Autonomous demand side management - a decentralized approach to use hot water storage for load management

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Introduction

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Application to Stationary Battery Storage

Outlook (Josef Ressel Centre)
Motivation

The electrical energy system is changing concerning the generation as well as the grid infrastructure.

→ Communication
  - Communication networks (Smart Grids)
  - Optimized Control (Grid operation, load shedding, ...)

→ Integration
  - Strongly transient intermittent, decentralized generation (PV, wind)
  - Inhomogeneous, decentralized storage (E-Mob., stationary batteries, thermal storage)

Goal: Optimal supply and usage of energy
  -> Demand side management (DSM)
  For utilization of existing storage
Approaches for DSM

Centralized approach for demand side management
Approaches for DSM

Decentralized approach for demand side management
Autonomous DSM for decentralized storage

Decentralized approach for demand side management, concept for device integration
Autonomous DSM for decentralized storage

*Integration of decentralized storage for demand side management*

→ Utilization of existent storage

→ Autonomous DSM for small, decentralized storage, because of...
  
  - Minimal technical requirements on communication interface (only integrity and availability, no confidentiality issues)
  
  - Local intelligence for highly accurate system modeling
  
  - User privacy protection (no communication of user data possible)
  
  - High system robustness

→ In case of unavailability: energy optimized scheduling
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Domestic Hot Water Heaters for DSM

Why use resistive domestic hot water heaters for load management?

→ Relatively high nominal power (~ 2.5 kW)

→ Relatively high capacity (~5 kWh / Tag)

→ High market penetration:

→ In Vrlbg (~300'000 Inh.): ~90'000

→ Equals ~200 MW, ~160 GWh / y

→ Pump-storage Kops II: 175 MW per machine set (525 MW in total)

→ Hydro reservoir Kops: ~130 GWh
Integration of thermal storage for DSM

Status quo for resistive domestic hot water heaters.

- User centered approaches:

- User centered market driven field tests:
**Integration** of thermal storage for DSM


Sundström, O., Binding, C., Gantenbein, D., Berner, D., & Rumsch, W. C. (2012, October). Aggregating the flexibility provided by domestic hot-water boilers to offer tertiary regulation power in Switzerland. In Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on (pp. 1-7). IEEE.
Integration of thermal storage for DSM

Virtual Power Plants


Decentralized autonomous DSM


Hubert, T., & Grijalva, S. (2011, January). Realizing smart grid benefits requires energy optimization algorithms at residential level. In Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES (pp. 1-8). IEEE.


Problem Statement for DSM for hot water heaters

- Communication
- Sensorics
- State estimation
- System ID
- Modelling
- Optimization
- Prediction

- Reduciton of hardware → integration cost reduction
- Higher model accuracy → Higher load shift potential

Field tests
Simulation studies
Modelling of domestic hot water heaters

Multi-node model of a resistive domestic hot water heater.
Modelling of domestic hot water heaters

Energy accounting using effective conductivity model → System of $n$ ODEs

Energy balance: \[ C_w \frac{dT_i}{dt} = m c_w (T_{i-1} - T_i) + \dot{W}_{el,i} - \dot{Q}_{c,i} + \dot{Q}_{c,i+1} - \dot{Q}_{l,i}, \]

El. work: \[ \dot{W}_{el,i} = \delta_{i1} u(t) P_{el}, \]

Conduction: \[ \dot{Q}_{c,i} = (1 - \delta_{i(n+1)} - \delta_{i1}) k_{i-1}(T_i, T_{i-1}) A_c \frac{(T_i - T_{i-1})}{x_i - x_{i-1}}, \]

Eff. Conductivity: \[ k_i = \begin{cases} k_1 = k_w + k_{wall} \frac{A_{c,wall}}{A_c} : T_{i+1}(t) \geq T_i(t) \\ k_2 = \infty : T_{i+1}(t) < T_i(t) \end{cases} \]

Heat loss: \[ \dot{Q}_{l,i} = UA_{s,i} (T_i - T_\infty). \]

Mass flow: \[ \dot{m}_k = \frac{\dot{Q}_{dem}^{(k)}}{c_w (T^{(k)}_n - T_0)}. \]
Optimization based on bulk model

Single node (bulk) model results in

\[ p_2 \frac{dT}{dt} = -\dot{Q}_{\text{dem}}(t) + \dot{W}_{\text{el}}(t) - p_1(T(t) - T_\infty). \]

Discretized and iterative solution reads:

\[
T(t_0 + i\Delta t) = T(t_0)\lambda^i \\
+ \sum_{j=0}^{i-1} (1 - \lambda)\lambda^{i-j-1} \left( \frac{\dot{W}_{\text{el},j}}{p_1} - \frac{\dot{Q}_{\text{dem},j}}{p_1} + T_\infty \right),
\]

\[ \lambda = e^{-(p_1/p_2)\Delta t}. \]

This can be used to formulate a binary linear optimization problem

\[
\min_{u(t)} \int_{t_0}^{t_0+N\Delta t} c(t) \cdot P_{\text{el}} \cdot u(t) dt \quad \text{s.t.} \\
T_{\text{max}} \geq T(t) \quad \forall t \in [t_0, t_0 + N\Delta t], \\
T_{\text{min}} \leq T(t) \quad \forall t \in \{t_0 \leq t \leq t_0 + N\Delta t : \dot{Q}_{\text{dem}}(t) > 0\}. 
\]
Optimization based on bulk model

Simulation procedure for bulk model based optimization

Simulation linear optimization approach
Simulation linear optimization approach
Simulation linear optimization approach
Simulation results for linear optimization approach

- Optimization based on perfect knowledge of mean temperature
- Simulation of multi-node model taking stratification into account
- User prediction based on historic data (knn)
- Based on Austrian day-ahead market
- Price-optimized: ~ 12% Cost reduction (DSM potential)
  - Energy-optimized (flat price): ~ 12% Energy savings

Optimization based on full model

Full system be solved analytically via homogenization:

\[
\frac{dT_i}{dt} = A_{i,i-1}T_{i-1} + A_{i,i}T_i + A_{i,i+1}T_{i+1} + b_i, \\
T(t_0 + \Delta t) = \exp(\Delta t A) (T(t_0) + A^{-1}b) - A^{-1}b.
\]

Results in binary optimization problem with linear cost function and non-linear constraints.

\[
\min_u \sum c_k u_k \quad \text{s.t.} \\
g_k(u, T) = T_{\text{min}} - T_n^{(k)} \leq 0 \forall k \in \{k: 1 \leq k \leq N, \dot{Q}_{\text{dem}}^{(k-1)} > 0\}, \\
h_k(u, T) = T_n^{(k)} - T_{\text{max}} \leq 0 \forall k.
\]
Optimization based on full model

Bulk model used to formulate a priori bounds for the non-linear constrained problem

\[
\sum_{j=0}^{N} u_j P_{el} \leq \sum_{j=0}^{N} \dot{Q}_{dem}^{(j)} + UA_s(T_{max} - T_{\infty})N - C_w \frac{T^{(0)} - T_{min}}{\Delta t} =: E_u.
\]

\[
\sum_{j=0}^{N} u_j P_{el} \geq \sum_{j=0}^{N} \dot{Q}_{dem}^{(j)} + UA_s(T_{min} - T_{\infty})N - C_w \frac{T^{(0)} - T_{min}}{\Delta t} =: E_l.
\]

\[
\left| \frac{E_l}{P_{el}} \right| \leq \sum_{j=0}^{N} u_j \leq \left| \frac{E_u}{P_{el}} \right|.
\]

Reducing the search space for feasible solutions from \(2^N\) to

\[
2^{(N)}_{B_1} + \cdots + 2^{(N)}_{B_u}
\]
Optimization based on full model

Dynamic Optimization

Optimization time window checked stepwise regarding:

1. temperature constraints
2. power constraints
3. optimality
Simulation results for nonlinear optimization approach

LO: Linear Optimization (Bulk model)
MNO (k): Nonlinear optimization (incl. Stratification)
→ User prediction based on historic data (k nearest neighbors)
→ Based on dynamic programming approach
→ Uses limiting estimates from bulk model to reduce possible paths.

Simulation results for nonlinear optimization approach

Field Test SmartCity Rheintal

- FFG Smart City Rheintal
- In cooperation with VKW
- Retrofitting of 16 thermal storage devices
- Ends Dec. 2017
- Webportal for users
- Local data acquisition
- Local intelligence (In-house SW/HW)
- EXAA Day-ahead based
Field Test SmartCity Rheintal

Simulierter NachtTarif. Wirkungsgrad: 0.682. Kosten kWh thermisch: 0.0386 EUR. Kosten kWh elektrisch: 0.0263 EUR.

Preisoptimal - gemessen. Wirkungsgrad: 0.75. Kosten kWh thermisch: 0.0319 EUR. Kosten kWh elektrisch: 0.0239 EUR.

RTP Einsparungen: 17.4%. Stromeinsparungen: 9.09%.
Field Test SmartCity Rheintal

Simulierter Nachttarif. Wirkungsgrad: 0.597. Kosten kWh thermisch: 0.0461 EUR. Kosten kWh elektrisch: 0.0275 EUR.

Preisoptimal - gemessen. Wirkungsgrad: 0.675. Kosten kWh thermisch: 0.0328 EUR. Kosten kWh elektrisch: 0.0221 EUR.

RTP Einsparungen: 28.9%. Stromeinsparungen: 11.5%.
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Autonomous DSM for battery storage systems

- Zebra Battery (Zero Emission Battery Research Activities)
- Second use for Batteries from electric vehicles
- Models based on real 2nd use system
- Linear optimization using on one-way communicated cost function.
- Simulated system with coupled non-linear differential equations.

Simulation results for battery storage systems

System behavior of an autonomous optimized battery storage system.
→ Comparison of 1h-based and 15 min- based day-ahead prices.
Simulation results for battery storage systems

Earnings on the 1 h-based day-ahead market between 2003 and 2015.
Simulation results for battery storage systems

Earnings and losses based on variation of the battery capacity-to-power ratio for hourly-based time products.
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Outlook (Josef Ressel Centre)
Josef Ressel Centre
for applied scientific computing in energy, finance and logistics

CDG funded research in cooperation with industry partners


Volume: EUR 1.3 Mio.
Josef Ressel Centre
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Energy Model Library (WP4)

Simulation and predictive control
- Thermal storage (DHWH)
- Stationary and mobile battery storage (E-Mobility)

Distribution grid simulation including many autonomous loads
- Real test grids and base load data
- Simulation of decentralized renewable generation

Optimization of unidirectional cost function
- Demand-shifting
- Distribution grid optimization (integration of renewables)
Thank You!

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