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An auspicious combination: Fast-ramping battery energy storage and high-capacity pumped hydro

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Abstract

Pumped hydro represents the most mature energy storage technology and accounts for more than 99 % of bulk storage capacity worldwide. Nevertheless, energy storage is becoming today increasingly diversified. Battery costs have fallen massively the last years due to increased deployment and interest in storage for variable renewable energy integration. The most dramatic cost developments have been for Li-Ion chemistries, driven by the development and perspectives of the electric vehicle market. Existing or new build pumped-storage hydro power plants (PSP) provide potential for being extended by container-based battery energy storage systems (BESS) as the techno-organisational set-up can be commonly used. Apart from the technological infrastructure (high voltage installations with grid interface as well as the control, communication and monitoring systems), the required marketing and energy trading competences are available. Due to their very fast ramping capabilities, BESS are well suitable for the participation in the primary reserve (R1) market. Compared to secondary (R2) and minutes reserves (R3) markets, the R1 market promises the largest benefits for any kind of storage. By pooling of PSP and BESS, the control aggregate can make use of the advantages of the two individual technologies: the fast ramping capability of BESS and the large autonomy of PSP. In the paper, the authors discuss different modes of aggregation of PSP and BESS for their joint participation in the R1 market. Therefore, boundary conditions of possible operation on the R1 market defined by TSOs are laid down and their implications on the PSP-battery aggregate are presented. The authors show, how an aggregation of PSP and BESS can operate. Herein, the objective is to maximise the marketable reserve capacity. The contribution is based on the implementation and commissioning experience of a 12.5 MW / 13 MWh Li-Ion BESS, which enhances the reserve capacity of the existing Pfreimd hydro power plant group in Germany.

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1. Introduction

With increasing relevance, grid-integrated renewable generation affects the operational characteristics of existing networks because of the stochastic nature of the sources. Consequently, in countries with high renewable infeed a shift from downstream power delivery to bi-directional load flows can be detected. The transition towards a more sustainable electricity supply requires a more flexible and smarter power infrastructure, prepared to cope with the massive growth of renewable generation. With an increasing share of fluctuating renewable infeed, the dynamics and complexities in operating the electric power supply infrastructure rise [1-3]. Apart from grid reinforcement planning and automated grid control demonstration projects, a further important flexibility option for mitigating the effects of an increasing share of renewable generation is in the focus: grid-scale battery energy storage systems (BESS).

The rapid growth of infeed by wind power and solar photovoltaic drives the need for high-capacity as well as rapid-response energy storage technologies to smoothen out intermittent generation (e.g. [4]). Storage can help to limit the need for investments in grid capacity, to reduce operation costs of generation facilities and to increase the reliability of the supply. With its capability in providing a range of energy services such as grid-stability ancillary services and long-term storage, hydropower's role in renewable-based energy systems is becoming increasingly important. Pumped hydro represents the most mature energy storage technology and accounts for more than 99% of bulk storage capacity worldwide. Nevertheless, the landscape for grid-scale energy storage is evolving from being almost exclusively supplied by pumped hydro to include a number of new technologies [5]. Today, we experience that energy storage is becoming increasingly diversified. In a recent technology-agnostic tender by UK's National Grid, calling for 200 MW of enhanced frequency response capacity, exclusively fast-ramping electrical energy storage assets (and no pumped hydro solution) were offered [6].

2. 12.5 MW battery energy storage reference project Pfreimd

An innovative battery storage project is developed by ENGIE Germany at the site of the Pfreimd hydro power plant group in the Upper Palatinate, Germany, which is intended to provide additional balancing energy for grid stabilisation. The 13 MWh battery storage is to supplement the existing pumped storage power station plants, which today already contribute to a secure energy supply with the provision of primary and secondary balancing power as well as tertiary operating reserve [7]. In the course of the real live testing of the power batteries, the joint operation with the existing PSP will be tested and optimised. A harmonised control strategy will be developed.

3. Overview on reserve power markets

In the European electricity system, grid control has been structured by ENTSO-E into three different reserve categories: primary, secondary and tertiary reserve. The primary reserve (Frequency Containment Reserve, FCR) is an automatic decentralised frequency reserve which is provided through all ENTSO-E TSOs according to the solidarity principle. Its automatic complete activation has to be realised within 30 seconds and provided for up to 15 minutes. The secondary reserve (Frequency Restoration Reserve – automatically activated, FRR-a) represents the energetic compensation of each ENTSO-E control zone in order to free the primary reserve for frequency regulation. It is directly activated by the concerned TSO in an automatic way. Its complete activation must be realised within 5 minutes. The tertiary or minutes reserve (Frequency Restoration Reserve – manually activated, FRR-m) is activated by the concerned TSO through telephone and within the generation schedule of quarter hours. Its complete activation has to be realised within 15 minutes from telephone call. It has to be provided until 4 quarter hours per disturbance and up to several hours in case of several disturbances [8]. Reference is made to Fig. 1.

Due to their very fast ramping capabilities, BESS are well suitable for the participation in the primary reserve (R1) market. Compared to secondary (R2) and minutes reserves (R3) markets, the R1 market promises the largest benefits for any kind of storage. For this reason, in this paper the focus has been set on the R1 market.

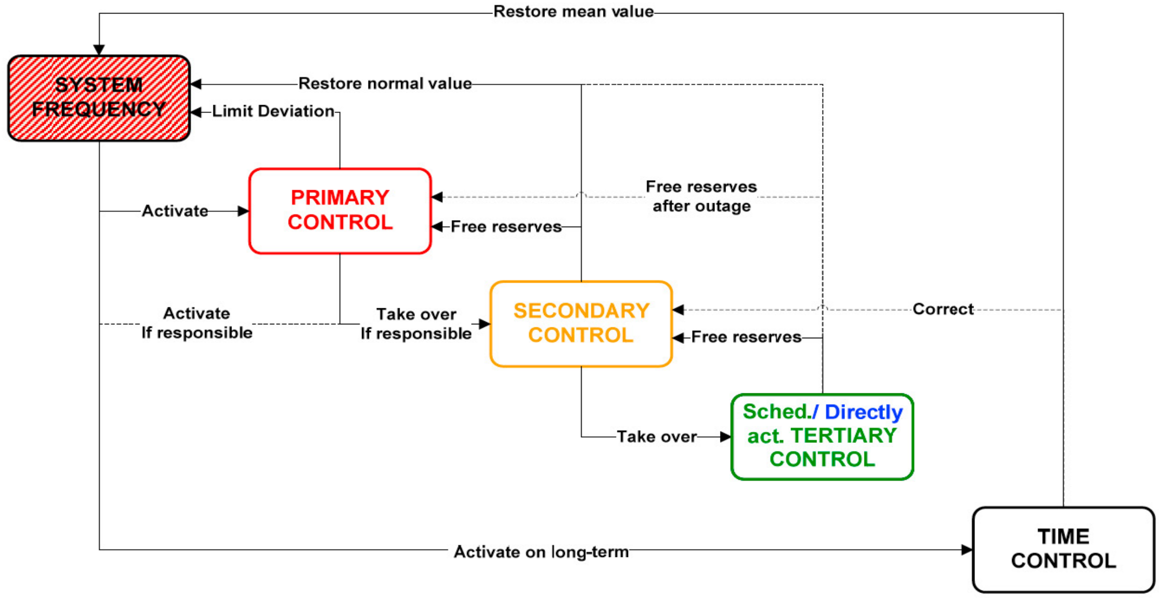

Fig. 1. Frequency control scheme and actions starting with the system frequency [13]

In Germany, the provisioning of R1 power has been realised by each TSO separately until 2007. Since then the four German TSOs have set up a common market platform which is known as “regelleistung.net”. The common provisioning enables a larger pool of suppliers and potential cost reductions. With the aim of enabling further synergies in the common provisioning of R1, also TSOs from neighbouring countries have joined the market which is now called the International Grid Control Cooperation (IGCC). In 2014, the Dutch TenneT joined the common auctioning platform followed by the Austrian and Swiss control power markets in 2015, the Belgian Elia in 2016 and just recently the French RTE in beginning of 2017. Furthermore, the Danish TSO energinet.dk is expected to join the soon. With a total tendered R1 capacity of approximately 1,400 MW the IGCC represents the largest R1 market in Europe.

The IGCC realises the auctioning of the tendered R1 capacity in a pay-as-bid procedure. In the beginning of the common market platform, the R1 provisioning had been done for an entire month. Since 2011, the R1 bids have to be submitted for each week. Also in 2011, with the aim of lowering barriers for BESS operators the minimum marketable R1 capacity has been decreased from before 5 MW to then only 1 MW [14].

4. Evolution of the IGCC Frequency Containment Reserve (FCR/R1) market

The largest individual demand for FCR or R1 demand is still the one from Germany (620 MW in the beginning of 2018) followed by the one of France (550 MW). Another 80 MW are required by the Netherlands, further 70 MW by Switzerland and 60 MW by Austria. Belgium has weekly varying demands on the IGCC FCR market of some 25-55 MW [9].

Fig. 2 shows the evolution of the R1 market for the period 2014-2017 [10]. The R1 demand increased from some 630 MW in 2014 to approximately 1,400 MW at the end of 2017 (dashed line). The increase in R1 demand goes together with an increase in supply due to the geographic extension of the market. However, the weekly auction results of the marginal capacity price (straight line) show a slightly decreasing tendency. The common sourcing of R1 capacity by European neighbouring countries leads to cost synergies reflected in lower marginal prices. In particular, through the joining of large French RTE in the beginning of 2017 the market prices have come down, most probably triggered through the inclusion of (subsidised) cheap nuclear power plants. The market is characterised by some annual periodicities with peaks at the end of the year, mostly in the week of and after Christmas as essential power plant capacities are maintained in this period which leads to shortage in supply.

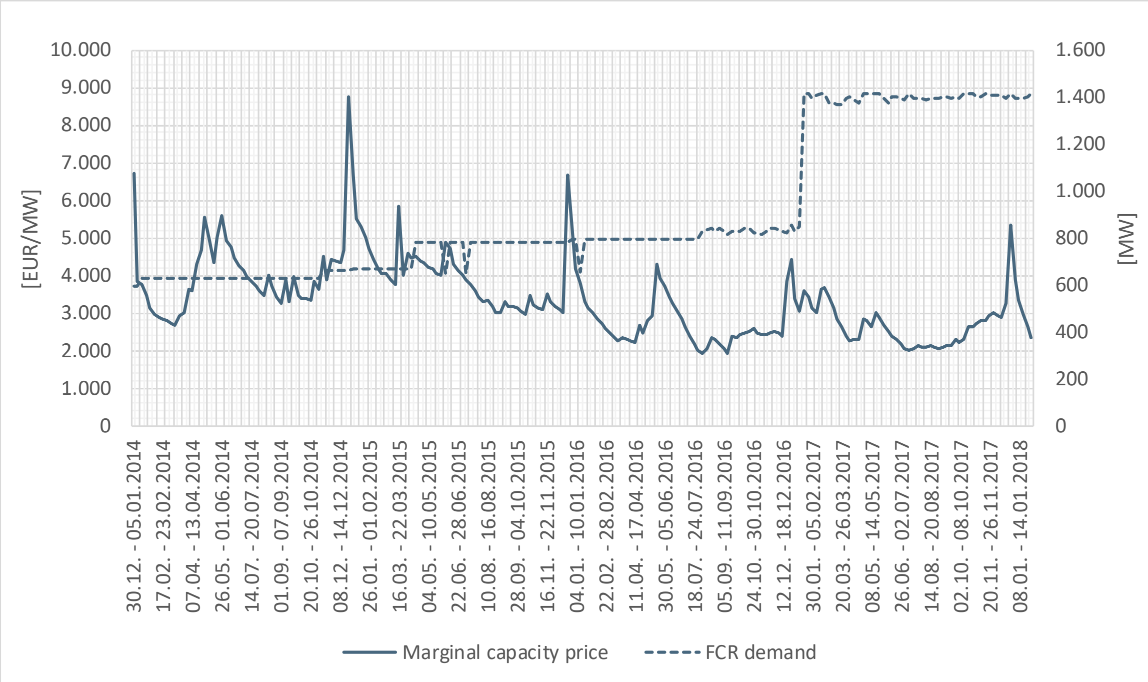

Fig. 2. Evolution of the IGCC FCR market

5. Requirements for the provision of primary reserve power

The German TSOs have drafted their requirements for energy resource limited storage devices for the participation in the R1: 30-minutes-criteria (Fig. 3). The 30-minutes-criteria had imposed on storage operators, that the storage would have to be able to provide the full range (of prequalified) positive as well as negative R1 capacity for at least 30 minutes at any point of time without having to resort to recharging/re-discharging. This, however, would have meant that a 1 MW / 1 MWh BESS could not have been prequalified for the provision of R1 with its full capacity because then it would not be able to provide any reserve energy. According to the TSOs an E2C ratio of 2:1 would have been ideal, i.e. for a 1 MW / 1 MWh BESS only 0.5 MW could have been prequalified for the provision of R1. With this, the BESS could operate freely between 25% and 75% of SoC (here recharging/re-discharging measures are allowed) and still would always be able to provide the full range of its prequalified capacity in positive and negative direction without the resort to recharge/re-discharge measures [11]. The 30-minutes-criteria has been controversially discussed as it discriminates battery storage solutions for the participation in the R1 market, where the R2 capacities are supposed to free the R1 capacities at latest after 5 minutes [12].

In this sense, the new Electricity Transmission System Operation Guideline of the European Commission defines the 15-minutes-criteria (see also Fig. 3) as the valid rule for the prequalification capacity of energy resource limited storage devices [13]. According to this rule, a 1 MW / 1 MWh BESS can be prequalified for 1 MW R1 capacity and is now able to operate between 25% and 75% SoC.

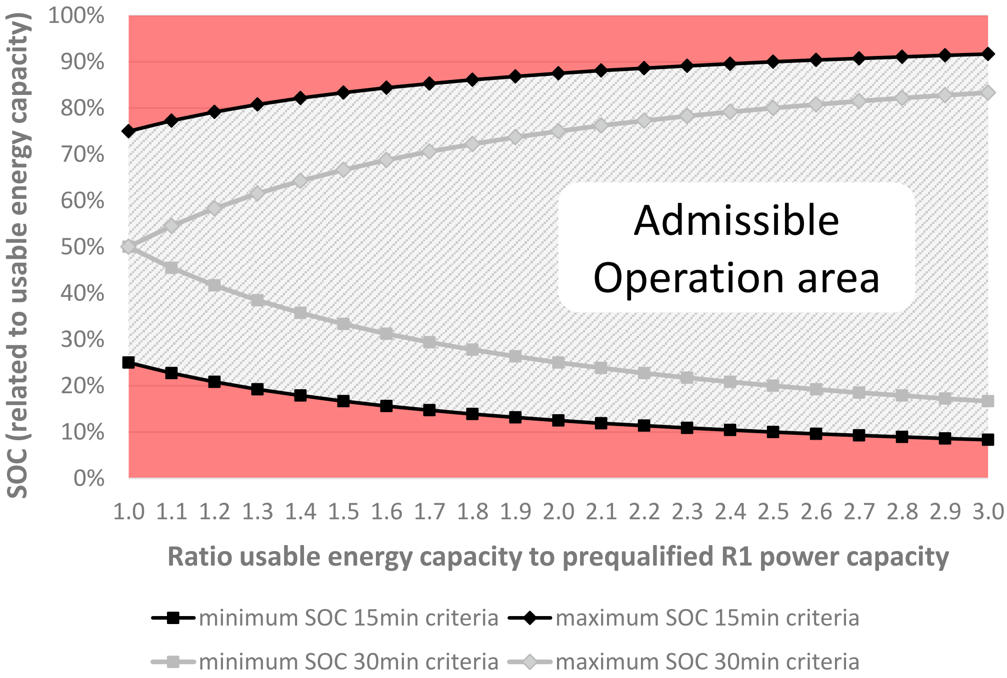

Fig. 3. Original 30-minutes-criteria (grey) and actual 15-minutes-criteria (black) [15, adapted]

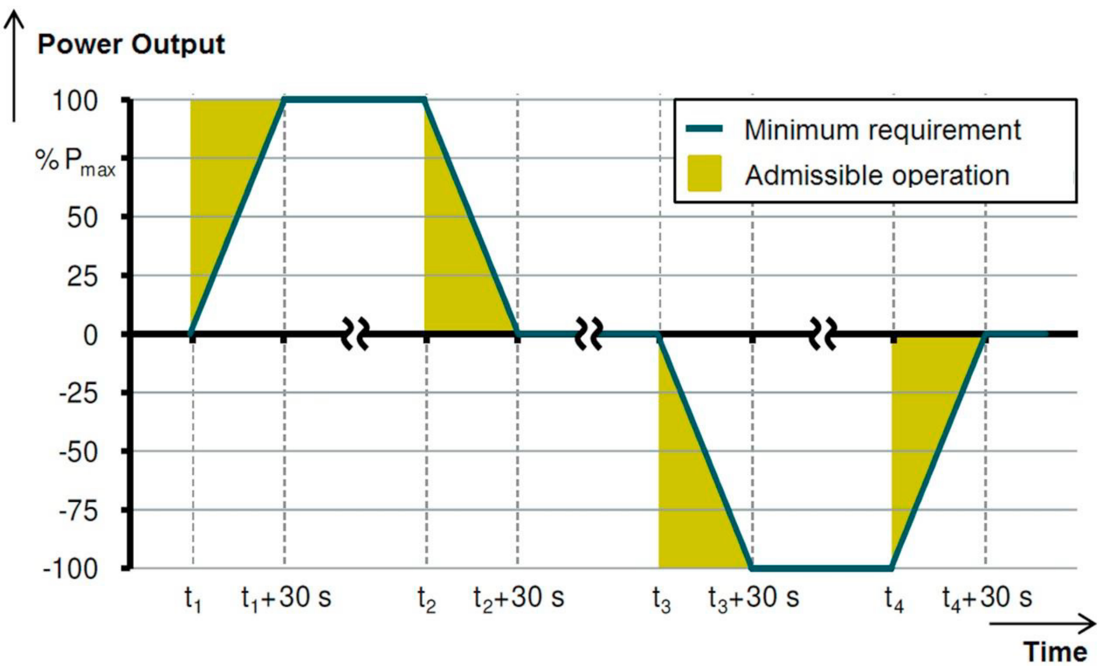

Fig. 4. Admissible operation points for the provision of primary reserve (R1, FCR) [18]

A second criterion for the prequalification constitutes the ramping speed. Here, the TSOs require the R1 capacity to be fully available after 30 seconds at the latest. In Fig. 4 the targeted operation is depicted. Accordingly, when the frequency drops down to 49.8 Hz in t_1 (and remains constant until t_2), then the admissible operation points are along the diagonal curve between zero capacity in t_1 and 100% of R1 capacity in t_1+30s as well as above it. The same is valid for negative provision: When the frequency increases up to 50.2 Hz in t_3 (until t_4), then the admissible operation is depicted in the green surface with the full capacity available in t_3+30s. The respective decrease in R1 capacity for the frequency having restored in its nominal value of 50 Hz at t_2 (until t_3) is analogue. The fulfilment of the ramping criteria as well as the determination of the usable range of possible states of charge is to be proven by reference curves showing that the full positive R1 capacity has to be activated for 15 minutes twice (with a pause of 15 minutes) followed by the activation of the full negative R1 capacity twice [12,14].

6. Complementing high-energy PSP with fast-ramping BESS

The preconditions for the participation on the R1 market, however, are the harshest among the reserve power markets. However, when pumped storage plants (PSP) are complemented with BESS in a pool, they can use (i) the synergy of energy storage volume and (ii) the synergy for the prequalification capacity.

As has been defined in the 15-minutes-criteria, any BESS has to remain within its defined SoC ranges (e.g. 25% ≤ SoC ≤ 75% for a 1 MW / 1 MWh BESS). For this, first of all, the BESS itself can use certain freedoms in the provision of R1 capacity. Here, (i) the freedom of operation in the dead band between 49.99 and 50.01 Hz allows the BESS to provide or not provide R1 power. Also, (ii) the BESS has the freedom to overfulfil the required R1 capacity calling by 20%. With these two measures, the BESS alone can already regulate its SoC in the continuous R1 provisioning operation. However, these two measures cannot safeguard the BESS in the continuous R1 provisioning to always stay in between its defined SoC limits. For this, any energy resource limited storage device has to rely on a sound recharging/re-discharging strategy, which can intervene in case the storage device itself is not capable to stay in its SoC limits. Here, a PSP represents a good instrument for adjusting the BESS' SoC by delivering or drawing electricity to or from the BESS. Although the PSP itself is also energy resource limited, it disposes of an essentially larger autonomy than the BESS.

Moreover, for the R1 provisioning, in particular the ramp rate is of essential importance. Here, conventional fix speed pumped storage plants are in disadvantage compared to batteries based on their electro-mechanical latency. As the ramping behaviour of modern PSP enables to participate in the R2 market, the 30 second ramping requirement of the R1 market is too restrictive and cannot be met.

A PSP equipped with ternary sets (three-machine type units), consisting of a motor-generator and two hydraulic machines, i.e. a separate turbine and a separate pump, can provide R1 capacity if operated in so-called hydraulic short circuit. The principle of this operation mode is based on the idea that only the difference between the constant pump load and the flexible turbine output, both rotating on one common shaft, is exported to the grid. Full regulating capability exists in both, the turbine and the pump mode operation from 0% to 100% of the unit output.

Compared to pump turbine type PSP and even ternary sets, BESS can react much faster due to absence of moving parts and the dependency on only the power electronics as well as the cell chemistry. In Fig. 5, the technical prove for the fulfilment of the ramping constraints of the 5 MW / 5 MWh Li-Ion battery in Schwerin is shown.

It can be seen that the BESS fulfils the ramping requirements without practically any delay. The admissible ramp-up delay of 30 seconds is not needed, the required capacity is provided nearly instantly. This characteristic can be used in a pool with a PSP, the ramping characteristic of which would only allow for the provision of R2 capacity, where the full reserve power has only to be provided after 5 minutes.

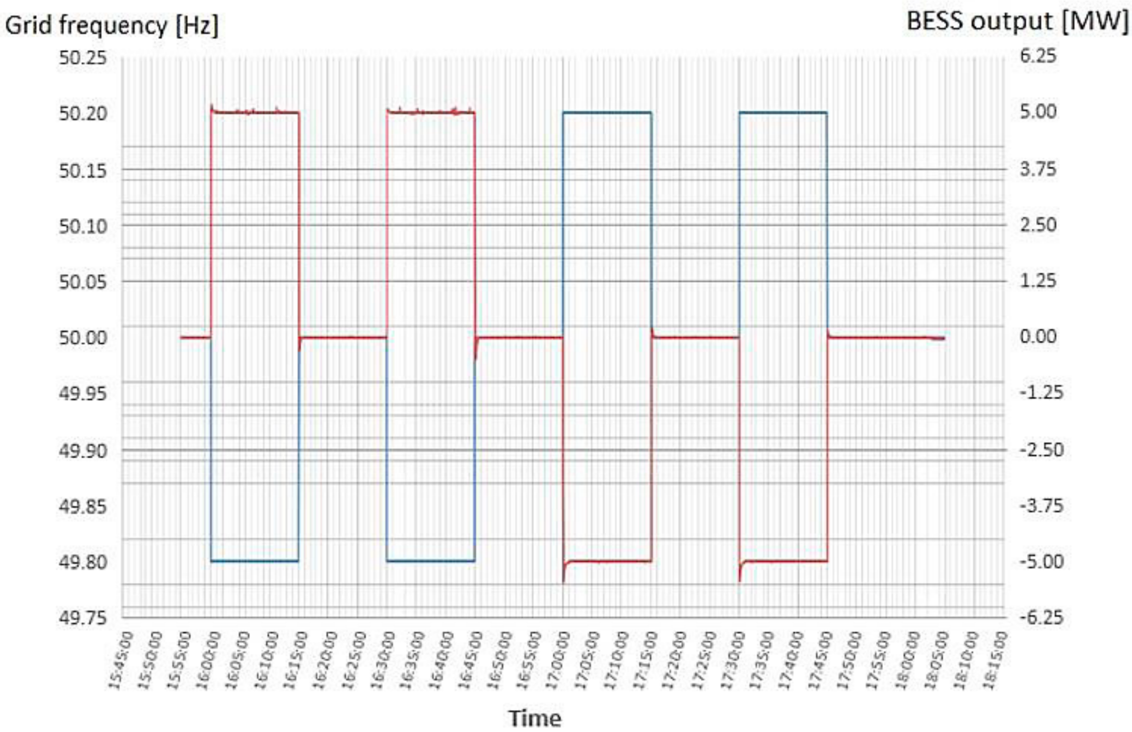

Fig. 5. Prequalification test of 5 MW WEMAG BESS, Schwerin, Germany 10.06.2014 [15]

However, if the PSP and the BESS are jointly controlled by one single controller, the respective benefits of each technology can be brought in so that the control aggregate can benefit of maximised ramping functionality and high storage capacity. In such a pool the PSP is made more flexible so that it can comply to the R1 ramping requirement. The pool of the R2 capable PSP together with the BESS is then able to provide parts of the PSP's R2 capacity as R1 capacity. In this sense, in Fig. 6 and Fig. 7 two different flexibilisation modes of PSP/BESS pooling are shown: In the pooling mode shown in Fig. 6, the BESS is operated upfront of the PSP, which based on its dead band needs a longer

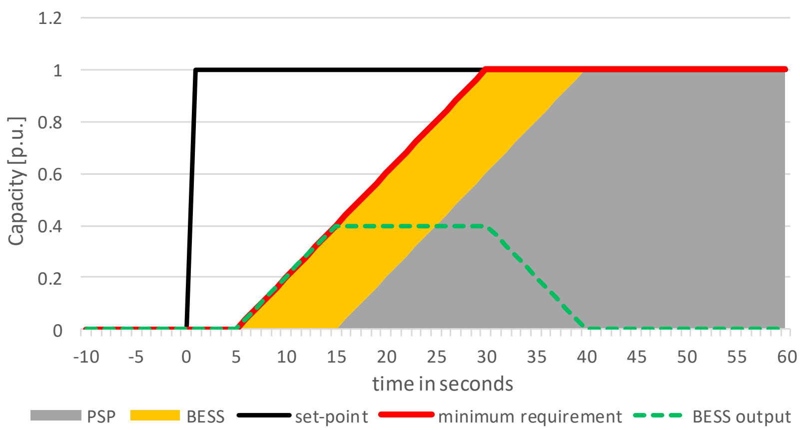

Fig. 6. Joint operation of a PSP/BESS pool for the provision of R1 / BESS bridges dead band

time for the activation of its capacity. The BESS bridges thus this dead band, so that, as a result, the response of the PSP/BESS pool to the set point complies with the minimum required operation. The second pooling mode shown in Fig. 7 foresees the BESS to ramp up in parallel to the PSP, which alone would be too slow to activate the full needed capacity. Together, however, they provide the minimum required capacity response to the set point. Once, the PSP has activated its entire capacity, the BESS output can decrease and wait for the next set point.

In reality, set points are given continuously by the load-frequency controller which realises the R1 regulation policy that foresees full positive provisioning at 49.8 Hz and full negative provisioning at 50.2 Hz. Here, the BESS does not wait for the PSP to have fully reached the set point which steadily changes. Instead, the BESS behaves rather like a continuously changing spearhead of the PSP/BESS pool which takes over the fast ramping activities and leaves the longer lasting capacity provisioning to the PSP so that itself is freed to the potentially next required fast ramping activity.

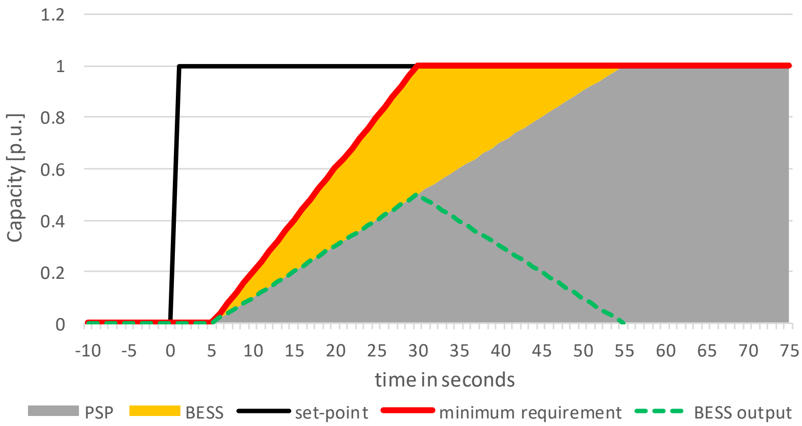

Fig. 7. Joint operation of a PSP/BESS pool for the provision of R1 / BESS increases gradient

It is worthwhile mentioning that for both modes of pooling the BESS does not have to have the same capacity as the larger PSP. In the shown examples a BESS capacity of only 40% and 50% of the PSP capacity is sufficient for the dead band bridging and gradient increase respectively. The respective power output without offset is shown as green dashed line in Fig. 6 and Fig. 7.

7. Conclusion

The dynamics and complexities of the operation of power systems are rising due to the transformation of the power systems towards renewable based generation, which are, to a large extent, subject to volatility. As a consequence, flexibility gains more and more importance in the operation of the power infrastructure.

It is a recent trend, that BESS systems are installed in numerous places. Battery energy storage systems are characterized by their fast-ramping capabilities and are thus ideally suitable to stabilize power grids with high renewable energy infeed, as generation/demand fluctuations can be compensated locally, limiting grid reinforcement measures which would otherwise be necessary. BESS are predominantly operated to provide primary reserve power (R1, Frequency Containment Reserve, FCR) because of their very fast electro-chemical behaviour with response times in the range of milliseconds. In the beginning of 2018, in Germany around 180 MW of BESS are active on the R1 market. Also, this promises the largest income to them. However, for their standalone deployment for R1, BESS are short in their level of energy capacity. Most BESS systems dispose of E2C ratios of only around 1, which is too low for securing the R1 provisioning.

PSP can provide secondary reserve power (R2, Frequency Restoration Reserve – automatically activated, FRR-a), which represents a valuable contribution for the flexibility of the power system.

For the outlined reasons, the idea of pooling BESS with PSP to bring in the fast ramping capability of BESS and to also use the large energy capacity of PSP seems promising. To make use of the individual benefits of PSP and BESS, the two systems have to be operated under one harmonised control regime.

Battery costs have fallen massively in the last years due to increased deployment and interest in storage for variable renewable energy integration. The most dramatic cost developments have been for lithium-ion chemistries, driven by the development and perspectives of the electric vehicle market [16]. Battery energy storage systems represent a game-changer as battery costs are expected to further drop due to the electric vehicle development.

The opportunity of pooling batteries together with PSP enables their large-scale deployment in power systems for the provision of R1 capacity. With this, PSP can experience a revival in providing flexibility to power systems, which in the future will be needed more and more. Existing or new build pumped hydro schemes provide potential for being extended by container-based BESS as the techno-organisational set-up can be commonly used. Apart from the technological infrastructure (high voltage installations with grid interface as well as the control, communication and monitoring systems), the required marketing and energy trading competences are already available.

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