Polygeneration system design with optimal predictive control strategies

Ramanunni P Menon
Prof. François Marechal
Ecole Polytechnique Fédérale de Lausanne
E-technology: Smart households

- Fuel-Cell GT
- Domestic Hot water tanks
- Heat pump/HVAC
- Electrical grid
- Natural gas grid
- Buildings
- Small industries
- E-technology: Smart households
- Price
- Reserve
- Meteo
- Smart info (WIFI-GPS-GSM)
- Water grid
- Waste Water Grid
- Big Data grid
- CO2 grid
- Comfort
- T/Air People
- Light
- T storage
- Heating/Cooling tanks
- Cogeneration
- Batteries
- Solar panels
- PV
- PV
- T ambient
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
    \[ \forall u \in Units; \forall n \in Nodes \Rightarrow Size_{u,n} \forall s \in Storage; \forall n \in Nodes \Rightarrow V_{s,n} \]
  
    \[
    \sum_{n=1}^{Nodes} \sum_{u=1}^{Units} \frac{1}{\tau_{y,i}} (I(\text{Size}_{u,n}) + I(V_{s,n}))
    \]

- Operating costs (expected operation time = 25x8760h)
  - Management strategy
    \[ \forall s \in Storage; \forall n \in Nodes; \forall t \in time \Rightarrow \dot{m}_{u,n}(t), V_{s,n}(t), \dot{E}(t) \]
    \[ \int_{t=1}^{Time \ units} \left( \sum_{u=1}^{Units} \left( c^+_r(t) \dot{m}_r(u,n)(t) + c^+_e(t) \dot{E}^+(t) \right) \right) dt \]

- **Constraints**
  - Energy services
  - Grid capacities
  - Grid constraints
    \[ \forall n \in Nodes; \forall t \in Time; \forall c \in \text{Cons.} \Rightarrow \dot{Q}_{n,c}(t), \dot{E}_{n,c}(t) \]
    \[ \forall t \in Time : \sum_{n=1}^{Nodes} \dot{E}(t) \leq \dot{E}_{max}(t) \]
    \[ \forall q \in \text{quarter}(Time) : \sum_{n=1}^{Nodes} \int_{t=q}^{q+15} |\dot{E}_n(t) - \dot{E}_n(t-1)| dt \leq \Delta \dot{E}_{max}(t) \]
Constraints

**Electricity production**

\[ (el_{SOFC}(t) + el_{grid}(t)) - (el_{RC}(t) + el_{PAC}(t) + cons_{el}(t)) \geq 0\text{ (kW)} \]  

**Heat production**

\[ el_{SOFC}(t) \eta_\text{el} \eta_\text{th} - ((AC2(t)/AC2_{COP}) + HEX_{\text{heat}}(t) + unusable_{\text{heat}}(t)) \geq 0\text{ (kW)} \]  

\[ \text{stored}_{\text{energy}}(t) = \text{stored}_{\text{energy}}(t - 1) - \text{storage}_{\text{losses}}(t) - \text{storage}_{\text{out}}(t) + \text{storage}_{\text{in}}(t)\text{ (kJ)} \]  

**Storage balance**

\[ T_{\text{stock}}(t = 1) = T_{\text{stock}}(t = 24)\text{ (C)} \]  

\[ \text{losses}_{\text{param}} = 10\% \times \text{stock}_{\text{size}} \times \rho_{\text{water}} \times C_{\text{water}} \times (T_{\text{max}} - T_{\text{room}})\text{ (kJ)} \]  

**Storage losses**

\[ \text{storage}_{\text{losses}}(t) = \text{losses}_{\text{param}} \times \frac{1\text{ hour}}{24 \times 3600} \times \frac{T_{\text{stock}}(t) - T_{\text{room}}}{(T_{\text{max}} - T_{\text{room}})}\text{ (kW)} \]  

\[ \text{cons}_{\text{heat}}(t) = \text{HEX}_{\text{heat}}(t) - \text{heat}_{\text{stock in}}(t) + \text{heat}_{\text{stock out}}(t) + el_{PAC}(t) \times COP_{PAC}\text{ (kW)} \]  

**Heat/cool cons**

\[ \text{cons}_{\text{cool}}(t) = AC2(t) - \text{cool}_{\text{stock in}}(t) + \text{cool}_{\text{stock out}}(t) + el_{RC}(t) \times RC_{COP}\text{ (kW)} \]  

\[ t=1\ldots24 \]
E-technology: Optimal design of solar systems

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

Single family house: 4 pers 160 m²: with heat pump

Fig 4. Pareto front for HP system configuration

SF and SC as a function of the PV area
Self sufficiency?

Single family house: 4 pers 160 m²: with heat pump

Fig 4. Pareto front for HP system configuration

Case I
Energy system
- PV array: 88 m²
- Battery: 4.95 kWh
- HW tank: 2.43 m³
- Heat Pump: 3.59 kW

Off-site storage
- Redox Battery: 8.14 MWh
- 8'070'000 € (500 €/kWh)

Long term storage: 85%

Case II
Energy system
- PV array: 109.7 m²
- Battery: 7 kWh
- HW tank: 2.46 m³
- Heat Pump: 3.7 kW

Off-site storage
- Redox Battery: 10.8 MWh
- 5'400'000 €

Long term storage: 85%

Case III
Energy system
- PV array: 156.9 m²
- Battery: 8.63 kWh
- HW tank: 2.39 m³
- Heat Pump: 3.7 kW

Off-site storage
- Redox Battery: 17.1 MWh
- 8'550'000 €

Long term storage: 55%
Comparison – typical operating periods (winter, summer, mid-season)

- **Shaded** self-consumption
- **Blue** Import [kW]
- **Green** Export [kW]
- **Red** Generation [kW]

**Case III**

**Winter**

**Summer**

**Mid-season**
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

Prediction methods
E-technology: Optimal management box

- From design to operation

Data acquisition and database

States database
(Current state & previous states)
(House structure - Matlab)

Optimization Problem data set - up

System Model
- System Equations & constraints
- System parameter values

Previous states

Predicted data

Actual State data

Optimization Problem Resolution

MILP PROBLEM DESCRIPTION
(AMPL)

OPTIMIZATION
(CPLEX)

Operation set-points

Tariff info

Grid connexions

Sensors

T_in

T_ext

T_sh

T_dhw

Collazos et al., Computers and Chemical Eng. 2009
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)
- Predictive Control Algorithm: Moving horizon
  - hour 1: set-point control + 24 h Cyclic: strategy
Adaptation of the cost function

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

subject to:
\[ w = 10^6 \]
\[ T_{inf}(t) \geq 0 \]
\[ T_{inf}(t) \geq T_{profile}(t) - T_{inside}(t) \]

where:
\[ J_1 = \sum_t \left( \sum_n^{Nodes} \sum_u^{Units(n)} (\dot{m}_{r(u),n} c_{r(u),n}) \right) + \dot{E}^+(t) c_{el}^+(t) - \dot{E}^-(t) c_{el}^-(t) \Delta t \]

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

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

\[ \sum_u^{Units(n)} \dot{m}_{r(u),n} \eta_{th,u,n} - \sum_s^{Storage(n)} \dot{Q}_{s,n} - \dot{Q}_{c,n} = 0 \quad \forall n \in Nodes \]
Predictive Controller

- **Structure of the predictive controller**
  - **start-up/ shut-down**
    \[ \dot{Q}_{cg}^{\text{min}} \cdot cg_{on}(t) \leq \dot{Q}_{cg}(t) \leq \dot{Q}_{cg}^{\text{max}} \cdot cg_{on}(t) + cg_{\text{start-up}}(t) \cdot \eta_{cg,th}^{\text{start-up}} \cdot \dot{Q}_{cg,\text{gas}}^{\text{max}} \]

  - **Non linear efficiency**
    \[ \dot{E}_{cg}(t) = cg_{on} \cdot \dot{E}_{cg}^{\text{min}} + cg_{\text{start-up}}(t) \cdot \eta_{cg,el}^{\text{start-up}} \cdot \dot{Q}_{cg,\text{gas}}^{\text{max}} + cg_{pw} \left[ m_{el,1} \left( \dot{Q}_{cg}(t) - \dot{Q}_{cg}^{\text{min}} \right) + \dot{E}_{cg}^{\text{min}} \right] + (1 - cg_{pw}(t)) \left[ m_{el,2} \left( \dot{Q}_{cg}(t) - \dot{Q}_{cg,pw} \right) + m_{el,1} \left( \dot{Q}_{cg,pw} - \dot{Q}_{cg}^{\text{min}} \right) \right] \]

- **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

<table>
<thead>
<tr>
<th></th>
<th>( \text{cost}_{\text{op}} [\text{€}] )</th>
<th>Potential gain [€]</th>
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<tbody>
<tr>
<td>Reference day</td>
<td>36.00</td>
<td>0.0</td>
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<tr>
<td>Regular day</td>
<td>30.55</td>
<td>5.45</td>
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<tr>
<td>High cost days</td>
<td>21.14</td>
<td>14.86</td>
</tr>
</tbody>
</table>

Same heat
EEX market price
40% heating cost reduction