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Elaboration of Supervision Process Applied to The Pressurized Nuclear Reactor Using Graphical Approach

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Abstract

The fault detection and isolation method based on bond graph for nuclear reactor with pressurized water is introduced in this paper. Using a knowledge representation of bond graph modeling, which includes system structural, functional and behavioral information and there relation. The main objective developed in this paper is to find a graphic technique for supervision of the industrial systems. The importance of this method is much apparent when it is about a complex system such as the nuclear reactor with pressurized water. In this case the analytical approach is heavy and does not give a fast idea on the evolution of the system. The simulation demonstrates that the bond graph fault diagnosis method is effective, corrective and flexible.

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Keywords: Bond Graph; Directed Graph; Supervision; Pressurized Reactor.

Nomeculre:

PWR : Pressurized water reactor
CEA : Commission of Atomic Energy
SG : Steam Generator
HP : Turbine high pressure
LP : Low pressure turbine
RRAs : Analytical Redundancy Relations
FDI : Fault detection and insulation
f : flow variable
e : effort variable
De : effort detector
Df : flow detector
x_i, y_i : binary variables

1. Introduction

Modeling and simulation of engineering dynamical systems is an essential analysis and synthesis tool. 'Pencil-and-paper' approaches to find the equations of the system and analyzing the implications behind them is tedious for large complex systems. Numerical simulation on digital computer aids in understanding the dynamical behaviour of such systems [1].

Many software packages on multiple platforms are available which perform simulation of complex physical systems that are represented in mathematical form. This has led to enhanced comprehension on the behaviour of the systems. Before embarking on the simulation process, the mathematical representation of the system is an important issue to be considered and overcome. One needs to get a sufficiently accurate model (mathematical representation) of the given system. There are various approaches for modeling systems. Graphical approach consists of the following methods: block diagram, signal flow graph, bond graph from which one gets the mathematical model of the system. Block diagram and signal flow graph provide a picture of the equations. They portray operators acting on the signals. Hence block diagram and signal flow graph do not give much insight into the topology of the system [2].

This paper focuses on the use of bond graph method for modeling, simulating engineering systems and supervision. It seamlessly integrates modelling of multidisciplinary systems like electrical, mechanical, magnetic, thermal, etc. It is a well-established graphical method for modeling dynamical systems.

The causality property of bond graph gives cause effect relationship between the system energy variables. Bond graph with assigned causality displays the structure of state space equations. One can write state equations from the bond graph just by inspection. Further, it provides an algorithmic way of extraction of state equations for computer simulation.

Industrial statistics show that 70% of the industrial accidents are caused by human errors. These abnormal events had the impacts of an economic nature, but especially of the impacts on safety and the environment, like nuclear accident of Three Island Mile in United States 1979 [3]. This accident is classified on 5 level, 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

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Ukraine 1986, poses the development problem of supervision techniques [1]. Moreover, industrial statistics show that small accidents are very frequent every day, causing important economic losses.

2. Process Description

In the pressurized water reactor (PWR), the water which passes over the reactor core to act as moderator and coolant does not flow to the turbine, but is contained in a pressurized primary loop. The primary loop water produces steam in the secondary loop which drives the turbine. The obvious advantage to this is that a fuel leak in the core would not pass any radioactive contaminants to the turbine and condenser (see figure 1).

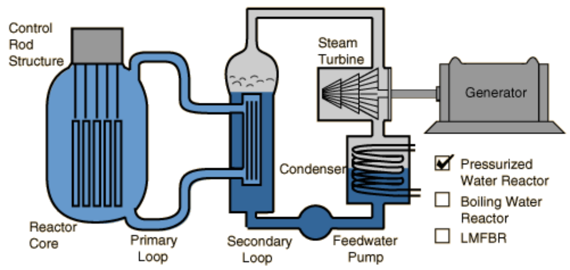


Figure 1. Pressurized Water Reactor.

Another advantage is that the PWR can operate at higher pressure and temperature, about 160 atmospheres and about 315 C. This provides a higher car not efficiency than the BWR, but the reactor is more complicated and more costly to construct. Most of the U.S. reactors are pressurized water reactors [4], [5].

3. Fault Detection and Isolation (FDI)

Immediately after the abstract, provide a maximum of six keywords (avoid, for example, 'and', 'of'). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible.

A number of methods have been developed for fault detection and isolation [7]. All methods of fault detection work by designing residual functions. The residual represents the difference between an estimated value and a measured one, which should be zero during normal operation, but large in the presence of faults [8].

In practice, there is a distinction between the detection of fast-acting, possibly safety-critical faults, and faults which are non-safety-critical and slower to develop, for example due to wear. The former are most likely to be detected by state-estimation and instantaneous comparison of prediction with measurement, while the latter are detected using parameter estimation techniques which require a certain time window and excitation of the system. Probability analysis can be used to judge, from the residual values, when a fault or change has taken place [7]. This paper is concerned primarily with detection of fast-acting faults, detected via state estimation. Isolation, in the literature, means diagnosis of the faulty component. If faults are allowed to occur simultaneously, then for a diagnosis, at least as many independent residual functions as faults considered are required. In practice, it is usually assumed that only one fault occurs at a time, which facilitates more robust fault diagnosis [8].

4. Bond Graph Modeling of PWR

Bond Graphs were originated by Henry M. Paynter with the specific purpose of handling variety within multi domain dynamic systems, based on energy and information exchange [6]. The physical model developed using Bond Graphs is detailed down to the topological level of the system being studied through a simple set of idealized elements. It is comprehensive as well and captures inter domain dynamic interaction through a uniform notation drawn on the concept of analogies among physical systems residing in different energy domains [7], [8]. The Bond Graph model of a PWR is presented by figure 2.

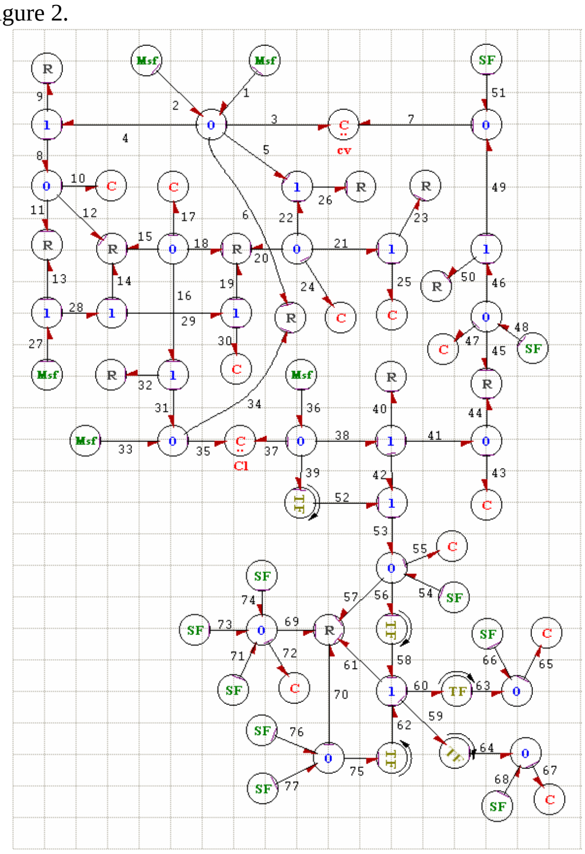


Figure 2. Bond Graph Model detailed of a pressurized water reactor.

5. Operational Characteristics

Table 1 shows the typical operational characteristics of a PWR.

6. Simulation Results

The actual control and FDI properties of the process may differ from that obtained through structural analysis when parameter values, process uncertainties, and sensor noises are taken into consideration. Thus, validations through nonlinear control analysis and simulation are necessary before finalizing the process instrumentation. Simulation requires a behavioral model derived from causal linking of components at the equation level.

Residual sensitivity to faults can be tested by using offline data or a simulation model. This requires linking ARR equations with the behavioral model by using a hybrid simulation tool and solving them together with the introduction of various faults.

7. Representation by A Structural Model

The monitoring of the processes is often based on the analytical redundancy, less expensive than the physical redundancy. The graph theory was largely used in this field like method with models. In this work, we approached the monitoring by the approach structural under the angle of the graphs bipartis [9].

Table 1. shows the typical operational characteristics of a PWR.

characteristic	Value
Thermal power output	3.800 MWth
System pressure	2.250 psia
Fuel enrichment	1.9/2.4/2.9
Coolant flow	1.5910^3 Ibs/hr
Inlet temperature	565°F
Outlet temperature	622.4 °F
Maximum fuel temperature	3.420 °F
Average linear heat rate	5.34 KW/ft
Maximum linear heat rate	12.51 KW/ft
Average heat flux	206.000 BTU/(hr.fr^2)
Maximum heat flux	550.000 BTU/(hr.fr^2)
Minimum Departure from nucleate boiling	1.3
Ratio (DNBR)	
Active height	150 inches
Equivalent active diameter	142.9 inches
Height of diameter ratio	1.05
Active core volume	1413 ft^3
Average core power density	2.690 KW/ft^3
Fuel weight	103.000 kgs
Specific power	36.9 kW/kg U
Burnup	33.000 Mwdays/MTU
Conversion ratio	0.5
Number of fuel assemblies	241
Fuel element array	16x16
Assembly dimensions	8 in x 8 in
Number of fuel rods per assembly	236
Total number of fuel rods	56.876
Fuel element pitch	0.504 in
Fuel element outer diameter	0.382 in
Pitch diameter ratio	1.33
Cladding thickness	0.025 in
Fuel pellet diameter	0.325 in
Pellet to clad gap size	0.0035 in

8. Constraints

The constraints C can be seen as any relations which connect the variables and the parameters of the system. They are represented by the structural constraints, of behavior, measurement, the control device and the controlled sources [9].

8.1. Structural equations ϕ_s :

They represent the whole of the conservation laws (mass, energy…) and/or equilibrium equations. They are deduced from the equations to the junctions. The number of equations is equal to the number of equations in junctions 0 add of junctions 1 add of the two ports elements (transformer TF, and gyrator GY) [10].

$$\begin{aligned}\phi_s = &\{\phi_{j1_1}\} \cup \phi\{_{j1_2}\} \cup \{\phi_{j1_3}\} \cup \{\phi_{j1_4}\} \cup \{\phi_{j1_5}\} \cup \\ &\{\phi_{j1_6}\} \cup \{\phi_{j1_7}\} \cup \{\phi_{j1_8}\} \cup \{\phi_{j1_9}\} \cup \{\phi_{j1_{10}}\} \cup \{\phi_{j1_{11}}\} \\ &\cup \{\phi_{j0_1}\} \cup \{\phi_{j0_2}\} \cup \{\phi_{j0_3}\} \cup \{\phi_{j0_4}\} \cup \{\phi_{j0_5}\} \cup \{\phi_{j0_6}\} \\ &\cup \{\phi_{j0_7}\} \cup \{\phi_{j0_8}\} \cup \{\phi_{j0_9}\} \cup \{\phi_{j0_{10}}\} \cup \{\phi_{j0_{11}}\} \cup \\ &\{\phi_{j0_{12}}\} \cup \{\phi_{j0_{13}}\} \cup \{\phi_{j0_{14}}\} \cup \{\phi_{jTF_1}\} \cup \{\phi_{jTF_2}\} \cup \{\phi_{jTF_3}\} \\ &\cup \{\phi_{jTF_4}\} \cup \{\phi_{jTF_5}\}\end{aligned} \quad (1)$$

$\phi_C \in \Re^{nj+2n_{2p}}$ n_j : is the number of junctions 0 and 1, and n_{2p} is the number of two ports elements (TF and GY).

8.2. Behavior equations ϕ_b :

The physical laws expressing the way in which energy is converted, represent the model of behavior. The model of behavior of each component expresses the constraints which this component imposes on the variables which are dependent for him. We can thus associate each component a whole of relations whose expression depends on the type of knowledge available on the activity of the component to model. The models of behavior of the components of the system can have varied representations. These models can be linear, nonlinear, static, dynamic, qualitative, containing rules of evolution or numerical tables (for example for models Bond Graphs). The need for a formalism unified to determine the common elements of the various models of the components, justifies the structural approach. This one makes it possible to establish the constraints which exist between the various variables and system relations. This fact we can treat models of components very varied from a complex system being able to cohabit in the same system which does not require the complete definition of the model describing its behavior. In the Bond Graph model, they describe the physical phenomena on the level Bond Graph elements (R, C, and I), and are called "constitutive laws" [11].

$$\phi_b = \{\phi_{C_1}\} \cup \{\phi_{C_2}\} \cup \{\phi_{C_3}\} \cup \{\phi_{C_4}\} \cup \{\phi_{C_5}\} \cup \{\phi_{C_6}\} \cup \{\phi_{C_7}\} \cup \{\phi_{C_8}\} \cup \{\phi_{C_9}\} \cup \{\phi_{R_1}\} \cup \{\phi_{R_2}\} \cup \{\phi_{R_3}\} \cup \{\phi_{R_4}\} \cup \{\phi_{R_5}\} \cup \{\phi_{R_6}\} \quad (2)$$

$\phi_b \in \Re^{n_e}$, n_e : is the total number of the power bonds in the Bond Graph elements, R, C and I.

9. The Measurements Model

It describes available measurements on the Bond Graph model. This model expresses the way in which the sensors transform the state variables of the process into output signals which can be used in the laws development of order and in the failures detection and insulation. In Bond Graph model the sensors are represented by effort and flow detectors (De and Df).

$$\phi_m = \{\phi_{De_1}\} \cup \{\phi_{De_2}\} \cup \{\phi_{De_3}\} \cup \{\phi_{De_4}\} \cup \{\phi_{De_5}\} \cup \{\phi_{De_6}\} \cup \{\phi_{De_7}\} \cup \{\phi_{De_8}\} \cup \{\phi_{De_9}\} \cup \{\phi_{Df_1}\} \cup \{\phi_{Df_2}\} \cup \{\phi_{Df_3}\} \cup \{\phi_{Df_4}\} \cup \{\phi_{Df_5}\} \cup \{\phi_{Df_6}\} \quad (3)$$

n_s : is the number of detectors (or sensors).

9.1. Model of the command algorithms ϕ_C :

It describes the command algorithms in which the entries of the regulators are the values of the instructions and sensors measurement. The regulators output operate the actuators represented by modulated sources of effort or flow. Contrary to the structural and behavior equation which uses the variables of power effort flow like variables of output input, the command and measurement laws use the information signals.

$$\phi_C = \{u\_ref, y_m, \theta_{reg}\} \quad (4)$$

9.2. Model of the controlled sources ϕ_A :

These models describe the controlled or modulated energy sources by the control signals (controlled pump, control tension ...).The input signals U are provided by the regulators and the output signals are the controlled variables MSe and MSf.

$$\phi_{A1}(MSf, u) = 0, \phi_{A2}(MSe, u) = 0 \quad (5)$$

The constraints whole ϕ apply to the variables whole Z: known (K) and unknown factors (X).

$$Z = X \cup K \quad (6)$$

The unknown variables X are the variables of power (flow and effort) supported by the power bonds of the Bond Graph model. Vector X container all the power variables is:

$$X = \{e_1(t), f_1(t)\} \cup ... \cup \{e_{nc}(t), f_{nc}(t)\} \quad (7)$$

The unknown variables of our example are the effort and flow variables of the power bonds in Bond Graph model.

$$X = \{e_{10}(t), f_{10}(t)\} \cup \{e_{17}(t), f_{17}(t)\} \cup \{e_{24}(t), f_{24}(t)\} \cup \{e_{43}(t), f_{43}(t)\} \cup \{e_{47}(t), f_{47}(t)\} \cup \{e_{55}(t), f_{55}(t)\} \cup \{e_{72}(t), f_{72}(t)\} \cup \{e_{65}(t), f_{65}(t)\} \cup \{e_{67}(t), f_{67}(t)\} \cup \{e_9(t), f_9(t)\} \cup \{e_{26}(t), f_{26}(t)\} \cup \{e_{23}(t), f_{23}(t)\} \cup \{e_{32}(t), f_{32}(t)\} \cup \{e_{40}(t), f_{40}(t)\} \cup \{e_{50}(t), f_{50}(t)\} \quad (8)$$

The subset K of the known variables contains the sources values, the regulators output and the measured variables by the sensors.

$$K = MSe \cup MSf \cup Se \cup Sf \cup \phi_m \quad (9)$$

For the Bond Graph model of our application:

$$K = \{Sf_{48}\} \cup \{Sf_{54}\} \cup \{Sf_{71}\} \cup \{Sf_{73}\} \cup \{Sf_{74}\} \cup \{Sf_{66}\} \cup \{Sf_{68}\} \cup \{De_1\} \cup \{De_2\} \cup \{De_3\} \cup \{De_4\} \cup \{De_5\} \cup \{De_6\} \cup \{De_7\} \cup \{De_8\} \cup \{De_9\} \cup \{Df_1\} \cup \{Df_2\} \cup \{Df_3\} \cup \{Df_4\} \cup \{Df_5\} \cup \{Df_6\} \quad (10)$$

$\theta \in \Re^p$: is the parameters vector.

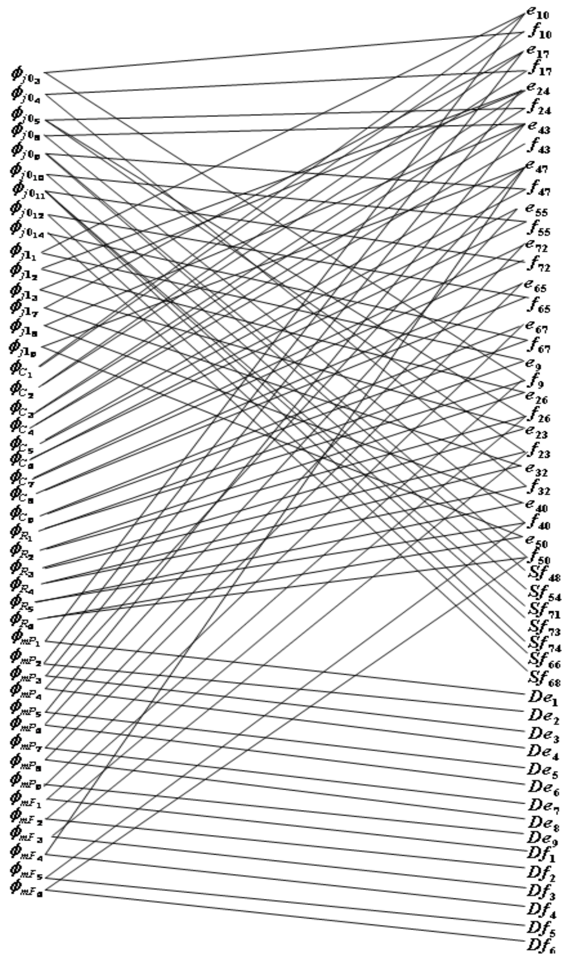


Figure 3. Analyze of Bond Graph model.

10. Adjustment in Steam Generator

The temperature in the boiler varies exponentially according to time because the phenomenon of energy storage with t=1.53s. The temperature becomes stable what carries out the system in a state of permanent balance then the temperature is equal to 300°C (see figure 4).

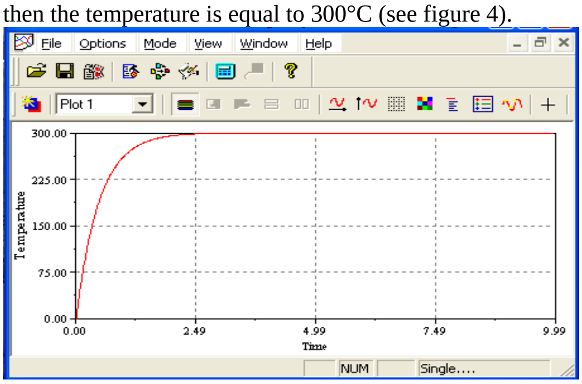


Figure 4. Variation in the temperature according to time in Steam Generator.

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 generators has the temperature is equal to 270°C. The regulator is a PID type (Proportional Integral and Derived). Its adjustments are variable according to the water alimentation temperature. For adapting the regulator to the process characteristics, variables are loaded (figure 5).

The measurement of the steam flow is added on the outlet side of the regulator to constitute the instruction of food water flow. That makes it possible to pre-empt the regulator response at the time of the flow steam transient. Finally, the regulation comprises a control of water flow.

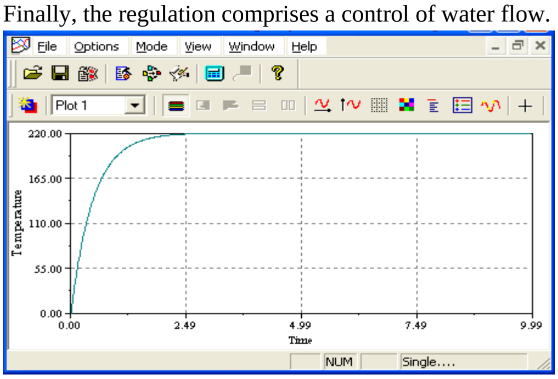


Figure 5. Temperature variation according to time at output of steam generator.

11. Adjustment of mass throughput:

The enthalpy grows exponentially according to time because the influence of the thermal power which provided calorific energy to the boiler and at the moment t=7.5s the mass throughput becomes stable and is equal to 60000 m3/h and according to the temperature stability (figure 6).

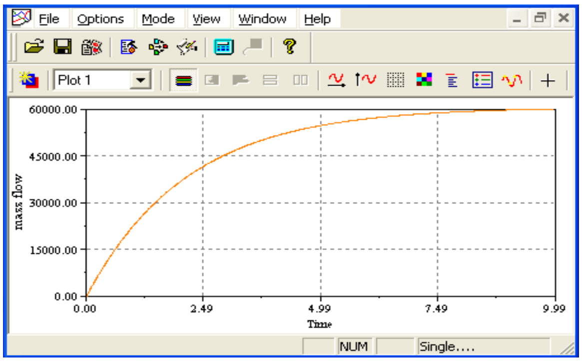


Figure 6. Variation of mass throughput according to time in steam generator.

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. The adjustment of the temperature in the reactor heart is that the coolant temperature varies exponentially 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 order bars, to adapt the temperature value to the process characteristics which varies in function of the load (see figure 7).

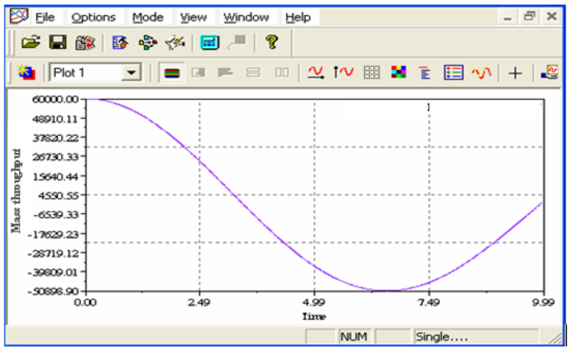


Figure 7. Mass throughput variation according to time at steam generator output

The temperature measurement is made using sensor placement on the level of the reactor heart and its role is to check the temperature value at every moment thus it plays a fundamental role on the control rods movement, otherwise the input and output speed is dregs with the temperature and pressure values (see figure 8).

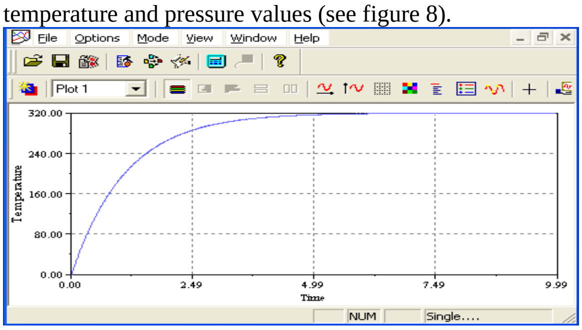


Figure 8. Temperature variation in the reactor heart

12. Adjustment of The Pressure in The Reactor Heart

The pressure varies in the heart of almost linear reactor according to time to 75 bars at the moment 10s (see figure 9). The pressure adjustment of heart consists generally with the introduction of the bars which influences directly on the pressure and the temperature values. The variation of the function of pressure binds to the variation in the temperature i.e. when the temperature also increases the pressure increases.

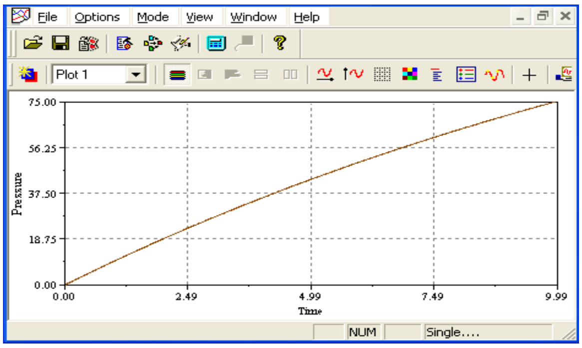
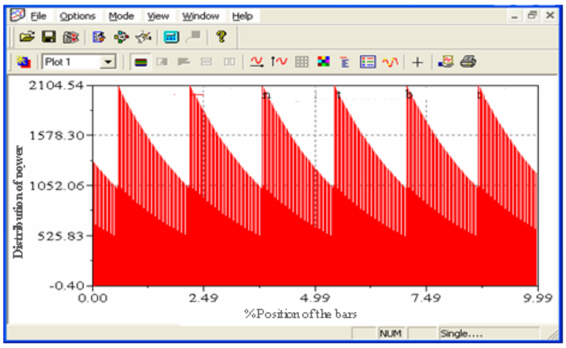


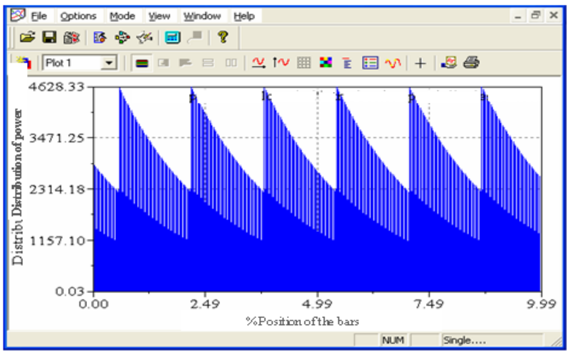
Figure 9. Pressure variation in the reactor heart

13. Power Instantaneous

The instantaneous adjustment of the power consists generally with the introduction of the rigging bars. These rigging bars have as common property which is made of a material strongly absorbing for the neutrons like Bore, Cadmium, Argent or Indium. The physical form can be different; we know for example, needles and plates. According to the aim, we also make the distinction between scram rods, control rods and bars of fine adjustments.



(a)



(b)

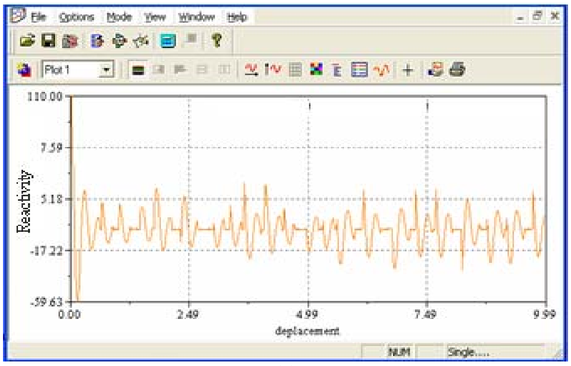
Figure 10 (a, b). Disturbance of the inflow distribution by the rigging bars

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

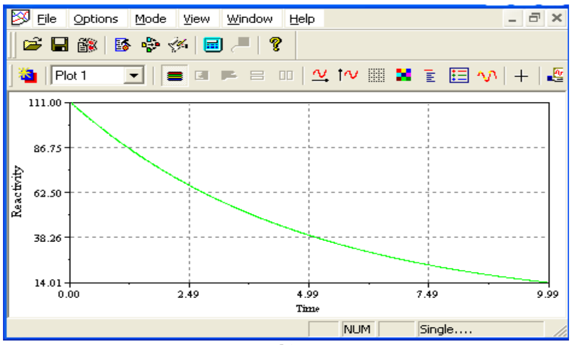
Moreover, the bars of fine adjustments can be used to maintain the power stable at the level wished without having to use the control rods. The introduction of the control rods involves a deformation of flow owing to the fact that locally more neutrons are absorbed. Figure 10 shows how the distribution of inflow is disturbed by the introduction of an absorbing rigging bar.

14. Reactivity

Figure 11 illustrates the flow radial distribution up to what point is disturbed by the rigging bars introduction. The reactivity change introduced by the fact of inserting or of withdrawing an absorbing bar is depend on the position of the rigging bar.



(a)



(b)

Figure 11(a, b). Disturbance of the flow radial distribution by absorbing 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 Figure 12.

When we trace the total negative reactivity introduced by the absorbing bars according to the position of the rigging bars, we obtain the integral effectiveness as shown with the following Figure (see figure 13).

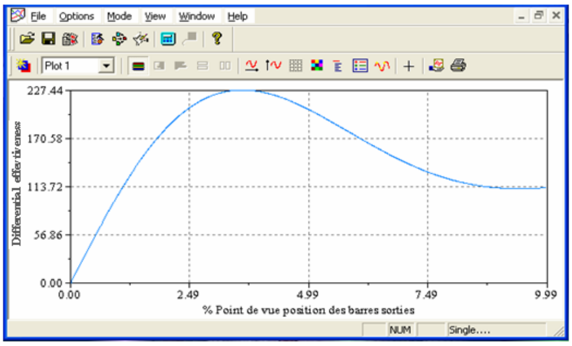


Figure 12. Differential effectiveness of a rigging bar.

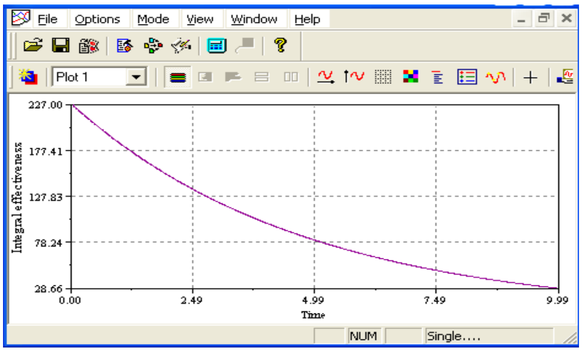


Figure 13. Integral effectiveness of a rigging bar.

15. 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.

The curve representing the pressure follows an exponential law according to time checks the empirical equation, this variation is due to accumulate matter in the steam generator which makes increased the pressure up to value 155 bars i.e. 155.105 Pa (see figure 14).

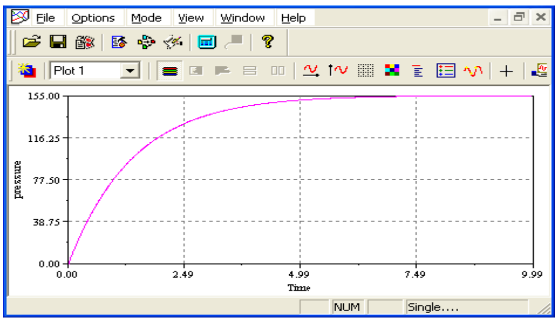


Figure 14. Variation of the pressure according to time.

The temperature of the output steam of steam generator decreases 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 (figure 15).

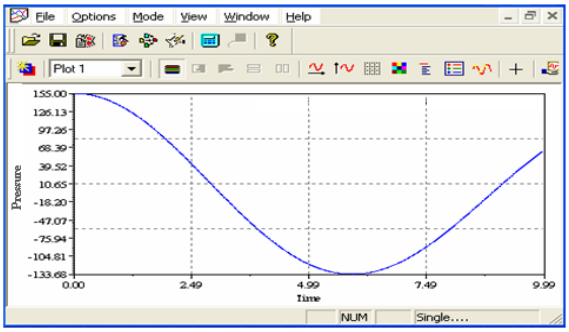


Figure 15. Variation of the pressure according to time at steam generator output.

16. Monitoring of Nuclear

We suppose that sensors and sources are not affected by faults [12]. For our application, the equations in junctions are given by:

For 0i junction we have

$$\begin{cases} e_4 - e_8 - e_9 = 0 \\ f_9 = f_8,\ f_9 = f_4 \\ e_{R1} = e_9 = \phi_{R1}\left[(1-y_1)f_9 + y_1 Df_1\right] \\ f_{R1} = f_9 = (1-y_1)\phi_{R1}^{-1}(e_9) + y_1 Df_1 \end{cases} \quad (11)$$

For 1j junction we have

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

For TF_k junction we have

$$\begin{cases} e_{52} = \frac{1}{m} e_{39} \\ f_{39} = \frac{1}{m} f_{52} \end{cases} \quad (13)$$

17. 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 behavioral model of the system through different procedures of elimination of unknown variables [13]. Numeric evaluation of each ARR

is called a residual, which is used in model based fault detection and isolation (FDI) algorithms [14].
From equations of junctions we obtain the following system:

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

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

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

$$r_4 : \phi_{R2}\left[(1-y_2)f_{26} + y_2 Df_2\right] + msf_1 + \frac{1}{s}(1-x_3)\phi_{C3}^{-1}(f_{24}) + x_3 De_3 = 0$$

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

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

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

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

$$r_9 : -\phi_{C3}\left[s\{(1-x_3)e_{24} + x_3 De_3\}\right] - (1-y_3)\phi_{R3}^{-1}(e_{23}) - (1-y_2)\phi_{R2}^{-1}(e_{26}) + y_2 Df_2 - \overset{*}{Df_9} + y_3 Df_3 = 0$$

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

$$r_{11} : -\overset{*}{Df_{10}} + (1-y_4)\phi_{R4}^{-1}(e_{32}) + y_4 Df_4 + msf_{33} - \overset{*}{Df_{11}} = 0$$

$$r_{12} : \overset{*}{De_4} - \overset{*}{Df_{12}} - \overset{*}{De_5} = 0$$

$$r_{13} : -\overset{*}{Df_{13}} + msf_{36} - (1-y_5)\phi_{R5}^{-1}(e_{40}) + y_5 Df_5 - \frac{1}{m}((1-y_5)\phi_{R5}^{-1}(e_{40}) + y_5 Df_5) = 0 \qquad (13)$$

$$r_{14} : -\phi_{R4}\left[(1-y_4)f_{32} + y_4 Df_4\right] + x_2 De_2 - msf_{33} + \frac{1}{s}(1-x_2)\phi_{C2}^{-1}(f_{17}) = 0$$

$$r_{15} : -\phi_{C5}\left[s\{(1-x_5)e_{43} + x_5 De_5\}\right] + (1-y_5)\phi_{R5}^{-1}(e_{40}) - \overset{*}{Df_{14}} + y_5 Df_5 = 0$$

$$r_{16} : -\phi_{R5}\left[(1-y_5)f_{40} + y_5 Df_5\right] + msf_{36} + x_5 De_5 - \frac{1}{m}msf_{36} + x_6 De_6 - \frac{1}{s}(1-x_5)\phi_{C5}^{-1}(f_{43}) - \frac{1}{s}(1-x_6)$$
$$\phi_{C6}^{-1}(f_{55}) = 0$$

$$r_{17} : -\phi_{C5}\left[s\{(1-x_5)e_{43} + x_5 De_5\}\right] - \overset{*}{Df_{15}} + sf_{48} + y_6 Df_6 - (1-y_6)\phi_{R6}^{-1}(e_{50}) = 0$$

$$r_{18} : -\phi_{R6}\left[(1-y_6)f_{50} + y_6 Df_6\right] - sf_{51} + x_4 De_4 + \frac{1}{s}(1-x_4)\phi_{C4}^{-1}(f_{47}) = 0$$

$$r_{19} : -\phi_{C6}\left[s\{(1-x_6)e_{55} + x_6 De_6\}\right] + sf_{54} + y_5 Df_5 - \overset{*}{Df_{15}} - \frac{1}{m}\overset{*}{Df_{16}} + (1-y_5)\phi_{R5}^{-1}(e_{40}) = 0$$

$$r_{20} : \phi_{R5}\left[(1-y_5)f_{40} + y_5 Df_5\right] + \frac{1}{m}msf_{39} + x_6 De_6 - \frac{1}{s}(1-x_6)\phi_{C6}^{-1}(f_{55}) = 0$$

$$r_{21} : -\phi_{C7}\left[s\{(1-x_7)e_{72} + x_7 De_7\}\right] - \overset{*}{Df_{17}} + sf_{71} + sf_{73} + sf_{74} = 0$$

$$r_{22} : -\frac{1}{r}\left(\frac{1}{s}(1-x_6)\phi_{C6}^{-1}(f_{55}) + x_6 De_6\right) l(\frac{1}{s}(1-x_9)\phi_{C9}^{-1}(f_{67}) + k(\frac{1}{s}(1-x_8)\phi_{C1}^{-1}(f_{65}) + x_8 De_8) - \overset{*}{Df_{16}} + \frac{1}{h}sf_{76}$$
$$+ x_9 De_9) - = 0$$

$$r_{23} : k\,\overset{*}{Df_{16}} - \phi_{C8}\left[s\{(1-x_8)e_{65} + x_8 De_8\}\right] + sf_{66} = 0$$

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

$$r_{25} : k\,\overset{*}{Df}_{16} - \phi_{C9}\left[s\left\{(1-x_9)e_{67} + x_9 De_9\right\}\right] + sf_{68} = 0$$

From the binary variables x_i (i=1, 14) and y_j (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?

$$For\ [x_1 y_1 x_2 y_2 x_3 y_3 x_4 y_4 x_5 y_5 x_6 y_6 x_7 y_7 x_8 y_8 x_9 y_9\ x_{10} y_{10} x_{11} y_{11} x_{12} x_{13} x_{14}] = [1111111111\ \ 111111111\ \ 111111\ \ ]$$

Table 2: Fault signature table

The fault signatures (table 3) 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 2. Fault signature table.

	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

$$For[x_1 y_1 x_2 y_2 x_3 y_3 x_4 y_4 x_5 y_5 x_6 y_6 x_7 y_7 x_8 y_8 x_9 y_9\ x_{10} y_{10} x_{11} y_{11} x_{12} x_{13} x_{14}] = [0111011010\,0001111\ 11110101]$$

It is noticed that the structures of the residuals are different but fault signatures are not different [(C_4 and R_2), (C1 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 (table 3).

Table 3. Fault signature table

	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	1	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

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For $[x_1 y_1 x_2 y_2 x_3 y_3 x_4 y_4 x_5 y_5 x_6 y_6 x_7 y_7 x_8 y_8 x_9 y_9 x_{10} y_{10} x_{11} y_{11} x_{12} x_{13} x_{14}]$ = [1100110010 1011101 11010101]

The fault signatures (table 4) 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 4. Fault signature table.

	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

18. Simulation and Interpretation

From SYMBOLS software, 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 [9].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].

19. Sensitivity of detector De_2:

In the first time, we create a fault between the instant t_1=2s and t_2=4s (figure 16).

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 residuals must be constantly null. The following figures present the evolution of residuals ARR_8, ARR_9, ARR_{10}, and ARR_{11} over duration of 4s corresponding to the equations of redundancy.

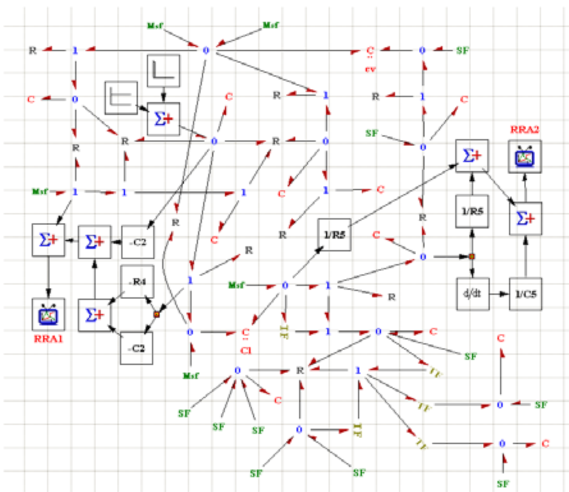

Figure 16. Generated ARR_1 and ARR_2 .

Figure (17) shows the response of the residuals. It is noted that residual ARR_8 presents a short change compared to its initial state between the moments t_1=1.4s and t_2=4s and other residuals ARR_1, ARR_2, ARR_3, ARR_4, ARR_5, ARR_6, ARR_7, ARR_9, ARR_{10}, ARR_{11}, $ARR1_2$, ARR_{13}, ARR_{14} and ARR_{15} remain invariant. If we refer to the signature of the C_2 component given to table 4 we note that this result is in conformity with what is envisaged; i.e. that in the event of failure of the C_2 component only the residual ARR_8 will be sensitive.

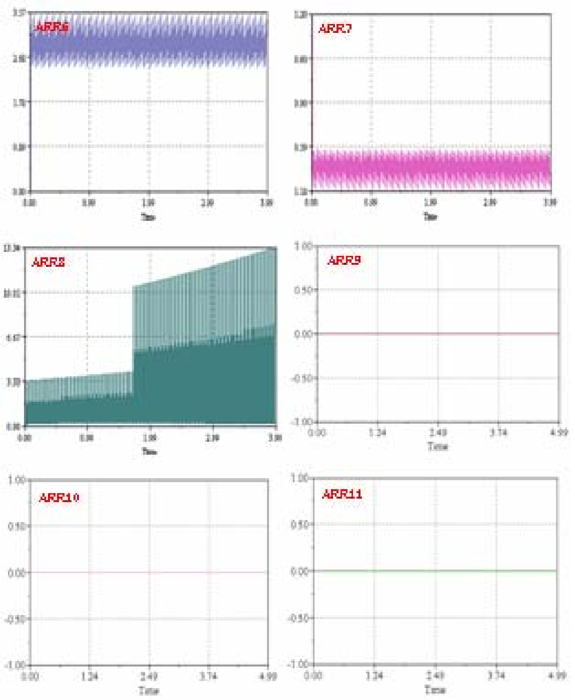

Figure 17. Sensitivity of detector De_2

20. Sensitivity of detector Df_2:

The generated ARRs reaction is very fast see Figure 18.

The deviation of the relations ARR_2,ARR_3, ARR_4, ARR_6, ARR_7, ARR_8, ARR_9, ARR_{10}, ARR_{11}, ARR_{12}, ARR_{13}, ARR_{14} and ARR_{15} in this time are normal (i.e. with constant value). We see that residuals ARR_1 and ARR_5 are sensitive to the failure due to the presence of Df_2 in these relations (see figure 19).

21. Conclusion

The modeling of pressurized nuclear reactor was realized and validated by Software SYMBOLS that is very adapted to the simulation of our problem. Bond graph is very powerful tool of research and recommended for the use of the great industrial systems. The supervision is assured by sensors placement algorithm which has permitted us to generate ARR and fault signature tables for detection and isolation analysis of optimal case.

The method used illustrates the process principle working. We have using the structural junction equations for generating the analytical redundancy relations like failures indicators. The Bond Graph tool is the unified modeling method and it facilitates the functional and structural analysis of the complex systems. 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.

A method has been demonstrated for detecting faults in complex control systems, by dividing the complete system into simpler subsystems.

Weak coupling between subsystems may be allowed if the resulting errors are small.

The different residuals should be designed to facilitate simple fault diagnosis logic, each using as few measured signals as possible.

The number of possible diagnoses is limited by the number of independent residuals designed, which in turn depends on the number of available measurements.

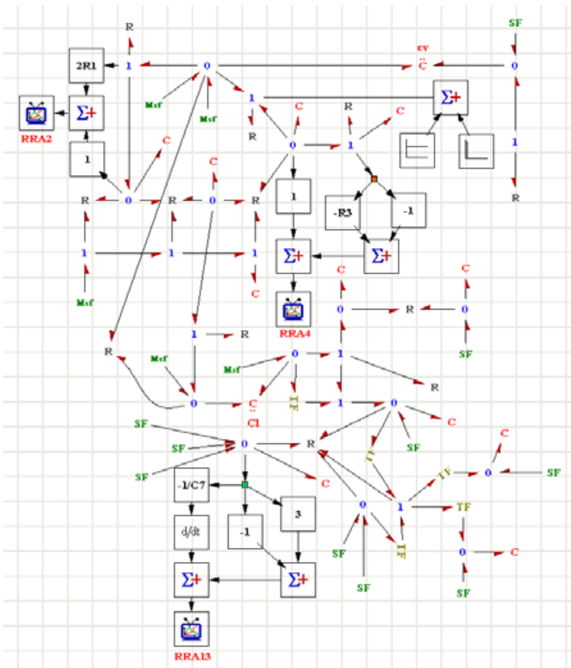

Figure 18. Generated ARR_2, ARR_4 and ARR_{11} .

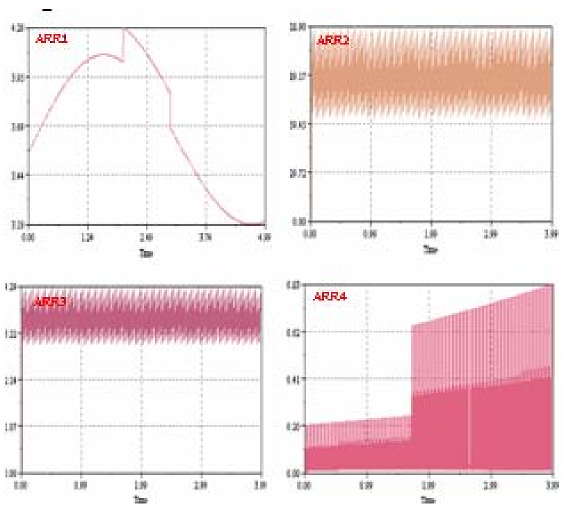

Figure 19. Sensitivity of the detector Df_2.

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