OPTIMIZED DEPLOYMENT OF STORAGE SYSTEMS FOR INTEGRATION OF DISTRIBUTED GENERATION IN SMART GRIDS

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ABSTRACT

Due to an increasing share of distributed generation and recently emerging options in smart grid planning, distribution system operators (DSOs) are confronted with new challenges. Especially storage systems are frequently discussed in a smart grid context due their high flexibility. However, holistic analyses of energy storage together with traditional expansion measures are still rare. This paper addresses the optimal integration of storage systems into the planning process of smart grids. An algorithm for siting and sizing of storage systems and new overhead lines or cables is presented. The exemplary application of the algorithm proves the need for an integrated analysis of storage systems together with other expansion technologies and illustrates an economic advantage for independently operated storage systems in multifunctional operation in comparison to DSO-controlled energy storages providing only grid support.

INTRODUCTION

Supported by attractive feed-in tariffs, the number of photovoltaic and wind power plants is increasing rapidly in Germany. The grid integration of distributed generation (DG) already leads to congestions and problems with voltage stability for DSOs.

At the same time, an increasing number of potentially cost-efficient alternatives are emerging for the expansion of distribution grids. Smart grids relying on ICT infrastructure are being investigated to improve grid utilization and prevent traditional expansion or reinforcement measures. In such smart grids, storage systems are discussed as one important component due to their high flexibility and versatility [1].

However, the integration of storage systems into the planning process of distribution grids needs further investigation. Locations, sizes and in particular the dispatch strategies determine the grid impact of deployed storage systems and are thus of importance from a DSO's perspective. Entirely market-oriented storage operation can cause even more congestion than relieve in a grid. On the other hand, a storage dispatch focused only on grid support is likely to be economically unattractive. A combination of market and grid-related applications appears as a promising option [2],[3]. Additionally, when discussing storage deployment, it needs to be considered that storage systems are only one option for the enhancement of distribution grids. Existing works with regard to placement and sizes of storage systems in distribution grids lack a comprehensive analysis of storage applications and/or DSO options [4],[5]. On the other hand, numerous works regarding distribution grid planning can be found (e.g. [6]), but storage systems are often not considered as expansion alternatives.

SMART GRID PLANNING ALGORITHM INCLUDING STORAGE SYSTEMS

This paper presents an algorithm for distribution grid planning under consideration of storage systems, traditional grid reinforcements and DG curtailment. Storage systems can be DSO-controlled or operated by an independent storage operator (IStO).

Problem formulation and solution concept

The task of distribution grid expansion planning under consideration of storage systems can mathematically be formulated as a mixed integer programming problem. The objective is the minimization of total cost:

$$\begin{aligned} min \Big\{ TC = AF * \left[\boldsymbol{c}^{inv,l} * \boldsymbol{l} + c^{inv,p} * \boldsymbol{p} + c^{inv,e} * \boldsymbol{e} \right] \\ + \sum_{t \in T} C_t^{OP}(\boldsymbol{p}_t^{s,ch}, \boldsymbol{p}_t^{s,dis}, \boldsymbol{p}_t^{c}) \Big\} \quad (1) \\ \boldsymbol{l}, \boldsymbol{p}, \boldsymbol{e} \in \mathbb{N}_0, \quad \boldsymbol{p}_t^{s,ch}, \boldsymbol{p}_t^{s,dis}, \boldsymbol{p}_t^{c} \in \mathbb{R} \end{aligned}$$

With:

TC	Total annual costs (annuity)
AF	Annuity factor
C_t^{OP}	Costs of grid operation in time step t
T	Set of time steps
$\boldsymbol{l}$	Vector of new line/cable variables
$\boldsymbol{p}$	Vector of installed storage power variables
$\boldsymbol{e}$	Vector of installed storage capacity variables
$\boldsymbol{p}_t^{s,ch}$	Vector of storage charging variables per node
$\boldsymbol{p}_t^{s,dis}$	Vector of storage discharging variables per node
$\boldsymbol{p}_t^{c}$	Vector of curtailment variables per node
$\boldsymbol{c}^{inv,l}$	Vector of investment costs per line
$c^{inv,p/e}$	Investment per installed storage power/capacity

Among the constraints of the expansion problem are the power flow equations, voltage and line flow limits as well as limits for storage power and capacity.

Two key challenges exist for the solution of the formulated problem: Firstly, the operational decisions for storage and DG units ($\boldsymbol{p}_t^{s,ch}, \boldsymbol{p}_t^{s,dis}, \boldsymbol{p}_t^{c}$) are strongly dependent on the investment decisions ($\boldsymbol{l}, \boldsymbol{p}, \boldsymbol{e}$).

E.g., the chosen storage power and capacity ratings limit the operational possibilities of the storage units. Secondly, all investment decisions are integer decisions, which complicate the solution process.
With the proposed algorithm (see Figure 1), the overall problem is split into a master-problem coordinated by a genetic algorithm (GA) and an operational sub-problem solved with a linear programming (LP) approach.
Besides coordinating the overall solution process, the GA also fixes the integer decisions of the expansion problem for each individual in the population. Consequently, only the linear storage and DG operational variables need to be determined for each individual in the sub-problem.

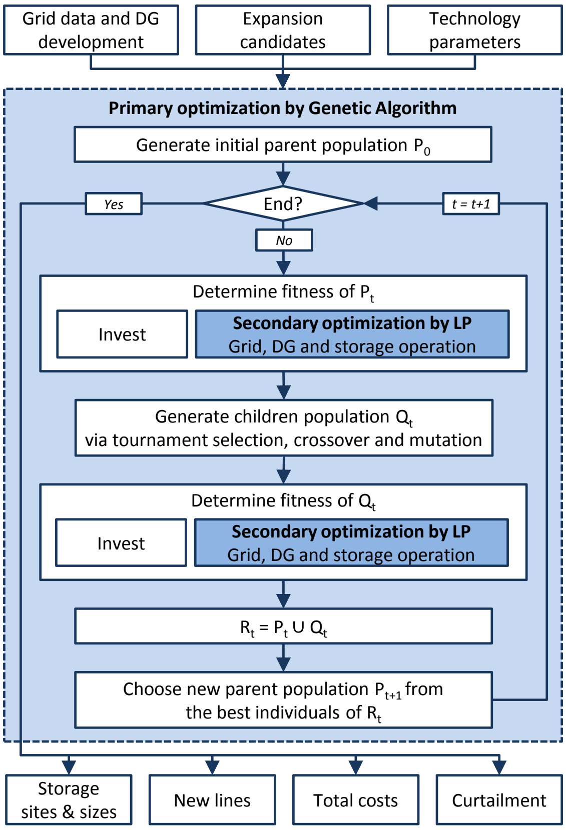

Figure 1: Flowchart of hybrid optimization model

Primary optimization by Genetic Algorithm

Genetic algorithms can be attributed to the class of stochastic optimization. Basically the GA copies two major evolutionary principles: variation (mutation, crossing-over) and selection. The solution quality is steadily increased through the iterative selection of individuals on the base of the so called fitness value (in case of multi-objective optimization more complex selection criteria like pareto-optimality [7] are applied).
When using GAs, the coding of information is known to be a critical issue. In the specific case a coding scheme has been selected, which encodes each potential storage and line candidate by a fixed positioned integer value within the gene-string. Investigations have shown an advantage in convergence speed in relation to schemes which code the asset position as well. In case of encoding the asset position, marginal changes in the decision space might lead to large changes in the optimization space (see Figure 2).

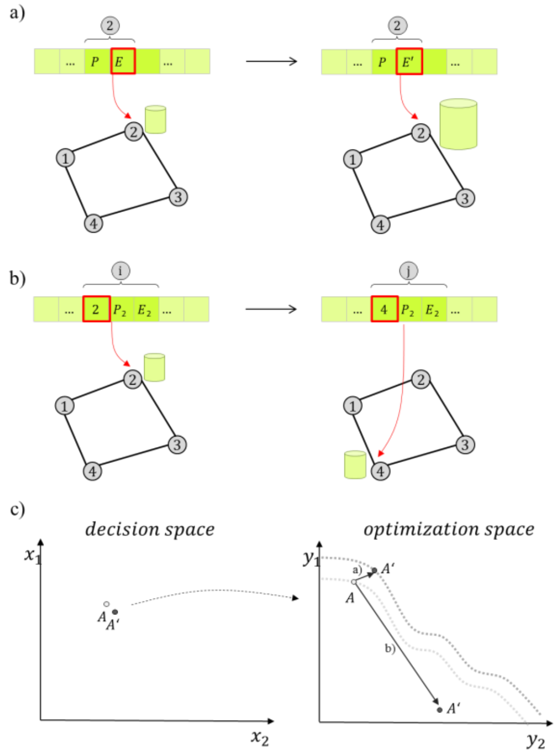

Figure 2: Comparison of different coding-schemes a), b) changes in decision and optimization-space c)

Secondary optimization by LP

The secondary optimization determines the operational variables of storage dispatch and DG curtailment for each individual in the GA. The overall objective is the minimization of all costs of operation for the DSO:

$$min \left\{ TC^{OP} = \sum_{t \in T} C_t^C + C_t^L + C_t^S + C_t^G \right\} \qquad (2)$$

With:

TC^{OP}	Total annual operational costs
C_t^C	Costs of curtailment in t
C_t^L	Costs of grid losses in t
C_t^S	Costs of DSO-controlled storage operation in t
C_t^G	Costs of grid services from IStO in t

DSO-controlled storage systems

The DSO can decide to invest in storage systems and subsequently use the installed units for his purposes like any other grid asset. Charging and discharging of the deployed storage units is optimized to prevent curtailment, reduce grid losses and improve voltage stability. Due to unbundling, market participation with the deployed storage systems is not possible for the DSO. Costs of storage operation (C_S) result from storage efficiency losses.

Independently operated storage systems
Alternatively, storage systems can also be installed and operated by independent storage operators (IStOs). In this case, the DSO only procures supporting grid services. This setup implies a close interaction of DSO and IStO to adapt storage schedules in a grid supportive manner. However, an IStO in a liberalized market is a profit maximizing actor and will choose the most attractive dispatch option [2],[3]. Day-ahead, intraday and reserve markets are considered as market-related applications.
The fees for grid services paid by the DSO to the IStO need to be high enough to incentivize grid supportive behaviour. The minimum necessary grid service fee amounts to the difference in revenues between a market driven storage operation without consideration of any grid restrictions (R_t^M) and a grid compatible storage operation in the given distribution grid (R_t^G):

$$C_t^G = R_t^M - R_t^G \qquad (3)$$

For independently operated storage systems there are no investment costs for the DSO. The IStO makes the investment and refinances via the revenues earned from market operation and grid services.

Constraints
Technical constraints for storage systems and DG units are considered. For storage units, these include keeping the maximum charging and discharging powers and the maximum capacities in each time step. DG units can only be curtailed within the limits of given generation.
On the other hand, the power flow equations, voltage and line flow limits need to be considered. In order to be able to use LP with improved computational times, the non-linear power flow equations are linearized. The approach is based on AC power flow sensitivities, which are determined for the current grid state to provide a good approximation of the non-linear relations (see [2],[3]).

Reduction of expansion candidates

Providing all network nodes as possible storage locations and all possible node connections as line candidates to the GA leads to a very large solution space and consequently long computational times. In order to derive a limited initial population of potentially good solutions, a pre-selection procedure is used.
Congested lines are identified based on an initial power flow analysis for a representative year within the planning horizon. Only reinforcements in parallel to congested lines are allowed as line candidates for the GA.
In order to identify the best storage locations, the nodes with the highest AC sensitivity for congestion relieve are determined. The AC sensitivities indicate how line utilization changes when a node injection is altered.

Choice of representative simulation periods

In the traditional grid expansion problem it is usually sufficient to consider the point in time with the highest expected load. However, when including storage systems in the planning process, multiple time steps need to be considered in order to correctly depict storage behaviour. Simulating the entire lifetime of storage systems though is also not practical due to computational restrictions.
A choice of a limited number of representative simulation periods seems to be a good trade-off. The chosen periods have to ensure that the most critical grid situations and the most critical periods for storage systems (e.g. the maximum needed charging duration) are covered. When analyzing independently operated storage systems, also uncongested periods should be considered in order to evaluate market participation correctly. In this paper a basic cluster analysis serves as a basis and three weekly periods are chosen[1].

CASE STUDY

For demonstration purposes, the developed algorithm is applied for an exemplary medium voltage (MV) distribution grid. The grid is congested due to a high penetration of distributed renewable generation units. The DSO has to face the decision on how to upgrade its grid.

Exemplary grid

The case study network is a 20 kV grid with a ring structure and a total of 14 buses and 15 branches. The grid is fed by one 110/20kV primary substation. The considered DG units are wind farms feeding into the network at 3 different buses and with a peak power indicated in Figure 3.
The previously introduced pre-selection procedure determines the lines 2-5 and 7-8 as congested and consequently line candidates are placed in parallel. The highest sensitivities to relieve the congestions with storage systems are determined for nodes 5 and 8.

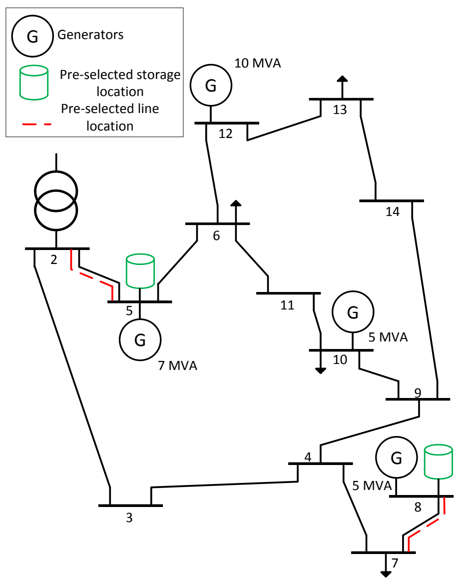

Figure 3: Exemplary MV case study grid

[1]A more elaborate analysis and choice of simulation periods is due to be published by the authors, but is not the main focus of this paper.

Scenarios

Three different scenarios are considered for the expansion options in order to illustrate the range of possibilities provided by the algorithm:

1. **S1:** Only DSO-controlled storage systems, no new lines
2. **S2:** Only independently operated storage systems providing grid services, no new lines
3. **S3:** Storage systems (DSO- and IStO-operated) and new lines

Results

The resulting new lines, storage systems and the remaining curtailment in the grid are presented in Table 1. The GA parameters to generate these results are set to 100 generations, 100 individuals, a tournament size of 4 and a mutation probability of 5%. Storage investment costs are set to 500 €/kWh and 150 €/kW. Investment costs for MV cables are assumed to be 130 k€/km.

	S1	*S2*	*S3*
Storage node 5	-	2 MW 8 MWh	2 MW 8 MWh
Storage node 8	-	-	-
Line 2-5	-	-	-
Line 7-8	-	-	1
Curtailment	1270 MWh	751 MWh	615 MWh

Table 1: Optimal expansion plans

When only considering DSO-controlled storage systems as an expansion option (S1), no storages are placed. Using only DG curtailment is more economical.

In case of IStO-operated storage systems (S2), one unit is placed at node 5 leading to a curtailment reduction of more than 500 MWh per year. A storage system at node 8 is not chosen. This can be explained by the weak grid connection of node 8 which would also limit storage market operation in times of less wind power feed-in.

In the integrated analysis with new cable connections (S3), the same storage unit in IStO-mode is deployed. Additionally, one new cable between node 7 and 8 is determined as optimal. An upgrade of line 2-5 is very expensive and is not chosen.

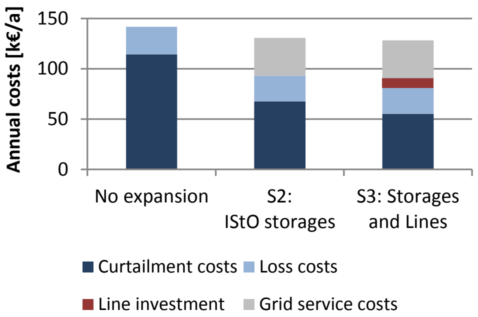

Figure 4: Annual costs of different expansion options

The three scenarios also lead to different total costs. Figure 4 illustrates the magnitude and composition of total costs for the three presented expansion plans. Since no storage systems are deployed in S1, the results are the same as for a reference case without any expansions.

The total annual costs in S2 and S3 can be reduced by 8% and 10% compared to the case with no expansion, respectively. Significant reductions in curtailment costs can be achieved, but payments for grid services have to be made by the DSO. The placed cable in S3 leads to an additional annuity of the line investment, which is however overcompensated by the additional reduction in curtailment costs.

CONCLUSIONS AND OUTLOOK

An algorithm for distribution grid planning including storage systems has been introduced in this paper. The proposed hybrid approach splits the problem into a master problem coordinated by a GA and an operational sub-problem solved by LP. DSO-controlled storages focused only on grid support and independently operated storage systems providing grid services and participating in markets can be considered in the model.

The results for an exemplary MV grid show that DSO-controlled storage systems are not an economic alternative for the DSO. However, IStO-operated storage units providing grid services to the DSO can be an attractive option. Thus, storage systems should rather be considered as “shared assets” than as “grid assets”. In addition, the results also prove the need for an integrated analysis of different expansion options. The lowest costs for the given grid can be achieved, when considering IStO-operated storage systems and new cables.

In future research, the algorithm is to be tested on large scale examples with more expansion options and several add-ons are planned by the authors. These include e.g. the consideration of multiple investment decisions (“multi-stage”), specific improvements of the GA operators for the grid expansion problem and the integration of additional load and asset flexibilities in a smart grid.

REFERENCES

[1] Eurelectric, 2012: “Decentralised Storage: Impact on Future Distribution Grids”, *Study Eurelectric*, July 2012.

[2] S. Koopmann, B. Wasowicz, S. Raths, T. Pollok, A. Schnettler, 2012: "Evaluating multifunctional storage usage for the integration of renewable energies", 7th *International Renewable Energy Storage Conference, Proceedings*, 1-5.

[3] B. Wasowicz, S. Koopmann, T. Dederichs, A. Schnettler, U. Spaetling, 2012: “Evaluating regulatory and market frameworks for energy storage deployment in electricity grids with high renewable energy penetration”, *9th International Conference on the European Energy Market, Proceedings*, 1-8.

[4] F. Geth, J. Tant, E. Haesen, J. Driesen, R. Belmans, 2010: „Integration of energy storage in distribution grids”, *IEEE Power and Energy Society General Meeting, Proceedings*, 1-6.

[5] A. Alarcon-Rodriguez, G. Ault, 2010: “Multi-objective planning of Distributed Energy Resources with probabilistic constraints”, *IEEE Power and Energy Society General Meeting, Proceedings*, 1-6.

[6] S. Haffner, L. F. Pereira, L. A. Pereira, L. Barreto, 2008: “Multistage Model for Distribution Expansion Planning With Distributed Generation”, *IEEE Transactions on Power Delivery*, vol. 23, No. 2, 915-923.

[7] M. Scheufen, H. Natemeyer, Y. Surmann, A. Schnettler, 2012: „Erzeugung und Bewertung pareto-optimaler Netz-Ausbauoptionen“, *VDE Kongress 2012 Smart Grid, Proceedings*,1-6.