Dispatching active distribution networks through electrochemical storage systems and demand side management

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Motivations

Definition of a balance group (from the Swiss grid code):

“A balance group is a virtual construct for the purposes of billing and accounting. […] Every distribution grid operator, trader, power producer, supplier and end consumer must belong to a balance group. The balance group manager (BGM) can conduct energy transactions with other balance group managers at home and abroad, offload energy from power stations or transfer energy to end consumers. To do this the BGM sends schedules within the planning phase to Swissgrid. On completion of the energy deliveries, Swissgrid balances all import/export schedules of the balance group […] as well as all measured feed-ins and feed-outs per balance group (measuring values which Swissgrid receives from all grid operators) and, in the event of deviations, charges the purchased or sold energy to the BGM as balance energy. The BGM is responsible for ensuring that his or her balance group is as balanced as possible at all times.”
Motivations, cont’d

- Achieving dispatched-by-design operation of traditionally stochastic prosumption allows reducing grid reserve requirements.

- The dispatch plan is built to satisfy a local objective, such as peak shaving, load levelling or minimization of the cost of imported electricity.
The operation of a group of stochastic prosumers (generation + demand) is dispatched according to a profile established the day before operation (called dispatch plan) by controlling the real power injection of the battery.
Formulation – A two stage process

Time (hours before the beginning of the day of operation)

-1

The feeder is dispatched according to the dispatch plan.

0

Tracking of the dispatch plan.

24

Receding horizon MPC to control BESS injections.

TSO

Dispatchable feeder operator

BESS

Day-ahead scheduling

Intra-day and real time operation

The feeder dispatch plan on a 5-minute basis is determined.
The dispatch plan is a sequence at 5 minute resolution that denotes the power flow at the grid connection point that the feeder should follow.

It is the sum between prosumption point predictions and the so-called offset profile:

\[ \hat{P}_t = \hat{L}_t + F_t \quad t = 1, \ldots, N \]

The latter is with the objective of restoring an adequate battery state-of-energy such that, during operation, enough up/down-flexibility is available to compensate the mismatch between presumption and realization.
Formulation – Offset profile problem (non convex)

We seek for the smallest offset profile $F$ such that the battery state-of-energy is within bounds in the scenarios with highest and lowest possible prosumption $L_i^\uparrow, L_i^\downarrow$.

$$F^o = \arg \min_{F \in \mathbb{R}^N} \left\{ \sum_{i=1}^{N} F_i^2 \right\}$$

subject to

$$\text{SOE}_{i+1}^\uparrow = \text{SOE}_i^\uparrow + \beta^+ \left[ F_i^o + L_i^\uparrow \right]^+ + \beta^- \left[ F_i^o + L_i^\downarrow \right]^-$
$$\text{SOE}_{i+1}^\downarrow = \text{SOE}_i^\downarrow + \beta^+ \left[ F_i^o + L_i^\uparrow \right]^+ + \beta^- \left[ F_i^o + L_i^\downarrow \right]^-$

$$\text{SOE}_{i+1}^\uparrow \geq \text{SOE}_{\text{min}}$$

$$\text{SOE}_{i+1}^\downarrow \leq \text{SOE}_{\text{max}}$$

$$F_i + L_i^\downarrow \geq B_{\text{min}}$$

$$F_i + L_i^\uparrow \leq B_{\text{max}}$$

$$\hat{P}_i \leq P_{\text{max}}$$

for $i = 0, \ldots, N - 1$

Note that this is a non convex problem due to the sign operators $[\cdot]^+, [\cdot]^-$.
Formulation – Offset profile problem (convex)

The previous problem can be formulated as a convex one by writing the sign operator as the sum of two mutually exclusive terms. We define:

\[ K_i^+ = F_i^o + L_i^\uparrow = K_i^+ - K_i^- , \quad K_i^+ \geq 0 , \quad K_i^- \geq 0 \]
\[ G_i^+ = F_i^o + L_i^\uparrow = G_i^+ - G_i^- , \quad G_i^+ \geq 0 , \quad G_i^- \geq 0 \]

which are used to rewrite the previous optimization problem. The cost function achieves to keep the positive and negative components mutually exclusive.

\[
\arg \min_{K^+, K^-, G^+, G^- \in \mathbb{R}^N} \left\{ \sum_{i=1}^{N} (K_i^+ + K_i^- + G_i^+ + G_i^-) \right\}
\]

subject to:

\[ K_i^+ - K_i^- - L_i^\uparrow = G_i^+ - G_i^- - L_i^\uparrow \]
\[ \text{SOE}_{i+1}^\uparrow = \text{SOE}_{i}^\uparrow + \beta^+ K_i^+ - \beta^- K_i^- \]
\[ \text{SOE}_{i+1}^\uparrow = \text{SOE}_{i}^\uparrow + \beta^+ G_i^+ - \beta^- G_i^- \]
\[ \text{SOE}_{i}^\uparrow \geq \text{SOE}_{\text{min}} \]
\[ \text{SOE}_{i}^\uparrow \leq \text{SOE}_{\text{max}} \]
\[
\vdots
\]
\[ F_i^o = K_i^{+ o} - K_i^{- o} - L_i^\uparrow \]
Formulation – The real-time control problem (MPC)

The objective is to track the dispatch plan. Since it consists in accomplishing a certain energy throughput, we rely on MPC rather a conventional feedback control loop to determine the current evolution while respecting BESS operational constraints. MPC is actuated at 10 sec resolution on a 5 min shrinking horizon by plugging in short-term prosumption forecasts and open-loop predictions of the BESS operational constraints (voltage and current).

Two formulations are possible:

1. Determining the BESS power to accomplish the energy throughput subject to BESS constraints. However, BESS constraints are nonlinear and nonconvex.

2. Determining the BESS current to minimize the distance from the target energy throughput while subject to linear voltage and current constraints. However the cost function:

\[ (E_k - e_k)^2. \]

is in the form \( q(r(x)) \). To be convex, it requires \( r(x) \) to be convex (it is) and \( q \) convex nondecreasing (it is not), thus it is nonconvex.
Formulation – The new (convex) MPC

The BESS energy throughput in the 5 minute interval is the integral over time of the product between BESS DC current, voltage and converter efficiency alpha:

\[ E_{k|k}(\cdot) = \alpha v_{k|k}^T i_{k|k} \]

The BESS voltage dynamic evolution depends on the charge/discharge current. It can be modelled by using a three-time-contant (TTC) model as a function of the initial BESS state \( x_{k} \) as the following linear relationship.

\[ v_{k|k} = \phi^v x_{k} + \psi_i^v i_{k|k} + \psi_1^v 1 \]

which replaced in the first expression leads to:

\[ E_{k|k}(\cdot) = \alpha \left( x_k^T \phi^v T i_{k|k} + i_k^T \psi_i^v T i_{k|k} + 1^T \psi_1^v T i_{k|k} \right) \]

The expression above is the sum of two linear expressions and a quadratic form in the current. It is therefore convex provided that \( \psi \) is SDP, which has been numerically proven for the adopted TTC model.
Formulation – The new (convex) MPC

We use the previous result to formulate a convex equivalency of the original MPC optimization problem. This consists in maximizing the current (linear cost function) subject to the energy throughput being less or equal to the target energy throughput $e_k$ (convex inequality).

$\hat{i}_{k|k} = \arg \max_{i \in \mathbb{R}^{k-K+1}} \left\{ 1^T \hat{i}_{k|k} \right\}$

subject to:

$e_k = \frac{300}{3600} \cdot (P_k^* - P_k^+) \quad \text{(Tracking error)}$

$\alpha \left( x_k^T \phi^T \hat{i}_{k|k} + i_N^T \psi_i^T \hat{i}_{k|k} + 1^T \psi_r^T \hat{i}_{k|k} \right) \leq e_k \quad \text{(BESS energy throughput, convex if $\psi_i$ is SDP)}$

$1 \cdot i_{\min} \leq \hat{i}_{k|k} \leq 1 \cdot i_{\max} \quad \text{(Current constraints)}$

$1 \cdot \Delta_i,\min \leq H \hat{i}_{k|k} \leq 1 \cdot \Delta_i,\max \quad \text{(Current ramping constraints)}$

$\hat{v}_{k|k} = \phi^v v_k + \psi_i^v \hat{i}_{k|k} + \psi_1 1 \quad \text{(Voltage model)}$

$1 \cdot v_{\min} \leq \hat{v}_{k|k} \leq 1 \cdot v_{\max} \quad \text{(Voltage constraints)}$

$\text{SOC}_{k|k} = \phi^{\text{SOC}} \text{SOC}_k + \psi_i^{\text{SOC}} \hat{i}_{k|k} \quad \text{(SOC model)}$

$1 \cdot \text{SOC}_{\min} \leq \hat{\text{SOC}}_{k|k} \leq 1 \cdot \text{SOC}_{\max} \quad \text{(SOC constraints)}$

Once the current is known from the MPC, it is multiplied by the voltage to determine the real power set-point to finally submit to the BESS converter.

- value of the prosumption set-point to match (from the dispatch plan)
- expected average consumption with short-term point prediction
Formulation – Modelling of energy storage

We apply grey-box modelling on offline measurements of the DC voltage vs. current to identify (linear) system dynamics.

- Measurements are from dedicated experiments where the BESS was excited by using a pseudo-random binary signal (PRBS, a two-state signal with random duration).

- Since parameters are state-of-charge (SOC) dependent, the identification experiment is carried out for different BESS SOC intervals.
The model which captures the best early to middle-range time dynamics is a third order linear model, an extension of the well known TTC.

The autocorrelation function shows i.i.d. model residuals.

For the MPC, we apply model scheduling, namely we select the set of parameters corresponding to the current SOC and we assume that this does not vary in the control period.

BESS equivalent circuit (set of parameters’ values for each considered SOC range).

Model prediction errors are i.i.d. (50% SOC).
The EPFL experimental setup

- Single measurement point at the GCP.
- 350 kW peak demand during winter.
- 95 kWp roof-top PV installation.
The EPFL experimental setup – The BESS specs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Capacity</td>
<td>720 kVA/560 kWh</td>
</tr>
<tr>
<td>GCP Voltage</td>
<td>20 kV</td>
</tr>
<tr>
<td>DC Bus Voltage Range</td>
<td>600/800 V</td>
</tr>
<tr>
<td>Cell Technology (Anode/Cathode)</td>
<td>Lithium Titanate Oxide (LTO) Nickel Cobalt Aluminium Oxide (NCA)</td>
</tr>
<tr>
<td>Number of racks</td>
<td>9 in parallel</td>
</tr>
<tr>
<td>Number of modules per rack</td>
<td>15 in series</td>
</tr>
<tr>
<td>Cells configuration per module</td>
<td>20s3p</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>8100</td>
</tr>
<tr>
<td>Cell nominal voltage</td>
<td>2.3 V (limits 1.7 to 2.7 V)</td>
</tr>
<tr>
<td>Cell nominal capacity</td>
<td>30 Ah (69 Wh)</td>
</tr>
<tr>
<td>Round-trip efficiency (AC side)</td>
<td>94-96%</td>
</tr>
<tr>
<td>Round-trip efficiency (DC side)</td>
<td>97-99%</td>
</tr>
</tbody>
</table>
Results – 14/01/2016, operation

- Prosumption worst-case scenarios (shaded band)
- Prosumption point predictions (dashed)
- Offset plan (black).

- Dispatch plan (gray)
- Composite power realisation at the GCP (dashed)
- Prosumption realization without the battery correction (black)
BESS state-of-charge, DC Current and DC voltage with respective limits.
Results

Dispatched operation -- 14 Jan 2016  
https://snapshot.raintank.io/dashboard/snapshot/PuW1Rf5d470Q0gsT7UNponM25bGDNTRA

Dispatched operation -- 13 Jan 2016  
https://snapshot.raintank.io/dashboard/snapshot/cDS4IDniZjRiePXvusnmQXOmMwpGLnR6

Dispatched operation + Peak Shaving -- 22/06/2016  
https://snapshot.raintank.io/dashboard/snapshot/LSF3bPxtWYDjHVu6siEr1VPb92EXNkd6

Dispatched Operation + Load Levelling -- 14/03/2016  
https://snapshot.raintank.io/dashboard/snapshot/4ztn800czpAzEFRzbGOmWc1A2pKeC9ab

Dispatched operation (continuos operation) -- 16 to 19/03/2016  
https://snapshot.raintank.io/dashboard/snapshot/TNbEgP7j1AWhaW7cEK1ZiK3tY1Or7P4U
Conclusions – Part I

- **A bottom-up approach** to tackle the challenge of increasing reserve requirements due to integration of larger shares of renewables.

- Suitable to operate in current **vertically operated power systems**.

- **Fully decentralized control mechanism** with no coordination requirements: complexity is masked behind the commitment of the operator to follow the dispatch plan.

- **No pervasive** monitoring/control **infrastructure**.

- Inherently allows to achieve **local grid operational objectives**, like peak shaving or load levelling.

- **The framework is flexible to include the control of other resources** (see part II).

- Grid constraints are not considered. It relies on the fact that storage can be sited and sized offline in the planning phase to mitigate localized network issues, thus without need of incorporating (which comes at the cost of much higher complexity and uncertainty).
The topology of a dispatchable feeder

The operation of a group of stochastic prosumers (generation + demand) is dispatched according to a profile established the day before operation (called dispatch plan) by controlling the real power injection of the battery.

Sources of flexibility:

- physical energy storage systems (part I)
- flexible demand (part II)
1. Dispatch plans for occupied buildings
2. Real-time control for dispatchability
3. Early experimental results (one week)
4. Optimal sizing
Dispatch Planning – Two Competing Objectives

1. Minimize energy

2. Maximize flexibility

Goal: Choose dispatch plan to maximize controllability during highly uncertain periods

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Cost</th>
<th>Comfort</th>
<th>Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
Optimal Dispatch Problem

Day-ahead plan for the thermal \((x, e)\) trajectory of the building and electrical dispatch \(d\)

\[
\min_{x, u} \sum \mathbb{E} \left( \text{cost}_i \cdot e_i + \rho(x_i - \bar{x}) + \|e_i - (d_i + p_i)\|^2 \right)
\]

s.t. \((x, e) \in C(w)\) \(\forall w \in W\)

Thermal trajectory must be input-admissible (feasible) and comfortable \(C(w)\) for all likely weather scenarios \(W\)
Optimal Dispatch Problem

Day-ahead plan for the thermal \((x, e)\) trajectory of the building and electrical dispatch \(d\)

Uncertainty model
- Weather
- Occupancy
- Prosumer consumption (PV & buildings)

\[
\min_{x,u} \sum \mathbb{E} \left( \text{cost}_i \cdot e_i + \rho(x_i - \bar{x}) + \|e_i - (d_i + p_i)\|^2 \right)
\]

s.t. \((x, e) \in C(w)\) \ \forall w \in W

Model of building and HVAC equipment
Building Modeling Tool

Linear time-varying model and constraints

\[ x_{i+1} = A_i x_i + B_i u_i + T_i w_i \]
\[(x_i, u_i) \in X_i \times U_i\]
\[ e_i = P_i u_i \]

- \( x_i \): thermal state
- \( u_i \): thermal energy to each building zone
- \( e_i \): energy consumed
Optimal Dispatch Problem

Day-ahead plan for the thermal ($x$, $e$) trajectory of the building and electrical dispatch $d$

Uncertainty model
- Weather
- Occupancy
- Prosumer consumption (PV & buildings)

$$
\min_{x,u} \sum \mathbb{E} \left( \text{cost}_i \cdot e_i + \rho(x_i - \bar{x}) + \|e_i - (d_i + p_i)\|^2 \right)
$$

s.t. \hspace{1cm} x_{i+1} = A_i x_i + B_i u_i + T_i w_i \\
\hspace{1cm} (x_i, u_i) \in \mathcal{X}_i \times \mathcal{U}_i \quad \forall w_i \in \mathcal{W}_i \\
\hspace{1cm} e_i = P_i u_i$$
Prediction with Gaussian Processes (GP)

Historical data

Estimates mean and uncertainty about the mean.
Uncertainty of GP interpretation grows away from previous observations.
Optimal Dispatch Problem

Day-ahead plan for the thermal \((x, e)\) trajectory of the building and electrical dispatch \(d\)

Empirical distribution with samples extracted from Gaussian Process

\[
\min_{x,u} \sum \mathbb{E} \left( \text{cost}_i \cdot e_i + \rho(x_i - \bar{x}) + \|e_i - (d_i + p_i)\|^2 \right)
\]

s.t. \(x_{i+1} = A_i x_i + B_i u_i + T_i w_i\)

\((x_i, u_i) \in \mathcal{X}_i \times \mathcal{U}_i, \quad \forall w_i \in \mathcal{W}_i\)

\(e_i = P_i u_i\)

Solve using standard stochastic optimization
Increased uncertainty results in higher energy expenditure and higher control authority
Real-Time Control – Every 5 min

Weather measurement and forecast $w_i$

Building measurements & state estimate $x_0$

Battery $SOC_0$ ≈ Dispatch error integral

1. Move battery to reference SOC

\[
\min_{x,u} \sum_{i} \|SOC_i - SOC_i^{REF}\|^2 + \sum_{j} \|T_jx_i - \sum_{k} T_kx_i\|^2
\]

s.t.

\[
x_{i+1} = A_ix_i + B_iu_i + L_iw_i
\]

\[
(x_i, u_i) \in X_i \times U_i
\]

\[
SOC_{i+1} = \alpha SOC_i + \beta (P_iu_i - b_i)
\]

2. All zones equal temperature

Enforce comfort constraints

Simple battery model

- Dispatch errors encoded in SOC → Restore SOC to nominal
- No prosumer forecast → Distributed operations
Laboratoire d’Automatique Demand Response

Solar radiation
Outside temp

Power measurement

Temperature
Occupancy
Light
Humidity
### LADR Experimental Configuration

1. LADR has been virtually scaled-up in all experiments

<table>
<thead>
<tr>
<th></th>
<th>Peak Consumption (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LADR</td>
<td>45</td>
</tr>
<tr>
<td>Battery</td>
<td>720</td>
</tr>
<tr>
<td>Uncontrollable prosumers (PV + Buildings)</td>
<td>350</td>
</tr>
</tbody>
</table>

- **Scaled up from a true peak consumption of 7.8 kW**
- **12% of loads are controllable**

2. Dispatch objective: **Maximize flexibility**
Good Prediction Day – Battery Only

- Dispatch plan (black)
- Prosumer consumption (red)
- SOC reference

Battery easily compensates for prediction errors (SOC)
Good Prediction Day – Battery & LADR

Building dispatch plan (black)

Building consumption (red)

SOC with battery (red)

Building reduces battery requirements significantly

Building zone temperatures
Poor Prediction Day – Battery Only

Dispatch plan (black)
Prosumer consumption (red)
Battery cannot compensate for forecast errors (SOC)
Poor Prediction Day – Battery & LADR

Building dispatch plan (black)
Building consumption (red)
Building reduces battery requirements significantly (SOC)
Building zone temperatures
Impact of Building Size – Preliminary Conclusion

- Experiments run at 12% controllable buildings result in 80% reduction in battery capacity.
- 20% controllable buildings result in 80% reduction in battery capacity.

The graph shows the relationship between the required battery capacity [kWh] and the percentage of controllable loads [%]. The current battery capacity is indicated by a speech bubble pointing to the graph.
Impact of Sample Rate – Preliminary Conclusion

Experiments run at 5min

Control of average energy over 60min requires 20% larger battery

Sample Period [min]

Required Battery Capacity [kWh]

Percentage of Installed Battery

0 20 40 60 80 100 120
0 20 40 60 80 100

0 100 200 300 400 500 600
Conclusion: Hybrid storage schemes provide much greater flexibility to offer a wide variety of services at lower cost.
Acknowledgements (i.e., they who did the work!)

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References

