Review of grid applications with the Zurich 1 MW battery energy storage system

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\textbf{A B S T R A C T}

Battery energy storage systems (BESSs), while at the moment still expensive, are from a technical point of view exceptionally well suited to support a distribution system operator (DSO) in the challenges created by increasing distributed, fluctuating and uncertain generation from renewable energy sources (RES), as well as by the unbundling of electricity retailing and grid operation. This paper presents three grid applications and measurement results from the grid-connected Zurich 1 MW BESS. Specifically, provision of frequency reserves, peak shaving and islanded operation of a microgrid are discussed in detail. The battery unit is able to perform these diverse tasks with outstanding quality. For the provision of frequency reserves the system has passed all prequalification requirements posed by the transmission system operator (TSO) in order to be granted access to the ancillary services market. Along with these applications, the paper aims to communicate the experience gained in designing proper control frameworks, communication infrastructure and the knowledge acquired concerning BESSs behavior.

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1. Introduction

The rapid deployment of generation from renewable energy sources (RES) is posing a challenge for utilities across Europe and worldwide. At the same time, regulators are giving increased attention to both the cost efficiency and reliability of grid operation. The challenges faced by the distribution system operator (DSO) include voltage rise in low voltage feeders due to power in-feed from distributed generation, quality of power supply and harmonics, as well as costs for infrastructure and line upgrades. These infrastructure costs may either be refinanced by an increase in energy-based grid tariffs or in the form of demand charges for peak power, to be paid by industrial and large commercial customers but also by the DSO for the connection to the transmission system. These tariffs in turn are an incentive to reduce demand peaks, possibly by relying on a battery energy storage system (BESS). Also, the overall power system experiences an increased demand for frequency control reserves, while conventional power plants that traditionally provide these reserves are replaced with renewable generation. BESSs, especially when based on Li-ion batteries, offer high efficiency and fast ramp rates and are therefore optimally suited to address the aforementioned challenges. Still, widespread deployment is held back by the high capital cost of BESS technologies.

This paper introduces the Zurich 1 MW BESS located in Dietikon, Switzerland, and operated by Elektrizitätswerke des Kantons Zürich (EKZ), the Utility of the Canton of Zürich. We will investigate for what applications the BESS can be used, and show results from actual measurements. All results are from grid-connected operation. An overview of the Zurich 1 MW BESS is given in Section 2. The applications discussed in detail are primary frequency control in Section 3, peak-shaving for an office building in Section 4 and islanded operation of a microgrid with additional generation in Section 5. Challenges experienced during the set-up of the system and test runs are recapitulated in Section 6, before Section 7 concludes with a summary and an outlook.

1.1. Battery project review

A good overview of battery technologies from a power system perspective can be found in [1]. Doughty et al. give a summary of early large-scale projects [2], with a focus on reserve provision. An up-to-date database of energy storage systems is maintained by the US Department of Energy (US DOE), covering several hundred projects around the world [3].

The worldwide first utility-scale battery used for frequency regulation was deployed in West-Berlin in the 1980s by BEWAG, the electric utility in charge of the then isolated city grid. Under the
Table 1

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1 MW</td>
</tr>
<tr>
<td>Overload power</td>
<td>1.3 MW for 15 min</td>
</tr>
<tr>
<td>Capacity(^a)</td>
<td>580 kWh</td>
</tr>
<tr>
<td>System integrator</td>
<td>ABB</td>
</tr>
<tr>
<td>Battery manufacturer</td>
<td>LG Chem</td>
</tr>
<tr>
<td>Cell type</td>
<td>Li-ion</td>
</tr>
<tr>
<td>Lifetime(^b)</td>
<td>3500 cycles</td>
</tr>
<tr>
<td>PCS manufacturer</td>
<td>ABB (PCS 100)</td>
</tr>
</tbody>
</table>

\(^a\) 250 kWh usable capacity with peak power of 1 MW.
\(^b\) Based on 2 cycles/day with 250 kWh using 1 MW for charging and discharging.

2. System description

2.1. Components and grid integration

The Zurich 1 MW BESS was commissioned in March 2012. Table 1 summarizes the properties of the system shown in Fig. 1. To allow for testing of a variety of grid applications the system was integrated on the low voltage as well as on the medium voltage level (see Fig. 2). The point of common coupling (PCC) is on the low voltage side, right after the 400 V isolation transformer which filters out the inverter switching frequencies from the common mode voltage. Note that for a medium voltage connection one step-up transformer alone would be enough to connect to the grid.

Some of the different configuration possibilities of the breakers illustrated in Fig. 2 and Table 2 allow for a number of test configurations and representation of typical grid situations encountered in the distribution grid. Illustrated in yellow is the direct medium voltage coupling with a step-up transformer to 16 kV. The BESS is located in the immediate vicinity of a 110 kV/16 kV substation and has its dedicated medium voltage feeder. Indicated in blue is the low voltage coupling which allows to include a variety of different loads and generators into the operation and control of the BESS such as Electric Vehicle (EV) charging stations (fast and conventional), a small photovoltaic (PV) plant and an office building. The red configuration shows the configuration of the microgrid, including an optional diesel generator to allow for an indefinite duration of islanded operation.

2.2. Supervision and control

The different grid configurations illustrated in Fig. 2 are controlled from a dedicated Supervisory Control and Data Acquisition (SCADA) system (see Fig. 3) operated from a small control room next to the BESS. The SCADA integrates the breakers and all measurements and alarms from the core system components, i.e. the Power Conversion System (PCS), Battery Management System (BMS) and the additional components shown in Fig. 2.

Time synchronization of measurements and events is achieved by an accurate time base from a Global Positioning System (GPS) clock, distributed via the network time protocol (NTP). The integrated process control (OPC) interface of the SCADA system allows to connect additional controllers and devices with a limited time resolution. The advanced control algorithms for frequency control and peak shaving shown in Sections 3 and 4 are implemented via OPC. The operation of the BESS by EKZ’s grid control center is at this stage of the project still limited but all the interfaces have already been prepared for the planned full operation, once the project moves beyond pilot stage.

2.3. General performance

Two years of BESS operation already allow to present robust intermediate results on cycling efficiency, ramp rate and initial battery cell degradation.

Table 2

<table>
<thead>
<tr>
<th>BESS grid connection</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium voltage coupling</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low voltage coupling</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Microgrid</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Fig. 1. Top view of the Zurich 1 MW BESS.
2.3.2. Table 130

Grids are valuable and cost-effective systems.

2.3.3. Battery leads

Batteries are the future of energy storage. They are indispensable in the grid.

2.3.4. Losses

Losses are associated with the battery operation and can be classified into several types.

2.3.5. Power conversion system (PCS)

Power conversion systems are essential for the efficient operation of the grid.

2.3.6. Efficiency

Efficiency is a critical factor in the operation of the grid.

![Diagram showing supervision and control architecture.]

**Table 3**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Island</th>
<th>Speed</th>
<th>Losses^4</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSI</td>
<td>Yes</td>
<td>⊗</td>
<td>⊗</td>
</tr>
<tr>
<td>CSI</td>
<td>No</td>
<td>⊗⊗</td>
<td>⊗</td>
</tr>
</tbody>
</table>

^4 During standby.
Auxiliary system losses are only partially a function of power levels (with the exception of HVAC) and add a constant load which manifests itself as a self-discharge or as additional power drawn from the grid if a dedicated auxiliary feeder is present. The constant power consumption of the auxiliary system heavily affects overall round trip efficiency over longer time periods with little cycling activity.

Many other factors such as voltage, temperature and state of health influence BESS efficiency but have a lower impact on measured efficiency than power levels.

3. Application I: primary frequency control

3.1. Theory and motivation

Power plants offering ancillary services such as frequency control reserves, the so-called must-run generation units, have to run in part load operation mode. This is detrimental both to an economic and an ecological power system operation. Economically, as fuel costs may not be covered by the current energy price; ecologically as fossil-fuel power plants keep running to produce reserves even though the energy demand is already supplied by RES. Whereas traditionally control reserve provision is merely a side-product of energy production and thus relatively cheap, in the case of low spot market price, energy production becomes an unwanted side-, by-, or even waste-product of control reserve power provision, leading to a suboptimal dispatch, see Fig. 4(a). Similarly, reserve provision reduces the maximum output a power plant can offer creating an opportunity cost that prevents both a better utilization of assets [4,10], Fig. 4(b), and likewise a better exploitation of RES generation, Fig. 4(c). Batteries can offer control reserves power without producing energy, effectively decoupling power from energy provision, Fig. 4(d). In addition, a 1 MW battery can offer 1 MW of up and down regulation, while a generator reserving a 1 MW band can offer only 0.5 MW of symmetric regulation power reserve.

The current frequency control framework of ENTSO-E allows up to 30 s for full activation of primary control reserves. This is suitable assuming an aggregated rotational inertia of 6 s in the power system, however, reduced rotational inertia will lead to faster frequency excursions after a major outage. With a rotational inertia of 3 s, frequency deviations can reach critical levels before primary frequency control is fully activated [11]. Such low levels of inertia will be commonplace in future power systems with high RES shares, as most renewable generation, as well as an increasing number of motors, are converter-connected and do not as such provide rotational inertia to the grid. Already today there is a number of hours each year where more than 60% of the German electricity production is provided by converter-connected RES units, considerably reducing the rotational inertia of that grid area [12]. As deployment of PV and wind generation units increases, storage units such as BESSs, which can react appropriately to very fast frequency excursions, might soon be needed.

Due to internal losses, the SoC of the battery inevitably decreases over time. In addition, control reserve activation signals are in general not zero-mean. Eventually energy constraints are reached, rendering the storage unit unable to further provide the contracted AS. A battery recharging strategy has to be implemented that allows to maintain the SoC without impeding the quality of reserve provision. In [4], the batteries were recharged during off-peak hours when sufficient conventional power plant capacity was available. Oudalov et al. [13] utilize the deadband around nominal system frequency to adjust the SoC. In [14], a fixed amount of energy is charged or discharged when a specific SoC level is reached. Dynamic recharging is proposed in [15]. Both [14,15] can be easily parameterized with respect to delay times and ramp rates.

The Zurich 1 MW BESS is too small to affect the frequency response of the continental European interconnected power system, which has a total of 3 GW of primary reserve capacity. It is shown in [16] that the power system can be operated as reliable as today when substantial parts of, or even all primary reserves are provided by battery units. Battery recharging and the frequency dynamics of the European interconnected power system were taken into account for the detailed analysis presented in [16].

3.2. Implementation and measurements

The recharging algorithms [14] and [15] were both extensively tested on the Zurich 1 MW BESS. The recharging control loops are implemented on an external PC which adjusts the working point of the battery through the OPC interface of the SCADA. The frequency measurement and droop control is implemented directly in the PCS controller to minimize latency. Refer to Fig. 3 for the communication layout. ENTSO-E regulations require full activation at 200 mHz deviation from the nominal grid frequency of 50 Hz. No activation is required in a dead band of ±10 mHz. Tests were run for both battery charging strategies. Results are shown for runs of one week duration and providing 1 MW of reserves, in accordance with the tender period and minimum capacity in the Swiss primary frequency control reserve market.

Recharging based on SoC limits. Recharging is activated when the SoC falls below 45%, discharging above 65%. These boundaries could easily be increased, but they were chosen to demonstrate the behavior of the recharging algorithm, as well as the ability to offer reserves even with small battery capacities. Charging starts without delay when these limits are reached, but a ramp is introduced in order to put as little stress on the power system as possible. The ramp duration is five minutes, as is the charging period and the ramp back to zero power provision. The battery is charged or discharged with 200 kW, each event changes the SoC by 33 kWh. If the SoC is still outside of the boundaries at the end of the charging period, i.e., before ramping down, it is prolonged by another five minutes.

Fig. 5 shows one day of acquired measurements. The top plot shows the system frequency. The middle plot gives the total BESS output in red, and the offset in green. More recharge intervals than discharge intervals are observed, which is due to cycling losses. The bottom plot shows the SoC evolution.
Recharging with moving average. Let $p^{\text{prim}}$ be the primary frequency reserve activation according to the grid code. The battery activation $p^{\text{BESS}}$ is the sum of the reserve and an offset $p^{\text{set}}$.

\[
p^{\text{BESS}}(k) = p^{\text{prim}}(k) + p^{\text{set}}(k),
\]

and the offset in turn is computed from a moving average over previous activation and losses.

\[
p^{\text{set}}(k + d) = \frac{1}{a} \sum_{j=k-a}^{k} (p^{\text{loss}}(j) - p^{\text{prim}}(j)).
\]

The parameter $d$ allows for a time delay, which might be needed if a back-up generator has to provide the energy. The ramp rate can be limited with parameter $a$; the longer $a$ the smoother the recharging signal but, in turn, the bigger the BESS has to be dimensioned. As the losses cannot be directly measured, they are estimated from the SoC evolution. More specifically, the expected SoC of a perfect storage system is predicted, and deviations from this are defined as loss. This approach relies on accurate SoC estimation, which is not trivial to achieve with BESS. The frequency dead band was neglected, as at the time of the test it was not possible to directly apply a power offset on the PCS controller. While this is a minor firmware issue, it affects battery utilization and thus cost incurred by the battery operator.

The maximum output power of the BESS is strictly limited to 1.2 MW. As the reserve provision and the recharging may have the same sign at times, the recharging is capped at 200 kW. The energy that is not recharged is counted and added to the offset at the next possible time-step.

Fig. 6 gives results of a test run. No delay was used, i.e., $d$ is zero, and the averaging period $a$ was set to 15 min. The top plot shows the frequency. In the middle plot the total BESS output $p^{\text{BESS}}$ and the offset $p^{\text{set}}$ are drawn, as well as the limit for recharging power. This limit is only rarely reached, for a few minutes each time. The bottom plot finally gives the SoC evolution. The SoC evolves much closer to the reference SoC of 55% than with the SoC-limit algorithm. At the same time, more energy is used for recharging, and accordingly power deviations from $p^{\text{prim}}$ are larger, albeit smoother.

The Zurich 1 MW BESS has been prequalified for the provision of primary frequency control according to the requirements posed by the Swiss transmission system operator (TSO) Swissgrid [17]. The prequalification includes minimum ramp rate and reaction time requirements which were tested by the TSO on the system using simulated and measured grid frequency signals. The successful prequalification provides the battery with access to the ancillary services market for primary frequency control. The combined primary frequency control market of Austria and Switzerland has a volume of 117 MW which is cleared in weekly auctions, where the lowest bids of the market participants are accepted by the TSO.

Summary. Both battery recharging strategies are capable of ensuring continuous availability of the full frequency control reserves of 1 MW during the whole week without any manual interference from the operator. Which strategy should be implemented depends on the grid code and rules concerning primary frequency control provision, as well as on battery characteristics.

4. Application II: peak shaving

4.1. Optimization problem and challenges

Peak shaving refers to the reduction of the required maximum electric power consumption $P_{\text{peak}}$ of an individual load unit or an aggregation of several loads for satisfying an end-use demand during periods of either high grid loading or high overall electricity demand. Peak shaving offers the opportunity to defer the costs of both grid expansions such as upgrading line ratings and transformer capacities as well as build-up of additional power plant capacity, which would have been necessary otherwise for satisfying peak load demand events, which usually only occur for short time periods.

Grid operators typically base their grid expansion planning on the extrapolation of current peak power loading and a grid capacity margin to allow for uncertainty in the expected mid- and long-term load development. Since BESS units can be deployed rapidly at practically any point of the grid topology, they can readily alleviate grid bottlenecks temporarily, e.g. until a grid expansion can be carried out, but also permanently. The comparatively short deployment time for BESS units allows electricity grid planners to reduce the capacity margins of newly planned transformers and lines as well as to increase the utilization of existing grid assets.

Likewise, peak shaving can be used by large customers to reduce their demand charges $J_{\text{grid}}$ for peak power grid out-take, i.e. $P_{\text{out,take}}$. Especially for load patterns with high ratios of peak power to peak duration such a reduction offers potential economic benefits. Usually, the grid demand charge $J_{\text{grid}}$ is based on the peak grid out-take over a longer period of time. In the following the minimization of the peak grid out-take and hence the minimization of the demand charge over the period of one month is explored.
Note that this minimization does not necessarily correspond to an economic optimum because the trade-off between demand charge reduction and battery wear costs over the period of one month is not considered here. In the case of the Zurich 1 MW BESS the peak shaving optimization is implemented via a predictive power dispatch optimization based on an MPC control scheme that tries to cover occurring peak events, i.e. when the value of \( p_{\text{outake, max}}^\text{grid} \) is lower than the peak load demand of the building, by discharging the BESS unit accordingly. The key advantage of this type of dispatch optimization is that available forecast information of future load demand as well as RES production profiles are explicitly incorporated. This greatly improves BESS operation performance. In accordance with the properties of Table 1 and the outlined MPC formulation, the optimal next BESS set point \( P_{\text{outake}}^\text{grid} \) can be found by solving (Eq. (4)). The grid utilization costs were chosen to be constant according to an average grid tariff but could also be made flexible by considering a commonly used day and night tariff or a real-time grid usage pricing scheme.

The optimization problem behind peak shaving is to minimize as much as possible the peak load demand, while at the same time minimizing the incurred battery degradation as well as cycling energy loss from the battery usage. The complete cost function for battery usage, based on accelerated battery degradation caused by aggressive BESS usage, can be approximated by [6]

\[
J_{\text{bat}}(k) = x_{\text{DoD}}(k) J_{\text{DoD}} + P(k)^2 Q_{p}(P(k) + (x_{\text{SOC}}(k) - x_{\text{SOC}_0})^2 Q_{\text{SOC}}.
\]

where \( k \) is the discrete time-step index. Cost function (3) is usable in a standard hybrid Model Predictive Control (MPC) formulation. The mixed-integer quadratic programming (MIQP) problem can be solved by readily available off-the-shelf optimizers, for instance CPLEX or Gurobi.

Since the overall efficiency of a BESS system exhibits a nonlinear behavior (see Section 2), a peace-wise affine (PWA) description of the efficiency behavior is a well-suited representation for the optimization model. There exists inherent uncertainty in the battery utilization strategies due to the usually long time-window used for peak pricing, i.e. monthly, compared to the available prediction horizon for end-use demand, i.e. daily to weekly. On the other hand, many load profiles of large customers do normally follow clearly identifiable daily and weekly cyclic patterns, influenced by production schedules and day of week. Such predictable load patterns allow a good a priori battery sizing (energy versus power capacity ratings).

\[
\min_{P_r} \sum_{k=0}^{N-1} J_{\text{bat}}(k) + J_{\text{grid}}(k) + J_{\text{soft}}(k)
\]

s.t. \( \sum p_{\text{outake}}^\text{grid}(k) - \sum p_{\text{load}}(k) = 0 \)

\( \forall k \in (0, \ldots, N-1) \).  

When choosing an unreachable low grid limit the optimization becomes infeasible. The technique of adding so-called soft limits prevents dispatch optimization infeasibility arising from either state or input constraints, by relaxing the initial limit via an additional decision variable \( \varepsilon \) that is employed as follows

\[
p_{\text{outake}}^\text{grid}(k) \leq p_{\text{outake, max}}^\text{grid} + \varepsilon(k)
\]

\( \varepsilon(k) \geq 0. \)

Compliance with the above stated soft limit for all feasible cases is ensured by penalizing the soft limit decision variable \( \varepsilon \) with a comparatively high cost term \( J_{\text{soft}} \) in the MPC cost function (Eq. (4)).

In order to minimize the peak grid out-take for a time interval that is longer than the MPC prediction horizon, the soft limit \( u_{\text{max}}^\text{grid} \) is adjusted whenever the next planned BESS operation set-point \( p_{\text{outake}}^\text{grid} \) contains a soft limit violation. This constraint adaptation technique solves the problem of only having a finite prediction horizon available in the storage dispatch optimization. This prevents the BESS from unproductive reduction of non-relevant peaks, i.e. it prevents the BESS from reducing peaks further than the previous maximum grid out-take over the relevant time period. Linear costs on \( \varepsilon \) will minimize the duration of the soft limit violation and quadratic costs on \( \varepsilon \) will minimize the soft limit violation magnitude over the prediction horizon. A quadratic cost term is thus better suited for minimizing the peak grid out-take power.

Fig. 7 illustrates the evolution of the adaptive soft limit for linear and quadratic soft limit costs. It is clearly visible how quadratic soft limit costs lead to soft limit violations with a smaller magnitude. Albeit violations occur more frequently, quadratic soft limits lead to a lower peak grid out-take.

4.2. Results

The MPC framework calculates set-points for the BESS unit with a time resolution of 15 min. These set-points are then written to the SCADA system over the OPC interface (see Fig. 3). Predictions of the day-ahead building load are generated at each sampling time-step using an auto-regressive artificial neural network with exogenous inputs (NARX). The used exogenous inputs are the temporal indicators time of day, day of the week, month of the year and public holidays (all known a priori). The building load of the last 8 h (32 values) represents the auto-regressive part of the network. The neural network was trained with the 15 min meter load profile of one year.

Fig. 8 shows the exemplary results from one day of peak shaving of the EZK office building. The BESS charges at night with small power bursts instead of a continuous charge interval because this leads to a lower DoD charge intervals which cause less Li-ion battery degradation [6]. Over a time resolution of 15 min compliance with the limit of the grid out-take is satisfactory. The active power measurements shown in Fig. 8 with a time resolution of 10 s exhibit high variability, which is compensated by the grid. Preventing such a variable out-take from the grid would require a fast load following control loop on the PCS of the BESS.

5. Application III: islanded operation

The PCS needs to run in VSI mode to regulate the microgrid as well as voltage and frequency. Voltage and frequency control is achieved by adjustable droop, which in the absence of a PI-control mechanism leads to a stationary frequency deviation w.r.t. the
The droop equation relates the stationary frequency deviation to the power output of the BESS.

\[
s = \frac{\Delta f}{\Delta P} = \frac{f_n}{P_n}
\]  

(6)

Here, the nominal grid frequency \( f_n \) is 50 Hz, the nominal reserve power \( P_n \) is 1 MW and the frequency droop \( s \) is set to 2\% which leads to a stationary frequency deviation \( \Delta f \) of 200 mHz at a BESS power output of 1 MW.

The zoom in Fig. 9 shows how the microgrid frequency follows the BESS power. This can be used to communicate the microgrid power balance (BESS charging or discharging) to all connected devices in real-time with perfect communication availability. Realizing local demand response in the microgrid or dynamic adjustment of controllable generators is then straightforward. Islanding of the system was carried out during office hours for 12 hours on a winter day. A diesel generator was included in the microgrid configuration and operated in grid parallel mode (see Fig. 2). The grid parallel mode of the diesel gen-set causes immediate activation of protection relays in the absence of grid voltage, i.e. BESS in this case. The power balance shown in Fig. 9 illustrates how the BESS reacts to all the variability in the load and quickly moves between discharging and charging depending on the residual microgrid load. No production from the PV plant is visible due to foggy weather conditions but all PV converters continued to feed into the microgrid and no disconnections due to automatic island detection mechanisms were triggered. This illustrates the robustness of the grid control that the BESS provides.

Also, no interruption in power supply was observed during the critical events of grid disconnection and grid reconnection and the whole 12 hour islanding period. No problems regarding power quality or grid stability were observed. Grid stability is also ensured during larger load steps, which are caused by freight elevators or EV fast charging events.
The setup of the Zurich 1 MW BESS therefore offers promising capabilities for stabilizing larger microgrids with high RES shares.

6. Challenges in battery operation

There are several challenges to operators of batteries regarding a variety of categories. Issues of control are especially challenging for operators.

A control challenge in most applications is the accuracy of the SoC value. Since the SoC value is the result of a nonlinear state estimation involving current integration and voltage measurements, large deviations from the real value and transient time behavior of the SoC estimate are possible. The uncertainty in SoC estimation therefore needs to be considered in all control strategies which aim at managing SoC.

The typical limited BESS capacities need careful management of SoC levels. In many applications it is desirable to prepare the SoC in anticipation of future grid states or events. Section 4 illustrated how this can be achieved dynamically in the case of peak shaving using predictive control of the BESS. In this early phase of Li-ion BESS deployments, the biggest uncertainty regarding cost estimates is the Li-ion cell lifetime and the influence that different BESS application profiles have on the degradation process. In contrast to mobile applications, where the usage profile of the battery is largely uncontrolled, in stationary grid-connected BESS units there are larger degrees of freedom on how to operate the battery (e.g., during off-peak times). Since Li-ion cell degradation is highly nonlinear with respect to a variety of operation parameters, the operation of the BESS has a large effect on battery lifetime. An approach on how to directly include battery aging mechanisms into the cost function of an MPC for peak shaving can be found in [6] and, if tuned correctly, allows to trade-off marginal costs of battery degradation with benefits of the given application considering grid constraints.

7. Conclusion and outlook

The configuration and current state of the Zurich 1 MW BESS pilot project was described in detail. Theoretical considerations and measurement results from the operation of the BESS for three different applications were presented. The control algorithms perform as expected in the field and no major problems were encountered in the operation of the Li-ion BESS, illustrating the quality of the components and the robustness of the communication infrastructure. The lessons learned in terms of grid integration, efficiency, degradation and SoC estimation from the Zurich 1 MW BESS will help to promote technology adoption and will prepare the power industry for commercial deployments of BESS in the electrical distribution grid.

The authors will continue the practical validations of theoretical concepts on the Zurich 1 MW BESS. In addition to the ongoing improvement of the three presented applications – frequency regulation, peak shaving and islanding – future work will look at voltage control in the distribution grid using the full active and reactive power capabilities of the PCS as well as multi-purpose BESS operation using cascading control schemes that provide different reserve and regulation services at the same time.

References