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Optimal Provision of Primary Frequency Control with Battery Systems by Exploiting all Degrees of Freedom within Regulation

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Abstract

Battery energy storage systems have a large potential for provision of grid ancilliary services. Specifically, large battery systems have been used for the provision of primary control reserve. Batteries providing this grid service must, using corrective energy measures and control algorithms, continuously keep their state of charge within limits in order to comply with European regulations. Operational degrees of freedom exist in the regulation which can be used by batteries to facilitate keeping the state of charge within desired levels. In this paper, such degrees of freedom are described, and the effect of their utilization on battery system operation analyzed.

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Keywords: Ancillary Services; Frequency Control Reserve; Primary Control Reserve; Battery Systems

1. Introduction

A stable grid frequency in power systems is maintained by a balanced power generation and demand. In case of unbalances, control power reserve is used to bring back the frequency to its nominal value within a short time. Out of the three types of control power reserve used in Germany (and other European countries), primary control reserve

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(PCR) is the first to be deployed for frequency stabilization and has to be activated at full power within 30 seconds after a frequency deviation [1]. Because of the short activation time for PCR, has been provided by fossil fueled power plants with fast load change gradients. Such plants have to run continuously at a power output higher than their must run capacity in order to provide PCR [2]. However, with the ongoing German energy transition towards distributed and renewable power generation, fossil fueled power plants have a decreasing role in the future German energy mix. Within few years, there will be hours where renewable generation will exceed power consumption. Therefore, the substitution of conventional power plants in the provision of ancillary services by new technologies is mandatory to decrease minimal conventional operation.

Battery energy storage (BES) systems can modify their output power rapidly and precisely, being able to appropriately react to frequency deviations. Additionally, prices for BES technology have been steadily declining in the last years [3], allowing them to compete in the PCR market. By May 2015, there was a total BES capacity of 30 MW participating in the German PCR market [4] with this number being expected to increase significantly in the coming years (e.g. STEAG GmbH plans to invest in 90 MW of battery capacity [5]). Furthermore, there are research projects studying other opportunities for PCR provision by BES systems, such as using a pool of residential solar battery systems [6].

PCR providers are required to provide both positive and negative PCR during the whole tendered period. In order to comply, participating BES systems operate in discharge mode for positive PCR provision, and in charge mode for negative provision. Due to their limited storage capacity, BES systems could fail to provide PCR during long lasting frequency deviations or during periods of biased PCR demand [6]. Therefore, BES systems must operate within state of charge (SOC) limits in order to be constantly available for provision.

Regulation by German transmission system operators (TSOs) defines these capacity limits to ensure each BES to be able to provide its total offered PCR for at least 30 minutes [7]. Nonetheless, on the EU level, the discussion is not over. An updated version of the draft for EU commission regulation establishing a guideline on transmission system operation was published in May 2016. It states that the minimum PCR provision time for Europe is to resolved in the months after the regulation is official. This decision will be based on suggestions from the member country's TSOs in terms of a cost-benefit analyses. This minimum provision time shall be between 15 and 30 minutes long. It also is stated that "Where no period has been determined (…), each FCR provider shall ensure that its FCR providing units or groups with limited energy reservoirs are able to fully activate FCR continuously for at least 15 minutes" (Art. 156, p. 9, [8]).

Operation algorithms for PCR provision by BES have been presented in literature [6,9,10,11]. Although they differ in some aspects, their common feature is the use of corrective charging or discharging of the BES to maintain the SOC within the desired limits. The purchase of the energy required for corrective measures increase operation costs for BES systems. Furthermore, the additional cycling from corrective charging and discharging of the BES decreases battery lifetime [12]. This increases the systems' costs due to earlier reinvestments.

A number of operational degrees of freedom exist in the German regulation for PCR provision [13]. They are partly caused by the historic needs of traditional thermal power plants, which are struggling to react instantaneously and precisely to PCR requirements. These regulatory degrees of freedom can be used by PCR providers on a voluntary basis, if their technical capabilities enable them to do so. Due to their fast reaction times and precise power output, BES systems can use them to increase the operational efficiency and reduce corrective energy and battery degradation costs.

In this paper, the existing degrees of freedom found in the German regulation and the effects of their implementation in BES systems are discussed. These are combined into an operation strategy aimed at reducing the amount of corrective charging and discharging energy for BES systems providing PCR. Finally, a high performance python based framework, specifically designed to simulate PCR provision, was used compare the operation of a BES system providing PCR for one year, with and without the use of regulatory degrees of freedom.

2. Degrees of Freedom for PCR Provision

The regulatory degrees of freedom for PCR provision in Germany are shortly explained in the following subchapters.

2.1. Deadband

It is allowed to use a deadband of ±0.01 Hz around the nominal frequency. This deadband can only be used if the resolution of the measurement and power control ensures provision before the frequency deviation reaches ±0.02 Hz [1]. When a frequency deviation falls within the range of the deadband, the PCR provider is not required to react to it. A BES system can decide to use or not the deadband for battery management purposes as long as it does not incur in counterproductive behavior (i.e. the BES should not be charged when there is a demand for negative PCR, even if this demand falls within the deadband).

2.2. Gradient

PCR providers must be able to provide all their offered PCR within 30 seconds after a measured frequency deviation of 0.2 Hz. Therefore, the slowest PCR provider must have a ramp rate (defined as the rate at which a power plant can increase or decrease its power output) of 2 MW/min per MW of PCR offered. Faster providers can choose to follow the minimum ramp or provide PCR faster than necessary depending on their needs. For thermal power plants continuously following the gradient seems to be beneficial due to fuel cost reductions, while for a BES system the dynamic use of the gradient, based on actual SOC, can reduce the need for corrective energy in a BES system.

2.3. Delay

Even the fastest thermal power plants are unable to instantaneously react to power adjustment commands. To account for the non-instantaneous reaction time of power plants, the ENTSO-E Continental Europe Operation Manual [1] states that PCR provision shall start “within a few seconds” after the incident (start of the frequency deviation), be at 50 % of offered power after 15 seconds, and at 100 % after 30 seconds. This wording implies that PCR can be provided with a small delay that could be somewhere between “a few” and 15 seconds, as long as their ramp rate allows for 50 % provision of their offered PCR at 15 seconds. This can be considered as degree of freedom for BES, due to their very brief reaction time, that would reduce the amount of energy required for PCR provision and can be selectively used for SOC management purposes.

Although this delay and its possible duration has not been clarified by German TSOs in further documents [13] [14], it is included in this paper as a usable degree of freedom in order to analyze its potential, and the effect of delay duration time on energy use for PCR provision.

2.4. Over-fulfillment

It is allowed to provide a PCR power that is anywhere between 100 % and 120 % of the instantaneous PCR requirement at any given time. Nonetheless, under-fulfillment (i.e. provide a PCR power which is below the instantaneous requirement.) is not allowed at any time. The permanent use of this degree of freedom by a BES, would increase the amount of energy cycled in the system, incrementing operation costs. However, if used dynamically, based on SOC, it can be quite beneficial to keep the SOC away from extreme values.

2.5. Frequency time correction

Grid time is a grid frequency based time measure used to coordinate grid related activities. Since grid time calibration depends on the grid frequency, sometimes deviations sum up and the grid time deviates from the measured astronomical time. Swissgrid is the TSO in charge of calibrating grid time in continental Europe. As long as the discrepancy between grid time and astronomical time is below 20 seconds, no measure is taken. On the other hand, when the discrepancy exceeds this 20 seconds time frame, the nominal frequency of the grid is modified by 10 mHz (i.e. from 50 Hz to 50.01 Hz or 49.99 Hz) for the duration of the whole next day. The modified nominal frequency is in place until the time discrepancy is reduced to less than 20 seconds at the end of the day [15].

According to [13] TSOs will publish whenever this system time correction measures are taken, and PCR providers will be able to use the new nominal frequencies if they desire to do so. The effect of using the time correction degree of freedom will depend on the nominal frequency at given time, and the PCR demand. As with most of the previously described degrees of freedom, dynamically deciding during operation to use or not the system time correction can decrease operation costs for BES systems.

2.6. Degrees of Freedom Analyses

The effects on the energy demand for providing 1 MW of PCR during a year was investigated using the frequency development of 2012, using each of the degrees of freedom individually. Figure 1 shows the results of these analyses. The bar labelled as instantaneous represents the PCR energy used for the operation of a BES when not using any degree of freedom, and was included for comparison purposes.

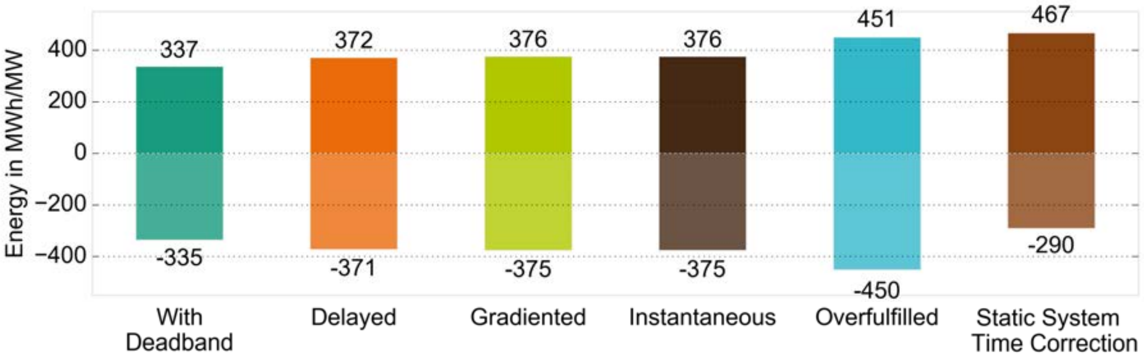

Figure 1. Effects of using each degree of freedom for PCR provision. In the case of BES positive and negative numbers are charging and discharging energy respectively.

Several conclusions can be drawn from the results. In terms of reducing energy use, the deadband degree of freedom is the most successful (-10.5 % as compared to instantaneous). For this reason, it is widely used both by BES and conventional power plants providing PCR, and was included in the base scenario BES simulation. The gradient degree of freedom has an imperceptible effect (-0.0005 %), due to the fact that most of the frequency deviations for 2012 fall below the gradient. The over-fulfillment degree of freedom, when used to its maximum extent (120 % of primary control power requirement) increases both charging and discharging energy by 20 % each. Finally, a 5 seconds delay decreases slightly the energy used (-1 %).

A sensitivity analysis for the use of different delay lengths in combination with deadband is shown in Figure 2. For each additional second in the delay, there is a decrease in energy use (sum of absolute values of charge and discharge) of approximately 1 %. Furthermore, by comparing the difference between the instantaneous and delay bars in Figure 1 with the difference between no delay and 5 seconds delay in it can be seen that the effect of the delay is larger when combined with the deadband. The reason behind this is that a delay begins when the PCR power changes from positive to negative (and vice versa) or demand is zero. The latter happens more frequently with the use of deadband.

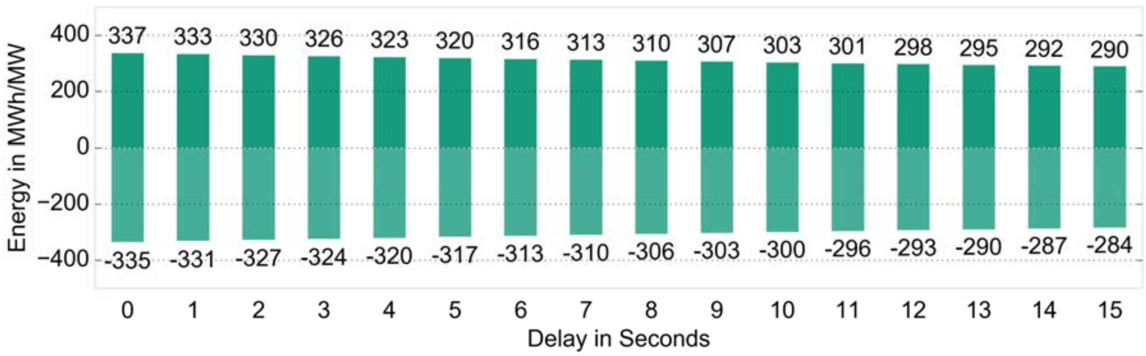

Figure 2. Sensitivity analysis for delay duration.

3. Operation Modes

By combining the dynamic implementation of a number of degrees of freedom, a number of operation modes can be created to achieve specific goals. The application of such strategies can be beneficial for the BES system in terms of SOC management and accompanying cost reductions. In this paper three operation modes are developed to achieve specific goals.

3.1. Minimize cycles

This operation mode takes advantage of every degree of freedom that reduces energy cycling due to PCR provision. It uses the delay and deadband degrees of freedom continuously. It uses the allowed gradient selectively, only when the absolute value of the PCR requirement is higher than the one in the previous time step (but not when it is lower). It uses the system time correction only during times in which its implementation decreases energy cycling. Finally, it never uses the over-fulfillment.

3.2. Maximize Charging and Maximize Discharging

Maximize Charging operation mode seeks to maximize charging of the BES. When there is a positive PCR demand, Maximize Charging follows the same rules as the Minimize Cycles operation mode. But in times of negative PCR demand, it combines the use of the over-fulfillment degree of freedom with a charge maximizing dynamic implementation of both the gradient and system time correction, while ignoring the deadband and delay degrees of freedom. On the contrary, Maximize Discharging is the exact opposite of the maximize charge operation mode. It follows the Minimize Cycles implementation in times of negative PCR demand, while dynamically using all discharge maximizing degrees of freedom when PCR demand is positive.

3.3. Operation Mode Analyses

Figure 3 shows the PCR power output (top panel) calculated from a synthetic frequency time series (bottom panel) when following some of the described degrees of freedom, and how these combine into the three operation modes.

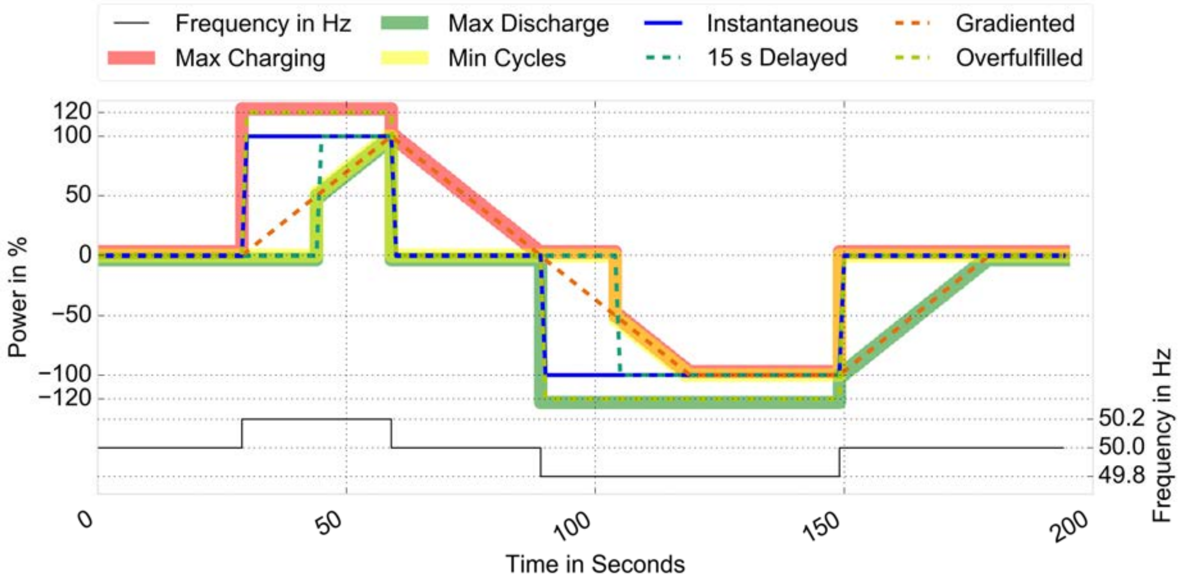

Figure 3: Example PCR power demand with implementation of different degrees of freedom and operation modes.

The left panel in Figure 4 shows the effect of implementing these operation modes using delay duration of 5 seconds and not including system time correction. Each of them achieves its goal, with the minimize cycles operation mode reducing the amount of energy required by 15.2 % when compared to the instantaneous PCR demand, and the other two maximizing the energy required for charging (or discharging) depending on their goal.

With regards to the system time correction, there were 172 days with a nominal frequency of 49.99 Hz due to system time correction in 2012, while only 25 days had a corrected nominal frequency of 50.01 Hz. Accordingly, the static implementation of system time correction during this year was biased towards charging, as seen in the respective bar in Figure 1. When it is included in the operation modes, as seen in the middle panel of Figure 4, the same bias towards charging is observed. This effect is so large that the maximize discharge operation mode fails to achieve more discharge than charge.

On the other hand, when the system time correction is used dynamically (i.e. it is only used when it benefits the current operation mode) the effectiveness of all operation modes increases. There is almost 5 % less charged energy and 30 % less discharged energy when using minimize cycles and comparing with no system time correction, and 4 % more discharged energy and 28 % more charged energy in maximize discharge and maximize charge modes respectively.

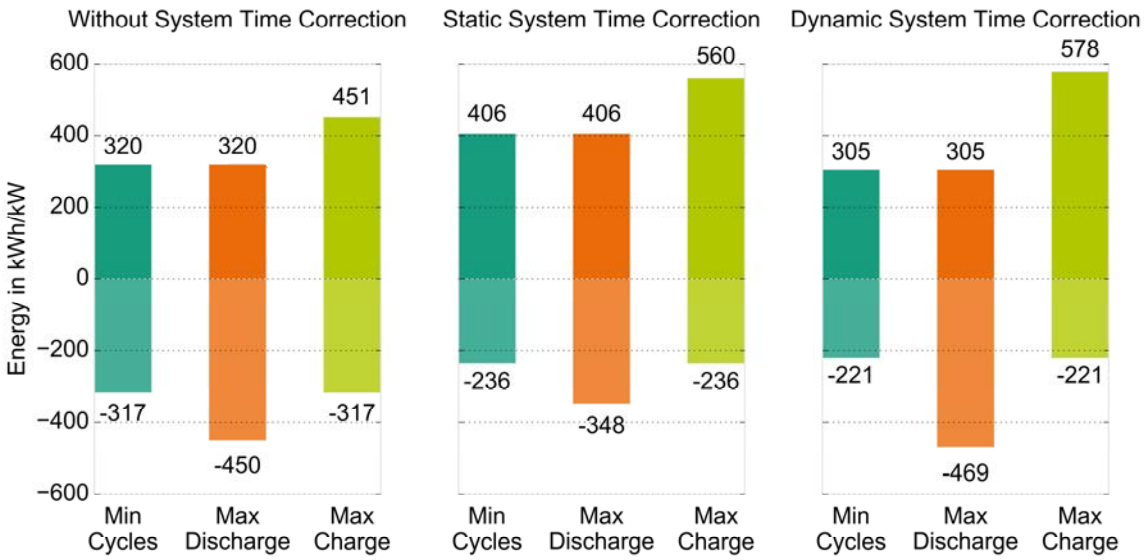

Figure 4: Effects of operation modes and the use of system time correction.

4. Methodology

A data set provided by Swissgrid, including one second resolution grid frequency values for the year 2012 was used for all the analyses carried out for aaazthis paper. Using this data, normalized power requirements for the provision of 1 MW of PCR were calculated for each second of the year. This process was repeated using each one of the degrees of freedom and operation modes described in the previous section. Thus, their effects in terms of required energy (both charged and discharged) for PCR provision per unit of offered PCR power offered, could be analyzed and compared.

In order to see the effects that the implementation of the described operation modes can have in terms of cycled energy and energy for corrective measures, a simulation was carried out for a hypothetical BES system providing PCR during one whole year. Table 1 shows the basic simulation parameters.

Table 1. Simulation parameters.

Battery Capacity	1.25	MWh
Max. Power at Worst Operating Point	1.25	MW
Self-Discharge over Time	7	%/Month
Battery Round-Trip Efficiency	96	%
Inverter efficiency	Variable	%

The inverter efficiency depends on the power applied, following an inverter efficiency curve with a maximum efficiency of 96.8 % at 50 % nominal power. The simulated system is a 1.25 MWh capacity BES with a power output of 1.25 MW (c-rate = 1). Its power output is divided into a 1 MW power band for PCR provision, while the rest (0.25 MW) is reserved to realize corrective charging and discharging without violating the reserve power band. Charging (discharging) corrective measures using the full available power from the corrective power band are initiated when the SOC moves below (above) the corrective capacity limits of 23.3 % (76.7 %) and stopped when the SOC reaches 40 % (60 %). With these correction limits, the BES can provide at least 15 minutes of full PCR power at any given time during normal operation. The power adjustment used for corrective measures must not violate PCR provision. Therefore, corrective energy has to be purchased and sold via the intraday market or balanced via the adjusted operation of another power plant or battery (as described in [6]).

Figure 5 illustrates the simulated operation of the described system during an example day. The top plot shows the SOC profile during the day. The dashed lines indicate the battery's corrective capacity limits. The plot in the middle shows the output power of the battery, both in terms of PCR and correction power, while the bottom panel shows grid frequency development for the day.

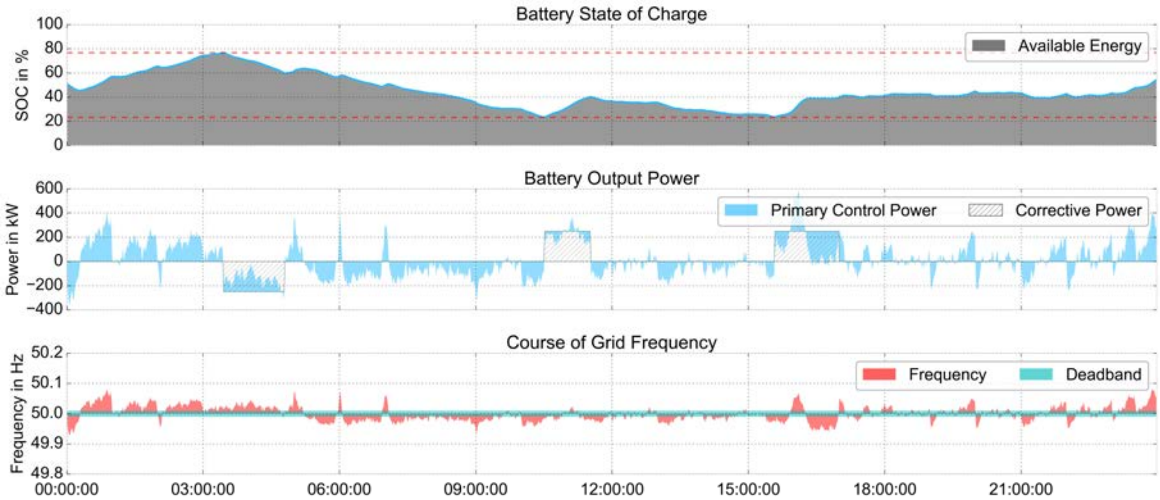

Figure 5: Representative day from the simulation of a BES providing PCR.

Simulations were performed for 3 scenarios described in Table 2. In the conservative and optimistic strategy scenarios, the operation mode of the BES varies depending on its current SOC as shown in Figure 6.

Table 2. Simulated scenarios.

Base Scenario	Conservative Scenario	Optimistic Scenario
- Only deadband implemented	- All degrees of freedom implemented except system time correction - Delay length = 5 sec	- All degrees of freedom implemented - Dynamic system time correction - Delay length = 15 sec

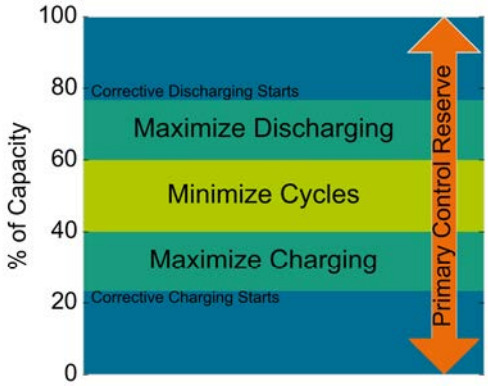

Figure 6: Energy capacity limits for selection operation mode activation.

5. Results

Figure 7 shows the results of the simulation performed for PCR provision by BES systems for the scenarios explained in the methodology section. The left side panel illustrates the corrective energy required for the operation of the BES. The conservative combination of degrees of freedom into operation modes is able to reduce the amount of total corrective energy (charge and discharge) by almost 25 %, while the optimistic scenario decreases corrective energy use by 70 %. Furthermore, in both cases the reduction is higher for charged than for discharged corrective energy (especially in the optimistic strategy) which is advantageous from an economical point of view since costs for charging corrective energy are potentially higher than for discharging corrective energy, considering that they must be balanced out by an increase of output power from a conventional power plant or bought in the energy markets [6].

The right side panel of Figure 7 shows the number of full cycle equivalents arising from PCR provision during a year. As observed, the conservative strategy is able to slightly reduce the number of full cycle equivalents. The small size of this effect is a result of a small increase in total PCR energy used (not shown in the graph) counteracting the decrease in cycled energy due to less energy used for corrections. On the other hand, the reasons behind the high decrease in full cycle equivalents when implementing the optimistic strategy are reductions in both PCR and corrective energy.

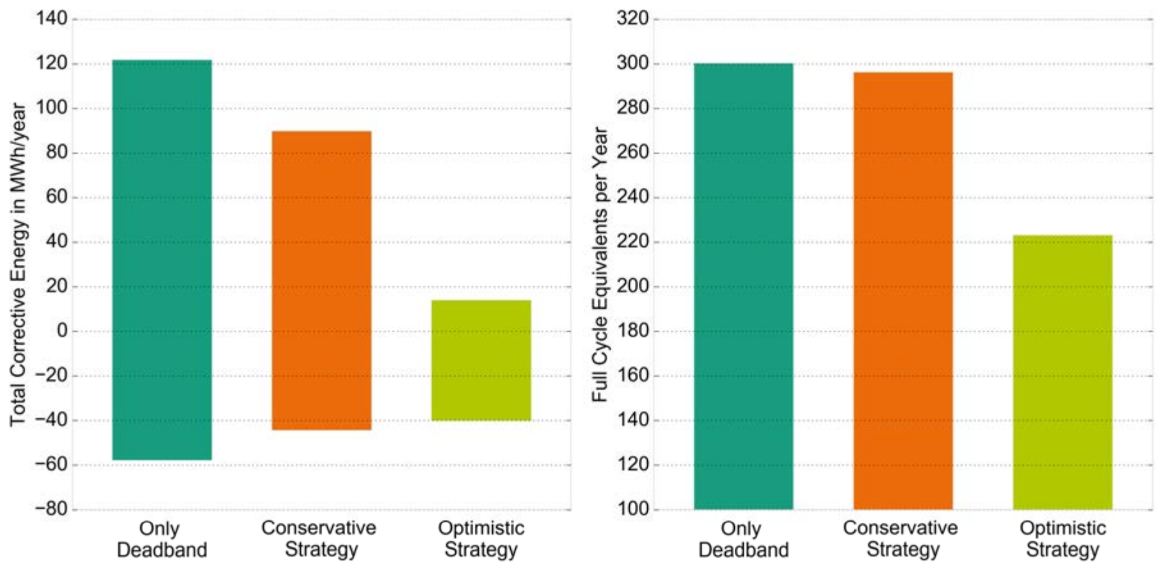

Figure 7: Simulation results of a BES providing PCR using different operation mode implementations.

6. Conclusions

The effects of degree of freedom implementation for the operation of a BES providing PCR were analysed. Each degree of freedom was investigated individually and in combination with others to achieve common operation goals. An operational strategy exploiting the regulative degrees of freedom for a BES providing PCR was developed and described. In this strategy, a number of degrees of freedom are combined to facilitate SOC management. Since the utilization of the delay and system time correction degrees of freedom is not clearly stated in the regulation, two versions of the strategy, conservative and optimistic, were created. Simulations show that both versions of the strategy are able to reduce corrective energy use and energy cycling in the system (represented in full cycle equivalents), with this effect being much larger in the optimistic implementation. These effects could have important impacts in terms of operative cost reductions for the system.

Finally, it is important not to forget that all of the degrees of freedom analysed in this paper are regulatory, and are therefore susceptible to be changed in the future. Therefore, their use in the operation strategies of BES systems should be implemented in such a way that they can be fairly easily modified with a short notice. Nonetheless, with an evolving legislation that has to be flexible enough to allow for the use of very different technologies, unique opportunities will arise for new technologies, such as BES systems, to optimize their operation by exploiting regulatory degrees of freedom.

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