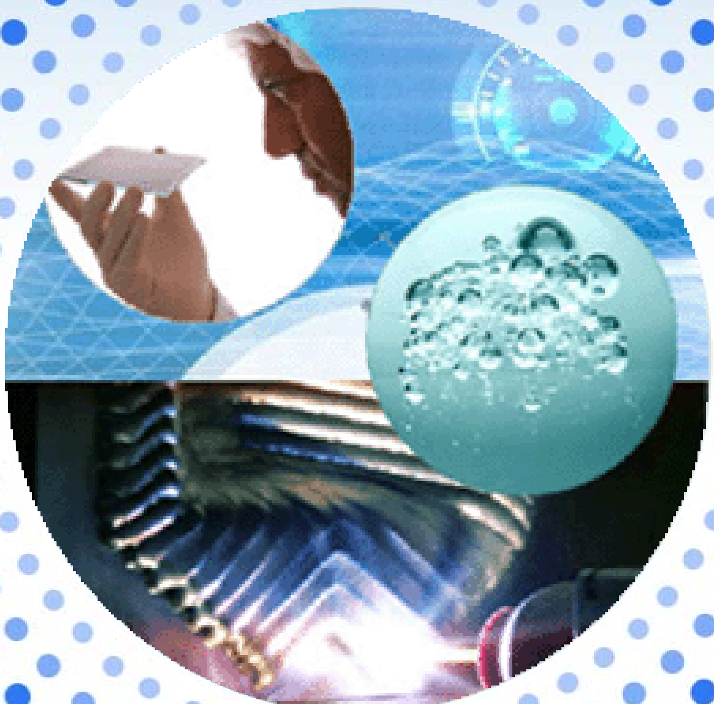
Optimization of CC & HPV power plants with HD-MPC



D. Faille, F. Davelaar (EDF)
A. Tica, H Guéguen (SUPELEC)

HD-MPC Workshop,Leuven,24/06/2011

HD–MPC

eDF R&D

Agenda

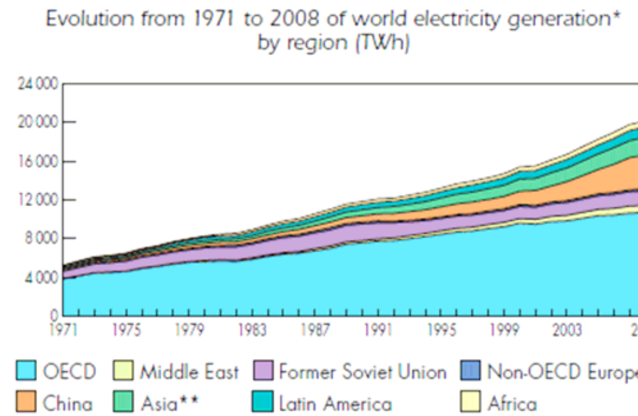
- Introduction
  - ✓ New Challenges for power generation
  - ✓ Motivation for HD-MPC solution
- Optimal control of CC & HPV Operation
  - ✓ Process Description & Control Objectives
  - ✓ HD-MPC solutions
  - ✓ Results
- Conclusion , Lessons Learned

Introduction

- ✓ Driving factors for Power Plant Optimization
- ✓ Grid requirements
- ✓ HD-MPC solutions for power plant optimization

Drivers for Power Plant Optimization

- ✓ World Demand Electricity Increases
- ✓ Raw Material Prices Increases
- ✓ Climate Changes
- ✓ Electricity Market Liberalization
- ✓ Grid Stability

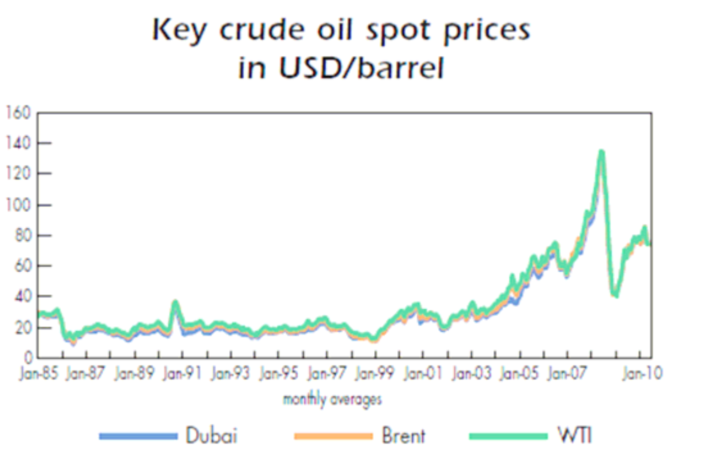


Environment
(air, water, waste)

Power Plants
Optimizations

Grid
(Voltage, frequency)

Cost
(Fuel, Maintenance)



HD–MPC
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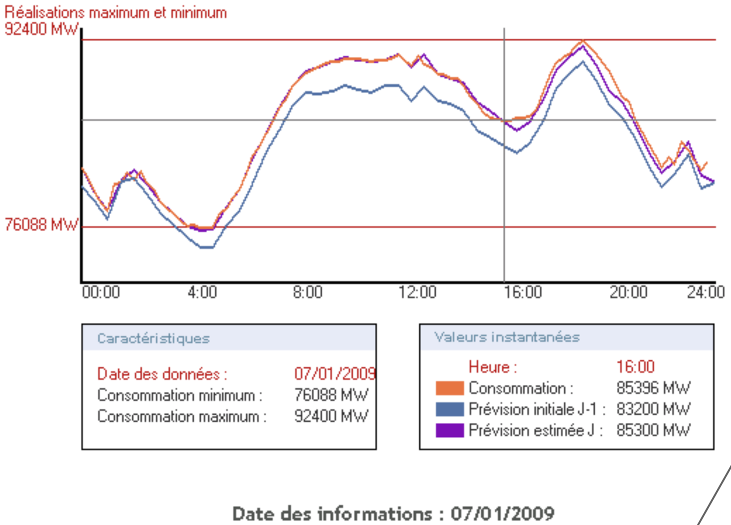
Ex: Grid Requirements. (UCTE)

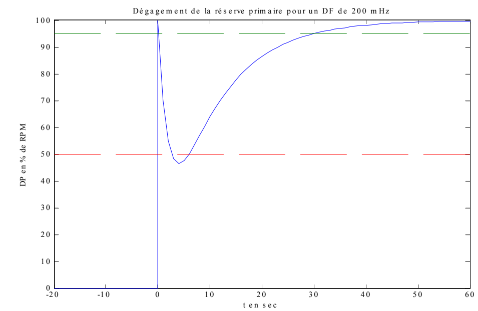


$P = Po + k\,\Delta F + N\,pr$

Active Power Set-point :

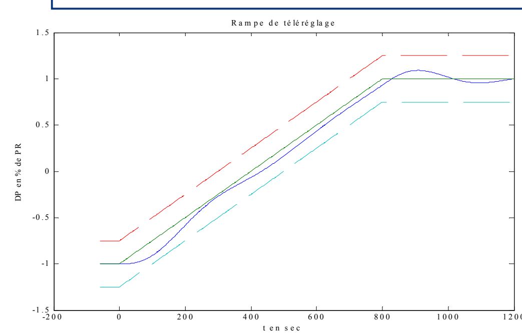
Po : Daily program

k ΔF : Primary. freq. response



100 % in 30s.

N Pr : Secondary . freq. response



2*Pr in 800 s

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HD-MPC for Power Plant optimization

Goal : Find new solutions for Power Plant Operations adapted to :

- ❑ Large Interconnected Systems
- ❑ Multiple objectives
- ❑ Non linear dynamics
- ❑ Different Time Scales

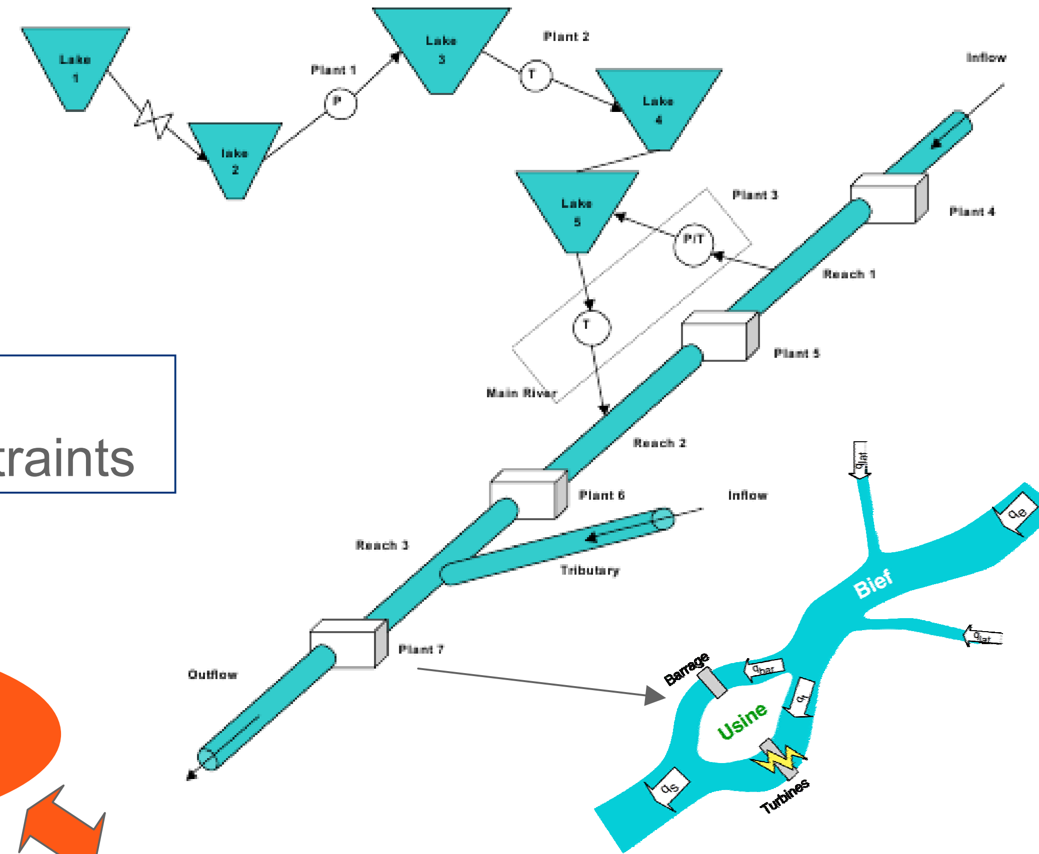
Hydro Power Valley

- ✓ Process Description & Control Objectives
- ✓ Modeling & HD-MPC solutions
- ✓ Results

HD–MPC R&D

Process & Control Description

- ✓ 4 run-of-river power plants
- ✓ 5 Reservoirs



Environment
Level, flow rate constraints

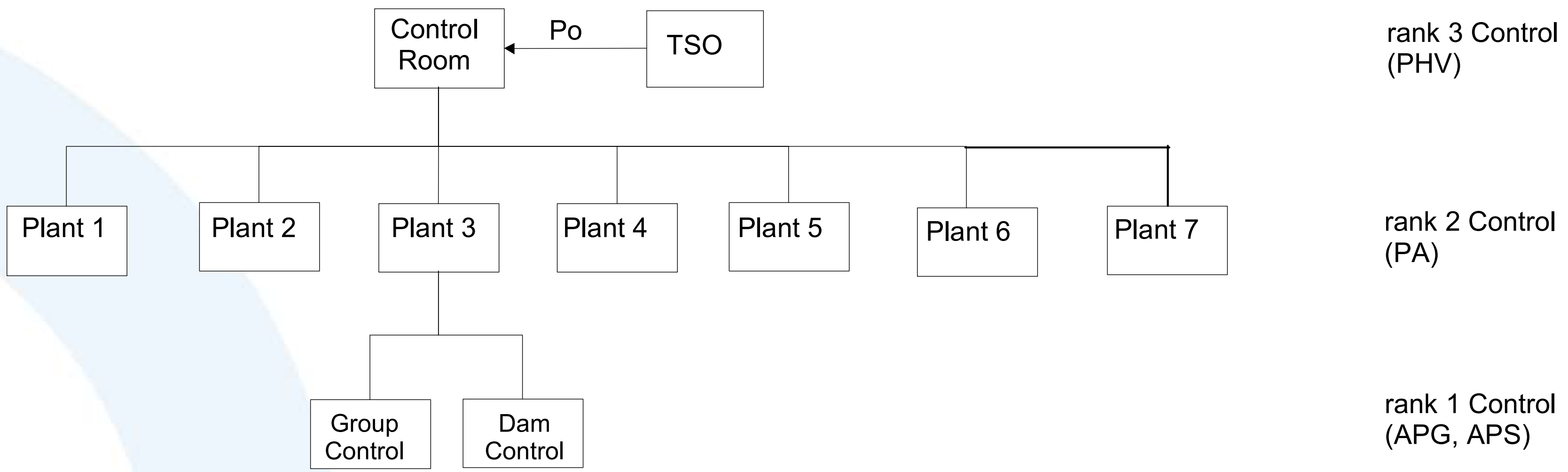
HPV Optimizations

Grid
Po + kDF + NPr

Cost
(Limited Storage)

HD–MPC eDF R&D

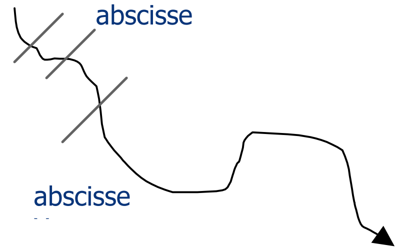
Process & Control Description

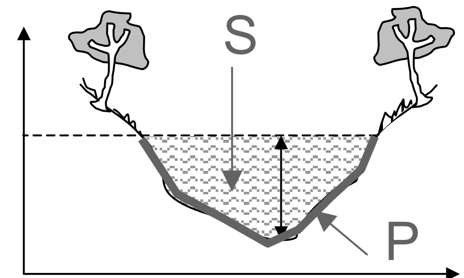


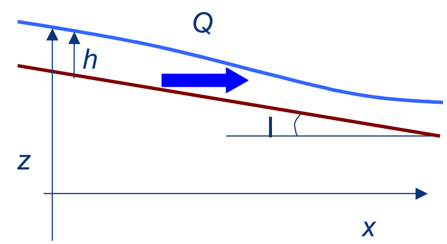
- Rank 3 : Alert, Supervision, Dispatching, Valley Control Room, Communication with TSO
- Rank 2 : Level/flow control, Machine Commitment, RSFP, RSFT
- Rank 1 : Safety functions, group start-up & shutdown

Modeling of a River Reach

x : longitudinal coordinate [m]
t : time [s]
S(x,t) : wetted section [m²]
P(x,t) : wetted perimeter [m]
Q(x,t) : volumetric flow [m³/s]
q_{lat} : lateral inflow per unit length [m²/s]
z(x,t) : height [m]
K : Strickler Coefficient [SI]
k : lateral inflow coefficient







Mass Conservation equation

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

Momentum conservation equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{S}\right) + gS\left(\frac{\partial z}{\partial x} + J\right) = k.q_{lat}.v$$

$$J = \frac{Q|Q|}{S^2 R_h^{4/3} K^2} \qquad R_h = \frac{S(x,t)}{P(x,t)}$$

Control Models

Spatial Discretisation of Saint-Venant Equations

$$\begin{cases} \dfrac{\partial h_1}{\partial t} = -\dfrac{1}{w_1} \cdot \dfrac{q_1 - q_e - q_{lat_1}}{dx} \\ \dfrac{\partial q_1}{\partial t} = -\dfrac{2q_1}{w_1 h_1} \cdot \dfrac{q_1 - q_e}{dx} + \left[\dfrac{1}{w_1} \left(\dfrac{q_1}{w_1} \right)^2 - g w_1 h_1 \right] \cdot \dfrac{h_2 - h_1}{dx} + \\ \qquad g w_1 S_b h_1 - \dfrac{g w_1 h_1}{k_{str}^2} \cdot \left(\dfrac{w_1 + 2h_1}{w_1 h_1} \right)^{4/3} \cdot \left(\dfrac{q_1}{w_1 h_1} \right)^2 \end{cases}$$

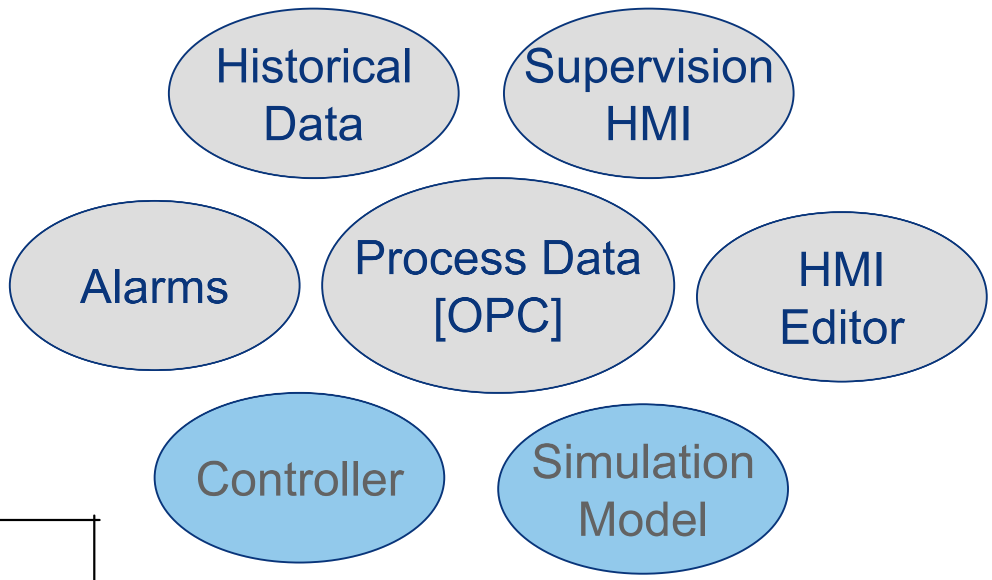
$$\begin{cases} \dfrac{\partial h_i}{\partial t} = -\dfrac{1}{w_i} \cdot \dfrac{q_i - q_{i-1} - q_{lat_i}}{dx} \\ \dfrac{\partial q_i}{\partial t} = -\dfrac{2q_i}{w_i h_i} \cdot \dfrac{q_i - q_{i-1}}{dx} + \left[\dfrac{1}{w_i} \left(\dfrac{q_i}{w_i} \right)^2 - g w_i h_i \right] \cdot \dfrac{h_{i+1} - h_i}{dx} + \\ \qquad g w_i S_b h_i - \dfrac{g w_i h_i}{k_{str}^2} \cdot \left(\dfrac{w_i + 2h_i}{w_i h_i} \right)^{4/3} \cdot \left(\dfrac{q_i}{w_i h_i} \right)^2 \end{cases}$$

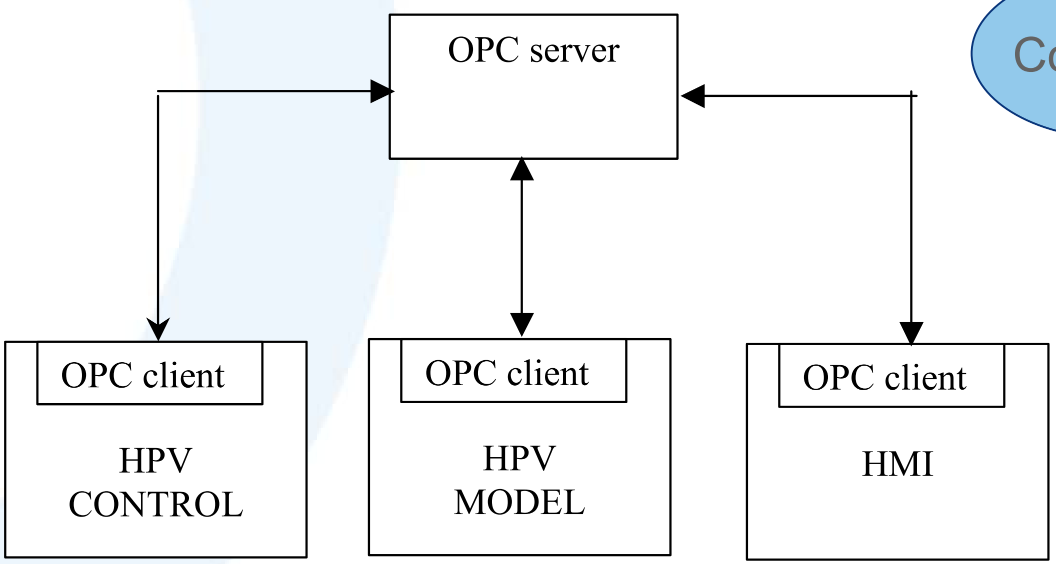
$$\frac{\partial h_{N+1}}{\partial t} = -\frac{1}{w_{N+1}} \cdot \frac{q_s - q_N}{dx}$$

Simulation platform

Platform made of :

- OPC server
- HMI (editor and supervisor)
- Alarms
- Archived data measurements
- Matlab + OPC Toolbox





HD-MPC solutions

Methods are under development

1) Centralized MPC controller – Reference
2) Two level Hierarchical MPC solution
3) Sensitivity-driven Gradient method (RWTH)
4) Multiple shooting Method (KUL)
5) Game theory (USE, UNC)
6) …

2-Level MPC solution

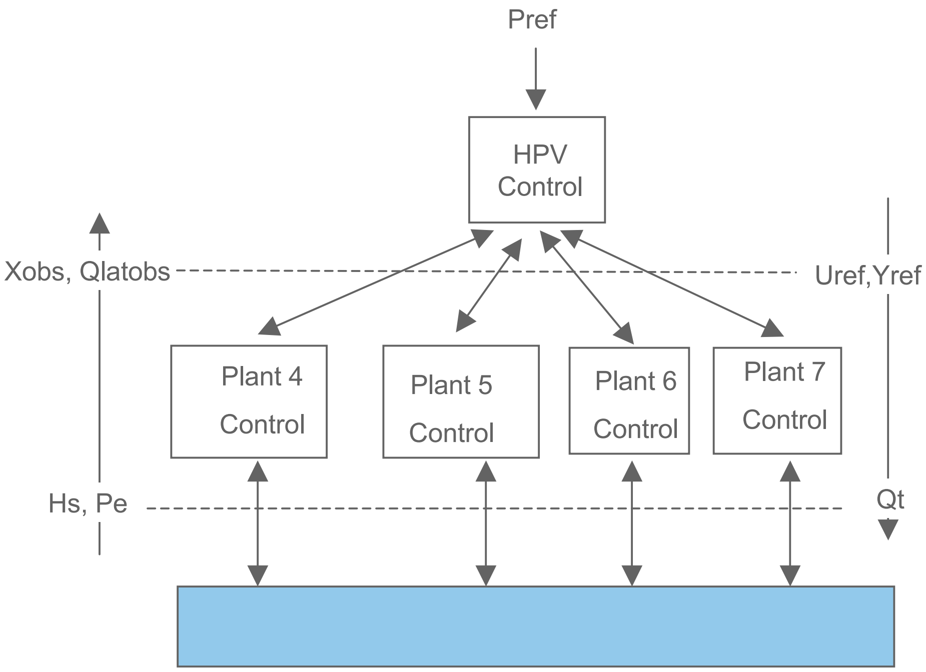
- Upper Level

$$J_{sup}[k] = \sum_{i=0}^{N_h^{sup}} (p_e[k+i] - p_{e\ ref}[k+i])^2$$

$$\underline{q_{t\ bief}} < q_{t\ bief} < \overline{q_{t\ bief}}$$

$$\underline{h_{s\ bief}} < h_{s\ bief} < \overline{h_{s\ bief}}$$

$$\left|q_t[k+1] - q_t[k]\right| < \overline{\Delta q_t}$$



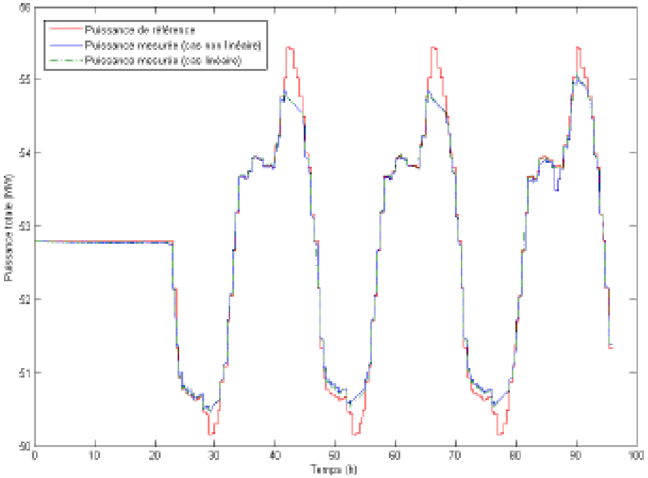
- Lower Level

$$J_{inf}[k] = \sum_{i=0}^{N_h^{inf}} \left\|u[k+i] - u_{ref}[k+i]\right\|_R + \left\|y[k+i] - y_{ref}[k+i]\right\|_Q$$

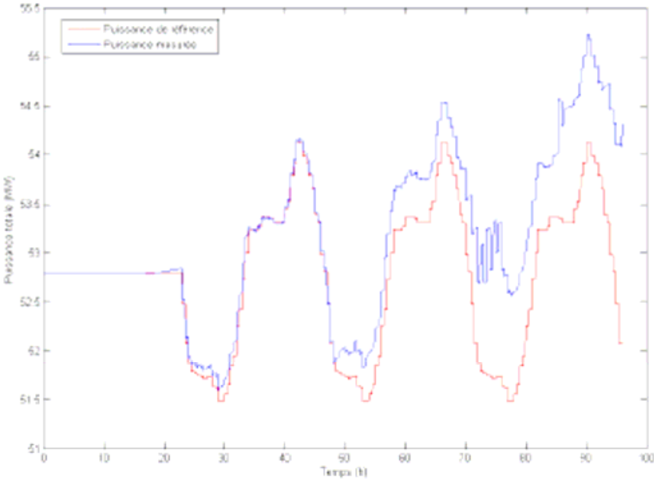
Results (Two level hierarchical MPC)

- Perturbation is correctly rejected when no constraints are active.
- Control performance decreases when constraints are active.

Load following



Load following with perturbation



HD–MPC

eDF R&D

Combined Cycle Start-up

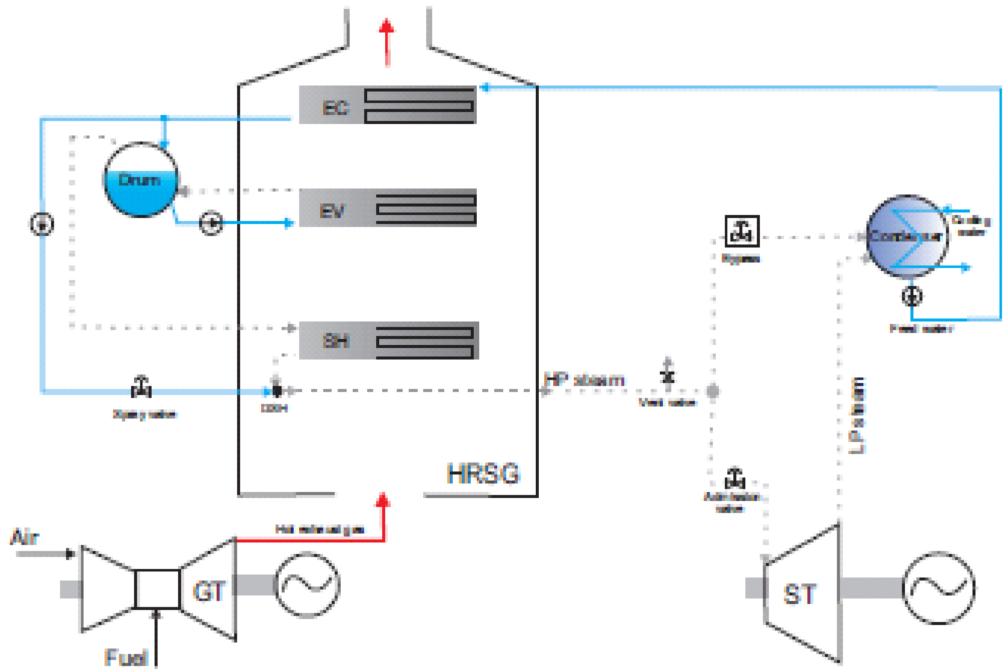
- ✓Process Description & Control Objectives
- ✓Modeling & HD-MPC solutions
- ✓Results

HD–MPC R&D

Process Description & Control

1 GT- 1 HRSG - 1ST

1 Pressure Level



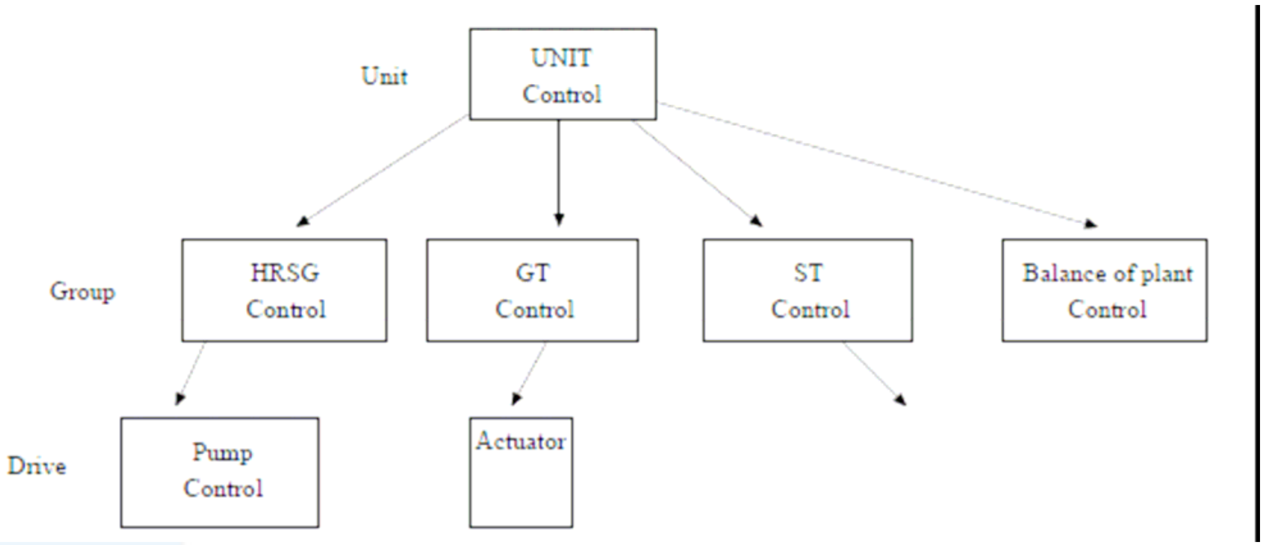
Environment
NOx, CO_2

CC SU Optimizations

Grid
Startup Time

Cost
Fuel, Water, Life Consumption

Process & Control Description



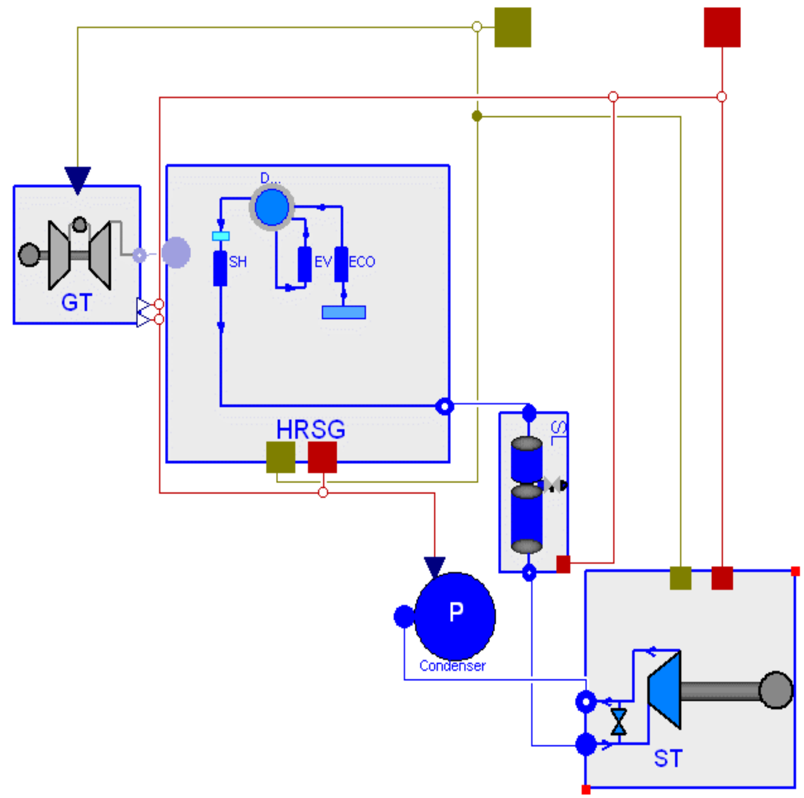
- Unit : General Sequence & Control
- Group : Sequence & Control Subsystem (Feedwater, Fuel, ….)
- Rank 1 : Sequence & Control of components (Pump, …)

CCPP modeling: Modelica

- CCPP model:
  - ✓ developed in Modelica language
  - ✓ using Modelica simulation environment, Dymola
- Modelica: modeling language for large, complex and heterogeneous physical systems:
  - ✓ Free language
  - ✓ Object-oriented
  - ✓ Equation based
  - ✓ Multi-domain

CCPP model - Dymola

- 1-1-1 configuration (GT-HRSG-ST)
- One single level of pressure (HP)
- Equations derived from first principles (mass, energy and momentum balances)
- Model complex: ~ 1500 equations
- Validated against experimental data
- Includes a model of thermal and mechanical stress in critical components (superheated steam header and ST rotor)
- Smooth model have been developed for optimization



CCPP - Plant inputs/outputs

Inputs:

- **load of GT**
- feed water flow rate for the HRSG circuit
- water flow feeding the desuperheater
- position of bypass valve
- position of throttle valve
- generator grid breaker of the steam turbine

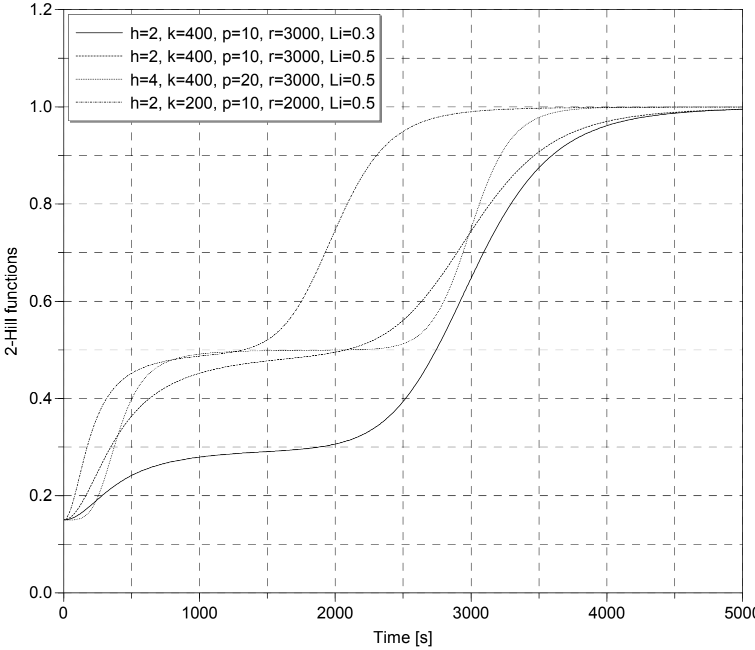
Outputs:

- power of GT
- fuel flow in GT
- drum level
- temperature of steam in the superheater
- steam flow
- header stress
- temperature of steam in the SL
- power of ST
- frequency of ST
- rotor stress of ST

GT Load profile –Optimization

CCPP non-linear model: $\dot{x}(t) = f(x(t), u, L(t))$

- x = model states (temperatures, pressures, enthalpy...)
- u = model inputs (feed water, feed DSH...)
- L = GT load
  - ✓ initial load L(t0) = Lm
  - ✓ full load L(tf) = LM



- Assumption:
  GT Load is a parameterized function:
  L(t,q) sum of 2 Hill functions

$$L(t,q) = L_m + (L_i - L_m)\frac{t^h}{t^h + k^h} + (L_M - L_i)\frac{t^p}{t^p + r^p}$$

$q=[h, k, p, r, L_i]$

HD–MPC eDF R&D

GT Load profile optimization

- Minimum time problem definition:

$$\min_{q,t_f} J = \int_{t_0}^{t_f} dt$$

Parameters to be optimized:
t_f, q=[h,k,p,r,Li]

- subject to the constraints:

$$\dot{x}(t) = f(x(t),u,L(t,q))$$
$$L(t_f,q) \geq L_M - \varepsilon_1$$
$$\left|f(x(t_f),u,L(t_f,q))\right| \leq \varepsilon_2$$
$$h(x(t)) \leq 0,\ t_0 \leq t \leq t_f$$

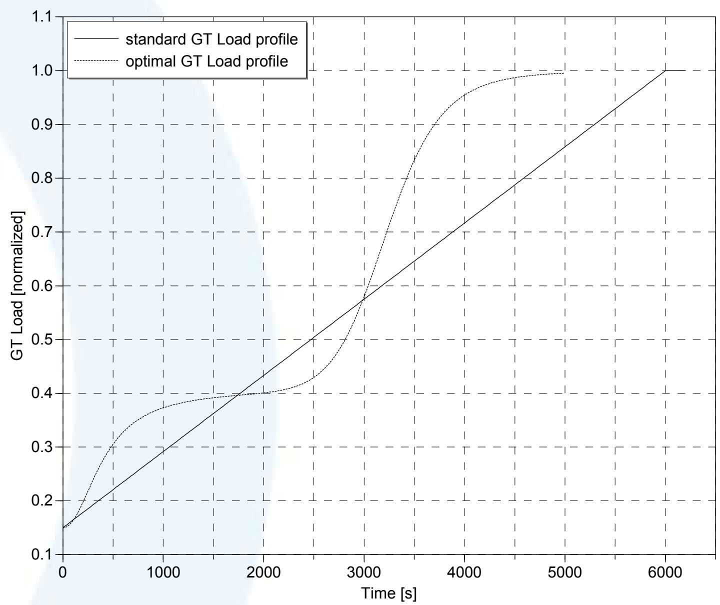
constraints on the state variables (temperatures, pressures, stresses)

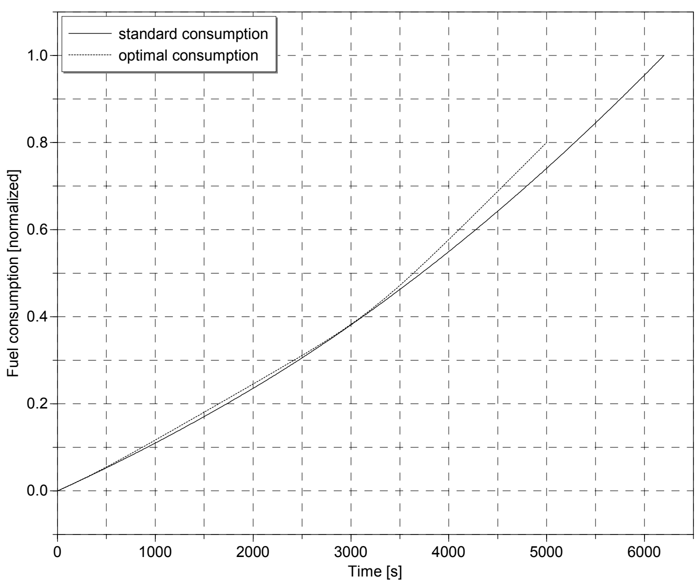
HD–MPC

eDF R&D

Optimization Results

- Optimal start-up is 20 minutes faster than a classical start-up (with a constant GT load ramp rate satisfying the stress limit)

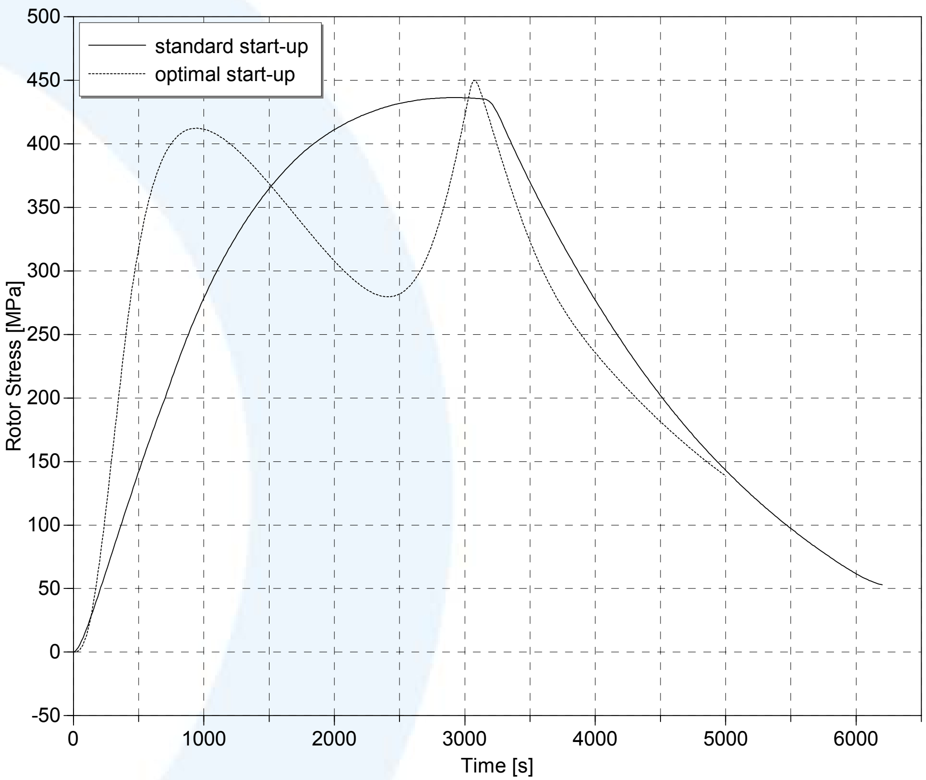




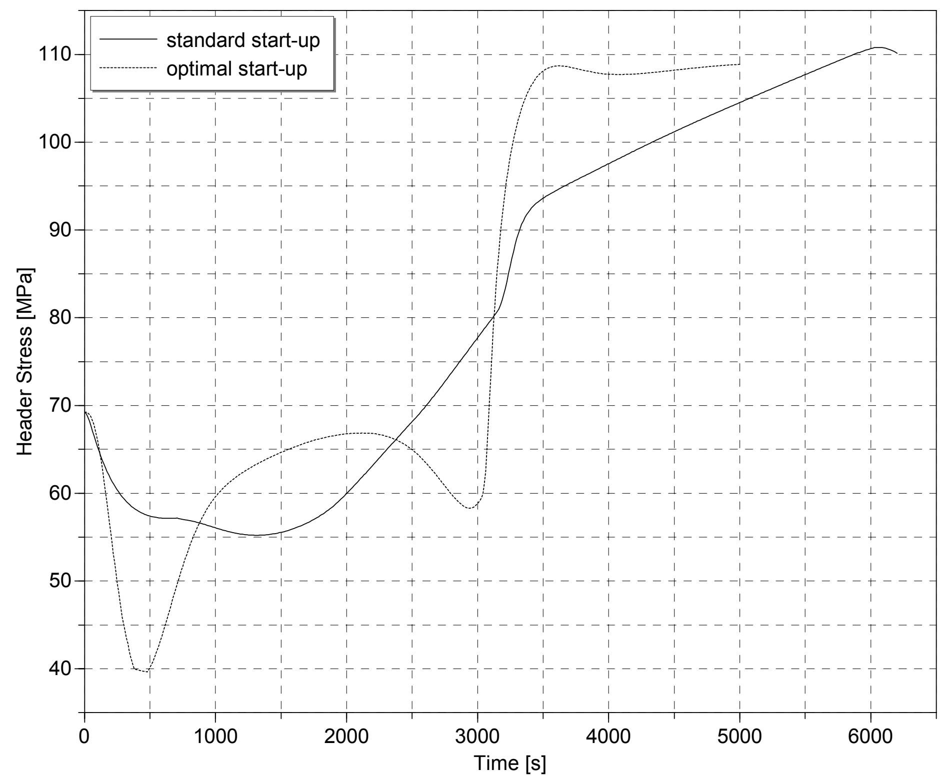
⇒ reduction of the operating costs due to lower fuel consumption (≈ 20 %)

Optimization Results

- Rotor stress:



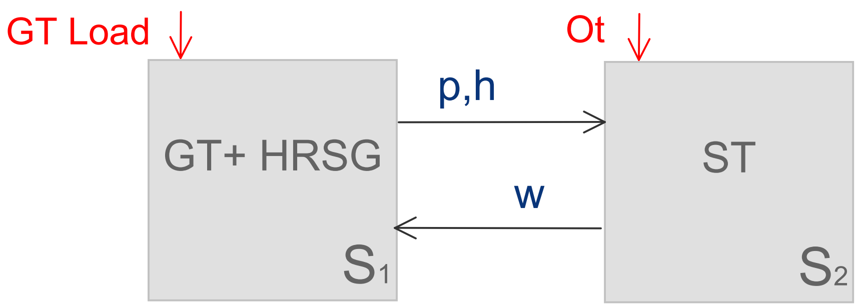
- Header stress:



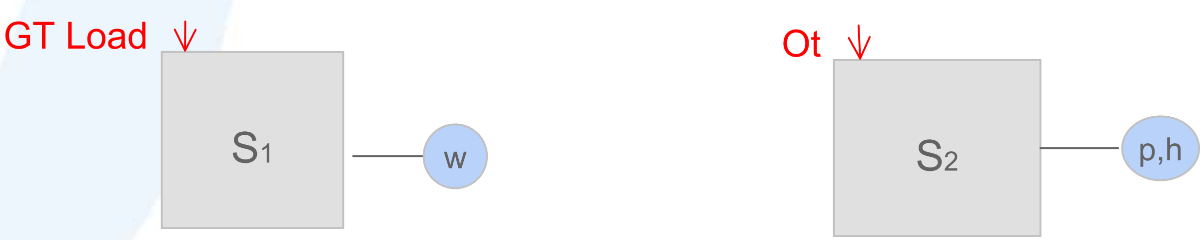
HD–MPC R&D

Distributed Approach

- Model decomposition



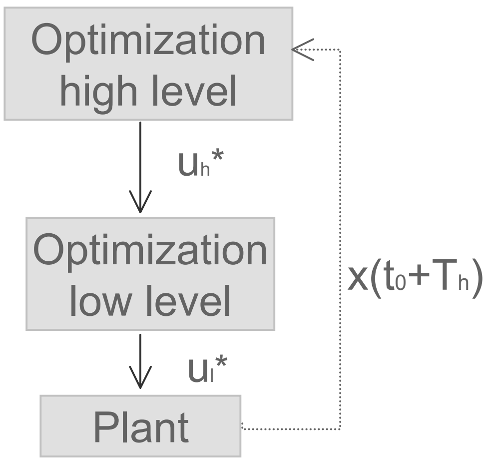
- 2 profiles optimization (GT Load, Ot)
- Physical decomposition: 2 Dymola models



HD–MPC eDF R&D

Hierarchical Approach

- High level:
  - Minimal time: $$\min_{q,t_f} J = \int_{t_0}^{t_f} dt$$
  - $u_h^* = L_1(q,t)$
  - T_h – HL sample time



- Low level:
  - Quadratic: $$\min_{u(q,t)} J = \int_{t_0}^{t_0+T_h} (u(q,t) - u_h^*(q, t_0 + T_c))^2 \, dt$$
  - $u_l^* = L_2(q,t)$, $T_c \geq T_h$
  - T_l – LL sample time

Summary

- A Modelica model based on the ThermoPower library is developed and used for start-up optimization
- The start-up optimization method is based on parameterized functions
- This approach is used to minimize the start-up time, while keeping the constraints within their limits
- The idea of solving the start-up problem by optimizing a parameterized function can be expanded in many ways (e.g. by considering other types of functions, by using as optimization signals other model inputs (ST throttle)
- Further work: use this optimization procedure in hierarchical and distributed feedback control algorithms (HD-MPC)

HD–MPC eDF R&D

General conclusion & lessons learned

- ❑ Solutions are still under development,
- ❑ HD-MPC solutions can be applied naturally in the HPV case.
- ❑ HD-MPC Optimization with Modelica CCPP models is difficult.
  - ✓ Library developed for simulation are not suited for optimization (discontinuities)
  - ✓ Initialization problems with Dymola
  - ✓ Analytical Jacobian is not available for complex Dymola models
  - ✓ Unfeasible simulation occurs (water-steam table)

HD–MPC eDF R&D