Evaluation of Energy-Storage for Reducing Grid Reinforcement in High Voltage Grids

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***Abstract*—This paper presents a new method for storage-dimensioning for the reduction of line loadings in high voltage distribution grids. Therefore, a probabilistic load flow analysis is executed based on a linearized load flow calculation using distribution factors. Several storage options are tested in a model for a 110 kV high voltage grid with the forecast of load and generation conditions for the year 2030. This study looks at different storage options. Each of them is based on only one storage at one specific node of the grid. The storage schedules are calculated based on the distribution factors with regard of the line loadings in the grid. The results show that one storage system is not sufficient for reducing line loadings on all lines caused by the power flow situation and the meshed structure of the grid.**

***Keywords*—storage; high voltage grid; grid reinforcement; probabilistic load flow; Monte Carlo method; linearized load flow calculation**

I. INTRODUCTION

The installed power of renewable energy sources (RES) is increasing because of the change of the structure for the electricity supply in Germany [1]. The most wind energy plants and solar plants are installed in the distribution grid. Their feed-in power is volatile so that the power supply depends on seasons and weather conditions at the installation sites [1]. The conventional grid was designed for load flows from higher voltage levels with large power generation units, as e.g. nuclear power plants, to the lower voltage levels with the demand for electricity. By using many RES units, the direction of the load flows inverts from lower voltage levels to high voltage levels [1]. This can lead to overloaded lines in the grid [1]. A reinforcement of the distribution grid is necessary. According to the scenario “NEP B 2012” in [1], alone in high voltage grids (HVG, usually 110 kV), there must be a reinforcement for over 24,000 km of already existent lines in Germany until 2030. Additionally, over 11,000 km of new lines must be built in the HVG [1]. The planned actions for the HVG are discussed controversial by the citizens. Consequently, new alternative concepts are searched to reduce the reinforcement of the grid. One concept is the use of energy storages so that the storages would operate in times when the lines are overloaded [1], [2].

Within this paper, several studies are analyzed that deal with the use of storages to reduce the reinforcement of the electricity grid. According to [2], storages used in the HVG are not economical in comparison to the reinforcement. It would be more economical to use a reinforcement in combination with e.g. a feed-in management for the RES. This statement is based on a study for medium voltage grids. In [1], it is just said that storages in HVG could be able to reduce grid reinforcement in the amount of 21 % less investment costs until 2030 in comparison to the conventional reinforcement of the NEP B 2012. But the costs for the storage systems are not considered, so that there is no detailed study that deal with storages for HVG. Furthermore, a time series based analysis is needed for an exact dimensioning for that kind of storages [2]. The look at extreme load conditions is not enough for a good assessment of the technical and economical utility of storages [2].

In this paper, methods for dimensioning storage systems preventing line overloading in HVG are shown. Therefore, probabilistic time series based loads for the year 2030 and a linearized method for load flow calculations are used. The necessary scales of the maximum power supply and the energy capacity for a storage are investigated independently of special storage technologies. The methods for dimensioning are tested in a model for a 110 kV HVG. In addition, the influence of the storage on the line loadings are analyzed.

II. METHODS FOR LOAD FLOW CALCULATION

A. *Probabilistic load flow analysis*

In traditional grid expansion planning, usually a deterministic method is used [3]. This normally uses two estimated worst-case conditions – one for a maximum consumption and a minimum generation and one for a maximum generation and a minimum consumption [4]. The probability of occurrence of these conditions is determined to 100 % [5]. To prevent a miscalculation of the worst-case conditions because of a volatile power supply of RES, a probabilistic load flow calculation (PLF) can be used instead [4]. Furthermore, the two chosen worst-case conditions must not be the conditions with that the lines of a grid have their highest loadings [4]. A PLF uses many possible conditions for the loads and the generation values that are analyzed separately [4]. The PLF is already used by the hybrid-planning for the reinforcement of electrical grids [4]. It prevents an oversized or an undersized dimensioning of lines [4].

For this paper, a yearly load flow calculation is used instead of a PLF. A Monte Carlo simulation is executed with the predicted values for the whole year of 2030. The load data have a resolution of 15 minutes. This resolution is enough because short time line overloads are normally not critical [4]. A static load flow calculation is executed for every time step.

B. Linearized load flow calculation

A yearly load flow calculation with many different operating conditions is a very time-consuming process caused by an iterative calculation method with non-linear equations, like e.g. the Newton-Raphson method. As described in [6], the load flows can be calculated linear depending on the loads at the nodes of the grid by using distribution factors. In this paper, these factors are called “alternating current distribution factors” (ACDF). The power flow on the lines is calculated according to (1). $\boldsymbol{P}_{\text{lines}}$ is the searched vector containing the active power of the load flows for all lines and for one operating condition. $\boldsymbol{P}_{\text{nodes}}$ is the vector with the active power of the load data for this condition $\boldsymbol{ACDF}_{\text{P}}$ is the ACDF-matrix for active power. Each distribution factor represents the relative influence of a certain nodal load on the load flow of a certain line [6].

$$\boldsymbol{P}_{\text{lines}} = \boldsymbol{ACDF}_{\text{P}} \cdot \boldsymbol{P}_{\text{nodes}} \tag{1}$$

Deduced from (1), the linearized line flow calculation is based on the superposition theorem [6]. The active power load $P_{\text{line h}}$ over a line h is the sum of the multiplication of every distribution factor $[\boldsymbol{ACDF}_{\text{P}}]_{\text{h k}}$ which deals with this line with the related nodal load values $P_{\text{node k}}$. This is shown in (2).

$$P_{\text{line h}} = \sum_{\text{k=1}}^{\text{n}} [\boldsymbol{ACDF}_{\text{P}}]_{\text{h k}} \cdot P_{\text{node k}} \tag{2}$$

According to [6], the calculation model can also be used for reactive power so that an ACDF-matrix is obtained for the reactive power. In this paper, both ACDF-matrices are calculated only one time for the considered grid and are used for every operating condition. A performed comparison between the linearized and iterative methods for load flow calculation showed that the differences are negligible. For this reason, the linearized method is used for the calculation of the load flows and line loadings. Furthermore, the linearization allows an inversed calculation. On the basis of this property, the searched power of the storage can be found to regulate the line loadings.

III. DIMENSIONING A STORAGE UNLOADING LINES

A. Calculating the storage power

First, a linearized load flow calculation is used for every time step of the year to get the active power flows and the reactive power flows of every line. It is supposed that the loading Λ of a line mostly depends on the active power flows. For the times when the line is overloaded (Λ > 100 %), the wanted active power load flow can be found with (3). It is supposed that the voltage level is constant on the whole length of the line. The wanted load flow $P_{\text{100 \%, line, d, t}}$ for the day d and time step t in combination with the actual reactive load flow $Q_{\text{line, d, t}}$ would result in the nominal apparent power flow of the line $S_{\text{nom, line}}$. This nominal apparent power flow approximately represents a loading Λ of 100 %.

$$P_{\text{100 \%, line, d, t}} = \pm\sqrt{{S_{\text{nom, line}}}^2 - {Q_{\text{line, d, t}}}^2} \tag{3}$$

In this paper, only one storage system is investigated at one specific node of the grid. Equation (4) calculates the power of the storage $P_{\text{storage, d, t}}$ which leads to the wanted active power flow $P_{\text{100 \%, line, d, t}}$. Therefore, the actual active power flow $P_{\text{line, d, t}}$ and the specific ACDF for the line and the storage node $[\boldsymbol{ACDF}_{\text{P}}]_{\text{line, storage node}}$ are used:

$$P_{\text{storage, d, t}} = \frac{P_{\text{100 \%, line, d, t}} - P_{\text{line, d, t}}}{[\boldsymbol{ACDF}_{\text{P}}]_{\text{line, storage node}}} \tag{4}$$

B. Implementation and methods for storage-dimensioning

The used model for this paper contains several functions to dimension the storage in the considered HVG. Different “storage-options could be chosen in the algorithm. Every storage option has a nodal where the storage is installed and a certain reference line is assigned. The reference line shall be unloaded by the storage primarily.

A special method for storage-dimensioning (MSD) must be chosen for every storage option. With the first method (MSD 1), the storage only supplies power in times when the chosen reference line is overloaded. The storage only tries to unload this reference line. The calculation of the storage power with MSD 1 is independent of times when other lines in the considered grid are overloaded. The application of the second method (MSD 2) tries unload all other lines. However, the reference line shall not be loaded more than before in this case. For that, the algorithm tests the directions of the power flows. In times unloading another line than the reference line, the sign of the storage power must have the same sign as in the case, in which the storage would unload the reference line. If it is not the same sign, the storage power to unload the other line would not be considered. The sign of the storage power depends on the signs of the load flows and on the ACDF for the storage node and the viewed line. If different lines are overloaded at the same time, the MSD 2 leads to a selection of the highest storage power according to amount to reduce the loading on one line.

After choosing a storage option and an associated MSD, the algorithm first calculates the storage power for each time value with the described method. Furthermore, the necessary energy capacity of the storage can be found. An energy value $\Delta E_{\text{storage, d, t}}$ for the day d and the time step t is calculated for every time as shown in (5).

$$\Delta E_{\text{storage, d, t}} = P_{\text{storage, d, t}} \cdot \Delta \text{t} \tag{5}$$

The capacity of the storage is equal to the maximum daily total energy $\Delta E_{\text{storage, daily total, d}}$ as shown in (6).

$$\Delta E_{\text{storage, daily total, d}} = \sum_{t=1}^{96} \Delta E_{\text{storage, d, t}} \qquad (6)$$

A further function of the model calculates the needed storage power for times when the lines are not overloaded. For that, the energy of the storage is balanced. The purpose is the locating of the state of charge (SOC) of the storage between the limits 0 % and 100 %. The algorithm calculates the variation of the SOC for every time value and the daily total variation. Because of these future expected variations, it is possible to fix a wanted SOC. This SOC must be reached before the storage works again to unload lines. Like with the MSD 2, the reference line cannot be overloaded again because of this extra working period of the storage.

Finally, the algorithm executes a linearized load flow calculation with the new time series for the storage load. The new load flow condition can be analyzed. Fig. 1 shows again the main functions of the described algorithm.

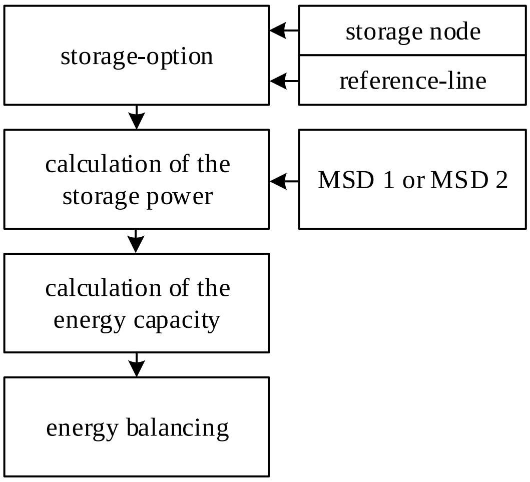

Figure 1. Flow diagram for the algorithm for the storage-dimensioning

IV. RESEARCHED 110 KV GRID

For this research, an already completed grid model from [6] was used to test the MSD. The grid contains 137 lines and 153 different loads. These loads can be consumers or generators. There are time series for the year 2030 with a time resolution of 15 minutes. The time series were generated with the method in [7]. The load profiles of the energy consumption are based on measurements. The generator power is based on weather data and forecasts for the developing of RES [7].

The storage is dimensioned in a subnet of the whole grid. It contains six lines and four nodes, but one of them is the slack bus. In result, there are three nodes where the storage can be installed. Only the six lines of the subnet are tried to unload by the storage. In Fig. 2, the subnet is shown. Additionally, the arising maximum load flows without a storage are represented with their directions. The red arrows show the power flow direction in case of an overloading of the lines. The values of the maximum active power flows and the maximum loadings Λ are presented in Tab. 1. Four of the six lines are overloaded with a line loading above 100%.

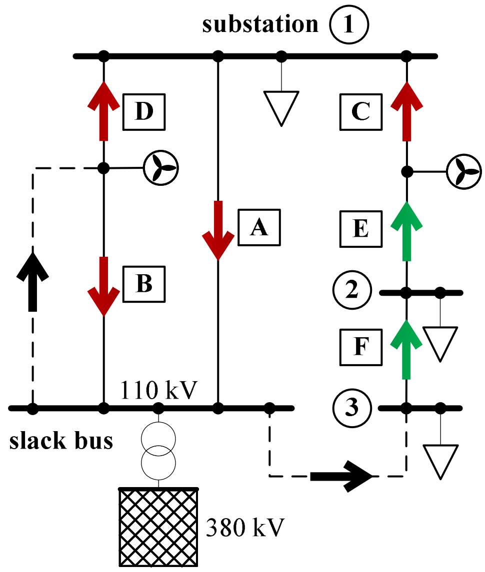

Figure 2. Schema for the considered grid with maximum load flows. (red: overloaded; green: not overloaded; black: not analyzed)

Table 1. Maximum load flows without a storage operation

Lines	Maximum load flows without storage	
	Maximum loading Λ	***Maximum active load flow P***
A	253.44 %	302.88 MW
B	225.81 %	260.30 MW
C	121.01 %	143.80 MW
D	118.92 %	105.56 MW
E	95.57 %	113.33 MW
F	49.02 %	58.01 MW

V. RESULTS FOR THE STORAGE-DIMENSIONING

A. *Evaluation of best storage options*

It is intended to determine the best storage option after dimensioning of all possible options. For that, the storage options are firstly sorted by the maximum number of lines that are unloaded. Secondly, they are sorted by the smallest maximum storage power that is needed to unload these lines. The best storage option for MSD 1 includes an installed storage at the substation “2” and it has the reference line “C” as defined in Fig. 3. The best option for the MSD 2 is the storage option that has a storage installed at the substation “1”. The reference line is the line “C” too. In Fig. 3 the number of the furthermore overloaded lines is shown, using these best storage options for MSD 1 and MSD 2 in comparison with the case without a storage. The needed maximum storage power is furthermore presented. These values are shown in Tab. 2 with the needed energy capacity in addition. The best storage option for MSD 1 can unload only one line and it needs a maximum power of 42.06 MW. The best option for MSD 2 can unload two lines. For that, it needs a maximum power of 276.39 MW.

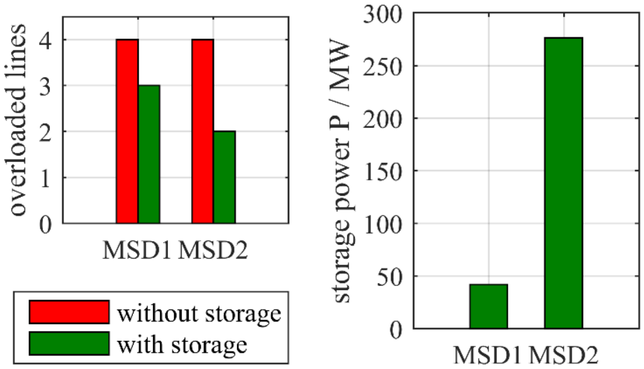

Figure 3. Bar charts of the number of overloaded lines with/without storage and maximum storage power of the best storage options for MSD 1 and for MSD 2

Table 2. Characteristics of the best storage options for MSD 1 and for MSD 2

Storage options	**Best storage options for MSD 1 and MSD 2**		
	Overloaded lines	***Maximum storage power P***	***Energy capacity E***
MSD 1	3	42.06 MW	98.78 MWh
MSD 2	2	276.39 MW	649.04 MWh

Furthermore, only the best storage option for MSD 2 is analyzed because the most lines are unloaded by using it.

B. Analysis of the operation of the best storage option for the MSD 2

Fig. 4 shows the typical schedule of the storage operation unloading a line. In this case, the day with the highest loading Λ of the reference line "C" is chosen. The storage feeds-in power into the grid (negative sign) when the loading of line "C" is over 100 %. The storage power is always as high as the line "C" needs to unload to a loading of 100 %. Additionally, the not-overloaded line "D" is also unloaded by the storage.

Fig. 5 shows a probabilistic load flow analysis. The loadings of all six lines for the year 2030 are presented. Each left box shows the loading without a storage and the right bar shows the loading with the storage of the best storage option for MSD 2. The previously overloaded lines "C" and "D" are unloaded to 100 % by the storage while the lines "A" and "B" have a higher line loading compared with the results without storage system. The loading of the lines "E" and "F" are still under 100 %. In most of the time of the year, all viewed lines are not overloaded. This is shown by the 75-% percentile which is under 50 % for every line. Tab. 3 shows the certain values of the maximum load flows and maximum loadings.

The influence of the storage operation on the occurrence of different loadings Λ of line "C" is shown in Fig. 6. The probabilities of occurrence for the times of the day is presented. In the case without using a storage, the loading is over 100 % at midday. By using the best storage option for MSD 2, the overloading power flow is cut off. The highest probability of occurrence at each daytime (yellow) is always under about 25 % of the line loading Λ.

The influence of the storage operation on the occurrence of different loadings Λ of line "A" is shown in Fig. 7. Line "A" is already overloaded with a maximum loading Λ around 250 % without using a storage. By using the best storage option for MSD 2, the line loading at midday increases to 388 %.

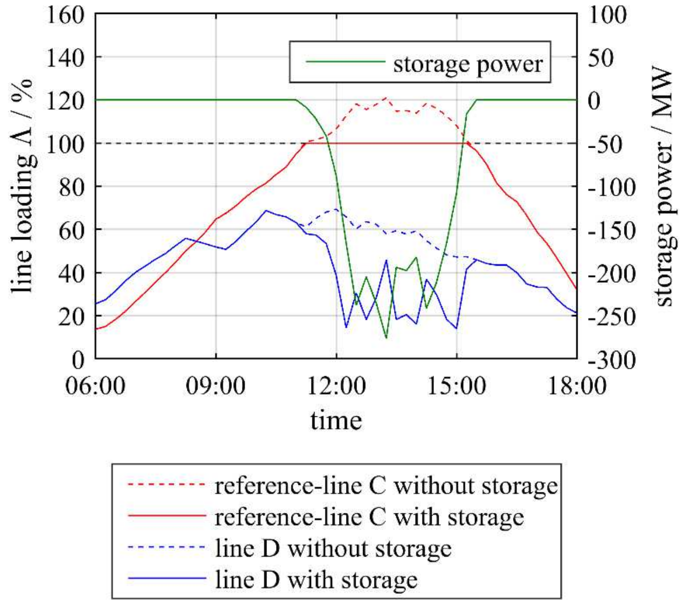

Figure 4. Schedule of the storage power according to the best storage option for MSD 2 and loadings of the lines "C" and "D" with/without storage operation at a typical day

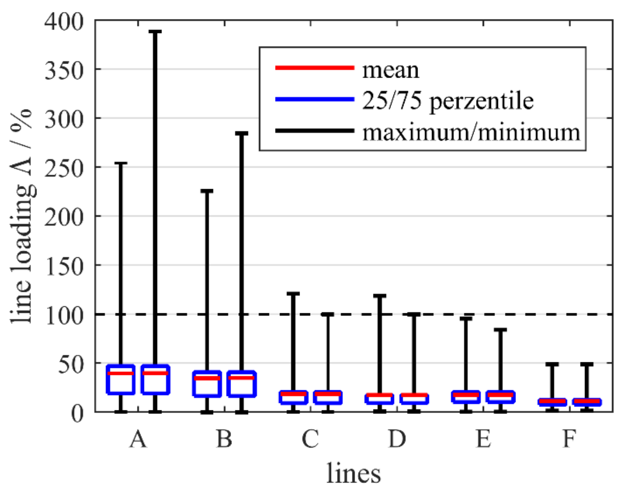

Figure 5. Boxplot with the line loadings for each considered line without (left) and with storage operation according to the best storage option for MSD 2 (right)

Table 3. Line Loadings and active power flow with storage operation according to the best storage option for MSD 2 in comparison to the case without a storage

Lines	Line Loadings with the best storage option for MSD 2	
	Maximum loading Λ	***Absolute variation of the maximum loading Λ***
A	388.50 %	+ 135.06 %
B	284.49 %	+ 58.68 %
C	100.00 %	– 21.01 %
D	100.00 %	– 18.92 %
E	84.25 %	– 11.32 %
F	49.02 %	+ 0.00 %

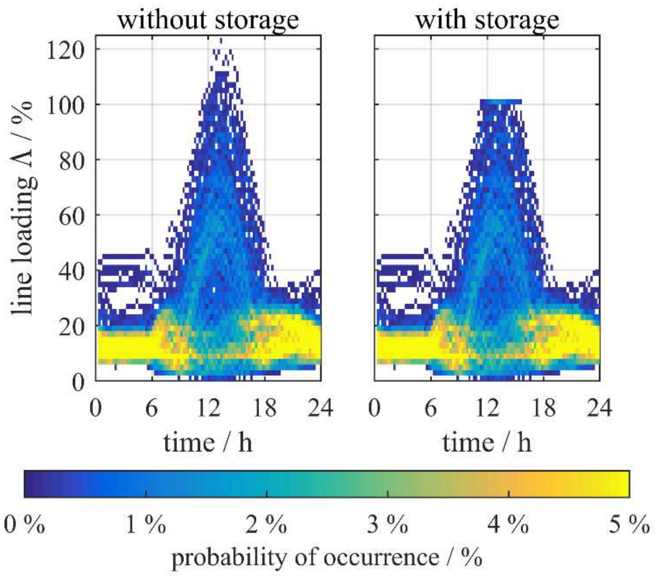

Figure 6. Pobability of occurrence of the loadings of line "C" with/without storage operation according to the best storage option for MSD 2

C. Storage operation with energy balancing

As already described in chapter 2, the algorithm leads to the balancing of the stored energy so that the SOC always lies between 0 % and 100 %. In Fig. 8, the line loading by using the energy balancing for the same day as in Fig. 4 is shown. After the storage operation to unload the line "C", the storage power inverts to recharge the storage. In result, the line "D" is overloaded. That means that the energy balance can lead to an overloading of other lines because in this case, the model just tries to prevent overloads of the reference line "C".

Fig. 9 shows the behavior of the SOC in the case of using the best storage option for MSD 2 with the energy balancing for the same day as presented in Fig. 8. The storage is uncharged in order to allow the unloading of the reference line. Afterwards, it is recharged again to a SOC of 100 % to be ready for the next unloading process.

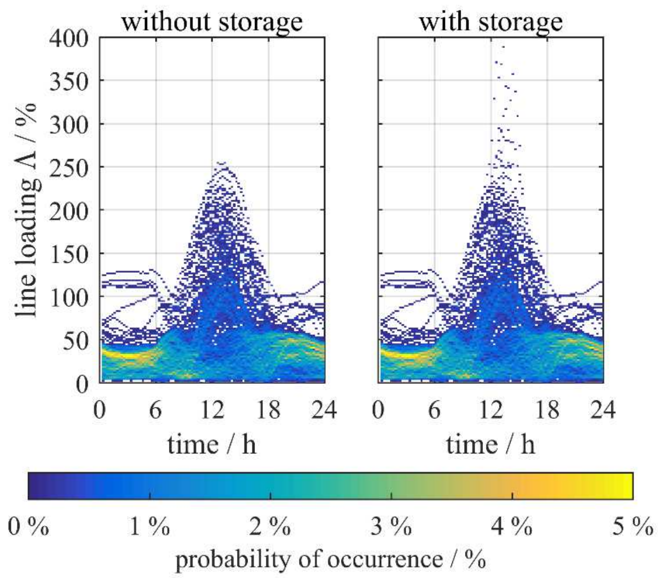

Figure 7. Pobability of occurrence of the loadings of line "A" with/without storage operation of the best storage option for MSD 2

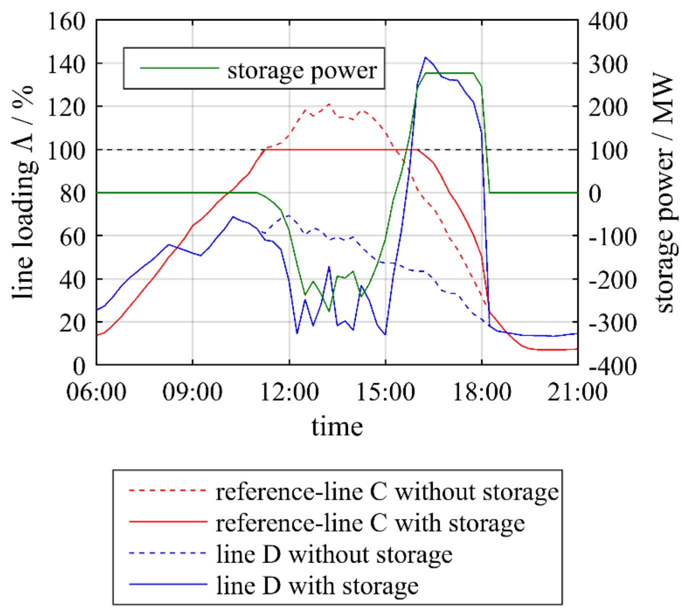

Figure 8. Schedule of the storage power according to the best storage option for MSD 2 and loadings of the lines "C" and "D" with/without storage operation at a typical day with energy balancing

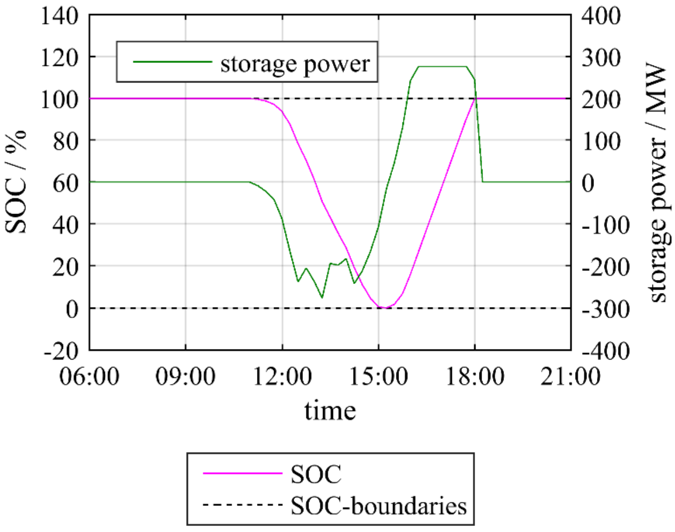

Figure 9. Schedule of the storage power according to the best storage option for MSD 2 and the run of the SOC at a typical day with energy balancing

VI. Conclusion

The installed power of volatile renewable energy sources in Germany is increasing. This leads to a needed reinforcement of the high voltage grid. The use of storages is a thinkable concept to reduce this reinforcement. A model was built that dimensions the power and energy capacity of a storage in a 110 kV grid. For that, a yearly load flow analysis with time series for the year 2030 was used. Moreover, a linearized load flow calculation method using distribution factors was realized. Two different methods for storage-dimensioning and different storage options were tested. In conclusion, the application of a storage only at one node of the grid has some disadvantages. Several lines can be unloaded by the storage, but other lines can be loaded more than without using any storage system. Additionally, the needed storage power is quite high. The economic advantage of those storages in the high voltage grid is doubtful in comparison with the reinforcement of the grid. A tested method to balance the energy of the storage leads to limiting the allowed states of charge. However, lines can be overloaded again by using the energy balancing. Here, a further research is necessary for the improvement of the power scheduling of the storage system. Moreover, the case of using more than one storage system at different nodes should be investigated in further studies.

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