IFAC World Congress - Milano 2011
Workshop on Hierarchical and Distributed MPC: Algorithms and Applications

Start-Up of Combined Cycle Power Plants

A. Tica, **H Guéguen**, D. Dumur - SUPELEC
D. Faille, F. Davelaar - EDF

HD−MPC

SEVENTH FRAMEWORK PROGRAMME

General context

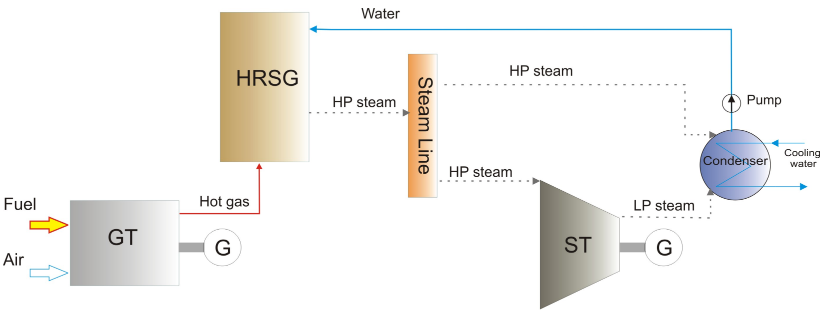
- Diffusion of Combined Cycle Power Plants (CCPP)
  - Efficiency
  - Lower pollutant emissions
- Production to consumption fit
  - Partial load (ancillary services)
  - Frequent start-up and shut-down
- Flexibility Improvement
  - Reduction of start-up and shut-down time
  - Avoidance of start-up failure
  - Minimization of life-time consumption

CCPP are complex plants with numerous systems and sub-systems

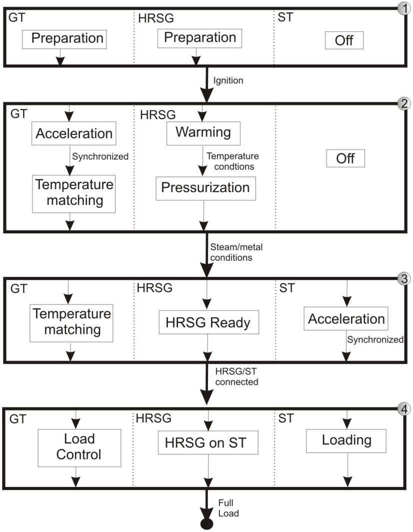
Objectives

- How can MPC control help to reduce start-up time while saving life-time consumption?
- How can Distribution and Hierarchy help to design and implement control?
- How can design models (Modelica) of the plant be used for operationnal phases?

Schematic view



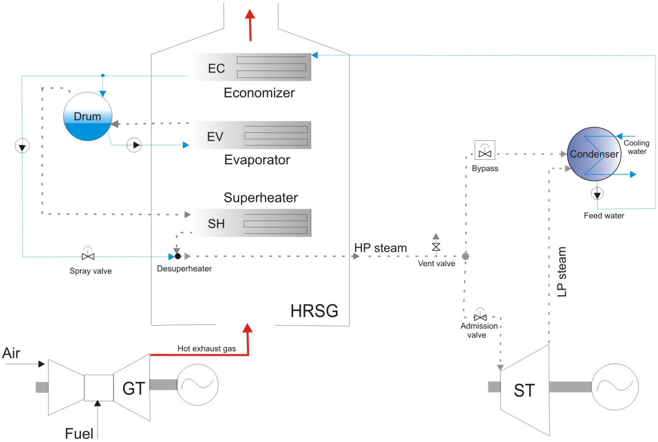
Start-up procedure



Modelica model
Politecnico di Milano (F Casella)

- 1 1 1 CCPP with 3 levels of pressure
- ThermoPower Library
- can be used from low load to high load
- Simplified model:
  - gas turbine
  - low pressure components
- Stress model of critical components
  - high and intermediate pressure superheated steam headers
  - high and intermediate pressure steam turbine rotor

1-1-1 CCPP with 1 level of pressure



Increasing Load Phase

Initial state

- Turbine generators are connected to the grid
- Gas turbine load is around 15%
- Pressure is around 60 e5 Pa
- Steam is admitted in steam turbine (Bypass valve is closed)

Aim: full load

- GT load near 100%
- admission valve: fully open

Local control

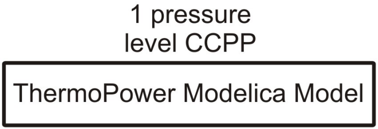
- Gas turbine control
- Feed water flow by drum level control loop
- *Steam turbine admission valve by control wrt gas turbine load*
  - when GT load $\leq 50\%$: open-loop control of pressure
  - when GT load $> 50\%$: fully open

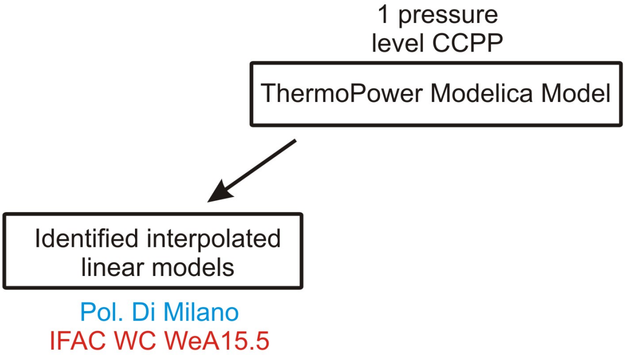
Control

- Minimize start-up time
- Constraints on stress level
- Control variables: GTload, *admission valve*

Modelica Model

- ThermoPower library
- Stress model (ASME)
  - Header stress: combination of mechanical and thermal stress
  - Rotor stress: thermal stress
- Complexity
  - $\approx$2400 equations
  - 42 state variables
  - simulation time for increasing load phase: 12.4s (PC with 2 GHz CPU)


1 pressure
level CCPP
ThermoPower Modelica Model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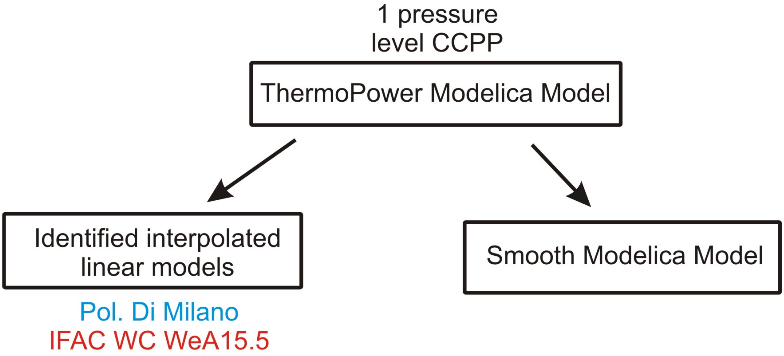
Identified interpolated
linear models
Pol. Di Milano
IFAC WC WeA15.5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Smooth Modelica Model
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- Aim:
  - elimination of discontinuities
    - *if* clauses
    - piecewise affine functions
    - steam/water tables
  - reduction of simulation time
- Constraint: keep the structure of the ThermoPower model
  - corresponding components
  - new media functions for steam and water

- simplification/specialization of some components (e.g. reverse flow elimination)
- discontinuities approximations

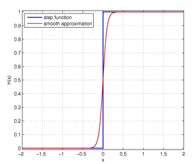
Smooth Model

- simplification/specialization of some components (e.g. reverse flow elimination)
- discontinuities approximations

Discontinuity approximation

$$\forall x \in R \; H(x) = \begin{cases} 0 & x < 0 \\ 1 & x \geq 0 \end{cases}$$

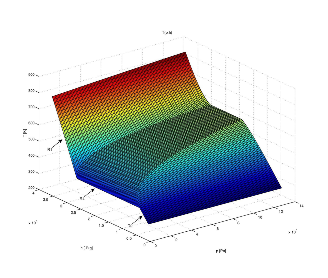
$$\forall x \in R \; H_k(x) = \frac{1}{1 + e^{-kx}}$$

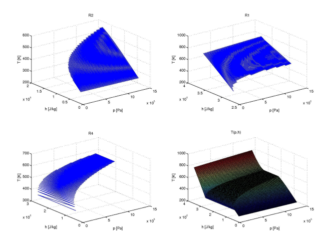


Steam/Water functions approximation

piecewise polynomial approximations of the Modelica.Media functions

e.g. $T = f(P, h)$

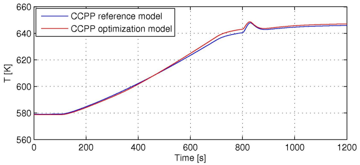




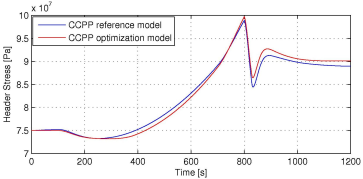
Complexity

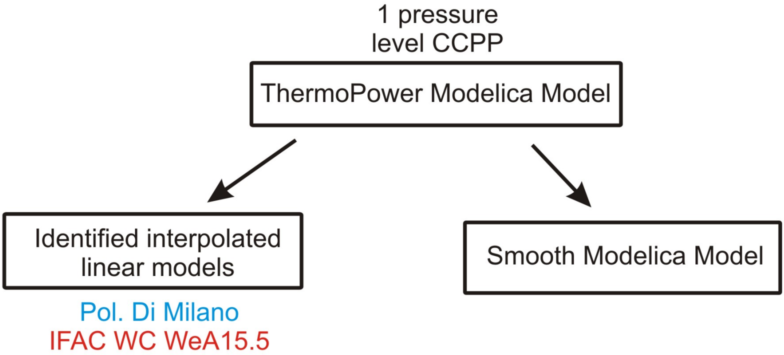
- ≈2000 equations
- 42 state variables
- simulation time for increasing load phase: 1.4s (PC with 2 GHz CPU)

temperature



header stress

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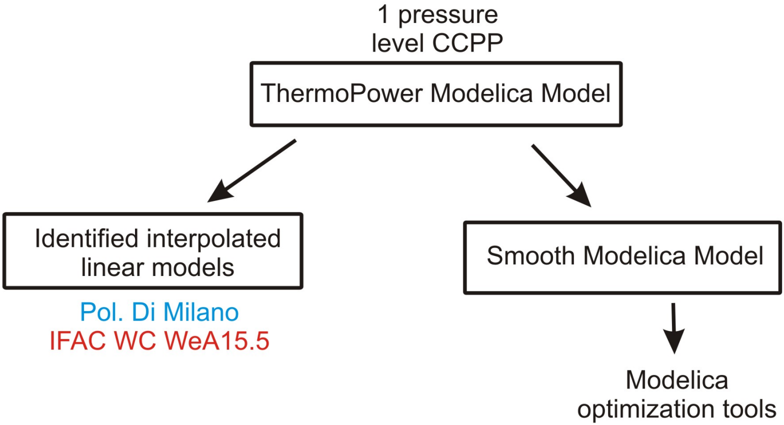
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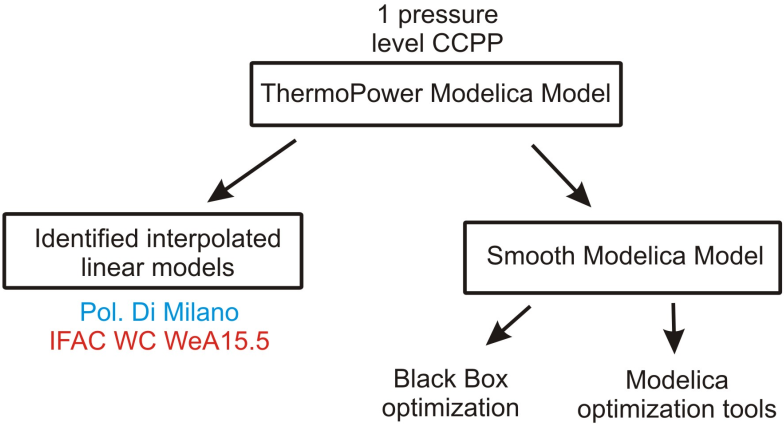
Modelica
optimization tools

Overview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Black Box
optimization
Modelica
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Profile optimization.

- Choice of parametrized profiles: $L(t) = L_p(t, q)$, e.g.

$$L_{2H}(t,q) = L_m + (L_i - L_m)\,\frac{t^h}{t^h + k^h} + (L_M - L_i)\,\frac{t^p}{t^p + r^p}$$

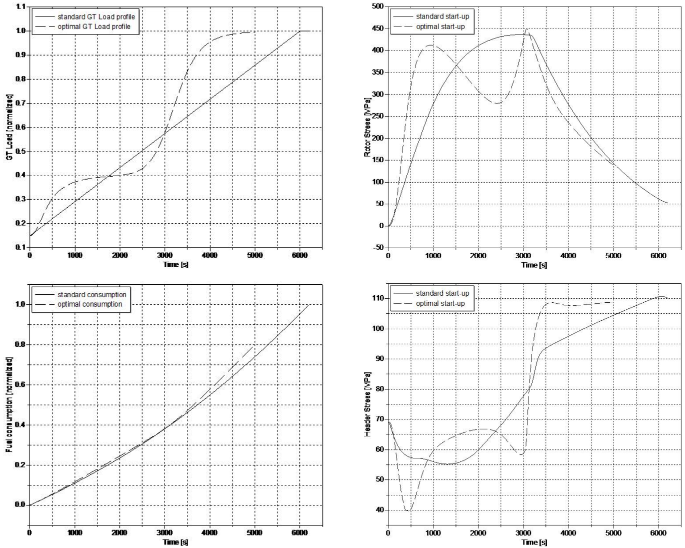
- Optimization problem

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

subject to the constraints

$$\begin{aligned} \dot{x} &= f(x, L_p(t,q)) \\ L_p(t_f, q) &\geq L_M - \epsilon_1 \\ \|f\,(x(t_f), L_p(t_f, q))\| &\leq \epsilon_2 \\ h\,(x(t)) &\leq 0 \end{aligned}$$

Example: $L_{2H}(t,q)$ gains wrt ramp: time 20%; consumption 20%



- Gas turbine load
  - 2 hills functions; start-up time: 4790s (-20%)
  - spline functions (3); start-up time: 4530s (-25%)
- Gas turbine load and steam turbine admission valve
  - spline functions (2); start-up time: 4440s (-26%)

- Control variable: gas turbine load
- Every computation time (T_C)
  - profile computation for the next $N.T_C$
  - Lagrange polynomials (N)
  - minimization of $J = \int_{t_0}^{t_0+N.T_c} \left\| L_{L_N}(t, q) - L_0\left(L(t_0)\right) \right\|^2 dt$

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Start-up time: 3400s (-43%) [$T_C = 60s, N = 5$]

Hierarchical MPC control

- Robustness of control
  - Introduction of variations into the model?
  - Simulation on sets?

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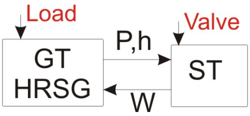
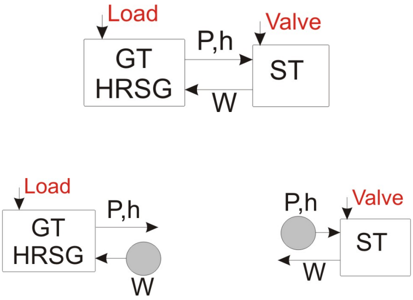
Distributed control

- Gradient based methods?
- Robustness?
- Range of admissible input signals

Example



Example



- Smooth Modelica model for a 1-1-1 1 pressure level CCPP
  - new components / media consistent with ThermoPower
  - systematic design of the optimisation model
- Start-up profile optimization
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  - importance of profile functions

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  - new components / media consistent with ThermoPower
  - systematic design of the optimisation model
- Start-up profile optimization
  - reduction of start-up time
  - importance of profile functions
- Such approach for such plants is still challenging
  - optimization tools / model development
  - simulation tools: admissible state and feasible trajectories
  - distributed approaches: steam interactions