ENERGY STORAGE IN DISTRIBUTION GRIDS - NEEDS FOR CROSS-VOLTAGE-LEVEL PLANNING AND OPTIMIZATION

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ABSTRACT

In the liberalized electricity market many different distribution system operators (DSO) are involved to ensure a secure and reliable power supply. Every single DSO independently aims to optimize its operation technically and economically. Nevertheless the DSOs have to face numerous tasks in the context of the massive integration of distributed generation (DG) that can be economically successful only through joint strategies, while maintaining a safe operation of the critical infrastructure. Such strategies include the use of energy storage to compensate for the fluctuating feed-in of DG in order to reduce the otherwise accruing network expansion costs. Studies show that the integration of storage has multi-voltage-level effects and the optimization of planning has to be done in an overall system design approach.

This paper describes three expansion planning variants for distribution networks with the sole usage of energy storage. They distinguish themselves by the effects of storage usage that are taken into account when planning networks of higher voltage levels. Therefore energy storage devices are dimensioned for each planning variant and the LV, MV and HV level in order to avoid any impermissible voltage deviations and overloads of the network equipment. Subsequently possible savings of the cross-voltage-level planning are pointed out by means of an economic evaluation of the expansion planning variants.

INTRODUCTION

In the context of the transition process of the German power system, two essential problems have to be resolved:

On the one hand the fluctuating supply of electrical power from distributed generators like wind turbines and photovoltaic systems and the power demand has to be balanced. On the other hand, the current distribution systems lack suitable network configurations for the high peak loads caused by the rising number of distributed generators. Even today this leads to overloads of the primary equipment and especially in LV and MV networks to impermissible voltage rises. Although these peak loads only occur for a few hours a year, conventional network reinforcement strategies rely on adding expensive primary equipment.

Properly operated energy storage can solve both these problems simultaneously. In this case the energy storage limit the DG's power fed into the network to a permissible value.

So far, network reinforcement measures are mostly planned separately for each voltage level. In addition to the simplification of the actual planning process this approach can be explained especially by typical property boundaries between primary equipment of the HV and the MV levels. However, the consideration of effects of storage connected to subordinated voltage levels in the network planning, henceforth referred to as a *cross-voltage-level* or *integrated* planning, may lead to significant savings that should be determined more precisely.

The following study is part of the research project "New planning principles for rural distribution networks in the context of the German energy transition" funded by the Federal Ministry for Economic Affairs and Energy". The project aims at defining planning principles with consideration of innovative planning methods as well as innovative network equipment.

EXAMINED GRID

The examination is based on a real distribution system located in the eastern part of Germany. Table 1 provides a summary of the network's essential characteristics.

Table 1 - Characteristics of the examined network

parameter		value
Load [MW]	Today	Min: 350 Max: 639
Installed capacity of DG [MW]	Today	1,327
	2050	2,576
Number of networks	HV	1
	MV	32
	LV	3,300
Line length [km]	HV	1,400
	MV	5,100
	LV	9,500

Long-term planning can be conducted with a definition of scenarios that describe the installed capacity of distributed generators up to the year 2050 [1]. These scenarios are derived from the results of multiple studies that take current political conditions into account. Accordingly, in 2050 there will be DG with an installed capacity of 2,576 MW.

TECHNICAL APPROACH

Dimensioning and positioning of energy storage

After applying the load and DG scenarios, all overloads and impermissible voltage deviations (hereafter referred to as *network state violations*) in the evaluated network are identified. Subsequently, conventional network reinforcement measures are replaced by the sole usage of energy storage devices that are dimensioned as follows: In the first instance, an optimized combination of storage positions and power are determined. Basically, the storage position (i.e. node of connection) depends on the sensitivity of nodes with a network state violation to a change of the energy storage's power. The exact approach differs depending on the voltage level and its typical topologies. In the HV network, all HV/MS substations are identified at which energy storage is necessary in order to avoid network state violations. In contrast, in the MV and LV networks there are either no or at most one storage per feeder, where the aim is to homogenize the maximal voltage rise across all feeders of the MV or LV networks. Afterwards the necessary storage power is chosen to avoid any overloads and especially deviations of the permissible voltage range: A deviation of ±10% from the nominal voltage is tolerated in the HV network. According to the standard DIN EN 50160 [2] in both the MV and LV networks the admissible voltage tolerance range is ±10% of the nominal voltage. Because in most cases there is no on-load controllable MV/LV-transformer, the acknowledged tolerance range has to be divided between MV and LV networks (see below).

The necessary storage capacity is determined by the analysis of annual residual load curves (cf. Figure 1): Every power value above the maximum transferable power of the considered network will result in charging the storage, whereas the storage is discharged whenever the power value gets below this threshold. The storage's capacity amounts to its maximal state of charge.

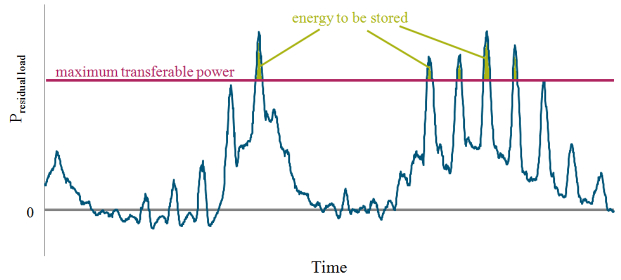

Figure 1 - Exemplary analysis of the load curve for determining the necessary storage capacity.

Planning variants

In this paper three planning variants are discussed to point out the effect of storage on network state violations in general as well as the synergy effects that result from a cross-voltage-level planning approach.

Base variant V1 – non integrated

The base variant describes a separate expansion planning per voltage level. Although the storage reduces the DG's power fed into subordinated voltage levels, those effects are neglected. Therefore it can be seen as a conventional planning approach using energy storage.

The lack of on-load voltage controlling of the MV/LV transformer in combination with the separate planning approach calls for a fixed division of the acknowledged voltage tolerance range (see figure 2). The chosen division ensures compliance with the standard DIN EN 50160 directly, so both simplifying directives BDEW-MS [3] and VDE AR-N 4105 [4] do not need to be considered.

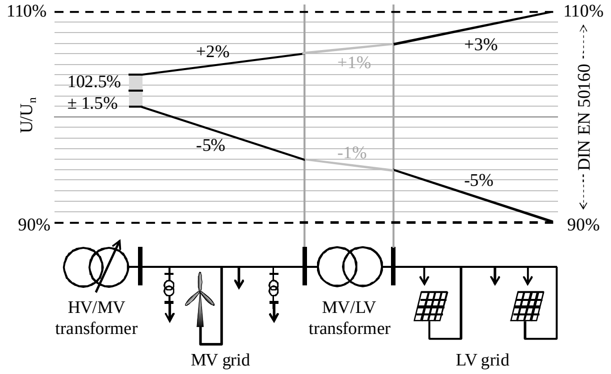

Figure 2 - Admissible voltage range in base variant V1.

Variant V2 – partly integrated

The second planning variant optimizes the dimensioning and positioning of storage across the MV and LV levels. In contrast the HV network is planned separately and therefore the results are equal to those of the base variant. First of all, the LV storage reduces the maximal power fed into the MV network by DG and thus the resulting voltage rise. Additionally, a suitable positioning can minimize the voltage rise across all feeders of the LV network allowing a greater voltage rise in the MV network without exceeding the acceptable voltage range at the LV network's feeders.

In this context the parameter $\frac{P_{Storage,LV}}{P_{DG,LV}}$ is introduced. It describes the relation between the storage power and the installed capacity of DG in the low voltage level. By varying this parameter the total costs of the sum of MV and LV storage can be minimized.

The partly integrated variant is especially relevant for DSOs that operate merely MV and LV networks.

Variant V3 – fully integrated

The fully integrated planning variant is based on the variant V2 and considers the reduced power fed into the HV network resulting from the MV and LV storage. For the penetration of storage in the LV and MV level, the cost optimized parameter $\frac{P_{Storage,\sum LV,MV}}{P_{DG,\sum LV,MV}}$ of variant V2 is set.

ECONOMICAL APPROACH

To evaluate not only technical but also economical effects of the described planning variants, forecasts of investment (CapEx) and operating costs (OpEx) of several storage technologies like Li-Ion batteries, electrolysis (H_2) or—via additional methanation—power-to-gas (PtG) as well as costs for power-to-heat (PtH) concepts in 2050 are taken into account. The investment costs can be divided into those that depend on the installed power (e.g. power electronics, control, electrolyser) and capacity-related costs (e.g. battery modules). For example, the storage capacity for the investment costs of Li-Ion storage is the dominant cost factor while the storage power for the energy storage in methane significantly determines the costs (see figure 3).

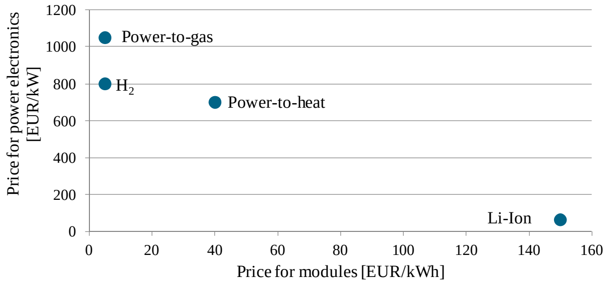

Figure 3 - Specific investment costs of different storage technologies – base price [5]

The economical evaluation is made with the storage dimensioning from the technical analysis (power and capacity) and with the technical applicability of the storage technologies in the particular voltage levels. Investment and operating costs as well as the costs for reinforcement investments are summed up (TotEx) for all variants as net present value with an interest rate of 5% over a period of 40 years. Subsequently the forecasted costs for the complete examined distribution network as well as in the different voltage levels can be compared for not integrated, partly integrated and fully integrated network planning approaches. Different cost distributions and price developments can be illustrated and an economical optimum can be determined.

RESULTS AND OUTLOOK

The specific use of energy storage allows the integration of the expected installed capacity of distributed generators up to 2050 without any further network expansion measures. To completely overcome the described issues it is inevitable to operate the storage in due consideration to the connected network, by relieving and supporting the network in times of feed-in peak.

Results show that the share of storage power as well as capacity in the HV level is dominant with over 80% in all expansion variants. Variant examinations suggest that the storage demand is strongly influenced by the used expansion strategy. Hence the necessary storage power and capacity in variant 1 (not integrated) is clearly the highest. With the partly integrated or the fully integrated planning approach significant savings of 4% respectively, 15% in the power dimensioning and 3% each at the dimensioning of the storage capacity can be achieved (see figure 4).

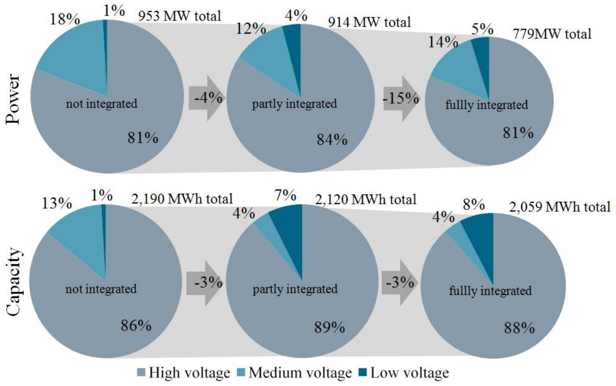

Figure 4 – Distribution of total storage power and capacity per planning variant

The partly integrated variant between MV level and LV level shows distinct savings of 22% in the storage power needed within these two voltage levels only. Due to the LV storage use and the resulting reduction in the voltage increase, the permitted voltage range in the MV level can be enlarged. Thereby, the storage power in the MV level decreases much more than the increase in the storage power in the LV level. This can be explained by the fact, that the currents in the LV level are higher at the same transmitted power causing a greater rise in voltage. Accordingly the transmittable power can be increased by a specific storage use in the LV level with comparatively low storage power and capacity. Furthermore, in this first step from not integrated to partly integrated planning approach the full-load hours in the LV level increase from 2.2 h/a to 4.2 h/a while decreasing in the MV level from 1.6 h/a to 0.7 h/a. Following this observation it might be advisable to curtail the surplus energy in the MV level instead of installing storage systems with only a few hours a year in operation.

The examination of the integrated expansion planning between all three voltage levels then shows that the energy storage in the subordinate levels—when operating in regard to the technical requirements of the system—relieve the HV network and the storage power within the HV level decreases by about 18% compared to the not integrated approach. Besides this notable impact, it has to be mentioned that the storage in the subordinate voltage levels do not lead to the same absolute reduction of the storage power in the HV level. This effect is explained by the circumstance that the storage dimensioning in the MV level is optimized for the MV planning only which leads to a uniform allocated unloading, while network bottlenecks in the HV level are distributed non-uniformly depending on the network topology. In spite of the high reduction potential for the necessary storage power, the capacity in the fully integrated planning can be reduced by not more than 3% because the storage of the subordinate levels exclusively store the energy of the occurring low-energy power peaks.

Along with the technical examination, one can notice that the total costs of the expansion measures are reduced with rising integration of the network planning. In figure 5 this effect is represented for the partly integrated planning of the MV level and LV level:

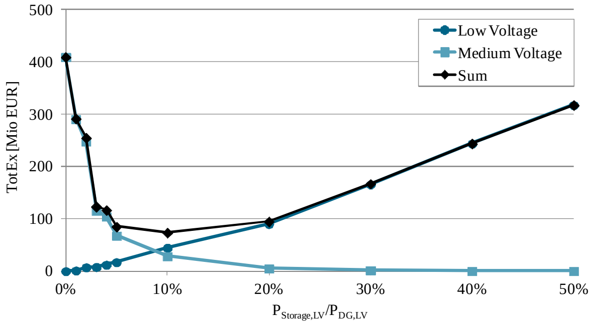

Figure 5 - Total expenditures of both MV and LV storage in planning variant V2 (partly integrated) depending on the share of LV storage

Due to the increasing level of energy storage penetration in the low voltage levels of the power system the costs increase approximately linear. Particularly, the necessary storage capacity and therefore also the costs for storage devices in the MV level heavily decrease due to the lower violation of the admissible voltage range in case of the partly integrated planning approach. Therefore the total costs for storage integration into LV, MV and HV networks to avoid overloading and voltage band violation can be reduced by more than 3% between LV and MV (V2 - partly integrated). Comparing the cost reduction of LV and MV networks only (without HV) the savings within these voltage levels are about 23%. This also illustrates that a major part of the CapEx and OpEx have to be invested into HV networks. LV and MV investments are a minor portion of the total investment costs. The fully integrated expansion planning leads to a total cost reduction of 8% compared to the separate planning approach. This includes a portion of 88% of the total costs coming from the storage devices in the HV networks, 5% in the MV networks and 7% in the LV networks. In this case, the reduction is about 60 million EUR by reducing the costs from 700 million EUR for the separate planning to 640 million EUR for the fully integrated planning. The maximum total costs are about 840 million EUR in case of separate planning (TotEX high price) considering 20% higher costs for storage as shown in figure 3. Even for the option of 20% lower prices for storage (TotEx low price) half a billion EUR are needed in case of a fully integrated planning approach to compensate all deviations of existing standards (see figure 6).

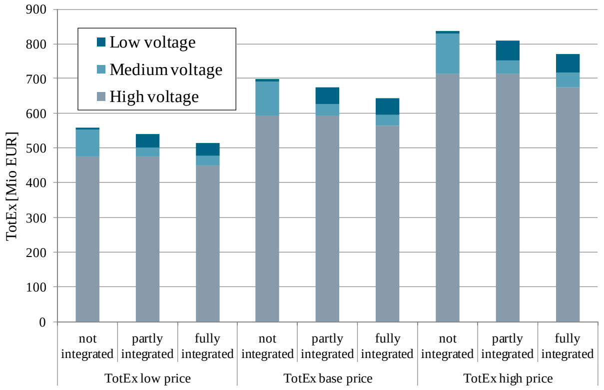

Figure 6 - Total costs of different options and price trends for storage devices

Due to the extremely low utilization, the Li-Ion storage devices are the most economic technology in this investigated case. As mentioned before, the costs for storage power are relatively low compared to the costs for storage capacity. Therefore it is recommended to prefer this kind of technology if the duration of peaks in power supply is low. Figure 7 shows the average costs of all calculations and for different technologies normalized to the expected costs for storage devices. It shows that the costs for power-to-heat storage have to be reduced by nearly 15% (compared to figure 3) to get nearly the same economic efficiency as Li-Ion. Additionally it is shown that power-to-gas is not an economic alternative for short-time storage due to 80% higher total costs compared to Li-Ion.

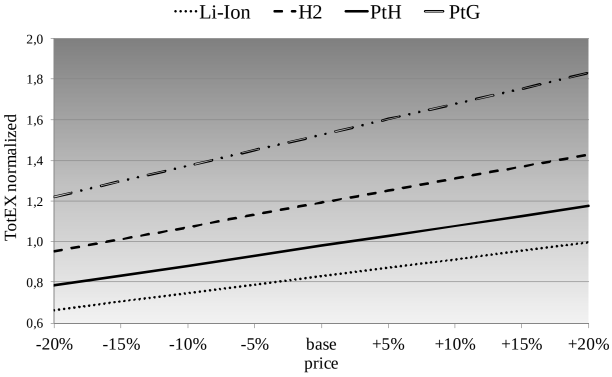

Figure 7 - Total costs of different options and price developments

Within the shown cases, the hours of operation are very low and offer the possibility to use the storage also for market driven operation. It has also been stated that the combination of power systems service and market driven operation of storage has to be analyzed to improve the economic efficiency. As long as the storage is used only to reduce investments into network upgrade and as long as the hours of operation are below 5 h/a, the Li-Ion technology is the cheapest option of the four mentioned technologies. With the increasing need of storage capacity, other technologies as H_2 or PtG (CH_4) have economical benefits due to lower costs for the storage capacity. Beyond the reduction of network extensions, storage can also be used to address other efforts as seasonal energy balancing, frequency control or they can be used to operate isolated grids. According to the regulatory framework and technical boundaries it is possible to combine different aspects of usage to increase the hours of operation. This finally leads to higher earning and to cost reductions.

SUMMARY

This paper describes the optimization potential of an overall voltage level planning for energy storage in existing networks. It has been shown that the integrated planning of LV and MV networks will lead to a costs reduction of more than 20% of the costs for storage which are to be installed in these grids. This kind of optimization is necessary for power system operators of LV and MV networks.
The integrated planning approach of all three voltage levels shows that the total power of HV storage devices can be reduced by 18% but the storage capacity will only be slightly reduced by 3%.
From the economical point of view, the benefits are higher in case of a coordinated storage roll-out via all voltage levels. For a coordinated planning of LV and MV network, about 20% savings can be achieved for these voltage levels only. This is about 3% for the whole system from LV to HV. For a fully integrated planning the costs will be reduced by 8% for the whole system which means cost savings of 5% in the HV network.

Finally it should be mentioned that the investigations are only based on the analysis of need for energy storage under the consideration that network extension will be reduced. This should not lead to the conclusion that the integration of storage devices is the only and most economical solution. This has to be analyzed for each network constellation under consideration of a variety of options to solve the challenges for integration of renewable fluctuating energy resources. A major benefit will only be possible if the full range of capabilities for storage in public network devices will be used by different stakeholders or interests.

LITERATURE

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