Pressurized Water Reactor Modelling with Modelica

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Abstract

In order to optimize and validate the design and the operation of its nuclear power plants facilities, EDF (Electricité de France) uses a proprietary tool called LEDA to perform static and dynamic simulation at the system level. EDF wishes to replace LEDA by state-of-the-art off-the-shelf tools, mainly to reduce maintenance cost while keeping up with the latest trend in modeling and simulation technology.

To validate the feasibility of replacing LEDA by Modelica based tools, several benchmarks models have been chosen, that represent the variety of engineering studies made at EDF. The objective of this work is to show that these tools are fit to dynamic modeling and simulation of a PWR plant. To that end, a reference LEDA model of such plant has been successfully translated into Modelica and simulated using Dymola. The results of the Dymola simulation experiments are compared to those obtained with LEDA.

This paper describes the structure of the Modelica model, and the modeling and the numerical difficulties encountered during the translation and simulation process.

1 Introduction

For more than 20 years, EDF has been using modeling and simulation at the system level for the sizing, design verification and validation, and the operation of its nuclear and conventional thermal power plants.

To that end, EDF has developed and maintained since the early 80's a modular code called LEDA. LEDA is used for static (plant sizing) and dynamic studies (modeling and simulation of the normal or incidental plant transients). It is an efficient tool, that has a complete model library and can solve direct and inverse problems. But, because of its now ageing architecture, it cannot keep up with the latest trend in modeling and simulation technology.

So, to improve the efficiency of its simulation tools while reducing their cost, EDF is studying the feasibility of using state-of-the-art readily available tools instead of LEDA code.

The replacement tools should at least have the same capabilities as LEDA, i.e. have an open component library, be able to perform static and dynamic studies, compute steady states and solve inverse problems. They also should not induce an excessive dependency upon the tool providers.

Modelica based tools offer such characteristics. That is why they are considered as good candidates to replace LEDA.

In order to evaluate the feasibility to replace LEDA by Modelica based tools, benchmark cases have been selected, which cover the variety of studies made at EDF. The first case to be studied was the quasi-2D modeling of a steam generator [1]. The next industrial case in the nuclear field to be studied, and objective of this work, is the dynamic modeling of a 1300 MW PWR power plant (P4).

The P4 LEDA model is a reference model used to study the behavior of the plant wrt. the power grid solicitations. In particular, it is useful for verifying the design of the control system against important transients, such as the house load operation.

This paper shows how the P4 LEDA model was translated into Modelica and tested with Dymola.

2 Description of the P4 model

The EDF nuclear plants belong to the PWR (Pressurized Water Reactor) type. For such type of nuclear plants, water acts both as the neutron moderator for the nuclear reaction, and as the heat transport fluid. Nuclear reaction occurs in fuel rods which are inserted into the vessel that contains water coming from the primary loop. The primary water is heated in the reactor core by the energy created from the nuclear reaction, while being maintained at high pressure in order to stay in the liquid phase. Hot water leaving the reactor vessel exchanges its heat with water coming from another circuit called the secondary loop. This heat exchange occurs through the steam generator, where primary water (in liquid state) and secondary water (in boiling state) are separated. The primary water is thus cooled and goes back to the nuclear reactor, while the secondary water heats up and becomes steam flowing to the turbine that drives the alternator to produce electricity. Steam leaving the turbine passes then through a condenser to go back to the steam generator as liquid feedwater.

The following circuits and components are included in the model: the primary loop and the pressurizer, point neutronic kinetics, the steam generator, the vapour line from the steam generator to the turbine admission valve, the steam generator feed water line. The main control systems are also taken into account in the model: the mean primary temperature control, nuclear power control, pressurizer pressure and level control, steam generator water level control, secondary pressure control, secondary power control, turbine power control.

A Modelica library of 0D and 1D thermal hydraulics components has been developed, based on the original equations of the equivalent Fortran LEDA model components. These equations are the basic mass, momentum and energy balance equations, completed with closure equations derived from empirical correlations valid for the operating domain under consideration. Steam generator and vapour lines are described by 1D models. Empirical correlations (heat transfer, pressure losses), adapted to the physical range of operation of PWR, have also been translated into Modelica. The Modelica components have even been improved when necessary: more stable numerical scheme for 1D thermal hydraulics, inertial terms added, more adequate correlations for heat transfer, ...

2.1 EDF Thermofluid Library

A thermofluid Modelica library is being developed at EDF. The objective is to provide the physical and technological model components needed for steady-state and dynamic simulation of nuclear and thermal power plants under normal and incidental operating conditions.

The library components must be able to describe single and two-phase flow, with heat transfer when needed, deal with zero and reverse flow, compressible and incompressible flow for water/steam, and smoke networks for thermal power plants.

The library uses a finite volume approach, based on the staggered grid scheme for space discretization, and the upwind scheme for the handling of flow reversal [2]. Both schemes are well suited for convection, which is the predominant energy transport law within the network. Discretization is performed along the main flow direction only (1D modelling).

The basic model components are divided into two groups: nodes and edges. Nodes represent mixing volumes such as tanks, boilers, splitters and mergers, etc. They implement the mass and energy balance equations. Edges represent flow resistant elements such as valves, simple pressure loss pipes, etc. They implement the momentum balance equations. The network is built by connecting edges to nodes in order to obtain a complete set of mass, energy and momentum equations with their closure equations, and automatically fulfil the numerical scheme requirements. Complex library components such as heat exchangers, evaporator pipes or steam generator are also built by assembling edge and node elements. A more complete description of the modeling approach chosen by EDF for the thermofluid library is presented in ref. [1].

It is also important to note that EDF has chosen not to use the Modelica inheritance mechanism, in order to keep the readability of the model: the complete set of equations can be found directly in the component model itself, instead of being scattered throughout the library when they are partially derived from super-classes.

2.2 Components of the P4 model

In order to build the P4 model within the physical limits described earlier, the following components have been developed:

- fluid flow in pipes (primary and secondary water loop),
- pressurizer (to maintain primary water as liquid),

- turbine,
- valve,
- pump and motor (primary loop),
- steam generator (secondary water loop), represented by a riser connected to an upper part (the dome),
- point neutronic kinetics (modelling nuclear reaction and resulting temperature).

As one of the main purposes of the model is to validate the response of the plant against the grid solicitations, the main control sub-systems of the plant have been also modelled. They have been tested separately in open loop, then connected to the P4 process model as shown in Figure 1.

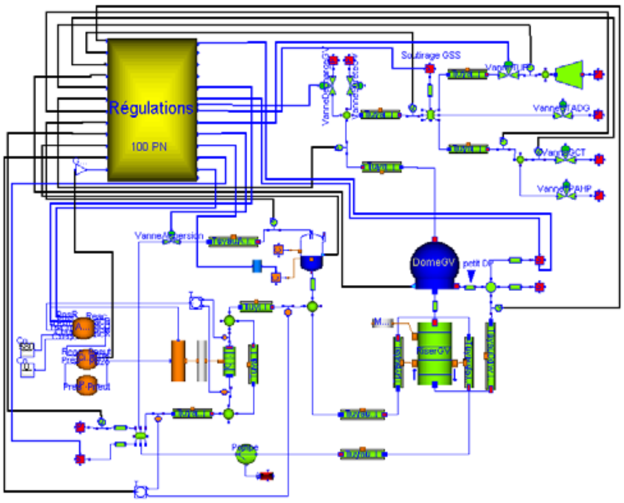

Figure 1: EDF 1300 MW Pressurised Water Reactor Modelica Model (P4)

2.3 Physics of the model

Fluid flow in pipes

A generic component has been developed. It can be used for different parts of the plant, either for the primary or the secondary loop. This model describes the behavior of a single phase fluid flow in one or several parallel conduits, where heat exchange can occur between the fluid and the internal metallic pipe wall, and between the external pipe wall and the outside environment. It is well adapted for the representation of connection circuits between the different equipments of the plant. Two-phase flow is only valid in the case of low vapor fraction, for no two-phase flow correlation has been implemented yet.

The model is based on mass, momentum and energy conservation equations, as 1-dimensionnal, partial differential equations. Discretization is performed along the main flow direction. The momentum conservation equation includes compressibility terms, while fluid inertia and acceleration terms can be neglected as an option. Radial heat transfer in the pipe metallic wall is not discretized (single radial cell), and longitudinal conduction of heat is neglected in the fluid flow and in the wall. As mentioned earlier, like other components of the EDF Thermofluid library, a finite volume approach is used, based on the staggered grid scheme for space disretization, to ensure a better stability of the numerical scheme. Two types of cells are defined: “edges”, which solve momentum equations, and “nodes”, which solve mass and energy equations for the fluid, with heat transfer conduction equations in the metallic pipe wall.

The Dittus-Boelter correlation is used for the heat transfer coefficient between the fluid and the wall.

The pressurizer

The role of the pressurizer is to maintain the primary water pressure at a fixed level, in order to avoid vaporization within the primary loop. This is done by ensuring that the liquid and vapour states are always present in the pressurizer, so the pressure inside the pressurizer (and hence inside the primary loop) can be controlled by acting on the water temperature in the pressurizer. To do so, the equilibrium between water and steam is maintained in the pressurizer at the saturation temperature corresponding to the pressure setpoint by heating or cooling the water in the pressurizer. Heating is achieved by the electric heaters immersed in water, and cooling is achieved by condensing the steam by aspersion of water extracted from the primary loop.

So, there are two separate regions in the pressurizer: a liquid region and a vapor region. The physical model is based on a non-equilibrium formulation of the fluid balance equations for each region. The mathematical model is based on the mass and energy balance equations for the liquid and the vapor, plus a heat balance equation at the pressurizer wall, taking into account the heat exchange between the wall and the liquid, and between the wall and the vapor. Two closure equations are used for the evaporation and the condensation flow rates at the interface between the liquid and the vapor regions. The evaporation flow rate is related to the connected enthalpies (liquid and liquid and vapor at saturation conditions). The condensation flow rate is related to the connected enthalpies (vapor and liquid and vapor at saturation), to the heat exchanges wall/vapor and wall/liquid, and to the conditions of aspersion (flow rate and enthalpy). These two closure equations also use empirical coefficients, related to the bubble rising time in the liquid and the droplet falling time in the vapor. Water and steam properties are computed from the IAPWS'97 formulations.

The turbine

The model is based on the Stodola law, which relates the flow rate through the turbine to the vapor conditions at the turbine inlet and outlet.

The valves

The model can represent the different types of valves to be found in the PWR plant. It calculates the flow rate through the valve as a function of the upstream and downstream pressure, the upstream enthalpy and the geometrical characteristics of the valve itself. It can represent a single phase (liquid or vapor) or two-phase flow. Special attention was given to the verification of the continuity between the different flow regimes. To that end, a non dimensional parameter analysis was used.

Pump and motor

The centrifugal pump model is based on the characteristic curves of the primary loop pumps in PWR type plants. No mass accumulation inside the pump is taken into account. Metal heat capacity and heat exchange with the outside are neglected. The mathematical model is based on the equation of variation of internal energy of the system, taking into account the mechanical power dissipation that heats the water flowing through the pump. Algebraic equations are also used. The first one is the relation between the rotational kinetics energy of the pump and the shaft speed, and the second is the energy balance of the fluid between the inlet and the outlet of the pump. The pump model is powered by an electric motor model.

The steam generator (SG)

The steam generator is a key component for the operation and the safety of the plant, because it is responsible for the cooling of the reactor.

The primary water flows into U-tubes and yields its heat to the secondary water. The secondary water, circulating outside the U-tubes, is liquid at the inlet of the SG, then flows down the outer part of the SG and starts to boil when reaching the bottom centre part of the SG, until the top of the boiling section. There, the ratio between the total flow rate and steam flow rate (circulation rate) reaches a value of 4 to 5 at nominal power. This part of the SG is called the riser, where the flow is mainly two-phase (a mixture of water and steam). Moreover, due to the non homogeneity of heat exchange inside the riser, two regions must be considered. When secondary water is flowing outside the first half part of U-tubes with hot primary water flowing in, the region is called "hot leg". When flowing outside the other half part of U-tubes with cooler primary water flowing in, the regions is called "cold leg".

The water and steam mixture passes then through separators where the two phases are separated in the upper part of the SG. The liquid part goes back to the SG feedwater, and the vapour part goes to the turbine. This part of the SG is called the dome.

The SG model has two different parts: the riser and the dome. Dedicated components have been developed because of the complexity of the flow, and the specificity of the geometrical characteristics of this type of heat exchanger.

The SG riser

The basic equations for this model are the same as the ones in the fluid flow model in pipes component described earlier. Options have been added to meet the specific needs of the riser:

- possibility to take into account two types of heat exchange for one cell of flow (one for the "hot leg" region, one for the "cold leg region"),
- implementation of a heat transfer correlation adapted to two-phase boiling flow for heat transfer coefficient (Thom correlation [3]).

The SG dome

As there are two separate regions in the SG dome (water and vapor), the basic equations for this component are the same as the ones modelling the pressurizer described earlier. The basic equations are the same for each phase. Evaporation and condensation flow rates are used as closure laws. Two equations have been added to calculate the flow rate entering the dome (pressure drop due to the separators between the riser and the dome), and the pressure at the entrance of the SG (the altitude of the entrance is lower than the dome, so there is a pressure drop due to gravity).

Neutronic kinetics

The model calculates the neutronic power generated in the fuel, as a function of the total reactivity of the core due to the coolant density effect, the fuel Doppler effect and the effect of boron concentration. It is a point reactor kinetics balance equation that describes the evolution of a neutron population, including the effect of precursors concentration leading to delayed neutron sources.

3 Simulation

3.1 Validation of the model

The reference benchmark test for this model is a house load operation. It is a high amplitude transient, that occurs when the plant is suddenly disconnected from the normal energy discharge network. This transient is used to check both the global operation of the reactor with the control system in operation, and the physics taken into account in the model.

The transient starts with neutronic and thermal hydraulic parameters set at values corresponding to the full power operating conditions of the plant. This means that before starting the transient, a stable regime must be reached at nominal conditions. To do so, the initial state for the model is calculated by (1) setting all the time derivatives to zero (simulation must start from steady state) (2) performing inverse calculations in order to adjust the parameter values to start the simulation from the nominal conditions.

The transient scenario is the following:

- At t = 0, the plant is disconnected from the grid by opening manually the electric circuit breaker. The turbine control system then closes the Turbine Admission Valve in about 1 minute. This leads to a vapor pressure rise, and consequently the opening of the bypass turbine condenser group valves.
- During the first minute, the nuclear power decreases rapidly, because of the insertion of the control rods in the core. During this phase, the pressure, water level and temperature of the primary loop show sudden rises due to the momentary deficit of the secondary load, then the thermal power balance between the primary and secondary loops is restored through the steam generator.
- After about 1 minute, the temperature control system leads to a stabilization, then a partial extraction of the temperature control rods. This slows down the decreasing rate of nuclear power, which stabilizes at about 30% of nominal power at the end of the transient. This value is reached in about 10 minutes, which is the time needed for the control rods to hit their setpoint.

3.2 Results of dynamic simulation

In order to cover the whole transient, the simulation time has been set at 2000 seconds.

The model has 7000 unknowns and 320 states.

The computing time is 600 seconds with a fixed time step solver, about 3 times faster than real time. Calculations were performed on a Pentium 4, 2.4 Ghz, with 512 Mo of CPU memory.

In order to reach this computing time, adjustments of phenomenological time parameters describing the actuators dynamics have been necessary. Also, numerical difficulties have been encountered due to the computing of the control rods insertion. Rods are inserted step by step. It is a discontinuous process controlled with hysteresis that trigger frequent threshold crossings. The number of resulting event detections to be computed turned out to be very large, leading to unacceptable computing time with the variable time step solver DASSL. This is why implicit fixed time step solver had to be used, in order to decrease the computing time of state event detection to acceptable level.

A previous validation of the model was made with the LEDA code against on-site experiments and transient recordings. Since the physical modelling is very close to the one implemented in the LEDA model, validation of the equivalent Modelica model was performed on the basis of the results obtained with LEDA. The following figures show the evolution of the main variables of the model versus time (in seconds); dotted lines are for LEDA simulation results and continuous lines for Modelica simulation results.

Figures 2 and 3 show the position of the control rods in the core. The two groups are inserted first, then the temperature control group is extracted again when the nuclear power has sufficiently decreased, trying to compensate for the primary loop mean temperature decrease (see also Figure 4 and 6).

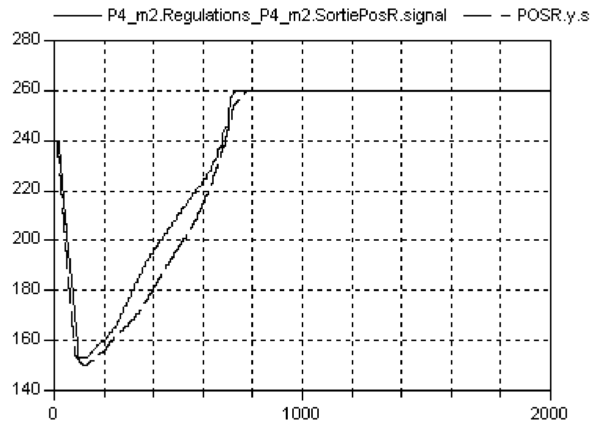

Figure 2: Position of Temperature control rods

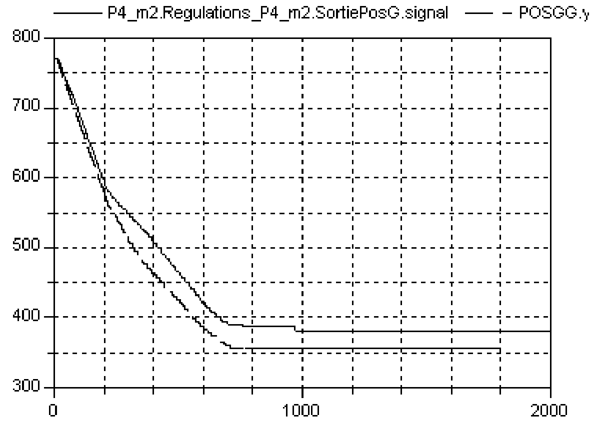

Figure 3: Position of Power control rods

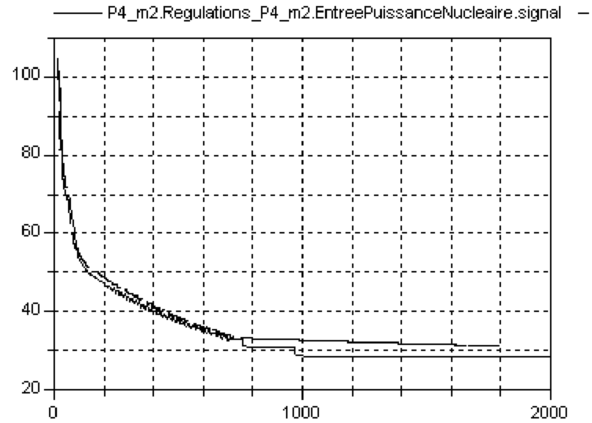

Figure 4: Nuclear Power

Figure 5 shows the evolution of the position of the bypass turbine condenser group valves, that open at the beginning of the transient, just after the closing of the turbine valve.

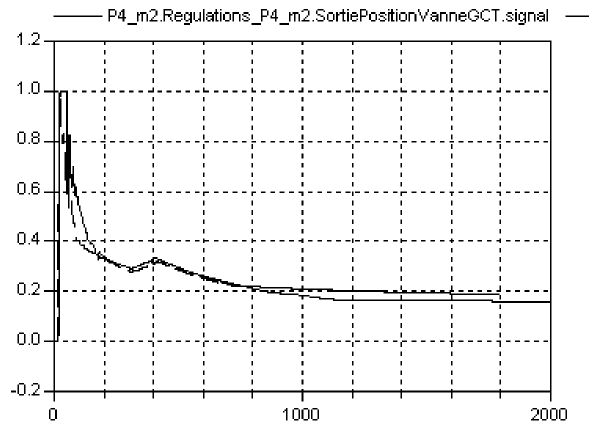

Figure 5: Position of by pass turbine condensers group valves

As previously written, the primary loop pressure and temperature exhibit a sharp rise at the start of the transient, due to the deficit of secondary load. Figure 6 shows the primary loop mean temperature peak. However, if the overall dynamic evolution is correct, there is a noticeable difference between the maximum temperature calculated with LEDA and the one given by the Modelica model.

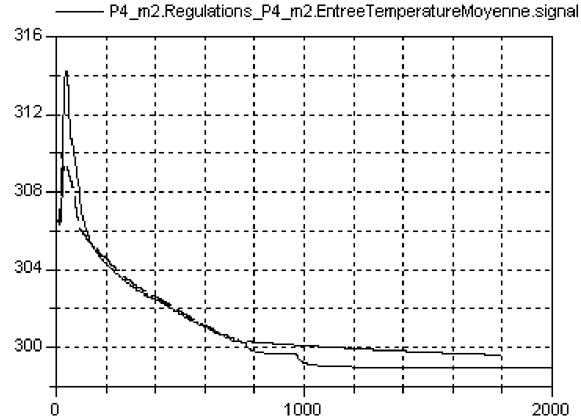

Figure 6: Primary loop mean temperature

The SG level is an important variable of the secondary loop, which is taken into account in the control and safety systems of the plant. The shrink and swell phenomenon is a variation of the water level in a two-phase fluid container, that occurs after a sudden change in vapor pressure or flow rate entering the container. This phenomenon is encountered in the SG, and must therefore be described by the model. As shown in Figure 7, the first shrink of water level in the SG is simulated, followed by a swelling of the water level before stabilization.

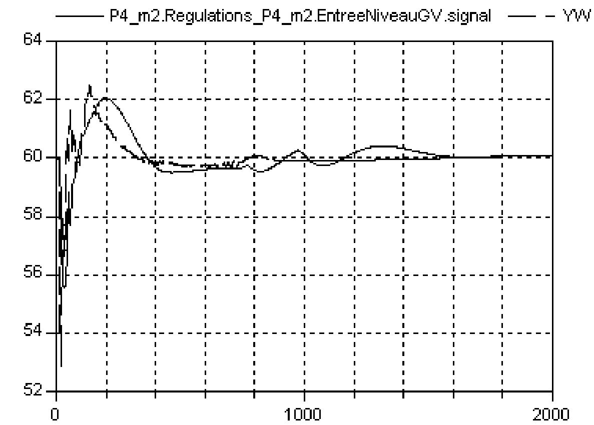

Figure 7: Water level in the Steam Generator

These results show that the dynamic response of the plant process and control system modelled with Modelica is quite satisfactory. However, a more complete validation of the model is needed, with a better (optimised) adjustment of the model parameters.

There are noticeable differences between the Modelica and the LEDA model. The LEDA model has a 1D neutronic model that takes into account the non homogeneity of nuclear power in the core, whereas the Modelica model has a simple point neutronic model. Figure 2 and 3 also show differences between the control rod positions, which may be due to differences in the control rod calibrations.

These modelling approach differences could explain the discrepancies observed in the simulation results from the two models.

4 Conclusions

A full model of a PWR 1300 MWe plant has been translated from LEDA to Modelica. It is a large dynamic model, that exhibits numerical difficulties due to the large number of states, and the step-by-step discontinuous operation of the control rods that lead to frequent state events.

Computing time has been reduced to an acceptable level by using an implicit fixed time step solver instead of the variable time step solver DASSL.

It would probably be possible to reduce computing time even more by a thorough analysis of the model equations, but due to the large number of equations, this is a difficult task. So further development of Modelica based tools should address the methodology issue of modelling large dynamic systems by e.g. giving to the user the possibility to perform incremental model development and analysis.

However, this study shows that it is possible to perform dynamic simulations of a PWR plant with Modelica. The next step will be to test the coupling of such a Modelica model with an existing non-Modelica code (e.g. neutronics code).

References

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