MID SIZE ENERGY STORAGES IN DISTRIBUTION NETWORKS – OPTIMAL SIZING AND MANAGEMENT

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Abstract – This paper analyses the application of mid size energy storage systems in distribution networks. Various use cases are structured with respect to an optimal and integrated design of a storage management system. Based on a proposed management system architecture typical utilization aspects will be discussed and validated. The main emphasize is given to the adaptation of sophisticated optimization algorithms. Based on real network data the capabilities of the proposed methods are demonstrated.

Keywords: Energy Storage, Energy management System, Distributed Generation, Optimization

1 INTRODUCTION

Due to the growth of non deterministic distributed generation units (e.g. wind energy) in distribution grids the operational characteristic has changed. Typical symptoms are power flow reversals towards the transmission grid and highly fluctuating line loadings and node voltages. The installation and coordinated operation of mid size energy storages in distribution systems can help to mitigate the impact of fluctuating energy infeed. The strategy for optimized sizing and management of these storages strongly depends on the operational objectives of the storage operators. I.e. distribution grid operators might have operational targets different from wind farm operators or industrial customers [1]-[6].

This paper identifies and discusses typical use cases for the utilization of midsize energy storages and gives a comparative survey on relevant application areas. The use cases cover most of the relevant application scenarios. Aligned to these scenarios typical storage requirements will be derived in order to formulate an optimized system integration strategy for each particular case. The optimization approach comprises typical storage capabilities like installed power and energy capacity, charging and discharging gradients. Based on real measurement data, examples for optimal storage design will be given. After having storage systems properly sized, their operation management is the decisive factor for an optimal system benefit. The main target for storage integration in distribution grids will be the reduction of the impact of fluctuating power infeeds. In the light of this scenario it will be discussed whether and how a coordinated energy management for storage devices might further help to improve the benefits of storage systems. The proposed system utilizes an optimal power flow algorithm with embedded storage models in a two stage optimization process.

The first part of this paper focuses on the definition of use cases covering the majority of application cases for energy storage systems. In a second step, a storage management system will be proposed that can be utilized for online operation of energy storage systems in distribution network. Offline application of the proposed system will allow for optimal storage sizing. Based on real network data – typical for distribution networks – the management capabilities will be shown.

2 MOTIVATION FOR ENERGY STORAGES

The application of energy storage systems (ESS) is mainly driven by a demand for load shifting or optimization between generation infeed and load demand. In particular the latter functionality becomes more important with an increased amount of non-deterministic generation infeed [1]. Actual storage technologies range from large scale storages (e.g. pumped hydro) to micro storage systems (e.g. fly wheel or small batteries) [1]. However, the generation and load balancing applications can be found in the distribution system area, where mid size ESS are most likely to be installed. Depending on the required loading gradients different storage technologies might be utilized (see Table 1 for examples).

Table 1: Examples of storage technologies with corresponding charging / discharging gradients

<table>
<thead>
<tr>
<th>Technology</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed Air</td>
<td>medium</td>
</tr>
<tr>
<td>Redox-Flow</td>
<td>fast</td>
</tr>
<tr>
<td>Hydrogen Fuel cell</td>
<td>medium</td>
</tr>
<tr>
<td>Lead Acid Battery</td>
<td>fast</td>
</tr>
<tr>
<td>High Temperature</td>
<td>fast</td>
</tr>
<tr>
<td>Batteries</td>
<td></td>
</tr>
<tr>
<td>Pump Hydro</td>
<td>medium</td>
</tr>
</tbody>
</table>
Typically, the installed power and capacity of those ESS ranges from 0.1 MW/1 MWh to 5 MW/50 MWh. Therefore this papers focuses on ESS application to distribution systems utilizing mid size energy storage systems.

The decision for a certain storage technology strongly depends on the requirements resulting from a particular application case. The same applies for the design and operation of an EES management system. Among the great variety of possible use cases the following ones have been identified to be representative for the majority of storage applications from an energy supplier perspective:

- Supply schedule provision.
- Market product generation.

From the customer perspective the following uses cases appear to be the most representative ones:

- Peak load limitation – peak load cap provision.
- Energy management applications – in the context of subsystem optimization.
- Uninterruptible power supply provision.

For a grid operator or grid operation in general:

- Optimal power flow and shift of network expansion.
- Island operation of grids.

In the light of a continuous growth of renewable infeed it seems to be likely to integrate them into an overall generation scheduling process which is state of the art for conventional generation. Against the background of their fluctuating characteristics it is most likely to include ESS in the scheduling process as well. The overall management objective for this supply schedule scenario is to utilize the ESS to compensate for the difference between generation forecast and actual infeed.

In those markets where the renewable energy generation policy grants a fixed energy based revenue out of corresponding generation plants, there is no incentive to bundle the plants in order to generation market products. In particular this applies for German conditions provided by the corresponding national regulations [10]. At a certain market price level for electrical energy this regulation becomes obsolete. If the actual energy price exceeds the guaranteed income, it becomes economically viable to sell renewable energy on the free electricity market. In connection with ESS one can provide certain market products (e.g. peak, block or hourly products). In this market product use case the ESS operation has to ensure “continuity” of the product provision.

The operation of end customer installed ESS might be interesting for small and medium size industries (SMI). The aim of the storage integration for corresponding cases is cost reduction regarding supply contracts and security of supply.

Many supply contracts of SMI imply a price component for a maximum power. Exceeding this maximum can cause extremely high penalty payments. ESS can help to avoid this situation by providing a peak load cap by compensation of load peaks. Since this application targets at the monetary aspect of peak load limitation the ESS operation has to focus on the relevant settlement period (e.g. 15 minutes or 1 hour). The storage capabilities strongly depend on customers load characteristics. However, this predominantly applies for discontinuous processes – like batch processes. They show great potential for peak load reductions with low storage capacities. In contrast to this, processes with smooth load characteristics and less dynamic require large storage capacities. In this case ESS application can easily become uneconomic.

Flexibility in load characteristic offers businesses or industrial customers’ possibilities to close economically optimal supply contracts with their suppliers. With an efficient energy management optimized supply schedules can be generated and kept with the aid of ESS.

Common market product could be contracted; but also a load shifting to night hours is conceivable. Seasonal influences can be considered as well as daily variation could.

The uninterruptible power supply (UPS) use case is the classical application for ESS. In relation with power quality approaches this application could be an advantage for distribution grid operators when offering diverse product above the typical range of network management services [2]. In the light of the actual responsibility of distribution grid operators (almost worldwide), this use case mainly applies for customers, not for system operators.

From the perspective of the distribution grid operation the application of ESS targets at the minimization of the load flow absolute value and integral over the transformers to the next higher voltage level. The economic benefit of this control objective is manifold:

- Reduction of network utilization fee charged by regional transmission system operator.
- Reduced device rating in mid-term and long-term network extension planning.
- Fewer decentralized generation units for islanding operation.

Key to these objectives is to provide an optimal power flow (OPF) that materialized in order to fulfill these objectives. Consequently the use case OPF + extension shift focuses on the reduced network utilization in general and reduced effort for network extension investments driven by both, load growth and increase in decentralized generation. The latter objectives becomes even more important if fluctuating energy infeed increases in distribution networks. Due to the complexity of this use case ESS might comprise different storage stages, optimized for providing short term and long storage capacities in combination.

Against the background of interconnected power systems a niche application for ESS is the use case island operation. However, with increased decentralized generation and more economic power supply close to end customers it can serve as viable use case. Here the primary objective of ESS management results from load following system operation. In case of large percentage...
of non-deterministic renewable infeed a proper storage management can not only provide economic system operation but also a reduction of CO₂ emission, since conventional generation units (e.g. diesel or micro gas turbines) do not need to serve as backup devices in hot or cold stand by operation mode. For all use cases a weighting of the overall importance of storage capacity, installed power, operation gradient and storage horizon show almost similar results (see Figure 1). Only the use case “UPS” shows slightly different requirements. However, UPS applications do not need to have an overall management system.

This requirement analysis serves as basis for the design of the proposed storage management system, which will be introduced in the following.

3 STORAGE MANAGEMENT SYSTEM

3.1 Description

In order to fulfill most of the above mentioned requirements a stage management approach is proposed. The first stage (long term storage scheduling) serves for the operation of all installed storages. Based on the long term schedule a short term storage dispatch instance will provide setpoints to the storage controllers. Each storage controller (decentralized on the device level) operates as a setpoint controller (see Figure 2).

Typical input data for the storage scheduling algorithms are forecast data like renewable infeed or load shapes. The “storage scheduler” computes the coefficients of the cost functions based on which the “storage dispatchers” optimization algorithms are executed (Figure 3).

Figure 1: Graphical representation of qualitative requirement analysis for ESS application areas

Figure 2: Time sequence for setpoint generation according to proposed management scheme

Figure 3: General architecture of the proposed three-step operation principle with a two-stage optimization

The objective function for the storage dispatch optimization comprises a cost component reflecting the actual network losses as well as the fixed and variable cost for the storage operation (see eq. (1)).

\[ OF = \chi p_{\text{loss}}(P_{\text{in}}) + \sum_{i=1}^{n_s} \left( \alpha_i + \beta_i p_{\text{in}} + \beta_i^d s_{\text{in}} \right) \]

(1)

The control vector consists of setpoint values for active and reactive power infeed provided by the converters:

\[ x^T = \left( p_{\text{in},1}^s, \ldots, p_{\text{in},n_s}^s, q_{\text{in},1}^s, \ldots, q_{\text{in},n_s}^s \right) \]

(2)

During the optimization the constraints of the converter systems have to be considered as well. In a first step all energy storage systems as assumed to have a voltage source converter based network interface, i.e. four quadrant operation is possible. If one further assumes an ideal characteristic the constraint for each energy storage systems at rated terminal voltage becomes:

\[ \left| p_{\text{in},i}^s \right| \leq \left( \kappa s_{\text{max}}^2 \right)^{\frac{1}{2}} \left( p_{\text{in},i}^s \right)^{\frac{1}{2}} \quad i=1,\ldots,n_s \quad 0 \leq \kappa \leq 1 \]

(3)

In this representation a scaling factor \( \kappa \) has been introduced in order to represent the voltage dependency of the maximum apparent power capability and security margin provision.
3.2 Long term optimization model

The long term optimization considers the planning of energy storage operation for a typical horizon of one to a couple of days ahead. The aim of the long term optimization is to determine the optimal operation of energy storages over the optimization horizon by using approaches of integrated resource planning [11]. For this optimization model a simplified model of an energy storage system can be used. It includes the overall efficiency factors \( \eta \) for the charging and \( \eta \) for the discharging process. These factors include all losses of the ESS. Because of the large sample time for the optimization model time constants of the storage system can be neglected. The actual stored energy \( W_{\text{ess},t} \) at time \( t \) is given by:

\[
W_{\text{ess},t} = W_{\text{ess},t-1} + \eta \cdot P_{\text{charge},t} \Delta t \frac{1}{\eta} \cdot P_{\text{discharge},t} \Delta t (4)
\]

Where \( W_{\text{ess},t-1} \) denotes the stored energy at time \( t-1 \), \( P_{\text{charge},t} \) the controlled charge power and \( P_{\text{discharge},t} \) the discharge power at time \( t \). The constraints are formulated as:

\[
W_{\text{ESS}_{\text{min}}} \leq W_{\text{ES}_{\text{max}}} \leq W_{\text{ESS}_{\text{max}}}
\]

\[
P_{\text{discharge}_{\text{max}}} \leq P_{\text{discharge}_{\text{max}}} \leq P_{\text{charge}_{\text{max}}} (5)
\]

\[
b_{\text{charge},t} + b_{\text{discharge},t} < 2
\]

The last constraint includes that the storage either is in charging or discharging mode. The variables \( b_{\text{charge},t} \) and \( b_{\text{discharge},t} \) reflecting the actual operation mode and are of integer type. Consequently, the optimization becomes a mixed integer linear programming problem. Generally, the objective of this optimization problem as mixed integer linear programming (MILP) can be written as:

\[
\min \{c^T \cdot x + d^T \cdot y \mid Ax + By \leq b\}
\]

\[
x \geq 0, x \in X \subseteq \mathbb{R}^n, y \in \{0,1\}^q (6)
\]

The general objective for the long term optimization is:

\[
\min \{\sum_{t=0}^{T} (C_{\text{ess},t} + C_{\text{loss},t})\} (7)
\]

Here, cost function of the ESS \( C_{\text{ess}} \) comprises the following description:

\[
C_{\text{ess}} = C_{\text{fix},P} + C_{\text{fix},W} + C_{\text{charge}} + C_{\text{discharge}}
\]

\[
C_{\text{charge}} = (1 - \eta) \sum_{t=1}^{T} P_{\text{charge},t} \cdot EP \cdot \Delta t
\]

\[
C_{\text{discharge}} = (\frac{1}{\eta} - 1) \sum_{t=1}^{T} P_{\text{discharge},t} \cdot EP \cdot \Delta t
\]

Where \( C_{\text{fix},P} \) are the fixed costs relating to the installed power and \( C_{\text{fix},W} \) are the fixed costs relating to the installed storage capacity of the ESS. \( C_{\text{charge}} \) describes the costs of charging operations depending of the charging efficiency \( \eta \), the charging power \( P_{\text{Charge}} \) and the energy price \( EP \), at time \( t \) in [\( \text{€/MWh} \)]. In the same line \( C_{\text{discharge}} \) represents the costs of discharging operations. The costs of losses \( C_{\text{loss},t} \) are considered according to the following expression:

\[
C_{\text{loss}} = C_{\text{fix},t} + C_{\text{transformation},t}
\]

\[
C_{\text{transformation},t} = f(P_{\text{transformation},t}, EP)
\]

Where \( C_{\text{transformation},t} \) represents the transformation costs depending on the power losses on transformation \( P_{\text{transformation},t} \) and the energy price \( EP, \) and the transmission costs which depend on transmission power losses \( P_{\text{transformation},t} \) and the energy price \( EP, \). All terms are relating to time \( t \).

The optimization includes the forecasts for customer load as well as the distributed generation. For a day-ahead optimization with a 15 minutes sample time an optimization problem over 96 time steps has to be solved and the optimized operation for energy storage systems needs to be calculated.

3.3 Storage Dispatch (Short Term Optimization)

In the short term optimization grid losses will be included in the ESS dispatch algorithms. To solve the optimal power flow problem, the methods from the MATPOWER toolbox will be utilized. MATPOWER provides an AC OPF solver (MINOPF) in generalized formulation [12].

\[
\text{Obj. function: } \min_{P_{\text{ESS}}} \sum_{t=1}^{T}(f_1(P_{\text{ESS}}) + \tilde{f}_2(P_{\text{ESS}})) (10)
\]

\[
P_{\text{ESS}} \leq P_{\text{ul}} \leq P_{\text{lim}} \quad \text{ESS: } \quad P_{\text{ul}}^\text{min} = -P_{\text{ul}}^\text{max} (11)
\]

Costs of reactive power provision can be included but have not been considered in the first step realization. In a first approximation the costs function has been set as linear function with high slope for every storage node in the benchmark system. Consequently, the grid losses dominate the objective function. The following assumptions have been made:

Load profile:

\[
\bar{p} = \frac{1}{T_{\text{b}}} \int_{t=0}^{T_{\text{b}}} p(t) dt (12)
\]

Ideal storage:

\[
\int_{t=0}^{T_{\text{b}}} p_{\text{ESS}}(t) dt = 0
\]

\[
\Delta P_{\text{loss}} = (\Delta p)^2 ; \quad u \geq \text{const.}
\]

\[
\sum_{t=0}^{T_{\text{b}}} p_{\text{loss}} \rightarrow \min \left( \frac{1}{T_{\text{b}}} \int_{t=0}^{T_{\text{b}}} p_{\text{ESS}}(t) dt \right)^2 (13)
\]

4 CASE STUDIES

The above mentioned algorithms within the proposed to stage storage management system been applied to benchmark system, that comprises a mix of industrial, commercial and residential customers as well as the
renewable energy infeed from wind energy plants (WEP) and photovoltaic (PV) systems. The WEA is installed on distribution voltage level of 10 kV; the PV systems feed the low voltage branch of the benchmark system at 0.4 kV (See Figure 4). The network data have been adopted from typical medium and low voltage networks of domestic utilities in Germany. The ESS have been placed on both, 10 kV and 0.4 kV voltage level.

4.1 Case 1: Load leveling and optimal power flow

The load leveling with certain parts of the grids targets at equalization of the renewable infeed and the load consumption. As a second objective the reduction of grid losses has been included. The first leveling objective allows for constant power output and the formation of market products.

The ESSs have been design for an equalizing period of 1h. It has been expected, that the relatively short control horizon only shows a minor impact on network losses. As depicted in Figure 6 even the 1h storage dimensioning leads to an acceptable load – power curve in the subject part of the grid.

Naturally, with an ESS that has been dimensioned for a leveling period of 24h the equalization of network loading can further be reduced. As shown in Figure 7, the leveling optimization for PV infeed and loads yields an almost constant loading of the affected 0.4 kV line. Over the investigated period of 30 days the entire grid losses could be reduced by almost 15% when considering both ESS in the optimization.

As a side effect the maximum loading of the step down transformer could even be cut in half. This further demonstrates, that ESS application plus power flow optimization could lead to a lower equipment rating for the case that ESS might become a regular measure for network expansion planning.
As expected, the optimal power flow based operation of the installed ESS leads to a significant reduction in grid losses over the investigated period of time. The simulation results presented here only comprises optimization steps that have been executed on the storage dispatch level. I.e. the time aspect of daily or even weekly variations of energy infeed and load shapes have not been considered yet but promises further loss reduction if both optimization horizons will be combined.

4.2 Case 2: Optimal sizing

The economic performance capabilities of ESSs are set by a proper dimensioning of the rated power and storage capacity during the planning stage. In the light of the proposed ESS management scheme an “offline” application of the underlying algorithms can be used for storage dimensioning purposes. The ESS sizing will be made by an iterative process. Depending on preferred locations and using typical load and generation profiles, an approximate optimal size could be computed by providing demanded power in 90% of time and full utilization of capacity. Against the background of the underlying benchmark system it could be observed, that the typical rating of the installed power of the ESS and the capacity varies with the voltage level (medium voltage, MV and low voltage, LV):

\[
\frac{P_{LP}}{P_{MV}} = 25\% \quad \frac{W_{LP}}{W_{MV}} = 20\%
\]

Even though different optimization objectives have been applied, the ratio almost corresponds with the typical ratings according to the different voltage levels.

The requirements on storage gradient, which determines the storage technology to be utilized, are derived from time series analysis. Figure 8 shows the results for the investigated benchmark system.

![Figure 8: Simulated load characteristics for determining the required storage gradient](image)

From the slope of the sorted time series of needed storage power the optimal gradient can be determined. Here, an economic tradeoff between the desired storage dynamics and economic benefits has to be applied.

5 CONCLUSION

This paper proposes an approach for the optimal sizing and management of mid size energy storage systems in distribution networks.

Based on a structured survey of typical application of mid size energy storage systems in the light of different operational objectives, it has been demonstrated that several applications places different requirements on energy storage systems. With respect to an overall storage management approach the comprehensive analysis of these requirements also shows a certain similarity within the majority of application cases.

For the application of storage systems in distribution grids the paper proposes a two stage approach for the purpose of optimal dimension and operational management. This approach combines resource planning methods as long term optimization with optimal power flow algorithms as short term optimization, namely storage dispatch. The long term optimization performs the task to plan the optimal operation mode for the storage systems over a certain time horizon. The storage dispatch stage is used to optimize the power flow and also the reactive power in the short term horizon.

Based on a benchmark system, reflecting typical distribution grid topology, load characteristic and renewable generation infeed, the properties of the proposed system could be demonstrated. In a first step realization it could be shown, that load leveling functions as expected and as a side effect, network losses can significantly be reduced, when utilizing power flow algorithms.

The realization of the proposed approach as a holistic solution for planning and operational management will be the next steps. One main focus for future research will be the integration of methods for the optimal location as well as algorithms of the coordinated operational management of several energy storages in distribution networks.

Acknowledgments

This work has been partly supported by the Fraunhofer Society within the Advanced Energy Storage program.

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