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SUPERVISIONANDCONTROLINDUSTRIALREFRIGERATORBYINTEGRATIONEXTERNALANDBONDGRAPHMODELS

Supervision and Control Industrial Refrigerator by Integration External and Bond Graph Models

Abderrahmene Sallami [α] & Maher Ben Hariz [σ]

Abstract- This article aims to solve the problems of supervision and PI controller of an industrial thermal system (the industrial static refrigerator). The structure of an industrial system from the point of view of the external model operates in several modes of operation (normal and abnormal). For this external model, we have two problems, the first problem is a fault location problem because we are talking about a global operation of the system and the second problem is a problem of visualization of the phenomenon of switching between the operating modes of the system. For this, in this article we have integrated two other models to solve the problems in question. For the localization problem, we used the bond graph model. This model, by its graphic nature and the use of a unified language, allows to model the industrial system element by element from which it helps the user not only to detect defects, but also to locate them when they appear in the system. For the visualization problem, we used the transfer function model. This model defines the relationship between the input and an output variable, this relationship allows us to visualize the appearance of the output signals for each mode. These techniques have been applied to monitor an industrial refrigerator, and analyzes and simulations are determined to validate the reliability of these models.

Keywords: supervision system, PI controller, bond graph model, external model, normal and abnormal, industrial refrigerator.

I. Introduction

Today, we find that industrial systems are becoming more complex. This complexity requires the enlargement of the traditional model; so far this model is limited to control algorithms. The supervisory design of these systems must be evolved to take into account several valuable information processing systems (sensors and actuators) for which decision making is inevitable. This evolving needs and technological progress made in the field of sensors, actuators and communication field bus lead to the design of the supervision system has used intelligent systems (sensors and actuators) that incorporate a very large information capacity with automated process.

In this context several works have been carried out to provide the object-oriented functional (model external) and behavior (object-oriented model) functions to analyze the design of the intelligent equipment supervision system (Jinghao et al., 2018; Praveen et al., 2018; Andrei, 2015; Merzouki et al., 2013; Chatti et al., 2013; Khalil et al., 2012; Loureiro et al., 2012; Bera et al., 2012; Samantary et al., 2008). As far as the external model is concerned, this model uses the concepts of services, missions and mode of operation which offer to the user organizations based on modes of operation information on the behavior of the component in different operating situations (normal or defective).

The disadvantage of the external model is that it describes the industrial system in terms of functions, without taking into account parameters of physical and dynamic behavior. This consideration leads to certain ambiguity such as the location of defects. This is why the leap-graph model as a graphical modeling language of industrial systems element by element is a practical and useful complementary tool for obtaining behavioral and diagnostic models. In addition, the causal properties of this model can help design FDI (Fault Detection and Isolation FDI) algorithms (Raghappriya and Kanthalakshmi, 2020; Jayaprasanth and Kanthalakshmi, 2018; Flett and Bone, 2016; Ahmed et al., 2013; Simani, 2006; Medjaher et al., 2006; Chen and Lee, 2002; Graisyhm, 1998; Duthoit; 1997; Staroswiecki, 1994; Cassar et al., 1994).

This integration allows us to obtain behavioral knowledge about intelligent industrial systems, but it is limited since switching between modes is not determined. For this article is determined, hence the contribution of this article is to use the transfer function model to determine the output dimmer in each operating mode of the industrial system by inserting a switching program between the operating modes according to the necessary tipping conditions. In this way, it becomes possible to obtain, on the one hand, the behavioral knowledge of the intelligent industrial system for monitoring in case of faults and, on the other hand, to see the switchover between the modes of operation; and therefore, to ensure a modernized security standard.

In this article, the work is distributed as follows; the first section focuses on the concept of the supervisory system and these advantages in the automation of industrial systems. The second section will be determined on the concept of the external model and these advantages and disadvantages to describe

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an industrial system. The third section a brief introduction to the bond graph model in the interest of monitoring industrial systems, then the method of integrating the bond graph model with the external model, to complete the description of the industrial system is explained. In the fourth section we will use the concept of the bond graph transfer function model to determine the tilting of the operating worlds of the industrial system. Then, the design of PI controllers for each operating mode is proposed (Jeyashanthi and Santhi, 2020; Čedomir et al., 2019; Kalaivani. and Lakshmi, 2014; Lutfy, 2010). Finally, a conclusion to illustrate all the work we have done.

II. SUPERVISION BY EXTERNAL, BOND GRAPH AND TRANSFERT FUNCTION MODELS

a) *Supervision System*

Supervision is generally defined as a task of controlling and monitoring the execution of an operation or work performed by other agents (men or machines), without going into the details of this execution. We have adopted the definition of the Research Group on Integrated Automation and Human Machine-Driven Systems, which stipulates that: supervision is the set of tools and methods used to conduct industrial installations both in normal operation and in the event of faults or disruptions for industrial system see figure 1.

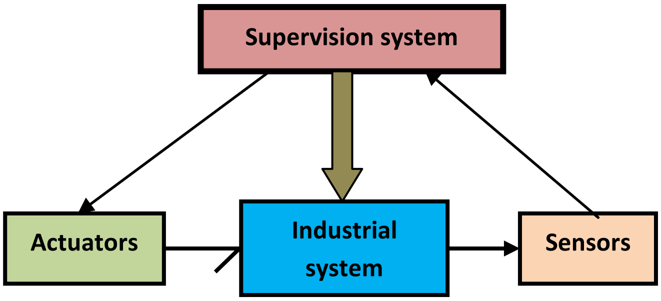


Fig. 1: Supervision System for industrial system

A supervisory system is active if it gathers all the events necessary to activate the decision-making see figure 1:

- *Real-time:* Decision-making will be effective and fast if the situational awareness is complete.
- *In delayed time:* Decision-making will be taken as appropriate and the analysis of concrete situations allows a formalization of the operations to be created for each provision.

A supervisory system can improve the process with:

- Continuous use of the system (no interruption),
- Minimization of fault tripping (speed and reliability),
- Optimization of the use of system components,
- Minimization of maintenance costs,
- Realization of benefits for industrialists (economic).

b) *External Model*

Industrial systems consist of a set of interconnected equipment. A hardware failure of one or more of these devices may jeopardize the achievement of some of the objectives for which the system was designed, so users should be warned by generating alarms. The latter must be sufficiently synthetic to express clearly the nature of the failure and its consequences. Research has developed modeling by external model (Sellami et al., 2018; Sallami et al., 2016; Imhemed et al., 2007; Maza et al., 2006; Bayart et al., 1998; Bayart et al., 1999).

This model is based on the following notions:

- Concept of services,
- Concept of missions,
- Concept of operating modes.

Industrial systems consist of a set of equipment (heat exchanger, motor, pump, etc.) that are organized in such a way that the systems can meet the objectives for which they were designed. These devices are arranged in two ways:

- *Low level:* These are basic services; they are directly interfaced with the process (valves, tank, sensors...).
- *High level:* These are composed services; they consist of basic services (cooling circuits, water booster unit, desalination unit...).

Elementary services (of low level) are associated with each other to define so-called composite services; the latter realize what we call a mission. A hardware failure means the unavailability of certain basic services and may call into question the continuation of certain missions.

The missions were the first to take responsibility for managing and managing systems 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 referred to as the operating mode.

An operating mode (*MEi*) corresponds to a set of service versions represented by Si, this set is the grouping of the subsets that define the desired operating mode, so we have the following relation: $MEi = \{S_1, S_2\ldots\ldots, S_n\}$.

At a given moment, the process is executed in an operating mode (represented by *MEi*), all the operating modes are available and interconnected to perform what we call operating mode management graph.

The request to change from one mode to another mode must be indicated for safety reasons because the system may fall on an operating mode *MEj* which is not available, hence the necessity of having a logical passage that leads The system on a mode of operation without getting into trouble. This passage is represented by a Boolean variable *bij*. The set of operating modes and the conditions of passage *bij* are described by a graph of management of the operating modes and which can be represented in figure 2.

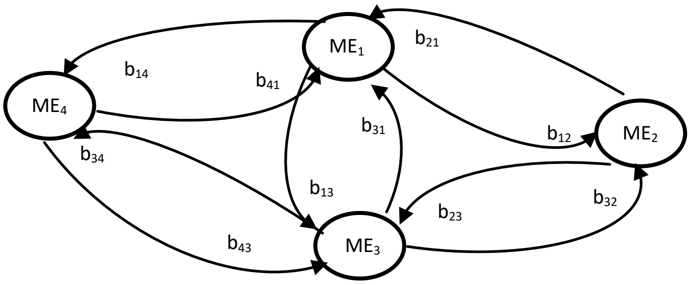


Fig. 2: Operating mode management graph

c) Bond Graph Model

The bond graph modeling tool was defined by Henry Paynter (Henry, 1961), it is a language of graphical representation of physical systems, based on the modeling of the energy phenomena intervening within these systems. This energetic approach makes it possible to underline the analogies that exist between the different fields of physics (mechanics, electricity, hydraulics, thermodynamics, acoustics, etc.) and to represent in a homogeneous form the multidisciplinary physical systems . In this article, we will present the utility of the bond graph tool for the supervision of industrial systems. In the first part we will give the different approaches using the bond graph for the design of a supervisory system (qualitative and quantitative approach), the second part is devoted to the integration of the external model and the bond graph model for the supervision systems (Joel and Christophe, 2018; Montazeri et al., 2018; Tapia et al., 2018; Nacusse, et al., 2015; Ould-Bouamama, 2014; Ould-Bouamama, 2013; Samantaray and Ould Bouamama, 2008; Benmoussa et al., 2012; Aitouche et al., 2008).

Bond graph based modeling relies mainly on the concept of generalized stress and flux variables that allow the representation of balance sheets and energy exchanges between different elements of a system. In this approach, an energy exchange between two elements is represented by a half-arrow link indicating the direction of the transfer. These half-arrows are called "leaps", each is labeled by a force variable e and a flux variable f. The product of these two variables corresponds to the power "carried" by the leap. This power is counted positively in the direction of the half-arrow. The advantage of this modeling is that the choice of e and f depends only on the physical domain of the system to be represented in figure 3.

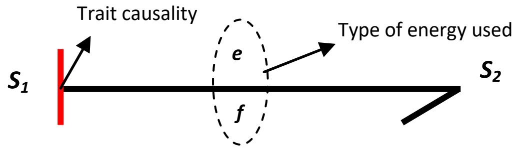


Fig. 3: Representation of a physical system by bond graph

This description is made in terms of components connected together by links through the ports they have, the components are classified by the number of ports they have, they are multiport or n-ports as described in. There are three types of Bond Graphs each used in a particular stage of the design process [22-28]:

- Bond Graphs with words where the components represent subsystems described by black boxes, this level allows a first decomposition of the system to have an overall view of the energy exchanges implemented;
- Bicausal Bond Graphs where the components are indivisible elementary components and whose behavior is known (resistance, inductance, capacitor, etc.), this level is used at an advanced stage of the design process, where the components can be assimilated Perfect elementary components;
- Causal Bond Graphs which allow establishing the equations of the system.

In the sense of bond graphs, the services provided by the equipment of energy sources of the mechanical (motor), thermal (thermo resistance, potential energy or kinetic of a fluid) and hydraulic (pump) type energy sources are represented by sources of energy, Effort *Se* (*MSe*) or flow *Sf* (*MSf*). The services provided by the functional role of the equipment (storing, transforming, transporting, etc.) are designated by the leaf graph elements *R*, *C*, *TF* and *GY*. The services offered by the sensors (measurements) are ensured by the force (*De*) and *flow* (*Df*) detectors, the requests associated with these services are modeled by information links.

It should be noted, however, that the leap graph services can be quantified by constitutive equations of the modeled leap graph elements. Missions represented by sets of the highest level services as defined in the external model must satisfy all the objectives set out in the specification and are of course based on the services offered by the lower level equipment.

At all times, an installation operates in an operating mode whose behavior is described by a bond graph model. Thus, each mode of operation (*MEi*) corresponds to a bond graph *MBGi* model represented by figure 4.

If *Si* is the set of jump graph elements and Vi is the version of each set, then the jump graph model is the sum of these sets associated with the *MEi* mode, ie the following relation: $MBGi = MEi = \{S_1(V_1)\ ,\ S_2(V_2)\ ...,\ S_n(V_n)\}$.

The bond graph *MBGi* models of the system are linked by bij transitions, for each two jump graph models there are corresponding transition elements specific to them, for example in figure 3, the pattern graph respectively MBG_2 and MBG_3 are linked by the transition elements b_{23} and b_{32}.

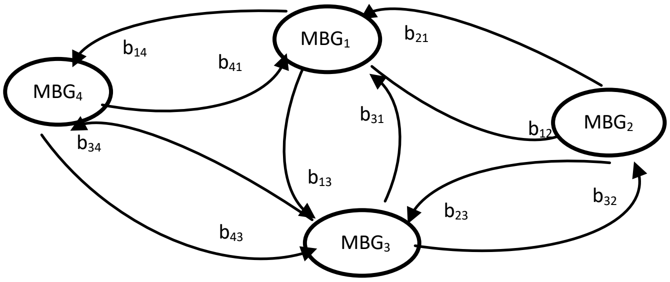


Fig. 4: Management graph of the *MBGi* using *MEi*

From the point of view of industrial process monitoring, the causal properties of the bond graph are used for the detection and isolation of faults affecting the sensors, actuators or physical components of the process. Thus, the availability of the services (necessary for the realization of a mission) will be provided by the monitoring algorithm to the graph of management of operating modes.

d) *Transfer Function Model*

Most physical systems can be described as operations that map responses from an input. These operations are transfer functions that explain the patterns of behavior between inputs and outputs. These transfer functions are obtained from linear or non-linear differential equations and can be in the form of a diagram containing all the information needed to simulate the system as a whole. At any time, the physical systems can operate in an operating mode whose behavior is described by a bond graph model (*MBGi*) corresponds to a transfer function model (*MFTi*) represented by figure 5.

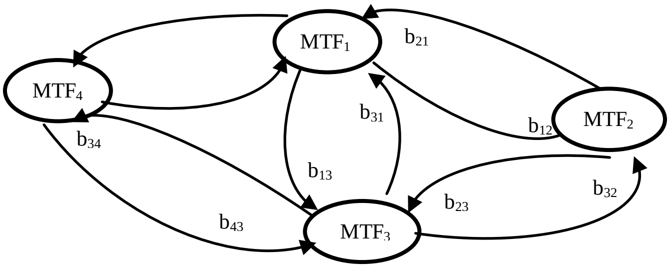
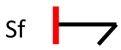
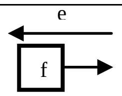
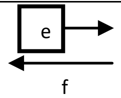
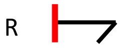
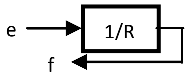
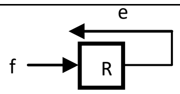
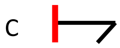
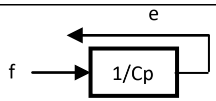
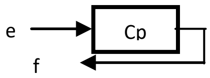
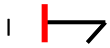
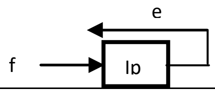
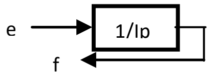
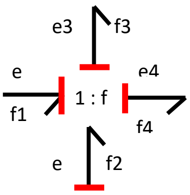
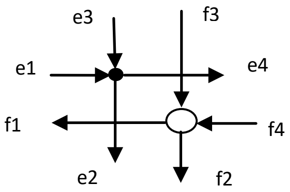
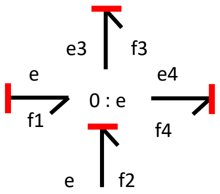
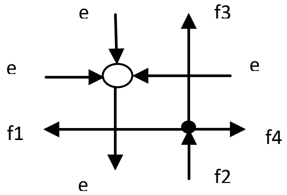
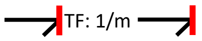
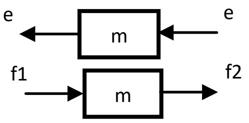
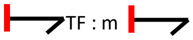
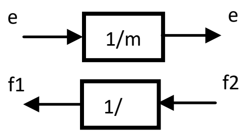
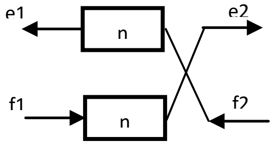
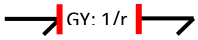
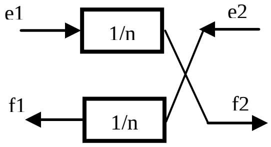


Fig. 5: Management graph of the *MTFi* using *MBGi*

Starting from the causality of each element of the bond graph model of a system, we will replace each element of this bond graph model with a basic functional schema. Indeed, each link of the model bond graph carries two signals the flow and the effort must represent by a full arrow each of the signals (f, e) associated with each link. The table 1 below shows the passage of each element of the bond graph model to the block diagram.

Table 1: Transfer function model of the basic elements

Elements	Bond graph model	Function transfer model
Flow source		
Effort source		
Restriction element		
		
Capacity element		
		
Inertial element		
		
Junction 1		
Junction 0		
Junction TF		
		

Junction GY		
		

The transition from the bond graph model to the functional diagram is done in a systematic way by following the following steps:

- Change the bonds of the bond graph model into two signals (flow and effort);
- Replace each junction 1 (respectively junction 0) in an algebraic sum of forces (respectively flow);
- Taking into account the causality of each element of the bond graph model, replace each element with the corresponding transfer function;
- Rearrange the functional diagram obtained to place the input and output variables;
- Simplify the functional diagram;
- Calculate the transfer function.

III. SUPERVISION AND CONTROL OF INDUSTRIAL REFRIGERATOR

In this article, we will use the domestic static refrigerator to develop our contribution. This refrigerator is equipped with freezer and a cooling compartment. The volume of behavior is 150 L with two plastic containers containing water and ice. Our work in this article focuses on heat transfers in the refrigerator compartment (see figure 6) (Sellami, 2018).

a) *External Model of Industrial Refrigerator*

The industrial refrigerator provides cooling of the air and fulfills the following tasks:

- Mission 1: Check for leaks at the heat exchanger;
- Mission 2: Check the seal at the refrigerator door;
- Mission 3: Check for ice water leaks;
- Mission 4: Check for leaks at the water tank;
- Mission 5: Ensure the cooling of the auxiliaries using only the cold heat exchanger with the presence of the water tank and iced water;

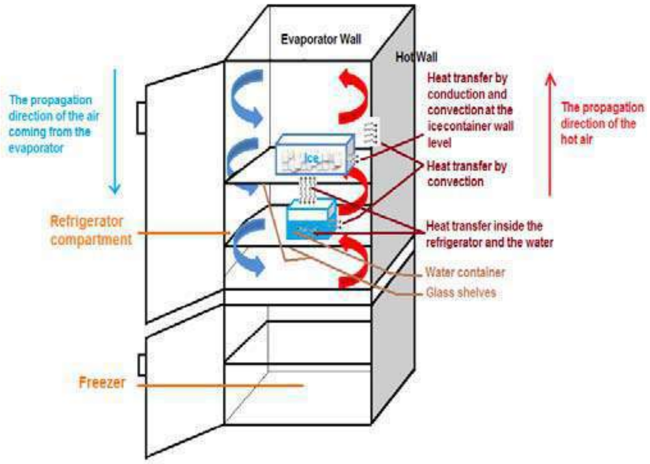


Fig. 6: Static refrigerator with heat transfers

- Mission 6: Ensure the cooling of the auxiliaries by using the cold water exchanger without iced water;
- Mission 7: Provide cooling of the auxiliaries using the cold water exchanger only;
- Mission 8: Shut down the system and empty it.
- Mission 9: Maintain the entire system circuit.

The tasks of the industrial refrigerator are those that are responsible for the management and management of the system in accordance with the objectives of the specifications. Indeed, at a given moment, only a subset of these missions is necessary to achieve the set objectives. Each of these subsets is called the operating mode.

For this cooling system, there are three modes of operation:

- Nominal operating mode: the refrigeration is ensured by two elements (the exchanger of cold and chilled water);
- Mode of operation without iced water: the refrigeration is ensured by a single element (the exchanger of cold);
- Mode of operation without water: the refrigeration is ensured by a single element (the exchanger of cold);
- Complete shutdown mode: the cooling air flow is stopped and maintenance can be ensured.

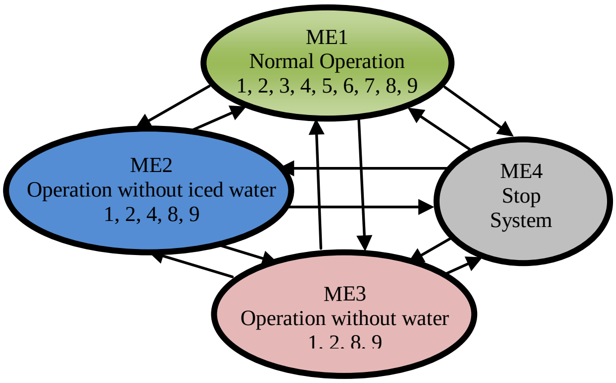


Fig. 7: Different functions of the industrial refrigerator

In case of hardware failure, the industrial refrigerator becomes unable to continue part of the missions for which it was designed. Operators of driving and maintenance must be informed. Manufacturers of the industrial refrigerator combine four (04) alarms. They are illustrated in table 2. This table gives for each defect a list of services and missions.

Table 2: Consequences of defects on the availability of services and missions

Alarmes	Defaults	Service Level 0	Service Level 1	Missions
A-01	Leak exchanger level	No cooling	Reduced cooling	1, 7
A-02	Leak door level	No sealing	Bad seal	2
A-03	Leak iced water level	Not iced water	Reduced iced water	3
A-04	Leak water level	No water	Reduced amount of water	4

Alarm A-01: This fault is associated with the leakage at the level of the exchanger of the industrial refrigerator, the mission concerned with this element are 1 where operating modes are threatened ME_1, ME_2 and ME_3. The absence of these missions makes the modes in question unavailable. If the normal operating mode (or the operation mode without ice, or the operating mode without a water tank) is the current mode, in the event of a fault, the automatic changeover to another mode must be taken into account. In this case, we find that the available mode is the stop mode ME_4.

Alarm A-02: This fault is associated with the leak at the door level, the mission concerned with this element is the mission 2 from which the operating modes are threatened ME_1, ME_2 and ME_3. The absence of this mission makes the modes in question unavailable. If the normal operating mode (or the operation mode without ice, or the operating mode without a water tank) is the current mode, in the event of a fault, the automatic changeover to another mode must be taken into account. In this case, we find that the available mode is the stop mode ME_4.

Alarm A-03: This fault is associated with the leak at the level of the chilled water, the mission concerned with this element is 3 where mode of operation is threatened ME_1. The absence of these missions makes the modes in question unavailable. If the normal operating mode ME_1 is the current mode, in case of a fault, it is necessary to take into account the automatic changeover to another mode. In this case, we can switch to the other modes ME_2, ME_3 or ME_4.

Alarm A-04: This fault is associated with the leakage at the water level, the mission concerned with this element is the missions 4 the operating modes are threatened ME_1 and ME_2. The absence of these missions makes the modes in question unavailable. If the normal operating mode is the current mode, in the event of a fault, it is necessary to take into account the automatic changeover to another mode. In this case, we find that the two available modes are ME_3 or ME_4.

b) Bond Graph Modeling Treatment

In this mode of operation ME_1, the refrigeration of the auxiliaries is ensured by the circulation of the air through two elements (the exchanger of cold and iced water);

The model of the bond graph MBG_1 corresponds to figure 10 which corresponds to the modeling of the dual flow air treatment unit.

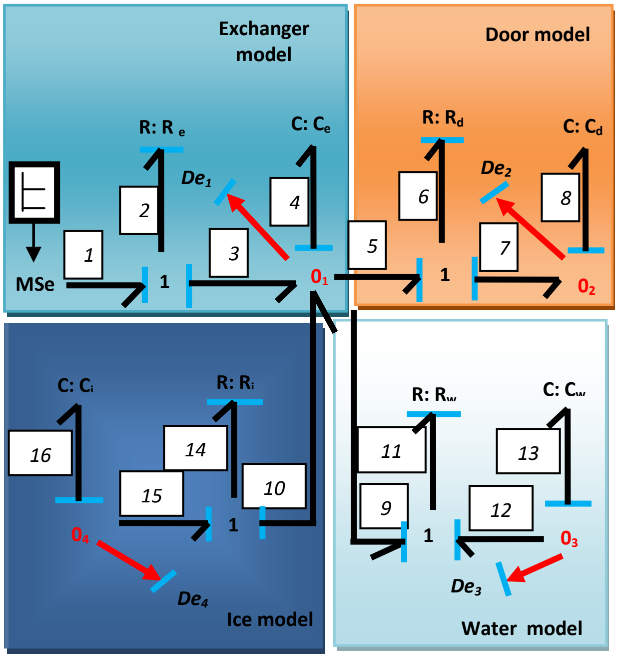


Fig. 8: Bond graph model in normal operation MBG_1

In this mode of operation ME_2, operation with a single element (the heat exchanger). The bond graph model for this (MBG2) can be easily deduced, then we obtain the link graph model shown in figure 9, which corresponds to the modeling of the industrial refrigerator with the cold heat exchanger only.

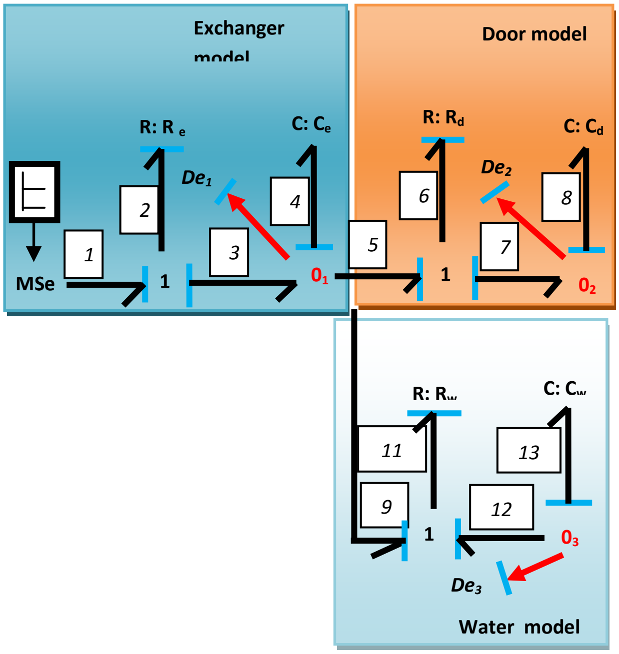


Fig. 9: Bond graph model operation without iced water MBG_2

In this mode of operation ME_3, operation with a single element (the heat exchanger) and also without water. The bond graph model for this MBG_3 can be easily deduced, and then we obtain the link graph model shown in figure 10, which corresponds to the modeling of the industrial refrigerator with the cold exchanger only and without the model of the water.

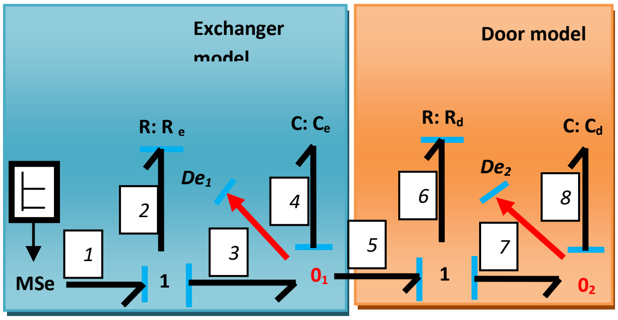


Fig. 10: Bond graph model operation without water MBG_3

To determine the residues using the redundant analytical relationship method. In our case we will change the temperature sensors (De_1, De_2, De_3 and De_4) by residues (r_1, r_2, r_3 and r_4) which are at the junctions 0_1, 0_2, 0_3 and 0_4.

✓ For the junction ''0_1'', the conservation relation is:

$$f_3 - f_4 - f_5 + f_9 - + f_{10} = 0$$

- $f_3 = \frac{1}{R_e}(MSe - De_1)$
- $f_4 = C_e \frac{dDe_1}{dt}$
- $f_5 = \frac{1}{R_d}(De_1 - De_2)$
- $f_{\varsigma} = \frac{1}{R_w}(De_1 - De_3)$
- $f_{10} = \frac{1}{R_i}(De_1 - De_4)$

The first residual r_1 can be written as:

$$r_1 = \frac{1}{R_e}(MSe - De_1) - C_e \frac{dDe_1}{dt} - \frac{1}{R_d}(De_1 - De_2) - \frac{1}{R_w}(De_1 - De_3) - \frac{1}{R_i}(De_1 - De_4) \quad (1)$$

✓ For the junction ''0_2'', the conservation relation is:

$$f_7 - f_8 = 0$$

- $f_7 = \frac{1}{R_d}(De_1 - De_2)$
- $f_4 = C_d \frac{dDe_2}{dt}$

The first residual r_2 can be written as:

$$r_2 = \frac{1}{R_d}(De_1 - De_2) - C_d \frac{dDe_2}{dt} \tag{2}$$

- ✓ For the junction ''0_3'', the conservation relation is:

$$f_{13} - f_{12} = 0$$

$$\bullet\ f_{13} = C_w \frac{dDe_3}{dt}$$

$$\bullet\ f_{12} = \frac{1}{R_w}(De_1 - De_3)$$

The third residual r_3 can be written as:

$$r_3 = \frac{1}{R_w}(De_1 - De_3) - C_w \frac{dDe_3}{dt} \tag{3}$$

- ✓ For the junction ''0_4'', the conservation relation is:

$$f_{16} - f_{15} = 0$$

$$\bullet\ f_{16} = C_i \frac{dDe_4}{dt}$$

$$\bullet\ f_{15} = \frac{1}{R_i}(De_1 - De_4)$$

The fourth residual r_4 can be written as:

$$r_4 = C_i \frac{dDe_4}{dt} - \frac{1}{R_i}(De_1 - De_4) \tag{4}$$

The residues are grouped with the elements of the industrial refrigerator in table 3. We obtain a boolean matrix (0 or 1). The columns are associated with the residues r_1, r_2, r_3 and r_4 and the lines are the fifteen elements.

Table 3: Matrix of faults signatures for the industrial refrigerator

	r_1	r_2	r_3	r_4
F_1:MSe	1	0	0	0
F_2:Ce	1	0	0	0
F_3:Cd	0	1	0	0
F_4:Ci	0	0	0	1
F_5:Cw	0	0	1	0
F_6:Re	1	0	0	0
F_7:Rd	1	1	0	0
F_8:Ri	1	0	0	1
F_9:Rw	1	0	1	0
F_{10}:De1	1	1	1	1
F_{11}: De2	1	1	0	0
F_{12}: De3	1	0	1	0
F_{13}: De4	1	0	0	1

According to this table 3, we can note that the elements F_1, F_2, F_3, F_4, F_5 and F_6 are sensitive by a single residue. While the elements F_7, F_8, F_9, F_{10}, F_{11}, F_{12} and F_{13} have several residues that are sensitive. To solve this monitoring problem, a linear combination of these different residues with other residues is necessary to eliminate some redundant variables.

i. *Normal Operation*

In this mode of operation the industrial system operates under the favorable conditions where the trend of the residues converges towards zero (figure 11) and the temperature curves indicate the following values Te = 0 C, Td = 25 C, Tw = 25 C et Ti = 0 C (figure 12).

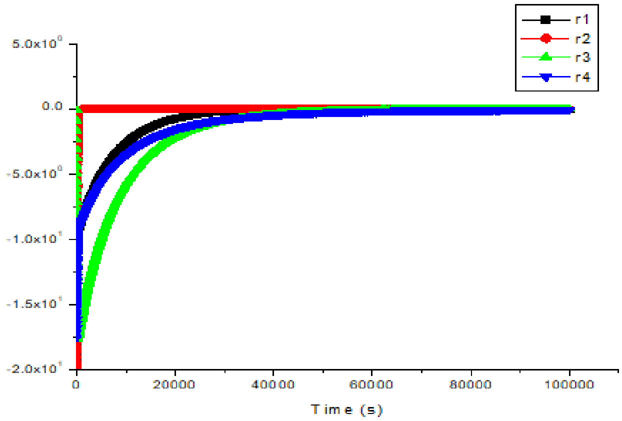


Fig. 11: Evolution of the residues in normal operation

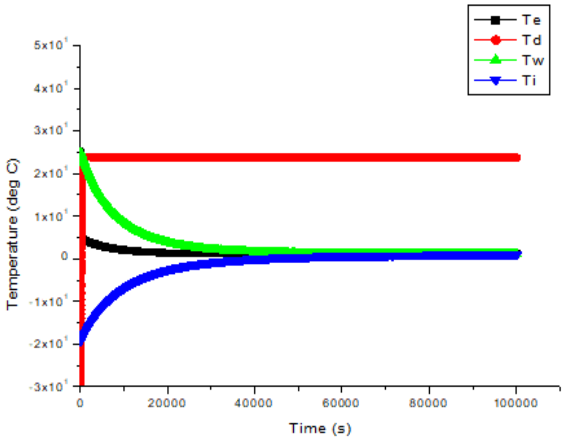


Fig. 12: Evolution of the temperatures in normal operation

i. *Abnormal Operation*

In this mode of operation the industrial system operates in unfavorable conditions from where the residues do not converge towards zero and the temperature trends indicate new values. To analyze this system we will insert four faults (four alarms).

Alarm 01: This fault corresponding to a fault (leakage) of the exchanger of the industrial refrigerator modeled by the element *Ce*, this fault causes a decrease in the amount of cooling potential (Figure 14). This element exists in the equation of the residue r_1 for each operating mode *MBG*$_1$, *MBG*$_2$ and *MBG*$_3$ (figure 13), from which only the residue r1 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue r_1). However, if this component is defective, all operating modes are affected. Therefore, switching to other modes of operation is not allowed because this element exists in operation mode without chilled water and in operating mode without water tank. In this case, the available mode is the stop mode *MBG*$_4$.

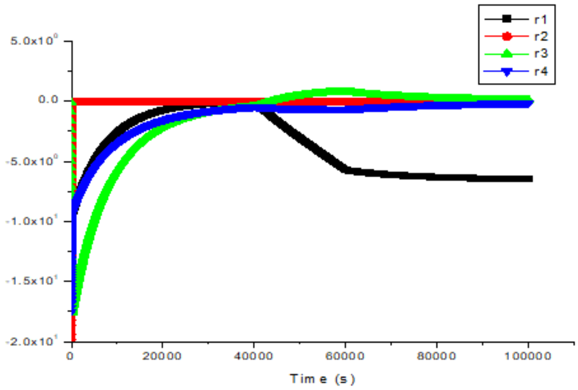


Fig. 13: Evolution of the residues with fault in the exchanger

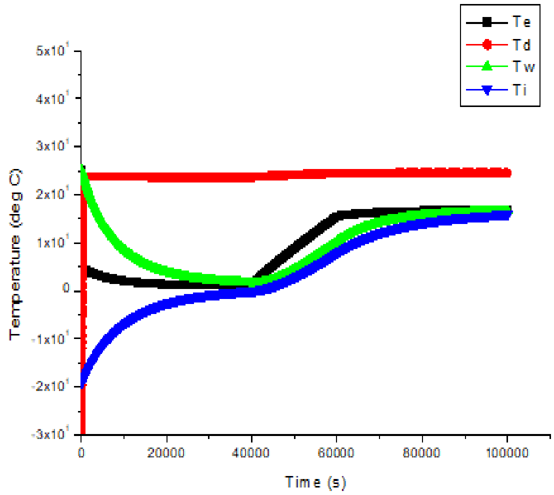


Fig. 14: Evolution of the temperatures with fault in the exchanger

Alarm 02: This fault corresponding to a fault (leakage) at the door of the industrial refrigerator modeled by the element *Cd*, this fault causes a decrease in the amount of cooling potential (figure 16). These phenomena are readable on the graph-hop model and can be quantified by the equations. This element exists in the equation of the residue *r*$_2$ for each operating mode *MBG*$_1$, *MBG*$_2$ and *MBG*$_3$ (figure 15), from which only the residue r2 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue *r*$_2$). However, if this component is defective all modes of operation are affected. Therefore, switching to other operating modes is not allowed because this element exists in the operation mode without chilled water and in the operating mode without water tank, in this case the available mode is the stop mode *MBG*$_4$.

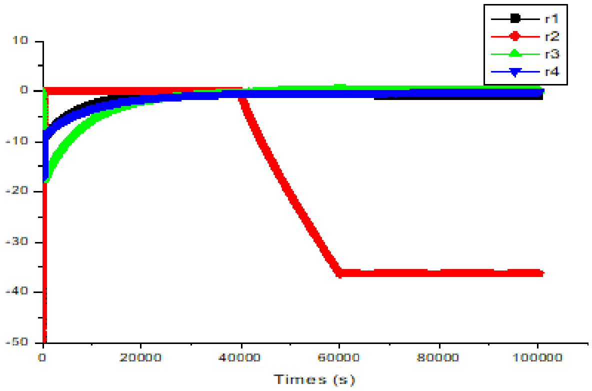


Fig. 15: Evolution of the residues with fault in the door

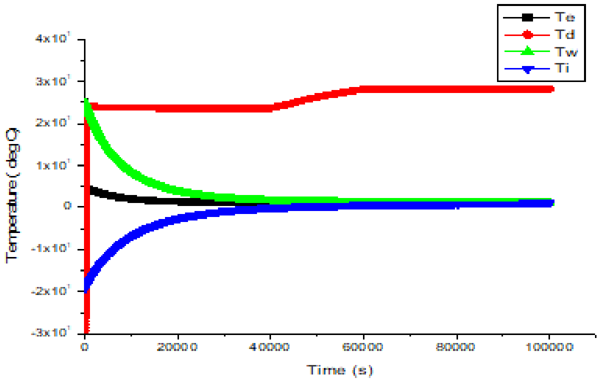


Fig. 16: Evolution of the temperature with fault in the door

Alarm 03: This fault corresponding to a fault (leakage) in the ice water of the industrial refrigerator modeled by the element Ci, this fault causes a decrease in the amount of cooling potential (figure 18). These phenomena are readable on the bond graph model and can be quantified by the equations. This element exists in the equation of the residue *r*$_4$ for the operating mode *MBG*$_1$ (figure 17), from which only the residue r4 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue *r*$_4$). However, if this component is defective this operating mode will be affected. Therefore, the transition to other modes of operation is allowed eg *MBG*$_2$, *MBG*$_3$ or *MBG*$_4$.

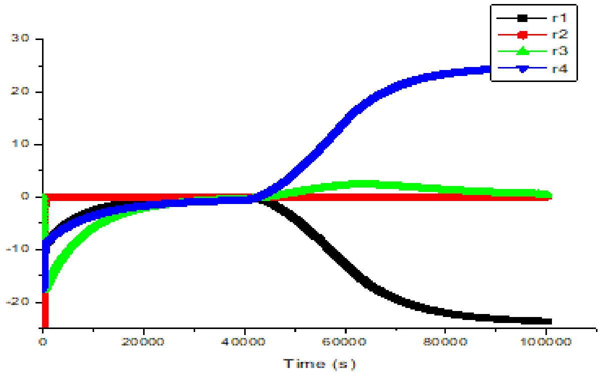


Fig. 17: Evolution of the residues with fault in the ice water

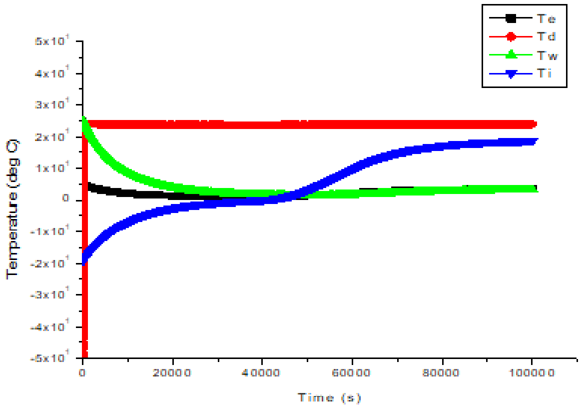


Fig. 18: Evolution of the temperature with fault in the ice water

Alarm 04: This fault corresponding to a fault (leakage) at the water of the industrial refrigerator modeled by the element *Cw*, this defect causes a decrease in the amount of cooling potential (figure 20). These phenomena are readable on the graph-hop model and can be quantified by the equations. This element exists in the equation of the residue r_3 for the operating mode MBG_1 and MBG_2 (figure 19), from which only the residue r_3 is sensitive to this defect in accordance with the table 3 of signature of the defects (this defect is localized by this residue r_3). However, if this component is defective these modes of operation will be affected. Therefore, the transition to other modes of operation is allowed eg MBG_3 or MBG_4. If the normal operating mode is the current mode, in the event of a fault, it is necessary to take into account the automatic changeover to another mode. In this case, we find that the two available modes are MBG_2, MBG_3 or MBG_4.

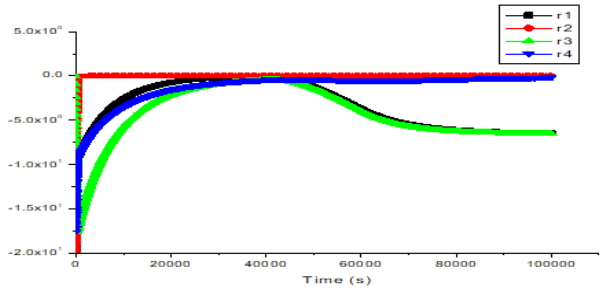


Fig. 19: Evolution of the residues with fault in the water

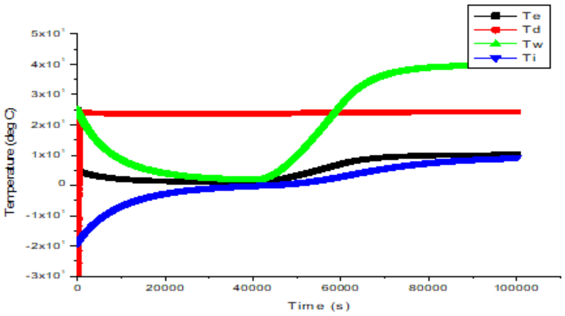


Fig. 20: Evolution of the temperature with fault in the water

c) Transfer Function Modeling Treatment

From the bond graph model MBG_1 industrial refrigerator in normal operation (figure 8), we can construct the block diagram of the below shown with duplicate links system (effort and flow) figure 21.

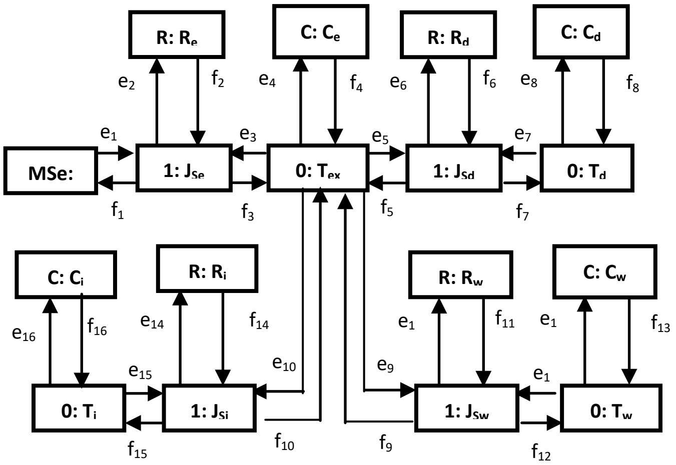


Fig. 21: Functional diagram of the industrial refrigerator with duplication of the link (effort and flow) in normal operation

The transfer function of the industrial refrigerator in normal operation H_1 (s) is the outlet temperature Tex (s) with respect to the inlet temperature Te (s):

$$H_1(s) = \frac{0.05283s^3 + 0.001319s^2}{s^4 + 0.08506s^3 + 0.001504s^2} \quad (5)$$

From the bond graph model MBG_2 industrial refrigerator in operation without iced water (figure 9), we can construct the block diagram of the below shown with duplicate links system (effort and flow) figure 24.

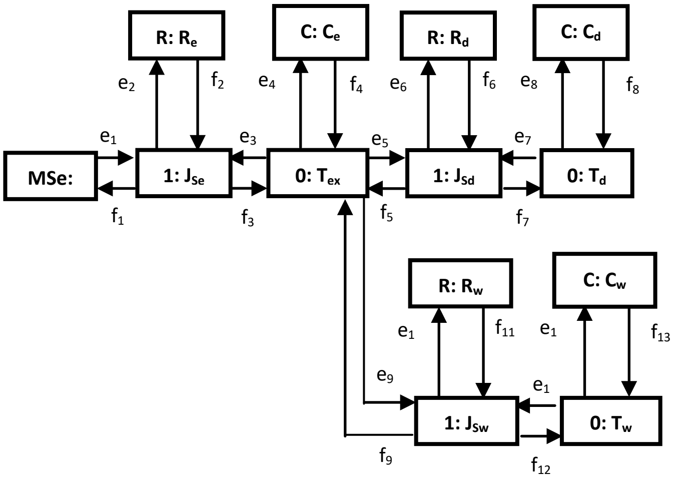


Fig. 22: Functional diagram of the industrial refrigerator with duplication of the link (effort and flow) in operation without iced water

The transfer function of the industrial refrigerator without iced water H_2 (s) is the outlet temperature Tex (s) with respect to the inlet temperature Te (s):

$$H_2(s) = \frac{0.05283s^2}{s^3 + 0.06014s^2} \quad (6)$$

From the bond graph model MBG_3 industrial refrigerator in operation without iced water (figure 10), we can construct the block diagram of the below shown with duplicate links system (effort and flow) figure 23:

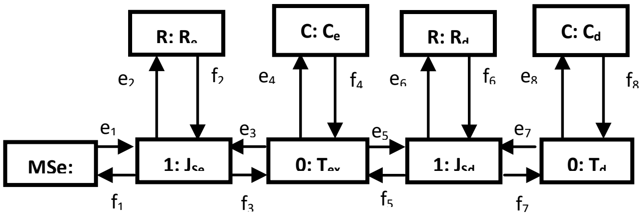


Fig. 23: Functional diagram of the industrial refrigerator with duplication of the link (effort and flow) in operation without water

The transfer function of the industrial refrigerator without water H_3 (s) is the outlet temperature Tex (s) with respect to the inlet temperature Te (s):

$$H_3(s) = \frac{0.05283s}{s^2 + 0.05682s} \tag{7}$$

Figure 24 shows the evaluation of the transfer function for the three modes of operation (normal operating mode, reduced operating mode and stop mode).

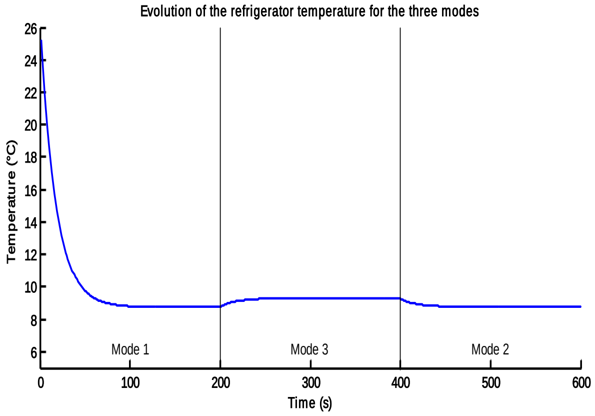


Fig. 24: Evaluate the transfer function for each mode

d) Control of the Temperature in Three Modes

In this part, we propose the control of the refrigerator's temperature for the three modes by the design of a PI controller for each mode. In fact the recursive equation of this controller is:

$$u(k) = u(k-1) + \left(K_p + K_I T_s\right)e(k) - K_p e(k-1) \tag{8}$$

Then, we will consider the recursive equation for each model. So by fixing a sampling time *Ts=1s* and a first holder folder we obtained the following recursive equations for the three models:

$$\begin{aligned} y_1(k) = {} & 1.496y_1(k-1) - 0.5513y_1(k-2) + 0.1615u_1(k-1) \\ & +0.004792u_1(k-2) - 0.1179u_1(k-3) \end{aligned} \tag{9}$$

$$\begin{aligned} y_2(k) = {} & 0.9416y_2(k-1) + 0.02589u_2(k-1) \\ & +0.02538u_2(k-2) \end{aligned} \tag{10}$$

$$\begin{aligned} y_3(k) = {} & 0.9448y_3(k-1) + 0.02592u_3(k-1) \\ & +0.02544u_3(k-2) \end{aligned} \tag{11}$$

The determination of the K_p and K_i parameters leads to the following control laws:

$$u_1(k) = u_1(k-1) + 6.41e(k) - 6.21e(k-1) \tag{12}$$

$$u_2(k) = u_2(k-1) + 6.495e(k) - 6.3e(k-1) \tag{13}$$

$$u_3(k) = u_3(k-1) + 6.3e(k) - 6.1e(k-1) \tag{14}$$

By implementing these control laws, we obtained the evolution of the temperature of the refrigerator for the three modes.

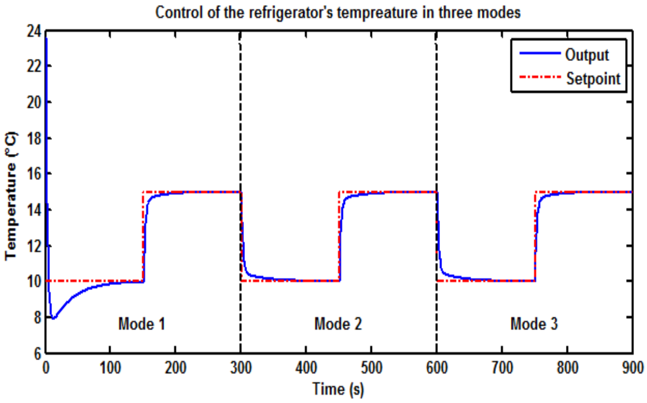


Fig. 25: Control of the industrial refrigerator's temperature for three modes

From Figure 25, it is noted that the designed PI controllers allow the regulation of the temperature in spite of the variation of the set-point and the switching between modes.

IV. Conclusions

In this article we used three models to determine the supervision of an industrial system. Indeed the external model provides a functional description for an industrial system; this task is insufficient to supervise the behavior of all elements of the system. To complete the inadequacy of this task, we have introduced another model called bond graph. The bond graph model is a tool based on a physical knowledge of the industrial system; this model bond graph models the industrial system element by element. This modeling, which clearly represents the physical phenomena of the industrial system, improves the surveillance system and the security (fault detection and localization). The use of the model of the transfer function by the bond graph model allowed us to see the ready for each mode of operation (normal operating mode, reduced operating mode and stop mode), also the model of the function transfer allowed us to see the swing of the industrial system for these modes. By considering these representations, we designed PI controllers in order to regulate the temperature for each mode.

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