Polygeneration system design with optimal predictive control strategies

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Outline

- Polygeneration and smart grids
- System Design perspective
- Optimal predictive control strategies
- Conclusions
Transition in grids technology

- Centralised unidirectional conventional grid
- Decentralised bidirectional smart grids
- Heat/cold and electricity

Smart grids configuration

- Connected to the main grid
  - Stochastic Renewable sources
- Virtual Power Plant (VPP)
  - Heat driven consumers/producers
    - Cogeneration
    - Heat pumps
- Heat/cold storage Tanks
  - Predictive control

*VPP: Virtual Power Plant
**MPC: Model Predictive Control
Polygeneration in a building

- Mid-season typical day demand

Exergy Power requirement [kW]

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Model predictive control characteristics

- Combined electricity and thermal supply
  - Comfort (T room)
  - Electricity cons.
  - Services (washing ?)
- Based on predictions
  - Heat/cold and electricity requirement
  - Energy market
- System management
  - Storage tanks levels and T
  - Energy conversion control
    - ON/OFF @ t
    - Level of usage during t
Energy system design problem

- **Energy system = for each VPP (n)**
  - Investments (expected life time: 20 Years)
    - Energy Conversion Units
    - Storage
    - \( \forall u \in Units; \forall n \in Nodes \Rightarrow Size_{u,n} \)
    - \( \forall s \in Storage; \forall n \in Nodes \Rightarrow V_{s,n} \)
    - \( \sum_{n=1}^{Nodes} \sum_{u=1}^{Units} \frac{1}{T_y,i}(I(Size_{u,n}) + I(V_{s,n})) \)
  - Operating costs (expected operation time = 25x8760h)
    - Management strategy
    - \( \forall s \in Storage; \forall n \in Nodes; \forall t \in \text{time} \Rightarrow m_{u,n}(t), V_{s,n}(t), \dot{E}(t) \)
    - \( \int_{t=1}^{\text{Time units}} \left( \sum_{u=1}^{\text{units}} (c_T(t)m_{T(u),n}(t)) + c_c(t)\dot{E}(t) \right) dt \)
  - Constraints
    - Energy services
    - Grid capacities
    - Grid constraints
    - \( \forall n \in Nodes; \forall t \in Time; \forall c \in \text{Cons.} \Rightarrow \dot{Q}_{n,c}(t), \dot{E}_{n,c}(t) \)
    - \( \forall t \in Time : \sum_{n=1}^{Nodes} \dot{E}(t) \leq \dot{E}_{\text{max}}(t) \)
    - \( \forall q \in \text{quarter(Time)} : \sum_{n=1}^{\text{Nodes}} \int_{t=q}^{t=q+15} |\dot{E}_n(t) - \dot{E}_n(t-1)| dt \leq \Delta \dot{E}_{\text{max}}(t) \)

**Constraints**

- **Electricity production**
  - \( (e_{SOFC}(t) + e_{\text{grid}}(t)) - (e_{RC}(t) + e_{PAC}(t) + \text{cons.}e(t)) \geq 0(\text{kW}) \) (2)
- **Heat production**
  - \( e_{SOFC}(t)/\eta_h \cdot \eta_h - ((AC2(t)/AC2_{COP}) + \text{HEX.heat}(t) + \text{usable.heat}(t)) \geq 0(\text{kW}) \) (3)
  - \( \text{stored.energy}(t) = \text{stored.energy}(t-1) - \text{storage.lost}(t) - \text{storage.out}(t) + \text{storage.in}(t)(\text{kJ}) \) (4)
- **Storage balance**
  - \( T_{\text{stock}}(t = 1) = T_{\text{stock}}(t = 24)(\text{C}) \) (5)
  - \( \text{losses.param} = 10\% \cdot \text{stock.size} \cdot \rho_{\text{water}} \cdot C_{\text{water}} \cdot (T_{\text{max}} - T_{\text{room}})(\text{kJ}) \) (6)
- **Storage losses**
  - \( \text{storage.lost}(t) = \text{losses.param} \cdot \frac{1}{24 \cdot 3600} \cdot (T_{\text{stock}}(t) - T_{\text{room}})/(T_{\text{max}} - T_{\text{room}})(\text{kW}) \) (7)
  - \( \text{cons.heat}(t) = \text{HEX.heat}(t) - \text{heat.stored}(t) + \text{heat.storage.out}(t) + e_{PAC}(t) \cdot \text{COP}_{PAC}(\text{kW}) \) (8)
- **Heat/cool cons**
  - \( \text{cons.cool}(t) = AC2(t) - \text{cool.storage.in}(t) + \text{cool.storage.out}(t) + e_{\text{RC}}(t) \cdot \text{RCOP}(\text{kW}) \) (9)
Challenges for smart grids system design

- **Predictions**
  - Ambient conditions
  - Behaviors
- **Multi-nodes**
  - Interactions via sub grids
    - Electrical (different type)
    - Heat
    - Information
- **Integration with main grids**
  - Electrical grid
  - Gas grid

Smart grids system design

- **Connected to the main grid**
- **Virtual Power Plant (VPP)**
  - Typified nodes
    - Cogeneration units
    - Heat pumps
    - Boilers
    - Cogen + Heat pumps
  - Can be district heating
- **Heat/cold storage capacity**

*VPP: Virtual Power Plant
**MPC: Model Predictive Control*
Design optimization strategy

- Multi-objective optimization
- For each unit in each node
- Configuration parameters and thermodynamic models
- Flow rates and temperatures of components
- Size of the storage devices
- Optimal control
  - Based on typical days
  - Each node
- Operation strategy for a set number of days
- Environomic model
- Electricity requirements, loads, data from grid
- Yearly emissions and cost

C. Weber et al., Optimization of an SOFC-based decentralized polygeneration system for providing energy services in an office-building in Tokyo, Applied Thermal Engineering

Defining the typical days

- **Represent 25 years of operation with a minimum time steps**
  - 7 Days + 7 steps sequence in 1 day
    - Cyclic constraints
    - Frequency calculation
    - Definition by Kmean clustering
  - from 219000 steps to 49 steps
  - => factor 5000 !
Example of results

Solution E
For each building:
Selected Technologies
Size of Technologies

Polygeneration system design results

- **Size of the units**
  - Active (e.g. cogen/heat pumps)
  - Passive (e.g. solar panels, wind)

- **Size of the storage tanks**
  - Volumes

- **Expected operating cost**!

- Engineer takes a decision
  => Now operate it!
Challenges for the management box

- **Stochasticity of demand**
  - Behaviours
  - Ambient conditions
- **Stochasticity of the market**
  - Prices
- **Efficiency of the components**
  - Part load
  - Start up/shut Down
- **Connection with main grid**
  - Grid support
  - Profit generation

Polygeneration system

**Emissions**

**Investment**

**Costs**

**Markets**

**Incomes**

**Services to users**

**Multi-services**

**Yearly variations**

**Daily profiles**
Optimal management box

Grid connexion

Tariff info

Data acquisition and database

States database

Previous states

Predicted data

Actual State data

System Model

System Equations & constraints

System parameter values

Optimization Problem data set -up

Prediction

Optimization Problem Resolution

MILP PROBLEM DESCRIPTION

(AMPL)

OPTIMIZATION

(CPLEX)

$u_{cg}^*$

$u_b^*$

$u_{vlv}^*$

$u_{sh}^*$

System Model

Optimization Problem data set -up

Prediction

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MILP PROBLEM DESCRIPTION

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OPTIMIZATION

(CPLEX)

$u_{cg}^*$

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$u_{vlv}^*$

$u_{sh}^*$

Predictive Controller

- Predictive Control Algorithm: Moving horizon
  - hour 1: set-point control + 24 h Cyclic: strategy

![Graph showing temperature changes](image1)

![Graph showing load changes](image2)
Adaptation of the cost function

\[ J_{\text{obj}} = J_1 + w \cdot \sum T_{\text{inf}}(t) \]

subject to:

\[
\begin{align*}
T_{\text{inf}}(t) & \geq 0 \\
T_{\text{inf}}(t) & \geq T_{\text{profile}}(t) - T_{\text{inside}}(t)
\end{align*}
\]

where:

\[
J_1 = \sum_{t} \left( \sum_{n} \sum_{u} \left( \dot{m}_{r(u),n} \dot{c}_{r(u),n} \right) \right) + \dot{E}^+(t) c_{el}^+(t) - \dot{E}^-(t) c_{el}^-(t) \Delta t
\]

\[
\dot{E}^+(t) - \dot{E}^-(t) + \left( \sum_{n} \sum_{u} \dot{E}_{u,n}^+(t) - \dot{E}_{u,n}^-(t) \right) - \sum_{n} \dot{E}_{c,n} = 0
\]

\[
\dot{E}^+(t) + \left( \sum_{n} \sum_{u} \dot{E}_{u,n}^+(t) - \dot{E}_{u,n}^-(t) \right) - \sum_{n} \dot{E}_{c,n} \geq 0
\]

\[
\sum_{u} \dot{m}_{r(u),n} \dot{c}_{r(u),n} - \sum_{s} \dot{Q}_{s,n} - \dot{Q}_{c,n} = 0 \quad \forall n \in \text{Nodes}
\]

Structure of the predictive controller

\[ c g_{\text{on}}(t) \in \{0, 1\} \]

\[ \dot{Q}_{\text{cg}}^\text{min} \cdot c g_{\text{on}}(t) \leq \dot{Q}_{\text{cg}}(t) \leq \dot{Q}_{\text{cg}}^\text{max} \cdot c g_{\text{on}}(t) + c g_{\text{start-} -1} \cdot \eta_{\text{cg,el}} \cdot \dot{Q}_{\text{cg,el}}^\text{max} \]

Non linear efficiency

\[ \dot{E}_{\text{cg}}(t) = c g_{\text{on}} \cdot \dot{E}_{\text{cg}}^\text{min} + c g_{\text{start-} -1} \cdot \eta_{\text{cg,el}} \cdot \dot{Q}_{\text{cg,el}}^\text{max} + c g_{pw} \cdot \left( m_{el,1} \left( \dot{Q}_{\text{cg}}(t) - \dot{Q}_{\text{cg}}^\text{min} \right) + \dot{E}_{\text{cg}}^\text{min} \right) \]

\[ + (1 - c g_{pw}(t)) \cdot m_{el,2} \left( \dot{Q}_{\text{cg}}(t) - \dot{Q}_{\text{cg,el}} \right) + m_{el,1} \left( \dot{Q}_{\text{cg,el}} - \dot{Q}_{\text{cg,el}}^\text{min} \right) \]

Prediction of

- the energy requirements (dhw, heat, electricity),
- the free gains (e.g. solar, from appliances, inhabitants, ...), and
- the electricity market conditions
Response to the market price variation

Electricity cost is changing

- Electricity cost is changing

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<td>Regular day</td>
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<tr>
<td>High cost days</td>
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Same heat
EEX market price
40% heating cost reduction

Electrical grid integration
Micro grid adaptation

- Market opportunities?

\[ J_1 = \sum_{i} \left( \sum_{n} \sum_{u} \left( m_{r(u),n}(c_{r(u),n}) + \dot{E}^+(t)c_{cl}^+(t) - \dot{E}^-(t)c_{cl}^-(t) \right) \Delta t \right) \]

\[ \dot{E}^+(t) - \dot{E}^-(t) + \left( \sum_{n} \sum_{u} \dot{E}_{u,n}^+(t) - \dot{E}_{u,n}^-(t) \right) - \sum_{n} \dot{E}_{c,n} = 0 \]

- Electricity production commitment

\[ J_1 = \sum_{i} \left( \sum_{n} \sum_{u} \left( m_{r(u),n}(c_{r(u),n}) + \dot{E}^+(t)c_{cl}^+(t) - \dot{E}^-(t)c_{cl}^-(t) + P \Delta \dot{E}^+(t) \right) \Delta t \right) \]

\[ \dot{E}^+(t) - \dot{E}^-(t) + \left( \sum_{n} \sum_{u} \dot{E}_{u,n}^+(t) - \dot{E}_{u,n}^-(t) \right) - \sum_{n} \dot{E}_{c,n} = 0 \]

\[ |\dot{E}^+(t) - \dot{E}_{committed}(t)| = \Delta \dot{E}^+(t) \]

Microgrid for peak shaving

- Add the maximum variation in the equations set
  - Islanding?
Heat storage is a battery

Engine : 2000 kWe
Heat pump : 2000 kWe
Storage 200 m3

Demand mean heating power = 3000 kW

- High electricity cost during the afternoon
  Storage tank = 200 m3

- Low cost cost during the afternoon
  Storage tank = 200 m3

Empty storage tanks before cheap elec price
Fill storage tanks during cheap elec price

Storage : 22480 kWh

Electrical grid : Integrating different time scale

- Heating time scale (1h) => strategy
- Electricity (s => 15min ) =>Corrections

Manage El. Power : MILP problem with limits sets form the 25 h strategy
- Traditional admittance-based electrical grid model
- Minimise power factor variations of the power flow with main grid

- Reactive/Active power management
  depends on
  - Power electronics
  - Equipments (AC/DC)
Integration of Photovoltaic panels

P. Stadler, A. Ashouri and Prof. F. Maréchal

Smart Household System Integrated
Hybrid optimization approach

- Control oriented MILP models
- Typical ES for building applications
  - Heat pumps (HP)
  - Cogeneration (CHP) units

Fig 1. Building configuration

Fig 2. Design Algorithm

Need for data reduction methods

- Master – Slave problem decomposition
- Typical operating periods
  - Temperature
  - Global solar irradiation

Fig 2. Design algorithm

Fig 3. Data profiles and load curves
Results

Single family house: 4 pers 160 m²

Self sufficiency (SF)
PV production/needs

\[ SF = \frac{kW_{PV}}{kW_{building}} \]

Self consumption (SC)
PV production used on site

\[ SC = \frac{kW_{used}}{kW_{PV}} \]

Off-site storage
Extra Electricity from PV
Used by the building later

Fig 4. Pareto front for HP system configuration

SF and SC as a function of the PV area
Comparison - Large-scale battery pilot plants

Fig 1. 500 kWh Li-ion battery tested at DESL-EPFL

Fig 2. 100 kWh Redox-flow battery tested at LEPA-EPFL

Cost optimal energy system (ES) configuration

- Total cost function using subsidies for PV
- Low grid interaction – weak export peaks

Design of ES

Case IV

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<td>HW tank</td>
<td>0.15 m³</td>
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<td>Heat Pump</td>
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<td>2.14 m²</td>
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IRR 3.5 years
Comparison – typical operating periods *(winter, summer, mid-season)*

**Case I**

**Case II**

**Case III**

**Case IV**

Configuration comparison

Heat pump

Direct el.

Long term vs short term

Battery
ES configuration comparison

**Cogen**

**Cogen + HP**

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<th>IRR [yr]</th>
<th>SF</th>
<th>SC</th>
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<td>Cogen + HP</td>
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<td>41%</td>
<td>68%</td>
<td>+100%</td>
<td>+94%</td>
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Potential of MPC

- Increase in Self Sufficiency and Self Consumption ranging from 100-47% and 0-47% resp. with DSM

NetZero

- SF + 41%
- SC + 68%
- BAT + 100%
- HST + 94%

HP = 3 kW, BAT = 0 kWh, Thermal storage = 0.15 m³
Control framework and problem formulation

- Virtual peak formation
- Coordination of the controllers

Iterative and sequential MPC formulation

![Fig 6. Control algorithm](image6.png)

![Fig 7. DMPC results](image7.png)

Conclusions

- **Design the system**
  - Design systems with constant demand to the grid?
  - Choose the right size of equipments and storage
  - Heat storage can store electricity
  - Integrate the control system in design

- **Combined heat/cold and electricity**
  - Different time scale => adapt the control strategy
  - Interaction with the main grid
    - micro grid can become an active instead of a passive component

- **Discussing with electrical engineers!**
  - V = Voltage, V = Volume
  - Q = reactive Power, Q = heat load
  - P = Power, P = Pressure