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Multiphysics analysis of power transients based on power system and nuclear dynamics software chaining

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Abstract—In the framework of energy transition, the massive insertion of Variable Renewable Energies leads to think to new ways of controlling and stabilizing electrical networks. Small Modular Reactors (SMRs) could be a sustainable solution if they are proven to be flexible enough. Previous studies have shown the positive influence of SMRs on grids at short-time scales due to inertia and frequency regulation phenomena. In addition, this article aims at studying the influence of constrained grid events on nuclear systems safety and operation. The models of a power system dynamics (PowerFactory) and a nuclear dynamics software (CATHARE) are compared and chained. Two application cases are carried out to quantify the impact and the relevance of this chaining: a short-circuit and a load loss. This article finally concludes that this chaining is relevant to accurately simulate nuclear reactor behavior following grid events. Moreover, a chaining could be insufficient for electrical simulations after severe events such as short-circuits or for high nuclear insertion's rate in an energy mix, a coupling, i.e co-simulation, could be considered.

Keywords – *Small Modular Reactor, Grid stability, Flexibility, Multiphysics coupling, chaining, Thermalhydraulics, Power system dynamics*

I. INTRODUCTION

Motivated by the reduction of anthropogenic greenhouse gases emissions, the current energy transition leads to an increasing part of variable electricity production sources (solar or wind farms) and to a decreasing part of fossil fuel production sources. However, the electrical power system stability is currently largely dependent on the fossil fuel abilities to be dispatchable and naturally designed to easily control the values ensuring the stability. Then, this trend to substitute fossil fuel plants for Variable Renewable Energy (VRE) plants might lead to a complete paradigm shift concerning the means to ensure grid stability.

Several non-nuclear technical solutions are under investigation by the electrical engineering international community (demand flexibility, power electronics, grid forming, energy storage, etc.). Besides these potential solutions, nuclear energy, which is dispatchable and carbon-free, may be a sustainable solution to this grid reliability issue if adequately designed and implemented on the grid. Among all the solutions aiming at improving the future nuclear power flexibility, an option is to consider Small Modular Reactors (SMR) which are intended to be more flexible than traditional Nuclear Power Plants (NPPs) [1, 2, 3]. This flexibility

improvement includes, among other things and according to [4], their easier integration with cogeneration applications, which may avoid or limit the power ramps supported by the core. In this case, the SMRs would operate in base mode, and adjust the electrical power delivered by bypassing the turbine towards secondary applications. This would enhance their availability and optimize their fuel life cycle. Besides, concerning the operational flexibility at the plant level, power capacities can be scaled by module by turning them on or off. This avoids intermediate power stages that is not ideal for the nuclear fuel because of the pellet-clad interaction [5].

The previous studies [2] and [4] showed that the presence of SMRs on the grid has a positive impact on the frequency stability. However, the future constrained and low inertia power systems could undergo more severe and more regular events that would impact the synchronous machines participating to the frequency regulation. Therefore, this could affect the hydraulic systems upstream of the turbine machines, potentially affecting their safety. That is why, the coupling of a power system dynamics software and a nuclear dynamics software appears as relevant to quantify the impact of grid severe events on nuclear reactors.

This paper firstly aims to present a brief literature review of the previous studies that have explored the coupling of those two fields, then to explain the different modelling approaches of the software specialized in each physics and in what way they can be complementary. This paper finally explains the assumptions made to simulate a short-circuit and a load loss event and presents the results of a one-way coupling application (also called chaining in this paper) for both physics fields.

II. LITERATURE REVIEW

A. Previous studies

As mentioned before, a previous work has been carried out with dynamical simulation by analyzing samples of random draws of location, part of SMRs in the electricity mix, maximum power ramp [2] and analyzing the electromechanical parameters of SMRs turbine machine [4]. It appears that the electrical and mechanical parameters of SMRs compared to large NPPs have a positive impact on the frequency stability related to inertia phenomena (time scale of seconds) and to a lesser extent in the frequency regulation time scale (around tens of seconds). In the opposite, enhancing the

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flexibility of nuclear power plants thanks to the SMR strategy that can be associated with other non electrical applications mainly have an impact on the frequency regulation time scale. Finally, the location of the SMRs has an impact in the short term linked to the inertia of the turbine-generator.

B. Different approach to couple nuclear and power system physics

Reference [6] shows a detailed list of the scope of the studies about the issues concerning the flexibility of SMRs. It goes from the mechanical and fatigue stress of high flexibility nuclear reactors to long-term financial and technico-economic studies. Reference [6] presents some studies (such as [7] and [8]) in which developed thermodynamic models of reactor are applied to cogeneration models in the idea of studying highly flexible reactors. But more importantly, this reference highlights that none of those studies have tried to integrate those models into electrical dynamical simulations.

That is why in [6] and [9], the same authors propose simplified models of neutron point kinetics, of thermal hydraulic equations for the hydraulic systems, steam generator and district heating. The authors incorporate those models in the dynamic simulation software PSS/E [10], similar to PowerFactory (PF), used in the current paper. Reference [6] finally applies his methodology to prove that coupling those two fields is interesting to quantify the needs of storage flexibility with flexible SMRs in short-time scale related to Frequency Regulation and Load-Following. However, this approach needs to develop and validate nuclear dynamics models inside the power system software, which is a long and unnecessary task when such a tool already exists separately and is already validated.

Then, this current paper adopts a similar approach to study the flexibility of SMRs at short-time scales but proposes a chaining with a nuclear dynamics software (CATHARE) that is validated for safety and operation analyses by the French safety authority [11] and allows to precisely study the impact of power systems issues on the nuclear reactors (PF).

III. COMPARISON OF THE MODELLING APPROACHES IN POWERFACTORY AND CATHARE

Fig. 1 shows the modelling of a power plant connected to a network in CATHARE (nuclear plant oriented software) and PowerFactory (power system oriented software). The role of the two following parts is not to detail exhaustively the calculation of dynamics simulations in power system physics

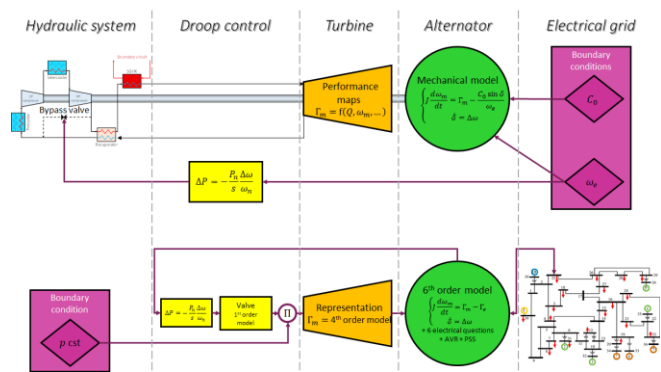


Fig. 1. CATHARE (up) and PowerFactory (down) modelling of a power plant connected to a grid

and thermohydraulic physics, but to show the main differences in the modelling choices.

A. PowerFactory models

Each box is explained hereafter:

- The network represents the buses and lines connecting them, in broad outline. The involved equations linking the currents I and the voltages V can be reduced into the nodal admittance matrix Y , as in (1), similar to the Ohm's law:

$$I = Y.V \quad (1)$$

- A synchronous generator can be modelled in several ways. The most common is a 6th order model [12] including two mechanical equations:

$$\begin{cases} \dot{\delta} = \Delta\omega \\ M\Delta\dot{\omega} = P_m - \underbrace{(E'_d I_d + E'_q I_q + (X'_d - X'_q) I_d I_q)}_{P_e} - D\Delta\omega \end{cases} \quad (2)$$

and four electrical equations representing the four windings taken into account in the model:

$$\begin{cases} T'_{d0} \dot{E}'_d = E_f - E'_d + I_d (X_d - X'_d) \\ T'_{q0} \dot{E}'_q = -E'_q - I_q (X_q - X'_q) \\ T''_{d0} \dot{E}''_d = E'_d - E''_d + I_d (X'_d - X''_d) \\ T''_{q0} \dot{E}''_q = E'_q - E''_q + I_q (X'_q - X''_q) \end{cases} \quad (3)$$

With the following notations:

- ($\dot{}$) temporal derivative
- ()' transient component
- ()'' subtransient component
- ()_d component relative to the direct axis (d-axis)
- ()_q component relative to the quadrature axis (q-axis)
- ()_f component relative to the field winding

and the following quantities:

- δ rotor angle (in rad)
- $\Delta\omega$ rotation speed deviation from the nominal rotation speed (in rad.s⁻¹)
- D asynchronous damping constant based on power (in per unit pu)
- E electromotive force (in pu)
- I current (in pu)
- M mechanical starting time (in s)
- J inertia moment (in kg.m²)
- P_m mechanical output power of the turbine (in pu)
- P_e electrical power of the alternator (in pu)
- R_s stator winding resistance (in pu)
- T₀ open-circuit time constant (in s)
- X reactance (in pu).

- The turbine is a part of the governor model. A standard model to represent a steam turbine and its droop speed control is the IEEE1 governor. This model is regularly used for large interconnected grids with small frequency deviations [13]. This model is shown in Fig. 1. The turbine part of this governor is represented by a 4th order system with the turbine mechanical power as an output.
- The droop speed control is the correcting controller which changes the turbine setpoint power depending on the frequency deviation. This part is represented in the IEEE1 governor (and in Fig. 2) by a droop, a lead-lag compensator and a first order system of the inlet turbine valve.
- In the IEEE1 governor, the hydraulic circuit upstream from the turbine is only represented by a boundary condition at constant pressure. Other models of this governor exist, modelling all the circuits (as the TGOV5 governor [13]) but knowing and fitting the right parameters is a complex task.
- Other systems are included in the turbine-alternator dynamics calculation such as the AVR (Automatic Voltage Regulator) and the PSS (Power System Stabilizer) which are respectively the field winding voltage regulation and the inter-area damping system (to avoid low frequency power oscillations between synchronous machines through the grid).

Finally, the models from the alternator to the network are very detailed and precise, thus a great confidence is placed in them. However, the governor model including the hydraulic circuit, the droop speed control and the turbine is very simplified and no feedback can be deduced by nuclear reactor designers concerning safety and operation issues.

B. CATHARE models

The following description of CATHARE is mainly extracted from [14]. CATHARE has a flexible modular structure for the thermal-hydraulic modeling in applications ranging from simple experimental test facilities to large and complex installations like Nuclear Power Plants (NPPs). The main hydraulic components or elements are pipes (1D), volumes (0D), a 3D vessel and boundary conditions, connected to each other by junctions. Other sub-modules feature pumps and turbo-machines, control valves, T-junctions, sinks and sources, breaks and many other ones. All CATHARE modules are based on a six-equation two-fluid model (mass, energy and momentum equations for each phase), with additional optional equations for non-condensable gases and radio-chemical components. A scheme of the links between the CATHARE models involved in a NPP

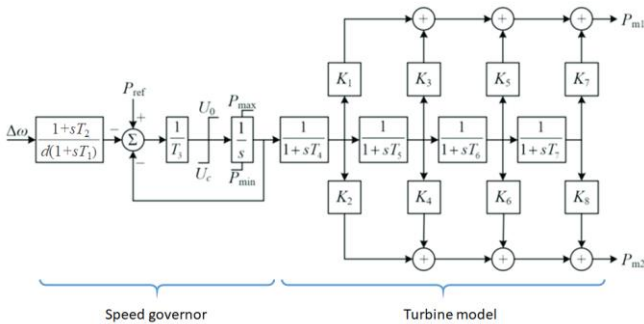


Fig. 2. IEEE1 governor

connected to the grid by a turbine is presented in Fig. 1. Each box is explained hereafter:

- The electrical network is only represented by two boundary conditions: a load power C_0 and a synchronism frequency ω_e .
- The alternator connected to a large grid is modelled by two mechanical equations, similar to (2) :

$$\begin{cases} \dot{\delta} = \Delta\omega \\ M\Delta\dot{\omega} = P_m - \frac{C_0 \sin \delta}{P_e} - D\Delta\omega \end{cases} \quad (4)$$

- The model of a turbomachine in CATHARE is characterized by performance maps produced with Computational Fluid Dynamics (CFD) calculations or experiments. Those performance maps link operating features (flowrate Q and rotating speed Ω) to the induced quantities such as the pressure ratio Π and the isentropic ratio η allowing to calculate the mechanical power such as:

$$P_m = C_p T \cdot \eta \left[1 - \frac{1}{\Pi} \right]^{\frac{\gamma-1}{\gamma}} \quad (5)$$

With:

Q mass flowrate (in $\text{kg}\cdot\text{s}^{-1}$)

C_p specific heat capacity at constant pressure (in $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)

T inlet temperature (in K)

- The droop speed control that can be simply implemented by changing the setpoint of the valve controller mastering the turbine power. The power difference ΔP is:

$$\Delta P = -\frac{P_n}{d} \cdot \frac{\Delta\omega}{\omega_n} \quad (6)$$

With:

P_n nominal power (in W)

d droop (in %)

ω_n nominal rotation speed (in $\text{rad}\cdot\text{s}^{-1}$)

- The hydraulic circuit that is represented by pipes, volumes, heat exchangers, head losses, etc. as explained in the previous paragraph describing CATHARE.

Finally, the models including the thermal-hydraulic physics are trustworthy, while the modelling of the alternator and its boundary conditions is too simplified to study the impact of transients coming from the network on the nuclear facilities.

C. Chaining the two codes

To sum up, both codes have their specificities and high degree of modelling on different parts. To ideally represent the impact of transient on NPPs, a coupling of the hydraulic, droop and turbine parts of CATHARE with the alternator and electrical network parts of PowerFactory is relevant. The first easier step is yet to set up a chaining from PF to CATHARE.

Indeed, when operating, NPPs are said being in “core-follow-turbine” mode, meaning that the grid disturbances drive the reactor. Before launching a chained simulation, we need to define which generator is coupled. The values of nominal power, operating power, nominal rotation speed and turbomachine inertia have to be manually set equal in both codes. After this manual check step, the chaining first launches a full dynamics simulation of a selected transient, then exports the results of the electrical torque, rotor rotation speed, synchronism rotation speed and rotor angle at each time step. Those quantities then feed the calculations of CATHARE that interpolates the torque and speeds at each of its own time steps. The CATHARE’s alternator model and its boundary conditions are disabled during the chaining, meaning that (4) is blinded. Those explanations are schematically represented in Fig. 3.

IV. APPLICATION CASE

A. Input data

1) *Power Conversion System (PCS)*: The chosen data set of hydraulic system in CATHARE is the PCS of the ASTRID reactor (sodium-cooled fast reactor) project that was lead by the CEA [15].

This data set had been approved by the CEA and its partners involved in the project but the references associated to its validity remain confidential. This PCS is relevant because the nominal alternator power is 300 MW, which remains in the SMR scope. This is a Brayton closed-cycle, meaning that the working fluid stays monophasic. The thermodynamic cycle includes:

- One heating at the Sodium-Gas Heat Exchanger (SGHX), itself heated by the nuclear core.
- One expansion (by two turbines in parallel)
- Two compressions (one at low pressure, then at high pressure)
- Two coolings and one recuperator.
- A bypass pipe from the outlet of the High Pressure (HP) compressor to the inlet of the precooler. The flowrate inside is controlled by a Proportional-Integral (PI) controller that finally leads to drive the turbine power.

A shaft links all the compressors, turbines and alternator. All the cooling and heating other sides are modelled by pressure, temperature and flowrate boundary conditions.

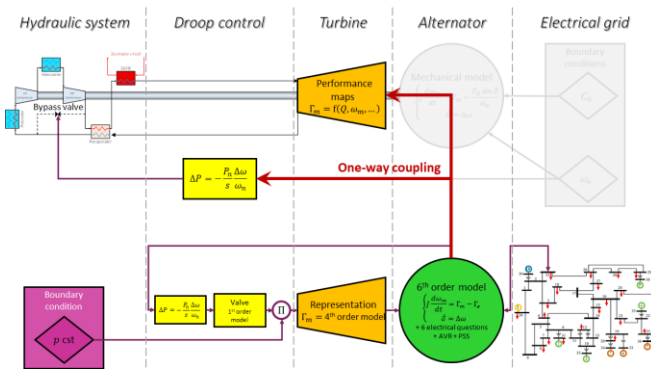


Fig. 3. Schematic diagram of a chaining PowerFactory to CATHARE

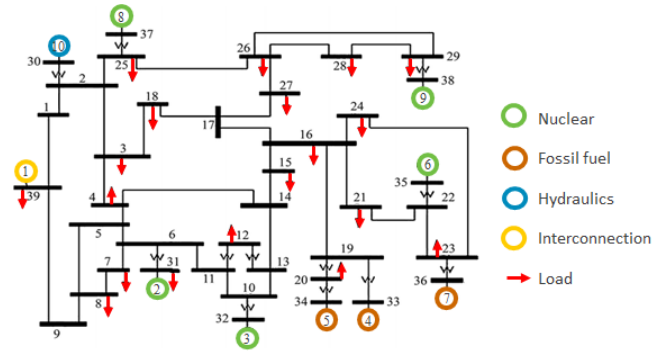


Fig. 4. 39-bus grid used for the chaining.

2) *Electrical network*: The network considered for this preliminary study is an adaptation of the 39-bus grid from IEEE [16] and shown in Fig. 4.

It represents a simplified version of the transmission electrical grid of the New England region in the USA. The nominal frequency is 60 Hz and the nominal voltage is 345 kV. Generator 1 represents the interconnection with the rest of the USA and Canada. Generators 2, 3, 6, 8 and 9 are nuclear power plants (NPPs). Generators 4, 5 and 7 are fossil fuel power plants and generator 10 is a hydraulic power station. The total installed capacity is 6 800 MVA + 10 000 MVA of interconnection.

Generators 2 to 10 are all equipped with classical governors, AVRs and PSSs. Their parameters are those used in [16] and [2]. However, contrary to those two references, the interconnection have no governor in order to amplify the behaviour of the other generators participating to the frequency regulation.

Generator 8 is the one concerned by the chaining. All the values of reactances and time constants of the generator model remain the same as the general literature about 39-bus grid (cf. [2]). However, the nominal active power is changed to 300 MW instead of 700 MW, the inertia is set to 5.006 s instead of 3.471 s according to the data given by the turbomachine constructor planned for ASTRID’s project. Because the operating active power of this generator is reduced from 540 MW to 280 MW, the operating power of generator 2 and 10 are respectively increased from 521 MW to 535 MW and from 250 MW to 490 MW in order to keep the production/consumption adequacy.

B. Transients

The time scale of interest is linked to the primary frequency control, in other words around 10^{-1} - 10^2 s. Two categories of event are analyzed in this paper.

The first type is a loss of load on bus 8. This load event is the most penalizing since load 8 is the most powerful on the 345 kV part of the grid (522 MW). Thanks to (6) and knowing the droop of each generator (see [16, 2]) it is possible to calculate that this event leads to an overall frequency increase by 285,5 mHz (or $4,75 \cdot 10^{-2}$ pu) and a power decrease of Gen8. by 28,6 MW. This allows comparing the same event with both codes in standalone but does not inform about the dynamics between the two states.

The other type is a short-circuit since it lasts less than one second, but its consequences in terms of frequency evolution last during several tens of seconds. The proposed event in this paper is a 100 ms fugitive three-phase short-circuit at the

coupled generator terminals (i.e. bus 25) with a resistive impedance of 1.19Ω .

This event is similar to the one used in [2, 4] but with more penalizing effect since it is as close as possible to the reactor. Moreover, this short-circuit event is the only one with whom the boundary conditions can be calculated by setting the resistive torque to zero during the time of the transient.

V. RESULTS

A. Load loss

The first event presented here is the loss of load on bus 8 at $t=10s$. The CATHARE-alone simulation is carried out by applying the change of boundary conditions as explained in the previous part, by a step function.

Figures 5 and 6 show that the final deviation frequency and ensuing power variation are correctly predicted without chaining thanks to the droop control formula (4). However, the extremum value of the turbine power is underestimated by the CATHARE-alone simulation about $1.4 \%P_{nom}$ (4.2 MW) compared to the chained simulation. That value is high, knowing that around 2.5% of the nominal power is generally dedicated to frequency reserve for the NPPs participating to frequency regulation [17]. Extremum frequency is overestimated about 62% (which represents 195 mHz), which is also very high, knowing that in Europe, a variation of 200 mHz represents the full activation of primary reserve [18].

Moreover, Fig. 7 shows that without chaining, the short-term peak of exchanged power at SGHX is overestimated by 3% of nominal power. The full dynamics of exchanged power is greatly more penalizing without the knowledge of the grid behavior because of the oscillations that are visible in figures 6 to 9. Those large oscillations are caused by a rapid change

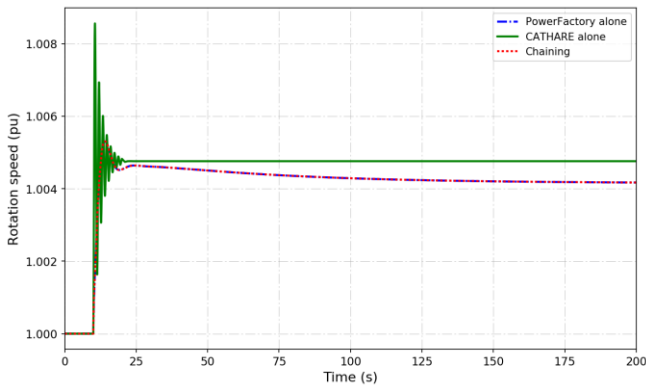


Fig. 5. Comparison of the rotation speed for a load loss

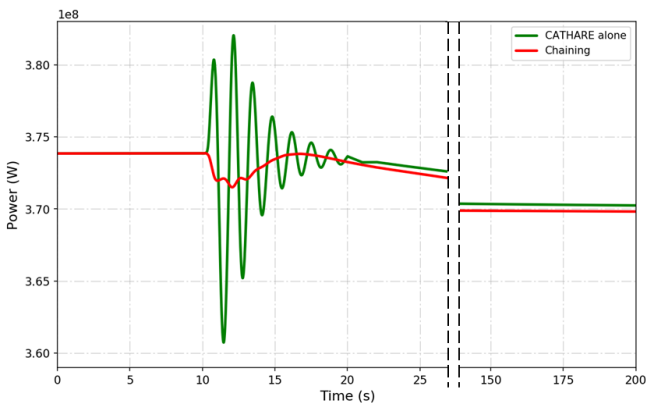


Fig. 7. Comparison of the heat power exchanged at the heat exchanger for a load loss

of torque balance that leads to an oscillation of the rotor angle around the new stable one as shown in Fig. 8. Those phenomena are studied in the angle stability definition of [19]. In the case of the chaining, the change of resistive torque is slower than in the penalizing case of CATHARE alone that assume a step change of torque. This leads to a smoother change of imbalance and then to less oscillations. This highlights that chaining brings important information for nuclear dynamics studies.

However, according to Fig. 6, the dynamics of the evolution of the turbine power are quite similar when calculated by PowerFactory and with the chaining. It means that in the case of few reactors coupled in a large grid, the chaining is not necessary for power system studies and that IEEE1 governor is sufficient.

B. Short-circuit

The second type of event presented here is a short-circuit at generator terminals. This event is carried out with CATHARE-alone by setting the resistive torque to zero at $t=10s$ then to its previous value 100 ms later. The synchronism frequency is assumed to remain constant.

The turbine power evolution in the cases of PF-alone, CATHARE-alone and the chaining are presented in Fig 9. The CATHARE-alone calculations overestimates the extremum power variation of the turbine and of the heat exchanged with the upstream circuit by $5.2 \%P_{nom}$ and $3.4 \%P_{nom}$ respectively, compared to the minimum-reached value of the chaining.

In the opposite, the PowerFactory-stand-alone calculation underestimates the dynamics of the turbine power rate by calculating its extremum rate of change of $-2.5 \%P_{nom}/s$ while the chaining shows its ability to reach $-46 \%P_{nom}/s$.

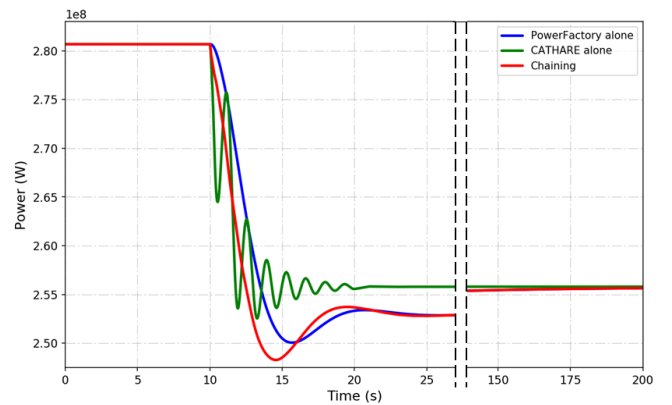


Fig. 6. Comparison of the turbine power for a load loss

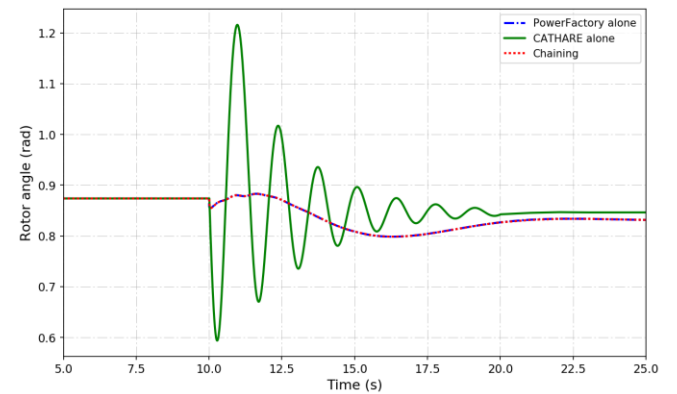


Fig. 8. Comparison of the rotor angle for a load loss

PowerFactory also underestimates the interval of turbine power variation by considering that this event leads to a maximum variation of $0.7\%P_{nom}$ while the chaining leads to a variation of $4.1\%P_{nom}$. Those estimation errors are here also caused by an overestimation of the event dynamics.

According to this short-circuit analysis, it is useful for nuclear dynamics studies to take into account the correct behavior of electrical physics not to overestimate the consequences of transients on nuclear safety and operation. Contrary to the first event, the short-circuit event shows that governor IEEE11 does not perfectly fit the ability of nuclear physics, which is not related to numerical issues but only because of the underestimation of the nuclear dynamics by the governor.

VI. CONCLUSION AND PROSPECTS

Motivated by the reduction of greenhouse gases emissions, the current energy transition leads to an increasing part of variable electricity production sources (solar or wind farms) and to a decreasing part of fossil fuel production sources. This substitution trend might lead to a complete paradigm shift concerning the means to ensure electrical grid stability. Nevertheless, in this context, grid stability might benefit from the advanced flexibility advantages of Small Modular Reactors. Some works have been done concerning the impact of SMRs in the future energy mixes or on the impact of the presence of SMRs on a grid, but few study the impact of the constraints of future power systems on SMRs.

This work allows to provide a first approach of coupling a validated nuclear reactor dynamics code (CATHARE) and a power system dynamics software (PowerFactory) by taking the best models of both to represent as best as possible the interaction of both physics. This paper first focuses on presenting the modelling approach of both codes. Then, this work tends to prove through application cases such as a short-circuit event and load loss, the relevance of a chaining.

Finally, it appears on the one hand that concerning the nuclear dynamics physics, the chaining brings a lot of information to correctly predict events coming from the turbine, i.e. the grid, without being penalizing. On the other hand, concerning the power system dynamics, it appears that for a slow transient or for a grid with few SMRs, the classical governor model used is sufficient to describe the hydraulic system of a gas turbine. However, for severe transients such as a short-circuit, the chaining shows that the

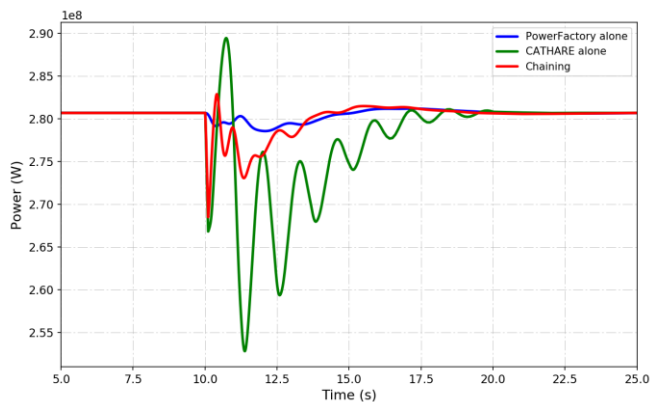


Fig. 9. Comparison of the turbine power for a short-circuit

thermohydraulics model is more responsive than a classical model as governor IEEE11. Because of this conclusion, it seems to be relevant to perform the coupling (co-simulation), to study the interaction of SMRs and constrained electrical grids for low power grids (as isolated power systems) or large interconnected systems with many SMRs.

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