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Impact of Frequency Control ReserveProvision by Storage Systems on Power System Operation

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Abstract:

Ancillary services, such as main frequency response, may be provided by batteries. However, they have a limited amount of energy. Because of this, it is required to alter the temperature set-points, and the energy for this must be given by power plants that are not constrained by energy. When ancillary service markets enable energy-constrained units to participate, this article examines several elements of and possible advantages for power system stability and operational efficiency.

Key Words: Battery Energy Storage Systems; Ancillary Services; Frequency Control Reserves (BESS).

INTRODUCTION

Production and consumption of electric energy must always be in balance in any electric power system. Automatic control systems that modify the output of certain power facilities to match current demand typically ensure this. Contingencies, such as a plant failure or a line outage, must be accommodated by these control techniques. Power mismatches may cause generators to either accelerate or decelerate, causing the system frequency f to rise or fall depending on the amount of electricity being generated or consumed. When there is a power mismatch, the rate of frequency shift is determined by the inertia of the spinning mass of generators. As long as the power imbalance persists and rotational inertia is not used, the system frequency will diverge until it reaches an uncontrollable point, which will then result in a blackout due to frequency fluctuations.Three layers of control are used in the European electrical transmission system to avoid this. 1) Primary control, a distributed control technique that adjusts power plant output according to the departure from the nominal system frequency and thereby restricts the frequency change in the power plant. Although the divergence from the nominal frequency persists in a steady state, This kind of secondary control utilises a central controller with an incorporated portion to restore frequency to nominal valuers. 3) Manually triggered tertiary control for re-dispatching production to alleviate secondary control as needed. All major electrical networks have similar systems in place, although with distinct nomenclature.

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In light of the growing amount of renewable energy in Europe's grid, although the above-described management mechanism is sufficient to ensure its security and stability, Rethinking the capacity of power plants to provide primary control reserves is required.

To respond to a frequency variation, main control power plants now have up to 30 s to do so. Even if a major line were to go down, the system's frequency would remain within tolerable ranges given the existing levels of inertia. However, since they are connected to the grid through converters, renewable energy sources often have very little or no rotational inertia. A decrease in the grid's inertia will lead to a quicker drop in frequency after an outage, as the percentage of renewables grows and conventional facilities are taken out of the mix. There may be a need to significantly boost initial response times for systems that provide back-up main control reserves. Faster ramp rates of main control units are also often considered to contribute to usually reduced frequency deviations. Batteries and flywheels might be used to produce such rapid ramp rates.

In addition, Demand Response is an option (DR). This is not a new idea; it was first presented by Schweppe et al. (1980), who went on to further study it in (Xu et al., 2011), as well as by others such as Molina-Garc'a et al. (2011) and (Molina-Garc'a et al. (2011)

Now imagine a system with a large proportion of renewable power. As supplementary services, conventional power plants are often used, despite the fact that renewable energy is abundant. This must-run generation runs counter to the goals of a cost-effective distribution and a decrease in carbon dioxide emissions.

Power systems research is increasingly focusing at auxiliary service supply using storage units and DR. There are a few obstacles ahead. Ancillary service signals aren't always zero-mean across any acceptable amount of time. The battery is

Because of this, the battery needs to be charged or discharged for a lengthy amount of time, which reduces its storage capacity. The storage system must be able to follow the auxiliary services signal at all times via an appropriate recharging procedure. Section 2 goes into further depth about these tactics. Off-set energy may be purchased on intra-day markets or obtained from secondary control reserves and used as balancing energy.

Researchers have only looked at how the storage system operates so far, rather than how the changing frequency response behaviour affects grid-wide problems and how it affects system stability. It is the goal of this study to fill this void. With regard to overall system stability, we examine the impact of various set-point modification procedures.

The following is the structure of the document: The recharging method utilised in this work is described in detail in Section 2. Simulated system-wide consequences of the recharging approach are discussed in Section 3. Section 4 provides a simulation to support the idea of using quicker units for main control. Both the results of a simulation based on historical data and those of a contingency analysis are presented and analysed in Sections 5 and 6, respectively.

RECHARGE STRATEGIES

In the past, several methods of recharging have been considered. In the following sections, we'll provide a quick outline.

Recharging on a regular basis. Ku nisch et al. (1986) explain the pi-lot battery project for West-then-islanding Berlin's frequency control system. Recharging three times a week during low-load hours, when the battery does not give frequency control, was suggested based on the lessons learned from that project.

The deadband is being recharged. Outside of a dead-band around the nominal system frequency, primary frequency control reserves are normally activated The dead-band is 10 mHz on the European grid. Recharging or discharging the battery when the system frequency is inside this dead-band, no set-point modifications are made when the system frequency is outside of the dead-band (Oudalov et al., 2007) Shorter resistors are used to drain surplus energy if the battery's State of Charge (SoC) is excessive. When the system frequency deviates from the nominal values, the battery provides the required reaction, but there are no assurances that the SoC limitations will always be met. One month of historical data might be used to demonstrate that the SoC remains within the limitations of the (Oudalov et al, 2007).

Recharging through the internet. Online set-point modifications are at the heart of two new techniques that have recently been introduced: (Borsche et al., 2013) and (M'egel et al., 2013). If the service is to be properly provided, then the offset correction must have a far slower dynamic range than the original signal. Regulatory frameworks aren't set in stone in this regard, but in general, power plants may inform the Transmission System Operator (TSO) of changes to their schedule with short notice. If you look at the online strategy, you may consider it as a kind of filtering of your data. Batteries with certain SoC levels should have set-point modifications made when they reach such values, according to (M'egel and colleagues, 2013). A time delay to enable for the procurement of the off-set energy from an alternate source is described in the set-point modifications. When compared to Oudalov's and Borsche's approaches, this one had the lowest energy cycle costs. In addition, the SoC may be assured to keep within a specified set of constraints. Nevertheless, the non-linear behaviour around the SoC limitations that prompt a recharge is far from perfect in SoC tests, and this may lead to vastly different responses from two identical sets of batteries.

(Borsche et al., 2013) employs a moving average to recharge the battery and to compensate for battery losses throughout the charging and discharging process. For example, the main control's P 1 request is calculated using the system frequency deviation f and droop S.

$$P^1 = -\frac{1}{S}\Delta f \quad . \qquad (1)$$

The battery output P^{bat} is then adjusted by an offset P^{off}

$$P^{off}(k+d) = \frac{1}{a}\sum_{j=k-a}^{k} P^{loss}(j) - P^1(j) \quad , \qquad (2)$$

$$P^{bat} = P^1 + P^{off} \quad . \qquad (3)$$

By decreasing the ramp rate of the offset, as well as the ramp rate needed by the second-tier service delivering the recharge energy, parameter a determines the average time. Delaying the purchase of electricity at intra-day markets or starting up a power plant to provide the offset energy may be advantageous. The battery's losses, referred to as P loss, are quantifiable.

It is possible to forecast the battery reaction only by monitoring the system frequency. Tests on historic time series show that far lower storage volumes are adequate for worst-case energy capacity needs, as shown by (Borsche et al., 2013). Note that P bat may be higher than P 1, which means that the necessary battery power is more than the quantity of reserves that can be supplied.

strategies based on the MPC (Ulbig et al., 2010) and more recently for inertia mimicking and control reserve provision with general power system units that are defined by their respective constraints in ramp rate, power and energy capacity, see (Ulbig et al) (Ulbig et al., 2013). Inter-temporal restrictions on storage systems may be dealt with using such control techniques, which can take into account typical patterns in system frequency, such as hourly and daily cycles. Because of the inherent uncertainty in system frequency predictions, no control method based on such an intricate controller can be said to be predictable.

Even though the emphasis of this work is on decentralised main control services, other TSOs have implemented or are planning to implement comparable principles. An example of this is the RegD- signal, which is provided by PJM and used for secondary control.

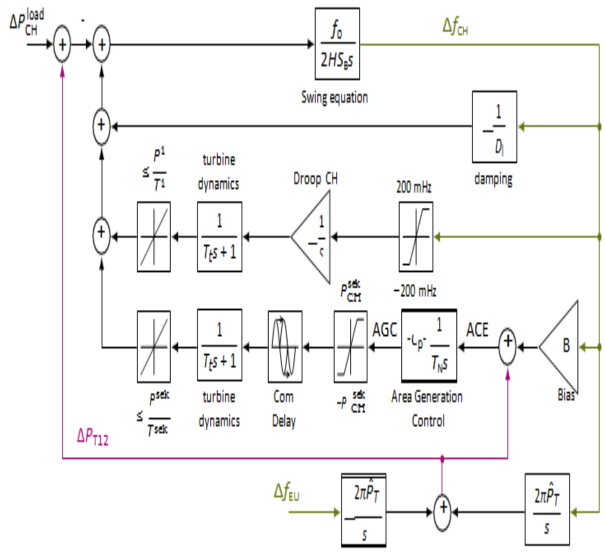

Fig. 1. One-half of the two-area system used for the simulation. Batteries not included.

the same auxiliary service (Pilong, 2013, Sec 3.1.2). In order to meet the needs of "dynamic or rapid reaction resources," this signal was created.

SIMULATION SETUP

Using a simulink model for the synchronous grid of continental Europe, the influence of main control reserves on the frequency evolution is studied. For the sake of this study, the grid is represented as a two-region system, with one area representing the Swiss control zone, and the other area representing the whole European grid.

The P load and P load power mismatches serve as inputs to the two-area system. The two-area arrangement shown in Figure 1 is shown in detail. Table 1 lists the parameters utilised in the simulation, which are based on data that was previously published (Weissbach and Welfonder, 2008). The general model has been extensively researched, as shown by, e.g. (Kundur, 1994). The swing equation is the model's nucleus.

$$\frac{d}{dt}\Delta f = \frac{f_0}{2HS_B}\Delta P - \frac{1}{D_l}\Delta f \quad , \qquad (4)$$

System inertia (H), nominal power (SB), and damping (Dl) by frequency-dependent loads (H) are all included in this equation. Additionally, the major and secondary control reserves are described in the blocks that follow. A simple low-pass filter is used to reflect the dominating dynamics when modelling the governor and turbine dynamics. For the auxiliary services, ramp rates are also defined that comply with the legislation. This means that in Switzerland all primary and secondary controls are fully activated at the end of 30 seconds, and at the end of 120 seconds elsewhere and at 300 seconds in the other control regions.

The Automatic Generation Control (AGC) activates the secondary control reserves (AGC). The ACE is sent into the AGC as an input. ACE is calculated as follows:

$$\mathrm{ACE}_i = \Delta f\, B + \sum_j \Delta P_{Tij} \quad . \qquad (5)$$

Unscheduled exports from area I to area j are represented by PTij and B is the bias factor. Additionally, the AGC is often used as an

Table 1. Parameters used in the simulation of the two-area system.

parameter	variable	value CH	value EU
inertia	H	6 s	6 s
base power	S_B	8 GW	240 GW
Primary control reserves	P^1	80 MW	2920 MW
Primary Response Time	T^1	30 s	30 s
droop	$1/S$	400 $\frac{MW}{Hz}$	14600 $\frac{MW}{Hz}$
Secondary control reserves	P^{sek}	400 MW	14000 MW
Secondary response Time	T^{sek}	120 s	300 s
AGC parameters	C_p	0.17	0.17
	T_N	120 s	240 s
Load-frequency damping	D_l	$\frac{1}{120}\frac{Hz}{MW}$	$\frac{1}{3750}\frac{Hz}{MW}$

implemented as PI-controller of the form.

$$\mathrm{AGC} = \quad -C_p - \frac{1}{sT_N}\,\mathrm{ACE} \quad . \qquad (6)$$

Numerous complexities are eliminated because to the model. Assuming just two control zones, the European grid has a much larger number. Although the AGC systems in different control zones are not specified, the Swiss system is an exception to this rule. Our chosen modelling technique does capture general system behaviour realistically enough, however, and this includes changes over longer time periods, as well as frequency dynamics and the use of control reserves.

FREQUENCY EVOLUTION IN SYSTEMS WITH LOW INERTIA

In the event of a contingency, the system frequency will deviate more quickly, resulting in a longer recovery time. A 3 GW increase in load is seen in Figure 2. ENTSO-E uses this instance as a standard for calculating the size of the main frequency control reserve. Despite the rarity of such an occurrence, (Weissbach and Welfonder, 2009) claim that big fluctuations in output are detected every entire hour, leading to significant changes in frequency. If the main frequency control reaction time T 1 is too long, the frequency may diverge from permissible values. This problem may be alleviated by reducing the reaction time, and may even result in a lower maximum deviation. (Mercier et al., 2009) claim that tiny island grids have a similar impact owing to a low base load and may be handled with batteries.

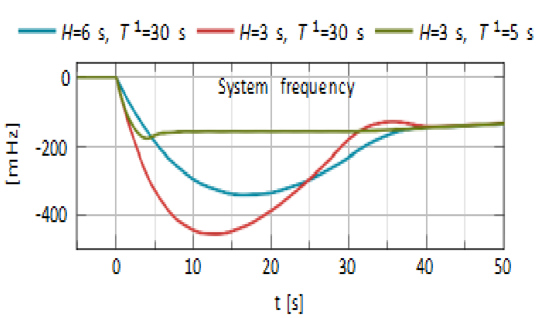

Fig. 2. Frequency change after a deviation depends on the inertia H and response time T [1] of the primary control. Reduced inertia might lead to problems forgrid operation in the future.

The secondary control's dead time and the load's frequency dependence also have an effect on the frequency development. The latter is once again linked to the overall system load. When the system's inertia is decreased due to a significant proportion of renewable energy, critical circumstances might arise, particularly at low loads.

CONTINGENCY ANALYSIS

Here, we report on the system and battery behaviour after a crisis. The following are the kinds of things we'd want to know: if energy-constrained units regulate the frequency, how does it change? Is it essential for the secondary control system to be expressly informed of the needed recharge energy? Do the average time and delay have any influence on system frequency? What is their relationship to recharge energy requirements?

Figure 3 depicts the batteries' position in relation to the overall control system. (1) and (2) include the equations that determine the offset P off and the battery output P bat (3). The parameter determines how much of the principal control reserves are given by batteries.

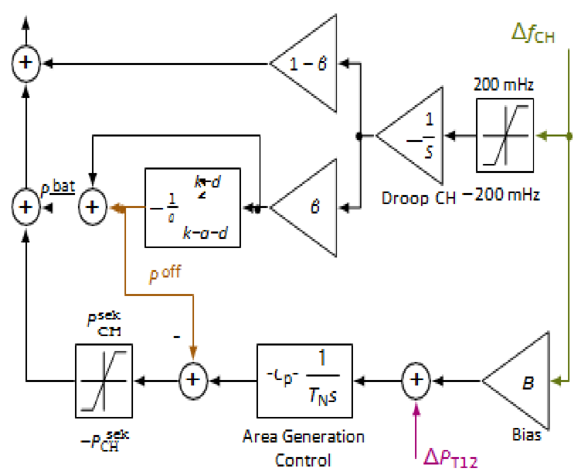

Fig. 3. Batteries as part of the control reserve framework, with recharging algorithm and explicit

communication of the offset. Turbine dynamics and rate limits omitted.

Messages conveying the ability to recharge. Section 2's recharge techniques presume that other services will provide the energy needed. Secondary control reserves must be used if the energy is not purchased openly on an energy market. Either the offset may be added to the AGC signal to express the needed quantity of energy, or secondary control can be activated implicitly through the system frequency to communicate the requirement.

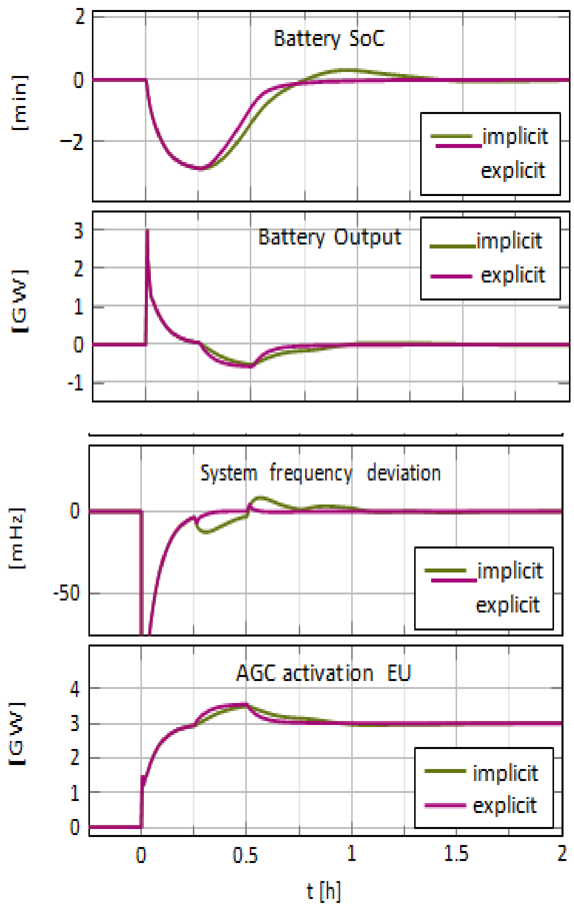

Fig. 4. Effect of communication of the battery offset to

the secondary control. Communicating the offset both implicitly via the system frequency and explicitly lead to a rather smooth response.

For a 3 GW loss in production and 100% primary control supply by energy limited units, i.e., = 1, the results are shown in Figure 4. a and d are both set to 15 minutes. If the offset is not transmitted, the results are shown in green; if the offset is provided, the results are shown in purple. System frequency is not affected, and battery SoC does not overrun in the latter technique. A little amount differs whether the offset is included or not. There is some evidence that conveying the offset is beneficial, although it is not required. It's good to know that these channels are only nice-to-haves and aren't absolutely necessary in the event that anything goes wrong.

Averaging period and delay sensitivity. The recharging approach includes both a delay d and an average period a. Reducing a and d has a positive impact on a battery's storage capacity needs, hence doing so is beneficial to the battery's owner. Choosing values that are too tiny, on the other hand, may be counterproductive to the requirements of the system. The offset was not given clearly for the following runs.

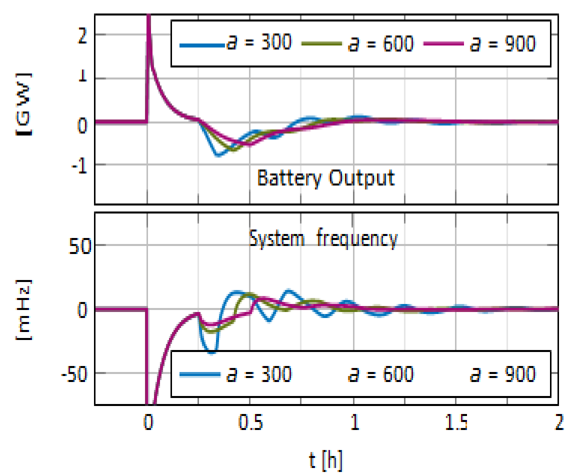

Fig. 5. Effect of averaging period a on system response, if offset is not communicated. Decreasing the averaging period leads to more pronounced oscillations.

A contingency is shown in Figure 5 in terms of battery output and system frequency. At 15 minutes, both f and P bats are quite stable. This may cause oscillations in the battery charging process, which can then lead to fluctuations in the system frequency. Shorter averaging durations seem to cause an undesirable interaction between the battery and the secondary control.. When the delay is changed, the system's behaviour does not change dramatically. Even a zero-delay time constant provides smooth frequency transitions. Secondary control reserves may be activated more quickly with no delay, using less offset energy at the same time, since the battery is freed sooner.

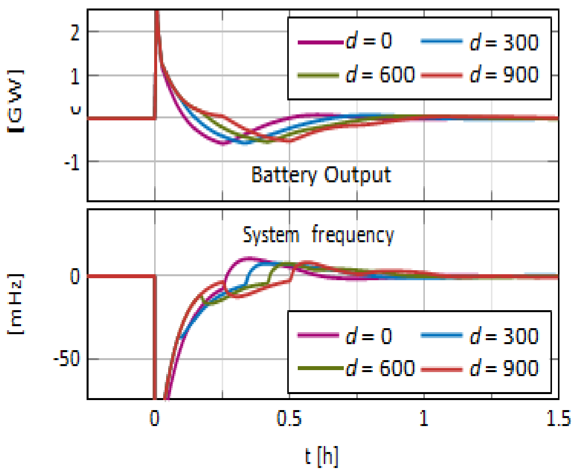

Fig. 6. Effect of delay d on system response, if offset is not communicated. Reducing the delay has no major effect on system frequency or battery output.

LONG-TERM SIMULATION

Normal power system functioning is examined in the following sections, following on from the contingency analysis in the preceding section. It is necessary to simulate a year in order to get findings that are somewhat reliable. System frequency and secondary control activation in the Swiss control zone are used as inputs for the simulation. A 10 mHz frequency discretization is provided for both data sets. The swing equation's dynamics restrict the data provided.

Table 2. Sensitivity of battery and AGC usage on design parameters. Results of one-year simulation. Colourings highlight correlation between parameters and outcome.

Parameters				AGC,CH		Battery response		
β [s]	offset	a [s]	d [s]	E^{pos}_{CH} [GW h]	E^{neg}_{CH} [GW h]	Δ SoC [min]	$\lVert P^{off}\rVert_\infty$ [p.u.]	$\lVert P^{bat}\rVert_\infty$ [p.u.]
0	-	-	-	317.1	-506.2	–	–	–
0.5	yes	900	900	317.7	-509.9	22.91	0.61	0.91
1	yes	900	900	318.5	-513.9	22.91	0.61	0.91
1	no	900	900	318.2	-513.7	22.94	0.61	0.91
1	yes	600	900	319.0	−514.3	20.81	0.64	0.93
1	yes	300	900	319.9	−515.1	18.87	0.66	0.91
1	yes	900	600	319.5	−515.0	18.49	0.61	0.92
1	yes	900	300	320.8	−516.6	14.03	0.61	0.92
1	yes	900	0	321.3	−517.7	8.85	0.61	0.84

are seconds and mHz apart. The frequency data may be used to calculate primary and secondary control activation and damping by frequency-dependent loads, while the AGC signal, along with frequency, also provides information regarding tie-line power. The P load may be calculated using this information. Power mismatches in the remaining European grid, known as P load, are addressed in the same way. For primary control, we'll look at how energy-constrained units impact system frequency and AGC activation, as well as how much store space is required. When the inertia of the system is lowered, we examine how the frequency of the system changes.

Normal functioning. According to Table 2, you can see how each parameter affects how sensitive it is to the other parameters. During each simulation run, the quantity of positive control energy Epos and the amount of negative control energy demanded by secondary control services in Switzerland is provided. SoC storage capacity, which is the difference between the highest and minimum SoC attained, is also indicated, as is the maximum offset power P off and the total battery power P batstorage .'s capacity Batteries are required to have a certain amount of power capacity. Note that over the simulation period, the greatest main control reserve activation was 0.78 p.u..

The use of secondary control reserves must be somewhat increased since batteries are taking the place of conventional primary control reserves, however this is only around 1% of the total energy cycled. It doesn't matter whether you communicate recharge energy implicitly or directly. Short aver- ageing times lower the required battery capacity significantly, while minimising the delay reduces it by more than half. In addition, lowering the delay also affects the storage system's minimum power capacity, although this impact is modest and seems to be reliant on the time series' individual properties. However, in conjunction with Section 5, it is possible to set d to 0 s and a to 15 minutes.

Inertia is lessened. As shown in Table 3, secondary control activation is shown, as well as the system's lowest frequency (F min), mean frequency (F mean), standard deviation (F standard deviation), and maximum frequency (F max). Using this method, it may be clearly observed.

Table 3. Frequency deviations and secondary control activation over one year, depending on use of batteries and inertia.

Set-up				AGC,CH		System frequency			
β []	H [s]	T^1 [s]	offset	E^{pos} [GWh]	E^{neg} [GWh]	f^{min} [mHz]	μ^f [mHz]	σ^f [mHz]	f^{max} [mHz]
0	6	30	–	317.1	−506.2	−155.96	2.88	22.11	142.88
1	6	30	yes	318.5	−513.9	−156.17	2.88	22.13	143.00
0	3	30	–	317.1	−506.2	−156.63	2.88	22.25	142.48
0	1	30	–	317.1	−506.2	−157.51	2.88	22.39	144.66

When it comes to frequency evolution, energy-constrained devices and the accompanying recharge have only a negligible impact, with only minor changes. An inertial decrease is also expected to contribute to increased system frequency deviations, it was hypothesised. However, our simulation did not show this. As to why this is happening, there are two possibilities. As long as the load mismatch is relatively gradual, main control reserves are able to keep pace with the consequent frequency shift. To put it another way, damping and primary control reserves restrict maximum frequency deviations, rather than inertia and primary activation rate. There is a time resolution of 10 seconds employed in the simulation of the data used. An interpolation rather than a step-by-step approach is used to deal with the load imbalance. The lack of correlation between inertia and frequency variations may be due to this assumption, which is valid in many cases. There is no way to tell whether 1) or 2) is correct based on the information supplied. In any event, a contingency analysis may be used to study the behaviour of a system after a contingency, as shown in Section 4.

CONCLUSION

Primary frequency control supply by energy restricted components, such as batteries or DR, was studied to see how it affected system function. So that the batteries may recharge and preserve their SoC limits, the secondary control must offer some extra energy. This does not have a significant impact on the system's frequency. The secondary control may be explicitly informed of the amount of recharging energy required, or the system frequency can be used to relay this information. In power systems with low inertia, a contingency analysis indicated the benefits of quicker primary control reserves. Batteries were found to be sufficient in all of the scenarios studied.

Primary control based on energy restricted units is as dependable as conventional primary control since it does not need new communication links or higher secondary control reserves. In terms of operational benefits, quick battery ramp rates and the decoupling of control and energy output are equally important to a battery-powered system.

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