Optimal Planning of High-Voltage Distribution Grids under the Combined Use of Energy Storage Systems and Dynamic Feed-In Management

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ABSTRACT

The expanding integration of renewable energies in the German distribution grids is nowadays leading to increasing overloadings of power lines, since to date distribution grids have essentially been dimensioned depending on the load situation rather than the generation situation of the decentralized generation units. This paper proposes a new approach for the optimal planning of high-voltage grids, taking into account a combined solution from energy storage systems and the feed-in management of decentralized generation units. The presented planning algorithm determines an optimal dimensioning of grid-supporting storage systems in combination with dynamic time series based feed-in management to overcome grid overloadings in due consideration of the (n-1) security criterion of power lines. The results of the method comprise the minimum required storage capacity and rated power as well as the charge-discharge schedule of the storage systems and the curtailed generating plants. The method has been applied and verified on a real 110 kV German power grid. The results show that the combined use of energy storage systems and dynamic feed-in management leads to the compliance of the power flow on the high-voltage lines with their maximum thermal loading limits. On the other hand, the required dimensioning of the storage systems is significantly reduced in comparison with the use of the storage systems only.

INTRODUCTION

Prior to the energy turnaround in Germany, the distribution grid was principally planned depending on the connected load in the grid. Nowadays, due to the increasing integration of renewable energies (RES), violation of the thermal current limits of power lines is a prominent issue. Such overloadings are becoming frequent in distribution grids in general and especially in high-voltage grids. The traditional solution to overcome this problem is grid expansion, although it does not always find public acceptance. In this context, the aim of this research contribution is to study the application of large energy storage systems (ESS) in combination with dynamic time series based feed-in management as an alternative to grid expansion to overcome line overloadings in the high-voltage grid. The proposed method is based on the NOVA principle, which signifies grid optimization, before grid strengthening before further grid expansion.

Supported by the Project Management Agency Karlsruhe Institute of Technology (KIT) with funds from the state of Baden-Württemberg.

The proposed method for the dimensioning of the storage systems in [1] is based on a linear optimization, which minimizes the total stored energy in every time iteration. The approach determines the optimal behavior of the storage systems for each time iteration of the simulation period taking into account the results of the previous iteration. Therefore, the deduced capacity for every storage system does not necessarily correspond with the minimum reachable capacity, since the minimization does not consider all simulation periods simultaneously. [2] also adopts the same dimensioning approach as in [1], albeit under the consideration of the (n-1) security criterion, which is a standard criterion in Germany for the planning of a 110 kV grid.

The application of dynamic power curtailment has already been examined in some other research works. [3] presents different formulations of dynamic optimal power flow for power feed-in curtailment. Hereby, the power curtailment is the only considered measure to maintain the active load flow under the allowed thermal limits of the power lines. In [4], a methodology for optimal grid planning is proposed considering active power curtailment and reactive power control. However, storage systems have not been here taken into account in the planning, despite the fact that they could provide further flexibility to the grid.

This research work contributes to developing a planning algorithm that determines the optimized number, placement, capacity and power rate as well as the power operation mode of ESS required to ensure the unloading of the power grid. Hereby, the optimization is realized for the whole simulation period at once.

In a second step, the planning algorithm has been expanded including a dynamic feed-in management as a further remedial measure for the unloading of the power grid, beside the storage systems. The intervention of the feed-in management is limited by the planning principles to 3% of the annual generated energy for every generating power plant [5]. This restriction is also considered in the implemented optimization model accordingly.

COMBINED USE OF ENERGY STORAGE SYSTEMS AND FEED-MANAGEMENT

In a first step, the planning algorithm has been implemented for the purpose of dimensioning the storage systems only. The algorithm thus determines the required capacity, power rate and placement of the storage systems, which allow the operation of 110 kV power lines, with the maximal loading of 100% of their thermal limit. The determined dimensions of the storage systems take into account the (n-1) security criterion through the consideration of different relevant outages, as in [2].

Dimensioning of the storage systems

The planning algorithm aims to determine the required dimensioning and power operation mode of the storage systems which ensure the unloading of the power lines for all considered critical outages, while avoiding an overdimensioning of the storage systems. The algorithm illustrates an adaptation of the dimensioning method in [2]. However, the added value constitutes expanding the iterative optimization for every time iteration to one linear optimization for the whole examined time period. The adopted linear optimization model has multiple objective functions aiming to minimize the maximum storage capacities and the total stored energies considering all time iterations at once:

$$\min\left\{\sum_{s=1}^{N_{stor}} E_{max,s}\right\} \quad (1)$$

$$\min\left\{\sum_{s=1}^{N_{stor}} \sum_{t=1}^{N_{days}\cdot 96} E_s(t)\right\} \quad (2)$$

$$\min\left\{\sum_{s=1}^{N_{stor}} \sum_{t=1}^{N_{days}\cdot 96} |P_s(t+1) - P_s(t)|\right\} \quad (3)$$

Since each node of the grid represents a potential location for a storage system, variables for the storage power P_s and storage energy E_s are assigned to every node of the grid.

The objective function (1) aims to minimize the maximum storage capacities $E_{\max,s}$ of all N_{stor} potential storage systems. The objective function (2) minimizes the sum of the stored energy $E_s(t)$ for all time iterations of the simulated period and for all potential storage systems. The total of the considered time iterations is the number of the simulated days N_{days} multiplied by the day iteration number by 15 minutes resolution time. The objective function (3) reduces the gradient of the storage power over time in order to obtain a realistic mode of operation of the storages. Due to the minimization of the total stored energy of all storages over the whole simulation period, as demonstrated through the objective functions (2), the nodes, whose contribution is negligible, are then automatically excluded by the planning algorithm. This leads to the optimal placement of the storage systems.

The considered constraints of the optimization problem aim to maintain the power flow $P_{\text{Lij}}(t)$ over every line i, at every time iteration t, and for every possible occurring outage j under the maximum thermal loading limits $P_{\text{Lj,max}}$:

$$-P_{Li,max} \leq P_{Lij}(t) \leq P_{Li,max} \quad (4)$$
$$\forall\, i \in N_{lines}, \forall\, j \in N_{outages}$$

Both objective functions and constraints have been implemented with 15 minutes time resolution. Through the adoption of a linear load flow calculation as presented in [6], the constraints for the power load flow on the lines of formula (4) can hence be reformulated and implemented in the optimization problem as introduced in [2]:

$$-\underline{P}_{Li,max} \leq [ACDF]^{(j)} \cdot \left(\underline{P}_N(t) + \underline{P}_s(t)\right) \leq \underline{P}_{Li,max} \quad (5)$$
$$\forall\, i \in N_{lines}, \forall\, j \in N_{outages}$$

Whereby $[\text{ACDF}]^{(j)}$ represents a matrix with the distribution factors of the nodal power $\underline{P}_N(t)$ on the lines for an outage j among all possible $N_{outages}$ outages. $\underline{P}_N(t)$ represents a vector with all nodal powers and $\underline{P}_s(t)$ a vector of the storage power at time iteration t.

Implementation of the dynamic feed-in management

Beside the use of ESS, the planning algorithm has been expanded to include the use of dynamic time series based feed-in management in a further step. The aim hereby is to reduce very high prognosed overloading peaks, which occur on few days of the considered year but with high power values due to the simultaneous high prognosed generation of RES. By reducing these high power peaks, the required dimensioning of the storage systems can also be reduced accordingly. The obtained dimensioning of the storage systems consequently corresponds with the prognosed overloading levels, which are the most frequent over the simulated year.

Nowadays, the distribution grid in Germany can be planned under the consideration of the feed-in management measures within the 3% limit. This limit refers to the curtailed energy amount of every generating plant in comparison with its total prognosed generation energy over the considered year. The feed-in management can be thus considered as a further degree of freedom to maintain the power loading on the lines within the allowed limits.

In order to consider the feed-in management in the planning algorithm, the constraints (5) of the linear optimization problem have been extended as follows:

$$-\underline{P}_{Li,max} \leq [ACDF]^{(j)} \cdot \left(\underline{P}_{Load}(t) + \underline{P}_{RES,C}(t) + \underline{P}_s(t)\right) \leq \underline{P}_{Li,ma} \quad (6)$$
$$\forall\, i \in N_{lines}, \forall\, j \in N_{outages}$$

The constrains in (6) ensure the maintaining of the load flow in both directions within the maximum limits $\underline{P}_{\text{Li,max}}$ and $-\underline{P}_{\text{Li,max}}$ over every line i with the help of the curtailed power of the generating power plants $\underline{P}_{\text{RES,C}}(t)$ and the storage power $\underline{P}_s(t)$ of the grid nodes for every time iteration t. $\underline{P}_{Load}(t)$ represents a vector of the connected loads to the grid nodes at time iteration t. The constraints can hence be reformulated depending on the curtailed part $\underline{\Delta P}_{\text{RES,C}}(t)$ of the generated power and the residual load before power curtailment $\underline{P}_{\text{N,prev}}(t)$ into:

$$-\underline{P}_{Li,max} \leq [ACDF]^{(j)} \cdot \left(\underline{P}_{N,prev}(t) + \underline{\Delta P}_{RES,C}(t) + \underline{P}_s(t)\right) \leq \underline{P}_{Li,n} \quad (7)$$
$$\forall\, i \in N_{lines}, \forall\, j \in N_{outages}$$

The constraints (7) can in turn be reformulated by means of the load flow on the lines without relief measures $\underline{P}_{L,prev}(t)$ as follows:

$$\begin{cases} [ACDF]^{(j)} \cdot (\Delta \underline{P}_{RES,C}(t) + \underline{P}_s(t)) \leq \underline{P}_{L,max} - \underline{P}_{L,prev}(t) \\ [ACDF]^{(j)} \cdot (\Delta \underline{P}_{RES,C}(t) + \underline{P}_s(t)) \geq -\underline{P}_{L,max} - \underline{P}_{L,prev}(t) \end{cases} \quad (8)$$

$$\forall j \in N_{outages}$$

On the other hand, a further constraint that limits the total curtailed energy over the simulated year has been implemented in (9). The constraint maintains the curtailed energy amount for every generation plant within the allowed 3% limit.

$$\sum_{t=1}^{N_{Tage} \cdot 96} 0{,}25\,[h] \cdot \Delta \underline{P}_{RES,C}(t) \leq -0{,}03 \cdot \sum_{t=1}^{365 \cdot 96} 0{,}25\,[h] \cdot \underline{P}_{RES,C}(t) \quad (9)$$

Furthermore, the curtailed power can only be realized within the limits of the generated power without any corrective measures $\underline{P}_{RES}$. This is considered in the optimization algorithm through further linear constraints for every time iteration *t* as follows:

$$0 \leq \Delta \underline{P}_{RES,C}(t) \leq -\underline{P}_{RES}(t) \quad (10)$$

DIEMSNIONING RESULTS

The described planning algorithm has been implemented for a real German 110 kV grid. The high adopted installed capacities on RES correspond to an optimistic scenario of RES expansion. The assigned times series to the loads and the generation plants have been generated based on a probabilistic approach according to [7]. In order to spare computational time and disk space, the constraints of the optimization model have been restricted to nine lines of the grid, the storage system's location to six possible nodes and the outages for the consideration of the (n-1) security criterion to nine line outages plus the (n-0) case. The line outages taken into account represent single lines as well as multiple segment outages which lead to the highest active power loading on the considered lines.
The linear load flow calculations over the adopted simulation year and under consideration of the relevant line outages show occurring power overloading situations. The boxplots of Fig. 1 describe the values of the power loading on the lines in percent for 25%, 50% and 75% of the total simulated states as well as the maximum and minimum occurring values. Fig. 1 shows that for two-thirds of the lines, the active power flow exceeds the 100% allowable thermal limit. This thermal limit is represented in the diagram by the red dotted line. These power flow transgressions are unfrequent in comparison with the total simulated time, although they occur over many hours of the simulated year and hence represent an impermissible operating state.

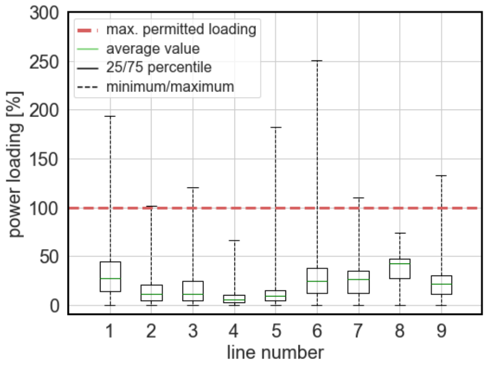

Fig. 1 Power loading on the lines without the use of ESS or feed-in management.

Dimensioning results by using ESS

In order to prevent the prognosed line overloadings of the 110 kV grid, the presented planning algorithm has been implemented. In a first step, the operation of storage systems only is considered. The required storage dimensioning to remedy the overloading on all days of the simulated year in due consideration of the (n-1) security criterion is resumed in Table 1. The resulting storage power schedules show that storages at node C and F are never used, since they would bring no significant contribution to the unloading of the lines in comparison with storages A, B, C and E. The exclusion of storages in node D and F is due to the minimization of the total stored energy over the complete simulation time. Furthermore, the storage in node E requires the highest capacity and power rate, as the placement of the storage there is efficient in reducing the power loading on the considered lines. The total required storage capacity and power rate are then 1513 MWh and 347 MW, respectively.

Table 1 Required dimensioning of the storage systems without feed-in management

	Capacity [MWh]	Power rate [MW]
Storage A	277	83
Storage B	386	81
Storage C	113	52
Storage D	0	0
Storage E	737	131
Storage F	0	0
Total	1513	347

Dimensioning results through the combined use of ESS and feed-in management

In a second step, the planning algorithm has been expanded including the dynamic time series based feed-in management of the generating plants. The aim here is to use the power curtailment at times when the generation power of RES reaches particularly high values. These power peaks occur unfrequently and would cause a high required dimensioning of the storages if no further aid beside the storage systems is deployed to remedy the power overloading on the lines. Table 2 delivers the required capacities and power rate of the storage systems by combination with dynamic feed-in management.

Table 2 Required dimensioning of the storage systems by combined use with dynamic feed-in management

	Capacity [MWh]	Power rate [MW]
Storage A	0	0
Storage B	127	77,3
Storage C	0	0
Storage D	0	0
Storage E	143	75,3
Storage F	0	0
Total	270	152,6

The dimensioning results show that an employment of storages on nodes A and C is no longer necessary, as is already the case for node D and F. Storages on these nodes would not be used, since it is more effective to deploy the storages in node B and E with less required cumulative capacity and power. Storages in node B and E are still the most effective here to maintain the active power loading on lines under the allowed thermal limits.
The total required storage capacity and power rate are now 270 MWh and 77,6 MW, which represent a decrease of the total capacity by 82% and the total power rate by 56% in comparison with the use of storage systems only. Fig. 2 and Fig. 3 present the storage energy and power for the day with highest prognosed line overloadings respectively. Combined with the feed-in management, the deployment of the storages on node B and E is sufficient to avoid active power overloading on the lines for that day. The stored energy and reached maximum power of the storage systems amount to 270 MWh and 121 MW, respectively. Through the simultaneous application of both ESS and feed-in management, the total necessary storage capacity is consequently reduced and the utilization rate of this disposable capacity has increased. Hereby, the dynamic curtailment has been limited through the 3% total generated energy for every generating plant.

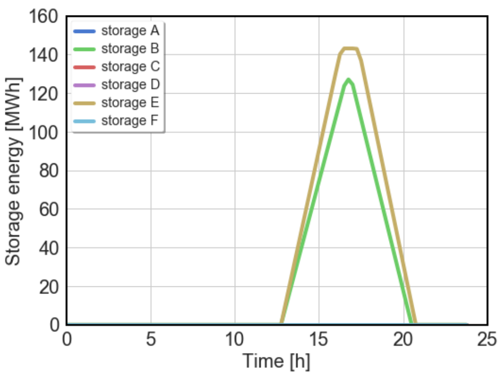

Fig. 2 Storage energy for the day with highet prognosed line overloadings

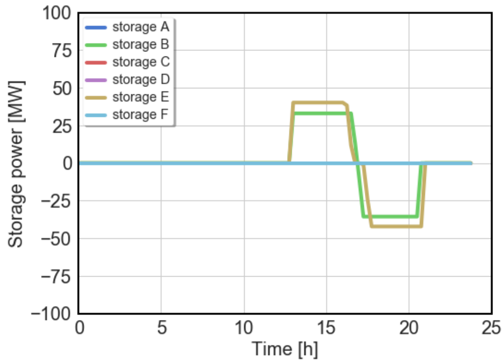

Fig. 3 Storage power for the day with the highest prognosed line overloadings

In order to illustrate the contribution of the dynamic time series based feed-in management in reducing the required total storage capacity, the days with prognosed line overloadings have been sorted according to the required maximum storage energy for each day, in case only storage systems are used. Then, the total curtailed energy as well as the maximum storage energy resulting from the planning algorithm, in case of combined use of feed-in management and ESS, have been evaluated according to this succession of days, as illustrated by Fig. 4.

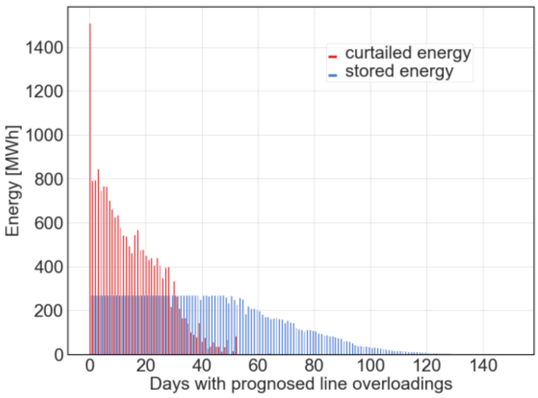

Fig. 4 Curtailed RES energy (in red) and stored energy (in blue) over the days with prognosed line overloadings

It can be deduced from Fig. 4 that the dynamic feed-in management operates unevenly over the days depending on the prognosed line overloadings. Since the primar aim of the linear optimization is the minimization of the storage capacities, the 3% permitted energy curtailment has been especially deployed on the days, with the highest prognosed overloadings, permitting hence the dimensioning of the ESS according to the most frequent prognosed overloadings over the simulated year.
Table 3 presents the total prognosed energy from PV and Wind systems in the study region as well as the resulting curtailed energy amount from the planning algorithm for the considered year. The resulting total curtailed energy amounting to 19.7 GWh accounts for 3% of the 658,1 GWh total prognosed energy.

Table 3 Total prognosed and total curtailed RES energy

	Energy RES [GWh]	Prorated [%]
Total prognosed RES energy	658,1	100
Total curtailed RES energy	19,7	3

Fig. 5 shows the power loading on the 110 kV lines by combined use of ESS and feed-in management. The loading of the lines for all possible relevant (n-1) states is now maintained under the 100% limit, presented by the red dotted line. Consequently, the 110 kV power lines could be operated safely through this combined use.

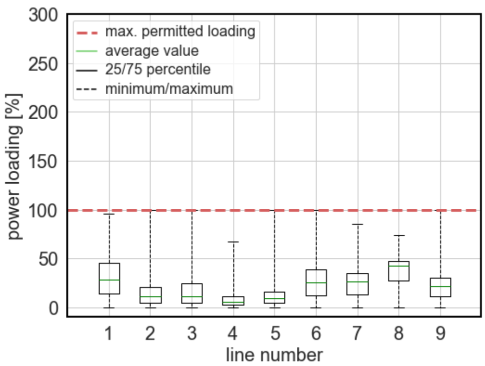

Fig. 5 Power loading on the lines with the use of ESS and feed-in management.

CONCLUSION

The proposed planning algorithm combines the use of ESS and dynamic time series based feed-in management to ensure the unloading of high-voltage grids. In a first step the algorithm optimizes the storage dimensioning necessary for the unloading of the power grid under the consideration of the (n-1) criterion, in case only ESS are used. In a second step, the planning algorithm has been expanded including the feed-in management as a further degree of freedom in the planing. The aim hereby is to help with the dynamic feed-in management in times of infrequent but high prognosed overloadings of power lines, thus achieving a reduction in the required storage capacities.

For the verification of the method, the algorithm has been implemented on a real 110 kV grid. The delivered results show that the dynamic curtailment of RES power plants can help to cap very high feed-in power peaks, which occur unfrequently within the simulated year. This allows the dimensioning of the storage systems depending on the RES supply average over the year and hence avoids otherwise high required storage capacities. The necessary total storage capacity is thus significantly reduced by 82% in comparison with the total required capacity without the use of dynamic feed-in management. Hereby the modeling of the feed-in management is compatible with the current planning principles, which implies that the total curtailed energy of a generating plant over a year must be maintained under 3%. The controlled use of ESS in combination with the dynamic curtailment of RES power plants could hence replace the planned grid expansion measures of the examined region, which are otherwise necessary to integrate future renewable energies.

The main disadvantage of the implemented planning algorithm with the combined use of ESS and dynamic feed-in management is the long computational time though the adopted simplifications. This is due to the numerous optimization variables and the long adopted simulation period, which are simultaneously considered in the optimization problem.

In a next stept, the combined use of ESS and feed-in management shall be, beside the technical examination, evaluated economically and compared with the costs of the planned grid expansion mesures.

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