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## ► To cite this version:

Katrin Handel, Katrin Schulte, Rémy Rigo-Mariani, Jens Haubrock, Jan Arens. Control of distributed energy storage systems for minimum reverse flow in a distribution grid with high share of photovoltaic. 2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Oct 2023, Grenoble, France. hal-04431464

**HAL Id: hal-04431464**

**<https://hal.science/hal-04431464>**

Submitted on 2 Feb 2024

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# Control of distributed energy storage systems for minimum reverse flow in a distribution grid with high share of photovoltaic

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**Abstract**—Due to the increasing numbers of photovoltaic (PV) systems installed at the low-voltage (LV) level, reverse power flow (RPF) between the LV and the medium-voltage (MV) grid occurs more frequently and with higher magnitudes. This poses a threat to grid security as RPF can cause overvoltage and thereby potentially damage system equipment. This paper proposes a method of reducing RPF and increasing the local consumption of renewable energies (RES) by collectively controlling distributed residential battery energy storage systems (BESS) in a LV grid. For this purpose, the charging and discharging powers of the BESS are set correlating to the expected RPF and power demand at the transformer level by using a linear optimization algorithm and a forecast of the power flow at the transformer. This method aims at RPF shaving by charging the BESS and at covering the power demand by discharging. Comparisons with BESS controlled individually at the household level show, that the proposed method leads to a more effective reduction of reverse power peaks.

**Keywords**—battery energy storage systems, grid optimized control, linear optimization, reverse power flow

## I. INTRODUCTION

The share of electricity from renewable sources in the overall electricity mix in Germany continues to rise. According to the Federal Environmental Agency, the share of RES was 49 % of the electricity consumption by the first half of 2022, which is already an increase of 14 % compared to the first half of 2021 [1]. One reason for that growth is the expansion of PV systems [1]. In 2021, 9.3 % of the entire generated electricity originated from the approx. two million PV systems, most of which installed in the private sector [2] [3]. These already high numbers of PV systems in residential areas only continue to grow due to increasing energy costs and the expansion and promotion of RES [4] [3]. However, depending on the system's size, only a fraction of the power generated may be consumed at household level while the remaining power is fed into the LV grid [3]. Since PV power generation is volatile and depends on weather conditions, generation peaks can occur during off-peak-periods and cause RPF between the LV and the MV grid. As the power system was originally designed for uni-directional power flow only, RPF can induce overvoltage and thus potentially damage equipment [5] [6]. A bi-directional power flow poses the threat of exceeding standard equipment thresholds and thereby endangers grid security [6].

RPF can also have a negative impact on the life span of system equipment, as it needs to be operated more frequently [6].

To reduce the infeed of surplus PV power into the LV grid and the resulting RPF and to increase the consumption of electricity generated by PV systems at the household level, residential PV systems can be combined with BESS. Since conventional residential BESS are typically designed for increasing self-consumption of PV power at a single household, their charging processes are usually aimed at storing a maximum of energy when there is a surplus of PV power and do not provide grid services [7]. To establish a grid optimized operation of distributed BESS in a LV grid and thereby reduce RPF, it is necessary to collectively control the charging and discharging processes of all BESS on the basis of the grid's state considering the load flow at the transformer level. For this purpose, this work describes an algorithm that generates charging and discharging profiles for distributed BESS on a day-ahead basis. The individual charging and discharging powers are determined by a linear optimization, which takes the state of the grid into account, based on a forecast of the power flow at the transformer. The aim of the grid optimized BESS control is to consume the electricity generated by the PV systems locally within the LV grid, and thus increase the share of RES, while reducing the negative impacts of RPF via RPF shaving by setting the charging powers of the BESS according to the occurrence and magnitude of the reverse power peaks. During times of grid demand, the BESS are discharged, and thereby partially cover the power demand of the entire grid.

The use of BESS for grid services is widely explored in research. In [8], BESS are charged during peak PV generation hours after being activated by a specific power threshold, which depends on the PV penetration, to prevent overvoltage. In [9], a method of using BESS to increase the local utilization of RES while performing grid services is presented. In this study, storage capacity is reserved for DSO to mitigate voltage and thermal violations. The remaining capacity is used to increase self-consumption of PV power. An ideal charging profile for the reduction of RPF is calculated in [7], based on an estimation of the daily maximum PV generation and then adapted to measurements of the actual surplus PV power. By not using an optimization-based approach, this strategy is independent of accurate forecasts of PV generation and power demand of the individual households. The method described in [10] addresses RPF reduction by increasing the voltage and frequency with the AC controller of a smart transformer and thereby causing a decrease of power injection from distributed

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This work was supported by the German Federal Ministry of Education and Research (BMBF) under the German-French Joint Call for Proposals on "Artificial Intelligence".

generators (DG). In [11] and [12] the mitigation of RPF by charging BESS is realized by using reinforcement learning (RL) methods. In this approach, the charging and discharging powers are set according to the RPF within an action space.

Since the method presented in this paper is based on a real suburban grid of a German distribution system operator (DSO), it is possible to obtain accurate forecast data and thereby utilize the potential of an optimization-based approach. In contrast to RL approaches, the charging powers can be set arbitrarily without being constrained to discrete states. Furthermore, by not depending on pre-defined capacity or charging power thresholds, the capacity of the BESS can be fully utilized so the revenue of the DG owner is not reduced.

## II. METHODOLOGY

In the following, the grid optimized BESS control is presented. Afterwards, as a comparison, a method of creating charging and discharging profiles for individually controlled BESS is described.

### A. Grid optimized BESS control

The objective of the proposed method is to control distributed BESS by setting charging and discharging profiles for all BESS in a LV grid on a day-ahead basis in order to perform RPF shaving. The discharging processes are aimed at supplying the grid demand during times of little to no PV penetration. An outline of the individual steps of the proposed method is depicted in Fig 1.

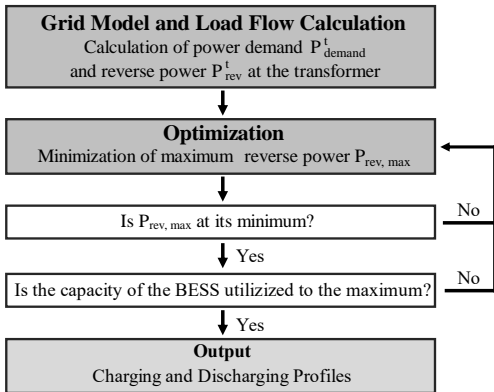


Fig. 1. Overview of steps of the proposed method

In order to reduce reverse power and grid demand, these have to be predicted for the respective day. In this study, power flows are predicted by modeling the grid and conducting a load flow calculation. The load flow calculation is based on PV generation and load profiles, the forecast of the power flow is thereby idealized. Furthermore, the charging and discharging of the BESS is not considered in the load flow calculation, so the results represent a worst-case scenario. The results of the load flow calculation are profiles of the reverse power and power demand for the respective day at a resolution of ten minutes. By using these profiles as input parameters for a linear optimization, RPF shaving and minimization of the power demand is performed by calculating charging and discharging profiles for the BESS. For this, the optimization is run repeatedly until each reverse power peak is reduced as much as possible. All reverse powers are thereby less than or equal to a maximum value of reverse power, that is determined by the optimization. When that is the case, it is also ensured, that the capacity of the BESS is used to its full potential. If reverse powers that are below the determined maximum value

occur, they are not considered in the first cycle of optimization as the objective is already satisfied. By running the optimization again for the period after the BESS have reached their full capacity, it can be determined whether the BESS can be discharged and store the lower reverse power afterwards.

### a) Model of the LV grid and assessment of the power flow

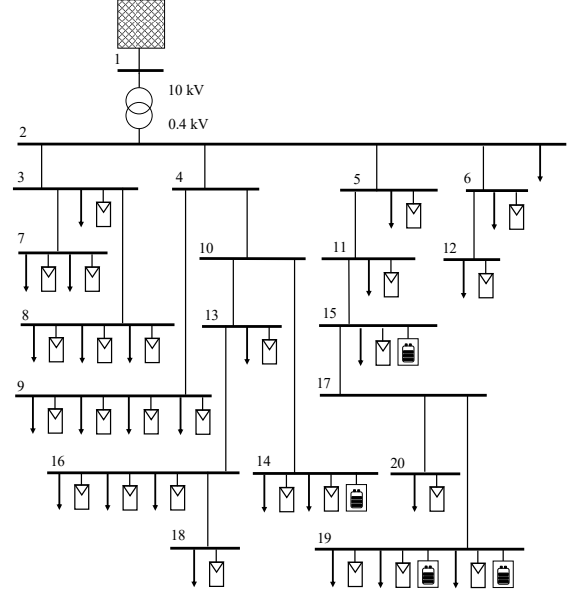


Fig. 2. Topology of the LV grid

The case study depends on a real suburban LV grid of a German DSO with a 250 kVA transformer, around 160 households and 26 PV systems with a total installed peak power of 207.6 kWp. Furthermore, four controllable BESS are integrated in the grid. For an assessment of the power distribution, a load flow calculation is conducted using the open-source tool Pandapower [13]. The behavior of the BESS is not considered in the load flow calculation, as the charging and discharging profiles are adjusted to the worst-case scenario of maximum PV penetration without mitigation by charging the BESS. Fig. 2 shows the topology of the grid and the locations of the BESS at the end users' level. As a simplification, only the loads of the 26 households, that are equipped with a PV system, are shown. The remaining households are aggregated. In this study, the load and generation profiles presented in [14] are used. The PV profiles derive from measurement data of a real PV system, while the corresponding load profiles are based on reference profiles of the VDI (Association of German Engineers) which were randomized in terms of power and time. Each profile covers an entire day and has a resolution of ten minutes. Both profile types are normalized so that various load or solar levels can be simulated easily. In case of a household with an equipped PV system, a peak load of 6.5 kW is assigned, as this is the average value of the peak loads used in [14]. For the remaining households aggregated within a single profile, the peak load is calculated according to the BDEW (Federal Association of the Energy and Water Industry in Germany) to avoid an unrealistic simultaneous behavior of the 134 households [15].

### b) Minimization of the RPF

The charging and discharging profiles are constructed through a linear optimization process with the aim of reducing reverse power peaks by storing surplus PV power. The charging powers are thus set according to the magnitude of the

reverse power. The objective function describes a minimax problem, which is the minimization of a maximum in a set of variables [16]. This minimized peak then acts as the maximum value for all other peaks at the respective step of the optimization. By running the optimization repeatedly, not only the maximum peak is reduced as much as possible, but all other peaks as well, thus RPF shaving is performed. For this, the charging powers of the BESS determined at each run of the optimization are increased in the following one. When a charging power has reached its maximum, the respective peak cannot be reduced further and is no longer considered in the following run. The maximum reduction of the reverse power is achieved, when no charging power can be increased further, which is the case when all BESS reach their maximum capacity. Once the RPF shaving is complete and the BESS are fully charged, the aforementioned optimization process is run again for the period after the BESS reach their full capacity, ensuring that the BESS also store lower reverse powers after discharging. The optimization regards one day (time horizon  $T$ ), where each individual timestep  $t$  has a length of ten minutes. Charging and discharging profiles are developed for each BESS  $s$  in the set  $S$ . Since the aim of the algorithm is to compute the charging and discharging profiles, the variables  $P_{ch}^{s,t}$  and  $P_{disch}^{s,t}$  are introduced for the individual charging and discharging powers over time. The variables get an optimal value during the optimization. Furthermore, the variable  $E^{s,t}$  is used for the energy stored within each BESS and at every timestep. The RPF shaving is implemented through a minimax problem, meaning that by minimizing the maximum reverse power peak, a maximum value for all other reverse powers is determined. This value is described by the variable  $P_{rev, max}$ , while the reduced reverse powers are described by  $P_{rev, red}^t$ .

The lower the maximum value for the reverse powers  $P_{rev, max}$ , the more the reverse power is reduced. Hence,  $P_{rev, max}$  is minimized in the objective function, as shown in (1).

$$\min(P_{rev, max}) \quad (1)$$

Since  $P_{rev, max}$  functions as an upper bound for all reverse powers at the respective step of the optimization,  $P_{rev, max}$  is greater than or equal to the reduced reverse powers  $P_{rev, red}^t$ .

$$P_{rev, max} \geq P_{rev, red}^t \quad \forall t \in T \quad (2)$$

The reduction of the reverse powers is achieved by subtracting the summarized charging powers  $P_{ch}^{s,t}$  of all BESS  $s$  from the reverse power  $P_{rev}^t$  at the timestep  $t$ , which is obtained from the load flow calculation. In case the charging powers have already been set to their maximum value  $P_{ch, max}^s$  in the previous step of the optimization and the respective reverse power cannot be reduced further, it is set to zero and is thereby not considered at the following runs of the optimization, as shown in (3):

$$P_{rev, red}^t = \begin{cases} P_{rev}^t - \sum_{s \in S} P_{ch}^t, & P_{ch, prev}^{s,t} < P_{ch, max}^s \\ 0, & P_{ch, prev}^{s,t} = P_{ch, max}^s \end{cases} \quad \forall t \in T \quad (3)$$

Since simultaneously charging and discharging the BESS is not reasonable for this application, the optimization clearly differentiates between these two scenarios at each timestep. Hence, the charging powers are greater than zero and less than

the maximum admissible charging power during times of RPF or equal to zero during times of grid demand:

$$P_{ch}^{s,t} \leq \begin{cases} P_{ch, max}^s, & P_{rev} > 0 \\ 0, & P_{rev} = 0 \end{cases} \quad \forall s \in S, \forall t \in T \quad (4)$$

The discharging powers are determined respectively:

$$P_{disch}^{s,t} \leq \begin{cases} P_{disch, max}^s, & P_{demand} > 0 \\ 0, & P_{demand} = 0 \end{cases} \quad \forall s \in S, \forall t \in T \quad (5)$$

To avoid additional RPF by discharging the BESS, the summarized discharging powers  $P_{disch}^t$  of all BESS are constrained by the grid demand at each timestep  $P_{demand}^t$  according to (6). This way, the discharging powers do not exceed the grid demand.

$$P_{demand}^t \geq \sum_{s \in S} P_{disch}^t \quad \forall t \in T \quad (6)$$

The optimization is run repeatedly until the reverse power peaks cannot be reduced further. To implement this, the charging powers are increased at each step of the optimization by storing the previously determined values in the variable  $P_{ch, prev}^{s,t}$  and setting the charging powers of the current step to a value greater than or equal to  $P_{ch, prev}^{s,t}$ . This way they can either be increased further or remain at their maximum value:

$$P_{ch}^{s,t} \geq P_{ch, prev}^{s,t} \quad \forall t \in T \quad (7)$$

Each BESS can only store as much energy as its capacity allows. The amount of stored energy  $E^{s,t}$  is calculated by multiplying each charging or discharging power with the charge efficiency  $\eta_{ch}^s$  or discharge efficiency  $\eta_{disch}^s$  and the duration of a timestep  $t$  and adding them to the stored energy of the previous timestep  $E^{s,t-1}$ :

$$E^{s,t} = E^{s,t-1} + \left( \eta_{ch}^s \cdot t \cdot P_{ch}^{s,t} \right) - \left( \frac{1}{\eta_{disch}^s} \cdot t \cdot P_{disch}^{s,t} \right) \quad \forall s \in S, \forall t \in T \quad (8)$$

The amount of stored energy  $E^{s,t}$  must at all times be less than the maximum admissible energy amount  $E_{max}^s$  and greater than the required minimum energy amount  $E_{min}^s$ , as shown in (9) and (10):

$$E^{s,t} \leq E_{max}^s \quad \forall s \in S, \forall t \in T \quad (9)$$

$$E^{s,t} \geq E_{min}^s \quad \forall s \in S, \forall t \in T \quad (10)$$

To run the optimization repeatedly, the current maximum of reverse power  $P_{rev, max}$  is compared to the one of the previous timestep. When both values differ from each other, it indicates that the reverse power can still be reduced, and the optimization is run again with updated values in order to increase the charging powers and thereby reducing the reverse powers. When all reverse powers are reduced as much as possible, the timestep at which all BESS reach their maximum capacity is determined and the optimization process is initiated again for the following timesteps. The optimization

problem is formulated in Python using the software package Pyomo and solved using the GLPK solver.

### B. Charging and discharging profiles of individually controlled BESS

As a comparison to the proposed control method, charging and discharging profiles for BESS controlled individually at the household level are calculated according to Fig. 3.

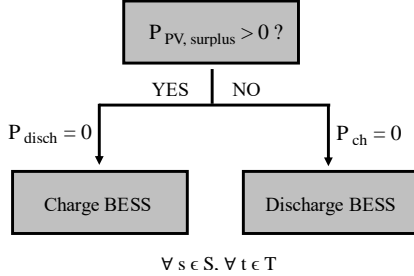


Fig. 3. Calculation of charging and discharging powers for individually controlled BESS

In this case, a BESS is either charged, when surplus PV power is present or discharged, when there is a surplus of power demand at the respective household. The individual charging and discharging powers are determined by two optimization problems with the objective of either maximizing the amount of energy stored at the BESS, when charging, or minimizing it when discharging. Since the two optimization problems follow the same pattern, only the charging process will be described in detail. As described above, the objective of the optimization problem used for determining the charging powers is to maximize the energy stored at the BESS:

$$\max(E) \quad (11)$$

To achieve this, each charging power is set to match the surplus PV power. In case the surplus PV power is greater than the maximum admissible charging power, the charging power is constrained to its maximum admissible value, as shown in (12).

$$P_{ch} \leq \begin{cases} P_{ch, \max} & P_{PV, \text{surplus}} \geq P_{ch, \max} \\ P_{PV, \text{surplus}} & P_{PV, \text{surplus}} < P_{ch, \max} \end{cases} \quad (12)$$

The amount of energy stored within each BESS is calculated according to (13) and constrained according to (9) and (10).

$$E = E_{t-1} + \eta_{ch} \cdot t \cdot P_{ch} \quad (13)$$

### III. RESULTS

The effectiveness of the proposed control method to reduce reverse power is compared to the one of individually controlled BESS, whose control aims at increasing self-consumption. For this, load flow calculations for both cases are conducted and compared to a baseline case, which does not consider any BESS. Each test considers great PV penetration levels within the grid due to consistently high solar irradiance. The impact of the different control methods on the active power flow at the transformer for the time period of one day is shown in Fig 4. Positive values represent reverse power, negative values represent a power demand from the MV grid. The peak PV power is 160.2 kW, the peak load amounts to 62.3 kW. A utilizable capacity of 10 kWh is assigned to each BESS. This value is based on the average of the peak powers

of the correlating PV systems, which is 10.475 kWp, and rounded to a typical BESS size. The maximum charging and discharging powers amount to 4.6 kW each, the charging and discharging efficiencies to 97 %, considering only the batteries themselves. These values are based on data sheets of leading German BESS manufacturers [17] [18]. All BESS provide their full capacity at the begin of the calculations

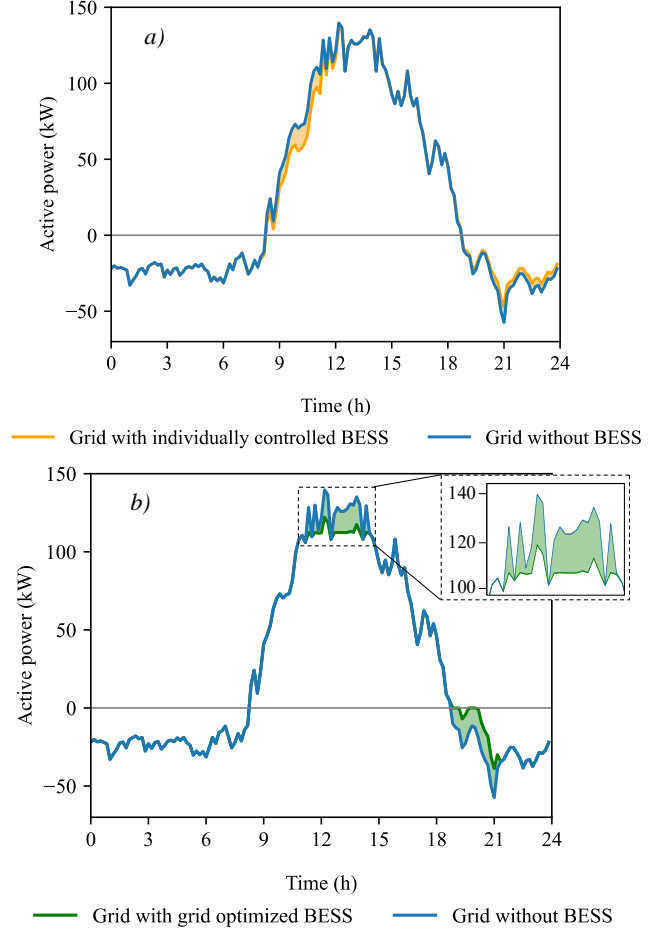


Fig. 4. Comparison of transferred active power at the transformer in a grid with individually controlled BESS and with BESS with grid optimized control

In the baseline case, RPF occurs between morning hours and midday with a maximum at around 12 pm. In the morning, the curve of the transferred active power in the grid with individually controlled BESS is slightly lower than the one in the baseline case due to the charging processes of the BESS. The discharging processes are initiated towards the end of the day and are used to cover the power demand of the respective households. Since the load of a single household is comparably low, the BESS are not fully discharged at the end of the regarded time period. The maximum of the reverse power in the baseline case is 139.7 kW, while the maximum of reverse power in the grid with individually controlled BESS amounts to 136.7 kW, which is a reduction by approx. 2.2 %. Fig. 4a) shows, that while individually controlled BESS do impact RPF, most of their charging processes occur before reverse power reaches its maximum along the simulated day. The individually controlled BESS reach their full capacity too early and are thereby not fit to reduce reverse power peaks.

The charging processes of the BESS with grid optimized control are contemporaneous with the occurrences of RPF peaks and thus perform RPF shaving. The maximum of the

RPF is reduced from 139.7 kW to 122.0 kW, which is a reduction by 12.6%. Furthermore, the BESS with grid optimized control fully discharge overnight and provide their full capacity the next day. The total reverse power of the baseline case is 5.3 MW, which is reduced by 4.5% to 5.1 MW in the case of individually controlled BESS as well as in the case of grid optimized BESS as both cases use the same capacity for a BESS. The comparison of individual and grid optimized control shows, that by establishing charging and discharging profiles corresponding to the RPF at transformer level, it is possible to identify and minimize RPF peaks. Thus, the reduction of the negative impacts of RPF peaks on the grid equipment is greater when applying grid optimized control to BESS. Furthermore, the adaptation of the charging and discharging powers to the state of the grid ensures, that the BESS are fully discharged at night and are thereby able to provide their full capacity at the next day.

To demonstrate the potential of the proposed method, the initial storage capacity is increased by raising the number of BESS to 13 and to 26, which represents a combination of 50% and 100% of PV systems in the grid with BESS (Fig 5).

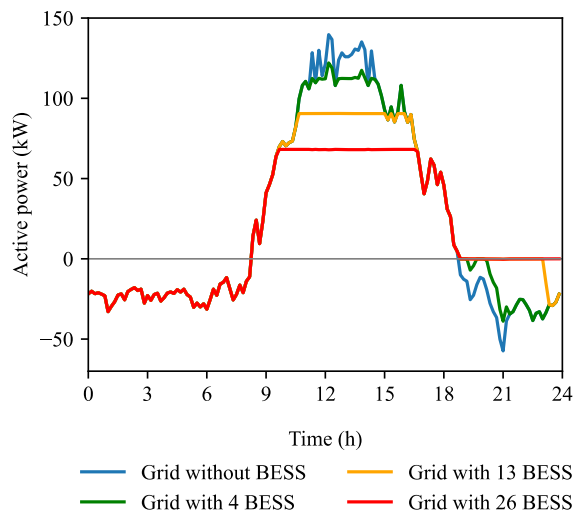


Fig. 5. Comparison of transferred active power at the transformer for higher numbers of integrated BESS with grid optimized control

With increasing numbers of BESS is not only the RPF reduced significantly, but also the grid demand is entirely covered overnight. This indicates a fitting scalability for future applications.

#### IV. CONCLUSION

In this paper, a method of controlling distributed BESS in a residential LV grid by defining charging and discharging profiles with the objective of reducing RPF peaks and increasing the local consumption of RES is proposed. The profiles are set by an algorithm, which uses a model of the LV grid and a load flow calculation to generate a forecast of the grid's state and a linear optimization process to determine the individual charging and discharging powers of all BESS. Applying those profiles to BESS in the LV grid and evaluating the results of a load flow calculation shows, that by adapting the charging behavior to power flow at transformer level, RPFs can be reduced with special consideration of RPF peaks. Thus, the proposed control method serves as an improvement of individual BESS control at the household level, which can

help reduce RPF as well but is not able perform RPF shaving. Since the accuracy of the forecast of the power flow heavily influences the success of the proposed control method, further research should compare the actual behavior of the power flow at the transformer to the one predicted by the algorithm and evaluate the influence of prediction errors on the proposed method. As an improvement, the integration of real time grid measurement data in the algorithm could be of interest. This way, forecasting errors can be minimized and the adaptability of the charging and discharging profiles to the actual power flow increases. The data can either replace the load flow calculation or be used to compare and adapt the charging and discharging profiles to the actual state of the grid.

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