Operation of Battery Storage as a Temporary Equipment During Grid Reinforcement Caused by Electric Vehicles

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Abstract: Electric vehicle charging stresses distribution grids significantly with high penetrations of electric vehicles. This will lead to grid reinforcement works in several distribution grids. Battery storage is a possible solution to bypass times of grid reinforcement due to electric vehicle charging. In this paper, different operation strategies for such a battery storage are tested at first in simulations. The main difference between the strategies is the necessary input data. Following the simulations, selected strategies are tested in reality in the project "Netzlabor E-Mobility-Allee". It is proved that battery storage is a functioning possibility to bypass times of grid reinforcement.

1. Introduction

The European Union wants to lower its greenhouse gas emission by 80 % until 2050 in comparison to 1990. The transition from fuel-based to electric mobility is one important aspect in achieving these goals [1].

Experts do not expect that the integration of electric vehicles (EV) and their charging infrastructure will cause extensive grid expansion in all voltage levels. EV will be connected to the low voltage grid, so that local accumulations of EV are probable there. Problems will initially arise at these accumulations, but their local occurrence is difficult to predict. Grid extension will be necessary to maintain grid stability, when major parts of the households have an EV in Germany. This is a result of an extensive study for different types of low voltage grids in Germany that was presented in [2]. In [3], a review is given of additional research activities in Germany that show similar results.

Owners of EV want to charge their vehicles as soon as possible after the purchase at home. This can be possible only with reduced charging power, if the installation of the charging infrastructure for the new EV requires grid expansion. Grid extension in a low voltage grid normally takes about 3–6 months in Germany, due to planning and necessary permissions. The main task of a distribution grid operator is to provide sufficient energy to all residents in his supply area all the time. Using battery storage, a distribution grid operator will be able to connect new charging infrastructure for EV immediately without having to influence the behaviour of vehicle owners. Therefore, this avoids possible disputes between EV owner and distribution grid operator and the distribution grid operator ensures the fulfilment of his mandate.

Besides battery storage systems, there are several other techniques to decrease the burden of EV charging on low voltage grids. In [4], it is proposed to control the charging process of EV to be able to prevent grid problems. In [5], authors additionally consider using vehicle-to-grid technologies. This means that besides controlling the charging process, also the discharging capability of an EV is used to reduce problems in a low voltage grid. Both ideas have been further developed in several research activities and a review is given in [6]. An advantage of using an external battery system in contrast to these techniques is that the grid operator does not have to influence the charging or discharging behaviour of the EV.

Presently, stationary battery storage systems are mainly connected to low voltage grids in households to increase the self-consumption of households with a solar power system as this is economical beneficial in many countries worldwide. For example, in [7], this is analysed for 400 residential and 26 commercial systems in the Netherlands. Results show that Batteries increase the self-consumption rate depending on the PV size and the battery size. The effect of the battery sizing on the self-consumption for an exemplary house in Sweden is shown in [8]. In [9], it is shown that the self-consumption level in a settlement increases by around 25 % using a battery system. Including an EV in such a system can have a positive influence on the self-consumption [10]. Increasing self-consumption as operation method of a battery system relieves the stress of the low voltage grids partly, as it is beneficial to charge the EV using energy out of the battery systems. Nevertheless, not all households owning an EV have a battery system and the state of charge of the battery system might not always be high enough to charge the EV completely.

In contrast, the battery storage for the application in this paper has only the goal to operate in a grid-friendly manner. To handle high photovoltaic (PV) penetrations, this idea was already proposed often in literature. In [11], a battery storage system is used to prevent overvoltages due to high PV penetration or in [12] a battery is used to flatten the energy demand of a neighbourhood. Also for EV, this was already adapted and presented. Hereby, a distinction has to be made between using the internal battery of an EV or an external battery. In the above mentioned vehicle-to-grid technologies, the internal battery is used. For example in [13], the grid load variance is minimized while in [14] and [15] the peak power is reduced using the internal battery of an EV. As the grid operator cannot influence if EV are at home and hence, if he is able to use vehicle-to-grid-services, this approach is not adequate for the problem in this paper.

Stationary external battery systems are available all the time. In [16], the basic idea of such a storage system was presented. In [17], a storage system was sized for different penetrations of EV to avoid undervoltages. In [18], a battery storage was dimensioned to decrease the peak power of a low voltage feeder under a given limit to avoid overloading.

The topic of this paper is also the use of a stationary battery system to relieve the stress of a low voltage grid in times of EV charging. In contrast to the other publications about this topic, the focus is not on sizing of a battery system. In this paper, innovative operation strategies for such a battery storage are presented that can be easily implemented in existing battery storage systems. The strategies have been developed and tested using simulations. Most research activity mentioned above is based only on simulations. The reason for that is that nowadays the penetration of EV is not high enough to test the developed algorithms in practice. In contrast, the most promising strategies that have been developed in this publication have been used in a field test in the project "Netzlabor E-Mobility-Allee" including ten EV in a low voltage feeder to prove their capability and validate the simulation results.

Only a few field tests in similar size have been performed until now. Existing projects mainly focus on car parks such as in [19] and not on home charging. In [20], 20 EV have been used to test the capability of a low voltage grid to cope with high penetrations of EV using home charging. Actions to decrease the stress is not part of the research.

The publication is structured as follows: In Section 2, the project "Netzlabor E-Mobility-Allee" is presented, where this approach was tested. The valid grid restrictions for this project are described in Section 3. In Section 4 and 5, the regarded low voltage feeder as well as the input data are described.

In Section 7, different operation strategies for the battery storage system are presented. For the testing, at first a simulation framework was used that is described in Section 6. The results of the simulations of the different strategies are presented in Section 8. After testing in the simulation framework, two strategies have been chosen for testing in the demonstration project. Results from measurements are shown in Section 9 and compared to the simulation results. Finally, in Section 10 conclusions are derived and an outlook is given in Section 11.

2. Project "Netzlabor E-Mobility-Allee"

The demonstration project "Netzlabor E-Mobility Allee" started in January 2018 and was finished in October 2019. Ten residents have been equipped with an EV and charging infrastructure since May 2018. The goals are to monitor and analyse the grid state during electric vehicle charging. Additionally, innovative approaches such as battery storage and intelligent charging management are tested. Furthermore, the behaviour of the residents, as well as their acceptance is being investigated. The results will be analysed to develop customer-friendly solutions for the integration of electric vehicles in the Netze BW GmbH distribution grid.

The results of [18] were used to dimension a central battery storage for the demonstration project. Two of the operation strategies that are developed in this paper, have been tested in reality in the project and the results are shown in Section 9.

3. Grid Restrictions

The standard DIN EN 50160/A1:2016-02 [21] defines the valid regulations for grid operation in Germany.

3.1. Voltage Deviation

At the interconnection point to end consumers the maximum voltage deviation allowed is +/-10 % of the nominal voltage. The grid operators split this deviation between the different voltage levels. For the low voltage grid, the maximum voltage drop is set to 5 % of the nominal voltage in this paper.

3.2. Overloading Of Equipment

The grid equipment may not be thermally overloaded. Therefore, we check limits of transformers and lines in our simulations. Additional equipment (e.g., protection devices) is normally coordinated with the thermal limits of lines and transformers so that an additional review of the thermal limits is not necessary.

4. Grid Data

Netze BW GmbH, a distribution system operator in the German state of Baden-Württemberg, provides the grid data. It is one part of a 400 V distribution grid in a suburban area and consists of 21 households. In this low voltage feeder the project "Netzlabor E-Mobility-Allee" takes place. The low voltage grid section is connected via a 630 kVA transformer to the medium voltage grid. The overall low voltage grid, which is connected to the transformer, consists of 15 feeders. In this paper, only one feeder of the low voltage grid is examined. Hence, it is not possible to model the use of the transformer appropriate. As an alternative, the maximum power allowed on this feeder is limited to 60 kVA.

$$S_{\text{Feeder,Max}} = \frac{630 \, kVA}{15 \times 0.7} = 60 \, kVA \tag{1}$$

A factor of 0.7 is used to take simultaneities and overload capacity into account. In Germany, this is common practice in grid planning processes in distribution grids.

In Figure 1, a simplified structure of the regarded low voltage feeder is shown. For the position of the battery storage, four positions (see 1, 2, 3, and 4 in Figure 1) are considered. At Points 2 and 4,

an cable distribution cabinet is installed, so the battery can be connected easily. Point 3 is the middle of the feeder. In Figure 1, the battery is connected to Point 4 as it is done in the project.

In [18], the approach to dimension a central battery storage for this demonstration project is explained in detail. For better understanding, a summary is given here. The energy demand of the low voltage feeder was modelled using measurement data of the regarded feeder without EV charging. Input profiles for the EV charging process have been applied randomly over a horizon of ten years. In simulations, the maximum necessary power (79.8 kW) as well as the maximum energy capacity (74.6 kWh) to maintain compliance with the given grid limits was determined. For the field test, second life batteries of a BMW i3 are used. It was decided to use two batteries, so in total a 66 kWh lithium ion battery system is installed with a maximum charging and discharging power of 60 kVA.
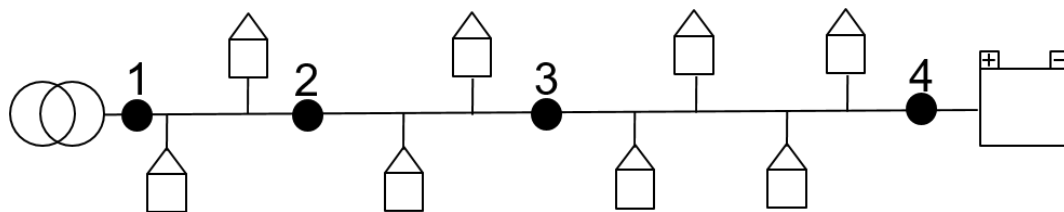

Figure 1. Structure of the low voltage grid.

5. Input Profiles

We are using profiles to take into account that the power flow in a distribution grid is different depending on the time of day. This is necessary to be able to test the operation strategies that will be presented in Section 7. The profiles will be used as input data for the simulation framework in Section 6.

The used input profiles are described more detailed in [18]. To improve understanding, the basic approach is presented here. In the grid, the energy consumption of the households, EV charging processes and the energy consumption of the electric heating devices in the feeder are modelled. A few households also have PV generation, but it is neglected in this paper due to the small amount and difficult predictability. As PV generation lowers the total load, this assumption leads to overestimating of the use of the battery storage. The modelling of the electric heating devices is explained in Section 5.1 in detail.

It is especially difficult to predict the charging of EV and household loads. Therefore, several hundred input profiles have been generated and included randomly in the simulations. The charging profiles for the electric vehicles have been developed in [22] and ten exemplary profiles for one day and a charging power of 11 kW can be seen in Figure 2. The profiles for the energy consumption have been generated using the tool presented in [23]. An exemplary profile for one day can be seen in Figure 3. Each profile is scaled using the yearly energy consumption of each household. In this paper, we are using profiles in 15 min intervals. The horizon of the simulations is one year. Therefore, 365 different courses for each profile as well as seasonal differences are taken into account automatically.

The operating hours depend on the season, which affects the heating demand. Therefore, two different seasons are considered to test the operation strategies. Winter (including electric heating) and summer (excluding electric heating). In Figure 4, profiles for all types of loads for the regarded feeder are presented for an exemplary weekend day.
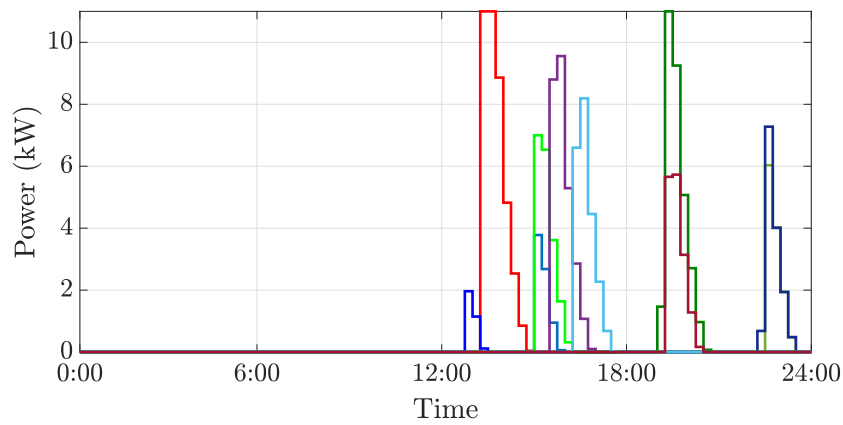
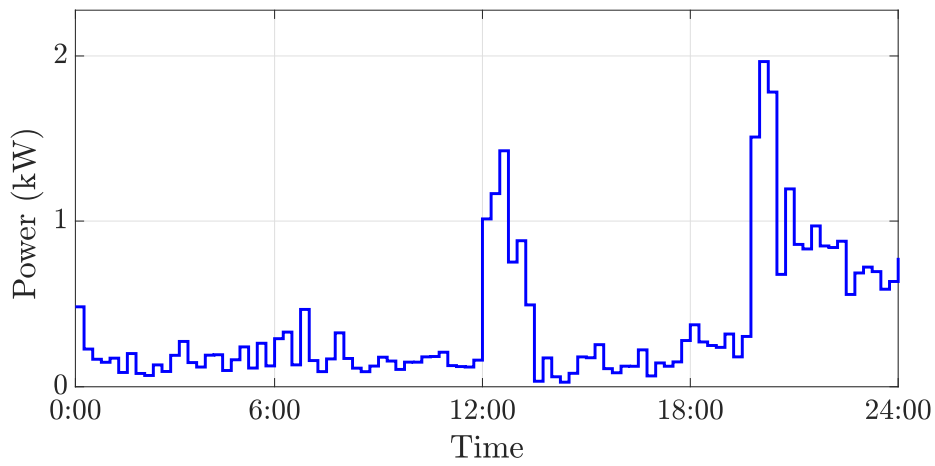**Figure 2.** Exemplary profiles for EV charging with 11 kW.

Figure 3. Exemplary profile for the energy consumption of a household.
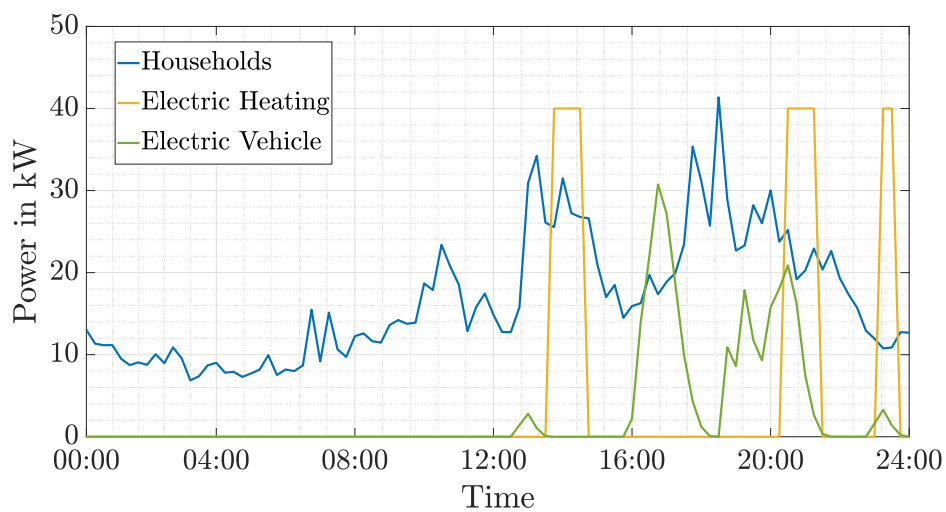

Figure 4. Profiles for the energy consumption of the households and electric heating as well as EV charging.

5.1. Electric Heating

Several households in the previously mentioned distribution grid use electric heating to heat their houses. As the rated power of these systems is comparably large, their operating hours are restricted in Germany by the grid operator. To reduce their effect on the distribution grid, they are only allowed to heat in off-peak hours. In this paper, we assume that the electric heating systems are only allowed to heat during the times that are listed in Table 1.

Table 1. Possible times of electric heating.

Days	Time
Monday to Friday	20:15–6:15
Saturday to Sunday	12:15–18:15 & 22:00–8:00

As we can see in Figure 4, the determination of off-peak hours should be adapted in the future when higher penetrations of EVs are expected as using the current specification leads to simultaneous EV charging and electric heating and hence extraordinary burden for the distribution grid.

In reality, the electric heating is not working during all permitted times. In Figure 5, measurement data of the power flow on the feeder for a winter day (blue) is displayed. As the electric heating has a total power of 40 kW, its influence on the power flow is significant. There was no additional measurement at the electric heating devices, so that it has to be estimated (yellow curve). Subtracting the power for the electric heating from the total power, the power on the feeder without electric heating (orange) is calculated.
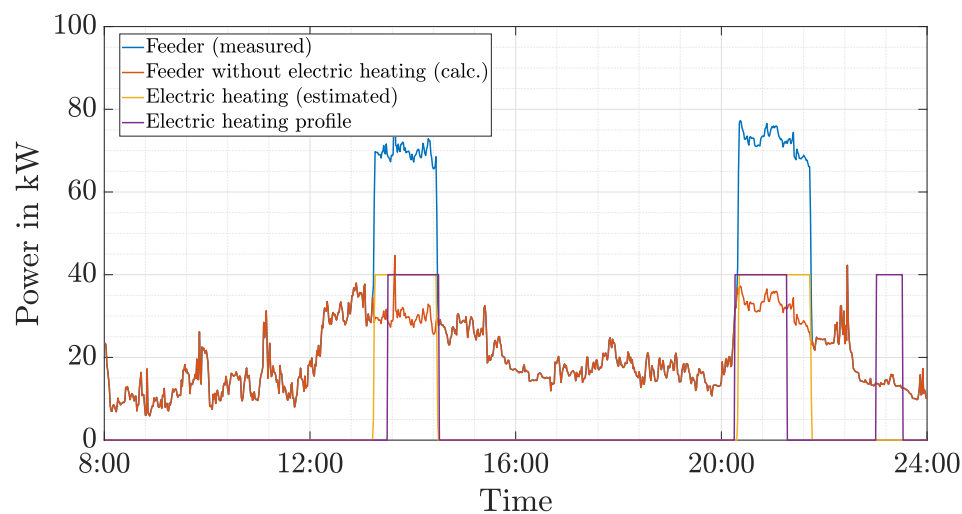

Figure 5. Profiles for the energy consumption of the households and electric heating as well as EV charging.

In reality, the energy consumption of the electric heating is not the same, but similar for all days. Through analysing measurement data for about one month, we assume that the electric heating is turned on in the times that are listed in Table 2. The assumed heating profile is shown in Figure 5 as purple line.

Table 2. Electric heating profiles.

Days	Time
Monday to Friday	20:15–21:45 & 23:00–24:00
Saturday to Sunday	13:30–14:30 & 20:15–21:15 & 23:00–23:30

6. Simulation Framework

To develop and test the operation strategies, a simulation framework was used to generate all necessary input data to test the different operation strategies in Section 7. Appropriate measurement data as input data from the field test was not available at that time.

As input data for the simulation framework, the profiles presented in Section 5 are used as well as the impedances of the regarded low voltage feeder. The start of the feeder is modelled as slack bus with a voltage of 1 pu.

The simulation framework calculates the currents, voltages and power flows at each point in the feeder in a 15 min resolution for given input profiles. With these results, the compliance with the given grid limits can be reviewed. This set of data is used as exemplary data to test the different strategies (see the explanation in Section 8).

The simulation framework is an optimal power flow algorithm that was presented in detail in [18]. It was developed to size the battery storage system in the research project "Netzlabor E-Mobility-Allee". For the purpose in this paper, the simulation framework delivers the same results as a power flow algorithm.

7. Operation Strategies for the Battery Storage

7.1. Fixed Schedule

The first strategy uses a fixed schedule for the charging and discharging power of the battery storage. As input, only data to characterize the power flow in the low voltage feeder is needed. In this paper, the number of households and their yearly energy consumption as well as the number of electric vehicles and their respective charging power is necessary to generate the necessary profiles as input data (see Section 5). Additionally, electric heating with specific use times is considered. Therefore, different schedules are used on weekdays and on the weekend. No actual real-time measurement data is needed.

To determine the schedule for charging and discharging, the simulation framework described in Section 6 is used to determine if there are violations of grid limits in the low voltage feeder for a horizon of one year. In the regarded low voltage grid, the only critical limit is the power limit of the feeder $S_{\text{Feeder,max}}$. In Figure 6, the daytimes when the feeder limit $S_{\text{Feeder,max}}$ is exceeded, are shown. The number of overloading events was evaluated in 30 min intervals. The horizon of the simulation was 365 days. As the simulation was done in 15 min intervals, the maximum possible number of events is 730 (=365 * 2). Under- or overvoltages did not occur in the regarded low voltage feeder.
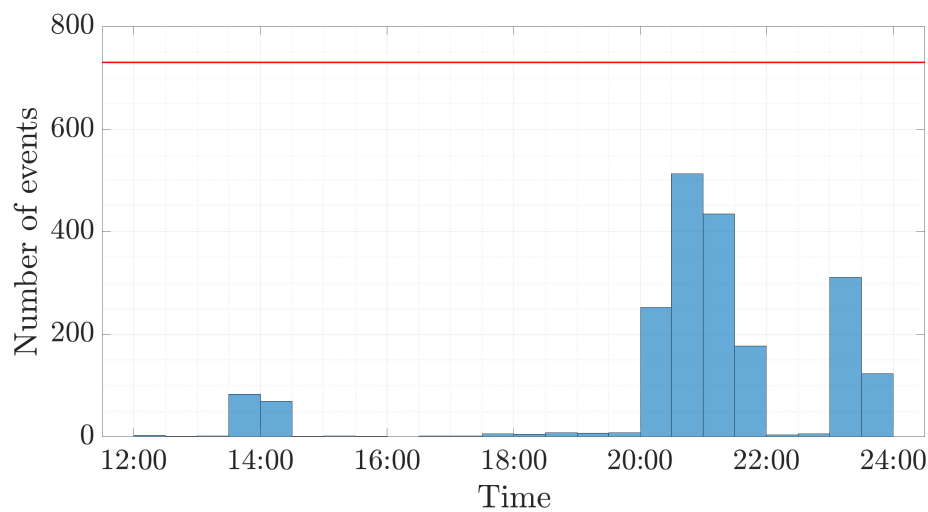
Figure 6. Time of the day with overloading of the feeder.

Overloading occurs mainly between 20:00 and 22:00 as well as between 23:00 and 24:00. The events between 13:30 and 14:30 mainly happen on the weekend due to the different operation times of the electric heating. As a result, it can be said that the times of overloading correspond to the operation times of the electric heating. As a consequence the schedule shown in Table 3 was determined as fixed schedule for the discharging of the battery system.

Table 3. Times of battery discharging.

Days	Time	Discharging Power
Saturday & Sunday	13:30–14:30	20 kW
All days	20:15–21:45	20 kW
All days	23:00–00:00	20 kW

In Figure 7, the times of the day with less than 20 kVA power flow into the feeder is shown. At these times, the battery can be recharged without causing any problems in the low voltage feeder. Especially in the morning hours between 04:00 and 08:00, the criterion is fulfilled regularly. Hence, these times are chosen for the charging of the battery system. On the weekend, an additional charging time during the daytime is assigned. The schedule shown in Table 4 was set for the charging of the battery.
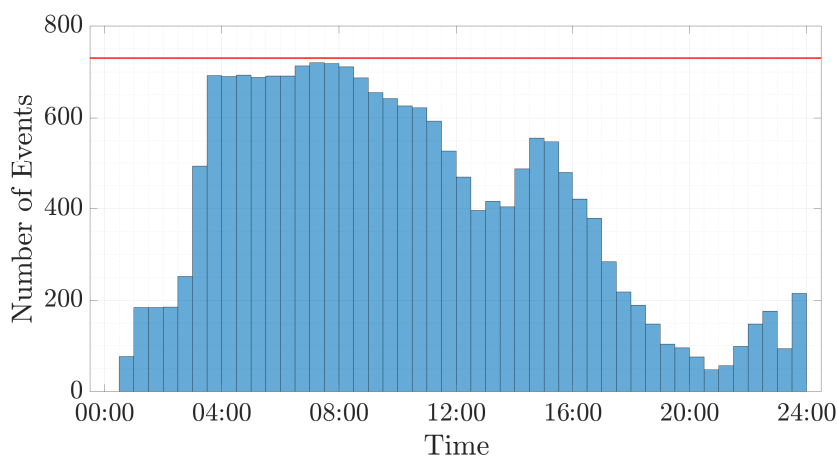

Figure 7. Time of the day with less than 20 kVA power flow into the feeder.

Table 4. Times of battery charging.

Days	Time	Charging Power
Saturday & Sunday	15:00–16:30	15 kW
All days	04:00–07:00	15 kW

In Figure 8, an exemplary course for the fixed schedule strategy for two exemplary days is shown. The blue curve is the power flow into the feeder S_{Feeder} without the battery system, which is calculated by the simulation framework. The charging power (yellow curve) and discharging power (purple curve) are as defined in Tables 3 and 4. The resulting power flowing into the regarded feeder including the battery system (orange curve) has significant lower peak powers than without out the battery system (blue curve).
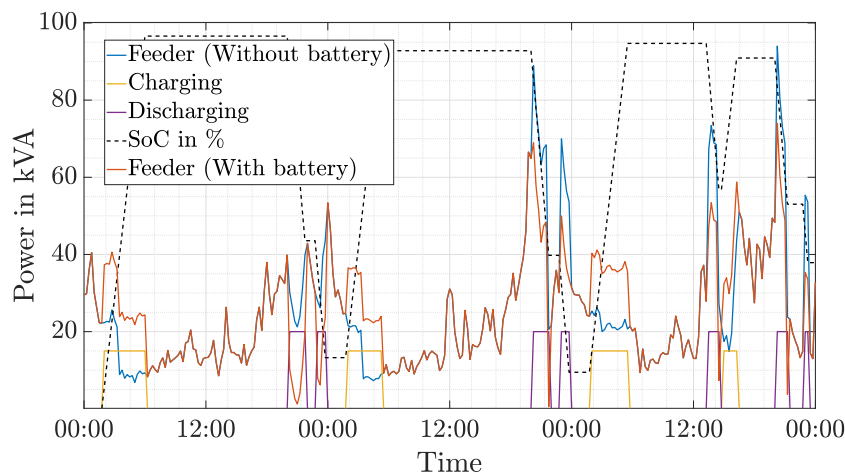
Figure 8. Exemplary course for the fixed schedule strategy.

7.2. Measurements at the Battery Storage

For the second strategy, real-time measurements at the battery storage are included in the operation strategy of the battery storage. As measured values voltage U_{Storage}, current I_{Storage} and power P_{Storage} are necessary. Battery storage systems have the necessary measurements already included in their battery management systems, so in the future these measurement devices could be used for such a strategy. In the research project "Netzlabor E-Mobility Allee", this was not possible, so an additional measurement device was installed close to the battery system.

To review the compliance with given grid limits at all points in the grid, the state of the grid at other points has to be estimated. To simplify, only the voltage at the end of the feeder and the power flow into the feeder are estimated in the following algorithm. As the low voltage feeder is neither meshed nor there are any junctions, the minimum voltage is always at the end of the feeder. As the power limit $S_{\text{Feeder,Max}}$ is more critical than the current limits for the lines, the currents are not estimated.

For the estimation, the impedance between the transformer and storage Z_1 as well as the impedance between the storage and the end of the feeder Z_2 have to be known to be able to calculate quantities that are not measured. The necessary calculations for the estimation are performed in the battery management system.

For the calculations, the voltage at the transformer $U_{\text{Transformer,Est.}}$ was set to its nominal value. Hence, the voltage drop between transformer and storage ΔU is estimated as

$$\Delta U = U_{\text{Transformer,Est.}} - U_{\text{Storage}} \tag{2}$$

Using ΔU, the current flowing into the feeder $I_{\text{Feeder,Est.}}$ is estimated as follows

$$I_{\text{Feeder,Est.}} = \frac{\Delta U}{Z_1} \tag{3}$$

and hence the power flowing into the feeder is

$$S_{\text{Feeder,Est.}} = U_{\text{Transformer,Est.}} \cdot I_{\text{Feeder,Est.}} \tag{4}$$

To estimate the minimum voltage in the grid $U_{\text{Min,Est.}}$, it is assumed that the current I_{Storage} is flowing till the end of the feeder.

$$U_{\text{Min,Est.}} = U_{\text{Storage}} - I_{\text{Storage}} \cdot Z_2 \tag{5}$$

The results for the minimum voltage and feeder power estimation depend on the location of the battery storage. Four locations as defined in Figure 1 are analysed.

In Table 5, the deviation of the estimated minimum voltage $U_{\text{Min,Est.}}$ from the voltage $U_{\text{Min,Calc.}}$, calculated using the simulation framework, for a horizon of one year is shown. The maximum and minimum deviation as well as the mean value of the deviation is shown.

If the battery system is installed at Point 4, the minimum voltage is measured there automatically, so there is no estimation necessary. At all other points, the deviation is always positive. Hence, the estimation is a worst case estimation. The maximum deviation occurs if the storage is at Point 1. It is 1.246 % of the nominal voltage while the mean deviation is just 0.241 % of the nominal voltage. To evaluate this numbers, it has to be taken into account that the voltage drop in the regarded low voltage feeder is quite small. For grids with longer cable lengths (e.g., on the country side) and therefore higher voltage drops, higher deviations are expected.

In Table 6, the deviation between the calculated values in the simulation framework $S_{\text{Feeder,Calc.}}$ and the estimated values $S_{\text{Feeder,Est.}}$ of the power flow into the feeder are compared. If the battery storage is placed at Point 1, the power is already measured through the battery storage, so no deviations occur. In comparison to Table 5, the minimum deviation is negative. Hence, the power flow is overestimated as well as underestimated. Deviation arise when the energy consumption along the feeder is not evenly distributed. The maximum deviation happens when the storage is connected to Point 4 with 89.1 kVA. The comparison with the maximum allowed power on this feeder $S_{\text{Feeder,Max}}$ (60 kVA) shows the extent of the deviation. This maximum deviation just happened on one time step. The mean deviation on Point 4 is just 5.6 kVA.

Table 5. Estimation faults for the minimum voltage for different locations.

Location	max($U_{\text{Min,Calc.}}$-$U_{\text{Min,Est.}}$)	min($U_{\text{Min,Calc.}}$-$U_{\text{Min,Est.}}$)	mean($U_{\text{Min,Calc.}}$-$U_{\text{Min,Est.}}$)
1	0.01246 p.u.	0.00046 p.u.	0.00241 p.u.
2	0.01254 p.u.	0.00033 p.u.	0.00184 p.u.
3	0.00674 p.u.	0.00013 p.u.	0.00085 p.u.
4	0 p.u.	0 p.u.	0 p.u.

Table 6. Estimation faults for the feeder power for different locations.

Location	max($S_{\text{Feeder,Calc.}}$-$S_{\text{Feeder,Est.}}$)	min($S_{\text{Feeder,Calc.}}$-$S_{\text{Feeder,Est.}}$)	mean($S_{\text{Feeder,Calc.}}$-$S_{\text{Feeder,Est.}}$)
1	0 kVA	0 kVA	0 kVA
2	59.3 kVA	−32.1 kVA	0.7 kVA
3	12.6 kVA	−3.2 kVA	1.3 kVA
4	89.1 kVA	−38.0 kVA	5.6 kVA

In Figure 9, the power flows into the feeder as well as charging and discharging power on two exemplary days are shown. For this simulation, the battery storage was connected to Point 2. The blue

curve is the power flow into the feeder S_{Feeder} without the battery system. The battery is discharging (purple curve), whenever S_{Feeder} (blue curve) is exceeding the limit $S_{Feeder,Max}$. The battery storage gets recharged (yellow curve) as soon as the power flowing into the feeder is less than 30 kVA.
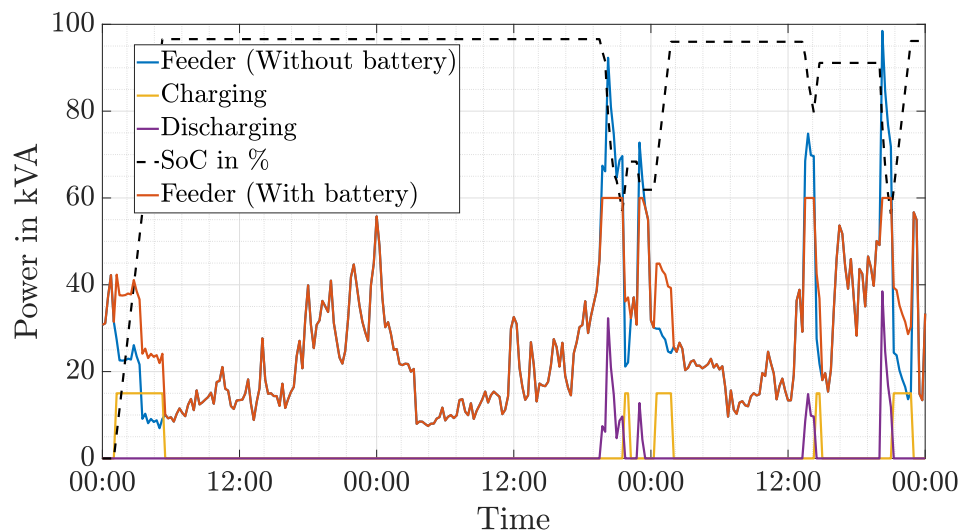

Figure 9. Exemplary course for the strategy including measurements at the storage.

7.3. Measurements at the Battery Storage and the Start of The Feeder

For the third strategy, in comparison to Section 7.2, an additional measurement device is added at the beginning of the feeder. The second measurement device measures the power flow in the feeder S_{Feeder} exactly, so that this quantity does not have to be estimated in contrast to Section 7.2. The minimum voltage in the feeder $U_{Min,Est.}$ does still have to be estimated as long as the storage is not connected at the end of the feeder. For the estimation of the minimum voltage in the feeder $U_{Min,Est.}$, the same approach as in Section 7.2 is used.

Disadvantages of this strategy are that an additional measurement device is needed as well as communication between the measurement device at the start of the feeder and the battery storage to transfer the measurement values. Main advantage is that S_{Feeder} is measured and does not have to be estimated.

7.4. Measurements Data from Smart Meter

Smart Meters are installed at each household already in several countries (e.g., Spain) or will be installed in the next years (e.g., Germany). Instead of own measurements devices in the low voltage feeder, also Smart Meter data could be used. The main advantage is that no new devices have to be installed and that data is available for each household. Therefore, no estimation of grid values is needed and hence no information about the low voltage feeder is needed in advance. Only a communication channel between Smart Meters and the battery management system has to be established.

In this scenario, the compliance with the given grid limits can be verified always and necessary actions performed. Therefore, it was not necessary to test this strategy in the simulations.

8. Simulation Results

In the following chapter, the simulations results are presented and discussed. The presented operation strategies have been tested using input data from the simulation framework as artificial measurement data. It is then tested if the proposed strategies are able to detect a necessary operation of the battery storage. Therefore, three different findings are possible:

- Correct: An operation of the battery storage is necessary and detected by the operation strategy

- Fault 1: An operation of the battery storage is necessary, but not detected by the operation strategy

- Fault 2: An operation of the battery storage is not necessary, but detected by the operation strategy

In Table 7, the results are shown for a scenario without a battery storage and with the fixed schedule. Without the battery storage, the grid restrictions are not fulfilled for 2248 15-min intervals for a simulation horizon of one year. Using the battery storage with a fixed schedule, only for 537 15-min intervals there is no compliance with the grid limits. This is a decrease of more than 76 %. However, the battery storage is also used in 1653 15-min intervals without a violation of grid limits (see Fault 2). The results for the Fixed Schedule strategy do not dependent on the position of the battery storage. For the following discussion of results, the strategy with the fixed schedule is set as reference as it is easy to implement and no measurements are necessary.

Table 7. Results for the scenario without storage and the fixed schedule.

	No Storage	Fixed Schedule
Position	-	1, 2, 3, 4
Correct	0	1711
Fault 1	2248	537
Fault 2	0	1653

In Table 8, the results for the strategy "Measurements at the battery storage" (see Section 7.2) are presented. The results depend on the position of the battery storage. In general, it can be seen that the correct detection of events decreases with increasing distance to the MV/LV transformer. The reason is that in the regarded low voltage feeder only feeder overloading problems arise. Hence, the power flow at the beginning of the feeder is the only relevant value to detect violations of grid limits. This power flow is estimated more accurate if the battery storage is closer to the beginning of the feeder as it is shown in Table 6.

Table 8. Results for the scenario with measurements at the storage.

	Fixed Schedule	Measurement at the Storage			
Position	1, 2, 3, 4	1	2	3	4
Correct	1711	2248	2241	2136	670
Fault 1	537	0	7	112	1578
Fault 2	1653	0	176	19	36

The results for the scenario "Measurements at the battery storage and the start of the feeder" can be seen in Table 9. As explained in the previous paragraph, for the investigated grid only $S_{Feeder,max}$ is the relevant value to detect grid violations. Consequently, all the violations can be detected with the measurement at the start of the feeder. As the measurement at the battery storage is not needed, the position of the battery storage does not have any influence.

Table 9. Results for the scenario with measurements at the storage and transformer.

	Fixed Schedule	Measurement at Storage + Transformer			
Position	1, 2, 3, 4	1	2	3	4
Correct	1711	2248	2248	2248	2248
Fault 1	537	0	0	0	0
Fault 2	1653	0	0	0	0

Finally, it has to be said that a detection of an event does not mean automatically that it can be solved. The charging and discharging power of the used battery storage is limited.

9. Results from The Project

After analysing the simulation results, two of the developed strategies have been chosen for testing in reality in the research project "Netzlabor E-Mobility-Allee". One strategy is the fixed schedule strategy as it is quite easy to implement. For the second strategy, measurement devices at the start of the feeder as well as the storage are used. For details on this strategy, see Section 7.3. This was chosen, as this strategy was able to prevent all violations of the grid limits for the given battery position in the project (Position 4 in Figure 1).

9.1. Fixed Schedule

The first strategy with a fixed schedule was tested from 05/02/2019 to 17/02/2019. Measurement data was recorded in a 3-min interval. In this period, in 493 intervals the power demand would have been higher than 60 kVA without the battery storage. As a consequence of new measurement data, the schedule for the battery storage was adjusted to the times in Table 10.

Table 10. Adjusted schedule for the battery storage system.

Days	Time	Charging Power
Saturday & Sunday	13:00–16:18	−20 kW
Saturday & Sunday	16:30–19:48	20 kW
All days	20:00–22:12	−30 kW
All days	22:30–2:30	10 kW
All days	03:00–05:00	−20 kW
All days	08:00–11:18	20 kW

The new measurement data was recorded during cold winter times, wherefore the electric heating was used more as seen in previous measurements. Therefore, the discharging time in the afternoon on weekends was extended and an additional charging time introduced. Additionally, the discharging power at 20:00 was increased and the discharging period lengthened. Furthermore, an additional discharging time between 03:00 and 05:00 was introduced, followed by a charging time between 08:00 and 11:18.

In Figure 10, the measurement data for the 05/02/2019 and the 06/02/2019 can be seen. Due to a time difference problem, there was a one-hour time offset between the real and the intented schedule for the battery storage. Overall, the number of intervals with more than 60 kVA power demand have been reduced by more than 16 % to 414 intervals during the test phase. As this is a significant difference to the simulation result (decrease of more than 76 %), the deviations will be analysed in the ongoing section.

In Figure 11, the course of the data can be seen after recalculating the time shift. Neglecting the time shift leads to a decrease of more than 41 % in intervals with feeder overloading. Hence, the correction of the time shift increases the correct fault prevention by around 25 %.

As can be seen in Figure 11, there is a malfunction of the battery system during charging or discharging (e.g., on the first day at 03:20). An additional removal of this malfunction (see Figure 12) would lead to a decrease of approximately 44.8 % in intervals with feeder overloading. In comparison to just correct the time shift, this is an increase of 3.4 %.

Furthermore, the whole energy capacity of 66 kWh of the battery system could not be used, which leads to decreased charging and discharging periods. Correcting this effect (see Figure 13), leads to another decrease of 3.7 % in the number of intervals with feeder overloading. In Figure 13, the charging and discharging times neglecting the decreased energy capacity, can be seen. In Figure 13, the schedule for the battery storage is equal to the original planned schedule.
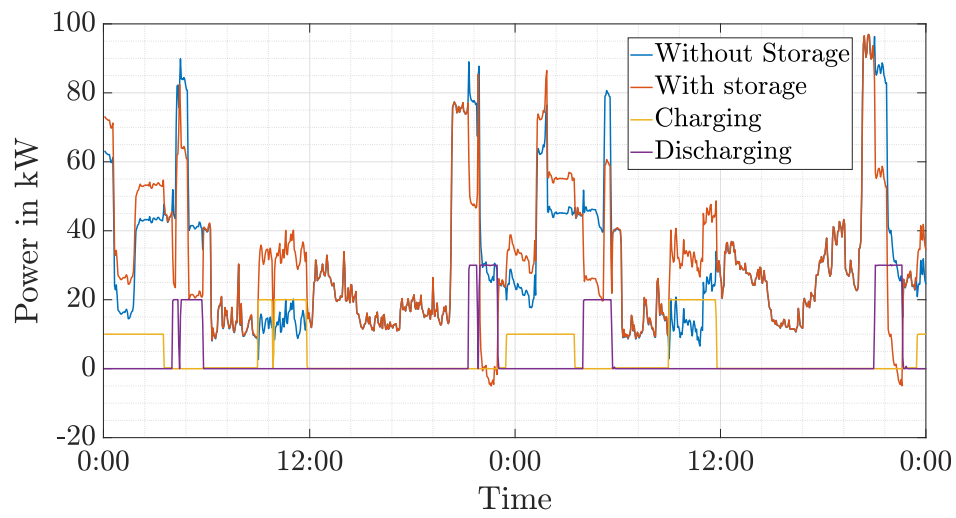
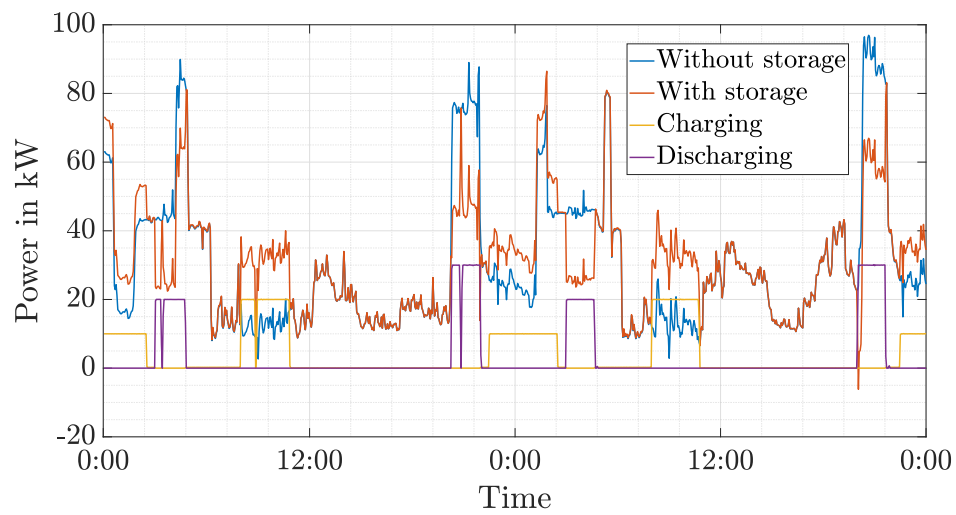**Figure 10.** Measurement data for the fixed schedule strategy.

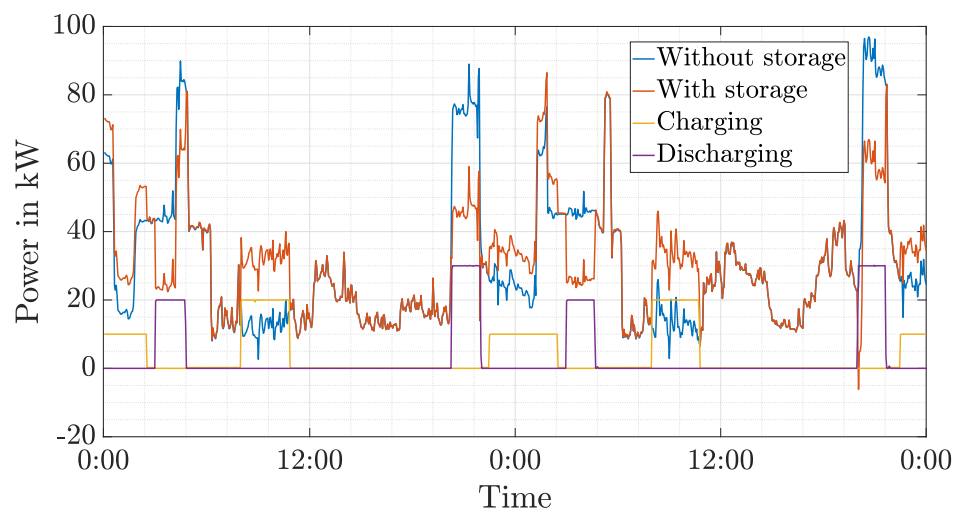**Figure 11.** Results after recalculate time shift for the fixed schedule strategy.

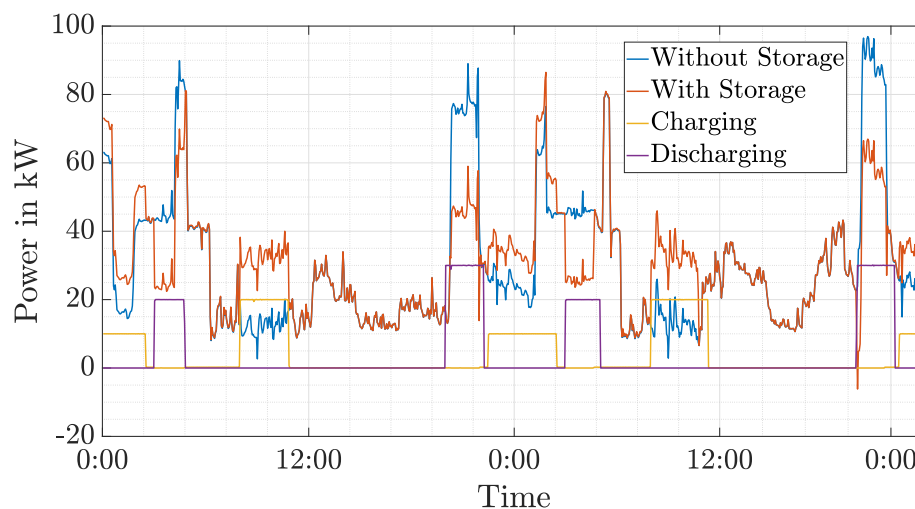**Figure 12.** Results after the removal of the malfunction for the fixed schedule strategy.

Figure 13. Results for the planned schedule for the fixed schedule strategy.

Nevertheless, there is still a significant difference to the simulation results. The reason is, that in the simulations the amount of intervals, where a overloading occurs and is detected was determined. The capability of the battery system to prevent the feeder loading was not checked. This leads to situation, that for many intervals the discharging power was not sufficient to prevent the feeder from overloading. Increasing the power limit of the feeder $S_{Feeder,max}$ by just 5 kVA to 65 kVA would lead to a total decrease of 71.6 % in overloaded intervals. This proves the given statement.

9.2. Measurements at the Battery Storage and the Start of The Feeder

The second strategy was tested between 19/02/2019 and 1/3/2019. As this period was quite warm, $S_{Feeder,max}$ was set to 40 kVA to be able to test the strategy appropriately. In Figure 14, measurement data for the 21/02/2019 and 22/02/2019 is shown.

During the test period, 491 intervals with feeder overloading would have been occurred without the battery system. Using the measurement devices and the battery system, only 22 intervals with overloading existed in reality (e.g., on the second day at 21:30 in Figure 14). This means that the number of overloading intervals could be decreased by 95.5 % during the test period. In the remaining 22 intervals, the overloading could not be prevented because of malfunction of the battery storage as well as discharging power limitations of the battery storage.

If the original $S_{Feeder,max}$ of 60 kVA would have been used, the number of intervals could have been decreased by 98.6 %. The residual 1.4 % of intervals are caused by malfunction only. Hence, the simulations results and field test results correspond for this strategy.
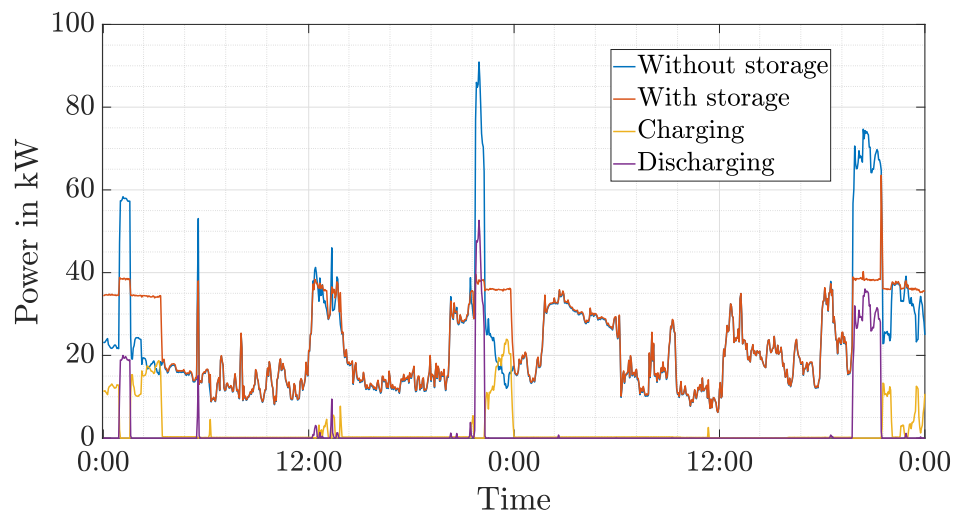
Figure 14. Measurement data for the strategy using measurement devices.

10. Summary and Conclusions

In this paper, different strategies for the operation of a battery storage as a temporary equipment during grid reinforcement have been developed and tested in simulations as well as in reality. Four different strategies have been simulated. A result of the simulation was that the ability of the battery storage to prevent the violation of grid limits depends on the position of the battery storage as well as the used measurements as input data. For the test in the project "Netzlabor E-Mobility-Allee" the two most promising strategies have been chosen.

For the strategy with a fixed schedule, a precise model of the low voltage feeder is necessary to determine an appropriate schedule. Nevertheless, it is not possible to prevent all grid limit violations using this strategy. Main advantage is that no measurement devices have to be installed. This decreases the effort in comparison to measurement-based strategies significantly. The strategy with a fixed schedule showed a different result in the field test than in the simulations. Instead of 76 %, only around 16 % of all grid violations could be prevented. The reason for that was a time difference problem, malfunction of the storage as well as limited capacity of the storage.

In a second strategy, only one measurement device was installed at the battery system. This measurement values have been used to estimate all important quantities to review the compliance with the given limits. In simulations, it was shown that the results show a good performance on average, but high deviations can occur in extraordinary circumstances.

In the third strategy, besides a measurement device at the battery storage, also at the start of the feeder a measurement device was installed. Disadvantage of this solution is not only the installation of additional measurement equipment, but also the need of communication infrastructure to transfer measurement values from the second device to the battery management system. In the regarded low voltage feeder, the critical parameter regarding the grid limits was only the power flow into the feeder. Using this strategy, in simulations all problems in the grid can be prevented. Using this strategy in the field test, 95.5 % of all grid violations have been prevented. The remaining violations occur because of a malfunction of the battery system. Hence, this strategy is the most promising strategy tested in this paper to be able prevent the violation of grid limits. At this point, it has to be mentioned that this statement is only valid for low voltage feeder with similar critical grid parameters.

In the future, the installation of measurement devices might not be necessary any more, as Smart Meters will be installed in the grids extensively. Their measurement data can then be used instead of other measurement devices that have to be installed.

11. Outlook

The use of equipment (especially the power limit for the feeder $S_{Feeder,max}$) was the limiting parameter regarding the grid limits in this paper. In the future, the same approach will be tested for further grids. Especially in grids, where the voltage dip is the limiting parameter concerning grid operation.

Abbreviations

The following abbreviations are used in this manuscript:

EV   Electric Vehicles
PV   Photovoltaic

References

1. European Commission. *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*; European Commission: Brussels, Belgium, 2011
2. Held, L.; Märtz, A.; Krohn, D.; Wirth, J.; Zimmerlin, M.; Suriyah, M.R.; Leibfried, T.; Jochem, P.; Fichtner, W. The Influence of Electric Vehicle Charging on Low Voltage Grids with Characteristics Typical for Germany. *World Elect. Veh. J.* **2019**, *10*, 88.
3. Jochem, P.; Märtz, A.; Wang, Z. How might the German distribution grid cope with 100% market share of PEV? In Proceedings of the 31th International Electric Vehicle Symposium, EVS31, Kobe, Japan, 30 September–3 October 2018.
4. Clement-Nyns, K.; Haesen, E.; Driesen, J. The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. *IEEE Trans. Power Syst.* **2009**, *25*, 371–380.
5. Clement-Nyns, K.; Haesen, E.; Driesen, J. The impacts of vehicle-to-grid on the distribution grid. *Electr. Power Syst. Res.* **2011**, *81*, 185–192.
6. Habib, S.; Kamran, M.; Rashid, U. Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks—A review. *J. Power Sources* **2015**, *277*, 205–214.
7. Litjens, G.; Van Sark, W.; Worrell, E. On the influence of electricity demand patterns, battery storage and PV system design on PV self-consumption and grid interaction. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, USA, 5–10 June 2016.
8. Ollas, P.; Persson, J.; Markusson, C.; Alfadel, U. Impact of Battery Sizing on Self-Consumption, Self-Sufficiency and Peak Power Demand for a Low Energy Single-Family House With PV Production in Sweden. In Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), Waikoloa Village, HI, USA, 10–15 June 2018.
9. Held, L.; Weber, G.; Zimmerlin, M.; Suriyah, M.R.; Leibfried, T.; Armbruster, M.; Höche, R. Self-consumption and self-sufficiency level in an energy cell with a high penetration of PV and a hybrid battery storage system. In Proceedings of the Solar Integration Workshop, Stockholm, Sweden, 16–17 October 2018.
10. Kaschub, T.; Jochem, P.; Fichtner, W. Interdependencies of home energy storage between electric vehicle and stationary battery. In Proceedings of the 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, Spain, 17–20 November 2013.
11. Held, L.; Gerhardt, N.; Zimmerlin, M.; Suriyah, M. R.; Leibfried, T.; Armbruster, M. Grid-friendly Operation of a Hybrid Battery Storage System. In Proceedings of the 25th International Conference and Exhibition on Electricity Distribution, Madrid, Spain, 3–6 June 2019.

12. Van Dun, J.J.C.M.; de Groot, R.J.W.; Morren, J.; Slootweg, J.G. Control of a battery energy storage system connected to a low voltage grid. In Proceedings of the 2015 IEEE Eindhoven PowerTech, Eindhoven, The Netherlands, 29 June–2 July 2015.

13. Hashim, M.S.; Yong, J.Y.; Ramachandaramurthy, V.K.; Tan, K.M.; Tariq, M. Coordinated Vehicle-to-Grid Scheduling to Minimize Grid Load Variance. In Proceedings of the 2019 International Conference on Electrical, Electronics and Computer Engineering, Aligarh, India, 8–10 November 2019.

14. Hofmann, M.; Raab, S.; Schaefer, M.; Ponomarov, P.; Ackva, A. Measurements on vehicle to grid application in industrial power grid for peak load reduction: Robust bidirectional charger for series production electric and plug-in hybrid vehicles. In Proceedings of the 2015 IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems, Aachen, Germany, 22–25 June 2015.

15. Marty, J.; Pietrowicz, S. Economic incentives for reducing peak power utilization in electric vehicle charging stations. In Proceedings of the 2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference, Washington, DC, USA, 19–22 February 2018.

16. Held, L.; Uhrig, M.; Suriyah, M.; Leibfried, T.; Junge, E.; Lossau, S.; Konermann, M. Impact of electric vehicle charging on low voltage grids and the potential of battery storage as temporary equipment during grid reinforcement. In Proceedings of the E-Mobility Integration Symposium, Berlin, Germany, 23 October 2017.

17. Piromjit, P.; Tayjasanant, T. Peak-demand management for improving undervoltages in distribution systems with electric vehicle connection by stationary battery. In Proceedings of the 2017 IEEE Transportation Electrification Conference and Expo Asia-Pacific, Harbin, China, 7–10 October 2017.

18. Held, L.; Krämer, H.; Zimmerlin, M.; Suriyah, M.R.; Leibfried, T.; Ratajczak, L.; Konermann, M. Dimensioning of battery storge as temporary equipment during grid reinforcement caused by electric vehicles. In Proceedings of the Universities Power Engineering Conference (UPEC), Glasgow, UK, 4–7 September 2018

19. Dronia, M.; Fischhaber, S.; Gallet, M.; Müller, M.; Mauch, W.; Doll, A.; Schaarschmidt, K.; Kerber, G.; Wruck, E.; Ensenmeier, K.; et al. *Endbericht: EPlanB—Lademanagement an Park and Ride Parkplätzen*; Technical Report; München, Germany, 2017. Available online: https://www.ffe.de/attachments/article/531/Endbericht%20ePlanB.pdf (accessed on 4 May 2020).

20. Hoogsteen, G.; Molderink, A.; Hurink, J. L.; Smit, G. J.; Kootstra, B.; Schuring, F. Charging electric vehicles, baking pizzas, and melting a fuse in Lochem. *CIRED—Open Access Proc. J.* **2017**, *2017*, 1629–1633.

21. DIN e.V. *Voltage Characteristics of Electricity Supplied by Public Networks*; DIN EN 50160/A1:2016-02; DIN e.V.: Berlin, Germany, 2016.

22. Wenig, S.; Schulze, W.; Moraleda, G.; Gebel, T.; Suriyah, M.; Leibfried, T.; Walker, G. Probabilistische Auswertung des Einflusses zukünftiger Elektromobilität auf vorstädtische Mittelspannungsnetze in Süddeutschland. In Proceedings of the 3. OTTI-Konferenz Zukünftige Stromnetze für Erneuerbare Energien, Berlin, Germany, 26–27 January 2016.

23. Uhrig, M. Lastprofilgenerator zur Modellierung von Wirkleistungsprofilen privater Haushalte. Available online: http://doi.org/10.5281/zenodo.803261 (accessed on 22 May 2020)