Optimization analysis of Pressurized Water Reactors in the framework of renewable energies deployment in the french energy mix

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Large scale deployment of **intermittent renewable energies** in France

**Highly fluctuating** production rate (up to 3 times the average)

*Increase* of the power variations as well in frequency as in amplitude
Introduction

Challenge: Optimize the nuclear power plant (NPP) toward **better manageability** (meeting the safety constraints), so they can cope with huge power variations.

Methodology:
- Develop a **multi-physics 3D model** of the NPP in the APOLLO3® code
- **Optimization** of the control systems using meta-heuristics methods

The model:
- Input: power transient
- Output: boron concentration, temperature, axial offset (AO), linear power

Problems:
- **robustness / precision** of the model (wide range of configurations)
- calculation **time** (thousands calculations for one optimization process)
**PWR 1300 in a nutshell**

- **PWR 1300** (electrical power: 1300MWe, thermal power: 3800MWth)
- **193** assemblies (120 UO₂, 73 UO₂+GdO₃)
- Dimensions: diameter = 3m, height = 4.5m

Representation of a reactor core
PWR 1300 in a nutshell

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Each control rod is made of 24 pins which are inserted in some fuel assemblies
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Representation of a reactor core

- Each control rod is made of **24 pins** which are inserted in some fuel assemblies
- **Temperature regulation** (R) : 9 “black” rods (B4C in the half top, AIC in the half bottom)
- **Power shimming** :
  - 4 “gray” rods G1 (AIC and stainless steel)
  - 8 “gray” rods G2
  - 8 “black” rods N1
  - 8 “black” rods N2
# Design of the multi-physics model

<table>
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<tr>
<th>Core</th>
<th>Neutronics</th>
<th>Thermalhydraulics</th>
<th>Fuel</th>
<th>Boron management</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Geometry : <strong>3D</strong>&lt;br&gt; Type : <strong>quasi-static</strong>&lt;br&gt; Solver 3D : <strong>Diffusion</strong>&lt;br&gt; Number of groups : <strong>2</strong></td>
<td>Geometry : <strong>multi1D</strong>&lt;br&gt; Calculation : <strong>enthalpy balance</strong>&lt;br&gt; Type : <strong>stationary</strong></td>
<td>Geometry : <strong>multi1D</strong>&lt;br&gt; Calculation : <strong>thermics</strong>&lt;br&gt; Type : <strong>stationary</strong></td>
<td><strong>Operator model</strong></td>
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<td>Primary – Secondary heat exchanges</td>
<td><strong>Steam generator model</strong></td>
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</table>


**Power transient**

*Definition of the power transient*

- **load-follow** type transient (6/18 : *day/night* consumption)

- Lower plateau at 30%PN and power variation of 5%PN/min = **more penalizing**

![Diagram](image-url)
We compare our model to the 0D Model described in [1]:

- **Point kinetics**
- Better description of the **secondary loop**
- **Simulator** approach
- Compared to data from **NPP in operation**

enable to ensure a good behavior of our model

Power transient
Comparison of the models

Thermal power evolution

Shape of the 0D Model well reproduced
Thermal power evolution

**Shape** of the 0D Model well reproduced

5\%PN difference on the lower plateau ↘ why?

Comparison of the models
\[ AO = \frac{(P_t - P_b)}{(P_t + P_b)} \]

\[ \Delta I = Pr \times AO \]

Control the state of the core during operation.
Power transient

Core management

Control diagram

AO = (P_t - P_b) / (P_t + P_b)

ΔI = Pr * AO

- Control the state of the core during operation
- Avoided drift on the plateau
- Operator effect (axial offset control)
Optimization methodology:
1) with the **actual mix**
2) after **massive deployment** of intermittent energies

Parameters of the **control rods** are targeted (speed program, overlap, insertion sequence, etc.)

Work in progress:
- Compute **good criteria** (control diagram characterization / PCI)
- Research and develop efficient **evolutionary algorithms**
Conclusions

- **Satisfactory** 3D model as regard to:
  - The 0D Model
  - Its performance (operator behavior, calculation time)

- Remaining work on the model: reduce the **calculation time** (cross sections)

- Perspectives: launch the **optimization process**
Thank you for your attention!

Any questions?

Relative power

Time

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