A New Frequency Control Reserve Framework based on Energy-Constrained Units

Theodor Borsche, Andreas Ulbig and Göran Andersson
Power Systems Laboratory, ETH Zürich
borsche | ulbig | andersson @ eeh.ee.ethz.ch

Abstract—Frequency control reserves are an essential ancillary service in any electric power system, guaranteeing that generation and demand of active power are balanced at all times. Traditionally, conventional power plants are used for frequency reserves. There are economical and technical benefits of also using energy-constrained units such as storage systems and demand response, but so far they have not been widely adopted as their energy constraints prevent them from following traditional regulation signals, which sometimes are biased over long time spans. This paper proposes a frequency control framework that splits the control signals according to their frequency content. This guarantees that all control signals are zero-mean over well-defined time-periods, which is a crucial requirement for the usage of energy-constrained units such as batteries. A case-study presents a possible implementation, and shows how different technologies with widely varying characteristics can all participate in frequency control reserve provision, while guaranteeing that their energy constraints are always fulfilled.

I. INTRODUCTION

Frequency Control is one of the most important ancillary services in any power system, as failure in preventing large frequency excursions can lead to load shedding, generation tripping and, in the worst case, wide-spread blackouts. It is directly tied to the active power balance. Most power grids use a two- or three-level control strategy. The fastest control is the primary frequency control, also known as droop or frequency response. It is a distributed, proportional control capable of arresting frequency changes after a change in production or demand. Secondary frequency control, also known as Load Frequency Control, employs in many systems a central controller called the Automatic Generation Control (AGC). The AGC reacts slower than primary control but has an integral part in the control loop. It is thus able to bring the system frequency back to nominal frequency, depending on the grid region 50 Hz or 60 Hz, as well as to keep exchanges between control areas at the scheduled value. While secondary control could also handle lasting generation-demand mismatches, it is desirable to relieve this service to prepare for future disturbances. Depending on the Transmission System Operator (TSO) and the market structure, different strategies are used. These strategies include activation of tertiary control, spinning and non-spinning reserves as well as the sourcing from intra-day markets. See [1] for a detailed technical description of frequency control reserves, and [2] for an overview over terminologies and strategies employed by different system operators.

Some energy-constrained units, such as batteries, have outstandingly high ramp rates and low or practically no ramping costs, making them promising candidates for frequency reserves. However, limits on the energy capacity are a challenge for these unit types when following reference signals that are not zero-mean: State of Charge (SoC) constraints may be hit, rendering the unit unable to continue provision of the agreed upon ancillary service. Current frameworks for frequency control reserves assume conventional power plants [3], and therefore do not explicitly take into account or regulate how energy constraints should be handled.

As of today, frequency control reserves are adequate and offer a high level of robustness against disturbances and contingencies. Nevertheless, there may be benefits associated with using energy-constrained units for frequency control reserves. These benefits are 1) of economic nature, as it allows for a more efficient unit commitment by effectively decoupling energy provision from reserve power provision and improves market liquidity by allowing more units to participate in frequency control provision, and 3) of technical dimension, as units with very fast ramping ability can improve frequency stability in grids with low rotational inertia. These issues will be discussed in detail in Section II.

Past research was looking at methods to provide frequency reserves using energy-constrained units in the current frequency reserve framework and was therefore concerned with the feasibility of using specific storage technologies. Most solutions propose workarounds or add-ons to allow for operation of energy-constrained units within the existing framework. Some authors, explicitly [4] or implicitly [5], employ band-pass and high-pass filters for the control signal. The contribution of this paper is to propose a generalized framework for frequency control reserves extending the idea of filtering to all parts of the frequency spectrum and to both primary and secondary control. The advantages of different storage technologies, be it fast ramp rates, high efficiency or cheap storage capacity, can then be harnessed within this framework in a straightforward and simple manner.

The paper is organized as follows: Section II gives a rough overview of past research on energy-constrained units for frequency control. Section III analyses the status quo, before Section IV proposes adjustments to the current control reserve framework. Finally, Section V shows in a tutorial how the system might work.

II. ECONOMICAL AND TECHNICAL BENEFITS

A. Pilot Projects and Economic Benefits

Using batteries for primary frequency control was already proposed in the early 1980’s. The electric utility company of West-Berlin, BEWAG, had to operate this city of about 2
To offer reserves, both conventional and hydro power plants have to produce a certain base amount of power, namely the minimum production of the plant plus the offered reserve. At hours with low prices, fuel costs or water value may be higher than what is earned at the power markets. Accordingly, the remuneration for the reserve capacity has to also cover the opportunity cost associated with the technologically necessary but economically loss-making energy production. When offering reserves with batteries, such a base production is not necessary – in other words, control reserve power is decoupled from energy production. The must-run generation may also displace energy from renewable sources, increasing overall CO₂ emissions. Similarly, at times when all of the load is covered by renewable in-feed, wind or photovoltaic (PV) plants must be down-regulated in order to provide control reserves. It might be more profitable to store excess energy in a storage with slow dynamics, e.g., electrolysis, and have a storage with fast dynamics provide frequency reserves.

**B. Recent Research and Implementation**

The uncertain energy content of frequency control reserve activation patterns makes it very difficult for units with energy constraints to offer frequency reserves. Considering primary frequency control, the energy content of the signal is usually so small that power plants are only remunerated for power capacity and not for the actual energy delivery. Still, as long as no guarantees are given, which would be rather difficult in the current frequency control framework, the frequency may be biased over prolonged periods of time, and units participating in the service have to be able to follow the signal at all times. Long tendering periods pose an additional challenge. On the other hand, a stable power system operation is paramount and it is therefore not feasible to allow less strict rules, and shorter tendering periods might increase both administrative costs and volatility.

Approaches to these challenges are manifold. Some authors conclude that the amount of secondary reserve power that can be reliably offered with Demand Response (DR) is high for short time periods but small for longer durations and argue for a reduction of tendering periods [8]. Furthermore, pooling of energy-constrained units with a conventional power plant is proposed. Thus large reserves can be offered and at the same time the flexibility of, e.g., electric vehicles can be harnessed [9], [10]. However, it does not explicitly offer a decoupling of power and energy provision – which we argued in Section II-A is favourable from a functional and optimization perspective – and it requires the aggregator to own or contract a power plant. Recent studies investigating electric vehicles, which have a substantial storage capacity and can also feed in to the grid, concluded that reserves can be offered – but even here, tendering periods limit the amount of reserves, as there are times when only some vehicles are connected to the grid [11], [12]. Finally, in [4] and [13] it is proposed to use Heating, Venting and Air-Conditioning systems of large commercial buildings to offer frequency regulation. To ensure continuous provision of the service and avoid interference with the actual building control while limiting the effect on indoor climate, the regulation signal is filtered with a band-pass.

Various recharging strategies have been investigated to provide primary frequency control with BESSs. The pilot project in West Berlin used recharging during low-load hours [6]. Oudalov et. al. propose recharging during periods when system frequency is in the dead-band around nominal frequency, but no strict guarantees on availability can be given [14]. The authors in [5] propose to subtracts a moving average from the control signal, thus ensuring that the required energy capacity is limited and that the battery is continuously able to offer reserves. At the same time, the battery closely follows the fast dynamics of the regulation signal. In [15], a strategy activating recharging when the SoC reaches a pre-set limit is investigated, and it is shown that this strategy leads to lower cycling of energy but also to more volatile and less predictable SoC evolution than the strategy proposed in [5]. DR has also been proposed for primary and emergency frequency response services. For example, [16] describes a system where loads with thermal storage are automatically disconnected when the system frequency drops by more than 100 mHz, thus helping to stabilize the grid. This approach offers much promise for actual implementation, but avoids the issues of SoC constraints as the regulation signal is only being followed in extreme cases.

Secondary control as a centralized control scheme has seen modifications to allow a wider range of units to provide control reserves. Notably, PJM, a Regional Transmission Organization responsible for a large part of the transmission system in the eastern part of the US, offers a modified signal. The signal is split in a high-frequency part, termed RegD, and a slower part, termed RegA [17]. Remuneration for following the faster RegD signal is significantly higher. A similar approach is currently being investigated by the Swiss TSO swissgrid [18].

**C. Benefits for System Operation**

Batteries are widely used in micro-grids and island systems to provide frequency control reserves. Optimal sizing of a BESS for an island grid is investigated in [19], and specifically notes the improvement of system frequency, both considering peak frequency and settling time, that is achievable by using fast-responding batteries for frequency control. While island systems with small load and fluctuating in-feed from PV or wind are a rather specific case, much can be learned for operation of large interconnected power systems. Renewable energy sources have a two-fold effect on system stability: not only does the fluctuating production require control reserves, but the fact that most wind and basically all PV plants are connected via inverters reduces the rotational inertia of power systems leading to faster and larger frequency deviations after a contingency [20]. Today’s frequency control reserves may not be able to counteract these more rapid frequency dynamics, and future frequency deviations may exceed acceptable limits – an effect similar to experience in small island grids. Very fast responding units such as batteries are one solution for this challenge.
III. Analysis of the Current Situation

In this section, we will analyze the current primary and secondary regulation signals in more detail. Specifically, we will have a look at the frequency spectrum of the regulation signals. It is very important to distinguish between the system frequency, which refers to the actual rotational speed of generators in the system, and the frequency spectrum of this signal. If we refer to low or high frequencies, this refers to the frequency spectrum, while low or high system frequency refers to a situation where system frequency deviates from nominal frequency. Also, the amplitude frequency response denotes the behavior of a control loop when faced with a signal of a certain frequency, rather than the activation of, e.g., the primary frequency response control service.

A. Amplitude Frequency Response of Regulation Signals

The first plot in Figure 1 shows a Fourier analysis of the system frequency of the continental European grid. Data is in 10 s resolution, covering a period of one year. If the system frequency were exactly 50 Hz over the considered period the frequency spectrum would be zero for all frequencies. Certain characteristic effects are of interest. First of all, higher frequencies are well dampened. This is an effect of the inertia of generators. Second, there are several distinct peaks. Annotations in the figure designate the period of these modes. These peaks are artifacts created by the market structure. The load changes continuously, while markets are run in hourly and quarter-hourly blocks. The load often increases or decreases due to a change in production or load, it also describes the effect that the electric power output contains a peak with the frequency of the wave itself, but also smaller peaks at multiples of this frequency. The peaks with a period of sixty, thirty, twelve and ten minutes are most likely induced by the hourly blocks in day-ahead markets, while peaks at fifteen, seven-and-a-half and five minutes result from the intra-day markets. Low frequencies are also not very prominent. Keep in mind that the figure represent a system with active control services, meaning that secondary control handles longer lasting deviations.

A similar behavior can be observed for AGC activation, see lower plot in Figure 1. While peaks in the middle part of the AGC spectrum are congruent with the spectrum of system frequency, higher frequency peaks are basically nonexistent – which results from the low-pass filter effect of the AGC. On the other hand, low frequency peaks are much more pronounced, as secondary control is responsible to bring back system frequency to nominal values and provide power as long as the imbalance persists.

B. Amplitude Frequency Response of Control Reserves

Analogous to the analysis of the control signals, the amplitude frequency response of the different control services can be investigated. The rotational inertia couples frequency deviations $\Delta f = f - f_0$ and power mismatch $\Delta P$ in the system according to the swing equation, here given in the frequency domain and neglecting load damping

$$\Delta f = \frac{1}{s^{2H/S_B}} \Delta P \quad \Rightarrow \quad \Delta P = \frac{2HS_B}{f_0} s \Delta f . \quad (1)$$

While this equation is usually interpreted as system frequency increasing or decreasing due to a change in production or load, it also describes the effect that the electric power output
of a generator is increased or decreased proportionally to the rate of change of system frequency $\dot{f}(t) \propto s\Delta f$. While the mechanical power production can only be adjusted comparatively slow by the turbine governor, the electric power output is changed instantaneously. The required energy for that is taken from or stored as rotational energy in the spinning generator. The generator inertia is therefore the first level of frequency control reserve, it has the characteristics of a differential controller and can also be seen as an energy storage.

Primary frequency control is a proportional control with the system frequency deviation $\Delta f$ as input. There is no dependency on the frequency rate of change $\dot{f}$, i.e., the control response is independent of how fast or slow the system frequency changes

$$P_{\text{prim}} = -\frac{1}{S} \Delta f \quad . \tag{2}$$

The amplitude frequency response in a bode plot is therefore flat, as long as ramp rate constraints and response times of power plants dynamics are neglected. Due to these limitations, primary control effectively has a low-pass behavior with a cut-off frequency around $1 \times 10^{-2} \text{Hz}$.

Secondary frequency control is a centralized control scheme. Usually, a PI-controller is implemented. For a one area system it may take the form

$$P_{\text{sec}} = -B \left( C_p + \frac{1}{T_N s} \right) \Delta f \quad . \tag{3}$$

The proportional part has the same effect as the primary frequency control, but with significantly smaller amplitude as $C_p \ll 1$. The integral part is designed to bring the system frequency back to nominal values by cancelling out lasting generation-demand mismatches. In a Bode plot, this is seen by an increasingly strong response to low frequencies. $B$ is mostly of relevance in multi-area systems where the Area Control Error is augmented by the power exchange schedule deviations to neighboring areas. $B$ usually is chosen as $\frac{1}{2}$, which has the advantageous properties of non-interactive control.

Tertiary control is not automatically activated, only a qualitative analysis is possible. Tertiary control is used to relieve secondary control, which may be interpreted as a low pass filter with steep flanks. Generally, activation depends on many more system and economic parameters making it hard to predict.

Figure 2 shows the different services in one bode plot. For this qualitative plot, the droop is set to $400 \text{MW/}%$. AGC parameters $T_N$ and $C_p$ are chosen as $120 \text{s}$ and $0.17$, respectively, and inertia is assumed to be $6 \text{s}$ with the base-load at $8 \text{GW}$. These values are typical for the Swiss system. Dashed lines show power plant activation with some dynamics taken into account, namely a reheater with time-constant $T_{\text{rH}}$ of $10 \text{s}$ and a delay, modeled as low-pass filter, between valve activation and high-pressure turbine $T_{\text{CH}}$ of $0.3 \text{s}$. Compare this also to the amplitude plots of system frequency and AGC, Figure 1. For frequencies below $1.33 \times 10^{-3} \text{Hz}$, that is a period of $12 \text{minutes or more}$, secondary control is the dominant control service. Signals with frequency higher than $0.033 \text{Hz}$, or a period less than $30 \text{s}$, are mainly dampened by inertia. This time happens to coincide with the activation time allowed for primary frequency response. In between $1.33 \times 10^{-3} \text{Hz}$ and $0.033 \text{Hz}$, primary frequency control is the dominant control reserve.

IV. FREQUENCY BANDS OF FREQUENCY CONTROL RESERVES

All recharge strategies described in Section II-B can be seen as high-pass filters, ensuring that the regulation signal is zero-mean over a certain time, or in a less strict interpretation that the integral of the signal and thus the energy content is bounded and finite. In Section III, we found the system frequency deviations to have a characteristic frequency spectrum. Finally, the currently implemented control reserve framework has a very characteristic amplitude frequency response. Considering all this: why not define services that are a-priori limited to certain bands of the frequency spectrum? Such a system is implemented in the PJM interconnection specifically for the secondary control signal [17]. We aim to derive a generalized framework, applying this approach to all bands of the spectrum.

Some properties of the current control structure are essential for the robustness of frequency reserves. The integrating behavior of secondary control must be kept in order to ensure that system frequency and tie-line exchange powers are brought back to nominal values. Such a control can only be implemented using a centralized control, or at least a control scheme with exchange of information between the participants [22]. On the other hand, one of the advantages of primary control is its distributed topology. No communication is needed, making the primary frequency response independent of failure of communication and therefore robust in practical terms. If a new framework restricts primary frequency control to high frequencies and a secondary control to low frequencies, communication outage might lead to system failure: the AGC is no longer active, and primary control would not arrest lasting power mismatches and the system would soon be unstable. When communication is lost, the units providing slow control services following a central signal would need to fall-back to provide slow proportional control.

Tertiary control should be activated in such a way that the AGC signal is guaranteed to be zero mean over a predefined time interval. This could be done by averaging over the AGC...
signal and adjusting tertiary output continuously or after fixed times, or could also be implemented using an optimal predictive control policy with constraints ensuring that the energy in the AGC signal is bounded. Such predictive methods were already successfully applied to an economic activation of tertiary control to preemptively relief secondary control [23] for the well-known phenomenon of deterministic frequency deviations caused by power market operation [21] at the hourly change. In principle, it would also be possible to completely replace the tertiary control by an intra-day market, with the TSO placing bids according to reserve needs – however this would require liquidity at intra-day markets and expose the TSO to market risk. This is not elaborated on in this paper, but could be easily worked into the proposed framework. It would also be possible to include the provision of rotational inertia as an ancillary service in this framework. While inertia used to be provided by all generation, inverter coupled units do not offer this service and generators with inertia may therefore receive a bonus.

A. Control Power and Balancing Energy Pricing Based on Frequency Bands

Pricing of services could also be adjusted to frequency bands. While a unit providing the whole spectrum should get similar reimbursement as today, there might be different pricing for different parts of the spectrum. Fast responding units would probably be able to receive high payments for offered control power, while slow ramping units could still participate in the market but would only see comparatively low payments, as is done in the PJM ancillary service market today. This could give an incentive to install and market storage technologies with high ramping capabilities, such as Li-Ion batteries, super-caps or flywheels. As all faster services follow zero-mean signals, energy payments are restricted to the slowest service, that is tertiary control or power from intra-day markets. Depending on the amount of available dispatchable energy production capacity, energy might yield very high or low prices – but importantly, energy prices would be decoupled from control power reimbursements which may reveal the actual price of each.

Vice versa, Balance Groups (BGs) could be charged according to the spectrum of their deviations. A Fourier analysis of the daily or hourly mismatch between schedule and consumption, measured in sufficient time resolution, would indicate what kind of service was required by the specific BG, different from the state-of-the-art but crude punishment of power trajectory deviation by using the energy mismatch over a time-interval of 5 or 15 min as the relevant metric. For example, if storage units able to provide regulation services with a period of one hour are very expensive, BGs introducing mismatches with the according frequency and phase could be charged more. This might promote actions by BGs in scheduling or real-time control that reduces specific types of disturbances. While this might increase fairness it may also excessively burden small BG and would only constitute an incentive if BGs have the ability to influence their demand.

B. One Possible Implementation Scheme

In the following we will develop an implementation based on the recharge strategy in [5] guaranteeing that all regulation signals are zero-mean except the slowest service in the cascade. First, let us recapture the battery algorithm. Let $P_{\text{prim}}$ be the primary control signal, and $P_{\text{bat}}$ the actual output of the battery which has an offset $P_a$, ensuring that $\int P_{\text{bat}}$ is bounded for bounded signal $P_{\text{prim}}$. Indices denote the time. We have

$$P_{t} = P_{\text{prim}} + P_{a} = \int_{t}^{t+1} P_{t}' dt$$

Parameter $a$ is the averaging period and defines maximum ramping if $P_{\text{prim}}$ is bounded. $d$ adds a delay, offering additional flexibility if start-up times or delays of slower units have to be taken into account. We will assume $d$ to be zero. Storage losses can be taken into account explicitly, see [5].

1) Distributed, Proportional Control Reserves: We want to split the primary frequency response in different signals for different units. Slower units should take-over from faster units, and by doing so provide the energy to recharge faster units and bring them back to their nominal SoC. Let assume a storage technology with small energy capacity but fast ramping and high cycle-lifetime, as well as a bigger storage with higher ramping or cycle costs. Technologies in this thought experiment could be super-caps and Li-Ion batteries, respectively. The desired behavior $P_{\text{sc}}$ and $P_{\text{bat}}$ can be achieved by

$$P_{t} = P_{\text{prim}} + P_{\text{sc}}$$

and

$$P_{t} = P_{\text{prim}} + P_{\text{bat}}$$

with $a_{\text{bat}} > a_{\text{sc}}$. In this formulation, $P_{\text{sc}}$ follows the fastest parts of the frequency signal, while $P_{\text{bat}}$ follows slower parts. Lower frequencies of the spectrum are not being followed. Both signals, $P_{\text{sc}}$ and $P_{\text{bat}}$ are zero-mean, and the offset energy for $P_{\text{sc}}$ is provided by $P_{\text{bat}}$. More levels could be easily added according to specific needs and available storage technology.

2) Centralized, Integrating Control Reserves: Accordingly, the secondary control signal can be split into several parts. Above examples assume the offset to be adjusted at every time-step, leading to a continuous adjustment of the power that is transferred to slower control services. For units that are currently providing tertiary control, this continuous change of set-point might be undesirable. However, the average could also be sampled on a 15 min or hourly basis.

V. ILLUSTRATIVE EXAMPLE

A small case study is defined to illustrate the proposed framework. Frequency control reserves from a pool of different technologies are used. For the distributed proportional control
super-caps, flywheels and Li-Ion-batteries are chosen, and for the centralized integrating control DR and a thermal power plant. Distributed control is active only for high frequency parts of the spectrum, being relieved after 900 s, while the integral control only handles low frequencies with a maximum ramp rate of 300 s for full activation. Secondary control is relieved with power from intra-day markets that can, as assumption, be brought back to the original SoC. Fast units have minimal energy capacity requirements.

The reserves providing fast response split the frequency spectrum according to their ability. Super-caps are relieved after 5 s, fly-wheels after 30 s and batteries after 900 s. Some indices are omitted for brevity, the detailed formulation is given in (6) and (7). The superscript ‘off’ refers to the offset as in (4) and (6), e.g., $p^{\text{fw,off}} = - \frac{1}{a_{\text{fw}}} \int - p^{\text{sec,off}} \, dt$. The units follow

\[
p^{\text{sec}} = p^{\text{prim}} - \frac{1}{a_{\text{sc}}} \int p^{\text{prim}} \, dt , \tag{8}
\]

\[p^{\text{sec,off}} = \int - p^{\text{sc,off}} \, dt , \tag{9}\]

\[p^{\text{fw,off}} = \int - p^{\text{fw,off}} \, dt . \tag{10}\]

Slower units do not need to know the power output of fast units. It is sufficient if the parameters are known, which are fixed beforehand, and which determine the activation.

Both DR and the thermal plant can ramp within five minutes. DR can handle changes of consumption for up to 30 min before starting to relieve, and provides 70% of the reserve during this time. The thermal power plant participating is more expensive for fast actions and its bid in an imagined ancillary service auction was successful for 30% of the reserve power in this specific frequency band. Lower frequencies are completely handled by the thermal plant. Finally, intra-day markets are used to both relieve the secondary control, and to guarantee that the activation of all units is zero-mean within their respective time spans. Energy reserves are activated by averaging AGC activation over 1 h. While energy might not be a constraint for the thermal plant, the case study will show that the zero-mean condition holds for all units. The activation follows

\[
p^{\text{DR}} = 0.7 \left( p^{\text{sec}} - \frac{1}{a_{\text{DR}}} \int p^{\text{sec}} \, dt \right) , \tag{11}\]

\[p^{\text{therm}} = p^{\text{sec}} - p^{\text{DR}} - \frac{1}{a_{\text{therm}}} \int p^{\text{sec}} - p^{\text{DR}} \, dt . \tag{12}\]

A one area system with parameters corresponding closely to the central European interconnected power system, given in Table I, was simulated. A loss of a 1.5 GW plant after 100 s disturbs the system. Figure 3 shows activation of the reserves. It can clearly be seen how different reserves are activated according to the response capabilities, but also how they are relieved and recharged. The SoC returns to the starting SoC for all units. Figure 4 shows system frequency response in blue and AGC activation in green. The system frequency is quickly returned to nominal values, and AGC is soon relieved by the energy bought at intra-day markets. Numerical results are indicated in Table II. This is just an exemplary case study.

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Figure 3. Results of the case study. Top: Activation of different control reserves. Units are ramped according to their ability. Recharging leads to a negative power consumption, e.g. for the battery (grey). Start of tertiary control / intra-day units (light blue) are scheduled to full quarter hours. Total activation is according to system needs (dashed black). Bottom: SoC evolution. All reserves are brought back to the original SoC. Fast units have minimal energy capacity requirements.

Figure 4. Evolution of system frequency and AGC. Frequency is rapidly brought back to nominal values. AGC activation is relieved by tertiary control in due time.

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**Table I. Simulation Parameters**

<table>
<thead>
<tr>
<th>parameter</th>
<th>variable</th>
<th>value</th>
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<td>base power</td>
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<tr>
<td>Secondary Control reserves</td>
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<td>AGC parameters</td>
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<td></td>
<td>$T_{S}$</td>
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<td>Load-frequency damping</td>
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**Table II. Simulation Results**

<table>
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<tr>
<th>Unit</th>
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<th>SoC [MW h]</th>
<th>$E^{\text{sec,off}}$ [MW h]</th>
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<td>Super-cap</td>
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<td>Flywheel</td>
<td>−50.41</td>
<td>756.30</td>
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<td>Battery</td>
<td>−257.03</td>
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<td>DR</td>
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<td>872.53</td>
<td>−240.56</td>
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<td>Thermal</td>
<td>−793.47</td>
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<td>−550.47</td>
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<td>Intra-day</td>
<td>0.00</td>
<td>2327.08</td>
<td>−</td>
</tr>
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</table>

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\[
P^{\text{DR}} = - \frac{1}{a_{\text{DR}}} \int - p^{\text{sec,off}} \, dt , \tag{9}\]

\[p^{\text{fw,off}} = \int - p^{\text{fw,off}} \, dt . \tag{10}\]

\[
p^{\text{DR}} = 0.7 \left( p^{\text{sec}} - \frac{1}{a_{\text{DR}}} \int p^{\text{sec}} \, dt \right) , \tag{11}\]

\[p^{\text{therm}} = p^{\text{sec}} - p^{\text{DR}} - \frac{1}{a_{\text{therm}}} \int p^{\text{sec}} - p^{\text{DR}} \, dt . \tag{12}\]
to illustrate the proposed frequency control reserve framework. Many simplifications were made. Especially, all storage units are assumed to be ideal, that is loss-less. However, [5] showed how losses can be explicitly included in such a framework. There is ample room for improvement on the inter-play between the different units, also, the amount of information that needs to be exchanged should be studied in more detail. Specifically, effects of inaccurate or missing information should be investigated. Nevertheless, it is the belief of the authors that the set-up is very robust against inaccuracies introduced by storage losses and incomplete information.

VI. CONCLUSION

To motivate the proposed frequency control reserve framework, economic and technical benefits of allowing energy-constrained units to provide reserves were discussed in detail. Specifically, decoupling of control power provision and energy production is found to be economically and environmentally beneficial in a wide range of situations, as it leads to more optimal dispatch results due to the vanishing of must-run generation constraints and improves ancillary service market liquidity by allowing more units to participate.

Next, the frequency spectrum of the current control signals and system frequency were analyzed. Even today, each frequency regulation service is mainly responsible for a certain part of the spectrum, however the crucial difference to our proposed framework is that in current schemes no guarantees are given on the signal being zero-mean over any period of time – which is critical for any practical integration of energy storage units.

A control reserve framework allowing units to bid for a certain part of the spectrum was introduced. This creates a market and thus a price for parts of the spectrum of both disturbances and reserves and allows to reimburse units according to their actual benefit to power system stability. One possible way of splitting the spectrum into frequency bands is described, and an example employing this approach demonstrate the interplay between different participants. The aggregated response is as smooth as the response of the current frequency control framework, and the framework is robust against communication failures.

While this paper motivates the general framework and shows its different advantages, there are many details that should be further scrutinized. This includes the optimal interplay between units providing reserves in different parts of the spectrum, and the required control power for different frequency bands with respect to both every-day operation and contingencies.

REFERENCES


