Robust Model Predictive Control with Scenarios for Aggregators in Grids with High Penetration of Renewable Energy Sources

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The Danish Wind Power Case

In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK).

In 2017 more than 44 pct of electricity load was covered by wind power.

For several days the wind power production was more than 100 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power.
Challenges

Preparatory study on Smart Appliances

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market and political aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.
Data Intelligent and Flexible Energy Systems
Temporal and Spatial Scales

The *Smart-Energy Operating-System (SE-OS)* is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for *operating flexible electrical energy systems* at all scales.
Models for Systems of Systems

Intelligent systems integration using big data and ICT solutions are based on models for real-time operation of flexible energy systems.
Smart-Energy OS

Day Ahead Market

Transmission System Operator (TSO)

Aggregated loads

Intraday market

Balance Responsible Party

DIRECT CONTROL (DC)
Individual consumption schedules

Aggregator

INDIRECT CONTROL (IC)
Price signals

Sub Aggregator A Forecast services

Meteorological forecasts
Local data

Real time price

Sub Aggregator B Forecast services

Real time price

Advanced controller

Actuation state info

Industrial processes

Transport

Water distribution & treatment

Intelligent heating/cooling

Intelligent buildings

Solar thermal

Industrial processes

CHP plant

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Control and Optimization

**Day Ahead:**
Stoch. Programming based on eg. Scenarios
Cost: Related to the market (one or two levels)

**Direct Control:**
Actuator: **Power**
Two-way communication
Models for DERs are needed
Constraints for the DERs (calls for state est.)
Contracts are complicated

**Indirect Control:**
Actuator: **Price**
Cost: E-MPC at low (DER) level, One-way communication
Models for DERs are not needed
Simple 'contracts'

# Try to parallelize anyway

```r
require(multicore)
numcores <- multicore:::detectCores()
mclapply(...1:N,...
  function(i, data) {
    print(paste(i, "/", N))
    # Find the indices of rows corresponding to
    j <- which(data$dt_agg %in% aggdata$dt[i])
    # Filter out those who are NA
    j <- j[!is.na(data$last_one_min_power[j])]
    # Count number of readings
    aggdata$num_readings[i] <- length(j)
  })
```
Proposed methodology
Control-based methodology

\[
\begin{align*}
\min \quad & E \left[ \sum_{k=0}^{N} w_{j,k} || \hat{z}_k - z_{ref,k} || + \mu || p_k - p_{ref,k} || \right] \\
\text{s.t.} \quad & \hat{z}_{k+1} = f(p_k)
\end{align*}
\]

We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool of flexible prosumers.
Data Intelligent Energy Systems

- Automatic and self-cal. methods based on Big Data analytics and AI
- Labs – Virtual, HiL, Live
- Peer-to-peer communication (incl. blockchain)
- Nested sequence of systems – systems of systems
- Hierarchy of stoch. optimization (or control) problems
- Multivariate probabilistic forecasting
- Control principles at higher spatial/temporal resolutions
- Cloud or Fog (IoT, IoS) based solutions – eg. for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ..)
- Allow for new players (specialized aggregators)
- Simple setup for the communication and contracts
- Harvest flexibility at all levels
Robust and Scenario-based Control at Aggregator Level
Example: Scenario-based Robust Control (Level III)

The scenarios generated $k = 1, \ldots, K, \forall k \in \mathcal{K}$ are applied to a robust optimization problem by minimizing the cost at the worst case scenario. This leads to the formulation of the robust Aggregator problem as:

$$\begin{align*}
\text{minimize} & \quad \max_{k=1,\ldots,K} \sum_{j=1}^{J} \phi_{j}^{(k)}(u_{j}^{(k)}) \\
\text{subject to} & \quad \sum_{j=1}^{J} u_{j}^{(k)} = 0, \quad \forall k \in \mathcal{K} \\
& \quad u_{j}^{(1)}(t) = u_{j}^{(k)}(t), \quad \forall k \in \mathcal{K}, j \in \mathcal{J}
\end{align*}$$ (2)
D. Advanced Controllers

Advanced controllers are DER units that operate with a more complex controller such as MPC. Their optimization problem is represented in (6).

\[
\begin{align*}
\text{minimize} \quad & \sum_{k=0}^{N-1} p' u_k + \rho' s_k \\
\text{subject to} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k \\
& y_k = Cx_k \\
& u_{\text{min}} \leq u_k \leq u_{\text{max}} \\
& \Delta u_{\text{min}} \leq \Delta u_k \leq \Delta u_{\text{max}} \\
& y_k + s_k \geq y_{\text{min}} \\
& y_k - s_k \leq y_{\text{max}} \\
& s_k \geq 0
\end{align*}
\] (6a)

(6b)

(6c)

(6d)

(6e)

(6f)

(6g)

(6h)
Example: Wind turbine scenarios

Fig. 2. Four wind turbines scenarios. For each turbine, 10 different scenarios are calculated for a period of 6 days starting from time $t$. In dark blue the real production data from the wind turbines, while the scenarios are represented by the light dash blue lines. In red the real power production for each turbine.
Results:

![Graph showing time series data for various parameters over time]

Fig. 4. Closed loop robust MPC simulation over ten days of data using 10 scenarios and 48 hours ahead prediction horizon.
Case study No. 1

Control of heat pumps for swimming pools
(Minimization of Cost / CO2)
SE-OS
Control loop design – logical drawing

Data

Termostat
actuator

Sensors
Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016

Source: pro.electricitymap.org
Example: Price-based control
Example: CO2-based control
Penalty Function (examples)

- **Real time CO$_2$.** If the real time (marginal) CO$_2$ emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.

- **Real time price.** If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the building is *cost efficient*.

- **Constant.** If a constant penalty is used, then, the controllers would simply minimize the total energy consumption. The smart building is, then, *energy efficient*. 
Summary

- A framework called Smart-Energy OS based on AI and Big Data Analytics is described for implementing smart energy systems.

- The SE-OS setup can focus on:
  - Energy Efficiency
  - Cost Efficiency (Minimization)
  - Emission Efficiency (→ accelerating the transition to a low-carbon energy system)
  - Smart Grid demand (like ancillary services needs, ...)

- We have demonstrated a large potential for unlocking the flexibility and for demand response using big data analytics and AI.

- We have suggested a method for characterizing the energy flexibility which facilitates smart grid applications.
Some 'randomly picked' books on modeling ....
For more information ...

See for instance

www.smart-cities-centre.org

...or contact

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