. However, this faulty component ($CACS_1$) is in the normal operating mode (MBG_3), so switching to the reduced operating mode (MBG_4) or the normal stop operating mode is allowed. For the generation of the residues of each mode, we applied the method of the redundant analytical relationships ($RRAs$), we also call residues. In the case of over normal mode (MBG_5) we end up with the following equations of residues:

The residual curves ($r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9$ and r_{10}) in over normal operating mode (MBG_3) converge to zero, see Figure 10.

When a fault in the cooling system ($CACS_1$), the residues (r_1, r_2 and r_3) are sensitive to this defects. Or their curves become different to zero at the moment of failure (between 20000s and 40000s) see Figure 11 (evolution of residues) a Figure 12 (evolution of temperatures for each system $CACS_1, CACS_2$ and $CACS_3$).

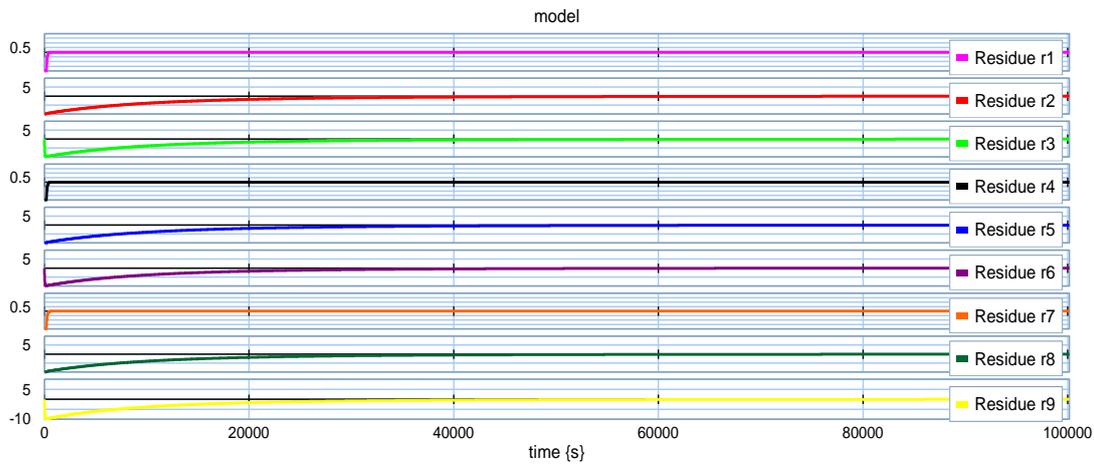


Figure 10. Evolution the residues $r_1(t), r_2(t), r_3(t), r_4(t), r_5(t), r_6(t), r_7(t), r_8(t), r_9(t)$ and $r_{10}(t)$ for over normal function mode MBG_5 without fault

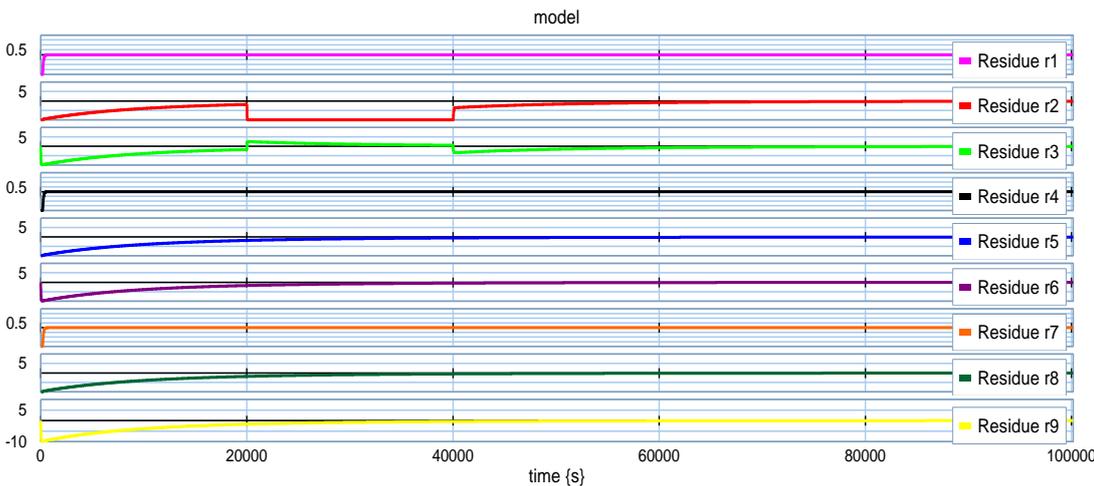


Figure 11. Evolution residues $r_1(t), r_2(t), r_3(t), r_4(t), r_5(t), r_6(t), r_7(t), r_8(t), r_9(t)$ and $r_{10}(t)$ for over normal function mode MBG_5 with fault (leak at the cooling system)

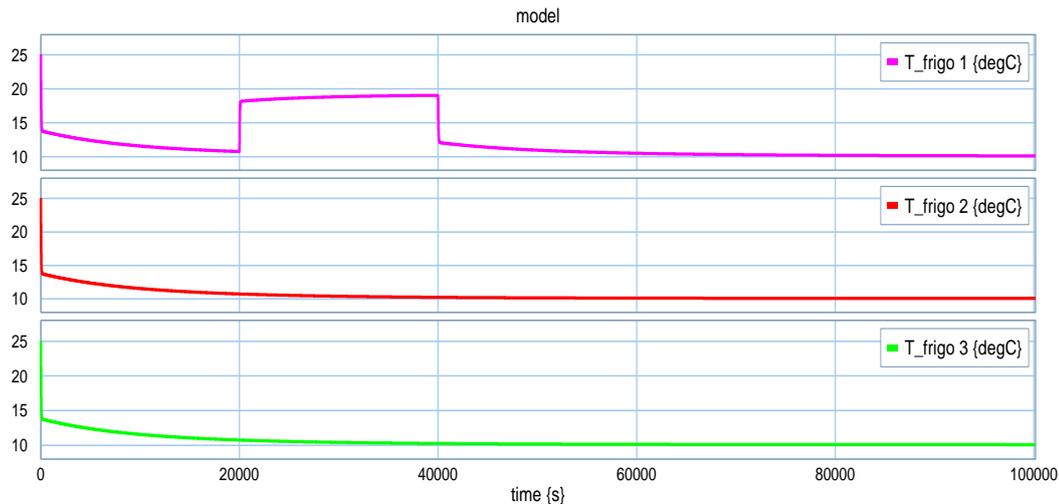


Figure 12. Evolution the evolution of the exit temperatures of the CS_1 , CS_2 and CS_3 systems for over normal function mode MBG_5 with fault (leak at the cooling system)

4. CONCLUSIONS

In this part, we give for the treatment of alarms of the System of intermediate Refrigeration (CACS) specific to each modeling:

The external model: Structure the operation of CACS system according to several modes of operation, switch from one mode to another when a mission disappears and evaluate the relevance of the alarm system;

The bond graph model: Clearly visualize the physical system (storage, dissipation, transfer as well as the dynamics of process phenomena, find the origins of the alarms by its causal organization, determination and localization of failures by RRA relationships and possibility to use the tools of the external model.

ACKNOWLEDGEMENTS

We thank the National School of Engineers of Tunis, University of Tunis El Manar to support our work.

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