FREQUENCY REGULATION AND MICROGRID INVESTIGATIONS WITH A 1 MW BATTERY ENERGY STORAGE SYSTEM

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ABSTRACT

Two years of experience with The Zurich 1 MW Battery Energy Storage System (BESS) have offered valuable insights into the real life performance of BESS.
This paper covers mainly the results from the provision of frequency reserves and the regulation of a small microgrid. A novel algorithm is proposed for the control of State of Charge (SoC) during frequency control. Measurements from system operation are presented for both applications.

INTRODUCTION

Increasing penetration of distributed generation in combination with an aging grid infrastructure demands for a more flexible and efficient utilization of grid assets. Battery energy storage systems (BESS) are well suited to provide the needed flexibility for the integration of renewables and a variety of additional services, but their prospective economics remain unclear.
The first competitive and economically sound application will therefore depend on the exploitation of various revenue streams and optimal utilization of the capital intensive battery storage capacity. Investigations on optimal control strategies for various applications are currently under way at the Zurich 1 MW BESS demonstration project, commissioned in spring 2012.

Outline of Content

The following sections will briefly look at the various investigated applications with the Zurich 1 MW BESS and the remainder will then focus on two of the applications which were investigated most recently: provision of primary frequency regulation and low voltage microgrid operation.

THE ZURICH 1 MW BESS

Figure 1 shows a picture of the Zurich 1 MW BESS and its components and Table 1 summarizes the key properties of the system. The grid integration and all surrounding components are depicted in Figure 2. Among the elements included in the control of the BESS and its dedicated SCADA-system are electric vehicle charging stations, a photovoltaic (PV) plant, an office building as well as measurements from the substation nearby.
The versatile grid integration allows for the investigation of a variety of different grid connection scenarios, such as direct medium voltage coupling to the 16/110 kV substation, low voltage integration and the possibility to operate the low voltage feeder and all its components in island mode (see red path in Figure 2).

Figure 1: Top view of the Zurich 1 MW BESS.

The universal system design of the BESS is ideally suited in order to investigate several different applications with proposed benefits for the distribution grid such as peak shaving, voltage control, scheduled power exchanges, islanded system operation and the provision of frequency control reserves [1].

Peak Shaving

Peak shaving offers the opportunity to defer (or prevent altogether) grid upgrades caused by increased system loading due to demand growth or increased distributed generation [2]. The costs of adding additional grid capacity follow a step-function and do not scale linearly with capacity. Therefore in extreme situations, where adding additional grid capacity is very cumbersome, a storage solution might well be economically feasible even at today’s storage prices. The required storage capacity for peak shaving depends on the duration and magnitude of the expected peaks. Li-Ion based battery

Table 1: Key metrics of the Zurich 1 MW BESS.

Property	Value	Comment
Power	1 MW	charging and discharging
Capacity	580 kWh	250 kWh @ 1 MW
System Integrator	ABB	
Technology	Li-Ion	cells from LG Chem
Efficiency	80 – 90 %	round trip

solutions are especially competitive where large peaks with a short duration dominate the load pattern because only small storage capacities and relatively large current rates are required.

Voltage Control

BESS can regulate the distribution grid voltage with an ideal mix of active and reactive power. No stored energy is used when providing reactive power but it causes higher grid currents leading to larger grid losses. The fast reaction times of BESS are especially useful to counteract voltage problems caused by the infeed from variable renewables such as PV plants which require quick switching between current injection to support the grid voltage and current withdrawal to lower the grid voltage.

Scheduled Power Exchanges

Similar to conventional power stations the Zurich 1 MW BESS is also capable of performing scheduled power exchanges at predefined times which can be used to improve the utilization of a power station portfolio, for day-ahead schedule compliance or optimal procurement of energy at power markets.

PERFORMANCE

The overall efficiency of the Zurich 1 MW BESS has been investigated based on measurements from various applications. The system efficiency is a complex function based on the opposing nonlinear behavior of its components. While the efficiency of the power converter increases at higher power levels, the efficiency of the battery cells is higher for lower currents. Overall the efficiency was found to be dominated by the decreasing efficiency behavior of the converter at levels below 100 kW (0.1 pu) and to stay approximately constant at power levels beyond 100 kW where the opposing efficiency characteristics largely seem to cancel each other out. Round trip efficiency disregarding auxiliary consumption was found to be between 80 – 90% at all power levels (see Table 1).

FREQUENCY REGULATION

Due to their high ramp rate capabilities BESS are well suited to provide fast frequency regulation services [3]. Primary frequency control is the fastest of the three-tier frequency regulation framework in place in the synchronized grid zone of continental Europe. It simply requires the participating power stations to change their output linearly in dependence of the locally measured frequency deviation from 50 Hz.

Procurement of frequency control reserves in Switzerland is based on markets which are cleared in weekly auctions. Bidding in those markets represents a direct opportunity for the storage owner to capture additional revenue. The business model of bidding into frequency control markets in combination with a peak shaving application in the distribution grid is especially compelling: peak load problems caused by high demand typically occur during winter and peak load problems caused by high PV generation during summer. If only one of the two causes violations of grid limits the storage is underutilized during the greater part of the year and might well be used to bid into ancillary service markets for frequency control.

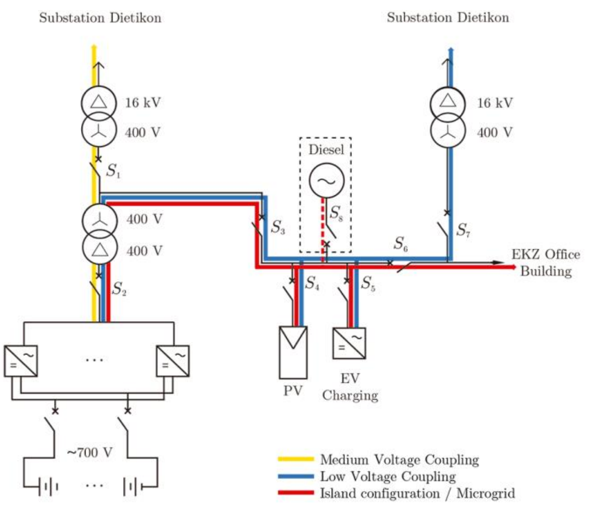

Figure 2: Single line diagram of the Zurich 1 MW BESS. The battery is integrated into the low and medium voltage grid.

Traditionally frequency control reserves are provided by conventional power stations connected to the high voltage grid. However, this is not a necessity as the main function of the frequency control reserves is to contain the grid frequency deviation in case of an outage of a large power plant and to balance out short term deviations between overall load and generation in the synchronized grid zone. At what voltage level the service is provided is not of primary importance to power system operation.

While the fast reaction times of BESS are favorable for the performance of primary frequency control [4], BESS are typically heavily constrained in their energy storage capacity. Cycling losses and frequency biases over longer time periods can fully drain or fill the storage. To guarantee availability of the power reserves at all times, the State of Charge (SoC) of the BESS needs to stay within acceptable limits in order to be able to charge or discharge at all times.

Theory

Previous techniques for optimizing battery energy storage systems to provide primary frequency control include deadband-charging [5], adjusting the working point by using a state of charge (SoC) based offset [6] or by a moving average approach presented by Borsche et al. in [3]. Borsche's way to calculate the offset power (p_{off}) is:

$$p_{\text{off}}(k+d) = \frac{1}{a}\sum_{i=k-a}^{k}\left(-p_{\text{resp}}(i) + p_{\text{loss}}(i)\right) \tag{1}$$

where d is a delay, a is the averaging period, p_{resp} is the primary frequency control power, and p_{loss} is the sum of all power losses in the battery system. The main idea is that the offset is changed only slowly in order not to interfere with frequency control performance while the actual reaction to the grid frequency remains instantaneous.

The technique implemented for the Zurich 1 MW BESS builds upon this theoretical approach, but extends it to include a maximum offset power which is necessary due to the limited power capability of the inverter and the battery cells. This drastically reduces the maximum total power capability required by the system to provide a certain reserve power quantity compared to the minimal storage sizes published in [3]. Compliance with the original idea is achieved by introducing a new state variable E_{diff}, which remembers the extra energy contained in the theoretical moving average offset power that lies above the maximum offset power and p_{diff} which adds the extra energy to the real offset power as soon as p_{off} is not saturated anymore. The modified moving average approach is then described as:

$$p_{\text{off}}^{\text{th}}(k) = \frac{1}{a}\sum_{i=k-a}^{k}\left(-p_{\text{resp}}(i) + p_{\text{loss}}(i)\right) \tag{2}$$

$$p_{\text{diff}}(k) = \frac{E_{\text{diff}}(k)}{a\ \cdot \Delta t} \tag{3}$$

$$p_{\text{off}}(k) = p_{\text{off}}^{\text{th}}(k) + p_{\text{diff}}(k) \tag{4}$$

$$E_{\text{diff}}(k+1) = E_{\text{diff}}(k) - p_{\text{diff}}(k)\Delta t \tag{5}$$

$$p_{\text{tot}}(k) = p_{\text{resp}}(k) + p_{\text{off}}(k) \tag{6}$$

subject to:

$$p_{\text{off}}^{\min} - p_{\text{off}}^{\text{th}}(k) \le p_{\text{diff}}(k) \le p_{\text{off}}^{\max} - p_{\text{off}}^{\text{th}}(k)$$

Where equation (2) averages the response power p_{resp} and the power losses p_{loss} over the averaging period a, as is done in equation (1), although the delay d was disregarded because it has no performance benefits for the power system and causes larger SoC variations [4]. In equation (3) the power difference p_{diff} is calculated by dividing the energy difference E_{diff} by the averaging time constant $a\,\Delta t$ and by adding boundary conditions to ensure that the offset power p_{off} will not exceed the maximum/minimum theoretical offset ($p_{\text{off}}^{\max}$ and $p_{\text{off}}^{\min}$) when it is calculated using equation (4). Equation (5) calculates the energy difference that results from the difference of the theoretical and the real offset. Finally the real offset is added to the response power in equation (6) to compute the total BESS power output p_{tot}. For the simulation and the real time implementation described in the next two subsections, the value for a has been set to 15 minutes which corresponds well to the ramp rate capability of secondary frequency control [4]. The values for $p_{\text{off}}^{\max}$ and $p_{\text{off}}^{\min}$ were set to 200 kW and -200 kW respectively, which enables the Zurich 1 MW BESS to provide 1 MW of frequency response power in both directions.

Simulation

Primary frequency control was simulated using the aforementioned approach with one year of frequency measurements from March 2013 to March 2014 with a time resolution of one second and the parameters of the Zurich 1 MW BESS. Figure 3 illustrates how the modified moving average approach worked as desired in keeping the SoC close to a medium level and how the storage was never empty or full during the complete simulation period. Note that the ideal SoC is slightly above 50% at $\text{SoC}_{\text{ideal}} = 50\%/\eta_{\text{average}}$ which represents 50% of the storage energy from the perspective of the grid (including efficiency losses).

Table 2 shows some of the key results from the simulation. Of particular interest is the SoC, which remained more than 25% from being fully charged or fully discharged at all times. The BESS had to provide up to 996 kW of power at the most extreme time period of the year. The largest depth of discharge half cycles were around 20-30% while most cycles were much smaller, which is preferable in terms of Li-ion cell degradation [2].

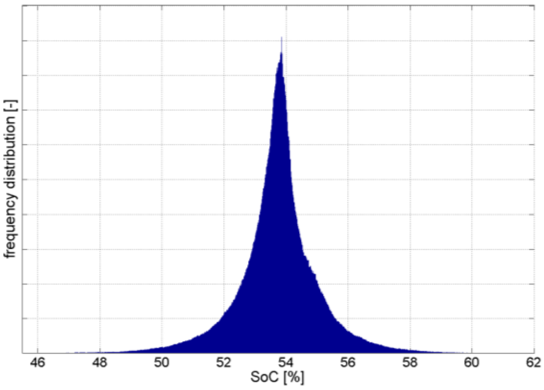

Figure 3: SoC frequency distribution from the simulation with one year of grid frequency measurements using the modified moving average algorithm.

Table 2: Key simulation results.

Variable	Value
Max. discharging power	996 kW
Max. charging power	689 kW
Max. SoC	71.51 %
Min. SoC	25.03 %
Max. DoD$_{\text{half cycle}}$ (charging/discharging)	0.24/0.3
Avg. offset charging power	23.6 kW

Real Time Measurements

Figure 4 shows a typical excerpt of measurements from real system operation of the modified moving average algorithm. As the frequency is dropping, the response power follows and the offset is going into the opposite direction. At around 18:26 in the evening the offset reaches its predefined maximum value (200 kW). The difference between real and theoretical offset is now integrated over time and added to E_{diff}. When the theoretical offset decreases below the 200 kW, p_{diff} is added to the real offset which lowers E_{diff} again. The SoC follows the total power which is the sum of the offset and the response power. During the whole period the BESS reacts fast and accurately to all variations in the grid frequency.

MICROGRID

Islanding or the capability of establishing a small microgrid can provide added value to sensitive customers in the distribution grid by improving security of supply and ensuring uninterruptible power supply in the case of system wide disturbances (for instance during heavy storms). Grid connected microgrids are also regarded as a threat to the traditional utility business model because due to their large share of generation they depend less on energy supply from the utility and use the larger grid only for balancing purposes.

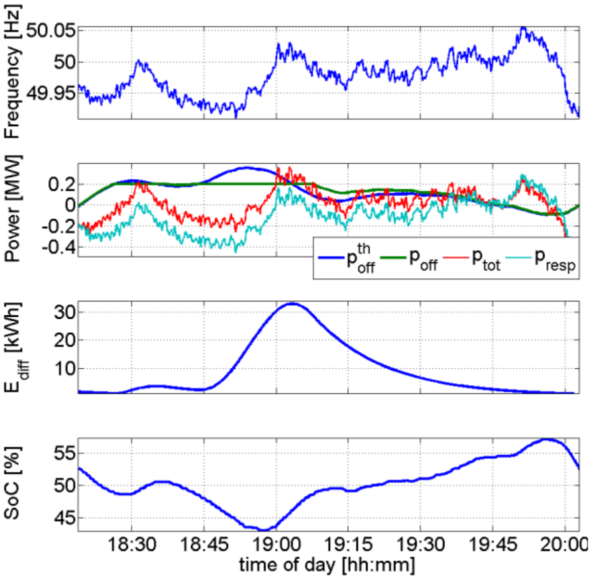

Figure 4: Measurements of primary frequency control with the Zurich 1 MW BESS showing grid frequency, theoretical and real offset power ($p_{\mathrm{off}}^{\mathrm{th}}$ and p_{off}), frequency response power (p_{resp}), total power (p_{tot}), the energy difference (E_{diff}) and the battery State of Charge (SoC).

EKZ Microgrid

The EKZ Microgrid consists of the Zurich 1 MW BESS, several electric vehicles charging stations, a small PV plant, a diesel genset and an office building. The microgrid is connected on the low voltage level and connects to the larger grid via a medium voltage line (see Figure 2).

Measurements

Figure 5 shows the power balance during islanding of the EKZ Microgrid during normal working hours in the EKZ office building. No interruption of supply occurred during the most critical moments of disconnection and reconnection to the grid. The diesel genset operated in parallel mode and provided power at a fixed setpoint. Note that the genset offers no active control of voltage or frequency to the microgrid apart from its rotational inertia. The BESS levels out short term mismatch between generation and consumption in order to stabilize frequency and voltage in the microgrid (it even rapidly alternates between charging and discharging if necessary). The BESS adjusts its power output to control the voltage and frequency using droop control, which leads to stationary deviations from the nominal frequency (due to a missing integral term in the controller). Although at first sight this might seem like a disadvantage of droop control, the stationary frequency deviation is very useful in order to communicate among

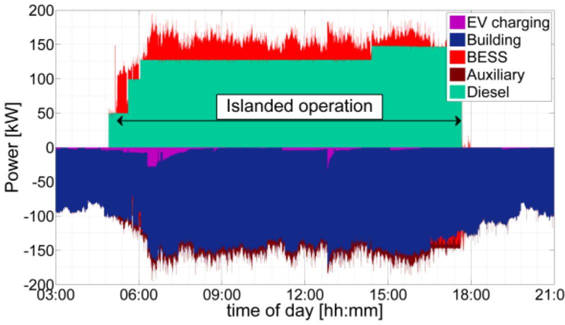

Figure 5: Measurements of the three phase power balance during the islanding of the office building. No PV generation can be seen due to the foggy weather conditions. Seamless disconnection and reconnection to the grid was possible. Even large steps in load could be handled by the BESS without any disturbances in the power quality of the microgrid.

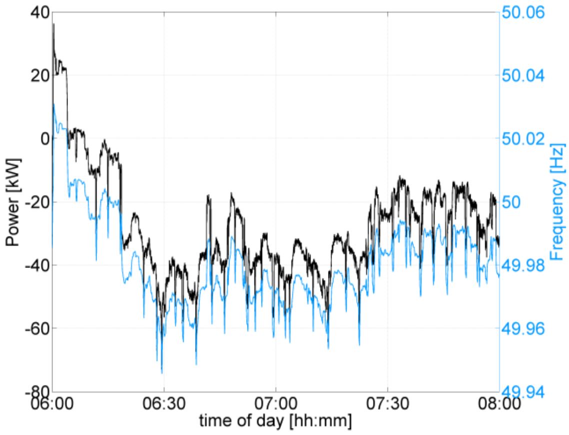

Figure 6: Parallel evolution of BESS power output and microgrid frequency (measurements). The BESS is discharging which results in a frequency below 50 Hz.

all the devices of the microgrid in real time. Figure 6 illustrates the evolution of residual power demand covered by the BESS and the microgrid frequency. Droop control causes the frequency to evolve in parallel to the residual power. The frequency therefore offers a true real time communication signal to all devices connected to the microgrid with perfect reliability at no additional costs. The frequency contains information about the precise grid state (excess generation or load) and can be used as an input for various control schemes such as demand side management or curtailment of excess renewable generation within the microgrid.

Power Quality

Islanded operation of a microgrid typically leads to a much smaller short circuit power than when connected to the larger grid. This causes more susceptibility to voltage harmonics than in the grid connected state due to a higher grid impedance.
Table 3 compares total harmonic distortion in voltage (THD_U) during islanded operation with the same time period during grid connected operation one day before. The average value slightly increases in the islanded configuration as expected but note that all those values are well below the limit specified in EN50160 which requires THD_U levels to remain below 8% for 95% of the time [7].

Table 3: THD_U of all three phases during the twelve hour microgrid period compared to grid connected operation one day before.

	Islanded Min. / **Avg.** / Max. **[%]**	**Grid connected** Min. / **Avg.** / Max. **[%]**
$THD_{U,R}$	0.86 / **1.34** / 1.51	0.79 / **1.01** / 1.51
$THD_{U,S}$	0.82 / **1.21** / 1.36	0.68 / **0.88** / 1.36
$THD_{U,T}$	0.79 / **1.26** / 1.39	0.68 / **0.88** / 1.36

CONCLUSION

The configuration and grid integration of the Zurich 1 MW BESS was described in detail and illustrated the versatility of the system to provide various different benefits to the distribution grid.
The results from simulation and measurement from the proposed frequency regulation algorithm are promising and the authors will proceed to work towards the participation of the Zurich 1 MW BESS in the Swiss ancillary service markets. Measurements from islanded operation showed no issues in power quality and proved that the system is well suited to control voltage and frequency in a commercial microgrid setting.

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