GRID-FRIENDLY OPERATION OF A HYBRID BATTERY STORAGE SYSTEM

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ABSTRACT
Battery storage systems are nowadays mainly operated to maximise economical profits. In case of occurring problems, battery storages can also support the power grid. In this paper, the potential of the Hybrid Battery Storage System, implemented in the research project ‘Hybrid-Optimal’, to operate in a grid-friendly manner is determined by simulations. After a description of the used algorithm and the input data, results for a prevention of overvoltages, reduction of the peak power demand and self-sufficiency in times of power outages are presented.

INTRODUCTION
The cellular approach
Increasing numbers of small and decentral generators (e.g. PV generation) are changing the current centrally organized power system and cause local problems like overloading of equipment. These developments have not been taken into account during the grid planning process in the past. In 2015, the VDE (Association for Electrical, Electronic & Information Technologies in Germany) published a study called “The cellular approach” [1]. The main result is that the segregation of the power system into smaller energy cells can be a promising alternative regarding market opportunities and power system stability.

Research project ‘Hybrid-Optimal’
In the project ‘Hybrid-Optimal’, funded by the ministry of environment, climate and energy of the German State of Baden-Württemberg, a grid section with a high penetration of renewable energy sources is developed into an energy cell to demonstrate the benefits of the cellular approach in practice. The project partners are Stadtwerke Bühl (Utility), Karlsruhe Institute of Technology and SCHMID Energy Systems (Battery manufacturer). The main objectives of the project are to demonstrate that the cellular approach is able to increase the power grid stability and allow the public to take part in and profit from the energy transition. The core component of the cell is a central Hybrid Battery consisting of a 5 kVA / 45 kWh Vanadium Redox Flow Battery (as medium-term storage), delivered by SCHMID Energy Systems, and an additional 40 kVA / 56 kWh Lithium-Ion Battery (as high-power short-term storage). The operating strategy of the battery system will be optimized periodically regarding current market opportunities. The project commenced in September 2016 and will be completed in July 2019. A detailed description of the project can be found in [2].

SIMULATION FRAMEWORK
A dynamic optimal power flow algorithm is used to determine the optimal operation of the battery storage. This algorithm was presented in detail in [3].

Problem formulation
All loads are modelled as simple PQ loads. The external grid is modelled using two generators. Hence, two separate cost functions can be used. One generator represents import from the external grid, the other generator represents export. Only one generator needs to provide reactive power. The limit of power of the generators is set to the maximum power of the transformer.

\[
0 \leq P_{G1} \leq P_{TR,\max} \quad (1) \\
-P_{TR,\max} \leq P_{G2} \leq 0 \quad (2) \\
-Q_{TR,\max} \leq Q_{G1} \leq Q_{TR,\max} \quad (3) \\
0 \leq Q_{G2} \leq 0 \quad (4)
\]

The PV generation is also represented using a generator. The maximum generated PV power of each time step t and plant X \(P_{PV,X,\text{Max}}\) is calculated using a reference time series and the yearly amount of generated energy of each plant. As shutdown of PV plants is possible, the actual PV generation \(P_{PV,X}\) is constrained as follows:

\[
0 \leq P_{PV,X} \leq P_{PV,X,\text{Max}} \quad (5)
\]

The battery storage contains an energy of \(E_s\), which depends on the energy in the previous time step \(E_{t-1}\) and \(\Delta E_s\).

\[
E_s = E_{t-1} + \Delta E_s \quad (6)
\]

\(\Delta E_s\) is the energy which is inserted or extracted from the battery storage in a time step \(\Delta t\). It depends on the charging efficiency \(\eta_c\), discharging efficiency \(\eta_d\) as well as the charging power \(P_{SC}\) and discharging power \(P_{SD}\).

\[
\Delta E_s = (\eta_c P_{SC} - \eta_d P_{SD}) \Delta t \quad (7)
\]
The energy $E_S$ and powers $P_{SC}$ and $P_{SD}$ are limited to the rated values of the battery storage $E_{S,max}$ and $P_{S,max}$
\begin{align}
0 & \leq E_S \leq E_{S,max} \quad (8) \\
0 & \leq P_{SC} \leq P_{S,max} \quad (9) \\
0 & \leq P_{SD} \leq P_{S,max} \quad (10)
\end{align}
The battery storage is also able to provide reactive power $Q_S$, which is limited by $Q_{S,max}$.

\[-Q_{S,max} \leq Q_S \leq Q_{S,max} \quad (11)\]

The cost function $F$ for one time step $t$ contains the energy import $P_{imp}$ as well as the export $P_{exp}$ and PV generation $P_{PV,t}$. Additionally, $P_{SC}$ and $P_{SD}$ are included to be able to control the behaviour of the battery storage.

\[
F^t = (c_{exp} P_{G2}^t + c_{imp} P_{G1}^t + c_{PV} P_{PV,t}^t + c_{SC} P_{SC}^t + c_{SD} P_{SD}^t) \Delta t \quad (12)
\]

As we are not focusing on economical results, the cost function does not represent real costs in this paper. The coefficients $c_{exp}$, $c_{imp}$, $c_{PV}$, $c_{SC}$ and $c_{SD}$ are used to influence the behaviour of the battery storage.

The load flow equations are given as
\[
P_{bus} - Re(Y \cdot x) \cdot Y \cdot (\bar{Y}^t)^* = 0 \quad (13)
\]
\[
Q_{bus} - Im(Y \cdot x) \cdot Y \cdot (\bar{Y}^t)^* = 0 \quad (14)
\]
where $Y$ is the admittance matric and $\bar{Y}$ the node voltages. $x$ denotes element-wise multiplication. $P_{bus}$ and $Q_{bus}$ are the injected active and reactive power at a bus. The branch flow real power is limited by
\[
(P_{br})^2 \leq (P_{br,max})^2 \quad (15)
\]
For all buses, there is a limit for the voltage magnitude. The voltage $\bar{Y}$ is defined as $\bar{Y} = e + jf$. The limits are given as
\[
(V_{min})^2 \leq (e)^2 + (f)^2 \leq (V_{max})^2 \quad (16)
\]

**Dynamic optimal power flow algorithm**

Optimal power flow (OPF) problems can be described in the following form:

\[
\text{Min } F(x) \quad (17)
\]

Subject to
\[
g(x) = 0 \quad (18)
\]
\[
h(x) \leq 0 \quad (19)
\]
$F(x)$ is the so-called cost function, which is minimized while the equality constraints $g(x)$ as well as the inequality constrains $h(x)$ have to be fulfilled. In this paper, we use a dynamic OPF with a horizon of $T$. Therefore, the state vector $x$ contains optimization variables for all time steps.

\[
x = [x^1 \ldots x^t \ldots x^T] \quad (20)
\]

Additionally, the cost function sums up to

\[
F(x) = \sum_{t=1}^{T} F(x^t) \quad (21)
\]

**Solver**

The Primal-Dual Interior Point Method (PDIPM) is used to solve this problem. The Langrangian multipliers $\mu$ (inequality constraints) and $\lambda$ (equality constraints) are assigned. The slack variables $Z$ are introduced to transform the inequality constraints to equality constraints. The slack variable $Z$ is weighted with the barrier coefficient $\gamma$ to keep the inequalities constraints away from zero in the first iterations. Finally, the Langrangian $L$ is built up as follows:

\[
L(x, \lambda, \mu, Z) = F(x) + \mu^T(h(x) + Z) + \lambda^T g(x) - \gamma \sum_{t=1}^{T} \ln(Z_t) \quad (22)
\]

In the PDIPM the Lagrangian is minimized while the multipliers are maximized. This leads to a minimization of the cost function $F$. A detailed explanation of PDIPM can be found in [4].

**Horizon**

The period of the simulation is one year. Hence, we take seasonal effects into account. We use a receding horizon control with a horizon of 48 hours. After one optimization, the starting point is shifted by one day. The simulation starts each day at 0:00 o’clock. The resolution of the simulation is 15 min as the profiles.

**INPUT DATA**

As input data, real data for the total PV generation and energy consumption of each household from the year 2016 is used. From this data, times series are created using data from a nearby PV reference plant and a load profile generator [5]. The voltage at the low-voltage (LV) side of the MV/LV transformer is assumed to be between 419.6 V - 420 V. This assumption was made analysing measurement data of one month. In reality, the voltage depends on the power flow in the regarded LV grids as well as the whole medium-voltage (MV) grid (no data available) and therefore cannot be modelled in more detail.

**VOLTAGES IN THE LOW-VOLTAGE GRID**

![Map including voltage drop of the project site](image)

The energy cell is connected to the MV/LV transformer via an approximately 1 km long 4x150 mm² LV cable (see Figure 1). In times of high PV generation, this can result in overvoltages in the energy cell. In this section, the influence of the battery storage on the voltages in the energy cell is investigated. Additional parameters like maximum charging and discharging power or battery capacity have also been monitored, but no problems occurred.

According to EN 50160:2010/A1:2015, voltage deviations of 10% of the nominal voltage are allowed. This means that voltages between 360 V and 440 V are within the limits. The voltage drops in the households are neglected in this paper.
Actual situation

Fig. 2: Voltage difference between transformer and energy cell depending PV generation

In Figure 2, the voltages between the MV/LV transformer and the farthest point in the energy cell are shown using realistic input data (orange). In the summer, during times of PV generation, the highest voltages occur. During the winter, when there is only few PV generation, the voltages are dominated by the loads and the voltage in the energy cell is usually lower than at the MV/LV transformer. Considering the actual installed PV power no overvoltages occur. Increasing the installed PV capacity to 137 % of the actual value (blue curve) the voltages in the grid are close to the given voltage limits. A further increase of the PV installations would lead to overvoltages.

Active power management of the battery storage

The battery storage can be used as additional load in times of high PV generation through charging. As the position of the battery storage is closer to the PV installations than to the MV/LV transformer, voltage drops are prevented. Discharging happens when voltages are in compliance with the given limits.

Using this method 207 % of the currently installed PV capacity can be installed. A disadvantage of this method is that charging and discharging is not lossless.

Reactive power management of the battery storage

Not only active power, but also reactive power can be used to influence voltages in the LV grid. For the following results, we assume that the battery storage is able to provide 45 kvar of reactive power (Nominal rating: 45 kVA) and no active power. The installed PV capacity can be increased up to 182 % using this method. In Figure 3, the reactive power flowing on the transformer and provided by the battery storage can be seen over the whole year. Additionally, the reactive power provided by the battery storage for a week in January can be seen in the third diagram of Figure 3 to highlight, that the reactive power is only provided in times of significant PV generation.

Combination of a controllable distribution transformer and active power management of the battery storage

The two most successful methods mentioned before can also be combined. The active power management is only used, when the controllable distribution transformer is not able to handle the voltages due to the losses during the charging and discharging process. An increase up to 472 % in comparison to the actual installed PV capacity can be realised using both methods.

Reduction of the peak power

The energy cell is connected via a long LV line to the MV grid via a LV/MV transformer (see Figure 1). During times with high PV generation, power is transported to the MV grid. The generation peak exceeds the load peak. In this chapter, the goal is to reduce the peak power using the battery storage.

In Figure 5, the energy generation and consumption can be
seen for the first two days of the year. At this time of the year, consumption exceeds generation. Hence, power is flowing from the MV grid to the energy cell constantly. In Figure 5, the power limit is set to 7 kW using a horizon of one day. For a limit of 6 kW the algorithm is not converging anymore, consequently it is not possible. Using a horizon of two days, also the scenario with 6 kW is converging. The reason for that can be seen in Figure 6. In this case, the battery storage is not empty at midnight. The remaining energy in combination with the energy that is charged during the second day is sufficient to feed the load peaks in the second day. Therefore, a horizon of two days is used in this paper. A further increase of the horizon does not lead to significant differences.

In Figure 7, an overview of the result for different power limits and energy storage sizes and their impact on the self-sufficiency- and self-consumption level can be seen. If there is no result shown, this configuration is not possible. As a result, it can be seen that the influence of the battery capacity on the self-sufficiency- and self-consumption level is higher than the peak reduction.

**Different low-voltage cable**

In the previous section, we have seen that the power peaks can be reduced significantly using a battery storage. In case of a replacement of the existing line or a construction of a completely new energy cell, hence, a decreased diameter for the LV line can be used to save investment cost. Besides a reduced power limit of the line, the impedance is increasing as the diameter is decreasing. As this influences the voltages in the grid, in Figure 8, the voltages are shown for different diameters of the LV cable. At the moment, a 4x150 mm² cable is used. Using the 4x150 mm² cable, the peak power is 37.57 kW. In this case the battery storage is not used. The peak power of the 4x25 mm² cable in the simulation (23.05 kW) is only 32.6 % of the nominal limit. This stresses, that the voltages in the grid are the important parameter here. Smaller cables than 4x25 mm² cannot be used, as the voltage peaks are too high.

**REACTIVE POWER IN THE LOW-VOLTAGE GRID**

In the future, it is expected that there are increasing demands also for distribution grids to provide reactive power. Exemplarily, we assumed that a possible requirement could be that the energy cell has to be self-sufficient regarding reactive power. In Figure 9, the result from a simulation is shown, where the necessary reactive power is provided from the battery storage. The maximum is 7.13 kvar, which is rather small in comparison to the maximum apparent power of 45 kVA.
SELF-SUFFICIENCY IN THE CASE OF DISTURBANCES

In case of a power outage, the battery storage can be used to provide power to the energy cell. The maximum possible duration of the power outage, during which the energy cell can be supplied by the battery storage, depends on the energy in the battery storage at the time of the outage and the consumption in the following hours. In Figure 10, the maximum duration is shown without any generation in the energy cell.

![Fig. 9: Reactive power provided from the battery storage](image)

In Figure 11, it is assumed that the PV generation is also available during the grid loss. Especially in summer, this increases the possible duration of self-sufficiency as generation exceeds consumption then (see the sharp rise end of May in Figure 11). In case of a low amount of stored energy at the time of the outage (e.g. 5.05 kWh), the duration also depends on the exact daytime.

![Fig. 10: Maximum duration of self-sufficiency depending on the date of grid loss without PV generation](image)

![Fig. 11: Maximum duration of self-sufficiency depending on the date of grid loss including PV generation](image)

To be able to be self-sufficient for three hours, at least 64.26 kWh have to be stored in the battery. Hence, only 36.74 kWh are left for the operation of the battery storage. This would affect the operation of the battery storage and the results of the previous chapters significantly (see Figure 12).

CONCLUSION & OUTLOOK

The potential of battery systems to behave grid-friendly is high as seen in the results. Considering the ongoing increase in decentral generation and the increase of power demand of households through electric vehicles or heat pumps the amount of local bottlenecks in the power grid will increase. In combination with grid-friendly behaviour of the battery storage, grid expansion could be prevented in several cases. Regulatory rules therefore have to be developed in the future. In the project ‘Hybrid-Optimal’ the results of the simulations will be validated as far as possible through real measurements.

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