Modelling of a water/steam cycle of the combined cycle power plant “Rio Bravo 2” with Modelica

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Abstract

In order to improve the performance of its simulation tools while reducing their cost, EDF is studying the interest and feasibility to replace LEDA, a tool developed and maintained by EDF for the modelling and simulation of the normal or incidental operation of nuclear and conventional thermal plants, by off-the-shelf available tools.

The combined cycle power plant “Rio Bravo 2” covers the important case of static studies. To test the capabilities of Modelica based tools to meet EDF needs for the modelling and simulation of such complex energy processes, the LEDA model of Rio Bravo 2 was translated from Fortran into Modelica and simulated using the commercial tool Dymola.

A library of fully static 0D thermalhydraulics component models was built. Each component is the complete translation of a LEDA model.

The full model was built by connecting the component models in a technological way, so that its topology reflects the functional schema of the plant.

A preliminary calibration of the model was made against measurement data obtained from on-site sensors using inverse calculations. The model was then able to compute precisely the distribution of the steam/water mass flow rates, pressure and temperature across the network, the exchangers thermal power, and the performance parameters of all the equipments. It converges very quickly, provided that the iteration variables are properly fed in by the user. The results are remarkably close to the LEDA reference.

Keywords : Combined Cycle Power Plant, Steady State Modelling, Inverse Problems

1. Introduction

Modelling and simulation play a key role in the design phase and performance optimization of complex energy processes.

Rio Bravo is a combined cycle plant designed, built, commissioned and operated by EDF. A model of the plant was built at the system level in order to verify and validate by simulation the energy and fuel consumption overall performance of the plant.

The modelling and simulation of the plant was originally carried out with LEDA. LEDA is a tool developed and maintained by EDF since 1982 for the modelling and simulation of the normal or incidental operation of nuclear and conventional thermal plants. LEDA models are used by researchers and engineers to improve their knowledge of existing or future types of power plants, verify the design accuracy and understand important transients.

In order to improve the performance of its simulation tools while reducing their cost, EDF (SEPTEN and EDF R&D) is studying the interest and feasibility to replace LEDA by off-the-shelf available tools.

Modelica based tools are considered as good candidates, because :

- Modelica is a multi-domain language which seems well designed for physical system modelling and simulation.
- Modelica is a declarative language, that captures the model equations in a way that is very close to their original mathematical form.
- Modelica allows to express inverse problems, which is a very important feature for computing operation points, which are defined by their observable outputs, and for system

sizing, to compute parameterised characteristics.

Besides these technical benefits, it is likely that using a common free non proprietary language will foster partnerships around joint R&D or engineering projects, thus giving the opportunities to share development costs between the participants.

Several important benchmark cases have been chosen, which cover the variety of modelling and simulation studies made at EDF [1].

The objective of this work is to evaluate the feasibility and efficiency of using Modelica based tools to perform steady state studies of power plants.

The Rio Bravo combined cycle plant has been chosen as a representative test case of the complexity of this type of study, aimed at verifying the design of the plant for a fixed set of operation points (nominal power output, 50 % of nominal power output, …).

The modelling and simulation were carried out with the commercial tool Dymola, as it is the most advanced Modelica based tool to this date.

2. The LEDA Solver

LEDA is a tool that was originally designed for the modelling and simulation of power plants. To that end, it allows the user to develop numerical components of the different parts of the plant, and assemble them to build the full model of the plant. Thus LEDA is a model library based tool. The component models are written in Fortran. They represent the various equipments of the plant (pumps, heat exchangers, …), and may be re-used across different projects.

Since LEDA has already been used by EDF over two decades, it offers the best available physical descriptions, for each improvement - correlations obtained from experimental results or 3D computations - is capitalized into the library.

As the initial state of the simulation is in general defined by the observable outputs of the system (e.g. the nominal power output, the pressure inside the boiler, etc.), it is necessary to solve an inverse problem to compute the initial state. Moreover, it is necessary to start the simulation from a stationary (or steady) state in order to avoid the numerical difficulties which arise when the system is started out of equilibrium (oscillations, stiffness, …).

That is why LEDA has the ability to start the simulation from a stationary state, and compute this initial state by solving an inverse problem (it is in fact a requirement from to the tool to start from a steady state). It is also possible to feed in the analytical Jacobian of the system to improve the speed and the accuracy of the simulation. LEDA uses a trapezoidal implicit fixed step integrator.

The inverse problem is entered into the tool by setting the output variables to their known measured values, and freeing (i.e. setting as unknowns) the parameters, inputs and internal states to be computed.

Figure 1 below shows the structure of a LEDA component model.

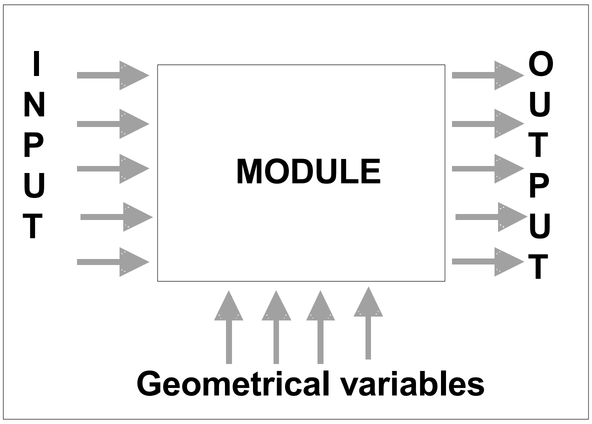

Figure 1 – Structure of a LEDA component model

The component model (also called module) is a series of Fortran files that contain the physical equations and the correlations of the modelled component. It is oriented, i.e. has computationally causal links. Geometrical variables are constant parameters (they would be referred with the Constant Modelica keyword in Modelica models). Parameters are considered as inputs, in order to be able to compute them by inverse calculation. More generally, all variables are either inputs or outputs, which means that the connections between the component models have to be carefully set in order to solve the simulation problem : outputs are always computed from inputs, so the user has to figure out the computational causalities of the problem at hand while building the model.

LEDA assembles the components in a way to produce a global matrix of the system. So the system is solved in a implicit way, not in a sequential way, in particular to solve algebraic loops and perform inverse calculations.

Application fields

- Nuclear power plants.
- Thermal fossil fuel fired power plants (pulverized coal, fluidized bed, ...).
- Combined heat and power plants.

- Waste to energy.

Utilization fields

- Operation and maintenance.
- Design and analysis.
- Innovate technology survey.

3. General presentation of a combined cycle power plant

The combined cycle includes a turbine cycle (gas turbine, which uses natural gas as fuel) and a steam cycle.

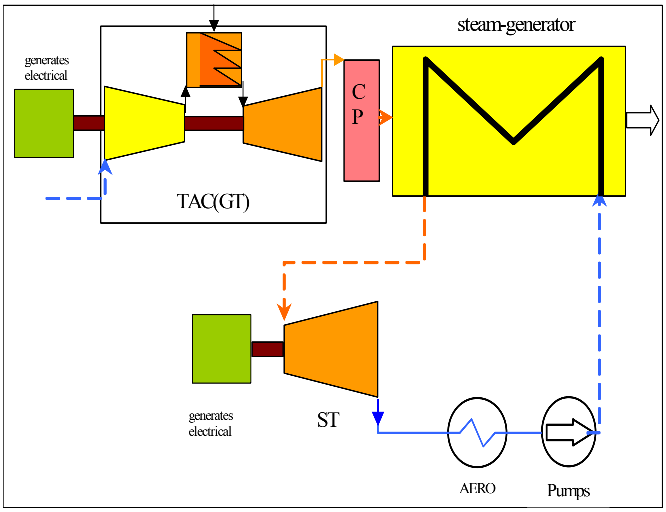

Figure 2 - Diagram of a Combined Cycle Power Plant

In the turbine cycle, air is compressed to the operating pressure of the gas turbine and heated in a combustion chamber (natural gas is burned in), followed by an expansion of the exit flue gas in a gas turbine, which in turn generates electrical energy in a turbo-generator.

The hot effluent of the gas turbine generates steam in the steam-generator of the steam cycle, which expands in the steam turbine and generates additional electrical energy. The steam cycle includes : the steam turbine, a boiler (with several tubular exchangers that transmits the heat of the exhaust gas to the water), 3 evaporating loops (low, medium and high pressure), an aero-condenser and several pumps.

4. The Rio Bravo component model library

As it has already been mentioned, Rio Bravo is a fully static model. Thus, a library of fully static 0D thermalhydraulics component models was built. Each component is the complete translation of a LEDA module. The library now contains models of a multifunctional heater (economizer, super-heater, evaporator), a turbine, pumps, a separating balloon, valves, an aero-condenser and pipes.

The model equations take into account the non-linear and the state-of-the-art physical behaviour of each phenomenon of interest. In particular :

- The multifunctional heater component model contains precise and up-to-date correlations for the heat exchange coefficients and pressure losses. Convection and pressure loss correlations are valid for any flue gas composition, and for water in any phase (liquid, vapour or two-phase flow). The conduction equation is adapted with a fouling coefficient. To feed these equations, each model contains a very accurate set of geometrical data (technology, number of tubes, lengths, diameters, characteristic of the wings, etc).
- The steam turbine component model is based on an ellipse law and an isentropic efficiency.
- The aero-condenser component model is based on correlations of the manufacturer.
- The pump models are based on the characteristic curves of the pumps.
- The collector is based on the mass and energy balances for the fluid.
- The pressure drop in pipes is proportional to the dynamic pressure ± the static pressure.

The Modelica translation required some reverse engineering of the component models, because :

- the LEDA components are Fortran codes, containing many procedural if … then … else constructs that cannot be written as such in Modelica,
- the LEDA documentation is sometimes incomplete.

Each new Modelica component had to be tested separately in order to remove as many modelling errors as possible before building the full Rio Bravo model. This task was not easy, as a model written in a declarative language has a totally different structure from a model written in a procedural language, so the LEDA experience was no great help.

In spite of these difficulties, it was possible to rewrite the complete LEDA modules in Modelica. The new Modelica component models behave exactly as their LEDA originals.

5. The Rio Bravo model

The full model is built by connecting the component models in a technological way, so that its topology reflects the functional schema of the plant (see Figure 3 in the appendix). It is composed of 91 component models, generating 5200 variables and 1100 non-trivial equations.

The model consists of 16 exchangers (3 evaporators, 6 economizers, 5 super-heaters and 2 re-heaters), 3 balloons, 3 steam turbine stages (HP, IP and LP), 6 pumps, 3 valves, 1 kettle boiler, 9 pressure drops, several mixers, several collectors, 1 power imposed and 1 aero-condenser.

The order of the exchangers downstream the exhaust gas flow is :

- the third HP super-heater,
- the second IP re-heater,
- the second HP super-heater,
- the first IP re-heater,
- the first HP super-heater,
- the HP evaporator,
- the fourth HP economizer,
- the IP super-heater,
- the third HP economizer,
- the LP super-heater,
- the second HP economizer,
- the IP evaporator,
- the first HP economizer and IP economizer,
- the LP evaporator,
- the LP economizer.

The low pressure loop

At the exit of the aero-condenser, water is pumped and heated in the LP economizer, then is sent to the LP balloon. The water leaving the LP balloon goes to the LP evaporator, the IP loop and to the HP loop. The produced steam is transmitted to the LP super-heater, then to a mixer with a pressure loss, then to the LP turbine. The steam at exit of the mixer is a mixture of the steam at the exit of the LP balloon, the steam at the exit of the IP turbine and the steam of racking at the HP turbine exit.

The intermediate pressure loop

At the exit of the LP economizer, water is pumped and heated in the IP economizer, then is sent to the IP balloon. The water leaving the IP balloon goes to the IP evaporator and the produced steam is transmitted to the IP super-heater, then to a mixer (to mix the steam at the exit of the IP super heater and the steam at exit of the HP turbine), then is sent to the first IP re-heater, then to the IP de-superheating, then to the second IP re-heater, then to the IP turbine.

The high pressure loop

At the exit of the LP economizer, water is pumped and heated in the first, the second, the third and the fourth HP economizer, then is sent to the HP balloon. The water leaving the HP balloon goes to the HP evaporator. The produced steam is transmitted to the first HP super-heater, then to the second HP super-heater, then to the HP de-superheating, then to the third HP super-heater, then to the HP turbine.

The aero-condenser

At the exit of the turbine LP, the steam is condensed in the aero-condenser, then the water is pumped and sent into the LP economizer.

The steam bleeding

Steam bleeding at the entry and the exit of the HP turbine is necessary to ensure the tightness of the bearing of the IP and LP turbines.

The model was easy to build from the graphical library : as opposed to LEDA, no causality analysis is required from the user, this task being handled automatically by the code generator.

But it was initially difficult to converge, because of the lack of information about the iteration variables chosen by the code generator (iteration variables are variables that need to be properly initialised by the user in order to compute the system equations for the first time step). Once this information was correctly provided by the tool, it was fairly easy to make the model converge. This task, which is equivalent to computing the initial state, would even be easier if the set of iteration variables were stable across moderate model changes, and, of course, from one version of the tool to another.

So it is very important to provide an efficient way to handle these iteration variables, as the task of setting them properly is time consuming. It is also by no way automatic, since it requires a good expertise of the problem to be solved (the number of iteration accounts roughly 5% of the total number of variables, so can be rather large for a human).

More generally, as the numerical structure of the system equations is automatically generated, it is necessary that the tool provides an efficient way to trace the numerical system back to the original mathematical equations.

6. Model calibration

The calibration phase consists in setting (blocking) the maximum number of thermodynamic variables to known measurement values (enthalpy, pressure), taken from on-site sensors during performance tests. This method ensures that all needed performance parameters, size characteristics and output data can be computed.

The main computed performance parameters are :

- the fouling coefficients of the exchangers,
- the ellipse law coefficients of the turbines,
- the isentropic efficiencies of the turbines,
- the pressure drop corrective coefficients of the exchangers and of the pipeline between the equipments.

Example : the pressure of the vacuum in the aero-condenser or the flow rate of the circulating cooling are computed from the available measurements.

7. The thermodynamic properties

Properties of fumes

The thermo-physical properties of the fumes (for the exchangers, the aero-condenser and the collectors) were computed using Fortran tables called MONOMELD, which are normally used with LEDA. Using the same tables for both tools facilitated the comparison of the simulation results.

Properties of water and steam

The properties for water and steam were computed from polynomials defined by the international standard IAPWS-IF97. The efficient original Modelica implementation of H. Tummescheit was used. LEDA utilizes a variant of this standard implemented as a look-up table.

8. The simulation results

A preliminary calibration of the model was made against measurement data obtained from on-site sensors. The model was then able to compute precisely the distribution of water and steam mass flow rates, pressure and temperature across the network, the exchangers thermal power, and the performance parameters of all the equipments. It converges very quickly, provided that the iteration variables (approx. 5 % of the total number of variables) are properly fed in by the user.

The table below shows the differences between the LEDA and the Dymola numerical computation results, for the reference conditions (i.e. 100% nominal power – natural gas – yearly average conditions).

Table 1 - Differences between the results of LEDA and DYMOLA

	LEDA	DYMOLA	Δ
Electric power output (MWe)	177,33	177,42	-0,09
Pressure in HP balloon (bar)	135,0	134,0	1
Output steam flow at HP balloon (kg/s)	52,67	52,31	0,36
Output steam temperature at HP balloon (°C)	561,1	566,6	-5,5
Pressure in IP balloon (bar)	31,8	31,8	0,0
Output steam flow at IP balloon (kg/s)	8,84	9,08	-0,24
Output steam temperature at IP balloon (°C)	310,6	310,9	-0,24
Pressure in LP balloon (bar)	5,11	5,17	-0,06
Output steam flow at LP balloon (kg/s)	77.27	77.37	0.1
Output steam temperature at LP balloon (°C)	180.75	180.13	-0.3
Power exchanged in the aero-condenser (Mw)	357.80	357.91	0.03
Temperature of the exhaust fumes of the boiler (°C)	113 .95	113.8	-0.13

The slight differences between the results of the two codes are due to the fact that the thermodynamic properties of water and steam are computed in different ways (as noted before, LEDA uses a variant of the IF97 standard).

The robustness of the model for different operating points was tested by varying the flow of the fumes in the range from 250 to 700 kg/s (250, 300, 350, 400, **464.48**, 500, 550, 600, 650, 700).

9. Conclusion

A static and rather large model of the Rio Bravo power plant has been translated from LEDA to Modelica with Dymola to evaluate the capacity of

Modelica based tools to perform steady state direct and inverse computations for the sizing of power plants.

The translation has been done without any loss of information from the original model, and at an acceptable, though still high cost.

To even further reduce the effort required to do Modelica modelling and simulation for such systems, it is necessary to provide more advanced tool functionalities to handle efficiently the iterations variables, and trace the automatically generated numerical system back to its original mathematical equations, as declared by the user with the Modelica language.

Nevertheless, this work shows that the Modelica technology is mature enough to replace proprietary solutions such as LEDA for the steady state modelling and simulation of power plants.

References

[1] Avenas C. *et al*. Quasi-2D steam generator modelling with Modelica. ISC'2004, Malaga, Spain.

Appendix

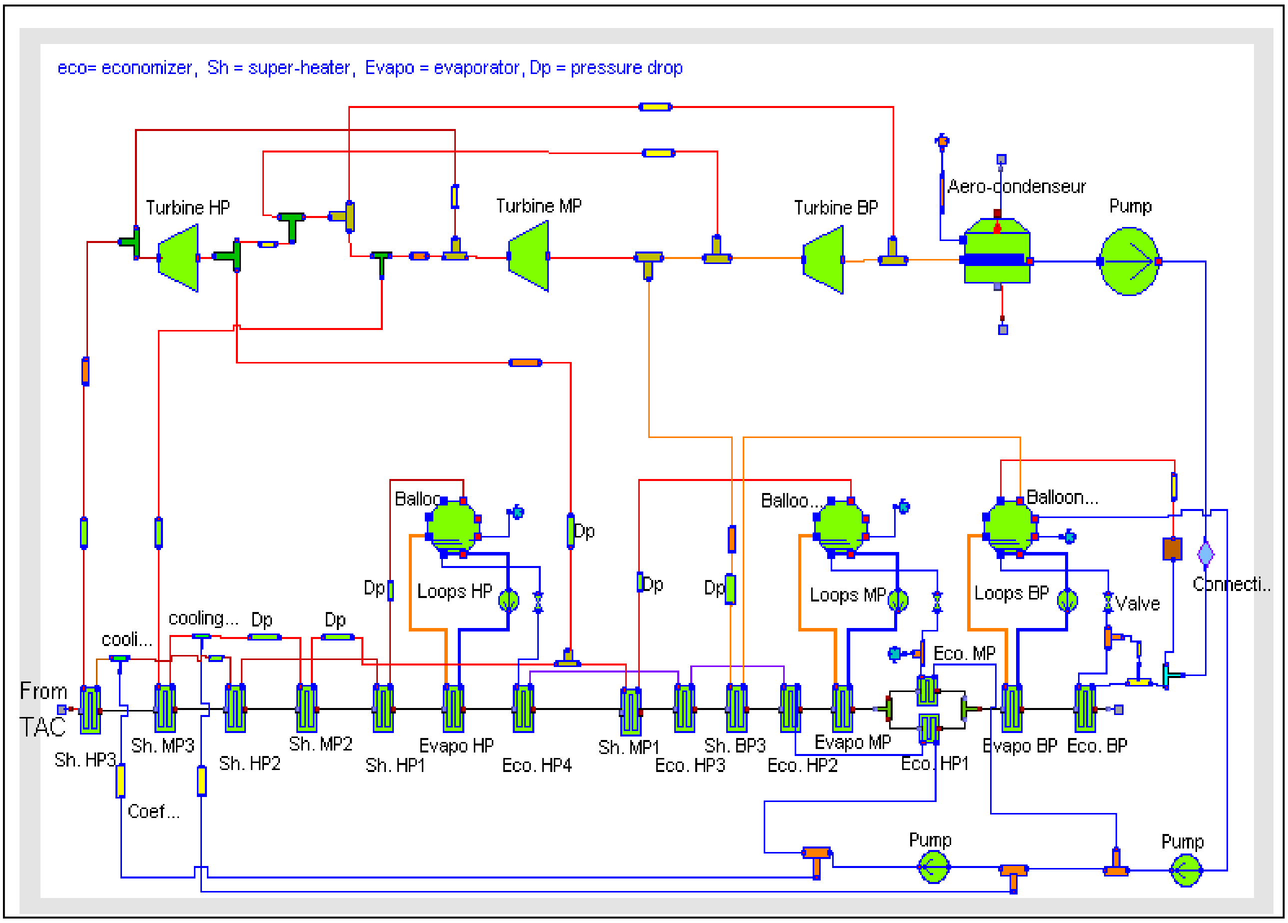

Figure 3 - The Rio Bravo Modelica model