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Modeling, Simulation and Monitoring of Nuclear Reactor Using Directed Graph and Bond Graph

A. Badoud, M. Khemliche, and S. Latreche

***Abstract*—**The main objective developed in this paper is to find a graphic technique for modeling, simulation and diagnosis of the industrial systems. This importance is much apparent when it is about a complex system such as the nuclear reactor with pressurized water of several form with various several non-linearity and time scales. In this case the analytical approach is heavy and does not give a fast idea on the evolution of the system. The tool Bond Graph enabled us to transform the analytical model into graphic model and the software of simulation SYMBOLS 2000 specific to the Bond Graphs made it possible to validate and have the results given by the technical specifications. We introduce the analysis of the problem involved in the faults localization and identification in the complex industrial processes. We propose a method of fault detection applied to the diagnosis and to determine the gravity of a detected fault. We show the possibilities of application of the new diagnosis approaches to the complex system control. The industrial systems became increasingly complex with the faults diagnosis procedures in the physical systems prove to become very complex as soon as the systems considered are not elementary any more. Indeed, in front of this complexity, we chose to make recourse to Fault Detection and Isolation method (FDI) by the analysis of the problem of its control and to conceive a reliable system of diagnosis making it possible to apprehend the complex dynamic systems spatially distributed applied to the standard pressurized water nuclear reactor.

***Keywords*—**Bond Graph, Modeling, Simulation, Monitoring, Analytical Redundancy Relations, Pressurized Water Reactor, Directed Graph.

I. Introduction

MODELING and simulation became currently a scientific and technological stake. The tool of design computerized becomes essential in industry. Indeed, these tools of prediction and analysis of behavior of a system, make it possible to reduce the costs and the times of study of a new product by deferring the phase of prototyping further possible. The evolution of the numerical computational tools enables us to very seriously consider the modeling of a complete system, like, for example, an industrial system complex (nuclear reactor).

It is necessary to adapt the level of representation of each model to the objectives of the user but it is to envisage the interconnection of all these models between them so as to lay out, in the long term, of an energy representation of the industrial system complexes in its totality. The need growing for multidisciplinary physical models, vital need to capitalize knowledge in the models libraries, and the new concern to take into account as of the design the aspects orders and reliability let consider a significant development of the industrial applications of this tool which releases the engineer of the vicissitudes of mathematical modeling and allows him to be interested in the structural properties and credits of what it conceives.

Among the automation objectives, we relate to the search for means of order for the physical systems which are often of various natures, electric, mechanical, hydraulic, and thermal. The modeling is the first stage of the development of a law of order. The model which makes it possible to describe physical reality is generally obtained on the basis of idealized description of the system and only the dominant phenomena are considered [13].

In many cases, the control engineers use mathematical models, which in spite of their flexibility lose the physical significance and do not allow to make a return on the model to refine modeling or to improve the systems design to simplify its order. The multidisciplinary nature of the systems does not allow the communication between the experts of the various fields. Moreover, the control engineers specialize in only one particular field. There is a need marked for a modeling language meeting these needs to optimize this important stage of modeling.

One of the tools answering these criteria is the Bond Graph. Indeed, this language is based mainly on the concept of power transfer between the various parts or components of the system and on the energy conversion in these components (dissipation, storage, conversion of the energy field). These various phenomena which are similar in all the physical fields are coded graphically. The unified character of the Bond Graph constitutes a universal language of communication between the experts of various disciplines [8]. It is easy to break up the system into parts or subsystems and to make a

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return on any subsystem to improve its design or to take account of a neglected physical phenomenon or not taken into account. The model Bond Graph can then be regarded as an intermediate model between the physical system and the mathematical model which is associated for him.

Industrial statistics show that 70% of the industrial accidents are caused by human errors. These abnormal events had impacts of an economic nature, but especially of the impacts on safety and the environment [14]. The most recent nuclear accidents with Three Island Mile in United States 1979. This accident is classified on level 5, the most level being 7 in the international scale nuclear events and extremely serious accident of level 7 on the scale INNATE in the nuclear thermal power station of Chernobyl in Ukraine 1986, poses the problem of the development of techniques of supervision [13]. Moreover, industrial statistics showed that small accidents are very frequent every day, causing important economic losses.

II. Process Description

The nuclear thermal power stations with pressurized water comprise two parts to convert the calorific energy released by the fission of nuclear fuel in the heart into mechanical energy, the latter making function an alternator which provides finally electric power [6]

A. Primary Circuit

Traversed by water pressurized in the liquid state, which passes in the heart of the reactor and recovers the heat produced by fission and transfers it to the secondary circuit by the means of a steam generator.

B. Secondary Circuit

Traversed by water, which in contact with the heat transmitted by the primary circuit in the Steam Generator, is transformed into dry steam and is then slackened in turbines HP and LP, these last making functions an alternator. The water function remained with the state of vapour and then condensed in contact with a cold source, then all condensed them are directed towards the cover food and given in circulation in the circuit. The cold source is generally an element of external medium, the ambient air, water or the sea for example [1].

The presence of two circuits is justified by considerations of safety. Because, the water of the primary circuit in contact with the heart of reactor is radioactive. The water of the secondary circuit not being in direct contact with that of the primary circuit, it is not it which limits to the maximum the passage of radioactive products towards outside. Other distinct circuits ensure the safety and make it possible to cool the reactor under normal operation quickly. The installation modeled in this example, and which we wish to determine the output, is the secondary circuit of a nuclear thermal power station.

The secondary circuit is the “traditional” part of the power station. But the cycle with vapour which is used is subjected to a certain number of particular constraints which make it different from the cycles of the him type of the power stations with traditional fossil fuels.

III. Bond Graph Modeling of Nuclear Reactor

The Bond Graph is a model of knowledge; the parameters which it uses have a physical interpretation, the transformations between input and output variables are clarified and the variables used by the model are potentially measurable [9]. There is also some Bond Graphs which we will further see where the product flow effort is not a power, they are called pseudo Bond Graphs, are used mainly for the modeling of the phenomena met in process engineering (thermal, hydraulic and chemical). [5]

Bond Graph modeling of a physical system makes it possible to obtain a chart independent of the studied field. To build the model Bond Graph it is necessary:

–To break up the system to be modeled in subsystems, it is the technological stage.

–To reproduce all the physical phenomena graphically, it is the physical stage.

–To write the constitutive laws of the components or the phenomena, it is the mathematical stage [3].

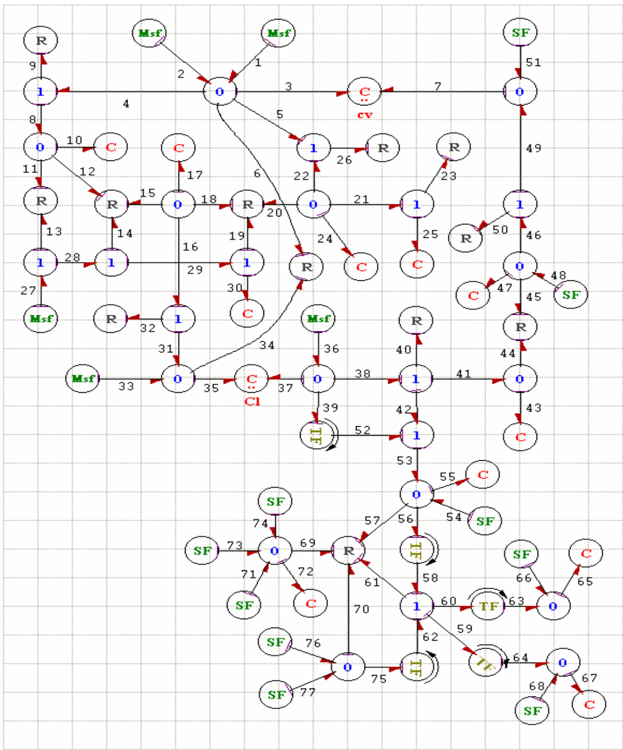

Fig. 1 Model Bond Graph detailed of a pressurized water reactor

IV. Directed Graph Model of a Pressurized Water Reactor

In its traditional text on the graph theory, König uses two types of tops to represent a matrix by a graph. The first represents the lines of the matrix and the second represents its

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columns [2]. The representation which interests in this work is that used within the framework of the resolution of the linear algebraic equations by the fluency graph [10], [12].

A. Modeling from a State Representation

For a square matrix $A = \{a_{ij};\ i, j \in (1,\ldots,n)\}$ of order n given, there is a correspondence between matrix A and the digraph G(A) which has n tops $z_i \in Z$. it exists a directed arc (z_i, z_j) of the initial top z_j towards the final top z_i, if the element of the matrix a_{ij} is non null $[i, j \in (1,\ldots,n)]$. the weight of the arc is given by the value of a_{ij} [3].

The representation of the matrices of order B and exit C is done according to the same principle.

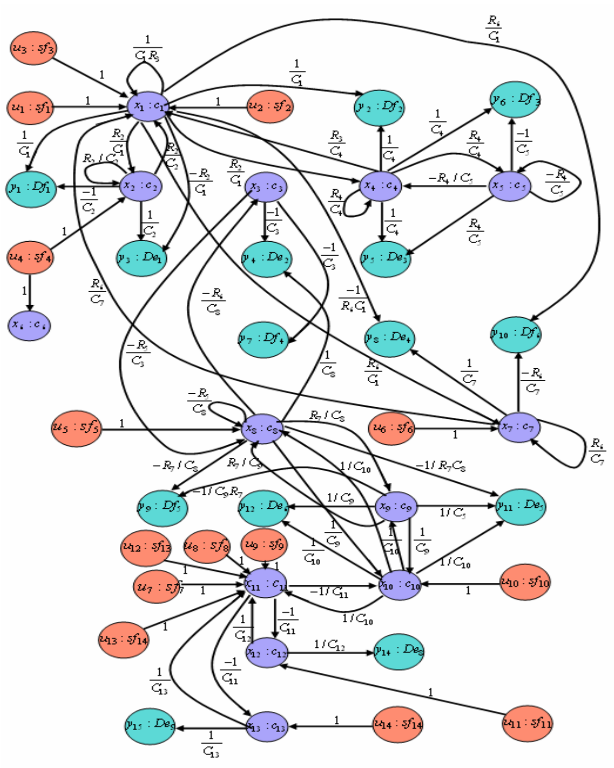

Fig. 2 Directed Graph model of a pressurized water reactor

V. Simulation Results

The simulation is a mean complementary to the experiment and analytical calculation to solve equations which we cannot find the solution. Simulation is less expensive and more rapid than the experiment; it is in full evolution.

Thus, in aeronautics, where simulation was impossible in the years 1970, twenty years later a plane could be developed entirely on computer and tested out of blower only in final phase. Simulation penetrated the majority of the fields of engineering.

In electric engineering success is complete; in geology it is less clear but mainly because of uncertainties on the parameters of the grounds; in meteorology where uncertainties on the data limit the quality of simulations, there is a theoretical limit which had with the stability of the equations of the mechanics of the fluids; in economy the models are in question, whereas in chemistry the difficulties lie in the great disparities of scales.

A. Adjustment of the Temperature in Steam Generator

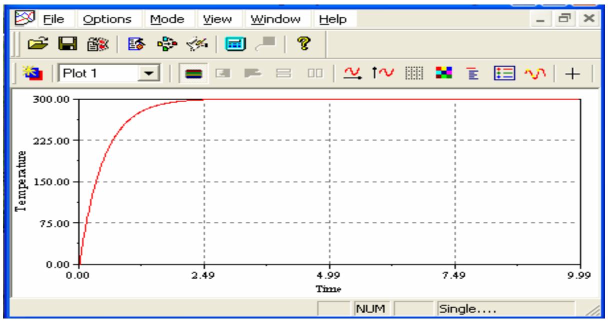

Fig. 3 Variation in the temperature according to time in Steam Generator

The temperature in the boiler varies exponentially according to time, this is due to the phenomenon of storage of energy with t=1.53s the temperature becomes stable what carries out the system in a state of permanent balance and the temperature equal to 300C.

Heat is transferred from the nuclear boiler (primary circuit) towards the secondary circuit comprising the turbine via several steam generators and this in the enclosure of the reactor. The steam produced at output of the steam generators has temperature of 270C.

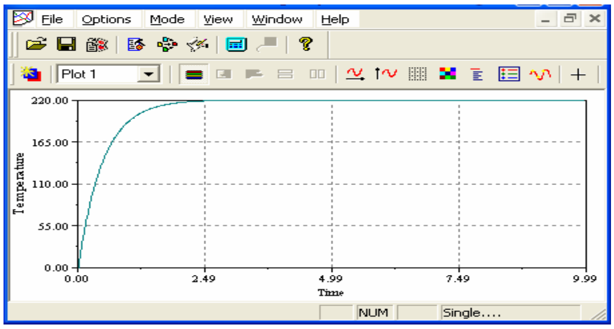

Fig. 4 Temperature variation according to time at output of Steam Generator

Heat is transferred from the nuclear boiler (primary circuit) towards the secondary circuit comprising the turbine via several steam generators and this in the enclosure of the reactor. The steam produced at output of the steam generators has temperature of 270C.

For the regulator is of type traditional PID (Proportional Integral and Derived). Its adjustments are variable according to the temperature of alimentation of the water, to adapt the regulator to the process characteristics, variables with the load.

The measurement of the steam flow is added on the outlet

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side of the regulator to constitute the instruction of food water flow. That makes it possible to pre-empt the response of the regulator at the time of the transients of flow steam.

Lastly, the regulation comprises a control of water flow.

B. Adjustment of Mass Throughput

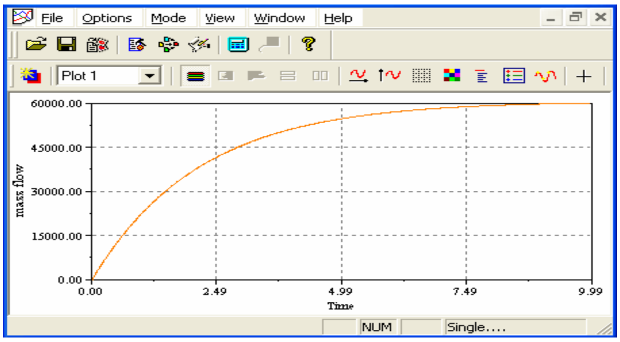

Fig. 5 Variation of mass throughput according to time in Steam Generator

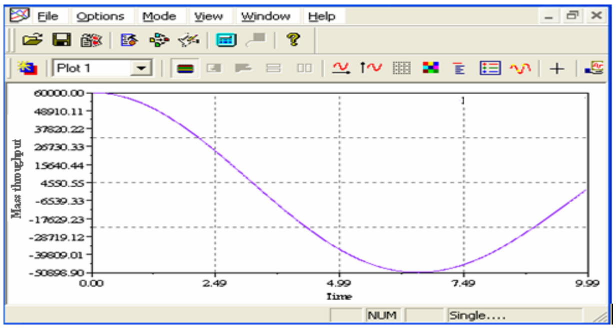

Fig. 6 Variation of mass throughput according to time at output of Steam Generator

The enthalpy grows exponentially according to time, this is with the influence of the thermal power which provided calorific energy to the boiler and the moment t=7.5s the mass throughput becomes stable and equal 60000 m3/h and according to the stability of the temperature.

The total mass in the boiler varies with time exponentially and evolves without stop, which is in conformity with the operation of such a process when it is not controlled. This phenomenon is explained by the fact why the mass accumulates in the tank and thus increases as much as the alimentation is provided.

C. Adjustment of the Temperature in the Heart of Reactor

The temperature of coolant in the heart of reactor east exponentially varies with time up to the end value 320°C at the moment t=5s and remains invariant (permanent mode). The variation in the temperature i.e. the adjustments are variable in bars of order, to adapt the value of the temperature to the characteristics of the process, variables with the load.¶

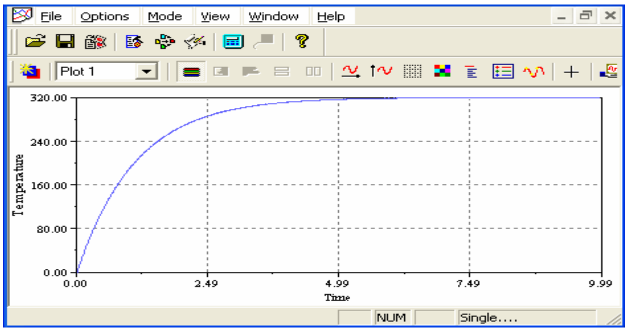

Fig. 7 Variation in the temperature in the heart of reactor

The temperature measurement is made using sensor to place on the level of heart of reactor and its role is to check the value of temperature at every moment thus it played a fundamental role on the movement of the control rods, otherwise the input and output speed as of the these bars is dregs with the value of temperature and pressure.

D. Adjustment of the Pressure in the Heart of Reactor

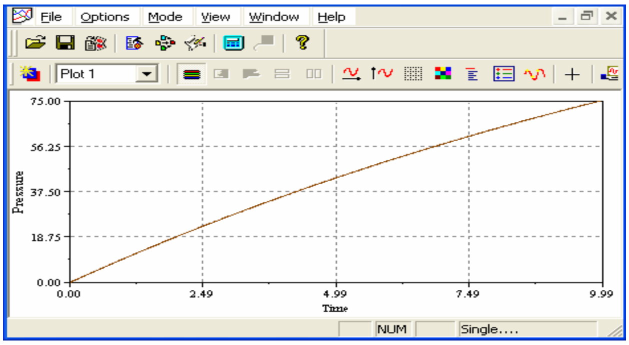

Fig. 8 Variation of the pressure in the heart of reactor

The pressure east varies in the heart of almost linear reactor of way according to time to 75 bars at the moment 10s.

The adjustment of the pressure of heart generally consists with the introduction of the bars of order which influences directly on the pressure and the temperature value, and the variation of the function of pressure binds to the variation in the temperature i.e. when the temperature also increases the pressure increases.

E. Power Instantaneous

The instantaneous adjustment of the power generally consists with the introduction of the rigging bars. These rigging bars have as common property which they are made of a material strongly absorbing for the neutrons like boron, cadmium, the money or indium. The physical form can be different. We know for example; needles and plates. According to the goal we also make the distinction between scram rods, control rods and bars of fine adjustments.

The scram rods are, in normal operating time completion left the engine and will not be released in the event of urgency to decrease the reactivity quickly and to reduce the power. The control rods are used in normal operating time to obtain transients which are necessary to the starting, the stop and the stabilization at the desired level.

Moreover, the bars of fine adjustments can be used to maintain the power stable at the level wished without having to use the control rods (with a higher specific reactivity worth). The introduction of the control rods involves a deformation of flow owing to the fact that locally more neutrons are absorbed. Fig. 5 shows how the distribution of inflow is disturbed by the introduction of an absorbing rigging bar.

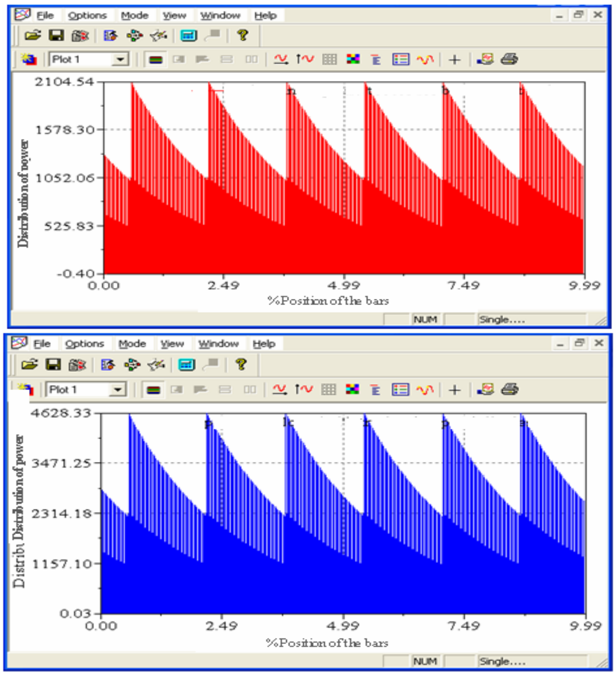

Fig. 9 Disturbance of the inflow distribution by the rigging bars

F. Reactivity

Fig. 10 illustrates the flow radial distribution up to what point is disturbed by the introduction of the rigging bars.

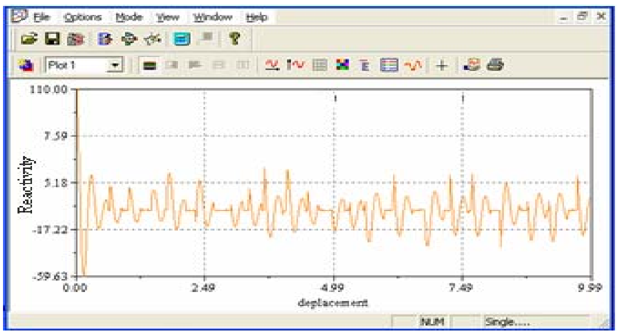

Fig. 10 Disturbance of the flow radial distribution by absorbing bar

The change of reactivity introduced by the fact of inserting or of withdrawing an absorbing bar is depend on the position of the rigging bar. When the rigging bar is located at the core periphery of the reactor, the impact is weaker than when the bar is in the centre of the heart. The relative impact of the rigging bars according to the position is highlighted with the differential effectiveness illustrated in Fig. 7.

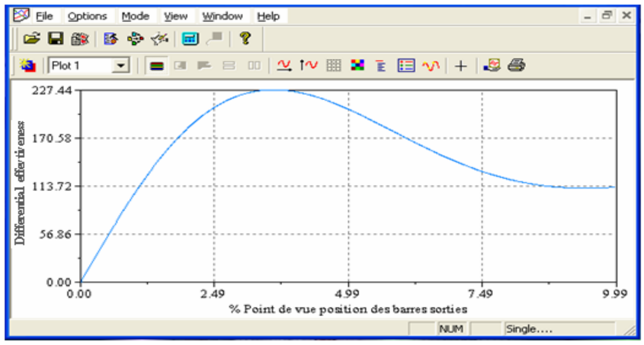

Fig. 11 Differential effectiveness of a rigging bar

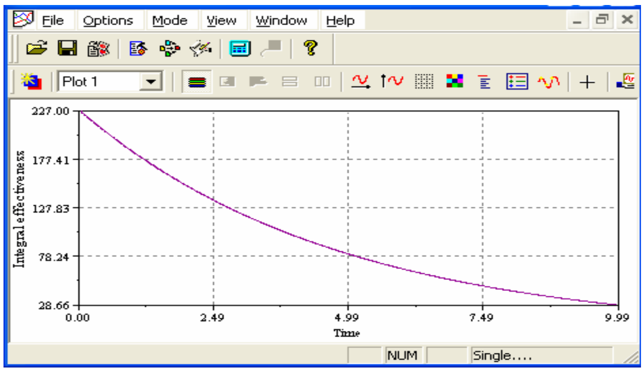

Fig. 12 Integral effectiveness of a rigging bar

The differential effectiveness is defined as the variation of reactivity in the heart introduced by a small displacement (1 cm) of the bar of control, on the basis of the state given on the X-coordinate. This is expressed in pcm/cm.

When we trace the total negative reactivity introduced by the bars absorbing according to the position of the rigging bars, we obtain the integral effectiveness as shown with the following Figure.

G. *Adjustment of the Pressure*

The pressure is regulated in the pressurisor using valves of sprinkling, connected to the cold branches of the primary circuit, foot-warmers with action proportional and foot-warmers to action all or nothing. The measured pressure is compared with a fixed set point. This variation enters a regulator which orders, with various programs, the valves of sprinkling, the foot-warmers with action proportional and action all or nothing.

In the event of excessive increase in the pressure, three spill valves intervene. The openings of those, spread out, are ordered directly, without forwarding by the closed loop.

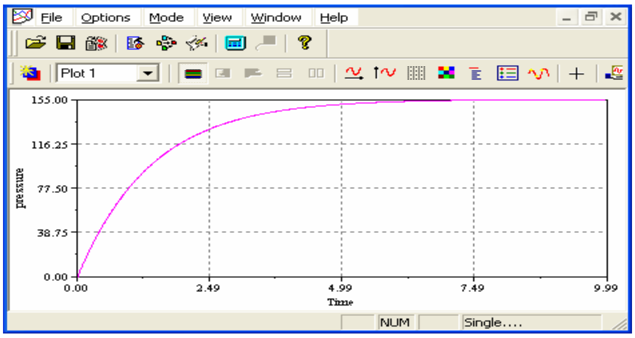

Fig. 13 Variation of the pressure according to time

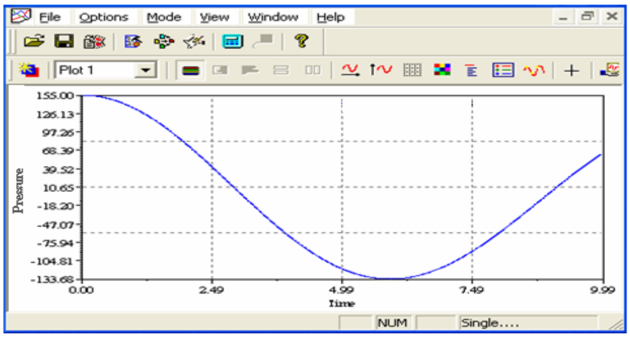

Fig. 14 Variation of the pressure according to time at output of Steam Generator

The curve representing the pressure follows an exponential law according to time checks the empirical equation well, this variation is due to accumulate matter in the Steam Generator which makes increased the pressure up to value 155 bars i.e. 155.105Pa.

The temperature of the output steam of steam generator decrease from 155 bars which is the steam pressure produced by the Steam Generator until - 133.68 bars at the moment t=5.92s then augment according to time up to 55 bars at the moment t=10s and as from this moment the value of pressure remains invariant (permanent mode).

VI. Monitoring of Nuclear Reactor

We suppose that sensors and sources are not affected by faults [7]. For our application, the equations in junctions are given by:

For 0i junction we have

$$\begin{cases} e_4 - e_8 - e_9 = 0 \\ f_9 = f_8,\ f_9 = f_4 \\ e_{R1} = e_9 = \phi_{R1}[(1-y_1) f_9 + y_1 Df_1] \\ f_{R1} = f_9 = (1-y_1)\phi_{R1}^{-1}(e_9) + y_1 Df_1 \end{cases} \tag{1}$$

For 1j junction we have

$$\begin{cases} e_{10} = e_8, e_{10} = e_{11}, e_{10} = e_{12} \\ f_8 - f_{10} - f_{11} - f_{12} = 0 \\ e_{C1} = e_{10} = \frac{1}{s}(1-x_1)\phi_{C1}^{-1}(f_{10}) + x_1 De_1 \\ f_{C1} = f_{10} = \phi_{C1}[s\{(1-x_1)e_{10} + x_1 De_1\}] \end{cases} \tag{2}$$

For TFk junction we have

$$\begin{cases} e_{52} = \frac{1}{m} e_{39} \\ f_{39} = \frac{1}{m} f_{52} \end{cases} \tag{3}$$

A. *Analytical Redundancy Relations*

Analytical redundancy relations (ARR) are symbolic equations representing constraints between different known process variables (parameters, measurements and sources). ARR are obtained from the behavioural model of the system through different procedures of elimination of unknown variables [7].

Numeric evaluation of each ARR is called a residual, which is used in model based fault detection and isolation (FDI) algorithms [11].

From equations of junctions we obtain the following system:

$$r_1 : msf_1 + msf_2 - \overset{*}{Df_1} - (1-y_1)\phi_{R1}^{-1}(e_9) + y_1 Df_1 - (1-y_2)\phi_{R2}^{-1}$$
$$(e_{26}) + y_2 Df_2 - \overset{*}{Df_2} = 0$$

$$r_2 : \phi_{R1}[(1-y_1) f_9 + y_1 Df_1] - \phi_{R1}[(1-y_1) f_9 + y_1 Df_1] - \frac{1}{s}(1-x_1)\phi_{C1}^{-1}(f_{10})$$
$$+ x_1 De_1 + \phi_{C4}[s\{(1-x_4)e_{47} + x_4 De_4\}] = 0$$

$$r_3 : sf_{51} + (1-y_6)\phi_{R6}^{-1}(e_{50}) + y_6 Df_6 - \overset{*}{Df_3} = 0$$

$$r_4 : -\phi_{R2}[(1-y_2) f_{26} + y_2 Df_{21}] + msf_1 + \frac{1}{s}(1-x_3)\phi_{C3}^{-1}$$
$$(f_{24}) + x_3 De_3 = 0$$

$$r_5 : -\phi_{C1}[s\{(1-x_1)e_{10} + x_1 De_1\}] + (1-y_1)\phi_{R1}^{-1}(e_9) +$$
$$y_1 Df_1 - \overset{*}{Df_4} - \overset{*}{Df_5} = 0$$

$$r_6 : -\phi_{R3}[(1-y_3) f_{23} + y_3 Df_3] + \frac{1}{s}(1-x_3)\phi_{C3}^{-1}(f_{24}) + x_3 De_3 - \overset{*}{De_1} = 0$$

$$r_7 : -\phi_{C2}[s\{(1-x_2)e_{17} + x_2 De_2\}] - (1-y_4)\phi_{R4}^{-1}(e_{32}) - \overset{*}{Df_6} -$$
$$\overset{*}{Df_7} + y_4 Df_4 = 0$$

$$r_8 : msf_{27} - \overset{*}{Df_8} - \overset{*}{De_2} = 0$$

$$r_9 : -\phi_{C3}\left[s\{(1-x_3)e_{24}+x_3De_3\}\right]-\overset{*}{Df_9}+y_3Df_3-(1-y_3)\phi_{R3}^{-1}(e_{23})-(1-y_2)\phi_{R2}^{-1}(e_{26})+y_2Df_2=0$$

$$r_{10} : \overset{*}{De_2}-\overset{*}{De_3}-\overset{*}{De_4}=0$$

$$r_{11} : -\overset{*}{Df_{10}}+(1-y_4)\phi_{R4}^{-1}(e_{32})+y_4Df_4+msf_{33}-\overset{*}{Df_{11}}=0$$

$$r_{12} : \overset{*}{De_4}-\overset{*}{Df_{12}}-\overset{*}{De_5}=0 \qquad (4)$$

$$r_{13} : -\overset{*}{Df_{13}}+msf_{36}-(1-y_5)\phi_{R5}^{-1}(e_{40})+y_5Df_5-\frac{1}{m}((1-y_5)\phi_{R5}^{-1}(e_{40})+y_5Df_5)=0$$

$$r_{14} : -\phi_{R4}\left[(1-y_4)f_{32}+y_4Df_4\right]+x_2De_2-msf_{33}+\frac{1}{s}(1-x_2)\phi_{C2}^{-1}(f_{17})=0$$

$$r_{15} : -\phi_{C5}\left[s\{(1-x_5)e_{43}+x_5De_5\}\right]+(1-y_5)\phi_{R5}^{-1}(e_{40})-\overset{*}{Df_{14}}+y_5Df_5=0$$

$$r_{16} : -\phi_{R5}\left[(1-y_5)f_{40}+y_5Df_5\right]+msf_{36}+x_5De_5+x_6De_6-\frac{1}{s}(1-x_5)\phi_{C5}^{-1}(f_{43})-\frac{1}{s}(1-x_6)\phi_{C6}^{-1}(f_{55})-\frac{1}{m}msf_{36}=0$$

$$r_{17} : -\phi_{C5}\left[s\{(1-x_5)e_{43}+x_5De_5\}\right]-(1-y_6)\phi_{R6}^{-1}(e_{50})-\overset{*}{Df_{15}}+sf_{48}+y_6Df_6=0$$

$$r_{18} : -\phi_{R6}\left[(1-y_6)f_{50}+y_6Df_6\right]-sf_{51}+x_4De_4+\frac{1}{s}(1-x_4)\phi_{C4}^{-1}(f_{47})=0$$

$$r_{19} : -\phi_{C6}\left[s\{(1-x_6)e_{55}+x_6De_6\}\right]+sf_{54}+y_5Df_5-\overset{*}{Df_{15}}-\frac{1}{m}\overset{*}{Df_{16}}+(1-y_5)\phi_{R5}^{-1}(e_{40})=0$$

$$r_{20} : \phi_{R5}\left[(1-y_5)f_{40}+y_5Df_5\right]+\frac{1}{m}msf_{39}+x_6De_6-\frac{1}{s}(1-x_6)\phi_{C6}^{-1}(f_{55})=0$$

$$r_{21} : -\phi_{C7}\left[s\{(1-x_7)e_{72}+x_7De_7\}\right]-\overset{*}{Df_{17}}+sf_{71}+sf_{73}+sf_{74}=0$$

$$r_{22} : -\frac{1}{r}\left(\frac{1}{s}(1-x_6)\phi_{C6}^{-1}(f_{55})+x_6De_6\right)l\left(\frac{1}{s}(1-x_9)\phi_{C9}^{-1}(f_{67})+k\left(\frac{1}{s}(1-x_8)\phi_{C1}^{-1}(f_{65})+x_8De_8\right)-\overset{*}{Df_{16}}+\frac{1}{h}sf_{76}+x_9De_9\right)-=0$$

$$r_{23} : k\overset{*}{Df_{16}}-\phi_{C8}\left[s\{(1-x_8)e_{65}+x_8De_8\}\right]+sf_{66}=0$$

$$r_{24} : -\overset{*}{Df_{18}}-\frac{1}{h}\overset{*}{Df_{16}}+sf_{76}+sf_{77}=0$$

$$r_{25} : k\overset{*}{Df_{16}}-\phi_{C9}\left[s\{(1-x_9)e_{67}+x_9De_9\}\right]+sf_{68}=0$$

From the binary variables xi (i=1, 14) and yj (j=1, 11) we can determine the final structure of the monitorable system. 25-sensor placement combinations provide the monitorability of the all components. The question arises whether we are able to supervise this system by only (15) sensors? And what are the combinations which provide this result?

$$For[x_1y_1x_2y_2x_3y_3x_4y_4x_5y_5x_6y_6x_7y_7x_8y_8x_9y_9x_{10}y_{10}x_{11}y_{11}x_{12}x_{13}x_{14}]=[1111111111111111111111111]$$

TABLE I
FAULT SIGNATURE

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	R_1	R_2	R_3	R_4	R_5	R_6
r_2	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
r_4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
r_5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
r_6	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
r_7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
r_9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
r_{14}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
r_{15}	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
r_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
r_{17}	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
r_{18}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
r_{19}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
r_{20}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
r_{21}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
r_{23}	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
r_{25}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

The fault signatures are different from each other and not equal to zero, then the components C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9, R_1, R_2, R_3, R_4, R_5 and R_6 are monitorable.

$$For[x_1y_1x_2y_2x_3y_3x_4y_4x_5y_5x_6y_6x_7y_7x_8y_8x_9y_9x_{10}y_{10}x_{11}y_{11}x_{12}x_{13}x_{14}]=[0111011010000111111110101]$$

TABLE II
FAULT SIGNATURE

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	R_1	R_2	R_3	R_4	R_5	R_6
r_1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
r_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
r_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
r_4	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
r_5	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
r_6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
r_7	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
r_8	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
r_9	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
r_{10}	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
r_{11}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
r_{12}	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
r_{13}	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
r_{14}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
r_{15}	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
r_{16}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

It is noticed that the structures of the residues are different but fault signatures are not different [(C_4 and R_2), (C_1 and R_1)] and not equal to zero.

Thus the components C_1, C_4, R_1 and R_2 are not monitorable. And the components C_2, C_3, C_5, C_6, C_7, C_8, C_9, R_3, R_4, R_5 are monitorable.

$$For[x_1y_1x_2y_2x_3y_3x_4y_4x_5y_5x_6y_6x_7y_7x_8y_8x_9y_9x_{10}y_{10}x_{11}y_{11}x_{12}x_{13}x_{14}]=[1100110010101110111010101]$$

The fault signatures are different from each other and not equal to zero, then the components C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9, R_1, R_2, R_3, R_4, R_5 and R_6 are monitorable.

TABLE III
FAULT SIGNATURE

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	R_1	R_2	R_3	R_4	R_5	R_6
r_1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
r_2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
r_3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
r_4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
r_5	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
r_6	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
r_7	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
r_8	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
r_9	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
r_{10}	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
r_{11}	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
r_{12}	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
r_{13}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
r_{14}	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
r_{15}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

VII. SIMULATION AND INTERPRETATION

From SYMBOLS 2000, we have implanted the uncoupled Bond Graph model. For the faults detection of the nuclear reactor (PWR) we use the precedent analytical redundancy relations (ARRs). We create the faults on monitoring components with this software fault here is considered in the total absence or the deviation of the nominal value given out by the component to monitor [2].

The numeric values of components are not considered, only their presence or absences in the relation are taken in account with evaluation term the operators (+, -). It is the qualitative approach for Bond Graph monitoring [10].

A. *Sensitivity of Detector De_2*

In the first time, we create a fault between the instant t1=2s and t2=2.5s.

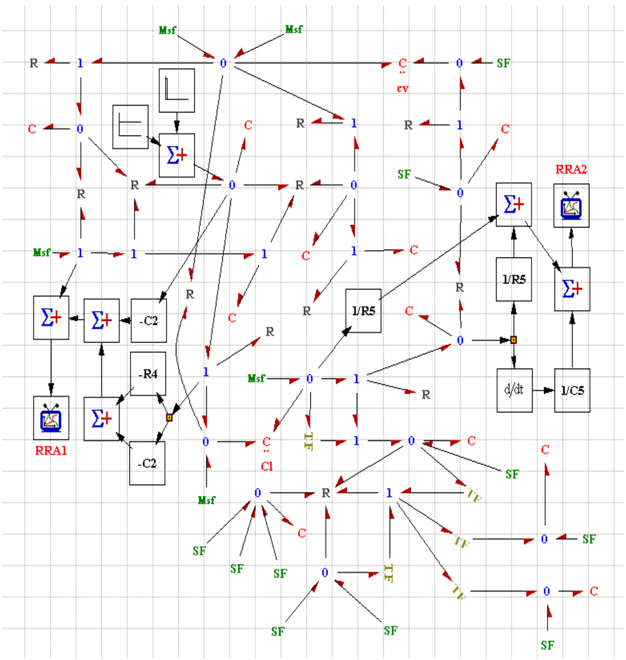

Fig. 15 Generated ARR_1 and ARR_2

These accidents, due to a loss of primary cooling agent via a breach located outside the enclosure, located on a circuit connected to the primary circuit and not isolated from this one, would show two particular characteristics:

• The loss of cooling agent taking place outside the enclosure, the recirculation of the system of injection of safety could prove to be impossible;

• In the event of core fusion, the fission products would be slackened directly outside the containment if the breach could not be insulated.

The rupture of the thermal barrier of the primary pumps can lead, for example, with situations of this type.

Under ideal operation, the residues must be constantly null. The following figure present the evolution of residues ARR8, ARR9, ARR10, and ARR11 over one duration of 5s corresponding to the equations of redundancy.

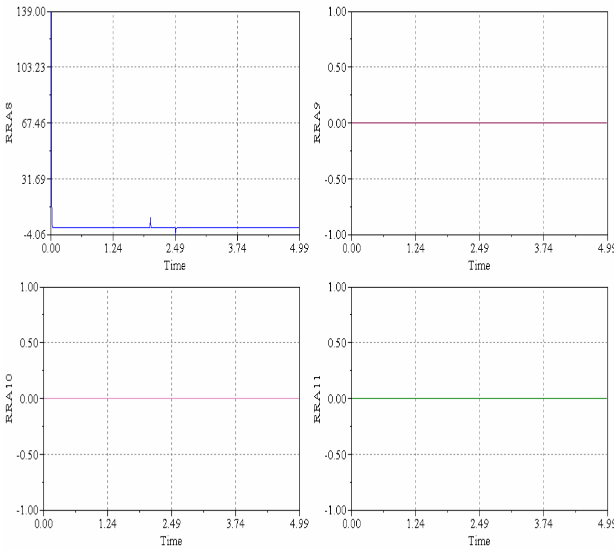

Fig. 16 Sensitivity of detector De2

The Fig. 16 shows the response of the residues. It is noted that residue ARR8 present a short change compared to its initial state between the moments t1=2s and t2=2.5s but turns over in their initial state from t=2.5 S and other residues A1, ARR2, ARR3, ARR4, ARR5, ARR6, ARR7, ARR9, ARR10, ARR11, ARR12, ARR13, ARR14 and ARR15 remain invariant (constants).

If one refers to the signature of the C2 component given to table 4 one notes that this result is in conformity with what is envisaged; i.e. that in the event of failure of the C2 component only the residue ARR8 will be sensitive.

B. *Sensitivity of Detector Df_2*

The generated ARRs reaction is very fast see Fig. 17.

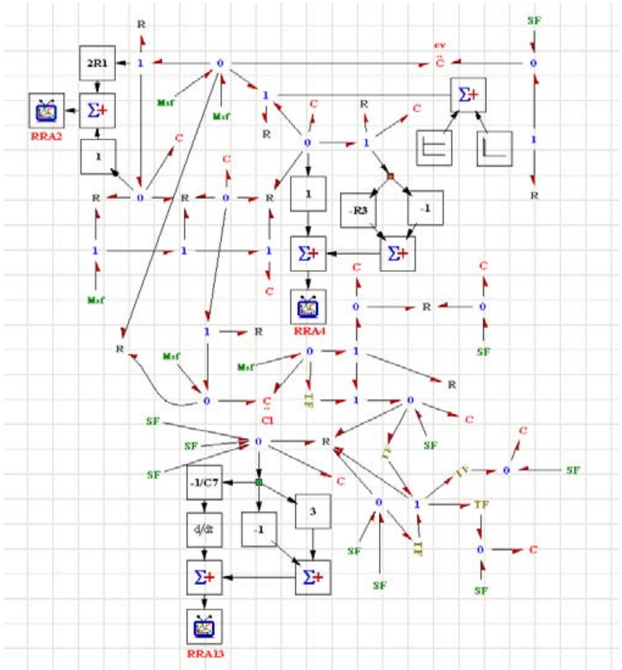

Fig. 17 Generated ARR2, ARR4 and ARR11

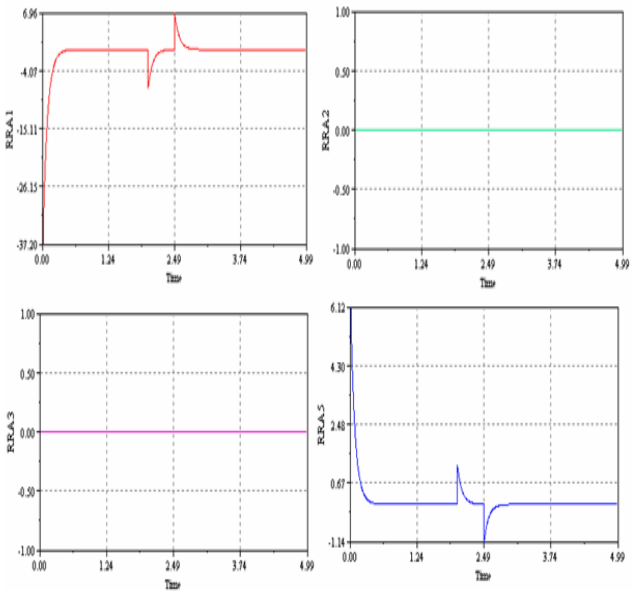

Fig. 18 Sensitivity of detector Df2

The deviation of the relations ARR2,ARR3, ARR4, ARR6,, ARR7 ARR8, ARR9, ARR10, ARR11, ARR12, ARR13, ARR14 and ARR15 in this time is normal (constant value). We see that residuals ARR1 and ARR5 are sensitive (seen the presence of Df2 in this relation).

VIII. Conclusion

This methodology enabled us to model in a homogeneous way, the systems has risk. They are based on the transformation of the matter and energy, for the analysis of the systems hydraulic, mechanical, electric and thermal. Coupled with the possibilities offered in term of analysis by the Bond Graph, this vision facilitated the approach "system" of the design. This last at summer achieved by using the tool Bond Graph, which appears adapted best then for the knowledge of such physical systems and particularly the systems complexes dangerous. It provides directly to the user original information.

The found results proved to be interesting because the found curves reveal a similarity between the found results and the results expected (real) in the specifications.

The diagnostic strategy and the form in which knowledge is available condition the method used to design the monitoring algorithm. According to the type of knowledge, the criterion of classification of the monitoring method distinguishes between two types of approaches: methods with or without model. Our contribution relates to the methods containing model.

–We used only one tool for modeling, the generations of the indicators of failures (residuals), the analysis of the monitorability and the sensors placement in order to satisfy the technical specifications for the monitoring.

–The generation of the analytical redundancy relations by the approach Bond Graph shows some interesting characteristics:

–They are simple to include/understand, since they correspond to relations and variables which are posted by the model Bond Graph image of the physical process, these relations are deduced directly from the graphic representation,

–They can be generated in form symbolic system and thus adapted to a data-processing implementation

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