Start-Up of Combined Cycle Power Plants

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HD–MPC

SEVENTH FRAMEWORK PROGRAMME
Introduction

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 of a Combined Cycle Power Plant.

- **GT (Gas Turbine)**: Fuel and Air enter, Hot gas exits.
- **HRSG (Heat Recovery Steam Generator)**: Water enters and HP steam exits.
- **Steam Line**: HP steam flows from HRSG to ST (Steam Turbine).
- **ST (Steam Turbine)**: HP steam enters and LP steam exits.
- **Condenser**: Cooling water enters and hot water exits.
- **Pump**: Water is pumped from the condenser back to the HRSG.
Start-up procedure

1. GT Preparation → HRSG Preparation → ST Off
2. GT Ignition → HRSG Warming → ST Off
3. GT Acceleration → HRSG Temperature matching → ST Synchronized
4. GT Temperature matching → HRSG HRSG Ready → ST Acceleration
5. GT HRSG Synchronized → HRSG/ST connected → ST Loading
6. GT Load Control → HRSG HRSG on ST → ST Full Load
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

Case Study

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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
1 pressure level CCPP

ThermoPower Modelica Model

Identified interpolated linear models

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Overview

1 pressure level CCPP

ThermoPower Modelica Model

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

Discontinuity approximation

\[ \forall x \in \mathbb{R} \quad H(x) = \begin{cases} 
0 & x < 0 \\
1 & x \geq 0 
\end{cases} \]

\[ \forall x \in \mathbb{R} \quad H_k(x) = \frac{1}{1 + e^{-kx}} \]
Steam/Water functions approximation

piecewise polynomial approximations of the Modelica.Media functions

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

Complexity
- \( \approx 2000 \) equations
- 42 state variables
- Simulation time for increasing load phase: 1.4s (PC with 2 GHz CPU)

- Temperature
- Header stress
Overview

1 pressure level CCPP

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- Smooth Modelica Model
  Modelica optimization tools

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Smooth Modelica Model

Black Box optimization

Modelica optimization tools
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
  \[ \min_{t_f, q}(J), \quad J = \int_{t_f}^{t_0} dt \]
  subject to the constraints
  \[
  \dot{x} = f(x, L_p(t, q)) \\
  L_p(t_f, q) \geq L_M - \epsilon_1 \\
  \|f(x(t_f), L_p(t_f, q))\| \leq \epsilon_2 \\
  h(x(t)) \leq 0
  \]
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 $N \cdot T_C$
- Lagrange polynomials ($N$)
- minimization of

$$J = \int_{t_0}^{t_0 + N \cdot T_c} \| L_{LN}(t, q) - L_0(L(t_0)) \|^2 \, dt$$
Control variable: gas turbine load

Every computation time ($T_C$)

- profile computation for the next $N \cdot T_C$
- Lagrange polynomials ($N$)
- minimization of $J = \int_{t_0}^{t_0 + N \cdot T_c} \| L_{L_N}(t, q) - L_0(L(t_0)) \|^2 dt$

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?
Hierarchical MPC control

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Distributed control

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

Hierarchy and Distribution
Example

Hierarchy and Distribution
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
- reduction of start-up time
- importance of profile functions
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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