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Power Management for Energy Systems

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April 2013, Tobias Gybel Hovgaard, Danvak Dagen 2013.

Challenge and Motivation

- Wind power is the most important renewable energy source today.
- Goals for reduced CO2 emission, increased utilization of renewable energy, and phase out of fossil fuels.
- E.g. in Denmark: increase the share of wind power to 50% of the electricity consumption by 2020 and fully cover the energy supply by renewable energy by 2050.
- Wind power production fluctuates → flexible power consumption is needed (smart grid technologies).



Intelligent load-shifting and scheduling by storing "coldness" for:

- Peak avoidance (foreseeing peaks can reduce dimensioning of the system)
- Minimal power consumption (Cooling at colder periods is more efficient)
- Minimal cost (Energy prices may vary over the day)
- Flexible consumption (More renewable energy calls for flexible power consumption)

Example: Drive from A to B with minimal fuel consumption.





Example: Smart Grid (Flexible consumption).





Example: Smart Grid (Flexible consumption).

Economic Model Predictive Control (MPC) demonstrated on power distribution portfolio including a cold storage with flexibility. Presented at CDC 2010.



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Regulating Power

A brief introduction:

- Ancillary service in order to balance production and consumption (stabilize frequency)
- Up-regulating power: increased production or decreased consumption
- Down-regulating power: decreased production or increased consumption
- Different types (amounts, activation times, automatic/manual)



Regulating Power



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Regulating Power

Primary regulation:

- Automatic frequency dependent activation
- Uphold activated capacity for 15 min, re-establish in 15 min.
- No extra payment for activated power
- Availability payment independent of actual activation (non-symmetric up/down)



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Flexible consumption with intelligent load-shifting and scheduling by storing energy in the form of "coldness":

- 1. Utilize thermal mass in e.g. stored goods in supermarkets.
- 2. Food temperatures allowed to vary within defined limits.
- 3. Our studies reveal electricity cost savings up to 30%.

But:

- 1. Food temperatures unknown!
- 2. Vast variety of systems!
- 3. Little computational power!







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Method



Economic Model Predictive Control (MPC)

Future

Predicted

u

time

Ν

- Controller cost function:
- With e.g. for regulation:
- MPC Control problem:

Past

Reconciled

$$\Phi(x, \mathbf{u}) = \sum_{k=0}^{N-1} L(x(k), u(k))$$

$$L(x, u) = \frac{1}{2} ((x - x_{sp})'Q(x - x_{sp}) + (u - u_{sp})'R(u - u_{sp}))$$

$$\min_{\mathbf{u}} \Phi(x, \mathbf{u}) , \mathbf{S.t.} \qquad x(k+1) = Ax(k) + Bu(k)$$

$$k = 0, \dots, N-1$$

$$g(x(k), u(k)) \leq 0$$

$$\square \text{ Data handling / }$$

$$= \sum_{k=0}^{N-1} L(x(k), u(k))$$

Estimation

k

0 N_e 0 Estimation Regulation

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Regulation

injected u

Process time



Economic Model Predictive Control (MPC)

- Solve an optimization problem at each sample.
- Minimize an economic objective related to operation of the system.
- Repeat in a receding horizon manner
- + Incorporates predictions of future prices, temperatures, etc.
- + Handles constraints naturally.
- + Intuitive formulation of the cost of operation into a control problem.
- Relies on a model of the system and predictions of the disturbances.
- Can involve quite complicated numerical optimization problems.





Example: Uncertain predictions and models.

Example: Drive from A to B with minimal fuel consumption. Stay on the road!





Example: Uncertain predictions and models.

Second Order Cone Programming (SOCP) for uncertainties in Economic MPC problems. Presented at CDC-ECC 2011





Overall setup



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Simulations:

- Covering a full year (2010).
- Outdoor temperature from Denmark.
- Electricity prices from Nordpool.
- Uncertain heat load disturbances and thermal masses.
- Verified models from supermarket in operation in Denmark.

Implementation:

- Optimization problem solved iteratively
- Ultra fast solvers for real-time implementation.
- Soft constraints and back-off for robustness.
- Predictors trained on historical data (previous three years).

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Temperature profile



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Demand response





Temperature distributions





Price distributions





Key findings:

- Cost savings around 30 %
- Potential for additional savings by offering regulating power.
- Very simple predictors are sufficient.
- Prescient simulation improves total cost with less than 2%.
- Closed-loop performance is quite robust against variations in model parameters.



Additional results include:

- Robustness investigations:
 - Advanced method with known probability distributions for the uncertainty.
 - Simpler version with back-off tuned to make constraint violations very infrequent.
- Modeling of dynamical systems for optimization and MPC purposes.
- Analysis of "active thermal mass" in foodstuffs.
- Experiments, identification, and validation on real systems in the lab.
- Investigation of optimization methods for industrial applications:
 - Standard linear and non-linear solvers.
 - Simplified problem formulations for linear solvers.
 - Dedicated fast embedded optimization techniques.



- We prove a potential for combining
 - wind speed forecasts,
 - control of wind turbines
 - and control of flexible power consumers (e.g. chains of supermarkets).
- Goals:
 - Improve integrability (grid friendliness) of wind power to the grid.
 - Obey tight grid codes.
 - Reject disturbances from wind speed changes with minimal power loss.
 - Avoid expensive energy storage solutions.

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Nominal controller with real wind scenario

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MPC controller with real wind scenario

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Findings in project:

- 1. Investigations and proof-of-concept for flexible power consumption in industrial refrigeration by use of Economic MPC.
- 2. Enabling load-shifting strategies and regulating power services with significant cost reductions.
- 3. Challenges in MPC for industrial systems tackled:
 - Model accuracy, computational load, predictions, etc.
- 4. Synergy and co-control potential with wind energy revealed.

Some selected references:

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Thank you for your attention Questions?

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