Flexible PWR

Flexibility of electricity production

G. Simonini, EDF, 18th September 2024

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1. Introduction

2. French PWR Flexibility

3. SMR & Cogeneration

Summary

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Electrical System Needs

Forecast of
Production / Consumption

Load Following

- Load profile (~24 hours) to be executed
- Can be modified (tertiary frequency control)

Online

Frequency Control

- Keep the frequency around its nominal value (50 Hz in EU)
- → Requirement

Grid Incident

- Resiliency
- Islanding
- Contribute to grid restoration

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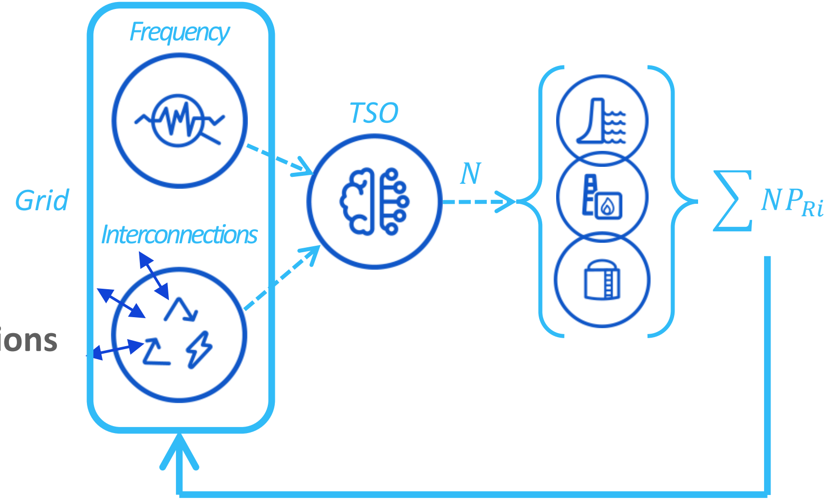
Frequency Control

Primary frequency control

- → **fast stabilization of the frequency**
- $k\Delta f$ (2%PN)
- In less than 30 seconds
- At least for 15 minutes

Secondary frequency control

- → **restoration of nominal frequency and interconnections**
- NP_R (5%PN)
- N can go from -1 to 1 in:
    - 800 seconds
    - Or 133 seconds in “emergency scenarii”



Schematic view of the secondary frequency control principles

Tertiary frequency control

- → **restoration of secondary power reserve**
- By modifying the load profile of some power units (e.g. start-up of additional units…)

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Principles of Power Control

- **Power Control** → $P = P_0 + NP_R + k\Delta f$
  - **Target:**
    - Mechanical Power → Steam Admission Valves
    - Thermal Power (@ Steam Generator)
    - Nuclear Power

  General principle:
  - Final power type: electrical
  - Deal with power transformation
  - Deal with the process inertia
    - Examples:
      - Potential energy of water
      - Chemical energy of fossil fuels (coal…)
      - …

- **Rotational inertia** → $J\frac{d\Omega}{dt} = C_M - C_E$

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French PWR Flexibility

Principles of Core Control

- **Nuclear fission control means**:

	Pros	Cons
Boron	Homogeneous	Slow
Rods	Fast (~1 m/min*)	Heterogeneous

* In normal operation, not SCRAM

Grey Operating Mode
→ Grey Rods, with reduced absorption power, to quickly compensate the *Power Reactivity Feedback* with lower power distortion → Open-loop control

- Self-stabilizing reactivity feedbacks (Doppler, moderator effects)
  → Control the temperature, not the power

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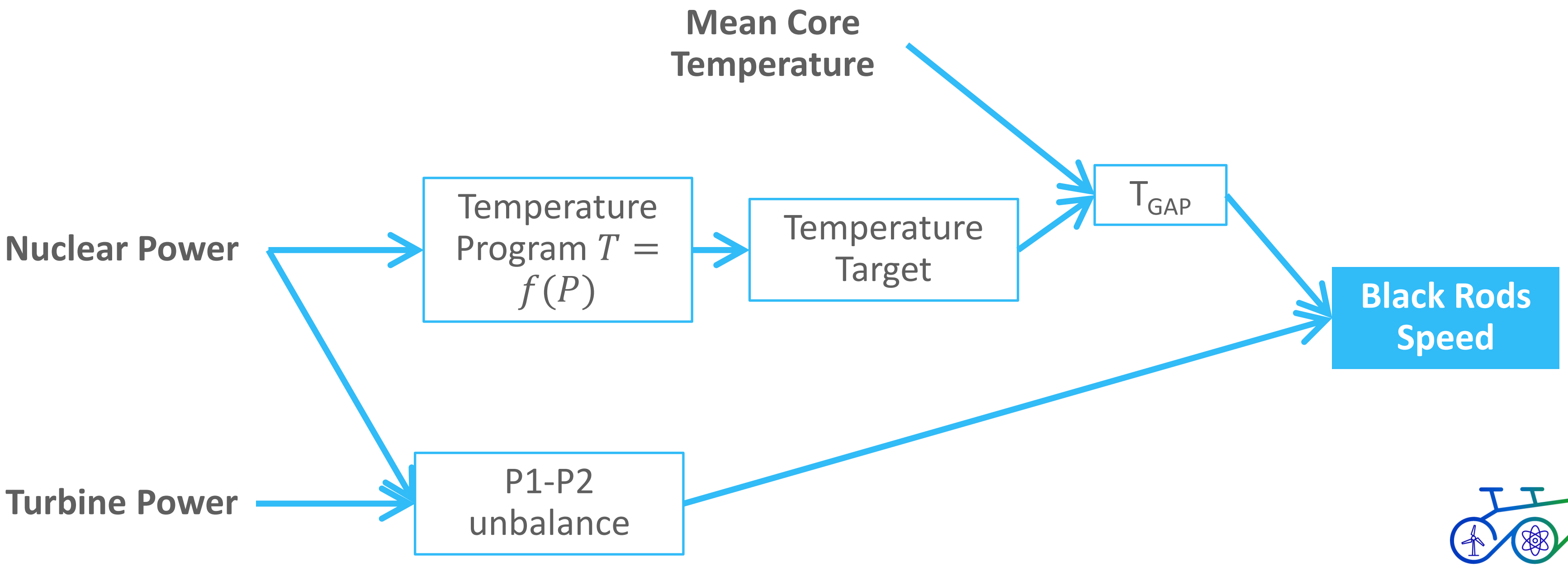
Principles of Temperature Control

- Simplified Regulation Scheme:



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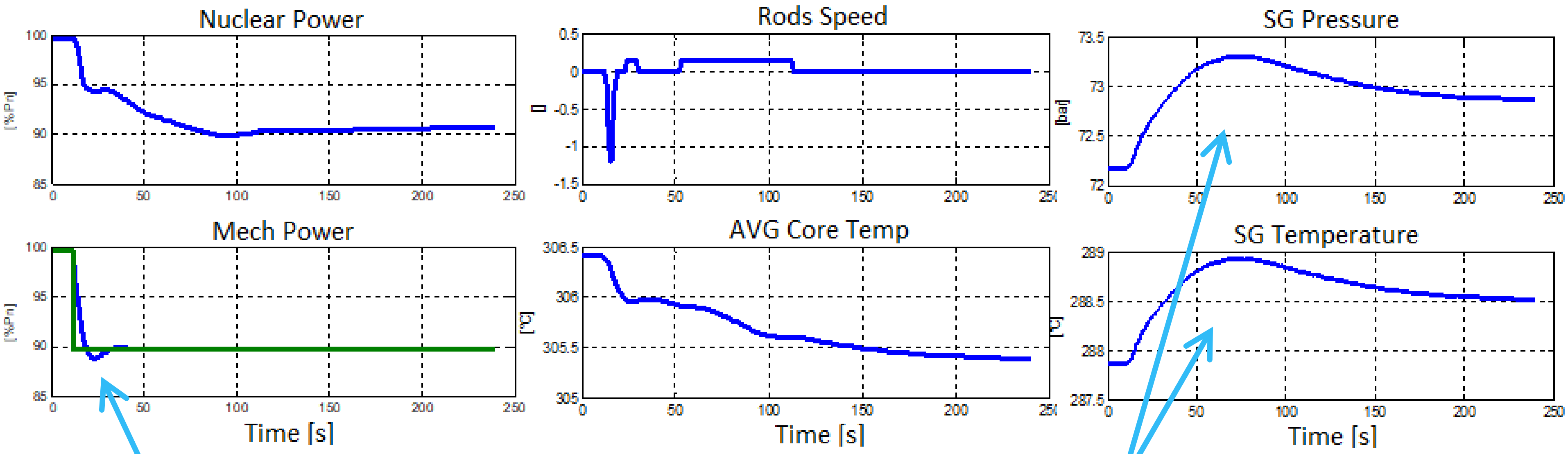
Transient Example → 10% Power Drop



Very "fast" P2 → Decoupling Inertia of SG

Linked by saturated steam production

SMR Typical "one-though SG" are different!

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Safety Constraints

Issues:

- Increased Reactivity Injection in case of Rod Ejection Accident
- Flux/power distortion due to rods insertion:
  - Local Hot Spots
  - Heterogeneous burnup → Hot Spots when rod is withdrawn, @ full load

  → Amplification due to 

- Pellet-Clad Interaction (PCI):
  Clad stress due to different thermal dilatation of the fuel (↑) and the clad (↓)

Countermeasures:

- Limits on max rod insertions and reduced rod worth of Grey Rods
- Restrictive Operating Domain Axial Offset vs. Power
- Credits: max allowed duration @ partial load, restored spending time @ full load
- Limits on power ramp speed:
  - 3% of NP/hour after refueling
  - 5% of NP/min otherwise

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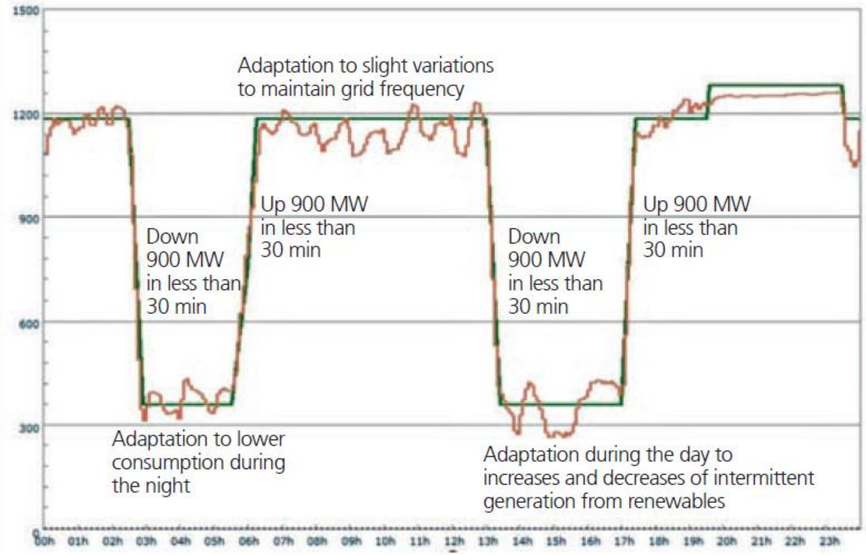
Flexibility Capabilities of EDF Fleet [1/2]

- 80% ramps up/down in less than 30 minutes
- Twice a day (separation of 2 hours min)
- Superimposing primary & secondary frequency control
- 2 reactors out of 3 capable of flexibility



Example on a 1300 MW_E PWR.
Courtesy of Morilhat et al. [ref 1]

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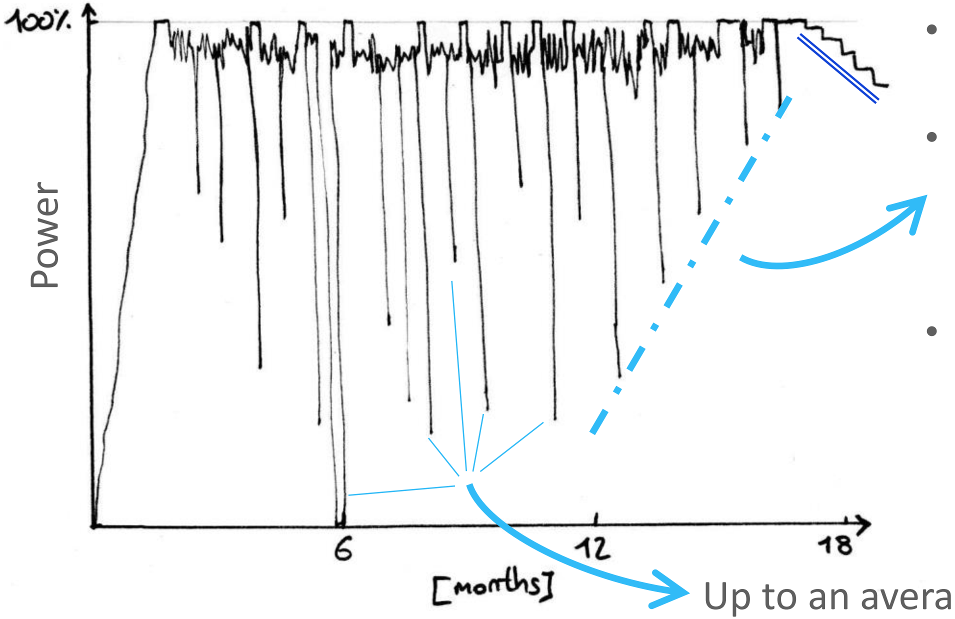
Flexibility Capabilities of EDF Fleet [2/2]

Typical cycle (*artist's rendition*):



Up to an average of
70 load transients/unit/year

- ~1 month/cycle off for refueling/maintenance
- ~7 days/month @ 100% for tests (safety or performance related)
- Reduced partial load capacity starting from about 2/3 of the cycle.
  → Due to decreasing boron concentration, making harder to compensate xenon by dilution
- Planning optimization:
  - Tests
  - Refueling:
    - Fuel saving
    - Shortening or Stretching-out

Other consequences on the “health” of the plant?

- **Fatigue** on the primary circuit (pressure, temperature variations)
  →Monitored by design: well under limits
- Wearing of **Control Rod Drive Mechanisms** because of greater usage
  → Counter: replacement when approaching the design limits (~millions of steps)
- **Primary effluents**:
  - Linked to more frequent boron dilutions/injections → retreated and reinjected, but need an efficient processing
  - Lower production of tritium and carbon-14, since they are linked to the produced energy
- Increase of **solid wastes** as ion-resins and filters because of the increased process of primary fluids
- **Statistical studies** demonstrated a very little impact on:
  - Wearing of Conventional Island components (leakages…)
  - Unavailability factor

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SMR & Cogeneration

SMR general specificities

- **<u>One-through Steam Generator</u>**:
  - Far lower inertia → strongly coupling primary and secondary system
  - Superheated steam production → decoupled Pressure and Temperature

  →Both lead to a harder to control system

- **<u>No boron in normal operation:</u>**
  - Use of burnable poisons
  - Increased usage of rods

  →More flux/power heterogeneities

- **<u>Reduced core size:</u>**
  - Greater spatial correlation → Lower flux oscillations (Xenon)

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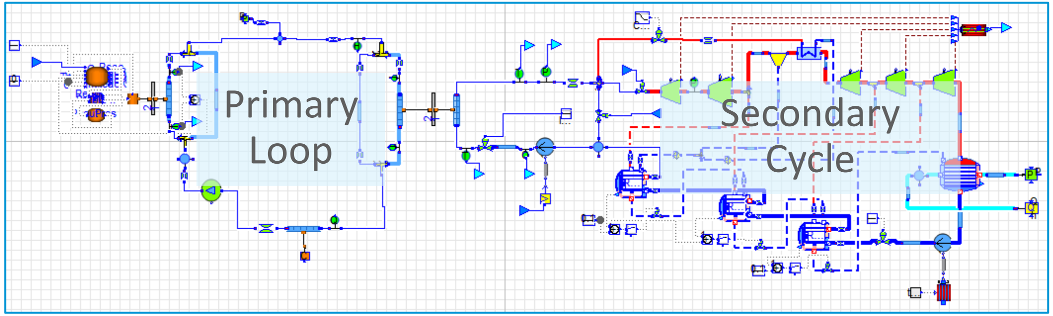
Control Design by 0D/1D modeling

1. Plant modeling based on reference data (whole operating range)
2. Model linearization (actuators effects on target variables)
3. Regulation design



thermoSYSPRO

See Baligh&Bouskela, 2019 [ref 3]

Actuators	Targets
Control rods, valves, pumps speed…	Power, primary temperature, steam pressure, SG inlet temperature…

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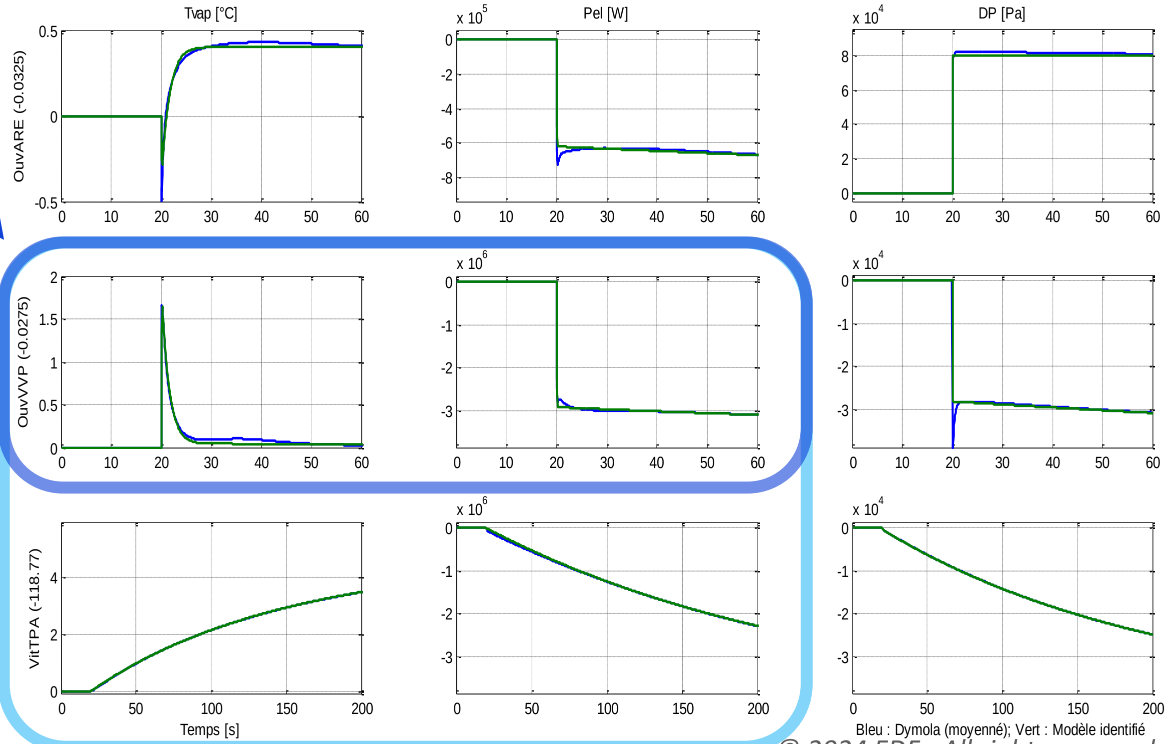
Control Design: dynamic characterization

Low Inertia:
Very fast variations

Strong interactions:
The steam admission valve and the pump speed impact both the steam temperature and power.

Depending on “requirements”, it may need complex control (e.g. Internal Model Control)



Modelica

Approx.

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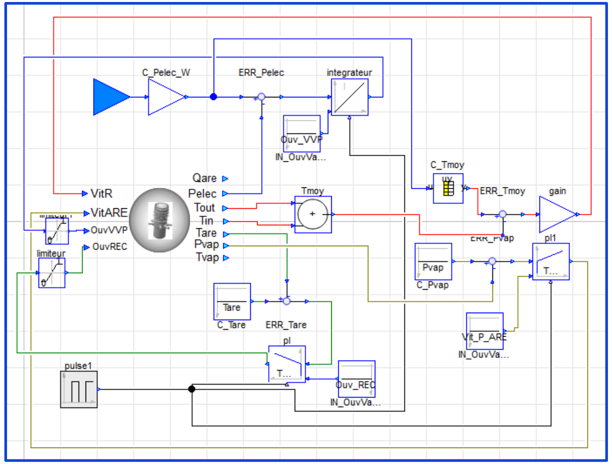
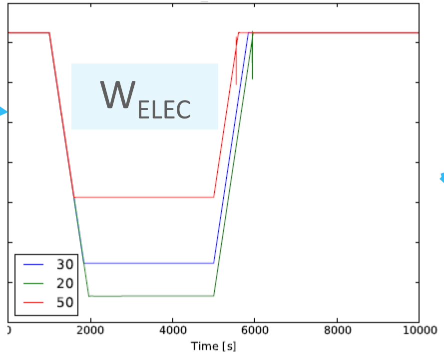
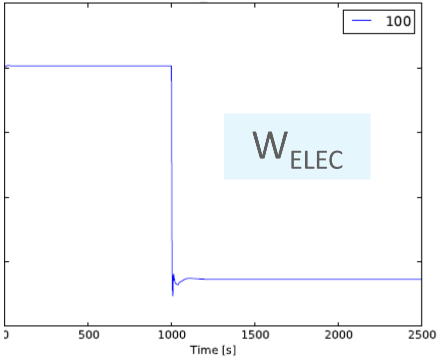
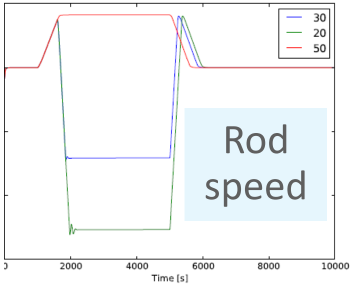
Control Design: transient studies

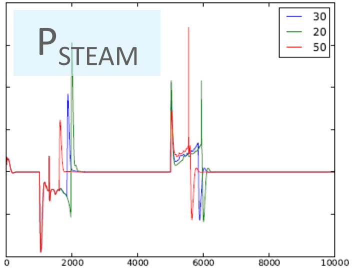
- Model with I&C
- Analysis of load transients:
  - Target variables evolution
  - Actuators behavior











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Flexibility & Cogeneration

→ Production of both electricity and heat (at different P,T conditions)

- New load transients to be respected (electrical grid + heat clients)
- Potential synergies between the “outlets”:
  - Variations may partially compensate
  - Variations of one product are less important on the whole capability
  - The thermal outlet may be used as damper

→ Interest of a Thermal Energy Storage system
See, for example, ref 4

→ R&D Topic

→ Modelica TANDEM Library [ref 5&6]

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Wrap-up

Main Takeaways

PWR can be used as **dispatchable** Power Units in partnership with variable Renewable Sources to constitute a **Carbon-Free Energy Mix**

- Thanks to the Grey Operating Mode (or "T mode" of the EPR) → Quick power ramps
- R&D work on Aid Tools, to especially deal with the Xenon poisoning

SMR → Lower inertia, superheated steam: different control strategies

Cogeneration → new perspectives for flexibility

0D/1D modeling is a valuable tool to help design flexible *Hybrid Energy Systems*

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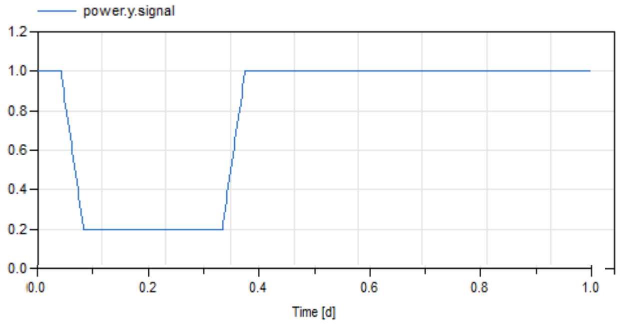
^{135}Xe

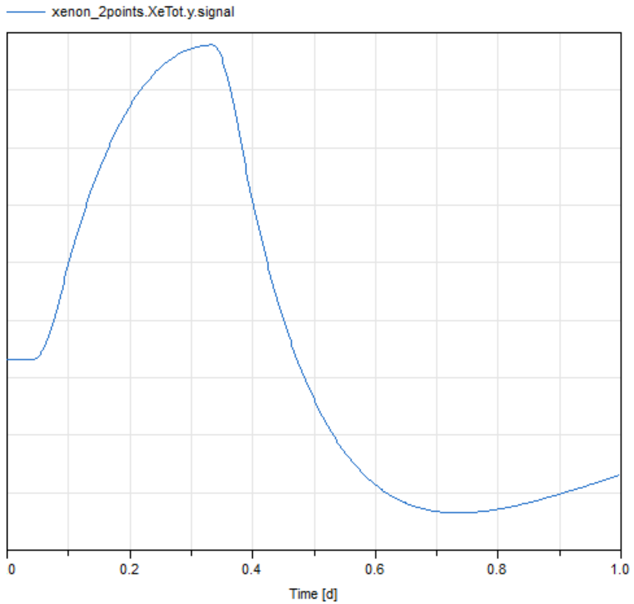
A fission product with strong impact on core operation

Xenon poisoning

Example of Load Following



Impact on xenon



→ Positive feedback + oscillations

→ The phenomena last well beyond the end of the original transient

→ It needs compensations by control means (usually, by boron dilution and injection)

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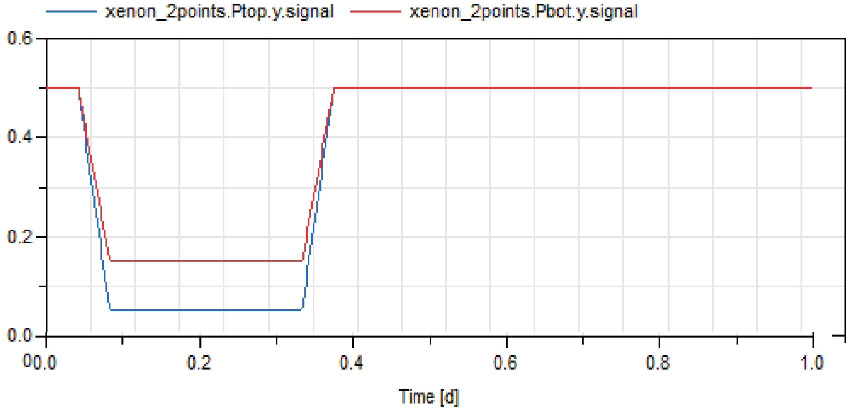
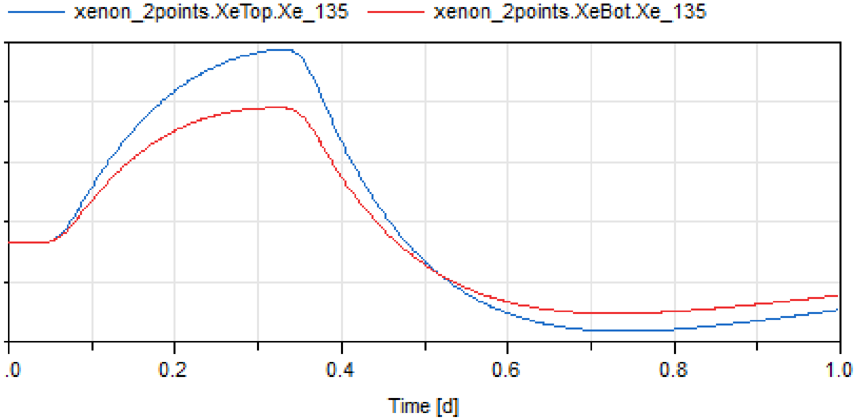
Axial Unbalance

The power evolution is not axially homogeneous (rod insertion, T profile…)





The heterogenous poisoning distorts even more the axial flux shape
→ self-amplifying phenomena

Compensation by control means → rods insertion/withdrawal

Complex phenomena + operating diagram to be respected → aids tools (R&D on simulators, AI tools…)

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