Optimized operation of energy storages for primary control reserve

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Abstract

The electrical energy system is facing different changes especially with the focus on system planning and operation. Due to the change of the power supply with big conventional power plants to a system with more and more decentralized feed-in of regenerative volatile generation, it becomes complex to remain the system frequency stable. New technologies like energy storage systems (ESS) are needed to compensate these instable situations. Never the less the energy output of such system is limited by their energy capacity and makes the need of a state of charge management vital. In this contribution, a state of charge optimized operation model for ESS participating in the primary control reserve (PCR) market is set up. In addition to take part in PCR and meet prequalification requirements, special degrees of freedom for storages are taken into account to find the optimal ESS operation schedule. The model was tested with up-to-date annual frequency data from 2015 – 2017. Finally, the impact on technical operation as well as the possible speed-up in getting the return of invest was evaluated and valued.

Keywords - *energy storage system, frequency control reserve, primary control reserve, state of charge optimization*

1 INTRODUCTION

The ambitious climate protection goals in Europe are causing an increasing number of installed renewable energy source (RES) in the electricity generation. Almost one-third (31.5%) of Germanys gross energy production was taken from RES [1]. Along with the growing number of RES, carbon emissions are reduced, but also the volatility of generation increases, caused by meteorological dependency, and the electrical system becomes more dynamically [2] and even harder to stabilize. The gap between local generation and demand of energy increases.

Also the associated decline of controllable thermal power plants is forcing system operators to find other solutions, like energy storage systems, to provide control reserve and keep the system frequency between given borders. Several solutions, like flexible loads [3], virtual power plants [4] or different types of energy storages [5], [6] has been discussed. The literature shows that effects on grid frequency while using ESS and providing primary control reserve has been a highly interesting field of interest, especially for energy storage systems for a long time [7]-[9]. Beside frequency regulation in independently operated power systems [10],[11] the usage in interconnected networks [12] or in RES-driven grids [13] has been discussed.

However, ESS power provision is limited by their energy capacity wherefore sizing for such applications is discussed in scientific community [14], [15]. As the feed-in of balancing energy has to be ensured by the ESS operator, a strategy to keep the state of charge (SOC) in certain range is needed.

This paper concentrates on algorithms for technology depending optimal operation strategies and potential valuation within the regulation for this purpose. A simulation model of the energy storage with additional state of charge control is set up using MATLAB Simulink and a frequency data set from ENTSO-E system is used to perform the simulation. The resulting SOC, the power correction, the control mechanism and the market pricing information are used to determine the technical and economic impact of different strategy stages and the potential of each stage as well as the intelligent combination of each of them to decrease the time of return of invest related to technical effort.

2 FREQUENCY CONTROL RESERVE

2.1 Overview

Fig. 1 shows an exemplary frequency dip with related FCR-stages.

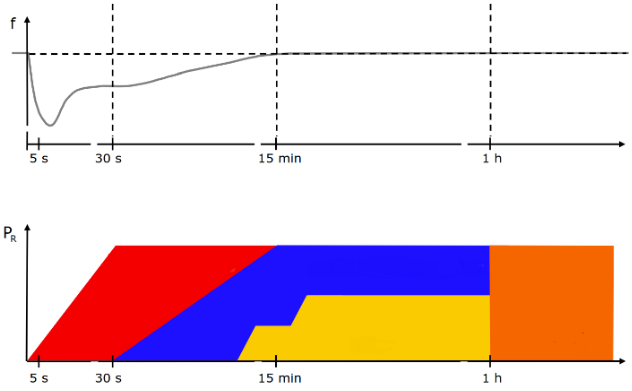

Fig. 1 Frequency control reserve stages [16]

The frequency control reserve (FCR) is separated into three stages with different tasks and activation/usage characteristics in case of power imbalance.

As the first part, the primary control reserve (PCR) is activated immediately and counteract the frequency drop. Its main purpose is to stabilize the frequency within a maximum deviation of ±200mHz. As frequency is a global system parameter in the electric grids, all participating supply units adduce the PCR depending on the rate of frequency deviation.

Subsequently the secondary control reserve (SCR) is added and lifts the frequency back to normal operation level. As all transmission system operators (TSO) has to ensure system stability by taking care of load and feed-in balance this is done in each TSO-zone independently. In our exemplary curve the operator, who causes the frequency drop, has to provide appropriate SCR.

In Case of mayor power imbalance the SCR gets supported and later on relieved by tertiary control reserve to keep the frequency at normal level.

2.2 PCR market &requirements

For primary control reserve in Germany a weekly tendering process is done via an internet platform. Suppliers are reserving certain power capacity and offering them with a related capacity price during the bidding process. After the call for tender is closed, the bids are set on merit order list and accepted until the need of PCR, which is set to 3000 MW for European network, is covered. Each country has to provide a share of global demand that is determined by its generation and has been more than 600 MW for Germany in 2017 [17].

To react immediately on frequency deviations an automated measuring and control system has to be set up. The frequency is measured in real time and a related PCR-power based on the *P(f)*-characteristic, shown in Fig. 2, is used.

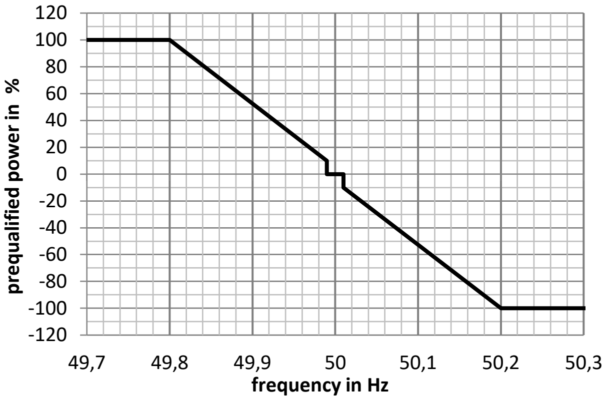

Fig. 2 ***P(f)*-characteristics of ESS power usage**

In order to participate in the primary control reserve market various technical requirements have to be fulfilled by the supply unit. The main requirements, listed in the transmission code [18] are:

- min. power capacity: ±1MW
- rated power feed-in within 30s
- feed-in for at least 15min
- deadband of ±10mHz around nominal frequency
- measurement accuracy below 10mHz

Additional to these global requirements the German transmission system operators laid down further conditions for so-called units with limited capacity. In case of independently operated ESS minimum feed-in duration is extended to 30 minutes. This leads to an upper and lower SOC limit for each specific ESS configuration, which has to be respected to ensure at least 30 minutes of full power feed-in and gives a scope of action to the ESS operator – see Fig. 3.

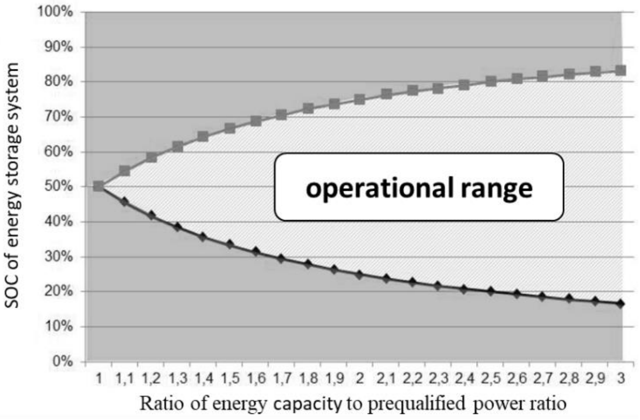

Fig. 3 boundaries of 30min criteria

3 SIMULATION MODELL

3.1 Degrees of freedom

Although the primary control reserve supply is highly restricted, some degrees of freedom (DOF) are offered by the TSO [20]. Those are not limited to, but adopted for ESS especially. Beside the global requirements, the following DOF can be used in PCR operation with ESS.

Overfulfilment (OF): In addition to the characteristic shown in Fig. 2 an optional overfulfilling up to 20% of the rated and prequalified power is allowed. This DOF is not limited to a specific point of operation but has to meet the *P(f)*-characteristic. The 20% additional power are always based on requested PCR demand, which only changes the gradient and not the baseline of the power-frequency-curve.

Deadband (DB): Furthermore, the deadband between 49.99Hz and 50.01Hz can be added to the operational range. A PCR-delivery in this normally blocked frequency area is allowed as long as *P(f)*-characteristic is maintained. Whenever positive PCR is requested it has to be feed-in, a negative PCR injection is prohibited in this case.

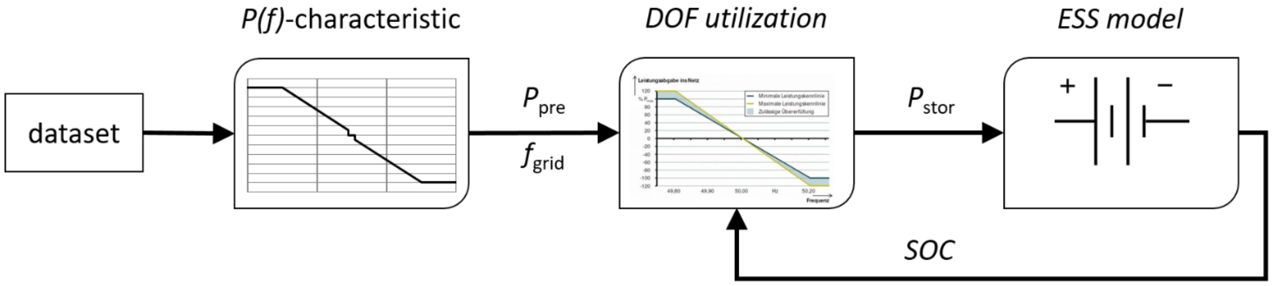

Fig. 4 storage management model for use in primary control market

Power gradient (PG): The power gradient for PCR providing supply units is not defined directly. The rated prequalified power capacity has to be obtained within 30s, which leads to rising requirements for more powerful units. A maximum is not set up. Units with ability of high power gradients can also use their dynamics and feed-in their rated power faster than 30s.

Scheduled transactions (ST): In case of reaching the upper or lower SOC limit the ESS operator is allowed to settle transactions at energy market. Those transactions has to be registered at least 15min before performing. The PCR provision is not stopped during the transaction, which leads to a shift of current operation point.

3.2 Operation model

The described requirements and degrees of freedom are used to set up a management model for storage operation, as shown in Fig. 4.

Based on the frequency measurements the nominal primary control reserve is determined using (3.1), with P_{pre} as prequalified power of the unit, Δf as deviation from nominal system frequency and P_{PCR} as accessed control reserve power of the unit.

$$P_{\text{PCR}} = \begin{cases} 0, & |\Delta f| < \frac{1}{100} \\ \Delta f \frac{P_{\text{pre}}}{0.2Hz}, & \frac{1}{100} \leq |\Delta f| < \frac{2}{10} \\ P_{\text{pre}}, & |\Delta f| \geq \frac{2}{10} \end{cases} \tag{3.1}$$

Afterwards the use of different degrees of freedom is established while taking the state of charge SOC of the energy storage system and the SOC-limits $SOC_{\min}$ and $SOC_{\max}$ of the unit management in consideration, like shown in (3.2) - (3.4).

$$P_1 = k_1 \cdot P_{\text{PCR}}, \tag{3.2}$$

where

$$k_1 = \begin{cases} 0.2, & P_{\text{Stor}} > 0 \wedge SOC < SOC_{\min,1} \\ 0, & P_{\text{Stor}} < 0 \\ -0.2, & P_{\text{Stor}} < 0 \wedge SOC > SOC_{\max,1} \end{cases}$$

$$P_1 = k_2 \cdot \Delta f \frac{P_{\text{pre}}}{0.2Hz} \tag{3.3}$$

where

$$k_2 = \begin{cases} 1, & |\Delta f| < \frac{1}{100} \wedge SOC < SOC_{\min,2} \\ 0, & |\Delta f| \geq \frac{1}{100} \end{cases}$$

$$P_3 = k_3 \cdot \left(\Delta f \frac{P_{\text{pre}}}{0.2Hz} - \frac{P_{pre}}{30} \right) \tag{3.4}$$

where

$$k_3 = \begin{cases} 0, & |\alpha_{\text{PCR}}| < \frac{P_{\text{pre}}}{30s} \\ -1, & |\alpha_{\text{PCR}}| \geq \frac{P_{\text{pre}}}{30s} \wedge SOC < SOC_{\min} \end{cases}$$

The optimised storage power P_{Stor}, according to (3.5), is given to the ESS model to calculate the state of charge for the following iteration.

$$P_{\text{Stor}} = P_{PCR} + \sum_{i=1}^{DOF} P_i \tag{3.5}$$

ESS parameters such as efficiency or self-consumption are included in this part of the model and further system indicator like full cycle equivalent (FCE) are computed.

Furthermore, power demand that would exceed 30min SOC borders and could not be levelled by explained DOFs had to be covered by market transactions – see (3.6).

$$P_{\text{EEX}} = P_{Stor}\Big|_{\substack{SOC \geq SOC_{30min,\text{up}} \\ SOC \leq SOC_{30min,\text{dw}}}} \tag{3.6}$$

For this approach, an ESS configuration with parameters presented in Table I is assumed.

Table I parameters of modelled ESS[1]

Power capacity	1MW
Energy capacity	2MWh
self-consumption	1%
efficiency	95%
cycle life	5000
calendric life	12 years
CAPEX	€ 1 600 000

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[1] parameters based on a lithium ion battery energy storage

3.3 Simulation Data

For testing the operation model, three frequency datasets of ENTSO-E grid has been taken from French transmission system operator RTE [21]. All datasets contain a whole year of frequency time series with 10s resolution, which makes the simulation precise and gives high competitiveness to the study. Missing or incorrect data points has been replaced with 50Hz nominal frequency. As the percentage of replacements is below 0.3% in all datasets, the correction will not have a noticeable influence on simulation results.

For evaluation of the financial impact, price information from European energy exchange (EEX) German spot market has been utilized [22]. Datasets are given as monthly averaged prizes, shown in Fig. 5, without peak and off-peak information.

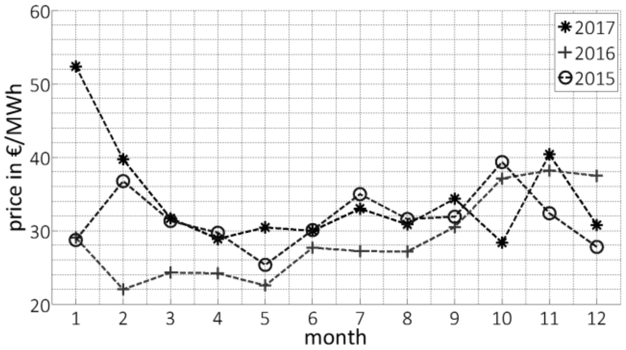

Fig. 5 monthly averaged EEX price information for simulation years

4 CASE STUDY

4.1 Impact analysis

To find an optimal operation strategy and evaluate the impact of the named degrees of freedom, simulations has been done for every single DOF and their combination also. As the amount of supply able energy reserve is still limited by the storage capacity, the system operator has to perform transactions on the energy market to level the ESS state of charge after the degrees of freedom are exhausted. Fig. 6 shows the amount of traded energy in different cases.

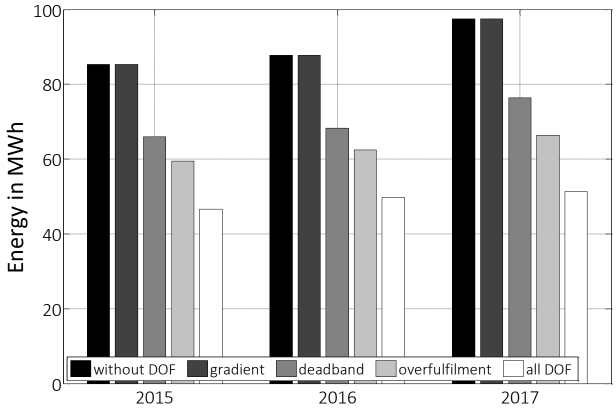

Fig. 6 traded energy for different DOFs and years

The amount of bought energy for refilling the storage system is used to evaluate the impact of the different optimization options. The black bars represent the basic characteristic with all DOF turned off in every simulation year. Beside small differences in total power demand, all simulation years are revealing comparable results in DOF impact.

It can be seen, that utilizing the power gradient (dark grey) has almost no impact on the traded energy. This can be justified by the fact, that the ENTSO-E grid is a very extensive and stable system with a smooth frequency curve. Due to the high number of loads and generators, normal daily fluctuations cause only small imbalances in comparison to the rest of the system and might compensate each other partially. This leads to a slow frequency changes, which are almost always covered by the standard gradient in the simulation. Since the power gradient requirements are proportional to prequalified system power, the simulation with minimal PCR power can been considered as best case for this DOF.

The deadband utilization (medium grey) as well as the overfulfilment (light grey) cause way stronger reduction in traded energy. Again the already very stable system leads to a high number of frequency measurements in the deadband region. During the single simulation, this DOF was used for 60.6% - 63.5% of simulation time. Even if the useable power rate is below 10%, the high usage time leads to a 22% energy reduction on average.

For the remaining 40% in simulation time the operation strategy can take advantage of the overfulfilment DOF based on current SOC. As the PCR power is only limited by the ESS rated power the impact can be more significant like shown in the simulation results with a reduction up to 32%.

Not surprisingly, a combination of all DOF (white bar) reduces the traded energy most. Because the different DOF are influencing the ESS SOC in different time steps, the overall energy savings are not a sum of single savings. The maximum reduction can be seen in 2017 simulation with almost 50%.

4.2 Operational cost analysis

As explained in section 3.1 scheduled transactions can be performed to level the system SOC in case of reaching the 30min boundaries, what causes operational expenditures (OPEX). While reducing the traded energy those costs are reduced evenly. Based on the EEX price c_{EEX} and the amount of recharged power P_{EEX} the annual OPEX can be estimated as shown in (4.1).

$$OPEX = \sum_{i=1}^{t_{\mathrm{sim}}} c_{\mathrm{EEX},i} \cdot P_{\mathrm{EEX},i} \qquad (4.1)$$

Results for the three study years with and without activated degrees of freedom are presented in Table II.

Table II OPEX with and without SOC management

	OPEX without DOF	OPEX with DOF
2015	€2706,8	€1482,8
2016	€2599,2	€1463,6
2017	€3346,9	€1812,7

The investigation reveals, that the OPEX can be reduces by approximately €1.300 p.a.. Taking into account the CAPEX and lifetime from Table I this will be 1% of linear annual depreciation and seems not worthwhile.

On the other hand no additional CAPEX must be considered as the utilization of DOF is linked to an optimisation of *P(f)*-characteristics only. All needed parameters has to be monitored in normal operation already, so there is no need for additional investment in measurement equipment or strategy tools. The power curve optimisation can be integrated in already existing ESS measurement and control system. This makes it a net profit of € 15 600 in ESS lifetime.

4.3 Potential for multipurpose use

As most ESS use cases are not cost effective in single purpose operation, the potential for multipurpose use is estimated finally. As the energy capacity is exceeded already by the PCR performance, an additional usage for real power injection would be difficult in operation management. Unlike this the use of power capacity behave much different and is shown in Fig. 7 for 2017 scenario.

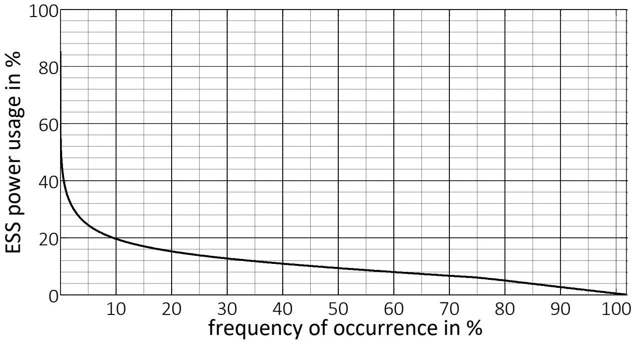

Fig. 7 histogram of ESS power usage

The investigation shows that the used power capacity is below 30% of prequalified power for almost 98% of the usage time. This reveals great potential for ESS with independent active and reactive power control, like battery energy storage systems. The inverter can be used for reactive power injection and take part in local voltage stabilizing.

5 CONCLUSION

In this contribution, the utilization of different degrees of freedom and also their combination for the state of charge management of energy storage systems participating in the primary control reserve market was tested.

The results show that, approximately 50% of the total amount of traded energy, compared to the standard operation, can be reduced by this optimization. Furthermore, the simulation shows extreme differences in the influence of the implemented DOF. While the overfulfilment is causing the majority of savings, the power gradient management can be neglected due to very high frequency stability in the ENTSO-E system.

Despite the great energy savings the reduction of operational expenditures is small compared to capital expenditures of such systems. Never the less the implementation should be considered as no additional investment costs occur.

Finally, the simulation shows great potential for additional use cases like voltage stabilisation. Especially for distributed storages, like electric vehicles in low voltage area, this might help to stabilize the electric grid und should be considered in future research.

In addition, the interaction between several ESS running such SOC management should be verified. Even if the implemented DOF are all within legal conditions, a greater use might cause imbalances and affect the overall PCR impact negative.

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