Influence of State of Charge Level on Frequency Control Reserve Provision by Energy Storage Systems

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Abstract — **Batteries in transmission grids can provide ancillary network services, such as primary frequency response, voltage control in network nodes or back up power. The Battery Energy Storage Systems (BESS) is often the most limiting factor within their more extensive usage for the frequency control. Because of this it is necessary to adjust the system charging SoC and the performance of battery systems so that they fulfil the same requirements as those ones which are applied in case of conventional providers of primary frequency control. This article says more about the possibilities of using and stability of battery systems and their ability to be a part of the ancillary services providers.**

Keywords — Ancillary services, frequency control, battery energy storage systems (BESS), battery charging (SoC).

I. INTRODUCTION

The share of the primary control performance in Slovak Republic within the common transmission grid ENTSO-E is ± 29 MW [1]. According to the technical requirements of the transmission grid operator (TSO) SEPS the maximum share of the primary control performance purchase (PRV) from abroad is 30 % [2]. The share of PRV ± 8 MW represents an import from neighbouring transmission grids. The primary control performance in Slovakia is provided by two blocks of the nuclear power plant Mochovce. Block 3 and block 4 of the nuclear power plant Mochovce are being certified at the moment. Block 5 and block 6 of the thermal plant Vojany, steam-gas power plant Energochem Svit and some generators of hydroelectric plant Gabčíkovo. Considering the fast of a stabile delivery of the primary control performance it becomes more and more problematic to be able to replace some blocks of power plants, for example the nuclear power plant Jaslovske Bohunice or steam-gas power plant Malženice. Furthermore, due to a performance reservation and providing of PRV, the lifetime of generators decreases. Within the European transmission system ENTSO-E, the pressure to create a common market with primary control energy is increasing what also would have an impact on the financial effectiveness if traditional rotary units for the PRV are used.

In any electric power system, production and consumption of electric energy has to be in balance at any time. This balance is guaranteed by an effective power controller (resp. rotation speed) of the machine providing PpS. The frequency corrector of the ASDR turbine adapts the effective power of the machine providing PpS [2].

These control schemes also have to be able to handle contingencies, such as the failure of a plant or the outage of the control block. If there is a power mismatch, system frequency *f* will change: with an increasing production, the performance will decrease or with a decreasing frequency the performance of generators will be higher. The inertia of the rotating mass in generators defines the rate of frequency change when a power mismatch is present and it also prevents the system frequency from making sudden jumps.

In the European electricity transmission grid, three levels of control are being used:

1) Primary Control, a distributed control scheme that divides the performance of generators proportionally to the frequency deviation from the nominal system frequency.

2) Secondary Control which has a central controller keeping the balance of the electric system of Slovak Republic and the ES frequency to nominal values.

3) Tertiary Control, which is activated manually – a centrally coordinated system service, which aims to support a reserve for a secondary performance control. Similar schemes are used practically in all major power grids.

Above control scheme is able to guarantee security and reliability of the European grid. When considering the increasing share of renewable generation, it will be necessary to rethink the adequateness of power plants for primary control reserves. There are two issues:

1) Power plants participating in the Primary control have currently up to 30 sec. to react to a frequency deviation. The inertia deviation of the PRV is being evaluated by the operator every 30 minutes. Renewable energy sources have usually low or no rotational inertia as they are coupled to the grid by converters. As their share is increasing, the inertia within the grid is reduced and the frequency will drop faster after an outage. It is also assumed that faster ramp rates of generators

providing the Primary Control lead to lower frequency deviations [3].

2) Assume we have a system with a very high share of renewable generation. Conventional power plants provide ancillary service, even though enough energy is produced from renewable sources what could also partially provide the control power. This contradicts the aim of an economic dispatch and of reduction of carbon-dioxide emissions. Power plants providing frequency control usually have lower efficiency than load units running at optimal performance [4].

Ancillary service signal is not $\eta < \pm$ 10mHz over any time period. The batteries therefore have either to charge or discharge for a prolonged time period and so get a charging balance of SoC. It is important to choose an appropriate recharge strategy which guarantees that the storage system BESS is able to follow the ancillary services signal at any time. This strategy is discussed more in Section 3.

In this article we focus on storage system and possibilities to keep the charging level in the optimal SoC at the time when the system is active while using deviations of required and real primary control approved by the operator. With a data analysis in CW 37/2012 we wanted to prove that the strategy of keeping the BESS system stability is appropriate. We have compared the weekly development of SoC at balancing the charging level on a maximum level aside from the service quality of the primary control at first place. This strategy is appropriate if the PRV provider is a part of a bigger balance group or is able to stabilize the battery charging level by a separate section. Then we have limited the values of the charging level Frame of Charge (FoC), Frame of Discharge (FoD) so that the quality requirements of PRV are kept.

This article is organized as follows: in Section 2, several recharge algorithms are discussed. We explain the used algorithm in more detail. In Section 3, this algorithm is used to identify critical points within the simulation process.

II. STRATEGIES TO KEEP CHARGING LEVEL

In the past various recharge strategies for the BESS have been discussed. An overview is given in following paragraphs.

Scheduled recharging. Kunich [4] describes a pilot project for a battery providing frequency control for an islanded system "West-Berlin". From the experience gained in the project they proposed a recharging three times a week during low-load hours (at these times the battery does not provide PRV). Another pilot project presented by Swierczynski [9] utilizes the fact that in Denmark separate bids for positive and negative Primary Control reserves can be placed.

Only positive reserves are offered and recharging is done when the system frequency exceeds the SoC limits.

Deadband recharging. Primary frequency control reserve is usually activated outside of a dead-band around the nominal system frequency. In the continental European grid, the dead-band is within ± 10 mHz of the nominal frequency (50 Hz). In the Quadalov [5] and Mercier [6] strategy the battery is recharged or discharged while the system frequency is within a dead-band. Outside of the dead-band, the performance follows the system frequency adjustment at the required SoC values. Under this approach, the battery provides exactly the expected response when the system frequency diverges from the nominal value which could mean, that in some limit cases the limits $\mathrm{SoC}_{\min}$, $\mathrm{SoC}_{\max}$ might not be kept. Qudalov [5] shows that SoC stays within limits for a one-month period on the historic data.

Online recharging. Recently, two strategies relying on online balance of the required SoC values were presented. Borsche [7] and Megel et al. [8] consider an offset adjustment of dynamics in order to guarantee proper and reliable provision of the PRV service. Regulatory frameworks are not definite in this respect for the required PRV, but there is a fact used, that the power plants are allowed to make changes in their schedule if they are known to the Transmission System Operator (TSO).

Megele et al. [8] propose set-point adjustments whenever the battery reaches specific SoC levels. The set-point adjustments have ramps with a limited slope and time-delay to allow an offset energy from an alternative source within one balance group. A problem within this strategy is that the SoC measurements are far from exact and the non-linear behaviour is close to the SoC limits. The approach from Theodor Borsche [7] is similar as in case of the *online charging* strategy, but it uses a moving average to recharge the battery and to adjust for losses during charging and discharging. If P^1 is the power requested by the Primary Control, which is computed using the system frequency Δf and S is the frequency corrector statics then:

$$P^1 = -\frac{1}{S}\Delta f \ . \tag{1}$$

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

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

$$P^{bat} = P^1 + P^{off} \ . \tag{3}$$

Parameter a defines the averaging period. Increasing of a reduces the ramp rate of the offset and thus the ramp rate required by the service providing the recharge energy. Parameter d is a delay, which might be useful if the power is bought at an intra-day market. The variable P^{loss} represents the losses of the battery which can be measured or predicated.

Charging within active points.

The charging strategy within active points is based on an assumption that the time is used effectively when the system is active and the dead-band of $\eta \pm 10$ mHz was not exceeded. By using an approved deviation or the required and real performance we can keep the level of SoC_{min}/SoC_{max} in defined limits. Such schema reduces losses which are developed within balancing the SoC level in the dead-band, because the frequency converters show the biggest losses when they have a low performance. Furthermore, within our simulation, we have concentrated on keeping the SoC within the active points (*AF*) provided that this does not mean a big reduction of battery capacities.

In the considered model, we decided for the control battery performance ± 2 MW (within the simulation of ancillary services). From the formulation of the maximum possible deviation defined by TSO it results that the difference between the real and requested performance considering the size of the source can be defined as follows:

$$\Delta P_{PRV} \leq 0{,}05 \times (PRR) \ , \tag{4}$$

$$\Delta P_{PRV} \leq 0{,}2 \ . \tag{5}$$

Within a real operation, a deviation due to the unit noise at a high performance of blocks represents ca. 25 % around the stator correction curve. In our simulation we considered $\Delta P_{PRV} \leq 0{,}2$. This means that a maximum absolute deviation defining the charging/ discharging performance *FoC*, *FoD* may not exceed this value but must be high enough to keep the charging level of the battery system within limits.

$$FoC = \left| \frac{\int_{t=1}^{t_n k} P_{TARGET}(t)dt}{AF_{avg}} \right| \tag{6}$$

$$FoC \leq 0{,}2$$

$$FoD = \left| \frac{\int_{t=1}^{t_n k} P_{TARGET}(t)dt}{AF_{avg}} \right| \tag{7}$$

$$FoD \leq 0{,}2$$

$$t \in \langle 1;900 \rangle [s], \ t \in N \tag{8}$$

During the whole simulation the system mustn´t be completely discharged SoC = 0 % or full charged SoC = 100 %. It is very important to define a battery size which is able to keep the capacity a balance SoC. What we cannot influence within the simulation of the online charging is the number of active points where the BESS performance can be changed. We consider a long-term prediction of the number of no-zero active points AF_{avg}.

$$\forall AF : f(AF) > \eta \tag{9}$$

III. SIMULATION

The BESS model for Slovakian transmission grid is based on the weekly analysis of the system frequency to analyse the influence of the battery on the primary frequency control. In Fig. 1, there is a flowchart of the proposed algorithm of the positive or negative performance balance.

To keep the *SoC* system BESS we decided for a controlling network. After the first 15 minutes of the PRV providing we suppose an activation of the secondary frequency control (SRV) and a capacity deviation by 50 % or more *SoC* will be balanced within next 15 minutes.

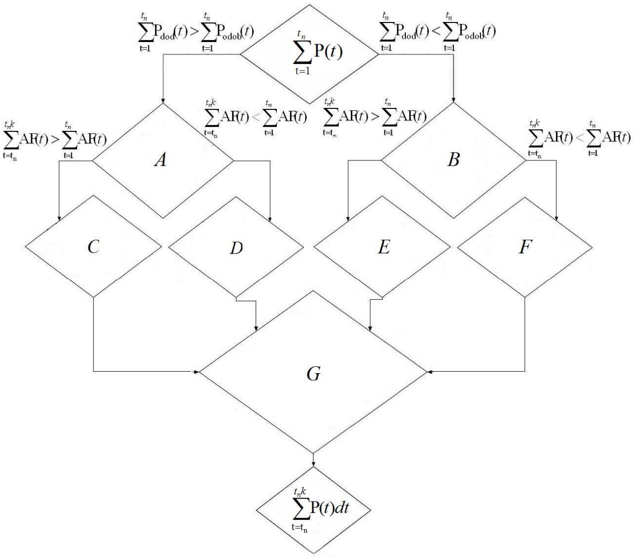


Fig. 1. Flowchart of algorithm balancing on 50 % *SoC*.

$$A = FoC = \frac{\int_{t=1}^{t_n k} P(t)dt}{AF_{avg}}$$

$$B = FoD = \frac{\int_{t=1}^{t_n k} P(t)dt}{AF_{avg}}$$

$$C = \sum_{t=1}^{t_n} \mathrm{P}_{\mathrm{REAL}\ (ODOD)}(t) = \sum_{t=1}^{t_n} \mathrm{P}_{\mathrm{TARGET}\ (ODOD)}(t)$$

$$\mathrm{D} = \mathrm{P}_{\mathrm{AB}(DOD)}(t)dt = \sum_{t=1}^{t_n} \mathrm{P}(t)dt - \sum_{t=1}^{t_n} \mathrm{P}_{\mathrm{REAL}(DOD)}(t)$$

$$E = \sum_{t=1}^{t_n} \mathrm{P}_{\mathrm{REAL}\ (DOD)}(t) = \sum_{t=1}^{t_n} \mathrm{P}_{\mathrm{TARGET}\ (DOD)}(t)$$

$$\mathrm{F} = \mathrm{P}_{\mathrm{AB}(ODOD)}(t)dt = \sum_{t=1}^{t_n} \mathrm{P}(t)dt - \sum_{t=1}^{t_n} \mathrm{P}_{\mathrm{REAL}(ODOD)}(t)$$

$$G = \Delta P(t) = \left[\sum_{t=t_n}^{t_n k} \mathrm{P}_{\mathrm{TARGET}(DOD)}(t) - \sum_{t=t_n}^{t_n k} \mathrm{P}_{\mathrm{TARGET}(ODOD)}(t) \right] + \left[\sum_{t=t_n}^{t_n k} \mathrm{P}_{\mathrm{AB}(ODOD)}(t) + \sum_{t=t_n}^{t_n k} P_{AB(DOD)}(t) \right]$$

As the batteries provide a control performance when the frequency exceeds the dead band $\eta < \pm 10$ mHz, also the performance needed to balance the capacity will be activated outside of this band. The time of the system discharging/ charging is called *AF* (Active Framework).

Every following 15 minutes we will deliver the performance unit *FoC* (Frame of Charge) or consume *FoD* (Frame of Discharge) to get the *SoC* balance by 50 % as follows:

$$P_{ext}(t) = P_{AS}(t) \pm P_{SOC}(t) \ . \tag{10}$$

The total capacity $P_{ext}(t)$ is a sum of the $P_{AS}(t)$ (Ancillary Service), working point signal BESS $P_{WP}(t)$ (Working Point) and state of charge $P_{SOC}(t)$.

$$P_{ext}(t) = P_{AS}(t) + P_{WP}(t) \pm P_{SOC}(t) \tag{11}$$

Within next 15 minutes of control in each *AF* we deliver/ consume a unit *FoC/FoD* to the required control performance assumed that:

$$\sum_{t=1}^{t_n k} \mathrm{AF}_t > \sum_{t=1}^{t_n} \mathrm{AF}_t \ . \tag{12}$$

If *AF* in time *t* = (901 s,1800 s) is lower as within the previous interval the state of charge by 50 % was not reached. The difference between the real P_{REAL} (MWh) and target performance P_{TARGET} (MWh) is then recalculated to the target delivered/ consumed performance within next 15 minutes as follows:

$$\sum_{t=1}^{t_n k} \mathrm{AF}(t)dt = \sum_{t=1}^{t_n} \mathrm{AF}(t)dt \tag{13}$$

$$P_{tk} = \left[\int_{t=+}^{t_n k} \mathrm{P}_{\mathrm{TARGET}\,(DOD)t} - \int_{t=1}^{t_n} \mathrm{P}_{\mathrm{TARGET}\,(ODOB)t} \right] + \\ + \left[\int_{t=1}^{t_n k} \Delta \mathrm{P}_{(ODOB)t} + \int_{t=1}^{t_n k} \Delta \mathrm{P}_{(DOD)t} \right] \tag{14}$$

TABLE I.
LOSSES IF THE CONTROL ALGORITHM AF IS NOT IMPLEMENTED

Center SOC	SOC Swing	Microcycles per week	Capacity loss [%]
0.01	<2%	17664	0.02137
0.03	2~4%	8162	0.01802
0.05	4~6%	349	0.00118
0.07	6~8%	4345	0.02681
0.09	8~10%	1146	0.01290
0.125	10~15%	217	0.00421
0.175	15~20%	67	0.00189
0.25	20~30%	11	0.00054
0.35	30~40%	1	0.00008
0.45	40~50%	0	0
0.55	50~60%	0	0
0.65	60~70%	0	0
0.75	70~80%	0	0
0.85	80~90%	0	0
0.95	90~100%	0	0
Total capacity loss per week [%]			0.08702
Total capacity loss per year [%]			4.87363

The implementation of the algorithm for the *SoC* balance defined by $P_{ext}(t)=P_{AS}(t)+P_{WP}(t)\pm P_{SOC}(t)$ causes that the performance supply P_{SOC} consisting of either charging *FoC* or discharging *FoD* has an impact on the absolute value of the battery system cycles. Tabs. I. and II. present a change of the discharge deviation DoD and a respective increasing of capacity loss. An annual capacity loss increased by 1.1 % is trivial if we consider a not exact measurement and other factors having influence of BESS capacity losses.

TABLE II.
LOSSES IF THE CONTROL ALGORITHM AFAVG IS FIX

Center SOC	SOC Swing	Microcycles per week	Capacity loss [%]
0.01	<2%	18426	0.02701
0.03	2~4%	8162	0.02175
0.05	4~6%	0	0.00065
0.07	6~8%	4345	0.03234
0.09	8~10%	1146	0.01517
0.125	10~15%	217	0.00564
0.175	15~20%	67	0.00271
0.25	20~30%	11	0.00055
0.35	30~40%	1	0.00013
0.45	40~50%	0	0
0.55	50~60%	0	0
0.65	60~70%	0	0
0.75	70~80%	0	0
0.85	80~90%	0	0
0.95	90~100%	0	0
Total capacity loss per week [%]			0.10596
Total capacity loss per year [%]			5.93381

As we see in Fig. 2, within the analysed day the *SoC* kept the limits when our model was used. During some 15 minutes intervals at the end of the day, the positive deviation of the system frequency caused that the batteries were being charged, the system did not make it within active points AF to reduce the *SoC* so the batteries were charged on a level of 91,99 %. Within the intervals t_n 91 a 92, no *AF* were outside the dead band. During the following intervals t_n 93 a 94 and with a high amount of active points, the system provided a control performance and the charging of *SoC* came back on 50 %.

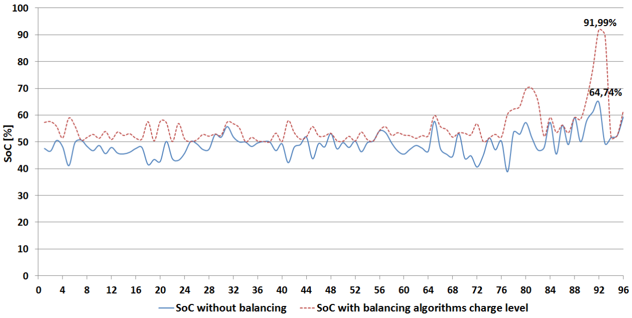


Fig. 2. Development of *SoC* on analysis day 13.09.2012.

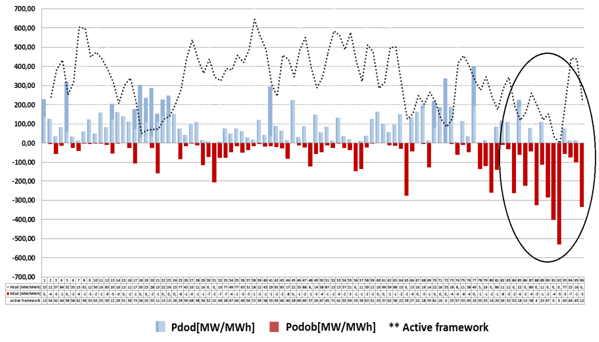
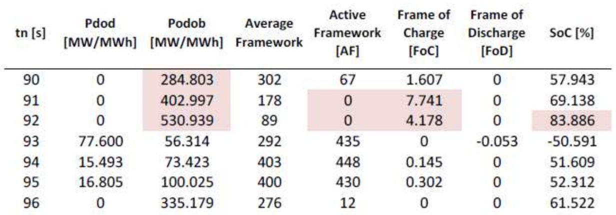
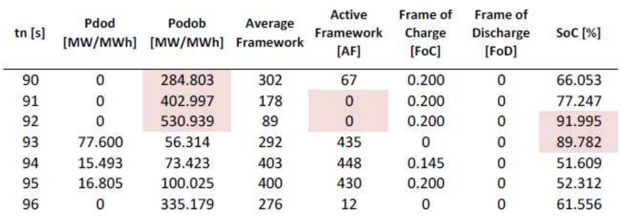


Fig. 3. 15-minutes values of delivered/ consumed performance and Active Framework.



tn [s]	Pdod [MW/MWh]	Podob [MW/MWh]	Average Framework	Active Framework [AF]	Frame of Charge [FoC]	Frame of Discharge [FoD]	SoC [%]
90	0	284.803	302	67	1.607	0	57.943
91	0	402.997	178	0	7.741	0	69.138
92	0	530.939	89	0	4.178	0	83.886
93	77.600	56.314	292	435	0	-0.053	-50.591
94	15.493	73.423	403	448	0.145	0	51.609
95	16.805	100.025	400	430	0.302	0	52.312
96	0	335.179	276	12	0	0	61.522

Fig. 4. Balancing of *SoC* at the analysis day.



tn [s]	Pdod [MW/MWh]	Podob [MW/MWh]	Average Framework	Active Framework [AF]	Frame of Charge [FoC]	Frame of Discharge [FoD]	SoC [%]
90	0	284.803	302	67	0.200	0	66.053
91	0	402.997	178	0	0.200	0	77.247
92	0	530.939	89	0	0.200	0	91.995
93	77.600	56.314	292	435	0	0	89.782
94	15.493	73.423	403	448	0.145	0	51.609
95	16.805	100.025	400	430	0.200	0	52.312
96	0	335.179	276	12	0	0	61.556

Fig. 5. Balancing of *SoC* at the restricted *FoC*, *FoD*.

During the next analysis day and our model at Fig. 6, the BESS system was charged on a level of 92,93 % due to a positive deviations of frequency. Within the time intervals t_n 2 to 21 the batteries were being charged nearly fully from P_{odob}. Due to an unbalance of the delivered and consumed performance the *SoC* was balanced in the time interval t_n.

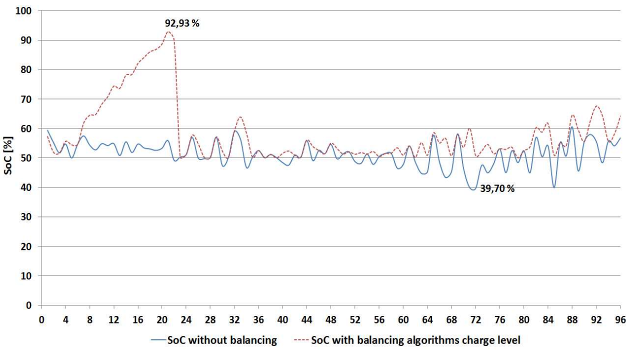


Fig. 6. Development of *SoC* on analysis day 09.09.2012.

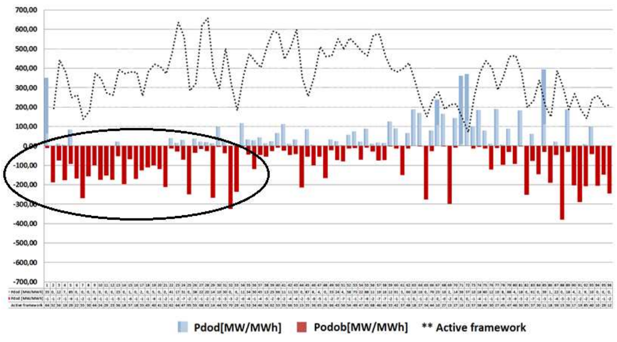
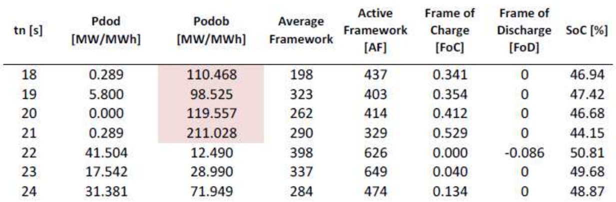
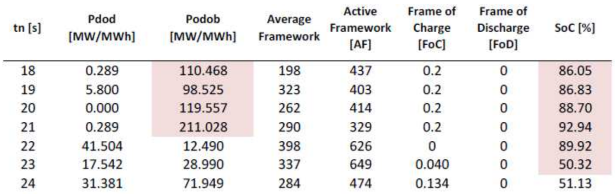


Fig. 7. 15-minutes intervals of delivered/ consumed performance and Active Framework.



tn [s]	Pdod [MW/MWh]	Podob [MW/MWh]	Average Framework	Active Framework [AF]	Frame of Charge [FoC]	Frame of Discharge [FoD]	SoC [%]
18	0.289	110.468	198	437	0.341	0	46.94
19	5.800	98.525	323	403	0.354	0	47.42
20	0.000	119.557	262	414	0.412	0	46.68
21	0.289	211.028	290	329	0.529	0	44.15
22	41.504	12.490	398	626	0.000	-0.086	50.81
23	17.542	28.990	337	649	0.040	0	49.68
24	31.381	71.949	284	474	0.134	0	48.87

Fig. 8. Balancing *SoC* during the analysis day.



tn [s]	Pdod [MW/MWh]	Podob [MW/MWh]	Average Framework	Active Framework [AF]	Frame of Charge [FoC]	Frame of Discharge [FoD]	SoC [%]
18	0.289	110.468	198	437	0.2	0	86.05
19	5.800	98.525	323	403	0.2	0	86.83
20	0.000	119.557	262	414	0.2	0	88.70
21	0.289	211.028	290	329	0.2	0	92.94
22	41.504	12.490	398	626	0	0	89.92
23	17.542	28.990	337	649	0.040	0	50.32
24	31.381	71.949	284	474	0.134	0	51.13

Fig. 9. Balancing *SoC* with *FoC*, *FoD* limits.

Figs. 10 and 11 present performance units *FoC*/*FoD* for a 30 minutes interval, where the balancing performance was limited in a way that the real performance matches the tolerance defined by the operator.

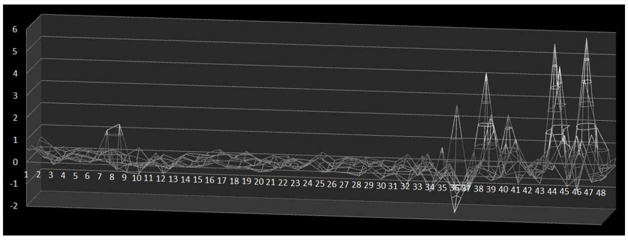


Fig. 10. Values *FoC*, *FoD* within two following 15 minutes intervals for the analysed week.

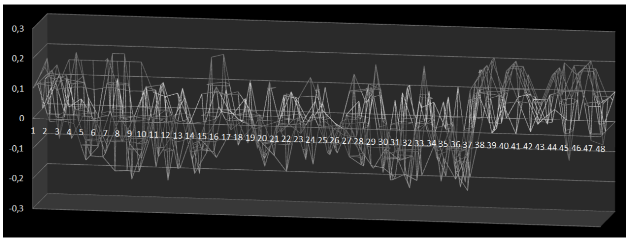


Fig. 11. Values *FoC*, *FoD* within two 15-minutes intervals in the analysed week if algorithm for PRV quality is kept.

CONCLUSION

In this article we analysed the strategies of usage of battery systems for primary frequency control. It was proved that keeping the limits of SoC can be explicitly executed and there is no need to use external sources within the tolerance defined by the operator. The algorithm we applied did not cause any early capacity loss of BESS. During the simulation the limits of SoC_{min}/SoC_{max} were not exceeded. This analysis also showed the advantages of battery systems and their ability to ensure a frequency control under same conditions as guilty for conventional PRV providers.

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REFERENCES

[1] ENTSO-E. (2009). Operation Handbook, Policy 1: Load-Frequency Control and Performance.

[2] SEPS. (2012). Technické Podmienky Prístupu a Pripojenia, Pravidlá Prevádzkovania Prenosovej Sústavy.

[3] Angel Molina-Garcia, Francois Bouard, and Daniel S. Kirschen. (2011). Decentralized demand-side contribution to primary frequency control. IEEE Transactions on Power Systems, 26, 411-419.

[4] H.-J. Künisch, K. G. Krämer, and H. Dominik. (1986). Battery energy storage another option for load-frequency-control and instantaneous reserve. IEEE Transactions on Energy Conversion, EC-1(3), 41-46.

[5] Alexandre Oudalov, Daniel Chartouni, and Christian Ohler. (2007). Optimizing a Battery Energy Storage System for Primary Frequency Control. IEEE Transactions on Power Systems, 22(3): 1259-1266, doi: 10.1109/TPWRS.2007.901459.

[6] Pascal Mercier, Rachid Cherkaoui, and Alexandre Oudalov. (2009). Optimizing a battery energy storage system for frequency control application in an isolated power system. IEEE Transactions on Power Systems, 24(3), 1469-1477, doi: 10.1109/TPWRS.2009.2022997.

[7] Theodor Borsche, Andreas Ulbig, Michael Koller, and Göran Andersson. (2013). Power and Energy Capacity Requirements of Storages Providing Frequency Control Reserves. IEEE PES General Meeting, Vancouver.

[8] Olivier Mégel, Johanna L. Mathieu, and Göran Andersson. (2013). Maximizing the potential of energy storage to provide fast frequency control. 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Copenhagen.

[9] Maciej Swierczynski, Daniel-Ioan Stroe, Ana-Irina Stan, Remus Teodorescu, Rasmus Laerke, and Philip Carne Kjaer. (2013). Field Tests Experience from 1. 6MW / 400kWh Li-ion Battery Energy Storage System providing Primary Frequency Regulation Service. 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Copenhagen.