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Abstract—Due to their fast response time and high ramp rates, storage systems are capable of providing frequency control reserves. However, the limit in energy capacity poses difficulties as frequency control signals are not unbiased. We describe a scheme to recharge or discharge the storage without impeding the quality of the provided service, and formulate an analyzing method to investigate the resulting size of the storage.

We show that even small storage sizes are sufficient to provide continuous and reliable primary and secondary frequency control reserves to the grid.

I. INTRODUCTION

With the introduction of intermittent energy sources and the advent of electric vehicles, much focus is given to storage technologies. Currently, only pumped hydro storage is used on a major scale, however pumped hydro is strongly dependent on geographical features. Other technologies, such as batteries [1], flywheels and electrothermal energy storage (ETES, [2]) are independent of location and have rapid deployment times. While costs for such systems are constantly decreasing, they are not yet able to compete with pumped hydro storage.

One possible business case for storage is provision of ancillary services, for example frequency control [3], [4]. Batteries have also an added benefit of being able to react very fast to frequency deviations. It is well known, that a faster response reduces overall frequency deviation and consequently reduces stress on the power system. It would therefore be in the interest of the TSO to include fast reacting storage systems in the primary frequency control scheme. In the course of this paper we will discuss primary and secondary frequency control in Europe, which is equivalent to spinning reserves and load frequency control (LFC) or area generation control (AGC) in other networks.

Ancillary services are not guaranteed to be zero-mean, and losses are inherent to any storage system. This leads to violations of the storage capacity constraints and thus to an inability to provide the promised service to the grid. We propose to enable storage systems to participate in ancillary services by adjusting the operating point to allow for an appropriate charging or discharging that keeps the state of charge within acceptable levels. The adjustment of the working point has to be considerably slower than the associated service. The paper starts by giving an overview over the relevant regulation in Section II, before the proposed recharge strategy based on slow changes in setpoint is outlined in Section III. We then continue by defining the method used for analysing the required energy capacity in Section IV and by giving results in Section V.

II. REGULATORY BACKGROUND

Traditionally, ancillary services are being supplied by power plants (§ 4.4, 4.5 in [5]) and regulation of frequency control reserves focuses on issues related to power plant operation. However, when using storage systems to provide ancillary services, new questions arise. In this paper, primary and secondary control reserves are investigated. Their task is to balance any power mismatch and resulting frequency deviation and unscheduled exchanges in the system, but not to sustain longer periods of energy mismatch. Payments for these fast ancillary service are based on power provision and not on energy delivery, while costs for storage systems arise mainly from energy capacity. For an economical operation of a storage within frequency control, it is essential to maximize the offered control reserves per storage capacity. Tertiary frequency control is neglected, as the aim of tertiary control is to provide energy to the system – something which is hard for a storage device with limited energy capacity.

A. Primary frequency control reserves

Primary control in ENTSO-E describes the first tier of frequency control. Participating units are responding in a proportional manner to deviations from nominal frequency, stabilizing the frequency after a mismatch in production and consumption. Full activation is at 200 mHz and after a maximum of 30s. There also is a dead band of no activation for deviations less than 10mHz [6]. The tendering period is one week, and in the ENTSO-E network currently 3000 MW of primary reserves are contracted. There are some conflicting statements about the energy capacity of a unit participating in primary control. In the following we will discuss the main aspects.

a) Power-to-Energy ratio: The Swiss TSO requires in its contracts, that the units must have an availability of 100 % [7], which would mean basically infinite energy capacity. On the other hand, the ENTSO-E operating handbook specifies, that a unit has to be able to sustain at least 15 minutes of full activation [6], and has to be able to do so again after frequency has been restored.
b) Operating point: German TSO’s explicitly allow the co-use of a plant for primary control and other services such as load-following and secondary control (§3.2.9 in [8]). One might now be tempted to claim that the plant was following a load with opposite behavior as the primary control signal. Thus the two control actions would cancel out and the plant could produce a flat output. Obviously, this is a misuse of the regulation. While no detailed specifications for adjusting the operating point of a unit taking part in primary control are provided, framework agreements for secondary control provide rules on this. Usually, there are two options. Either a change of working point at each full fifteen minutes, or with a five minute notice to the TSO (cf. [9], §3.2.3).

B. Secondary frequency control reserves

The amount of secondary control reserves and minimum requirements are set by ENTSO-E, but the implementation is organized and regulated by each control area independently. This leads to varying definitions even within Europe. As Switzerland utilizes mainly fast hydro power plants, the requirements for response time and ramp rates are far stricter than in Germany, which relies heavily on rather slow thermal power plants. There are attempts to align regulation to make trading in secondary control reserves between control zones possible. Table I gives an overview over secondary control in Germany and Switzerland.

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>Switzerland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full activation</td>
<td>&lt; 5 min</td>
<td>&lt; 140 s</td>
</tr>
<tr>
<td>Ramp</td>
<td>2% (P_N) min (^1)</td>
<td>0.5% (P_N) s</td>
</tr>
</tbody>
</table>

\(^1\) Step-response, including ramp
\(^2\) \(P_N\): nominal power

III. ANCILLARY SERVICES WITH LIMITED CAPACITY STORAGE

While primary and secondary control reserves are usually assumed to be utilized with no bias, this is not at all guaranteed. Ancillary services are designed to clear a reference incident, which is usually the failure of the largest generator in the interconnected network. In such a case primary control would need to provide control power for up to 15 minutes until secondary control takes over. A storage participating in primary reserves would need to have a storage capacity of 30 min in order to be able to provide 15 min in either up or down direction. However, prolonged periods with no change of sign and covering an energy content bigger than the reference incident are observed in historic time series. Such signals lead to a continued charging or discharging of the storage system, eventually violating the capacity constraints.

While a statistical analysis proofs the near-normal distribution of frequency deviations, there is a small bias of 1.5 %, which leads to the substantial cumulative energy shown in Figure 1. While energy capacity is a design parameter of many storage technologies, it is associated with high costs. In the case of Li-ion batteries, it is even the dominating cost factor. Increasing storage capacity to accommodate biased signals is therefore not an economically viable option.

In [3], it was proposed to use the dead band of primary control for adjusting the state of charge. Furthermore, using resistors for down control (reduced production/increased consumption) was investigated. However, former adds only some flexibility without actually solving the cause for imbalances, latter is only a unidirectional solution that wastes substantial amounts of energy.

Instead, by adjusting the setpoint of the storage system, the SoC can be kept within defined capacity bounds. We propose using an average over the previous usage to force the control signal to be zero-mean. A typical 2-hour period of primary control with averaging and delay time of both 15 minutes is shown in Figure 2. Assuming that the control signal is bounded, this leads to a bounded SoC. Furthermore, with bounded input the averaging period defines a maximum ramp rate which can be chosen to be slow enough as not to interfere with the offered service. Additionally, a delay can be added to give next tier ancillary services enough time to relieve the current tier service. This leads to new questions:

a) Setpoint adjustment: There are several options to contract the energy needed for adjusting the setpoint: 1)
intraday markets, 2) bilateral agreements, 3) pooling with a power plant or 4) consumption of balancing energy. Intraday markets and bilateral agreements are cheaper than balancing energy, but suffer from a longer time until delivery and may be fixed to 15 minute or hourly intervals, hence time granularity may not be sufficiently fine. Balancing energy is expensive but immediately available. To still provide the desired service to the grid, setpoint adjustments have to be made with a slower time scale and ramp rate than the service provided by the unit (cf. Section II).

b) System stability: System stability is paramount and may not be impeded in any way. This is guaranteed, as long as 1) the energy content of the storage is capable of clearing the reference incident as defined in the respective ancillary service regulation, 2) the amount of the next tier ancillary service is increased in such a way as to cancel out the setpoint service regulation, 2) the amount of the next tier ancillary service regulation, and 3) the energy content of the storage is capable of clearing the setpoint service regulation.

As the analysis would be very device dependent and quite involved without adding much value to our statement, we assume constant efficiency at all operating points. The loss can be computed as

$$P_{\text{loss}}(k) = P_{\text{out}}(k) + \begin{cases} \frac{(1 - \eta) P_{\text{ext}}(k)}{\eta} & \text{if } P_{\text{ext}}(k) \geq 0 \\ \frac{(1 - \eta) P_{\text{ext}}(k)}{\eta} & \text{if } P_{\text{ext}}(k) < 0 \end{cases}$$

The adjustment of the working point has to 1) cancel out any imbalance in the ancillary service signal, 2) adjust for losses in the storage system. We define $P_{WP}$ as the working point of the storage, and $P_{AS}$ as the power requested by the ancillary service signal. At time $k$, we can compute the offset, which will be applied after a delay of $d$ time steps

$$P_{WP}(k + d) = \sum_{j=k-a}^{k} \left( -P_{AS}(j) + P_{\text{loss}}(j) \right)$$

Here, $a$ is a parameter defining over what time period the average should be taken.

Finally, the actual setpoint for power to be consumed by the battery can be computed as the sum of the ancillary service signal and the current working point

$$P_{\text{ext}}(k) = P_{AS}(k) + P_{WP}(k)$$

The resulting power to energy ratio is computed as the difference between minimum and maximum state of charge reached for a certain parameter set and time series. This can be either expressed as power that can be offered per energy capacity with unit $[\text{MW} \text{kWh}^{-1}]$, or as the reciprocal thereof yielding storage capacity expressed in time that the offered $P_{AS}$ can be stored. We will mainly use latter notation. The required power capacity is computed as $P = P_{AS} + \max(|P_{WP}|)$. We will usually normalize this value with respect to $P_{AS}$.

V. RESULTS

To test the algorithm, different scenarios were investigated. As input a step signal, as well as historic time series provided by the Swiss TSO swissgrid were used. In all simulations, an ideal storage with $\eta = 1$ is compared to a lithium-ion battery system ($\eta = 0.95$), standard battery ($\eta = 0.9$) and ETES ($\eta = 0.8$). Note that these efficiencies translate to a
round-trip efficiency $\eta^2$ of 1, 0.9, 0.81 and 0.64, respectively. Furthermore, we neglect self-discharge as this is minimal compared to other losses and can be easily accounted for by a constant slow charging.

### A. Step response

Figures 4 and 5 show the step response for a controller with both 15 minute averaging period and 15 minute delay, and systems with varying efficiency. Specifically, Figure 4 shows the power consumed by the storage system. As defined by the delay, the storage provides fifteen minutes of full power before bringing back the power output gradually to zero. The overshoot is due to adjustments for the internal losses. The same can be observed in the SoC, which continuously decreases until it is limited by the controller to $22.5 \text{ min} \cdot P_{\text{AS}}$.

### B. Primary control time series

For the delay we assume 1, 5, 15, 45 or 60 minutes, where 1 and 5 minutes would be energy supply from balancing energy, 5 and 15 could be bilateral agreements or pooling with a power plant, and 45 or 60 minutes may be the delay of intraday markets. The averaging period is chosen from 5, 15 or 60 minutes, correlating again to balancing, pooling or trading.

As expected, in Figure 6a we see an increase in the required size of storage with both an increase in delay and averaging period. The increase is not linear, the difference between a 45 minute and 1 hour delay for example is quite small. It can further be observed, that the length of the averaging period has a comparably small influence, while the delay strongly affects the required capacity. Further results are displayed in Table II.

In Section II it was argued that a power-to-energy ratio of 2 or in other words a storage capacity of 30 minutes is a minimum requirement for primary control, guaranteeing system stability in face of the reference incident. If a delay and averaging period of 15 minutes is chosen, that capacity would also be sufficient for the investigated historic time-series.

### Table II: Required power capacity and energy capacity per offered unit of primary control reserve

<table>
<thead>
<tr>
<th>$\eta^2$</th>
<th>a: 5 min, d: 5 min</th>
<th>a: 15 min, d: 15 min</th>
<th>a: 60 min, d: 60 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/P_{\text{AS}}</td>
<td>E/P_{\text{AS}} [h]</td>
<td>P/P_{\text{AS}}</td>
<td>E/P_{\text{AS}} [h]</td>
</tr>
<tr>
<td>1</td>
<td>1.6733 0.1507</td>
<td>1.6161 0.3752</td>
<td>1.5272 0.9170</td>
</tr>
<tr>
<td>0.90</td>
<td>1.6685 0.1511</td>
<td>1.6114 0.3809</td>
<td>1.5043 0.9054</td>
</tr>
<tr>
<td>0.81</td>
<td>1.6631 0.1514</td>
<td>1.6063 0.3868</td>
<td>1.4808 0.8939</td>
</tr>
<tr>
<td>0.64</td>
<td>1.7466 0.1518</td>
<td>1.5942 0.3990</td>
<td>1.4311 0.8711</td>
</tr>
</tbody>
</table>

Interesting enough, perfect efficiency would increase the required energy capacity for certain cases. Generally, efficiency has only a weak effect on the capacity.

The maximum power required decreases somewhat with increased averaging period, and increases slightly with delay time assuming there are losses in the system (cf. Figure 6b). For an ideal storage behaviour is similar, just that there is no dependency on the delay. These results are as expected.
TABLE III: Required power capacity and energy capacity per offered unit of secondary control reserve

<table>
<thead>
<tr>
<th>$\eta^2$</th>
<th>$a$: 15 min, $d$: 15 min</th>
<th>$a$: 30 min, $d$: 45 min</th>
<th>$a$: 1 h, $d$: 105 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P/</td>
<td>P_{AS}$</td>
<td>$E/</td>
</tr>
<tr>
<td>1</td>
<td>2.0311</td>
<td>0.7472</td>
<td>2.0285</td>
</tr>
<tr>
<td>0.90</td>
<td>2.0766</td>
<td>0.7545</td>
<td>2.0619</td>
</tr>
<tr>
<td>0.81</td>
<td>2.1806</td>
<td>0.7672</td>
<td>2.1755</td>
</tr>
<tr>
<td>0.64</td>
<td>2.1506</td>
<td>0.7582</td>
<td>2.1460</td>
</tr>
</tbody>
</table>

C. Secondary control time series

The results for secondary control reserves are similar. We used slower operating point adjustments, which represent energy compensation by tertiary control or power markets. For delay and averaging period we scanned parameter sets of 15, 30, 45 and 60 minutes. Additionally, we added a run with delay of 105 minutes which represents the worst case intraday market delay. Secondary control reserves call for a higher power to energy ratio compared to primary reserves (cf. Table III). Efficiency has only minor influence on this, while the averaging period somewhat and the delay strongly affect the minimum storage size. As can be read from Figure 7a, values range between 0.75 and 4 for fast and slow set point adjustment. The storage also has to provide twice the power capacity of the offered reserve power (cf. Figure 7b).

It would be quite expensive to provide this kind of storage with lithium ion batteries. Other technologies such as the ETES, which have far lower round-trip efficiency but at the same time lower cost per kWh of storage capacity, might be more favorable for secondary control.

VI. CONCLUSION

In this paper, we have shown a way to use storage systems for the provision of ancillary services by adjusting the setpoint. Furthermore, we introduced a way to analyse the required storage size given historic time-series and parameters of the storage system itself.

We argued, why adjusting the setpoint would be acceptable to the TSO and would still guarantee system stability, while at the same time limiting the required energy capacity of the storage. While regulation has to be clarified on the issue of setpoint adjustment, we assume a storage capacity of 30 min for primary control and 2 h for secondary control to be reasonable. With falling prices for storage systems this might become an economically viable option in the future.

Future work may look at ways to improve the basic algorithm presented here. Especially taking into account varying prices for balancing energy or intraday trades at different times of the day may further improve the business case.

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REFERENCES