# IEEE PES Workshop on Energy Systems Simulation and Modeling

Turbine and Boiler Modeling
Impact on Generator's Performance

February 10 2010

*Mickael MIDOU*
*Daniel BOUSKELA*
*EDF R&D STEP Department*

CHANGER L'ÉNERGIE ENSEMBLE

# Why study Plant Performance ?

CHANGER L'ÉNERGIE ENSEMBLE

## Why study Plant Performance ?

- Plant - System interaction law

*Mechanical torque*

*Turbogenerator group rotational velocity*

*Turbogenerator group rotational inertia*

$$J\frac{d\Omega}{dt} = C_m - C_e$$

*Electrical load demand/torque*

  - Unbalance between power production and electrical consumption ⇒ frequency variation
  - Objective : to control the grid frequency by acting on the mechanical torque

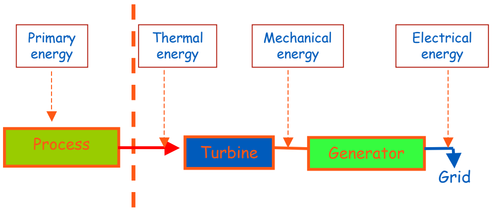
- Two main issues:
  - Electrical and mechanical variables have different dynamics ➔ must be taken into account for control system design
  - Turbine must be protected from system operation faults ➔ may be handled using a global control loop

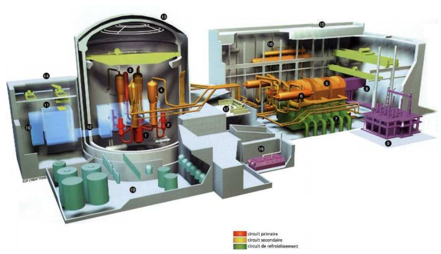
*EDF R&D : Créer de la valeur et préparer l'avenir*

## Why study Plant Performance ?

- Two main categories of power plants:
  - Electrical production can be adjusted to the grid demand
    - Nuclear
    - Fossil fuel
    - Combined cycle
    - Hydraulic
  - Electrical production cannot be adjusted to the grid demand
    - Renewable
    - Distributed production …

- ⇒ various characteristics (constraints and benefits)



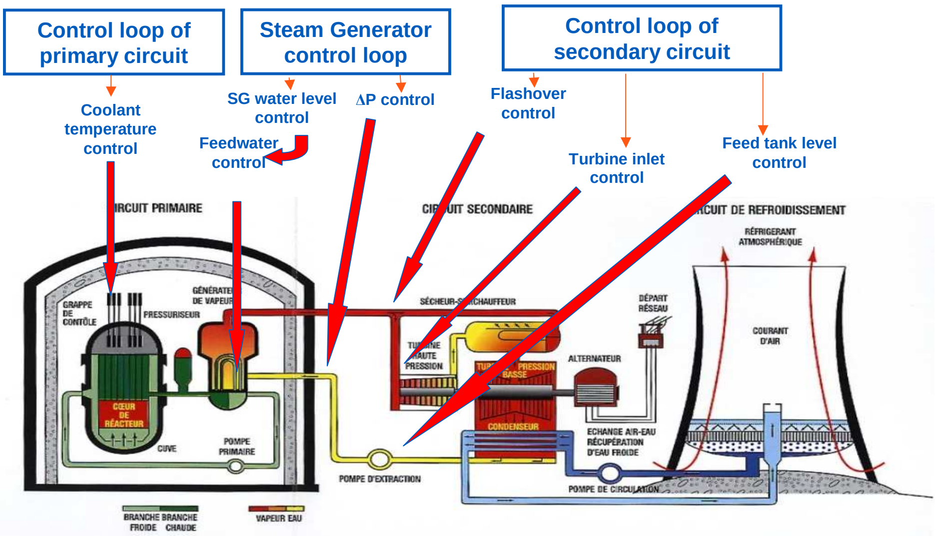



3D view of the EPR

*EDF R&D : Créer de la valeur et préparer l'avenir*

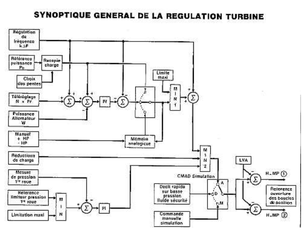
# Nuclear – PWR

Global view of Nuclear Power Plant and its control loops




# NPP

- Principle : At each instant time, the delivered electrical power is practically equal to the nuclear power (almost no energy storage)
- Primary coolant system (RCS)
  - Complex behavior : complex physics (radioactivity decay, xenon oscillations…)
  - With many operating constraints : fuel cycle, safety rules…
  - ➔ Two main control means : control rods, boron concentration
- Secondary coolant system : interface between RCS and grid
  - GRE : multiple functional control loop
    - Rotational speed turbine shaft control
    - Electrical power control
    - High pressure turbine stage control
    - Thresholds for safety control
    - Grid demand automatic adjustment



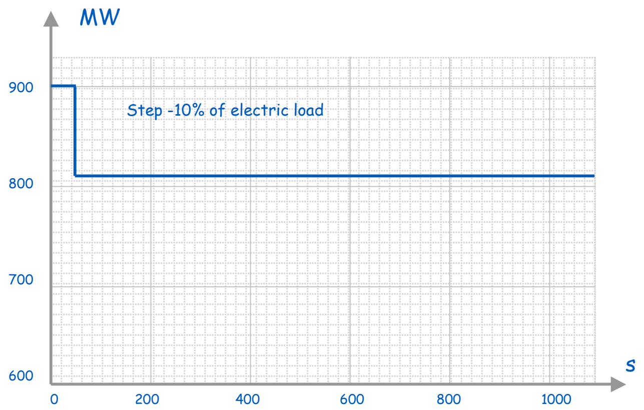
# NPP operation constraints

- Power plant limitations to the grid demand
  - Almost no energy reserve ➔ grid load variation impacts directly the RCS (no damping between the two systems)
  - ➔ Leads to frequent control rods movements
- Impact of grid operation faults on the NPP
  - How to maintain the electrical supply to the auxiliaries ? Is the auxiliaries operation compatible with electrical perturbations ?
  - What happens in case of islanding (rapid separation of the plant from the grid) ? In this case, how to rapidly evacuate the excess thermal power ?



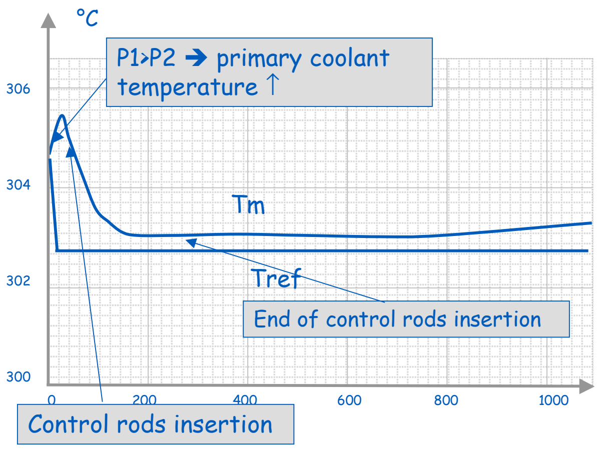
# NPP: Electrical load step

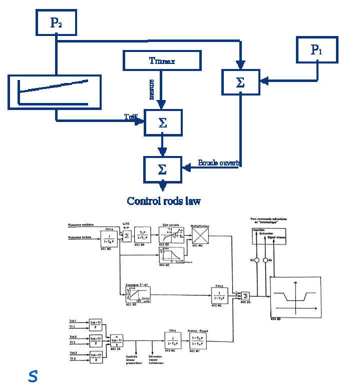
- Electrical load:



# NPP: Electrical load step

- Primary coolant temperature:

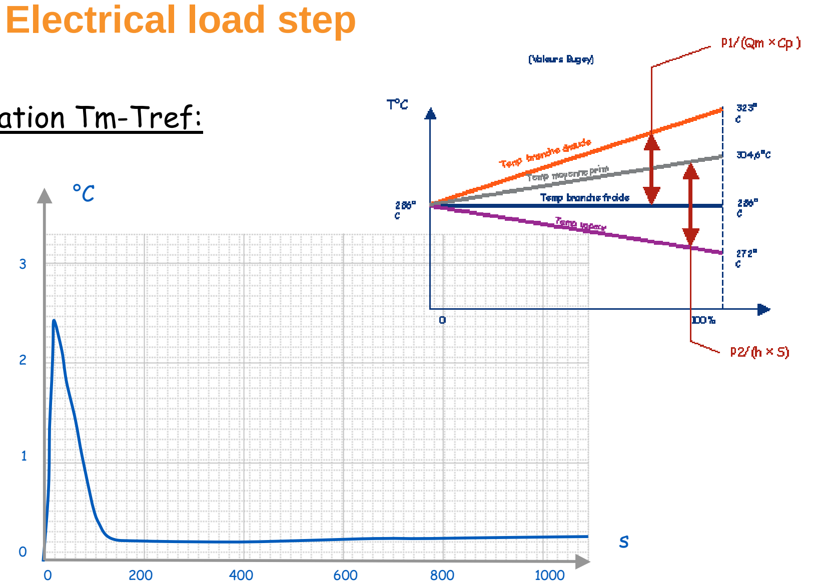




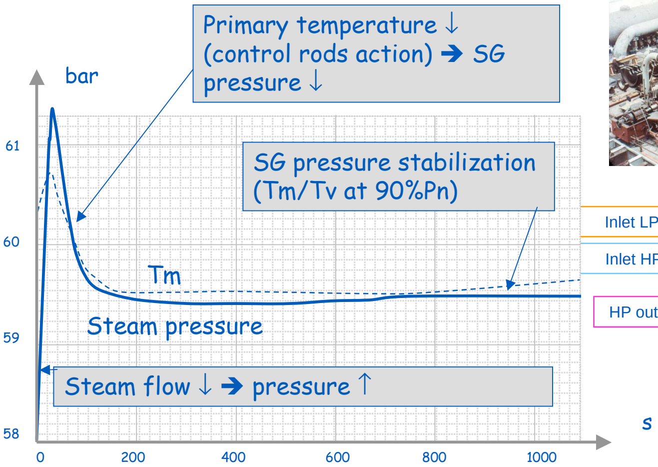

# NPP: Electrical load step

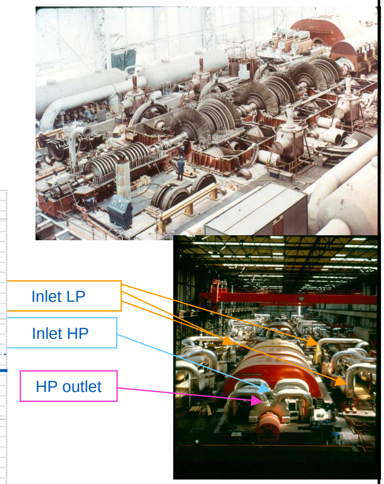
- <u>Deviation Tm-Tref:</u>



# NPP: Electrical load step

- <u>Steam pressure:</u>

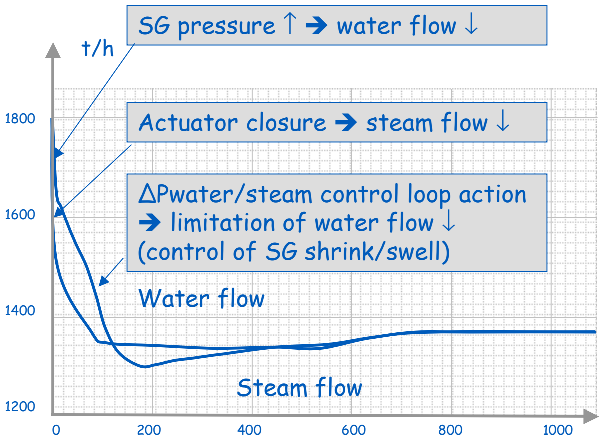


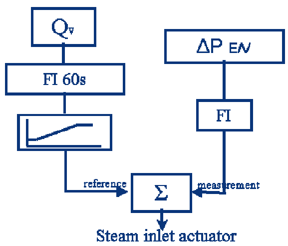






# NPP: Electrical load step

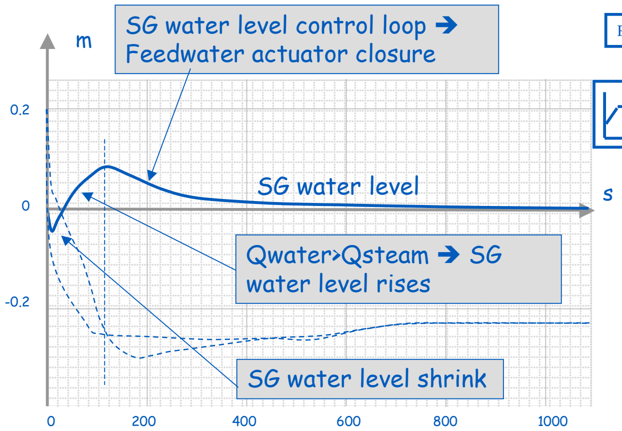
- <u>Water - steam flows:</u>

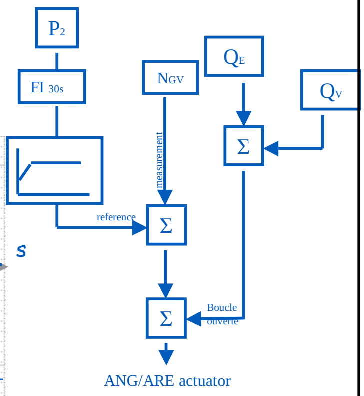


# NPP: Electrical load step

- <u>SG water level:</u>

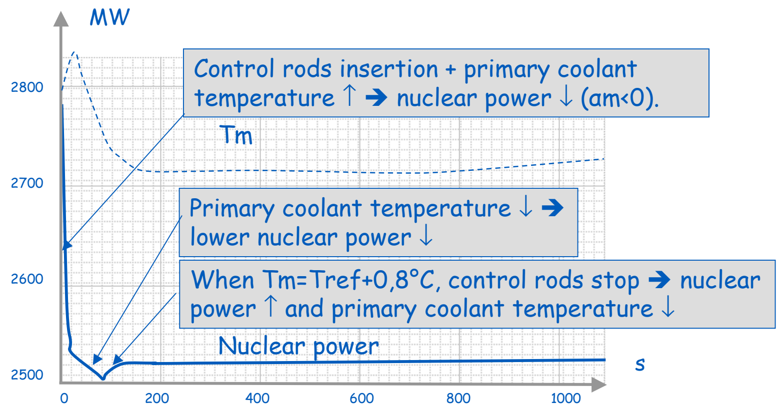




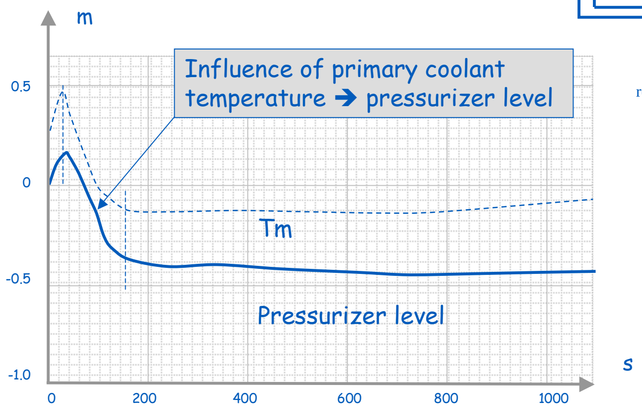

# NPP: Electrical load step

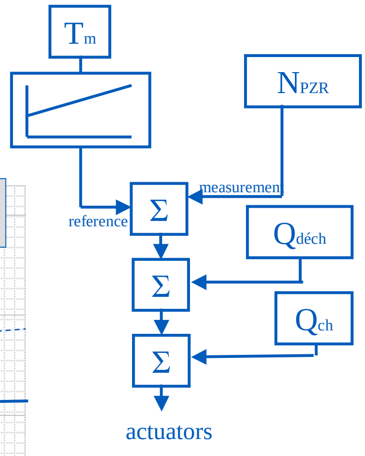
- <u>Nuclear power:</u>



# NPP: Electrical load step

- Pressurizer level:

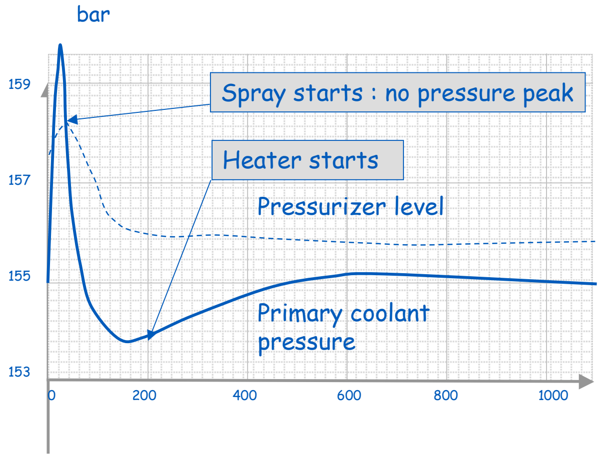


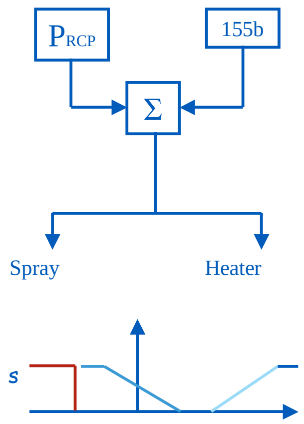






# NPP: Electrical load step

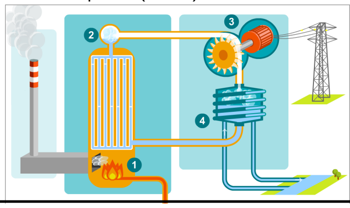
- Primary coolant pressure:



# Fossil/conventional Power Plant

- Principle: load demand = boiler power production
- Boiler
  - Different kinds: drum, once-through…
  - Different fuels: coal, oil, gas…
    - Impact of coal grinding, oil preheating… on the plant dynamic behavior
- Operation constraints
  - Grid demand
    - Better steam reserve compared to NPP (drums…): direct coupling between the drum boilers and the generator
  - Grid operation faults
    - How to efficiently operate the plant auxiliaries: coal grinder, pumps… ?
    - How to rapidly evacuate the excess thermal power (steam) ?

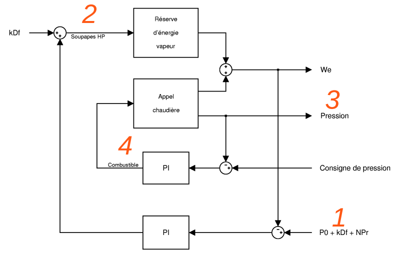


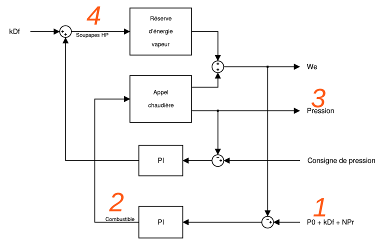



# Fossil/conventional Power Plant

- Two operating modes for drum boiler:
  - Overriding turbine mode

  - Overriding boiler mode

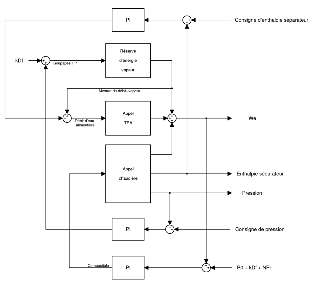


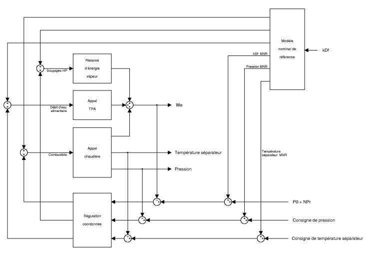



## Fossil/conventional Power Plant

- No drum = no steam reserve
  ➔ Need of more efficient feedwater control strategy

- Advanced plant control strategy
  - Boiler-turbine coordinated control strategy : all actuators are directly controlled from the load variation
  - Some optimized anticipations with kΔf variations (ancillary services)






## Why study Plant Performance ?

- Performances are heterogeneous depending on the plant type
  - Nuclear
  - Fossil fuel
  - Combined cycle
  - Hydraulic
  - …

- But only one plant performance rule : UCTE (TSO) rules !
  - Regulation compliance for the plant dynamic behavior
  - Performance regulation are different for primary and secondary reserves

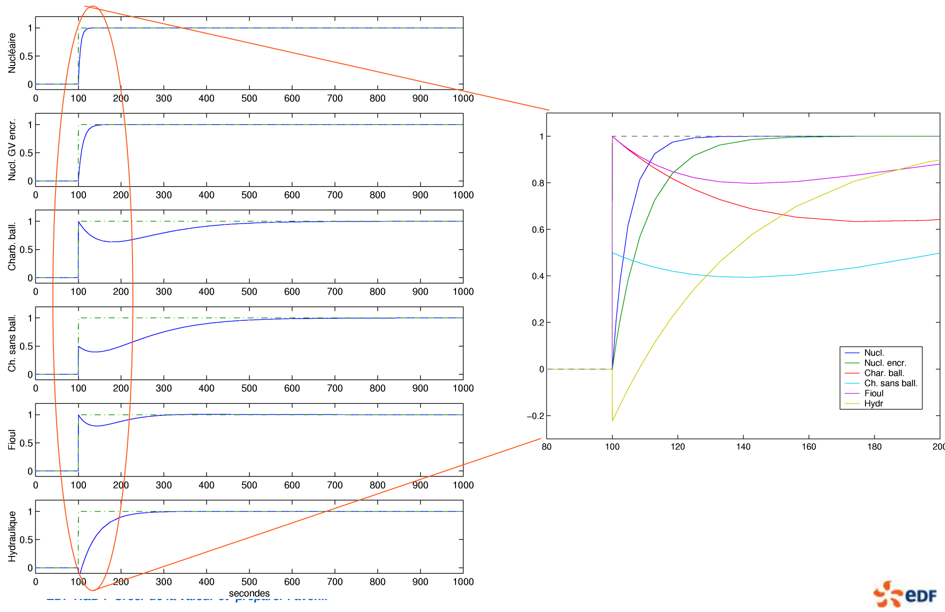
# Transfer Function Modelling

CHANGER L'ÉNERGIE ENSEMBLE

## Power plant step response: primary reserve

| Power plant | Frequency ➔ Load transfer functions |
|---|---|
| Optimal PWR | $\frac{1}{5s+1}\frac{1}{S_{nucléaire}}\frac{P_0}{f_0}$ |
| Fouling SG PWR | $\frac{1}{10s+1}\frac{1}{S_{nucléaire}}\frac{P_0}{f_0}$ |
| Drum equipped coal plant | $\frac{6400s^2+80s+1}{6400s^2+160s+1}\frac{1}{S_{charbon}}\frac{P_0}{f_0}\Delta f = \left(\frac{80s}{80s+1}+\frac{1}{(80s+1)^2}\right)\frac{1}{S_{charbon}}\frac{P_0}{f_0}\Delta f$ |
| No drum equipped coal plant | $\frac{3200s^2+40s+1}{6400s^2+160s+1}\frac{1}{S_{charbon}}\frac{P_0}{f_0}\Delta f = \left(\frac{40s}{80s+1}+\frac{1}{(80s+1)^2}\right)\frac{1}{S_{charbon}}\frac{P_0}{f_0}\Delta f$ |
| Oil plant | $\frac{200000s^3+8000s^2+160s+1}{200000s^3+10500s^2+180s+1}\frac{1}{S_{fioul}}\frac{P_0}{f_0} = \left(\frac{80s}{80s+1}+\frac{1}{(50s+1)^2}\right)\frac{1}{S_{charbon}}\frac{P_0}{f_0}\Delta f$ |
| Hydraulic plant | $\frac{-9s+1}{40s+1}\frac{1}{S_{hydraulique}}\frac{P_0}{f_0}$ |

## Power plant ramp response: primary reserve

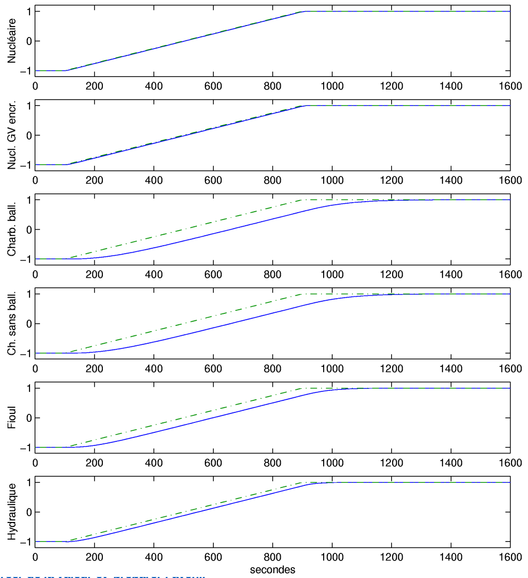



## Power plant step response : secondary reserve

- The grid remote control signal is not directly applied to the high pressure valve actuators

| Power plant | Frequency ➔ Load transfer functions |
|---|---|
| Optimal PWR | $\frac{1}{5s+1}P_r$ |
| Fouling SG PWR | $\frac{1}{10s+1}P_r$ |
| Coal plant | $\frac{1}{6400s^2+160s+1}P_r=\frac{1}{(80s+1)^2}P_r$ |
| Oil plant | $\frac{1}{2500s^2+100s+1}P_r=\frac{1}{(50s+1)^2}P_r$ |
| Hydraulic plant | $\frac{-9s+1}{40s+1}P_r$ |

## Power plant ramp response: secondary reserve






# MISTRAL : Simplified Power Plant Modelling

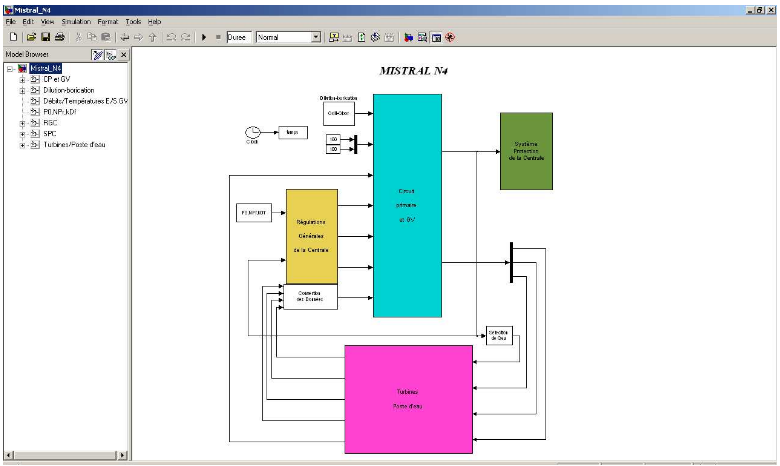
CHANGER L'ÉNERGIE ENSEMBLE

## MISTRAL models

- Simplified models (transfer functions) of plant dynamic behavior, developed:
  - by R&D/STEP/P1B with Matlab/Simulink for the EDF fleet,
  - for dynamic performance enhancement studies and new control design.
- A good trade-off between easy implementation and accurate physical representation
- Functional modular architecture:
  - Physical process modules: major physical phenomena (non linear mass, momentum and energy conservation laws)
  - Control loop modules : filters, thresholds, hysteresis…
- Validated with measurements data
- Scope: steady state and normal transients
  - Ancillary services, all kind of normal operation modes (upper than 20% Pn), major grid operation faults

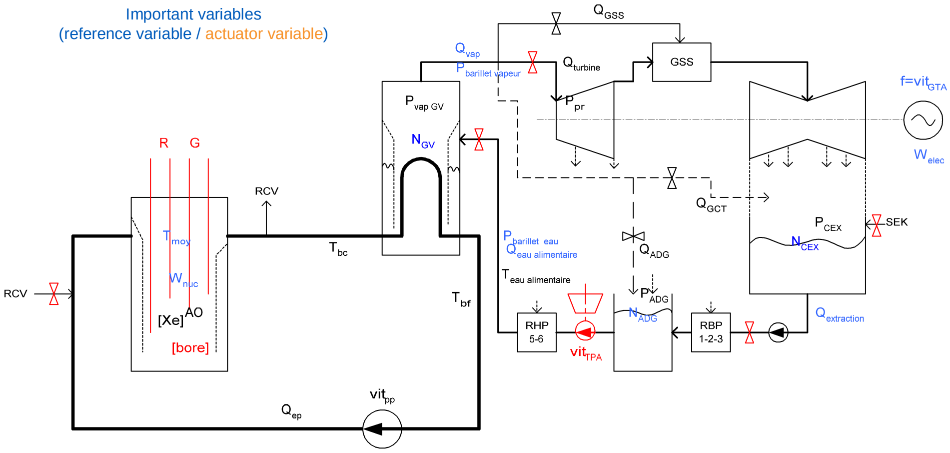


## MISTRAL models



# MISTRAL models

Important variables
(reference variable / actuator variable)




*EDF R&D : Créer de la valeur et préparer l'avenir*

# Physical Modelling

CHANGER L'ÉNERGIE ENSEMBLE

## Governing model equations

| Equation | 1D distributed formulation | Lumped formulation in model |
|---|---|---|
| Mass balance | $\frac{\partial(\rho_x \cdot A_x)}{\partial t} = -\frac{\partial(\rho_x \cdot v_x \cdot A_x)}{\partial x}$ | $A \cdot \frac{d\rho_x}{dt} \cdot \Delta x = m\_flow_x - m\_flow_{x+\Delta x}$ |
| Momentum balance | $\frac{\partial v_x}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{v_x^{2}}{2}\right) - \frac{1}{\rho_x} \cdot \frac{\partial P_x}{\partial x} - g \cdot \frac{\partial z_x}{\partial x} - F_x$ | $\frac{L}{A} \cdot \frac{d}{dt} m\_flow_x \cdot \Delta x = \frac{m\_flow_x^2}{A^2} \cdot \left(\frac{1}{\rho_x} - \frac{1}{\rho_{x+\Delta x}}\right) + P_x - P_{x+\Delta x} - F_x$<br>Staggered grid |
| Energy balance | $\frac{\partial}{\partial t}(\rho_x \cdot A_x \cdot u_x) = -\frac{\partial}{\partial x}(h_x \cdot \rho_x \cdot v_x \cdot A_x) + \pi \cdot D \cdot \varphi_x$<br>$u_x = h_x - \frac{P_x}{\rho_x}$ | $A \cdot \frac{d(\rho_x \cdot u_x)}{dt} \cdot \Delta x = h_x \cdot m\_flow_x - h_{x+\Delta x} \cdot m\_flow_{x+\Delta x} + \pi \cdot D \cdot \varphi_x \cdot \Delta x$<br>$\varphi_x = h_x \cdot (T_{w,x} - T_x)$ |

Homogenous model used for two-phase flow

GRETH correlations used to compute the friction and the heat transfer coefficient terms

IAPWS-IF97 polynomials used to compute the fluid physical properties

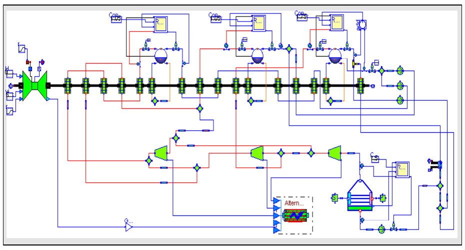


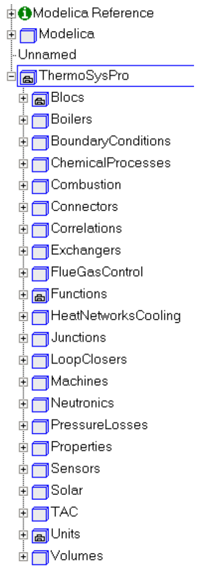
## Physical modelling with the Modelica language

- Modelica is a language for the modelling and simulation at the system level. Main benefits:
  - 0D/1D
  - Multi-domain: all branches of physics + control system
  - Hybrid: handles continuous (e.g. thermofluid) and discrete (e.g. control logics) interacting parts
  - Steady state/dynamic modelling
  - A-causal: automatic model reversal (inverse problem solving)
  - Declarative: optimized simulation code is automatically generated from the model equations
  - Open source: developed and promoted by the Modelica Association
  - Tool independent: language is supported by several commercial and open source tools (CATIA from DS, Scilab, OpenModelica…).

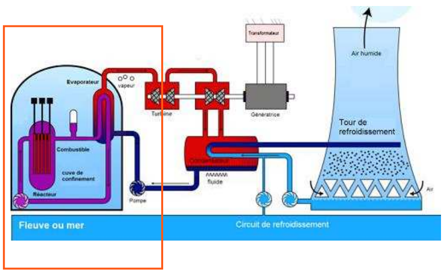
## ThermoSysPro library

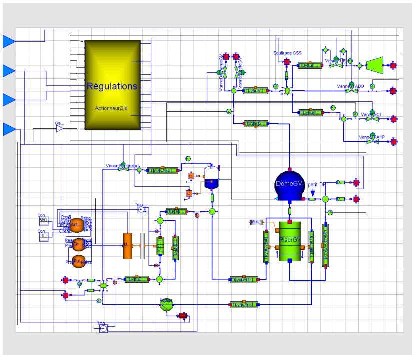
- Modelica library for static and dynamic power plant modelling
- Developed in the framework of the ITEA 2 EUROSYSLIB project
- Will be released as an open source library with two significant test-cases (concentrated solar power plant and combined cycle power plant)

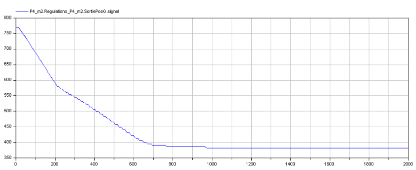


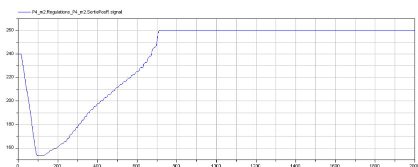



## Dynamic simulation of the islanding of the 1300 MWe NPP (P4)





*G control rods position*

*R control rods position*

***EDF R&D : Créer de la valeur et préparer l'avenir***

# Modeling of Steam Generators of Nuclear Power Plants to assess TSP blockage Phenomena and Performance

***EDF R&D STEP***
**Mickaël Midou**
**Daniel Bouskela**
**Julien Ninet**
**Jean-Mélaine Favennec**
**Baligh El-Hefni**

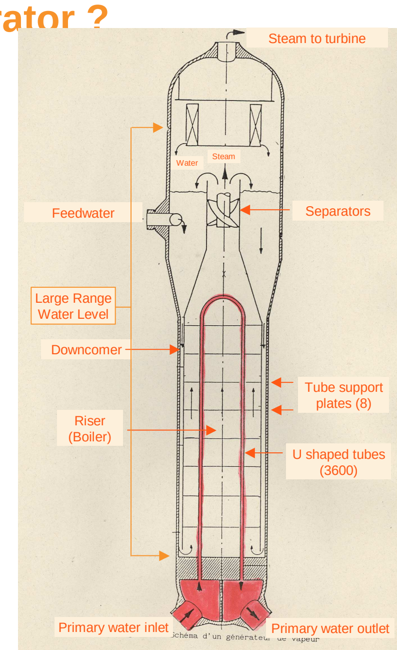
***in collaboration with***
**Vincent Chip *(École Polytechnique)***
**Aurélien Gay *(École Polytechnique)***

CHANGER L'ÉNERGIE ENSEMBLE

## What is a PWR steam generator ?

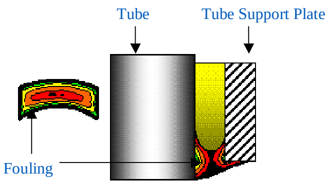
- Important component:
  - Barrier between the primary and secondary loops : 2nd safety barrier
  - Cool the fission reactor and produce steam for the turbine-generator
  - Works as a complex counter-current and co-current flow heat exchanger

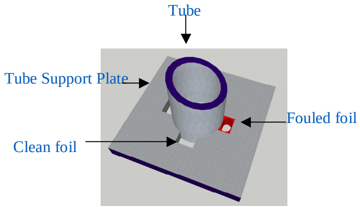
| | Primary loop | Secondary loop |
|---|---|---|
| Temperature at inlet | 322°C | 220°C |
| Temperature at outlet | 284°C | 270°C |
| Mean pressure | 155 bar | 55 bar |
| Mass flow | 15 900 t/h | 1 800 t/h |
| Steam quality at outlet | | 99.75 % |
| Circulation ratio = total flow / steam flow | | Between 4 and 5 |



## What is the TSP blockage phenomena and its consequence ?

- Deposits of iron oxide particles:
  - On the U-tubes outer walls
    - ↳ Impacts the heat exchange capacity
  - On the quatrefoil sections of the U-tubes support plates
    - ↳ Reduces the flow rate through the sections
- Problem:
  - Reduce cooling efficiency
  - May lead to safety issues

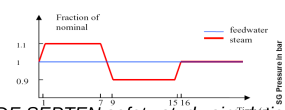


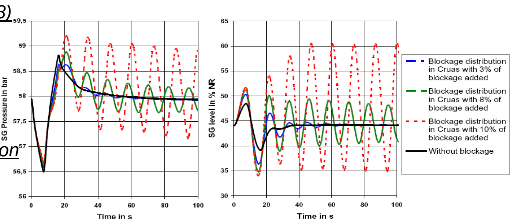





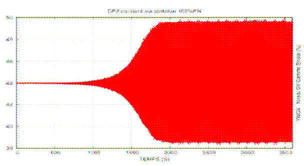

## What is the TSP blockage phenomena and its consequence ?

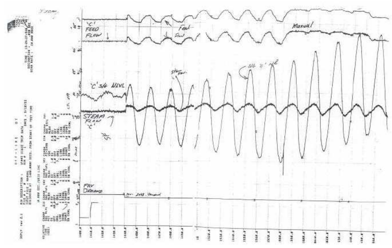
- *Impact on SG behavior during transient: oscillation of water level*
  - *IRSN article (ICONE 16 – May 2008)*




  - *EDF-SEPTEN safety study simulation*

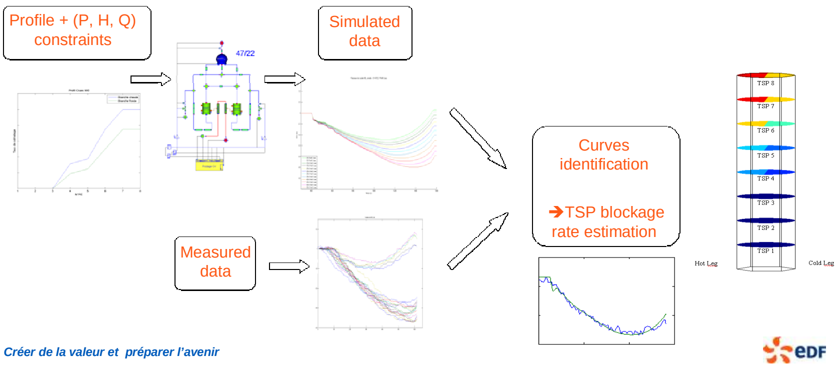




# New method to assess TSP blockage

## Proposed new method

- Based on the analysis of the response of the SG to a particular transient: the periodic testing of the control rods that leads to a 60% power derate in 20 minutes (EP RGL 4)
- Can be performed between two yearly outages (in comparison with local inspections such as eddy current measurements or camera inspections)
- Produces a global estimator (instead of local estimators)






# SG model: Modelica model

## U-shaped tubes:

- One equivalent distributed pipe
- Heat transfer (Dittus-Boelter)

## Riser:

- Dissymmetry between hot and cold leg
- Each leg modelled as a distributed pipe
- Friction coef. to represent the singular pressure losses due to blockage (Chisholm 1983)
- Heat transfer from U-tubes (Jens&Lottes)
- Two-phase flow model (Chisholm 1973)

## Downcomer:

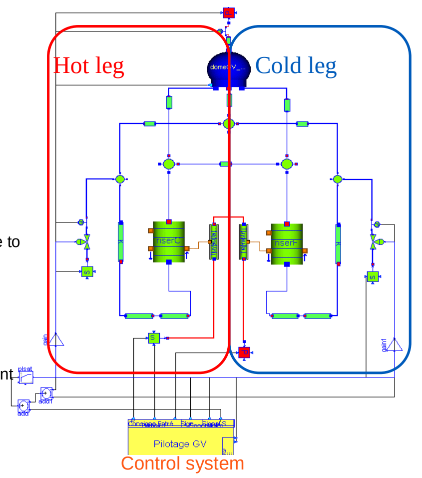
- Each leg modelled as one simple adiabatic pipe to represent the effect of gravity

## Separators:

- Pressure losses (simple pipes)
- Two-phase cavity

## Control system:

- Water level control
- Follow-up of primary mass flow temporal profile during EP RGL4 transient




Network of connected Modelica components

MODELICA

## Results and conclusion

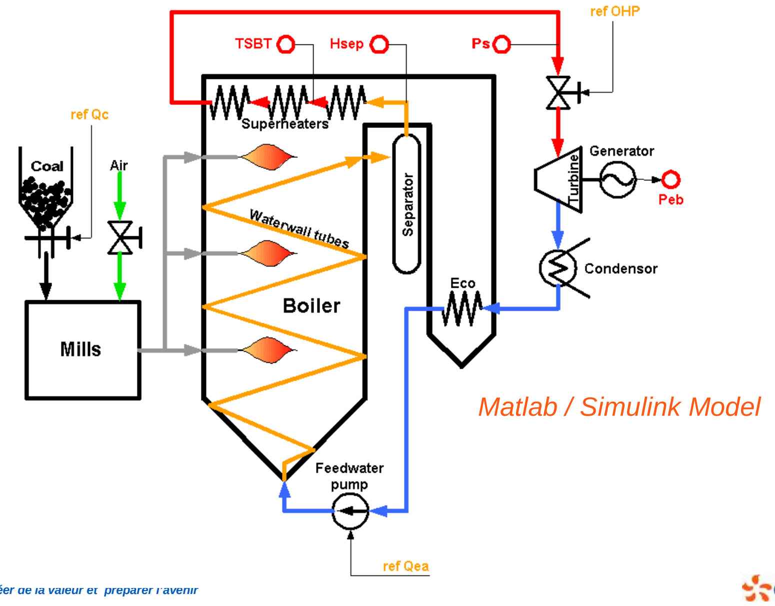
- It is possible to compute a global estimator of the TSP blockage rate. This indicator is very useful for the planning of the yearly maintenance operations.
- This global estimator is obtained using a dynamic model of the SG written in the object-oriented Modelica language.
- It is important to know how PWR components are for ancillary services : reserves must be available at any time



# New Advanced Controller at Cordemais 5 (France)

CHANGER L'ÉNERGIE ENSEMBLE

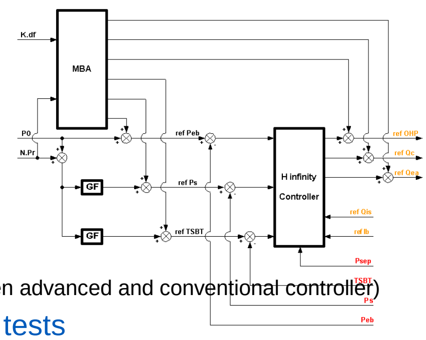
# Q600 coal power plant




*Matlab / Simulink Model*



# Advanced control methodology

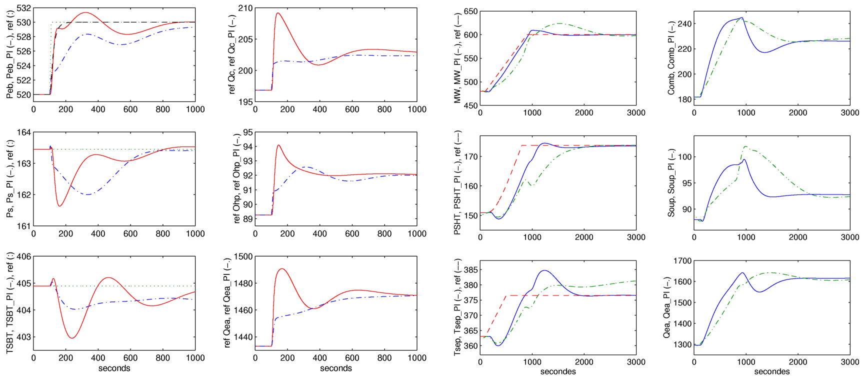



- On-site open loop tests
  - PI in manual mode
  - Steps applied to the process (actuators)
- Modelling, identification algorithms
- Design
  - Advanced controller synthesis (H∞ controller)
  - Simulation in closed loop (comparisons between advanced and conventional controller)
- Implementation & on-site validation tests

## Advanced controller for ancillary services

- Primary criteria
- Secondary criteria

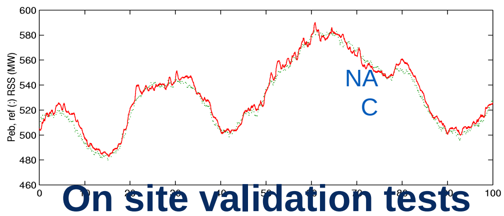
Response simulation



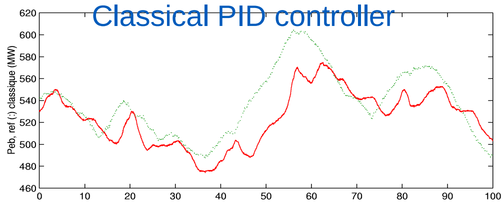


## Advanced controller for ancillary services

- Load follow-up under normal operation: ref Peb = P0 + K.Δf + N.Pr




**On site validation tests**

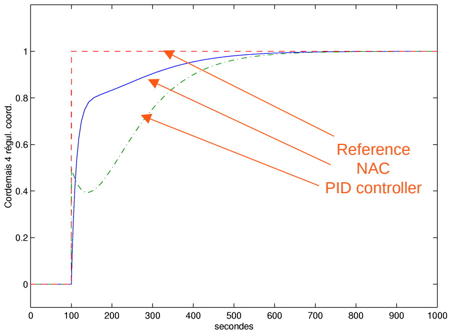


# Advanced controller for ancillary services

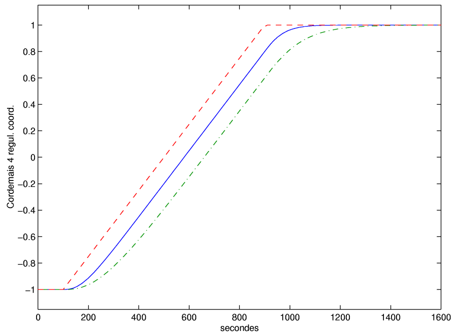
## The Model Base Anticipation (MBA) added value

- Open-loop anticipation on Actuators and References

➔ Enhancement of dynamic performance must be taken into account for system




Primary reserve




Secondary reserve