Controlling the Electricity Load in Future Intelligent and Integrated Energy Systems

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The Danish Wind Power Case

.... balancing of the power system

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

In 2016 more than 42 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
Wind integration in Denmark

**Power right now**
- Measured in MW:
  - Central power stations: 1,315
  - Local CHP plants: 298
  - Wind turbines: 3,951
  - Solar cells: 0
  - Net exchange export: 2,096
  - Electricity consumption: 3,469
  - CO2 emissions: 164 g/kWh

**LEGEND**

- Jutland - Norway: Exports: 1,530 MW
- Jutland - Sweden: Exports: 332 MW
- Zealand - Sweden: Exports: 1,026 MW
- Bornholm - Sweden: Exports: 16 MW
- The Great Belt: 590 MW
- Jutland - Germany: Imports: 473 MW
- Zealand - Germany: Imports: 336 MW

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From large central plants to Combined Heat and Power (CHP) production

1980

From a few big power plants to many small combined heat and power plants – however most of them based on coal

Today

DK has enough excess heat to cover the entire need for heating .... but ...
Solar district heating in Denmark

Planned in 2014
197,855 M2
Total collector area: 574,023 m²
Energy Systems Integration

Energy system integration (ESI) = the process of optimizing energy systems across multiple pathways and scales
The project SmartNet aims at comparing different architectures for optimized interaction between TSOs and DSOs in managing the purchase of ancillary services from subjects located in distribution.

An ad hoc simulation platform is built (physical network, market and ICT) around three national cases (Italy, Denmark, Spain); a CBA is performed to assess which TSO-DSO coordination scheme is optimal for the three countries. The simulation platform is then implemented in a full replica lab to test performance of real controller devices.

Three physical pilots are also developed to demonstrate capability to monitoring and control distribution by the TSO and flexibility services that can be offered by distribution (thermal inertia of indoor swimming pools, distributed storage of radio-base stations).
Flexible Solutions

**Center for IT-Intelligent Energy Systems in Cities (CITIES)** is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.

CITIES is currently the largest Smart Energy and ESI research project in Denmark – see http://www.smart-cities-centre.org.
The **central hypothesis** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) using grey-box models we can balance very large shares of renewables, and consequently obtain substantial reductions in CO2 emissions.

**Intelligent integration** will (for instance) enable lossless ‘virtual’ storage on a number of different time scales.
Existing Markets - Challenges

- Dynamics
- Stochasticity
- Nonlinearities
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...)
- Interaction between grid (voltage) levels
- Speed / problem size
- Characterization of flexibility
- Requirements on user installations
Challenges (cont.)

Preparatory study on Smart Appliances

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market and societal 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 EU-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.
COMPETITIVE BIDDING AND STABILITY ANALYSIS IN ELECTRICITY MARKETS USING CONTROL THEORY

Main idea: applying control theory to the study of power markets

Advantages in handling effectively

Dynamics

Control theory provides ways of modeling the dynamics which is intrinsic in energy markets

It is possible to develop advanced bidding strategies which exploit the inclusion of the dynamics in the model

Uncertainty

Stochastic control theory allows for taking into account different sources of uncertainty (wind, ...)

It is possible to develop bidding strategies which are optimal with respect to the stochastic characteristics of the market
Accounting information (energy, price/time) for the past 5 minutes \([t-10m; t-5m]\). Received at \(t-4m\) (or later, possible batch wise).

Price for the coming 5 minutes \([t, t+5m]\). Available at \(t-2m\) (?)

External info., e.g. spot prices

External info., e.g. spot prices

MET forecast

Price-prognosis for the time intervals: \([t+5m, t+10m]\), \([t+10m, t+15m]\), etc. Available at \(t-1m\) (?)

Load-prognosis for time-points after \(t\), but in larger time steps, e.g. \([t, t+2h]\), \([t+2h, t+4h]\), \([t+4h, t+6h]\), ...

Load measurement (time scale larger than 5m)

Secondary measurements, e.g. indoor temperature and reference indoor temperature, or even local climate measurements.

Prognosis service (FlexPower Prediction)

The blue color represents the minimal FlexPower requirements. The green color represents the additional requirements when external prognoses are used by the local controller. Possible multiple load forecasts may be required by the household. Also the load prognosis may be supplemented with additional information required by the local controller (assumed future \(T_i, UA\)-value, ...).

The price submitted to the local controller is the sum of the spot, regulation, and nodal prices. The price prognosis service is likely to benefit from having access to these prices separately.

The time index \(t\) refers to the beginning of the next 5 minute interval.
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.
Smart-Energy OS

- Day Ahead Market
- Transmission System Operator (TSO)
- Distribution System Operator (DSO)
- Intraday market
- Balance Responsible Party
- Aggregated loads

- DIRECT CONTROL (DC)
  Individual consumption schedules

- INDIRECT CONTROL (IC)
  Price signals

- Sub Aggregator A
  Forecast services

- Sub Aggregator B
  Forecast services

- Meteorological forecasts
  Local data

- Real-time price

- Advanced controller
  Industrial processes
  Transport
  Water distribution & treatment
  Intelligent heating/cooling
  Intelligent buildings
  Solar thermal
  Industrial processes
  CHP plant

- Actuation state info
- Real-time price

CITIES
Centre for IT Intelligent Energy Systems
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'

Direct vs Indirect Control

<table>
<thead>
<tr>
<th>Level</th>
<th>Direct Control (DC)</th>
<th>Indirect Control (IC)</th>
</tr>
</thead>
</table>
| III   | \[
\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})
\] \[
\downarrow u_1 \cdots \downarrow u_J \quad \uparrow x_1 \cdots \uparrow x_J
\] \[
\text{s.t. } x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J
\] | \[
\min_{z,p} \sum_{k=0}^{N} \phi(z_k, p_k)
\] \[
\downarrow z_k \quad \downarrow p_k \quad \uparrow \hat{z}_{k+1} = f(p_k)
\] \[
\text{s.t. } \hat{z}_{k+1} = f(p_k)
\] | \[
\min_{u} \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J
\] \[
\text{s.t. } x_{k+1} = f_j(x_k, u_k)
\] |

Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals \( u_j \) are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes the optimal prices \( p \) which are sent to the J-units at level IV. Hence the J DERs optimize their own energy consumption taking into account \( p \) as the actual price of energy.
The ‘market’ of tomorrow

- Space:
  - Country
  - Region
  - City
  - District
  - House

- Time:
  - Bidding & Clearing
  - Control based
    - \( \min_p (U - U_{ref})^2 \)
    - \( \min \sum (pU) \)

- Models:
  - Purpose based
    - Stochastic Control
  - Economic Model
    - Predictive Control
SE-OS Characteristics

• ‘Bidding – clearing – activation’ at higher levels
• Nested sequence of systems – systems of systems
• Hierarchy of optimization (or control) problems
• 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
• Provides a solution for all ancillary services
• Harvest flexibility at all levels
Probabilistic Forecasting
Forecast requirements

Day Ahead:
- Forecasts of loads
- Forecast of Grid Capacity (using e.g. DLR)
- Forecasts of production (e.g. Wind and Solar)

Direct Control:
- Forecasts of states of DERs
- Forecasts of load

Indirect Control:
- Forecasts of prices
- Forecasts of load
Which type of forecast?

- Point forecasts
- Conditional mean and covariances
- Conditional quantiles (Prob. forecasts)
- Conditional scenarios
- Conditional densities
- Stochastic differential equations
Wind and Solar Power Forecasting

- Methods for wind power forecasting have been continuously developed and used operationally since 1995 (solar power since 2005).
- Implemented for instance in WPPT, Anemos WPS, AWEFS, ASEFS, ..
- Sold for instance in systems provided by ENFOR (Denmark) and Overspeed GmbH (Germany)
- Today our systems are used worldwide (North America, Europe, Africa, Japan, Middle East, Australia).
- Used by all major players in Denmark (TSO, DSOs, BRPs, ...)
Grey-box Modelling
Models for systems of systems

Intelligent systems integration using data and ICT solutions are based on grey-box models for real-time operation of flexible power/energy systems.
The grey-box model

Notation:

- $X_t$: State variables
- $u_t$: Input variables
- $\theta$: Parameters
- $Y_k$: Output variables
- $t$: Time
- $\omega_t$: Standard Wiener process
- $e_k$: White noise process with $N(0,S)$
## Grey-box modelling concept

<table>
<thead>
<tr>
<th>White</th>
<th>Grey</th>
<th>Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>Prior Knowledge</td>
<td>Databased</td>
</tr>
<tr>
<td>equations</td>
<td></td>
<td>Input–output representation</td>
</tr>
<tr>
<td>Physical knowledge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed submodels</td>
<td></td>
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</tbody>
</table>

- Combines prior physical knowledge with information in data
- Equations and parameters are physically interpretable
Grey-Box Modelling

- Bridges the gap between physical and statistical modelling
- Provides methods for model identification
- Provides methods for model validation
- Provides methods for pinpointing model deficiencies
- Enables methods for a reliable description of the uncertainties, which implies that the same model can be used for k-step forecasting, simulation and control
Software solutions

Software for combined physical and statistical modelling

Continuous Time Stochastic Modelling (CTSM) is a software package for modelling and simulation of combined physical and statistical models. You find a technical description and the software at CTSM.info.

Software for Model Predictive Control

HPMPC is a toolbox for High-Performance implementation of solvers for Model Predictive Control (MPC). It contains routines for fast solution of MPC and MHE (Moving Horizon Estimation) problems on embedded hardware. The software is available on GitHub.

MPCR is a toolbox for building Model Predictive Controllers written in R, the free statistical software. It contains several examples for different MPC problems and interfaces to opensource solvers in R. The software is available on GitHub.
Intelligent Smart Grid

Control of Power Consumption, Summer Houses with a Pool
(H2020 SmartNet Project – Danish Pilot)
Goals for Pilot Project

- Demonstrate aggregation services (30 summer houses).
- Implementation in field of ICT technology to exchange data between TSO, DSO, aggregator and the summer houses.
- Use of on-line services for price and load forecasting + model predictive control.
- Development of architecture for ancillary services.
Overview - Danish Pilot

1. Receive Grid Load
2. Calculate residual capacity
3. Receive bids
4. Clear market
5. Activate bids
6. Send price signal incl. forecast
7. Measurements
8. Setpoint

Ancillary services:
- Frequency control
- Congestion management
- Voltage control

Energy trading and portfolio management:
- Day-ahead market
- Intraday market
- Real-time market

Local services:
- Local Frequency control
- Local Voltage control
- Congestion management

Technical aggregation:
- DER services
- Value Added services

Market Management System
- Day-ahead
- Intraday
- Real-time

Market Operator [MO]

TSO Trading System
EMS-SCADA
Transmission System Operator [TSO]

DSO Trading System
EMS-SCADA
Distribution System Operator [DSO]

High Voltage Sub-station
Primary Sub-station
Secondary Sub-station

DER gateway
DER trading system

Distributed Energy Resources

Commercial Market Party [CMP]
Lab testing ....
Control loop design – **logical drawing**

Data → Termostat actuator

Sensors → Data
SN-10 Smart House Gateway
How does it work?

Data measurement and information gathering

SN-10 backend

DTU/ENFOR backend

SmartNet

NOVASOL

Heat exchanger

Pool pump

Pool

relay1

relay2

S0.1 
S0.2

Power
How does it work?

Price based Control

SN-10 backend

DTU/ENFOR backend
The considered house

- $T_{sh}$ – summerhouse temperature
- $T_a$ – temperature of air in the pool area
- $T_{in}$ – water temperature into the swimming pool
- $T_{out}$ – water temperature out of the swimming pool (controlled)
- $T_o$ – outdoor temperature
- $T_g$ – ground temperature
- $Q_s$ – solar heat gain
- $w$ – wind speed
Model for simulation
(Using lumped parameter model)

- Based on equivalent thermal parameters model

- Dynamics:
  \[
  \frac{dT_{in}}{dt} = \frac{1}{C_{in}} [H_w(T_{out} - T_{in}) + Q_{in}]
  \]
  \[
  \frac{dT_{out}}{dt} = \frac{1}{C_{out}} [H_w(T_{in} - T_{out}) + H_g(T_g - T_{out}) + H_a(T_a - T_{out})]
  \]
  \[
  \frac{dT_a}{dt} = \frac{1}{C_{a}} [H_o(w)(T_o - T_a) + H_a(T_{out} - T_a) + H_{sh}(T_{sh} - T_a) + Q_s + Q_a]
  \]
Control problem (simplified)

\[
\min_u \sum_{k=0}^{N-1} c_k u_k
\]

s.t. \quad x_{k+1} = f_x(x_k, u_k, \theta_k)
\quad y_k = f_y(x_k, \theta_k)
\quad y_{min} \leq y_k \leq y_{max}
\quad u_k \in \{0, 1\}

- \( N \) – predictive horizon
- \( c_k \) – electricity prices
- \( f_x \) and \( f_y \) – discretized LPV model
- \( y_{min} \) and \( y_{max} \) – output constraints which guarantee customers’ comfort
Simulation Results

Simulation Results
Case study (Level III)

Price-based Control of Power Consumption
Data from BPA

**Olympic Pensinsula project**

- 27 houses during one year
- Flexible appliances: HVAC, cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption
Aggregation (over 20 houses)
Response on Price Step Change

Consumption step response (Olympic Pen.)

Consumption [kW]

0

0.2

-0.2

-10

-5

0

5

10

15

20

Hours

5 hours

COST TD1207 Final Conference, March 2017
Control of Power Consumption

Diagram:
- Consumption references
- Price generator (controller)
  - Model parameters
  - Prices
  - Price-responsive consumption
  - Aggregated consumption
Considerable reduction in peak consumption
Case study
(Level IV – Indirect Control)

Control of Heat Pumps
(based on varying prices from Level III)
Grundfos Case Study
Schematic of the heating system
Modeling Heat Pump and Solar Collector

Simplified System
The Economic MPC problem, with the constraints and the model, can be summarized into the following formal formulation:

\[
\begin{align*}
\min_{\{u_k\}_{k=0}^{N-1}} & \quad \phi = \sum_{k=0}^{N-1} c' u_k \\
\text{Subject to} & \quad x_{k+1} = A x_k + B u_k + E d_k \quad k = 0, 1, \ldots, N - 1 \\
& \quad y_k = C x_k \quad k = 1, 2, \ldots, N \\
& \quad u_{\text{min}} \leq u_k \leq u_{\text{max}} \quad k = 0, 1, \ldots, N - 1 \\
& \quad \Delta u_{\text{min}} \leq \Delta u_k \leq \Delta u_{\text{max}} \quad k = 0, 1, \ldots, N - 1 \\
& \quad y_{\text{min}} \leq y_k \leq y_{\text{max}} \quad k = 0, 1, \ldots, N
\end{align*}
\]
E-MPC for heat pump with solar collector (savings 35 pct)
Further Aspects
Flexibility Represented by Saturation Curves
(for market integration using block bids)
Control of Electricity Load
Some Projects

- Control of WWTP (ED, Kruger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (*SmartNet*: ONE, ENDK, SE, ..)
- Green Houses (NeoGrid, ENFOR, ..)
- CHP (Dong Energy, EnergiFyn, ..)
- Industrial production
- VE (Eurisco, Enfor, ..)
- .............
(Virtual) Storage Solutions

- Supermarket refrigeration can provide storage 0.5-2 hours ahead
- Buildings thermal capacity can provide storage up to, say, 5-10 hours ahead
- Buildings with local water storage can provide storage up to, say, 2-12 hours ahead
- District heating/cooling systems can provide storage up to 1-3 days ahead
- DH systems with thermal solar collectors can often provide seasonal storage solutions
- Gas systems can provide seasonal/long term storage solutions
Summary

- A Smart-Energy OS for implementing future and integrated future electric energy systems has been described. It consists of a hierarchy of nested stochastic optimization/control problems.

- The Power Grid is the backbone – we need an Intelligent Smart Grid – also across voltage levels – focus on TSO-BRP-DSO interactions for providing the needed services. Intelligence using either Coordination Schemes (H2020 SmartNet) or Control Theory (the full Smart-Energy OS)

- Modelling: Toolbox – CTSM-R - for combined physical and statistical modelling (grey-box modelling)

- Control and Optimization: Toolbox – for Optimization and Model Predictive Control

- Forecasting: Toolbox - for wind, solar, price, and load forecasting

- Two models for characterizing the flexibility have been suggested:
  - Dynamic models (used for E-MPC based on prices / indirect control)
  - Saturation curves (used for market bidding / direct control)
For more information ...

See for instance

www.smartnet-project.eu
www.smart-cities-centre.org

...or contact

- Henrik Madsen (DTU Compute)
- Gianluigi Migliavacca (RSE, Milan)

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