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Cost-Benefit Analysis of Battery Storage System for Voltage Compliance in Distribution Grids with High Distributed Generation

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Abstract

The increasing distributed generation of renewable energies in distribution networks leads to several challenges for distribution network operators (DNOs). During high feed-in times, voltage violations can occur if the hosting capacity of the grid for distributed generation is exceeded. The paper at hand investigates the installation of grid-supporting battery storage system (BSS) in the medium voltage (MV) level to serve mainly for voltage compliance and to defer grid reinforcement. A control approach for the BSS based on two characteristic curves is suggested. The BSS is then analyzed technically and economically for scenarios of high distributed generation. The results show that the alternative of BSS has potential to defer grid reinforcement in the presented case studies. However, the power curtailment is more viable than the BSS and grid reinforcement. The economic viability of BSS can increase in the future based on the expected reduction of battery costs. Furthermore, BSS have the technical potential for providing other services, since voltage violations occur during high feed-in times.

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Keywords: Grid-Supporting Storage, Battery Storage System, Grid Reinforcement, Voltage Compliance;

1. Introduction

The energy transition to renewable energy leads to substantial changes in the generation structure from large power plants to numerous small distributed generators (DGs). The increasing distributed generation of fluctuating

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renewable energy sources in distribution grids imposes several challenges for the distribution network operators [1]. If the penetration level of DGs exceeds the hosting capacity of the grid, the voltage at some critical nodes can violate the voltage tolerance band defined in EN 50160. To mitigate voltage violation problems, DNOs can undertake grid reinforcement measures, such as installing new lines or transformers. For the case of Germany, the dena study estimates grid reinforcement costs for the distribution system of approximately 27.5 billion € until the year 2030 [2]. Therefore, other alternatives should be investigated technically and economically, aiming for reducing the grid costs in future scenarios. In addition, flexibility options for the grid operation, such as battery systems, have to be investigated in order to successfully proceed with the German energy transition.

Battery systems have been discussed in several studies as an alternative to grid reinforcements [3, 4]. In addition, numerous studies focus on the grid integration of photovoltaic (PV) systems in the low voltage (LV) network level to support the voltage compliance. The focus on the LV level is pointed out in [5]–[9], while the medium voltage has only been in focus of few case studies, such as [10]. Some relevant studies and their results in relation to this paper are presented in Table 1.

Table 1. Overvirew on studies for grid storages in Germany

Ref	Investigations related to distribution grids	Findings	Comparison with this paper
[3]	Economic potential for battery systems to avoid grid reinforcement in the LV and MV level. Constant cosφ is considered for the DGs	Battery systems are economically viable in LV but not in MV level compared to grid reinforcements	- Sizing of battery systems is based on storing the power exceeding a defined limit - Control strategy for battery systems is not investigated - Battery losses are not considered
[14]	Evaluation of a grid-supporting BSS as a mobile asset compared to grid reinforcement in a real MV grid	BSS (25 kW, 1 MWh, lithium-ion) is a profitable option and technically viable	- The sizing of BSS is based on yearly simulations - The battery system's control is performing peak shaving
[4]	Economic potential of battery systems to avoid overloading in the MV and LV level compared to grid reinforcement	Battery systems are not economical at present prices compared to other alternatives (e.g., feed-in curtailment).	- Sizing of battery systems is based on storing the power exceeding the line capacity limit - Control strategy for battery systems is not investigated
[15]	Economic potential of different alternatives incl. battery systems compared to grid reinforcement in typical LV networks	The voltage supporting BSS can be viable for some networks	- A voltage dependent control of the battery systems is assumed - The examples are only for the LV level

Furthermore, an optimized planning for the installation of battery systems to support the grid is presented in [11]. Moreover, the voltage compliance can be supported by several strategies of reactive power (Q) provision by the DGs, as discussed in [12]. Besides, the installation of large BSS in Germany (larger than 1 MWh) is increasing since 2014. The use case for the installed battery storage systems so far is mainly the participation in control power markets [13].

In the literature, there is no comprehensive evaluation of battery systems compared to other grid reinforcement solutions at the MV level. Especially, a fair sizing approach is missing which indicates the trade-offs of designing a battery storage system to avoid grid reinforcements. Furthermore, the combination between local integration strategies of DGs, such as reactive power provision and BSS needs to be thoroughly investigated to derive a comparable benchmark.

Hence, this paper investigates the utilization of grid-supporting BSS in MV level to serve mainly for voltage compliance and to avoid grid reinforcement. A control approach for the BSS is developed. Grid-supporting BSS are then analyzed technically and economically compared to grid reinforcement. The costs are assessed from the perspective of DNOs in high distributed generation scenarios. The paper ends with a discussion of the competiveness of BSS as an option to avoid grid reinforcement.

2. Methodology

The work steps to be followed for performing the cost estimations are illustrated in Fig. 1.

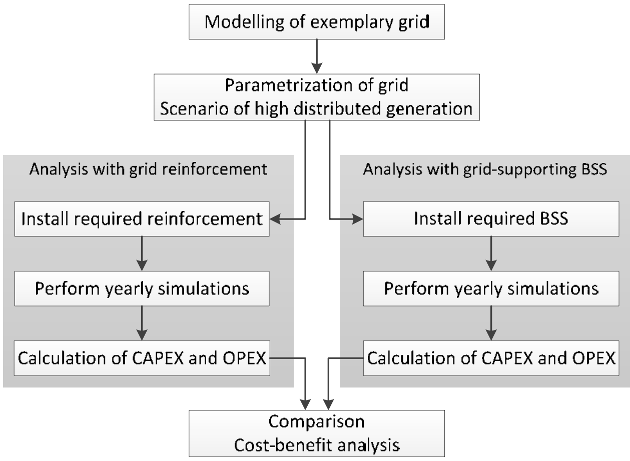

Fig. 1. Approach for performing the cost estimation of grid-supporting BSS and grid reinforcement

This paper presents a comprehensive cost-benefit evaluation of installing a BSS to avoid voltage violations compared to grid reinforcement. Therefore, several case studies with a high penetration of DGs in a generic MV network are designed. Thereafter, the costs associated to solve the voltage problems with different strategies are assessed and compared. A schematic illustration of the considered cases in the designed study is depicted in Fig. 2.

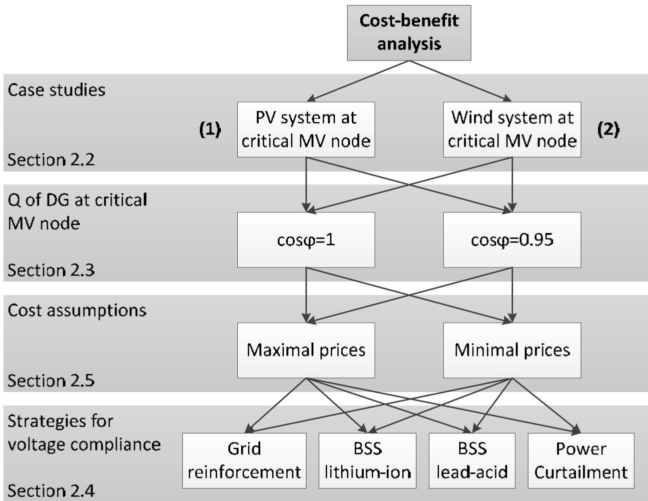

Fig. 2. Schematic illustration of the considered case studies

The modelling of an exemplary MV network for a scenario of increased distributed generation is presented in Section 2.1. Two case studies are assumed for the cost-benefit analysis, as described in Section 2.2. In addition, the provision of reactive power by the DGs in the MV level is discussed in Section 2.3. The assumed alternatives for solving the voltage problems are described in Section 2.4. The cost assumptions for the calculation of the capital expenditure (CAPEX) and operation expenditure (OPEX) are presented in Section 2.5.

2.1. MV network and its parameterization

A generic model of an MV network and some scenarios of high distributed generation are presented in [10]. This network model is also adopted for this study and depicted in Fig. 3. PYPOWER (i.e., an implementation of MATPOWER [16] in Python) is utilized for modeling and simulation of load flow calculations.

Each connection of LV network at the secondary side of each MV/LV transformer represents an equivalent load model and a PV model. The PV-dominant scenario of 2012 from [10] is assumed, which means each LV-network has 240 kWp installation of PV. However, it is assumed that the PV systems in the LV level do not supply the peak power at the same time, thus a simultaneity factor of 90 % of the nominal power is assumed. The voltage tolerance band in the MV level complying with the EN 50160 is assumed to be 0.94-1.05 p.u., which is dependent on the considerations of each DNO [10]. The voltage at the slack node, which represents the connection to the high voltage (HV) grid, is assumed to be 1 p.u.

For the yearly simulations, the resolution of load and feed-in profiles is assumed to be 5 minutes. The profiles of LV loads are accumulated load profiles generated by the tool presented in [17], assuming a power factor of (cosφ=0.98) for the loads. The PV and wind profiles for the simulation are measured profiles based on [10].

2.2. Case studies

Additionally to the network parameterization in Section 2.1, two case studies are assumed.

2.2.1. PV case study

A large PV system (3 MWp) is installed in the MV level at a critical node (i.e., a random node far from the main bus bar) as shown in Fig. 3. Therefore, voltage violations are expected at the point of common coupling (PCC) of the PV system and also at the end of the feeder A. The penetration level of distributed generation is defined as in [10], which is based on published data of DNOs.

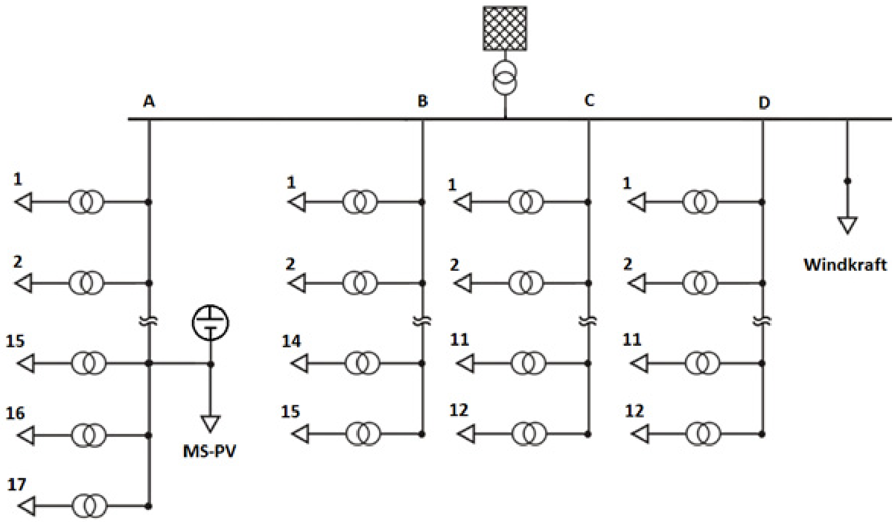

Fig. 3. Schematic depiction of the assumed generic MV network from [10] for the PV case study

2.2.2. Wind case study

The scenario of Section 2.2.1 is adjusted as shown in Fig. 4. To consider a second scenario with voltage violations caused by wind feed-in; a wind system of 3 MW is installed at the critical node, while a PV system of 750 kWp is installed at a noncritical node to keep the defined penetration level of distributed generation as in [10].

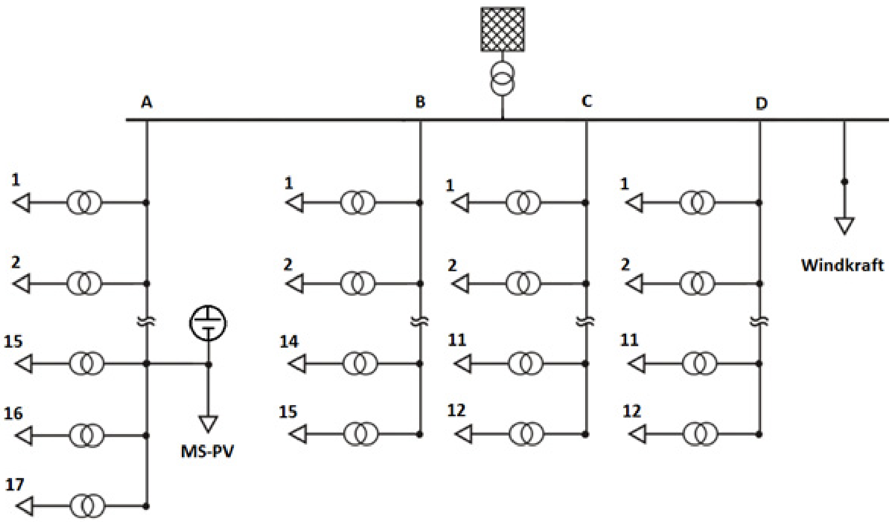

Fig. 4. Schematic depiction of the assumed generic MV network from [10] for the wind case study

2.3. Q-provision by DGs

Since this study focuses on the voltage compliance in the MV level, it is assumed that the PV systems in LV level do not provide reactive power. Two cases for the Q-provision in the MV level are considered, first it is assumed that the DGs in the MV level do not provide reactive power, second it is assumed that the large DG at the critical node (i.e., PCC) provides reactive power. The Q-provision is based on the fixed power factor (cosφ=0.95), as described in [18].

2.4. Strategies for voltage compliance

Grid reinforcements with conventional measures, the installation of BSS and power curtailment are the alternatives to be considered for solving the voltage problems. The alternatives are described hereinafter.

2.4.1. Grid reinforcement

Since grid partition is assumed in several studies as a standard grid reinforcement in the MV level (e.g., [2, 3]), it is also implemented for the cost-benefit analysis. The grid partition approach used in this paper works as follows: The feeder A which is susceptible to voltage violation is divided into two feeders, considering the shortest length of required cables. The partition for a certain node means the placement of a cable between the main bus bar and the node, while disconnecting the old cable in the direction to the main bus bar as shown in Fig. 5.

For determining the required grid reinforcement and the cable length, three steps are implemented. First, the network is parameterized according to the worst-case for the estimation of voltage violations. Hence, a maximum feed-in of all DGs and only 10 % of the capacity of all MV/LV transformers as loads is assumed. Second, the partition is performed once for each node in the feeder A. Third, the partition that can solve the voltage problems and requires the least cable length is chosen to be the cost-efficient grid reinforcement measure.

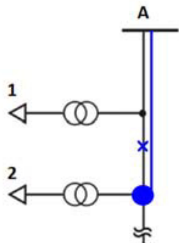

Fig. 5. Snap-shot from the test MV network showing a simplified example of grid partition. The blue line corresponds to a new cable in an existing track. The blue X corresponds to the disconnection of an existing cable

2.4.2. Installation of BSS: lithium-ion

Here, a BSS of lithium-ion is installed in the network at the critical node, which corresponds to the PCC node in Fig. 3. A new charging and discharging approach is implemented in this paper. The approach allows minimizing the BSS capacity used for voltage support compared to [10]. It is based on different droop functions and regulates the power flow of the BSS (P_{set}) depending on the voltage at the point of common coupling of the BSS (U_{pcc}) and on the state of charge of the BSS (SOC) as illustrated in Fig. 6. The first droop characteristics are for the voltage control in case the voltage at the PCC exceeds a certain band. In other words, if the voltage U_{pcc} increases because of the reverse power flow, the BSS charges to reduce the reverse power flow. The second droop characteristics are for balancing the SOC of the BSS, so that the BSS capacity will be available for voltage control. A dead-band of the characteristics of charge balancing is considered (i.e., 15-20 %), aiming for preserving a certain lower limit for the SOC (SOC_{min}). The lower limit for the lithium-ion BSS is assumed to be 20 %, which conserves a long lifetime of the battery [19]. The presented parameterization of the BSS control is aimed for overvoltage problems in high distributed generation scenarios.

It should be taken into account that the stability of the BSS control is not investigated in this paper, since steady state simulation and static modelling of the BSS is assumed to be sufficient for the aim of the study. An analysis of the dynamic stability and detailed parameterization of the BSS control can be associated in a further publication.

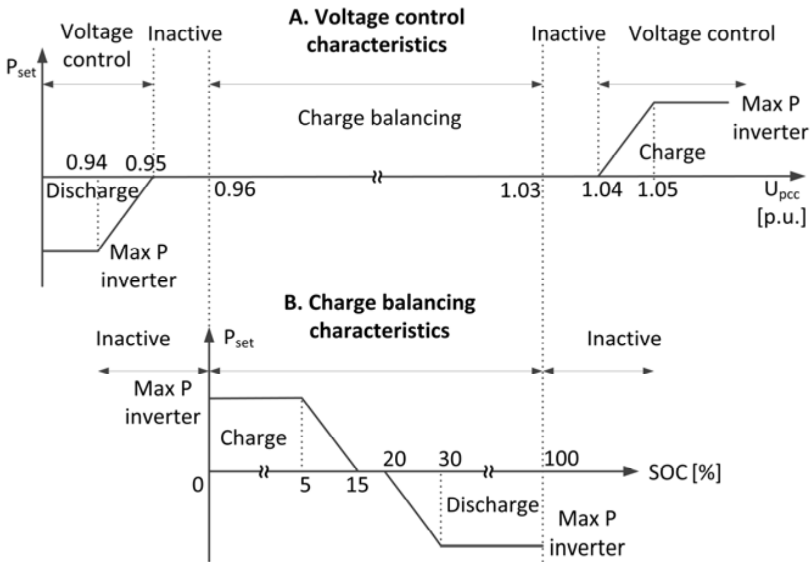

Fig. 6. Characteristics of the BSS control (lithium-ion)

For the dimensioning of the BSS inverter, the network is parameterized to the worst-case (defined in Section 2.4.1), while the BSS is in charge mode. The BSS power is increased iteratively from zero until the voltage violation at the PCC is solved.

For the sizing of the BSS capacity, a yearly simulation is performed, assuming a maximal possible capacity of 10 MWh. The maximum state of charge in the simulation is determined as $SOC_{max,10MWh}$. The usable capacity (C_{usable}) is determined as depicted in Equation (1). The total required capacity in MWh (C_{BSS}), with reserving capacity for the minimum limit of SOC is determined as depicted in Equation (2).

$$C_{usable} = \left(SOC_{max,10\,\mathrm{MWh}} - SOC_{min}\right) \times 10\ \mathrm{MWh} \quad (1)$$

$$C_{BSS} \approx C_{usable} \times (1 + SOC_{min}) \quad (2)$$

For the estimation of operation costs, the simulations are performed again with the determined BSS capacity. The self discharge of the BSS is not considered in this study.

2.4.3. Installation of BSS: lead-acid

Another considered alternative for the BSS is the lead-acid battery. Here the same concepts of Section 2.4.2 are implemented with different prices and cost-specific parameters. An important parameter for the sizing of the BSS is the typical state of charge window, which is assumed to be 50 % (i.e., SOC_{min}=50 %), while for the lithium-ion it is assumed to be 80 % (i.e., SOC_{min}=20 %) [19].

2.4.4. Power curtailment

This alternative represents the curtailment of feed-in of the DG at the PCC by its inverter as illustrated in Fig. 7. This strategy is assumed to analyze whether storing high feed-in powers by BSS is more viable than reimbursing them by DNOs. Therefore, the maximal curtailment is assumed to be equal to the nominal inverter power of BSS determined for the same case study.

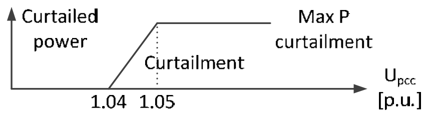

Fig. 7. Power curtailment of the DG at the PCC

2.5. Cost assumptions

Table 2. Assumed prices and cost-specific parameters

Cost components	Max			Min			Unit
Battery inverter	Year 0	Year 10	Year 20	Year 0	Year 10	Year 20	
	180	145	110	140	105	70	EUR/kW
Lifetime	10						years
Battery losses	0.24						EUR/kWh
Lithium-ion battery	Year 0	Year 15		Year 0	Year 15		
	750	450		400	250		EUR/kWh
Lifetime	15						years
Efficiency	90						%
Annual maintenance	2						% from investment
Typical SOC window	80						%
Housing and land usage	400.000			200.000			EUR/ MWh
Lead-acid battery	Year 0	Year 10	Year 20	Year 0	Year 10	Year 20	EUR/kWh

	220	180	140	180	140	100	
Lifetime	10						years
Efficiency	80						%
Annual maintenance	2						% from investment
Typical SOC window	50						%
Housing and land usage	400.000			200.000			EUR/ MWh
Cable: NA2XS2Y 240	Urban area			Rural area			EUR/km
	140,000			80,000			
Lifetime	30						years
Network losses	0.05						EUR/kWh
Q flow in HV grid	0.009						EUR/kvarh
Curtailment	0.15			0.1			EUR/kWh
Interest rate	9						%

The economic evaluation is based on discounted average yearly costs of each strategy for voltage compliance from the perspective of DNOs. Therefore, the costs are calculated as net present values and divided by the lifetime of the project which is assumed to be 30 years. The estimations of costs are based on cost-specific parameters and prices illustrated in Table 2. Most cost assumptions are assumed as in [3].

Maximal and minimal values for several prices are assumed to reflect the possible variations of costs. The CAPEX considered in the cost estimations are additional cables, the inverter and the battery bank of the BSS. The OPEX considered are network losses, the maintenance and housing costs of the BSS, losses of input/output power of BSS, reimbursement of curtailed power and the cost of the reactive power flow from the HV grid. For the consideration of the network losses and reactive power flow from the HV grid, the difference between the simulation results for certain strategy and the results for the case of no measures for voltage compliance are considered. It should be taken into consideration that the price of reactive power flow from the HV grid can vary according the agreement between the MV and HV DNOs.

3. Results

The required investments, the simulation results for one exemplary day as well as the cost results are presented hereinafter.

3.1. Required investments

By applying the assumed principles for determining the required grid reinforcement as well as the sizing of the BSS, the results in relation to investment costs are presented in Table 3.

Table 3. The required length of cables and size of BSS for the strategies of voltage compliance

Strategy	Case study	Battery [MWh]	Inverter [MW]	Cable [km]
Grid reinforcement	PV	0	0	25.82
	Wind	0	0	25.82
cosφ & grid reinforcement	PV	0	0	18.42
	Wind	0	0	18.42
BSS lithium-ion	PV	3.5	2	0
	Wind	5	2	0
cosφ & BSS lithium-ion	PV	0.5	0.9	0
	Wind	0.2	0.9	0
BSS lead-acid	PV	5.5	2	0
	Wind	8	2	0
cosφ & BSS lead-acid	PV	0.8	0.9	0
	Wind	0.3	0.9	0
Curtailment with / without cosφ	PV	0	0	0
	Wind	0	0	0

The results show that only grid reinforcement requires long lines (25.82 km) for solving the voltage problems for both PV and wind case studies. However, Q-provision by the large DG can reduce the required length of lines (18.42 km). Here, the results for both PV and wind case studies are equal, since the worst-case analysis considers the maximum feed-in of all DGs (Section 2.4.1). Similarly, the results of the inverter sizing for lithium-ion and lead-acid BSS are equal, considering the worst-case analysis. Yet, the capacity of BSS can vary with different battery types (e.g., 5 MWh for lithium-ion and 8 MWh for lead-acid) and different DGs. As the useable capacity is smaller for lead-acid BSS, it requires a higher capacity than lithium-ion BSS. In addition, the wind case study without reactive power provision leads to a higher capacity than the PV case study because of the long-term fluctuation of the wind feed-in (e.g., 3.5 MWh for lithium-ion in PV case study and 5 MWh in wind case study). However, Q-provision by DGs in the MV network leads to essential reduction in the required capacity of the BSS for both case studies, as voltage control is shared among the two control possibilities. For example, the BSS capacity is reduced by 85 % with the Q-provision for lithium-ion in the PV case study compared to the case without Q-provision.

3.2. Simulation results of PV case study

The simulation results of one exemplary summer day for the PV case study (Section 2.2.1) are depicted in Fig. 8. The red line corresponds to the results with only an installed lithium-ion BSS. The blue line corresponds to the results with a lithium-ion BSS with Q-provision by the PV system in the MV level. The violet line corresponds to the results if no measures for voltage compliance are undertaken. The grey line corresponds to the results with only grid reinforcement. The yellow line corresponds to the results with grid reinforcement and Q-provision by the PV system in MV level. The green line corresponds to the upper limit of the voltage tolerance band. The results for the lead-acid BSS are relatively similar to the lithium-ion BSS and power curtailment, thus to avoid overlapping they are not shown in Fig. 8.

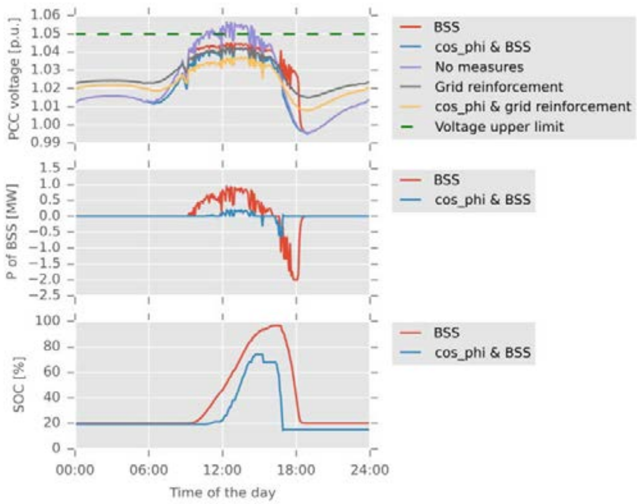

Fig. 8. Simulation results of one exemplary day in summer for the PV case study

The results show that all defined strategies are sufficient for voltage compliance in the network. The BSS charges during the day when the voltage increases, while discharging starts in the evening to balance the SOC. In other words, the operation of the BSS is based on daily cycles when it is connected to a PV system in the MV network. The SOC with the Q-provision can slightly drop under 20 % in the dead band of (15-20 %), since the BSS capacity in this case is low (i.e., 0.5 MWh). Yet, grid reinforcement with Q-provision leads to lower voltage values compared to other strategies.

3.3. Simulation results of wind case study

The results of a winter day for the wind case study (Section 2.2.2) are shown in Fig. 9. The results show that the voltage fluctuates frequently because of the variations of the wind power and also the overlapping with the accumulated PV power in the LV level. Therefore, the capacity of BSS considerably varies compared to the PV case study, as can be seen in Table 3. In other words, the dimensioning of the BSS is more complicated for the combination of PV and wind feed-in compared to the case of mainly PV feed-in, since no daily energy cycles for the BSS can be observed.

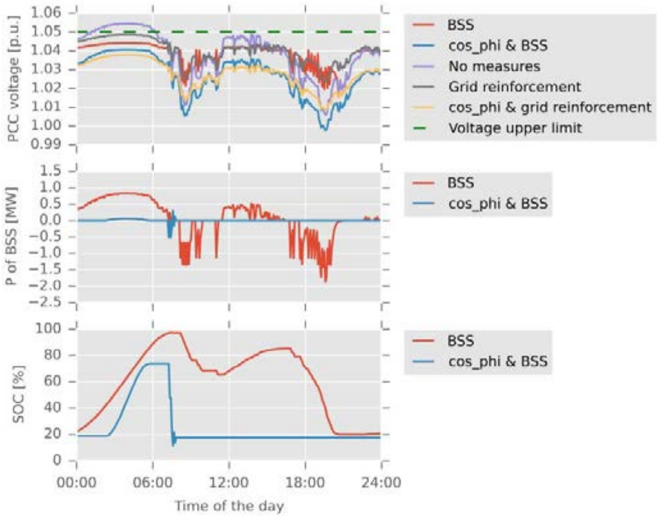

Fig. 9. Simulation results of one exemplary day in winter for the wind case study

3.4. Cost results of PV case study

The net present values of the different strategies for the PV case study (Section 2.2.1) are depicted in Fig. 10. The results show that the power curtailment is obviously more economic viable compared to grid reinforcement and BSS, since the curtailed energy along the year is relatively low (i.e., 6.8 - 0.4 % from total PV feed-in). In other words, storing the power during high feed-in times in the BSS is less viable compared to curtailing this power. The comparison between only BSS and grid reinforcement shows that the min. costs for grid reinforcement is slightly lower than the min. costs for both BSS alternatives. As a result, the grid reinforcement in rural areas is more viable than both BSS alternatives. However, the BSS can be competitive with grid reinforcement in urban areas, where additional lines are relatively expensive. The comparison between grid reinforcement and BSS strategy, in case the PV provides Q, shows that the BSS of both alternatives is competitive with grid reinforcement. The reason for this competitiveness is that the capacity required for the BSS is low, since voltage control is shared among both BSS and Q-provision control possibilities. Furthermore, the costs of both BSS alternatives are relatively similar, since the higher usable capacity and lifetime of lithium-ion compared to lead-acid compensates for it higher price.

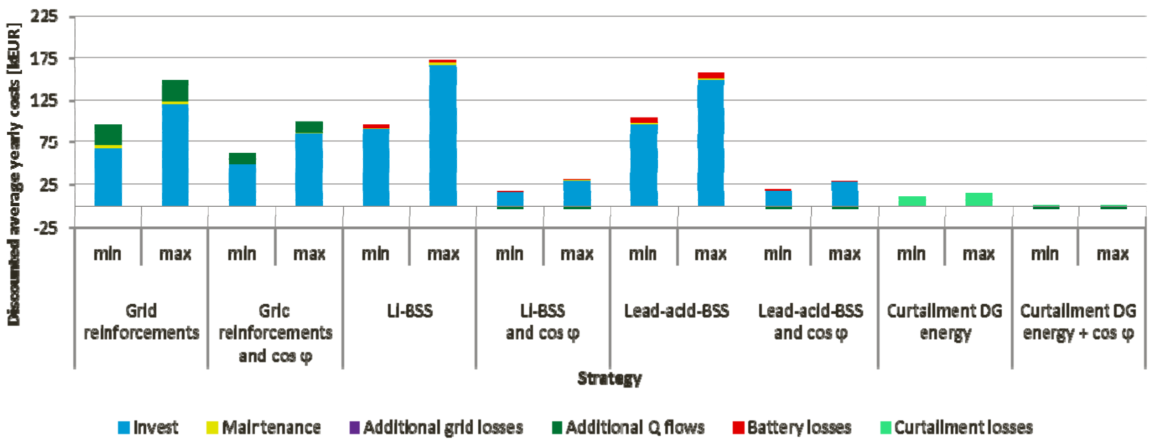

Fig. 10. Net present value for different strategies for the PV case study

In addition, the costs of additional Q flows in HV grid are lower for the BSS solutions and power curtailment compared to grid reinforcement, because adding new lines increases the capacitive currents in the network. The cost of BSS losses is relatively low compared to other costs, since the duration of charge/discharge of the BSS is short, and the BSS operates longer time in idle mode. The effect of strategies on the grid losses does not play an important role in the cost comparison.

3.5. Cost results of wind case study

The net present values for the different strategies for the wind case study (Section 2.2.2) are depicted in Fig. 11. The results show that the power curtailment strategy is more cost-efficient than grid reinforcement and BSS. In the wind case study, the total energy curtailed in the wind case study is lower than the PV case. The comparison between only grid reinforcement and BSS strategy shows that min. costs for grid reinforcement strategy is lower than BSS of both alternatives, while max. costs for BSS is obviously higher than grid reinforcement. As a result, the grid reinforcement is relatively more cost-efficient than BSS for the wind case, since higher BSS capacity is required compared to the PV case as discussed in Section 3.3. The BSS can be competitive only compared to lines for high cost case and considering the min. costs of BSS. In case the wind system provides Q, the costs for BSS strategy drops obviously, so that it becomes more viable than grid reinforcement. The effect of strategies on grid losses, BSS losses and Q flow in the HV does not play a decisive role in the cost comparison.

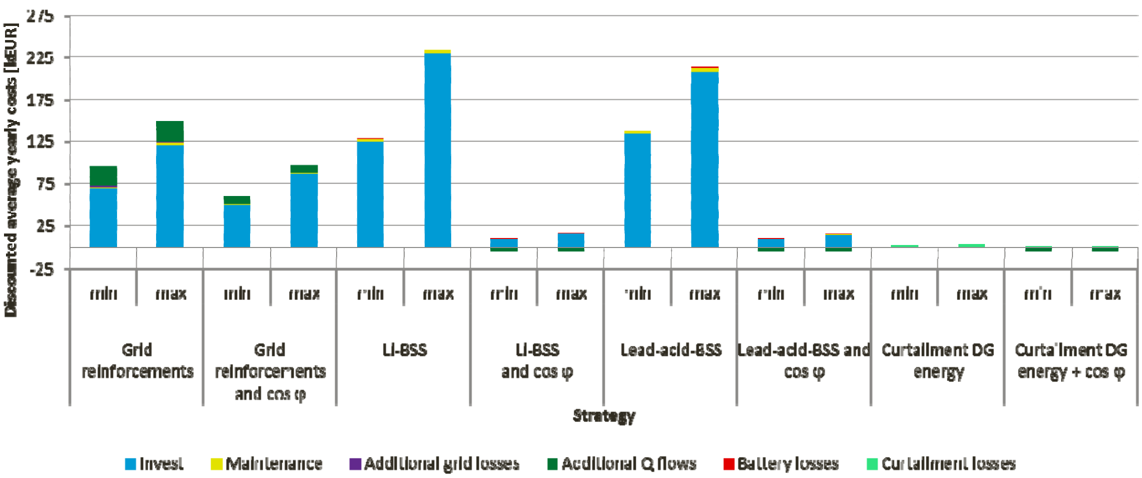

Fig. 11. Net present value for different strategies for the wind case study

4. Discussion

4.1. Costs per MWp

Since the considered reinforcement measures are lines between certain grid nodes, the required length of lines can only vary in discrete steps. Therefore, a reinforced network with certain lines might have an additional hosting capacity compared to a network with BSS, which has exactly the hosting capacity of the simulated scenario. For example, the network in the PV case for the strategy of grid reinforcement and Q-provision can host more 0.5 MWp for the PV system at PCC, considering the worst-case analysis. For only grid reinforcement strategy, the network can host more 0.3 MWp. The costs of Fig. 10 for the BSS and reinforcement strategies are divided by max. PV size at PCC and illustrated in Fig. 12. The results show that the BSS is competitive to replace grid reinforcement in case of Q-provision, while without Q-provision, the BSS can be competitive to replace reinforcement for the high cost case.

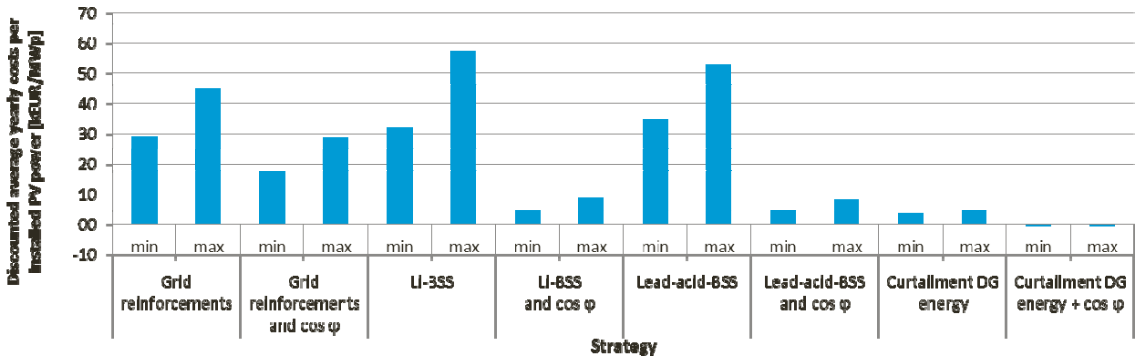

Fig. 12. Net present value for different strategies per MWp of the PV case study

4.2. Potential for multi-functions

The simulation results show that the charging/discharging of the BSS for voltage compliance over the simulated year is not continuous. The BSS operation is only necessary to prevent the voltage violations, which usually occur during high feed-in hours. The SOC for the strategy of only lithium-ion BSS over the simulated year is depicted in Fig. 13.

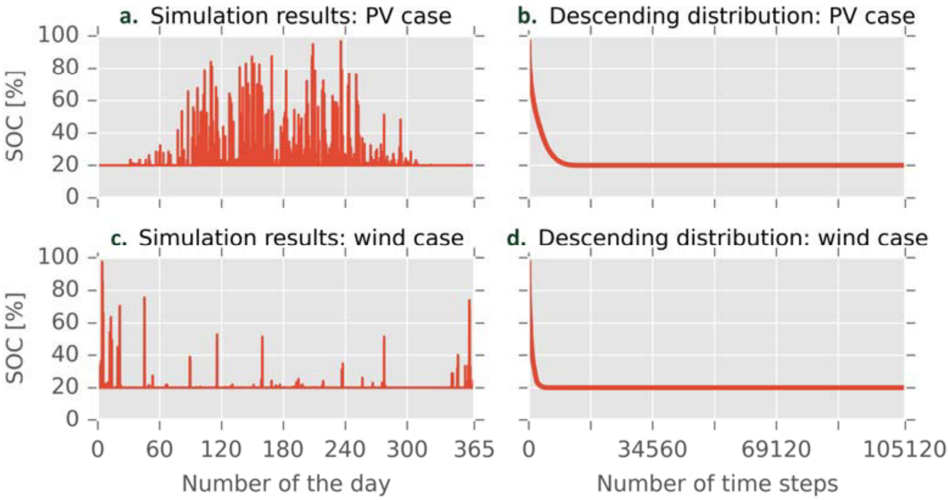

Fig. 13. State of charge of the lithium-ion BSS along the simulated year. Diagaram (a) and (c) represent direct depiction of simulated time series, while diagram (b) and (d) represent the depiction of the SOC values in desecending order

The simulation results of the lithium-ion BSS in the PV case study show that the BSS operates on 232 days, while during the rest of the year the battery is in idle mode. Furthermore, for the wind case study, the BSS only operates on 86 days. The descending distribution of SOC values further illustrates the high probability of idle operation of BSS. As a result, the BSS can be utilized for other services to increase its economic viability, when it is not needed for voltage compliance. Possible applications are the participation in energy markets or providing frequency control. However, this would require a suitable forecast of voltage violations to avoid a conflict of interest with the voltage control.

5. Conclusion and outlook

The paper at hand investigates the utilization of grid-supporting BSS in MV networks to serve mainly for voltage compliance. A control approach for the BSS is presented, aiming for reducing the size of the BSS. The BSS are then analyzed economically compared to grid reinforcement and power curtailment. The results for the assumed case studies show that the power curtailment, especially with Q-provision is more economical than the BSS and grid reinforcement strategy. However, a BSS in combination with local reactive power provision proves to be more cost competitive in the presented case studies than grid reinforcements. Moreover, by considering the reduction tendency of battery prices, the industrial advancement to increase the lifetime and the ability to provide other services, the grid-supporting BSS should be considered in cost comparisons as an alternative to defer grid reinforcement measures.

For future studies, the grid-supporting BSS should be analyzed with more networks and feed-in scenarios compared to further voltage control alternatives. In addition, a margin of extra capacity for the BSS sizing should be investigated, in order to increase its reliability for voltage compliance. Moreover, dynamic stability of the BSS control should be investigated. Also, there should be further investigations of technical and economic potential for providing more services by the BSS.

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