Journal of Energy Storage 8 (2016) 320–338

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Impact analysis of different operation strategies for battery energy storage systems providing primary control reserve

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A R T I C L E I N F O

Article history:
Received 26 November 2015
Received in revised form 3 February 2016
Accepted 3 February 2016
Available online 18 February 2016

Keywords:
Battery energy storage systems
Primary control reserve
Frequency regulation
Ancillary services

A B S T R A C T

Regarding the supply of primary control reserve (PCR), stationary battery energy storage systems (BESS) are a promising alternative to fossil fuel power plants. They offer the ability to respond fast and precisely to grid frequency deviations and may contribute to reducing the must-run capacity of fossil fueled power plants.

In Germany, primary control reserve is traded on a separate auction market with specific regulations, which enable the BESS to use a number of measures to balance its charge level and preserve operability. However, little is known about how the requirements from primary control deployment and the measures to keep the BESS operational during PCR contract periods affect operational parameters of the system. This study investigates the impact of operation strategies on different parameters including energy exchange through schedule transactions, total energy turnover, full cycle equivalents (FCE), and state-of-charge (SOC) distributions in a case study for a 2 MWh BESS under the German regulatory framework.

The results of this study are key to the economic assessment of BESS providing PCR, to an optimization of BESS operation, and to an estimate of battery aging in this specific application field.

Based on battery operation simulations, individual elements of operation strategies are identified and their influence on BESS operational parameters is analyzed in a parameter variation. These elements include the chosen measures for charge level management, the SOC ranges, within which these measures are used, parameters defining the schedule transactions, and the prequalified power rating of the BESS.

The results show that the choice of the measures for charge level management, the choice of schedule transaction parameters and the prequalified power rating of the BESS have a major impact on energy exchange through schedule transactions. The choice of the measures for charge level management and the choice of schedule transaction parameters have limited influence on the total energy turnover and the resulting number of FCE. These values are mainly influenced by the system design.

1. Introduction

The electric grid, in contrast to other supply networks like the gas grid, does not have the capability of storing energy. Hence, the feed-in of power to the grid and the use of power from the grid need to be balanced at all times. The grid frequency is the main indicator for grid stability. Its nominal value in the ENTSO-E[1] grid is 50 Hz. When the power feed-in exceeds the electricity use, the grid frequency increases. In contrary, when the electricity use exceeds the feed-in, the frequency decreases. Primary control reserve (PCR) for frequency regulation is required to compensate occurring imbalances.

On a worldwide level, PCR is currently mainly supplied by conventional power plants and pumped hydro power plants. However, the discussion about the possibilities of using BESS for PCR supply came up during the 1980s [1]. A 17 MW/14 MWh BESS for frequency regulation based on lead-acid batteries was successfully operated by the utility BEWAG in Berlin between 1986 and 1993 [2]. In the following years the application of BESS for frequency regulation has been limited to only a number of applications [3] due to limited battery lifetimes and relatively high battery prices. Over the last few years, the situation has changed

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[1] The ENTSO-E (European Network of Transmission System Operators for Electricity) is an association of European transmission system operators which covers virtually all of Europe.

http://dx.doi.org/10.1016/j.est.2016.02.003
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Nomenclature

BESS	Battery energy storage system
C	Battery capacity (MWh)
E	BESS charge level (MWh)
f	Current grid frequency (Hz)
f_n	Nominal grid frequency (Hz)
FCE	Full cycle equivalents
P_{grid}	Grid-side power demand (MW)
P_{PC}	BESS's response to the grid-side power demand (MW)
P_{PQ}	Power output prequalified for primary control provision (MW)
P_{ST}	Charging/discharging power in schedule transactions (MW)
PCR	Primary control reserve
SOC	BESS state of charge (%)
t,t_k	Time (s)
TSO	Transmission system operator
ΔE_{DU}	Energy exchanged through deadband utilization (MWh)
ΔE_{OF}	Energy exchanged through overfulfillment (MWh)
ΔE_{PC}	Energy exchanged through primary control provision (MWh)
ΔE_{SC}	Self-consumption of the BESS (MWh)
ΔE_{ST}	Energy exchanged through schedule transactions (MWh)
$\Delta E_{transaction}$	Energy exchanged in a schedule transaction (MWh)
Δf	Frequency deviation (Hz)
$\Delta t_{contract}$	Contract period for a schedule transaction (h)
Δt_{lead}	Lead time for a schedule transaction (h)
η_{ch}	Charging efficiency (–)
η_{dis}	Discharging efficiency (–)

significantly with the fast development of lithium-ion based batteries for electromobile applications and their rapidly falling costs [4].

With the transformation of energy systems in various countries towards more sustainable systems, the shares of fluctuating renewable electricity generation will rise significantly. It is expected that, consequently, the quantity of required grid services to secure system stability will increase likewise [5]. This trend opens various opportunities for energy storage technologies. Together with the technological and cost development of batteries, BESS for stationary applications have become more and more interesting. In this context, several projects for PCR/frequency regulation have been realized recently [6,7]. Although BESS operation has been successfully demonstrated in a number of research and commercial projects, BESS for grid applications are still in focus of ongoing research activities.

1.1. Literature review

The state of the art of large-scale stationary battery systems, including technical and economic parameters, is reviewed by Poullikkas [8] and Hamidi et al. [9]. In stationary applications, especially on grid level, storage systems are always in competition with alternative flexibility measures [10]. In this context, Pearre et al. [11] introduce a general methodology for initial feasibility assessment of energy storage technologies for grid services. Oudalov et al. [12] present an overview of different energy storage technologies and their possible applications in electric power systems. It is shown that frequency regulation and the integration of renewables are the grid services that will most likely be asked for by utilities in the future and that BESS are the most suitable technology for PCR applications. A monetary value analysis identified PCR supply currently as the application with the highest financial benefit for the BESS owner and operator [13].

Regarding frequency regulation applications, different model-based approaches exist for analyzing the techno-economic performance, and optimal system sizing and operation of stand-alone BESS [14–19] and hybrid systems consisting e.g., of a wind power plant in combination with a BESS [20]. Another focus is put on lifetime and aging characterization for BESS in PCR applications [21,22]. Based on simulation results, Ding et al. [23] point out the improved frequency regulation performance of BESS compared to coal-fired power plants in terms of fast response, precise tracking and reliability. Hollinger et al. [24] compare cost structures of BESS and fossil fueled power plants providing PCR finding BESS to be competitive in the German PCR market. Environmental impacts of BESS for PCR supply are assessed by Stenzel et al. [25].

Results from BESS operation of a realized 1 MW BESS for grid applications show an outstanding performance of the BESS for PCR supply. The system has been prequalified by the responsible transmission system operator (TSO) and different recharge strategies have been investigated [26]. Comparable field test results of a 1.6 MW BESS for PCR together with BESSs lifetime considerations are reported by Swierczynski et al. [27,28].

Furthermore, several studies investigated the possibility of applying BESS for PCR/frequency regulation in small isolated power systems (island grids) in combination with high shares of renewable electricity generation. The range of subjects includes studies dealing with economic assessments [29], system design [30,31], and technical aspects including the development of control strategies [32]. It is shown that BESS in small isolated power systems with low grid inertia completely fulfill the frequency control requirements and that BESS can significantly increase the power system stability, the grid security, and the planning flexibility [31].

1.2. Research objectives

Here we show, in a model-based approach, how different parameters of a grid-connected BESS used for providing primary control are affected by the operation profile resulting from this specific application. Based on the German regulatory framework, this study focuses on operation strategies which take into consideration the scopes and degrees of freedom which have recently been published the German TSOs [33]. It analyses the impact of different parameters, which are part of the operations strategy, and points out the influence of system design. The energy flows between the battery and the grid are identified and assigned to their cause (primary control deployment vs. schedule transactions to balance the charge level). Results cover the energy turnover of the battery, the amount of energy exchanged in schedule transactions and battery parameters, which are particularly relevant for battery aging. This investigation is a case study for the German control area and uses high-resolution frequency data of the Continental European ENTSO-E grid. It is beyond the scope of this study to examine the impact on battery lifetimes and the resulting economic feasibility.

The first section of this paper gives a detailed description of the legal framework of the German primary control reserve market. In the remaining part of the paper, the simulation model is described and the results obtained from the simulations are presented.

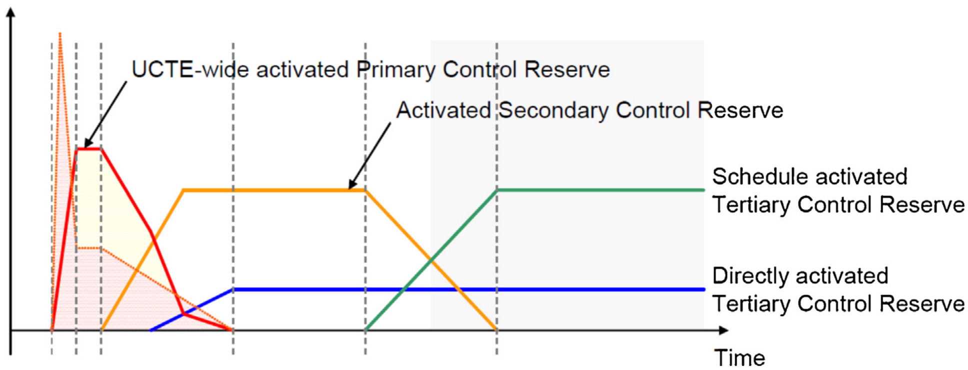

Fig. 1. Principle of frequency deviation and activation of reserves according to the ENTSO-E regulatory framework [35].

2. Regulatory framework

2.1. The market for control reserve in Germany

A permanent balance between electricity generation and demand is an important precondition for the stable and reliable operation of the electric grid. For the purpose of maintaining the balance between supply and demand, transmission system operators (TSOs) procure control reserve (also known as balancing power). A need for control reserve arises as soon as the current feed-in differs from current consumption. Deviations are e.g., caused by forecast errors regarding supply and demand or due to disturbances (e.g., power plant or power line outages). The indicator for the balance of supply and demand is the grid frequency. It drops when current consumption exceeds current generation, it increases when current generation exceeds current consumption. The objective of control reserve activation is, on the one hand, to maintain the system frequency within a narrow range around its target frequency, which is 50 Hz in the Continental European Synchronous Area (former Union for the Co-ordination of Transmission of Electricity, UCTE), on the other hand, to eliminate regional deviations in the balance from their reference value. For this purpose, different types of control reserve are deployed in a coordinated fashion for a dynamic and chronological interaction. According to the valid rules of ENTSO-E, the required types of control reserve in continental Europe include primary control reserve (PCR), secondary control reserve, and minute reserve, which is also called tertiary control reserve. These types differ according to the principle of activation and their activation speed (Fig. 1) [34].

The fastest measure of control power is primary control reserve. It stabilizes the system frequency at a stationary value after a disturbance or incident in the time-frame of seconds, but does not restore the system frequency and the power exchanges to their reference values. A steady state frequency deviation remains. In the next step, secondary control reserve is activated to bring the grid frequency back to its reference value and replaces PCR.

2.2. The primary control reserve market

In Germany, the three types of control reserve are traded on three different markets with distinct regulations. The primary control reserve market offers the most suitable conditions for battery storage systems to take part in the control power market due to limited capacity requirements and highest dynamic requirements. The capability of battery storage systems to respond in a highly accurate and dynamic manner is one of its key advantages compared to alternative technologies. The market for primary control reserve is therefore in focus of this study. The market framework is described in detail in the following section. A broader description of the load-frequency control concept and control reserve markets in Germany is given by Consentec [36].

The German transmission grid is divided in four control areas, each operated by a different TSO. The four TSOs established the so-called grid control cooperation in order to optimize control power deployment and the associated tendering procedure. In the case of primary control, the four interconnected control areas of the TSOs act comparable to one single German-wide control area [36].

The primary control reserve tendering procedure is organized via an internet platform (www.regelleistung.net). On this platform, calls for tenders are published, bids are processed, and bidders are informed about auction results. The call for tenders for PCR is symmetrical, meaning that there is no separate call for positive PCR and negative PCR. However, different technical units of one supplier can be deployed for positive and negative PCR. The contract period is one week and the minimum bid size is $\pm$1 MW. Pooling technical units (generation facilities, storage systems and controllable loads) enables suppliers with units smaller than 1 MW to comply with the minimum bid size and take part in the tendering process [34,36].

2.2.1. Bidding process and payment

In the bidding process each provider announces the amount of offered capacity and the related capacity price. The acceptance of bids is realized by capacity price ranking of all bids (capacity price merit-order). Bids are accepted until the tendered primary control capacity is met. If a bid is successful, the respective supplier must provide the offered amount of PCR throughout the whole contract period of one week. A failure to perform according to the market rules will lead to a fine and an exclusion from future bidding processes if a supplier fails to perform a second time. The compensation of primary control provision is realized by provider-specific capacity price payments (pay-as-bid) according to the offered capacity price (€/MW). A compensation of the actually deployed primary control energy based on an energy price (€/kWh) is not provided [34]. Table 1 shows a summary of the market characteristics for primary control reserve.

Table 1
Product characteristics of primary control reserve in Germany [36].

Primary control reserve (PCR)	
Tender period	One week
Product time-slice	None (total week)
Product differentiation	None (symmetric product)
Minimum bid amount	1 MW
Increment of bid	1 MW
Call for tender	Capacity price (€/MW) merit-order
Remuneration	Pay-as-bid (capacity price)

2.2.2. Prequalification

Prospective providers of the different types of control reserve have to complete a prequalification procedure to demonstrate their ability to meet the technical requirements in order to ensure the security of supply. In addition to technical competence, prospective providers also have to demonstrate their ability to perform to satisfaction according to the requested operational conditions and that their economic situation does not give any cause for concern. For primary control reserve the technical prequalification requirements include the specifications of automatic and complete activation within 30 s. The period t per incident with complete PCR activation to be covered is $0 < t < 15$ min, followed by a 15 min break between the next PCR call. Details about the prequalification test protocol can be found in [37]. The connecting TSO conducts the prequalification procedure for the technical units in its control area and is the sole contracting party of the supplier. [34,35]

2.2.3. Market size/PCR demand

The total demand for primary control in the ENTSO-E synchronous area of continental Europe is defined by the reference incident. Starting from undisturbed operation of the interconnected network, the reference incident is defined as a sudden loss of 3000 MW generating capacity (largest generation unit or generation capacity connected to a single bus bar in the synchronous area) which must be offset by primary control alone, without the need for customer load-shedding in response to a frequency deviation. The PCR to be maintained for each control area is determined annually. The total need of ±3000 MW PCR for the ENTSO-E Continental European Synchronous Area is distributed among the transmission system operators (TSOs) in proportion to the annual electricity feed-in. [35]

2.2.4. Primary control power activation

Primary control reserve is provided according to the principle of joint action by all TSOs interconnected within the ENTSO-E Synchronous Area Continental Europe. PCR is designed as frequency-proportional regulation. Its deployment proportionally follows the deviation of the grid frequency from its reference value (50 Hz). The deployment is fully controlled by the grid frequency and is realized by decentralized controllers of the participating technical units. The entire primary control reserve is activated in response to a quasi-steady-state frequency deviation of −200 mHz or more. Likewise, in response to a frequency deviation of +200 mHz or more, power generation must be reduced by the value of the entire primary control reserve [34,35]. The resulting power-frequency characteristic (*P*(*f*) characteristic) primary control of power activation normalized to the prequalified power output is shown in Fig. 2.

2.3. Scopes and degrees of freedom for batteries providing primary control reserve

The regulatory framework of the German primary control reserve market allows providers to deviate from proportional frequency control in particular cases. This is especially relevant for batteries providing primary control since they can use these opportunities for charge level management. In general, there are three options for the battery operator to balance the charge level and keep the battery within the operational range during primary control operation. These options are described in the framework agreement on scopes and degrees of freedom for PCR supply [33].

2.3.1. Option 1: overfulfillment

An optional overfulfillment of the required power output is permissible within the framework agreement. This overfulfillment may increase to 120% of the *P*(*f*) characteristic. However, the requirements of the *P*(*f*) characteristic have to be met and, consequently, an underfulfillment of the required power output is not permitted. This option can be used to selectively charge or discharge the battery if needed. Fig. 3 illustrates the permissible range of overfulfillment.

2.3.2. Option 2: deadband utilization

The deadband for primary control covers the frequency range from 49.99 to 50.01 Hz. Within this deadband, delivering primary control according to the *P*(*f*) characteristic is not mandatory. This gives battery operators the opportunity for charge level management. They can choose between complying with the *P*(*f*) characteristic and deviating from it (as shown in Fig. 4). However, counterproductive control behavior is not permitted, which implies that if positive primary control is required, the battery must not deliver negative primary control by charging the battery and vice versa. Operation of the battery must always contribute to grid stabilization. The operator has to verify system adequacy,

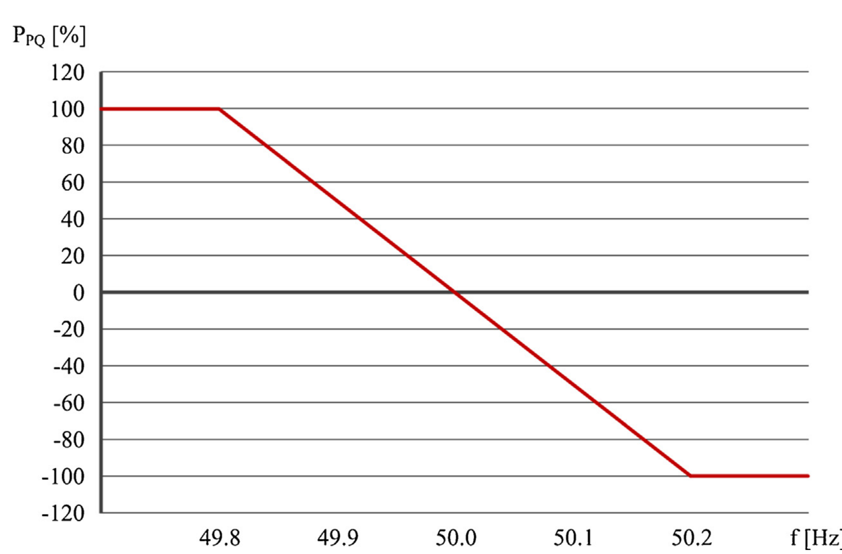

Fig. 2. P(f) characteristic of primary control power activation [34].

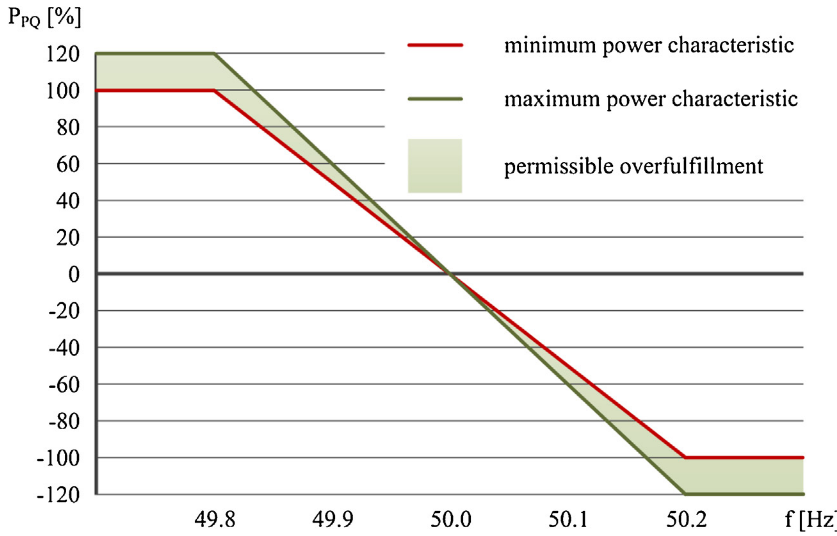

Fig. 3. Overfulfillment of required power output [33].

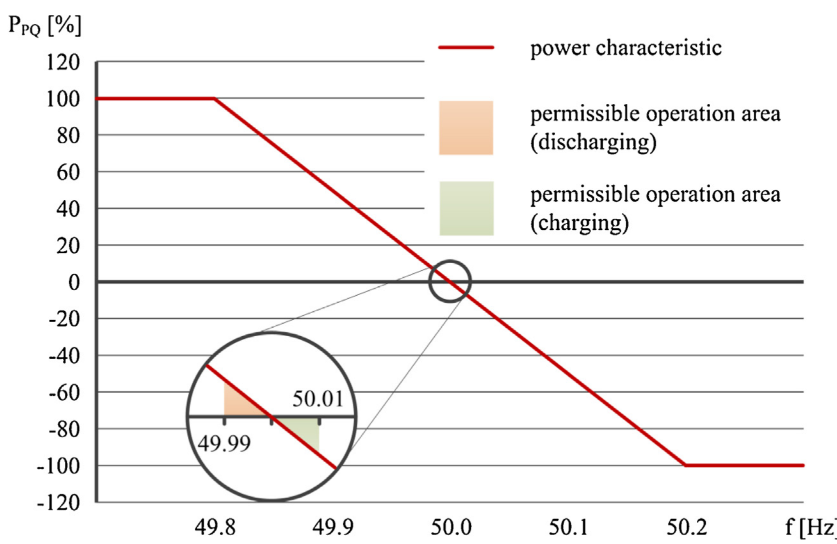

Fig. 4. Deadband and permissible operation range [33].

especially measuring accuracy of frequency measurement and control.

Using the deadband for charge level management is only possible with the frequency measurement accuracy being significantly higher than the deadband's range of tolerance. This is supposed to avoid counterproductive control behavior due to measuring inaccuracies. Fig. 4 visualizes the primary control deadband and its permissible utilization for charge level management.

2.3.3. Option 3: charging/discharging through schedule transactions

In order to restore the desired battery charge level, balancing energy can be purchased or sold on the intraday market, which is part of the electricity spot market. It has to be ensured that net PCR supply (battery power output minus power purchased/sold on the spot market) continues to comply with the PCR regulations. Charge level management and primary control delivery have to be energetically separated. When the BESS is charged or discharged with scheduled energy, its operating point is shifted to simultaneously enable primary control operation (Fig. 5). The BESS operator has to present the concept to the TSO responsible and notify the TSO 15 min before the operating point is shifted.

The intraday spot market is a wholesale electricity market where electricity is traded in relatively small volumes with short lead times. The products available on the intraday market include hourly and quarter-hourly electricity supply contracts. The minimum volume increment for a transaction is 0.1 MW. [38]. Fig. 6 illustrates the energy flows going into and coming out of the battery due to primary control provision and charge level management through schedule transactions.

On the German intraday market, a tender has to be placed 45 min before the scheduled energy transfer begins. Contracts can only begin at every full quarter of an hour. Thus, depending on the point in time, where the schedule transaction is initiated, up to 15 min waiting time might have to be added. Consequently, the lead time Δt_{lead} for charging/discharging is between 45 and 60 min, depending on the point in time, where a schedule transaction is initiated. In 2015, the time span between the tender placement and the physical performance of the contract was shortened to 30 min.

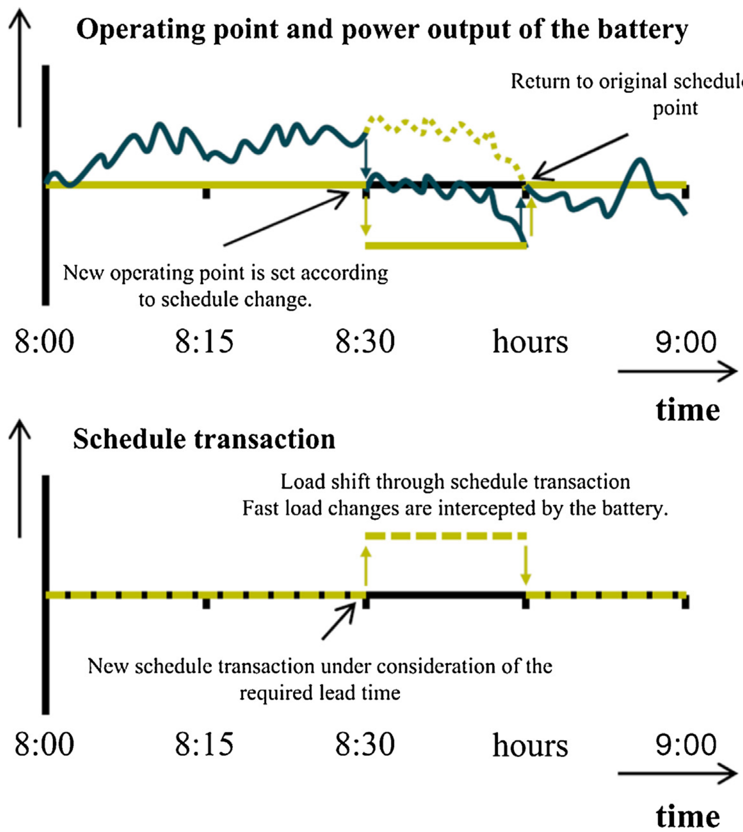

Fig. 5. Shift of the operating point of the BESS during schedule transactions [33].

While in options 1 and 2, the amount of energy which can be used for charge level management depends on the grid frequency, the energy purchased or sold on the electricity spot market (option 3) is independent from the grid frequency and can be used for major adjustments of the BESS charge level. However, while options 1 and 2 come free of charge, the energy purchased at the spot market is priced and therefore contributes to the BESS's operating costs. In turn, energy sold at the spot market generates additional revenues.

3. Methodology

3.1. General modeling approach

In order to investigate the impact of different operation strategies, a BESS operation simulation model has been developed. In this context, the term 'operation strategies' describes a combination of individual measures for charge level management, which aim at preserving the battery's operability. These individual measures include the battery design, the three options for charge level management described in Section 2.3, and several parameters which arise from the use of these options. The approach in this study is not to design different operation strategies and compare their impacts, but to analyze the influence of single measures, which are part of an operation strategy.

The total energy turnover of the battery is the sum of the energy turnover due to primary control deployment, which is determined by the grid frequency, and the amount of balancing energy exchanged through schedule transactions. In the impact analysis, a focus is put on the amount of balancing energy exchanged through schedule transactions. This is an important parameter since it depends on the operation strategy and determines the total energy turnover, and thus the amount of full cycle equivalents (FCE), and the operating costs of the battery. Furthermore, the SOC distributions and the *E*-rate distributions, which besides the FCE have a major impact on battery aging, are calculated.

3.2. The PCR simulation model

The overall model consists of three different parts: the frequency control module, the BESS simulation module and the

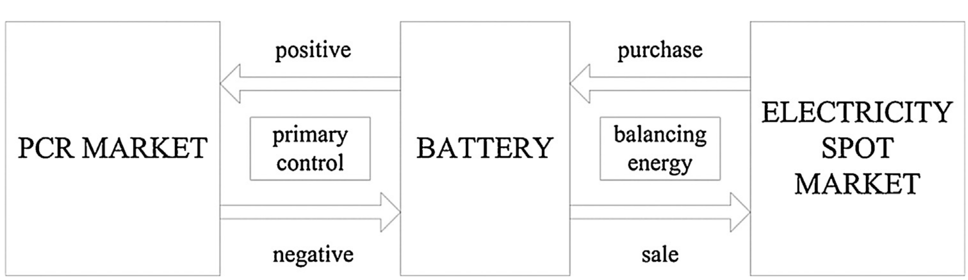

Fig. 6. Energy flows between the BESS and the corresponding energy markets.

statistical evaluation module. Fig. 7 shows the structure of the PCR simulation model.

The input data for the model include a grid frequency time series as well as several parameters to define the battery behavior and the charge level management. The simulation is time-discrete with a temporal resolution of one second. A case-study approach was chosen to investigate battery operation under the current German regulatory framework for primary control provision.

3.2.1. Frequency control module

The frequency control module simulates the requirements which result from the grid situation. It simulates the proportional frequency/active power control provided by the BESS and calculates the power demand from grid frequency data and the predefined tender size, which usually equals the power output prequalified for primary control provision P_{PQ}. $P_{grid}(t)$ reflects the grid-side power demand. It is proportional to the frequency deviation occurring in the grid:

$$P_{grid}(t) = P_{PQ} \times \frac{\Delta f(t)}{0.2\mathrm{Hz}} \tag{1}$$

The frequency deviation $\Delta f(t)$ indicates the difference between the current system frequency $f(t)$ at the time t and the nominal grid frequency $f_n = 50$ Hz.

$$\Delta f(t) = f_n - f(t) \tag{2}$$

$P_{PC}(t)$ reflects the BESS's response to the grid-side demand due to primary control. For charging processes ($P_{grid} < 0$), the condition

$$P_{PC}(t) = -\eta_{ch} \times P_{grid}(t) \tag{3}$$

must be fulfilled at all times. Power losses during charging are taken into consideration by the charging efficiency η_{ch}. For discharging processes ($P_{grid} > 0$), the condition

$$P_{PC}(t) = -\frac{1}{\eta_{dis}} \times P_{grid}(t) \tag{4}$$

must be fulfilled. The power output of the battery system is defined by the grid-side power demand. To compensate the power losses occurring during operation, the actual power output of the BESS must always be higher than the grid-side demand. Thus, the discharging efficiency η_{ch} is in the denominator.

3.2.2. BESS operation simulation module

The core of the model is the BESS operation simulation module. The BESS is modeled as a 'black box', which encompasses the battery itself and all auxiliary devices which are required to establish the grid connection (inverter, transformer) and to ensure operability (air-conditioning). The system is described by a set of parameters including the battery capacity in terms of energy C (MWh), its charging and discharging efficiencies (η_{ch}, η_{dis}), its self-consumption ΔE_{SC}, its charge level in terms of energy $E(t)$ and state of charge SOC(t), and its power output $P_{BESS}(t)$.

The BESS operation module gradually calculates the energy balance for every time step. For the energy balance at the time t_k, the energy content E of the BESS, the energy charged or discharged due to primary control (ΔE_{PC}), the additional charging or discharging energy resulting from measures for charge level management (ΔE_{OF}, ΔE_{DU}, ΔE_{ST}) and the self-consumption of the BESS (ΔE_{SC}) are taken into account:

$$E(t_{k+1}) = E(t_k) + \Delta E_{PC}(t_k) + \Delta E_{OF}(t_k) + \Delta E_{DU}(t_k) + \Delta E_{ST}(t_k) - \Delta E_{SC} \tag{5}$$

The contribution from primary control deployment is the battery power output $P_{PC}(t)$, integrated over time, multiplied with the charging efficiency for the case of charging. For the case of discharging, it is the battery power output $P_{PC}(t)$, integrated over time, multiplied with the inverse of the discharging efficiency.

$$\Delta E_{PC}(t_k) = \int_{t_{k-1}}^{t_k} P_{PC}(t)\mathrm{d}t \tag{6}$$

The additional charging or discharging energy resulting from measures for charge level management is divided into three terms, one for each option: overfulfillment (ΔE_{OF}), deadband utilization (ΔE_{DU}), and schedule transactions (ΔE_{ST}). The definitions of these terms depend on the state of the battery and, for options 1 and 2, on the grid frequency. They are listed in Tables 3–5.

Based on the energy balance (Eq. (5)), the state of charge (SOC) of the battery is calculated and the model verifies whether the SOC lies within the permitted SOC bandwidth

$$\mathrm{SOC}(t_k) = \frac{E(t_k)}{C} \tag{7}$$

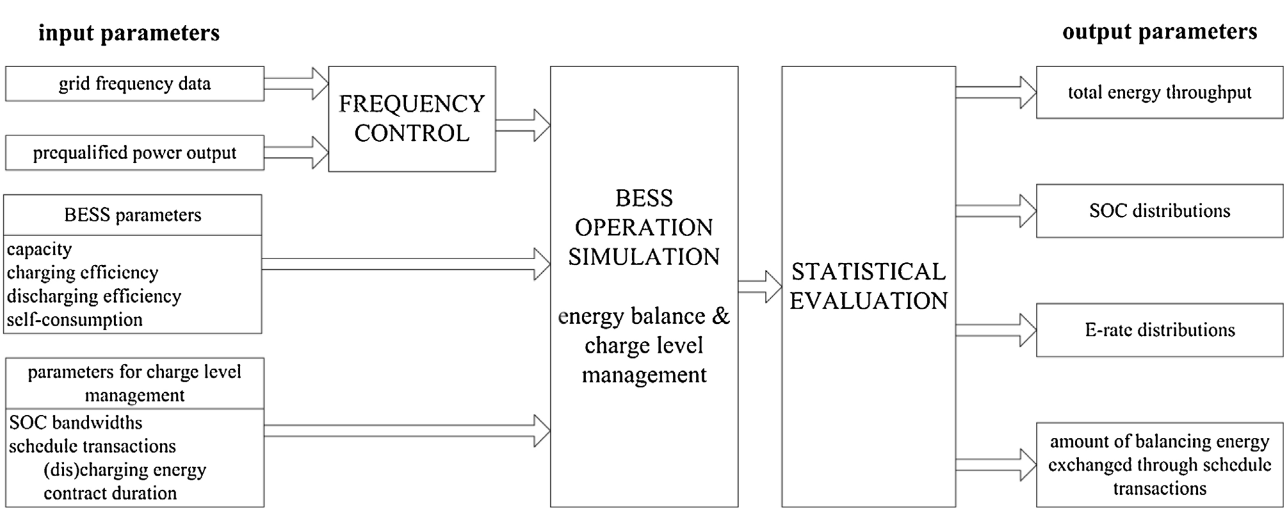

Fig. 7. Structure of the PCR simulation model.

Table 2
SOC limits and measures for charge level management applied in the simulations.

Charge level	Measure	Charge level	Measure
$SOC(t) \leq SOC_{1,low}$	Use overfulfillment (option 1) to charge battery	$SOC(t) \geq SOC_{1,high}$	Use overfulfillment (option 1) to discharge battery
$SOC(t) \leq SOC_{2,low}$	Utilize deadband (option 2) to charge battery	$SOC(t) \geq SOC_{2,high}$	Utilize deadband (option 2) to discharge battery
$SOC(t) \leq SOC_{3,low}$	Initiate schedule transaction (option 3) to charge battery	$SOC(t) \geq SOC_{3,high}$	Initiate schedule transaction (option 3) to discharge battery

Table 3
Simulation of overfulfillment (charge level management option 1).

	$SOC(t_k) \leq SOC_{1,low}$	$SOC_{1,low} < SOC(t_k) < SOC_{1,high}$	$SOC(t_k) \geq SOC_{1,high}$
$f > 50\,Hz$	$\Delta E_{OF} = 0.2 \times \Delta E_{PC}$	$\Delta E_{OF} = 0$	$\Delta E_{OF} = 0$
$f < 50\,Hz$	$\Delta E_{OF} = 0$	$\Delta E_{OF} = 0$	$\Delta E_{OF} = 0.2 \times \Delta E_{PC}$

If the SOC exceeds or falls below the predefined limits of the permitted bandwidth, the respective measure for charge level management will be applied. The charge management options described in Section 2.3 are implemented in the model and can be chosen individually or in arbitrary combination. The options, which are applied in a simulation, are selected before the respective simulation is run. For each option, the SOC limits ($SOC_{i,high}$ being the upper limit for option i, $SOC_{i,low}$ being the lower limit for option i) can be predefined individually. In addition, parameters for the schedule transactions (option 3) are defined. They comprise the power rating and the amount of energy for each transaction. Table 2 lists the individual measures for charge level management and their respective SOC limit.

In order to determine the value for ΔE_{OF}, six different case are distinguished. If the SOC exceeds the upper SOC limit ($SOC_{1,high}$) and the BESS has to deliver positive primary control ($f < 50\,Hz$), it exceeds the required power output by 20%. If the SOC falls below the lower SOC limit ($SOC_{1,low}$) and the BESS has to deliver negative primary control ($f > 50\,Hz$), the battery charges with 120% of the required power output. In these two cases, ΔE_{OF} is 20 % of ΔE_{PC}, in all other cases, ΔE_{OF} is zero. Table 3 gives an overview of the six cases to be distinguished. Although the regulatory framework allows for an overfulfillment between 0 and 20 %, the model only takes into account the maximum value for overfulfillment.

Charge level management option 2 is simulated through the parameter ΔE_{OF}. Like for option 1, six cases are distinguished. In normal operation (no charge level management required), ΔE_{DU} is zero. However, when the SOC is outside the permitted bandwidth ($SOC(t) \leq SOC_{2,low}$ or $SOC(t) \geq SOC_{2,high}$) and the grid frequency is inside the primary control deadband of $(50 \pm 0.01)\,Hz$, the charge level management can take advantage of this situation and the battery may deviate from proportional control. In two cases ΔE_{DU} equals $-\Delta E_{PC}$, i.e., the battery does not charge or discharge although this would be required to comply with proportional frequency control. In the first case, the SOC exceeds the upper limit and the grid frequency is in the range between 50.00 Hz and 50.01 Hz (the battery would have to charge). In the second case, the SOC is below the lower limit and the grid frequency is in the range between 49.99 and 50.00 Hz (the battery would have to discharge).

The simulation of charging and discharging balancing energy through schedule transactions is reflected by the term ΔE_{ST}. Again the model verifies for every time step whether the SOC complies with the predefined bandwidth. If the SOC exceeds the upper limit ($SOC_{3,high}$), the model will detect this and simulate a corresponding discharge process after the lead time Δt_{lead} has passed. If the SOC falls below the lower limit ($SOC_{3,low}$), the model will simulate a charging process after the lead time Δt_{lead} has passed.

A schedule transaction is characterized by three parameters: the amount of energy $\Delta E_{transaction}$, which is purchased and charged into the battery or sold and discharged from the battery, the contract duration $\Delta t_{contract}$ and the charging or discharging power P_{ST}. The power output is constant during the energy transfer. The amount of energy per transaction results from the power rating and the duration determined by the respective contract:

$$P_{ST} \times \Delta t_{contract} = \Delta E_{transaction} \tag{8}$$

All three parameters are specified before a simulation is run. When a charge/discharge process occurs during the simulation, the parameter ΔE_{ST} is set to the value indicated in Table 5, until the transaction period ends.

After a schedule transaction has been put in line, a second transaction cannot be initiated until the first one is completed.

3.2.3. Statistical evaluation module

The state of the battery and the power flows exchanged with the grid are recorded for every time step. Based on these SOC and power output profiles, the statistical evaluation module calculates parameters relevant for battery aging.

An important parameter for assessing battery cycle aging is the number of full cycle equivalents (FCE). A full cycle designates a complete discharge and recharge of a battery. The energy throughput in one full cycle is therefore equivalent with twice the capacity of the battery. Since batteries are usually not completely charged and discharged during operation, but perform smaller cycles instead. In order to enable a comparison between batteries of different capacities and cycles depths, the number of full cycle equivalents is calculated based on the total energy throughput.

$$FCE = \frac{\sum_k |E(t_k)|}{2C} \tag{9}$$

Furthermore, frequency distributions for the SOC and the E-rates occurring during operation are generated. The E-rate is a measure of the rate at which a battery is charged or discharged relative to its maximum capacity.

Table 4
Simulation of deadband utilization (charge level management option 2).

	$SOC(t_k) \leq SOC_{2,low}$	$SOC_{2,low} < SOC(t_k) < SOC_{2,high}$	$SOC(t_k) \geq SOC_{2,high}$
$50\,Hz < f \leq 50.01\,Hz$	$\Delta E_{DU} = 0$	$\Delta E_{DU} = 0$	$\Delta E_{DU} = -\Delta E_{PC}$
$49.99\,Hz \leq f < 50\,Hz$	$\Delta E_{DU} = -\Delta E_{PC}$	$\Delta E_{DU} = 0$	$\Delta E_{DU} = 0$

Table 5
Simulation of schedule transactions (charge level management option 3).

$\mathrm{SOC}(t_k) \le \mathrm{SOC}_{3,\mathrm{low}}$	$\mathrm{SOC}_{3,\mathrm{low}} < \mathrm{SOC}(t_k) < \mathrm{SOC}_{3,\mathrm{high}}$	$\mathrm{SOC}(t_k) \ge \mathrm{SOC}_{3,\mathrm{high}}$
$\Delta E_{\mathrm{ST}}(t_k + \Delta t_{\mathrm{lead}}) = \eta_{\mathrm{ch}} \int_{t_k} P_{\mathrm{ST}} \mathrm{d}t$	$\Delta E_{\mathrm{ST}}(t_k + \Delta t_{\mathrm{lead}}) = 0$	$\Delta E_{\mathrm{ST}}(t_k + \Delta t_{\mathrm{lead}}) = \frac{1}{\eta_{\mathrm{dis}}} \int_{t_k} P_{\mathrm{ST}} \mathrm{d}t$

4. Model calculations

4.1. Data basis

The calculation of primary control deployment is based on a time series of the continental European transmission grid frequency. This time series has been recorded by the Swiss TSO Swissgrid AG and is available for five characteristic months (153 days) from the years 2013 and 2014 in a one-second resolution.

Fig. 8 shows the histogram of the grid frequency time series used in this study. It contains 13,219,200 data points. The mean value of the grid frequency is 49.9983 Hz. For the simulations, a synthetic time series of one year has been created by randomly distributing the 153 original days over 52 weeks. The redistribution was implemented with the restriction that a day in the synthetic time series stays the same day of the week as in the real time series. This restriction aims at conserving effects from energy trading (e.g., start-up ramps of power plants) which occur regularly during the day and may differ between weekdays and weekend days.

4.2. Structure of the investigation and general assumptions

A parameter variation in the context of this study is a set of simulations where one parameter is varied while all other parameters of the simulation are held constant (ceteris paribus assumption). The parameter variations in this study are divided into two parts. In the first part, the impacts of using the options described in Section 2.3 are analyzed and a reference case as a basis for comparing the impacts of the other parameters is defined. The second section includes the parameter variations for different operation parameters.

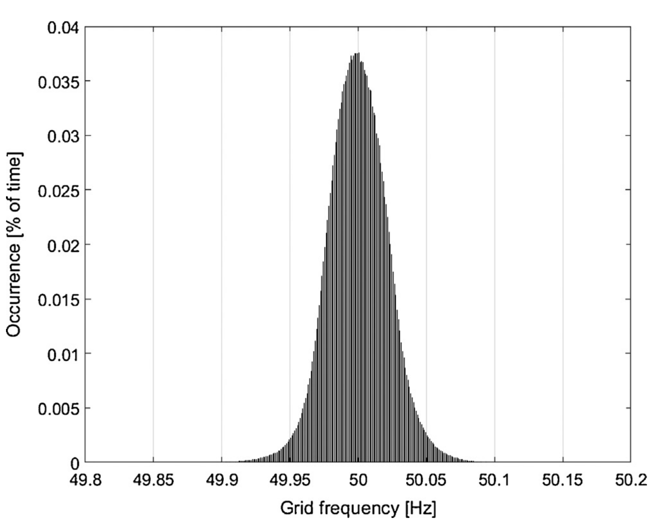

Fig. 8. Histogram of the grid frequency time series used for the simulations.

4.2.1. Comparison of different options for charge level management

In this section, the options chosen for charge level management are varied. The parameters held constant in the first section are listed in Table 6

Option 3 (schedule transactions) is included in all simulations. Without this option, the battery would arrive at SOC = 0 % (completely discharged) or SOC = 100% (fully charged) at some point of time during the simulation and thus become inoperable. The four different simulations performed are listed in Table 7

4.2.2. Parameter variations

This study comprises five different parameter variations. In the first parameter variation, the SOC limits, which mark the point where a schedule transaction is induced, are subject to variation. Different SOC ranges for overfullfillment and deadband utilization are compared in the second parameter variation. Parameter variations 3 and 4 focus on the schedule transactions again. No. 3 compares different charging/discharging power outputs which also mean different amounts of charging/discharging energy. In parameter variation 4, the power output is kept constant while the effects of the the two possible spot market contract durations (15 min and one hour) are compared. In parameter variation 5, the 1 $\mathrm{MW_{PQ}}$/2 MWh BESS, which is the design used in all simulations, is compared with a 2 $\mathrm{MW_{PQ}}$/2 MWh BESS. In parameter variations 4 and 5, the parameter $\mathrm{P_{ST}}$ is set to 0.8 MW, since simulations with $P_{\mathrm{ST}} \le 0.7$ MW led to invalid results (Table 8).

4.2.3. General assumptions for the simulations

In addition to the premises listed above, the following assumptions underlie the model calculations:

- The SOC limits chosen for the simulations presented in this paper, the charging and discharging efficiencies and the self-consumption are typical values for a lithium-ion BESS.
- Battery aging effects are not considered in the calculations.
- Primary control is deployed in the deadband except for certain cases in which the deadband is used for charge level management (see Section 3.2.2).
- Schedule transactions are initiated automatically when required. Offers on the spot market are always accepted.

5. Results

In this section, the results of the distinct simulations are presented and the effects of the parameter variations compared. The focus is put on the amount of balancing energy traded in scheduled transactions. Furthermore, the full cycle equivalents (FCE) per year and the SOC and *E*-rate distributions over time, which are relevant parameters for battery aging, are shown.

5.1. Comparison of different options for charge level management

In the first scenario, the effects of the different options for charge level management, which are explained in Section 2.2, are compared. Fig. 9 shows the energy exchange through schedule

Table 6
Simulation parameters held constant in the variation of charge level management options.

Parameter	Value
BESS capacity C (MWh)	$C = 2\text{MWh}$
Prequalified power output P_{PQ}	$P_{PQ} = 1\text{MW}_{PQ}$
Charging efficiency η_{ch}	0.95
Discharging efficiency η_{dis}	0.95
Self-consumption per second ΔE_{SC}	$\Delta E_{SC} = -3.85 \times 10^{-6}\text{MWh}$ [25]
SOC limits for the option "overfulfillment" ($SOC_{1,low}$, $SOC_{1,high}$)	$SOC_{1,low} = SOC_{1,high} = 50\%$
SOC limits for the option "deadband utilization" ($SOC_{2,low}$, $SOC_{2,high}$)	$SOC_{2,low} = SOC_{2,high} = 50\%$
SOC limits for the option "schedule transaction" ($SOC_{3,low}$, $SOC_{3,high}$)	$SOC_{3,low} = 30\%; SOC_{3,high} = 70\%$
Schedule transaction parameters	$P_{ST} = 0.5\text{MW}; \Delta t_{contract} = 1\text{h}$

Table 7
Options applied for charge level management.

Simulation	Option applied for charge level management
ST only	Schedule transactions (ST)
ST + OF	Schedule transactions (ST) + overfulfillment (OF)
ST + DU	Schedule transactions (ST) + deadband utilization (DU)
ST + OF + DU	Schedule transactions (ST) + overfulfillment (OF) + deadband utilization (DU)

We choose simulation 'ST + OF + DU' as the reference case for the following parameter variations.

transaction for a 1 MW_{PQ}/2 MWh battery system with different options for charge level management applied. It is apparent from this chart that the amounts of energy discharged through schedule transactions are on a considerably lower level compared to the energy charged. This is due to the fact that energy conversion losses and the energy self-consumption of the battery system need to be balanced. In addition, a slightly larger demand for positive than for negative power control reserve was observed.

Furthermore, it can be seen that overfulfillment and deadband utilization reduce the required amount of balancing energy to charge the battery by around 13% each, from 195.5 to 168.5 (overfulfillment) and 171.5 MWh (deadband utilization) respectively. Combining these two options leads to a reduction by 28 % of energy charged through schedule transactions to 140.5 MWh. In this simulation, using overfulfillment does not lead to a reduction in energy discharged through schedule transactions. However, using deadband utilization or the combination of deadband utilization and overfulfillment lower the amount of discharged energy by 12% and 26% respectively. Overall, these results indicate that using overfulfillment and deadband utilization as measures for charge level management has a significant impact on the amount of balancing energy exchanged through scheduled transactions.

Table 9 contains further simulation results with regard to the total energy throughput, the number of FCE and the share of energy exchanged through schedule transactions in total exchanged energy. It can be seen from the data that using overfulfillment leads to higher a higher energy throughput, while deadband utilization causes a lower energy throughput. This is an obvious result, since overfulfillment leads to 20% higher power outputs during control reserve retrievals. In the simulations without deadband utilization, frequency/active power control takes place throughout the complete frequency range including the deadband. The lower energy throughput in the case of deadband utilization is due to the reduced amount of retrievals. A combination of the two options (ST + OF + DU) results in an energy throughput lower than in the simulation without overfulfillment or dead band utilization, but higher than in the simulation with schedule transactions and deadband utilization. Correspondingly, the number of full cycle

Table 8
Overview of parameter variations.

No.	Varied parameter	Simulations performed
1	SOC limits for the option "schedule transaction" ($SOC_{3,low}$, $SOC_{3,high}$)	30–70%* 20–80% 10–90% 10–80% 20–90%
2	SOC limits for the options "overfulfillment" ($SOC_{1,low}$, $SOC_{1,high}$) and "deadband utilization" ($SOC_{2,low}$, $SOC_{2,high}$)	$SOC_{1,low} = SOC_{1,high} = SOC_{2,low} = SOC_{2,high} = 50\%$ (simulation '50/50')* $SOC_{low,1} = SOC_{low,2} = 40\%$ $SOC_{high,1} = SOC_{high,2} = 60\%$ (simulation '40/60') $SOC_{low,1} = SOC_{low,2} = 50\%$ $SOC_{high,1} = SOC_{high,2} = 70\%$ (simulation '50/70')
3	Charging/discharging power output in schedule transactions P_{ST} and contract duration $\Delta t_{contract}$	$P_{ST} = 0.8\text{MW}; \Delta t_{contract} = 15\text{min}$ $P_{ST} = 0.8\text{MW}; \Delta t_{contract} = 1\text{h}$ $P_{ST} = 0.5\text{MW}; \Delta t_{contract} = 1\text{h}^*$ $P_{ST} = 0.2\text{MW}; \Delta t_{contract} = 1\text{h}$
4	Prequalified power output P_{PQ}	$P_{PQ} = 1\text{MW}$ $P_{PQ} = 2\text{MW}$ In this parameter variation, P_{ST} is set to 0.8 MW.

Simulations marked with a star (*) correspond to the reference case 'ST + OF + DU'.

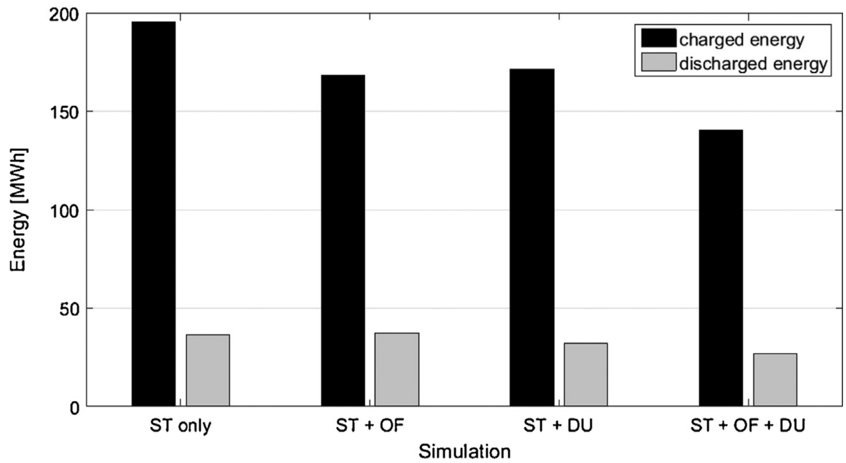

Fig. 9. Energy exchange through schedule transactions—comparison of different options for charge level management for a 1 MW_{PQ}/2 MWh battery system.

Table 9
Charging/discharging energy and full cycle equivalents for different charge level management measures.

Simulation	ST only	ST + OF	ST + DU	ST + OF + DU
Total energy charged into battery (MWh)	549	567	517	530
Total energy discharged into grid (MWh)	380	397	351	364
FCE/a	232	241	217	223
Share of energy charged through schedule transactions in charging energy total (%)	35.6	29.7	33.2	26.5
Share of energy discharged through schedule transactions in discharging energy total (%)	9.6	9.5	9.1	7.4

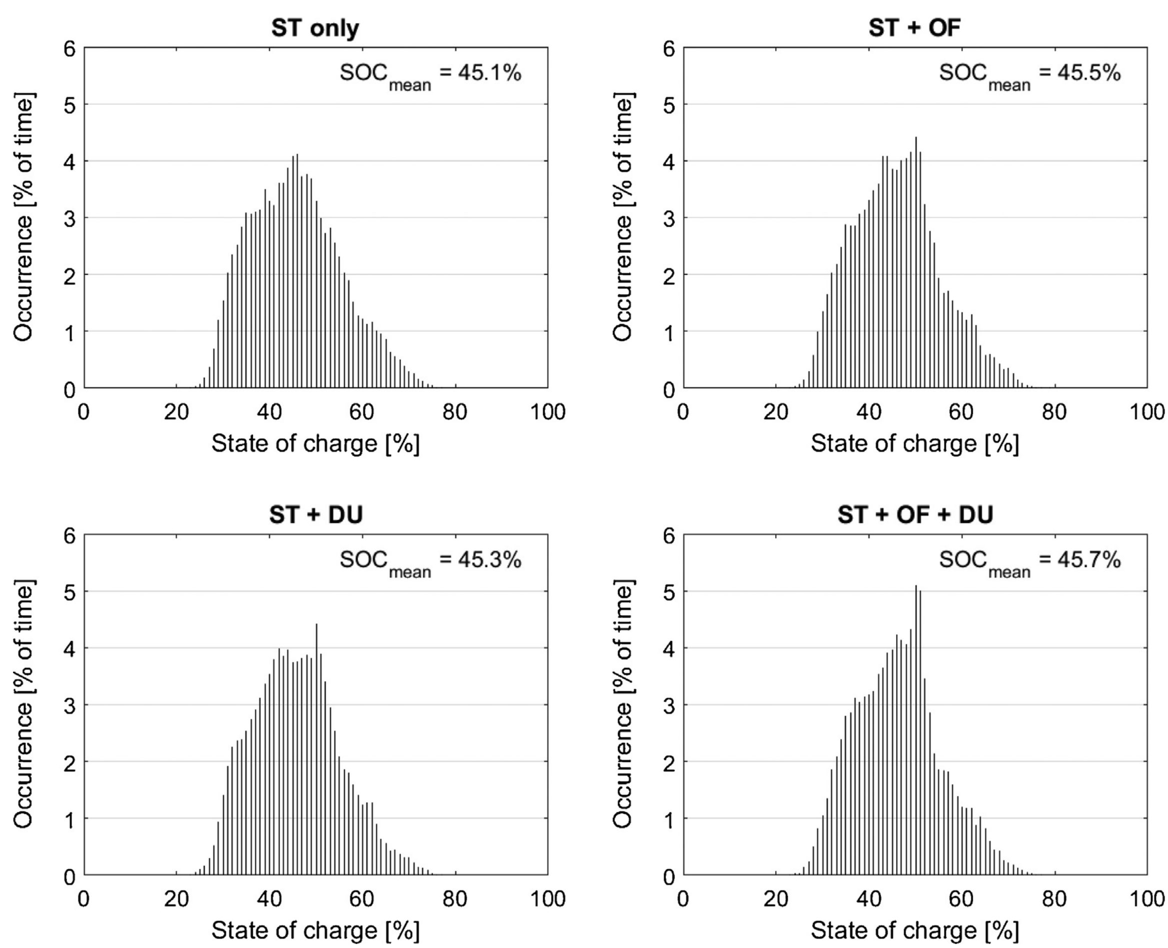

Fig. 10. SOC distributions over time—comparison of different options for charge level management for a 1 MW_{PQ}/2 MWh battery system.

equivalents varies between 217 and 241 FCE per year for these simulations with the lowest value for simulation “ST + DU” and the highest for simulation “ST + OF”. The two bottom rows in Table 9 show the share of energy charged through schedule transactions in charging energy total and share of energy discharged through schedule transactions in discharging energy total. When no additional measure of charge level management is applied (“ST only”), roughly one third of the energy flowing into the battery is schedule energy. Relating to the energy flowing out of the battery, the share of schedule energy is approximately one tenth. However, if both additional options are applied, both the share of energy discharged and the share of energy charged through schedule transactions decreases from 35.6 to 26.5% and from 9.6 to 7.4% respectively.

As can be seen from Fig. 10, the SOC distributions over time are characteristically shaped for each simulation. The distributions are unimodal with their modes in the area between 44 and 50% SOC. The average SOC does not significantly vary with values between 45.1 and 45.7%. The minimum SOC reached is 17% in the ‘ST only’ simulation, the maximum SOC is 85%, reached in the ‘ST + DU’ simulation. In the period between the initiation of a schedule transaction and actual charging or discharging process, the SOC may exceed or fall below the predefined limits.

5.2. Results of the parameter variations

5.2.1. Parameter variation 1

In the first parameter variation, simulations with different permissible SOC ranges are compared. Here, the SOC range refers to the range between $SOC_{3,low}$ and $SOC_{3,high}$, which are the limits for recharging or discharging through schedule transactions. In order to avoid the battery reaching states where it becomes inoperable (fully charged or fully discharged), $SOC_{3,low}$ and $SOC_{3,high}$ have to be chosen adequately. In addition to the 30–70% simulation (which corresponds to simulation ‘ST + OF + DU’), two simulations with symmetrical permissible SOC ranges (20–80 and 10–90%) and two simulations with asymmetrical permissible SOC ranges (10–70, 10–80 and 20–90%) are performed. In the 10–70% simulation, states occur, in which the battery is not operable. Hence, this simulation is not further analyzed. In all other simulations, the battery is operable all the time, however, critical states, in which the SOC falls below 5% or exceeds 95%, occur in the 10–90%, in the 10–80% and in the 20–90% simulations.

Fig. 11 compares the energy exchange through schedule transactions for the different simulations. In the three simulations with symmetrical SOC ranges, the energy exchanged through schedule transactions decreases from 140.5 to 93 MWh (charged energy) and from 27 to 5.5 MWh (discharged energy) as the permissible SOC range broadens. The results of the two asymmetrical simulations indicate that a lower $SOC_{i,low}$ limit leads to lower amounts of charged energy through scheduled transactions, while a higher $SOC_{i,high}$ limit results in lower amounts of discharged energy.

Table 10 shows the total amounts of energy flowing through the battery, the number of FCE and the share of energy exchanged through schedule transactions in total exchanged energy for the first parameter variation. All these parameters decrease with increasing permissible SOC range. The lowest values for total energy turnover and FCE and the lowest shares of energy charged (18.4%) and discharged (1.6%) through schedule transactions in total charging energy occur in the 10–90% simulation.

The permissible SOC range has a major impact on the SOC distributions over time (Fig. 12). Broader permissible SOC ranges lead to broader SOC distributions with a significantly smaller modus. Furthermore, the permissible SOC range has a strong influence on the average SOC, which decreases with broadening permissible SOC bandwidth.

5.2.2. Parameter variation 2

In the second parameter variation, the SOC ranges, in which overfulfillment and deadband utilization are applied, are varied. The 50/50% simulation corresponds to the reference case, where overfulfillment and deadband utilization are applied throughout the entire SOC bandwidth. If the SOC falls below 50%, charge level management is used to decelerate a further decrease in SOC, if it exceeds 50%, charge level management is used to decelerate a further increase in SOC. Two simulations with distinct SOC bandwidths for charge level management are run and the results compared to the 50/50% simulation. In the 40/60 simulation, there is no charge level management in the range between 40 and 60% SOC. Overfulfillment and deadband utilization are applied only below 40 and above 60%. In the 50/70 simulation, these limits are shifted to 50 and 70% SOC, allowing the battery to accumulate energy from control reserve retrievals and sell the additional energy in schedule transactions.

Fig. 13 presents the results of the second parameter variation in terms of energy exchanged through schedule transactions. Shifting the limits to 40 and 60% SOC leads to an increase in both charged (+5%) and discharged energy (+35%). This is due to the fact that the options overfulfillment and deadband utilization play a minor role in this simulation. In order to compensate for the reduced effectiveness of charge level management by options 1 and 2, more balancing energy from schedule transactions is required. The shift to 50 and 70% SOC results in a reduction of charged energy (−9%) and a 78% increase of energy discharged through schedule transactions compared to the reference simulation.

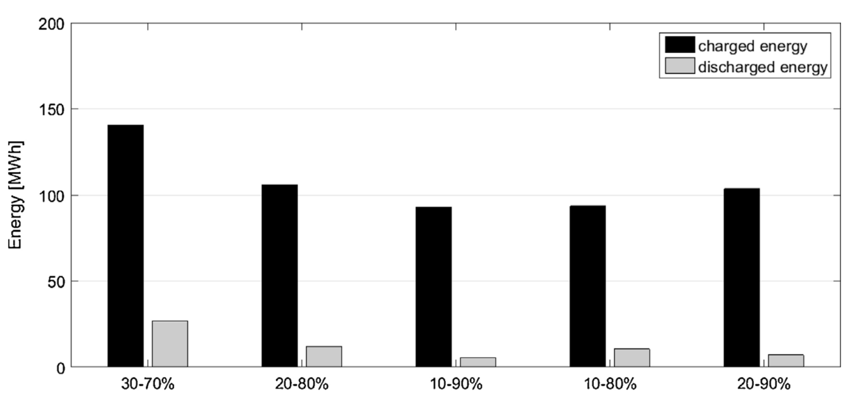

Fig. 11. Energy exchange through schedule transactions—comparison of permissible SOC ranges for a 1 MW_{PQ}/2 MWh battery system.

Table 10
Charging/discharging energy and full cycle equivalents in parameter variation 1.

Simulation	30–70%	20–80%	10–90%	10–80%	20–90%
Total energy charged into battery (MWh)	530	514	507	509	512
Total energy discharged into grid (MWh)	364	348	342	344	346
FCE/a	223	216	212	213	214
Share of energy charged through schedule transactions in charging energy total (%)	26.5	20.6	18.4	18.4	20.2
Share of energy discharged through schedule transactions in discharging energy total (%)	7.4	3.4	1.6	3.1	2.0

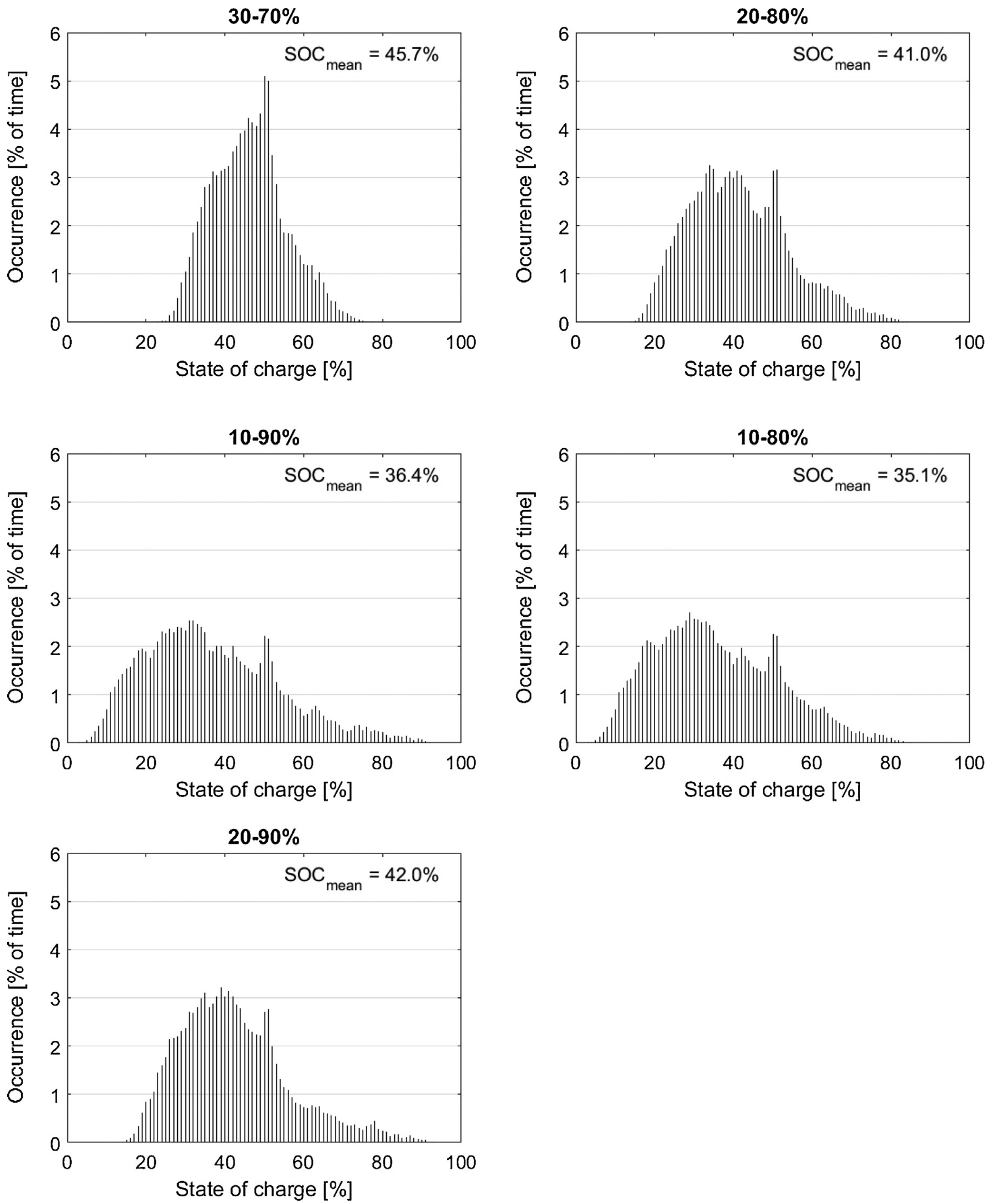

Fig. 12. SOC distributions over time—comparison of permissible SOC ranges for a 1 MW_{PQ}/2 MWh battery system.

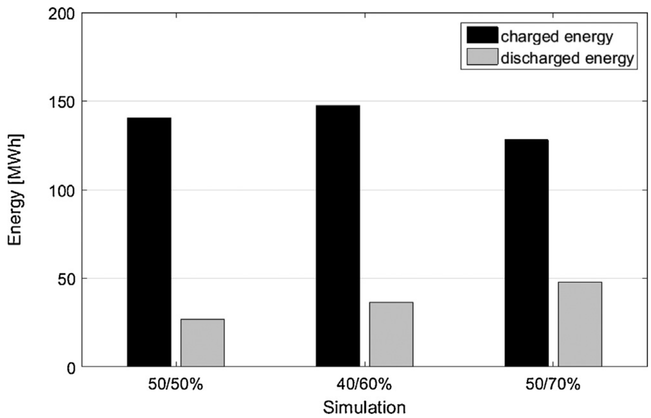

Fig. 13. Energy exchange through schedule transactions—comparison of different SOC limits for overfulfillment and deadband utilization for a 1 MW_{PQ}/2 MWh battery system.

Table 11 provides the simulation results for parameter variation 2 in terms of charging/discharging energy, FCE and share of energy charged through schedule transactions in total charging/discharging energy. Both in the 40/60% and in the 50/70% simulation, the total amounts of energy exchanged between the battery and the grid are lower than in the reference case, which implies a lower number of FCE as well. The reason for this effect is that no charge level management with additional charged or discharged energy is applied between 40 and 60% SOC or 50 and 70% SOC respectively. The share of energy charged through schedule transactions in total charging energy is the highest in the 40/60% simulation.

Shifting the SOC limits for charge level management also influences the SOC distributions over time. This is shown in Fig. 14. In the 40/60% simulation, the peak of the histogram shifts from 50 to 40% SOC. Moreover, the peak is less pronounced than in the 50/50 % simulation. Comparing the 50/70% to the 50/50% simulation, we find that the peak of the distribution does not significantly shift and is equally pronounced. All three distributions are unimodal

Table 11
Charging/discharging energy and full cycle equivalents in parameter variation 2.

Simulation	50/50	40/60	50/70
Total energy charged into battery (MWh)	530	518	525
Total energy discharged into grid (MWh)	364	352	358
FCE/a	223	217	221
Share of energy charged through schedule transactions in total charging energy (%)	26.5	28.5	24.4
Share of energy discharged through schedule transactions in total discharging energy (%)	7.4	10.4	13.4

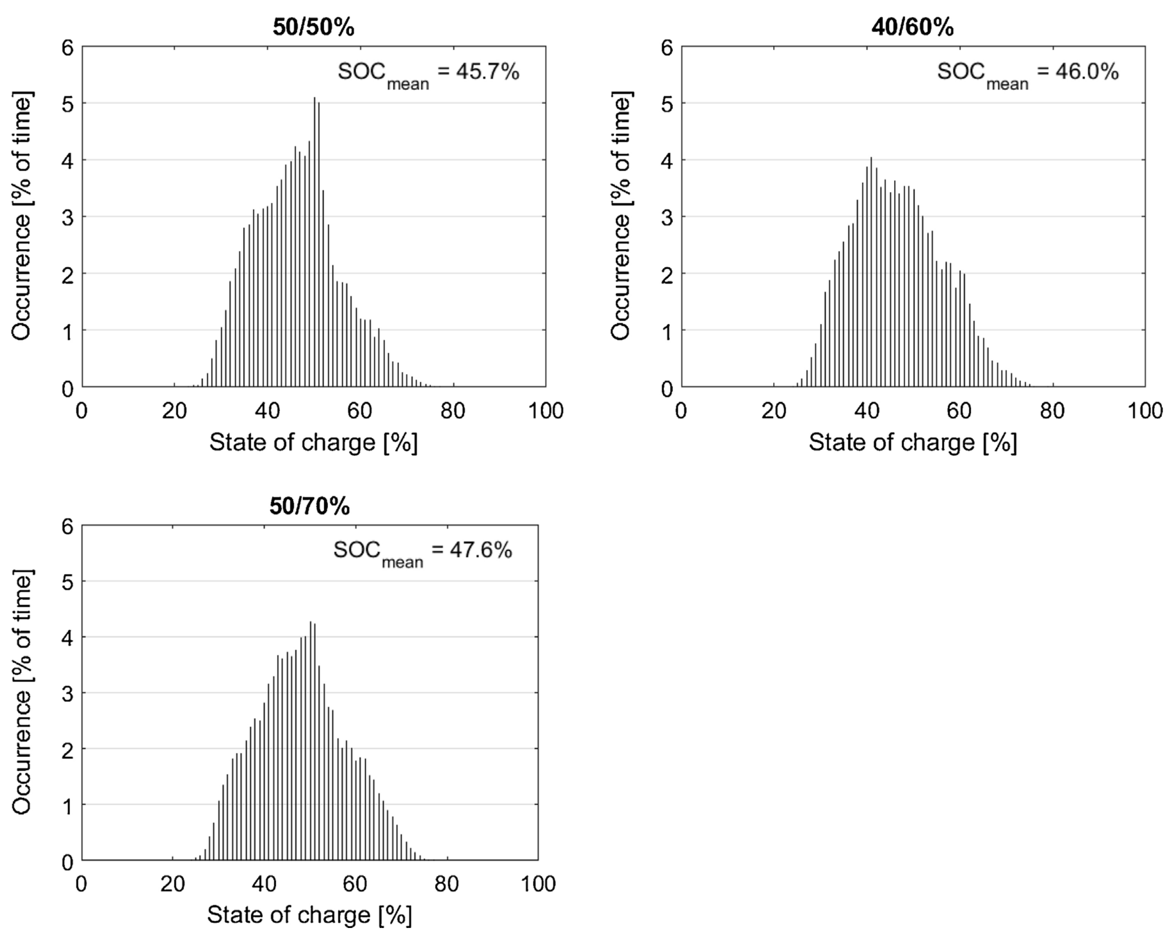

Fig. 14. SOC distributions over time—comparison of different SOC limits for overfulfillment and deadband utilization for a 1 MW_{PQ}/2 MWh battery system.

and right-skewed. The SOC does not fall below 17% or exceed 84% in any of the simulations.

5.2.3. Parameter variation 3

This parameter variation focuses on the parameters of the schedule transactions. As described in Section 3.2.2, a schedule transaction is characterized by the three parameters: $\Delta E_{\mathrm{transaction}}$, $\Delta t_{\mathrm{contract}}$ and P_{ST}. If two of these parameters are known, the third can be calculated according to Eq. (8).

As shown in Fig. 15, the results indicate that both the amount of charged and the amount of discharged energy decrease significantly with decreasing charging/discharging power. When balancing energy is traded in quarter-hourly contracts instead of hourly contracts and the charging/discharging power is kept constant, the amounts of charged and discharged energy also decrease significantly. The amount of charged energy is more than halved. The amount of discharged energy is reduced by 78%. The amount of energy per transaction ($\Delta E_{\mathrm{transaction}}$) is roughly the same in the 0.8 MW/15 min and in the 0.2 MW/1 h simulation. These two simulations deliver similar results in terms of energy exchange through schedule transactions, which indicates that the energy exchange through schedule transactions is determined by the amount of energy per transaction rather than power or contract duration. However, the amount of energy per transaction cannot be set to an arbitrarily low value. A simulation with hourly contracts of 0.1 MWh, which is the minimum volume for a spot market transaction, has been conducted, but lead to a loss of battery operability, meaning that the battery was fully charged or discharged at some point of time during the simulation.

While the amount of energy exchanged through schedule transactions decreases with decreasing amounts of energy per transaction, the number of schedule transactions rises—from 267 charging processes in the 0.8 MW/1 h simulation to 564 in the 0.2 MW/1 h simulation and 573 in the 0.8 MW/15 min simulation.

Both the total energy turnover of the battery (sum of charged and discharged energy), and thus the number of FCE, and the share of energy exchanged through scheduled transactions decrease significantly with decreasing amounts of energy per transaction, as can be seen from Table 12

Fig. 16 provides the SOC distributions over time for parameter variation 3. While the distributions for the 0.5 MW/1 h and the 0.8 MW/1 h simulations are clearly unimodal, the other two distributions show tendencies to develop a second peak. The amount of charging/discharging energy per schedule transaction does have an impact on the mean SOC values in this parameter variation. They vary between 43.1 and 47.9% here. The average SOC increases with an increasing amount of energy per transaction.

5.2.4. Parameter variation 4

In this parameter variation, both simulations refer to a 2 MWh battery. In one of the simulations, the battery is prequalified for 1 MW of primary control reserve, in the other for 2 MW, which means that a battery with a power-to-capacity ratio of 1:2 is compared to one with a power-to-capacity ratio of 1:1. The parameters for the schedule transactions are the same in both simulations (0.8 MW/1 h).

The energy exchange through schedule transactions for these simulations is set out in Fig. 17. When the prequalified power rating of the battery is doubled, the amounts of energy charged and discharged through schedule transactions both more than double. The amount of energy charged through schedule transactions rises by 127% from 213.6 to 485.6 MWh, the amount of energy discharged through schedule transactions by 190% from 72 to 208.8 MWh.

Table 13 provides the results in terms of total energy turnover, full cycle equivalents and shares of energy turnover through schedule transactions in total energy turnover. Both the total amount of energy charged into the battery and the total amount of energy discharged from the grid almost double with doubling value of prequalified power rating. Thus, the number of FCE increases by 99%. The shares of energy charged through schedule transactions in total charging energy and energy discharged through schedule transactions in total discharging energy increase from 36 to 41% and from 17.1 to 24.9% respectively.

Fig. 18 illustrates the SOC distributions over time. The average SOC in the 2 $\mathrm{MW_{PQ}}$ simulation is 0.9% lower than in the 1 $\mathrm{MW_{PQ}}$ simulation. Furthermore, in the 2 $\mathrm{MW_{PQ}}$ simulation, the battery reaches an SOC lower than 2 %, which can be regarded as a highly critical state.

5.2.5. E-rates

The *E*-rate describes the ratio of charge or discharge power to the battery capacity. When a battery is discharged with 1*E*, it takes one hour to discharge the entire battery. The *E*-rate is an important parameter to assess battery aging. The stress on a battery cell grows with an increasing *E*-rate.

In all simulations with a prequalified power rating of 1 MW, the *E*-rates occurring during the simulation period do not exceed 0.7*E*. The share of *E*-rates, which are below 0.1*E*, lies between 84 and 89% for these simulations. In the simulation with a prequalified power

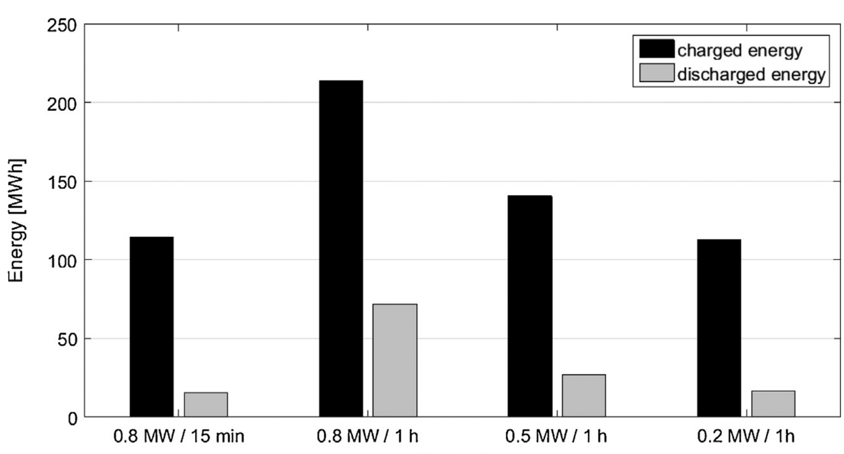

Fig. 15. Energy exchange through schedule transactions—impact of schedule transaction parameters.

Table 12
Charging/discharging energy and full cycle equivalents in parameter variation 3.

Simulation	0.8 MW/15 min	0.8 MW/1 h	0.5 MW/1 h	0.2 MW/1 h
Total energy charged into battery (MWh)	521	594	530	496
Total energy discharged into grid (MWh)	355	421	364	332
FCE/a	219	254	223	207
Share of energy charged through schedule transactions in charging energy total (%)	22.0	36.0	26.5	22.7
Share of energy discharged through schedule transactions in discharging energy total (%)	4.4	17.1	7.4	4.9

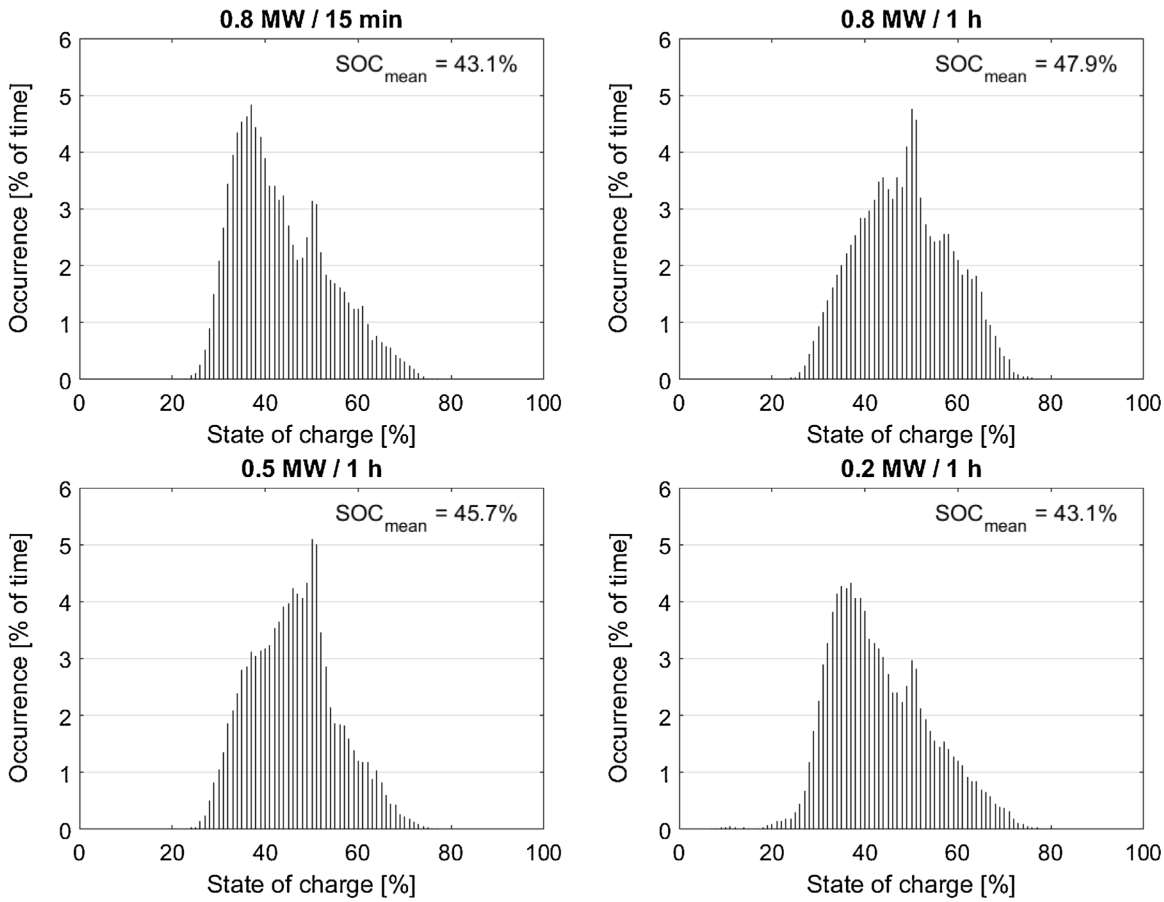

Fig. 16. SOC distributions over time—impact of schedule transaction parameters.

rating of 2 MW, the occurring E-rates are slightly higher. However, they do not exceed 1E during the simulation. 47% of the E-rates occurring in this simulation are lower than 0.1E.

6. Discussion

A number of parameters exist, which have significant influence on the amount of energy exchanged through schedule transactions. The amount of energy exchanged through schedule transactions is of high importance as it determines the total energy turnover of the battery and thus the aging behavior, and contributes significantly to the operating costs. However, the effects on total energy turnover and thus on the number of FCE, are partly working in opposite directions. While using overfulfillment leads to a higher energy turnover, deadband utilization reduces the total energy turnover. The results of this study show that overfulfillment, deadband utilization, and notably the combination of these two measures are effective methods to reduce the amount of balancing energy exchanged through schedule transactions.

First of all, the SOC bandwidth, within which the battery is permitted to operate, was found to have a major impact on both the amounts of energy exchanged in schedule transactions and the SOC distributions. It was found in this study that broadening the permissible SOC range leads to a reduction in energy exchanged through schedule transactions (see Fig. 11). This is due to the fact that positive and negative primary control have a better opportunity to balance each other out before balancing energy from the spot market is required (self-regulating effect). Choosing an asymmetrical SOC range may be helpful to selectively lower the amount of energy charged through schedule transaction, while increasing the amount of energy discharged, which can be sold at the intraday market. However, the permissible SOC range cannot be chosen arbitrarily. Attention must be paid that SOC ranges, which may lead to critical states or states where the BESS becomes inoperable (fully charged or discharged), are avoided.

This analysis suggests that the choice of the SOC ranges, in which overfulfillment and deadband utilization are applied, can be used to shift the ratio of charged energy to discharged energy in schedule transactions. It has a minor impact on the total amount of

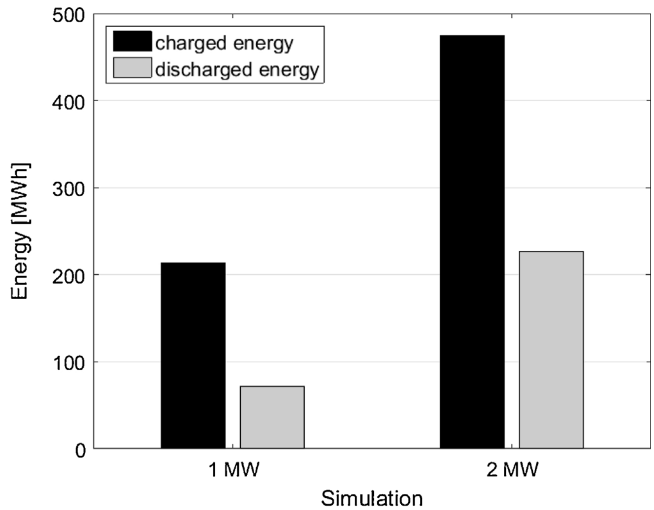

Fig. 17. Energy exchange through schedule transactions—comparison of a 1 MW_{PQ}/2 MWh and a 2 MW_{PQ}/2 MWh BESS.

must be designed with a power rating that allows for a superposition of primary control power deployment at full prequalified power output and charging/discharging through a schedule transaction. If the amount of charging or discharging energy per transaction is chosen too low, the battery may lose its operability despite being charged or discharged. It is essential to enable the BESS to bridge at least the period between a charging or discharging process and the earliest possible point in time when the next charging or discharging process can be started. Shifting from hourly to quarter-hourly contracts for the schedule transactions is likewise found to significantly reduce the amount of required balancing energy. Smaller amounts of energy per transaction and shorter contract periods offer a higher degree of flexibility and allow for a more precise charge level management.

The simulation results for a battery with a 1:1 power-to-capacity ratio indicate that the operability of the battery can be ensured for this case, but parameters like the permissible SOC range must be adapted to avoid that the battery reaches critical charge levels. From an economic point of view, the system with the 1:1 ratio is likely to be preferred, since the revenues, which can be realized on the market for primary control reserve, are twice as

Table 13
Charging/discharging energy and full cycle equivalents in parameter variation 4.

Simulation	1 MW_{PQ}	2 MW_{PQ}
Total energy charged into battery (MWh)	594	1185
Total energy discharged into grid (MWh)	421	840
FCE/a	254	506
Share of energy charged through schedule transactions in total charging energy (%)	36.0	41.0
Share of energy discharged through schedule transactions in total discharging energy (%)	17.1	24.9

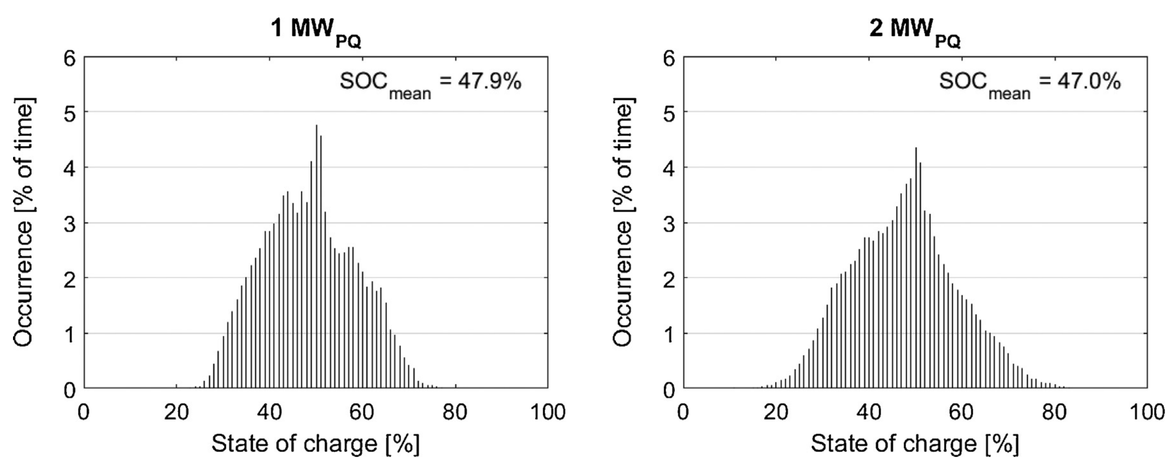

Fig. 18. SOC distributions over time—comparison of a 1 MW_{PQ}/2 MWh and a 2 MW_{PQ}/2 MWh BESS.

energy exchanged through schedule transactions, but choosing an asymmetric SOC range tends to be favorable in case the operation strategy aims at increasing the amount of energy sold on the spot market.

One interesting finding is that reducing the amount of energy that is charged or discharged per transaction leads to a significant reduction of the total required balancing energy. Due to the regulatory framework of the spot market, this parameter can only be varied in steps of 0.1 MWh. It is limited upwards technically by the maximum power output, which in turn is determined by the battery power electronics (battery inverter and transformer). Again it has to be paid attention that critical or inadmissible states of the battery are avoided to ensure operability throughout the contract period. Furthermore, the power electronics of the BESS

high as in the case of the 1:2 ratio. However, further investigation is required to determine the permissible operating conditions of a battery with power-to-capacity ratio of 1:1 and to estimate costs and revenues.

Both the E-rate and the SOC distributions over time, which result from the simulations, were found to be favorable for battery lifetimes. In all simulations with a power-to-capacity ratio of 1:2, the E-rate distributions show that more than 80 % of all occurring E-rates are smaller than 0.1E. E-rates higher than 0.7 E do not occur. In the simulation with the 1:1 power-to-capacity ratio, the occurring E-rates are slightly higher, but do not exceed 1E. The E-rate is directly linked with the currents occurring in the battery cells. Lower currents and lower cycle depths are generally favorable for cycle aging [39]. The SOC distributions indicate that the SOC is in the range between 30 and 70% most of the time in all simulation. Schmalstieg et al. [40] state that both capacity and resistance have the lowest aging while cycling around 50% SOC.

7. Conclusion and outlook

In order to ensure the operability of a BESS, which is used for primary control supply, adequate charge level management is required. The measures used for charge level management considered in this study include frequency-dependent measures and schedule transactions, which are independent of the grid frequency. The purpose of the current study was to identify parameters which have an impact on BESS operation characteristics and to quantify this impact.

The choice of frequency-dependent measures and their settings (e.g., SOC limits), the parameters of the schedule transactions (SOC limits, charging/discharging power, contract duration), and the ratio of prequalified power rating to BESS capacity were all found to have significant impact on the operation characteristics. The operation characteristics investigated in this study focus on the amount of energy exchanged through schedule transactions. Furthermore, the number of FCE and the SOC and *E*-rate distributions have been analyzed. To lower operating costs, it is desirable to minimize the amount of energy charged through schedule transactions, while the amount of energy discharged through schedule transaction is maximized. To minimize battery aging, the number of FCE and the *E*-rates should be minimized and it is desirable to keep the SOC near a value of 50%. To reduce the number of FCE, it is desirable to minimize the total amount of energy exchanged through schedule transactions.

A decrease of the amount of energy charged through schedule transactions can be reached by broadening the SOC range, in which the BESS is allowed to operate, by lowering the amount of energy per schedule transaction and by choosing the amount of energy per schedule transaction as low as possible. However, these measures also involve a reduction of the amount of discharged energy. By adjusting the SOC limits for the frequency-dependent charge level management measures, this effect can partly be counteracted.

The numbers of FCE per year occurring in the simulations vary between 207 and 254 for a 1 MW_{PQ}/2 MWh BESS. The FCE approach has been chosen to obtain first insights into battery cycling and battery aging in this specific application. Since typically only partial cycles occur during PCR provision, the effects caused by partial cycling should be investigated to quantify battery aging. It is therefore subject of ongoing research to couple the PCR simulation model with battery aging models which take into consideration the depth of discharge (DoD) of each cycle to achieve more detailed results for battery aging.

The *E*-rate and SOC distributions occurring in the simulations are estimated to be favorable for battery aging compared to mobile and other stationary applications. The influence of these parameters on battery aging may also be quantified by coupling the PCR simulation model with battery aging models.

To develop a full picture of primary control supply as application field for batteries, additional studies will be needed which focus on economic aspects. The problem of finding cost-effective charge level management strategies to ensure the BESS's operability during primary control supply can be approached by using optimization methods. The parameters identified in this study provide the foundation for optimization approaches.

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