Enhanced operational flexibility with Hybrid Battery Technology

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Abstract

In this paper, the hybridization of a turbine-governor unit (TG-unit), that would alone not qualify to provide frequency containment reserve (FCR) is studied. Hence, the non-hybrid TG-unit cannot change its output by 1 MW within 30 s. To anyhow utilize the existing flexibility of the non-hybrid TG-unit, this TG-unit is hybridized with a 0.6 MW/0.6 MWh BESS. In that way, the hybrid system can comply with the FCR rules. Furthermore, the BESS takes over to a large extend the FCR provision. In that way, the setpoint of the hybrid TG-unit can be adjusted in a defined way for FCR-contribution or State-of-Charge-Management (SoC-Management).

The hybrid system is then compared to a standalone battery energy storage system (BESS) with a rating of 1.6 MW/1.6MWh. The comparison of the BESS shows, that the SoC range can be utilized to a higher extend for the BESS of the hybrid system.

Introduction

The global hydropower fleet reached an installed capacity of 1416 GW in 2023, of which 179 GW is pumped storage hydropower. The total generation from hydropower in the same year was 4185 TWh ([1]).

Hydropower plants (HPPs) not only generate electricity, but also provide system services, flexibility, and storage capacity in power systems around the world.

The operational flexibility of HPPs is determined by several boundary conditions such as the type (e.g. run-of river, pumped hydro, etc.), regulations (e.g. water framework directive) and turbine type (Kaplan, Francis, Pelton, etc.). In [2], advanced control strategies to enhance ancillary services provision by hydropower plants is presented, including the hybridization with Battery Energy Storage Systems (BESS).

By hybridizing hydro power plants (HPP) with BESS, the flexibility to provide additional or enhanced ancillary services is enhanced ([3]). Some advantages of hybrid systems (BESS and HPP) are:

- Optimized hydraulic operation range incl. restriction and operation behavior in different operation modes
- Compensate response time of the Turbine-generator-units (TG-unit)
- Compensate limits of the hydrological system (e.g. waterway, penstock, surge tank, open channels)
- Increased lifetime of the TG-units and reduced downtime

In Figure 1, the concept of such a hybrid solution is depicted. New or additional system services can be provided, by increasing HPPs flexibility.

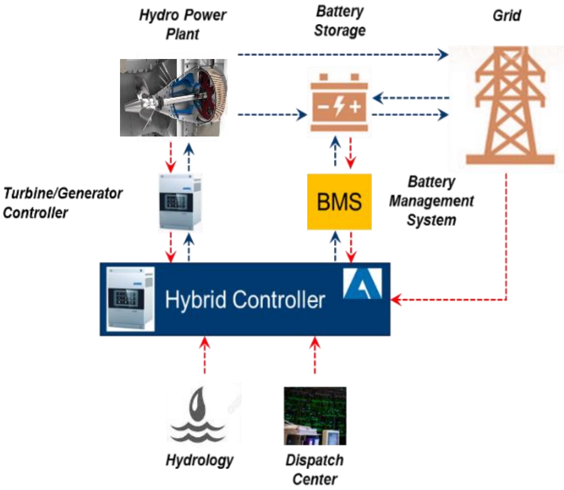

Figure 1 Hybrid concept.

One important system service is frequency containment reserve (FCR). To bid e.g. FCR on the continental European grid, the response time of TG-units for full activation has to be shorter than 30 seconds ([4], [5]). Participating units must counter frequency variations in the grid within the frequency band of ±200 mHz proportionally with the contracted power. Hence, the FCR is provided by varying the discharge control set point of run-of-river HPPs (RoR). The continuous variation in active power from the dispatch setpoint can have a significant impact on double-regulated Kaplan units in RoR ([6]). Because, depending on frequency variations in the power system, this can lead to a high number of set-point changes caused by FCR provision.

While stand-alone BESS can provide FCR, oversizing is essential to comply with the qualification requirements of the FCR-market. For example, in [7] an optimal BESS rated at 1.6 MW/1.6 MWh has the highest net present value to provide 1 MW of FCR. A optimized BESS sizing methodology for behind-the-meter stackable services is presented in [8]. Hybrid solutions enable to reduce the rating of the BESS and avoid additional grid connection charges, because of the installation on HPP site behind the meter. The FCR provision is offered and accepted in full MW steps only. Therefore, TG -units that are qualified for this kind of reserve, may miss the provision of an additional full MW only by a little amount of power within the required response time. By installing a BESS and a joint controller for the hybrid system, the participation at the FCR-market can be extended for such kind of HPPs. Furthermore, the hybrid TG-units are less stressed than non-hybrid TG-units offering the same service.

The combination and benefits of a BESS and HPP unit to primary frequency control has been evaluated by simulation and field studies in e.g. [9], [10], [11]. The results in [9] shows, that simple hydropower and BESS models show high accuracy for the hybrid system output.
In [12], conclude that valuation of hydropower hybridization must go beyond an assessment of the energy arbitrage potential of the battery to include reduced cost of hydropower operations. Further, it is identified that regulation and reserve market participation of RoR hybridization can be significantly improved.

In 2023, the demand for FCR in Austria was +/-72 MW. The activated FCR+ and FCR- reserve in Austria is published for each 15 minute interval ([13]).
Figure 2 shows the median and mean value of the active FCR reserve per month in the last 6 years. The FCR+ mean value was higher than 5 MW during 51 month. Most of the month where the activation was less than 5 MW (21 month) were before 2021. 5 MW equal 6.94 % of the FCR demand in the year 2023.
A similar trend is observed for FCR-, where the mean activation was more than -5 MW during 53 month. During the 19 month, the activation was less. The plot shows, that in December, the activation is usually less or equal 5 MW on average over all 15 minutes intervals.
The curves showing the median FCR activation shows, that 50% of the activations were lower than the mean value in the evaluated period. The difference varies mostly between 1.5 to 2.5 MW. In summary, the required activation of hybrid TG-units depends on the frequency variation in the power system, the BESS rating and the control strategy.

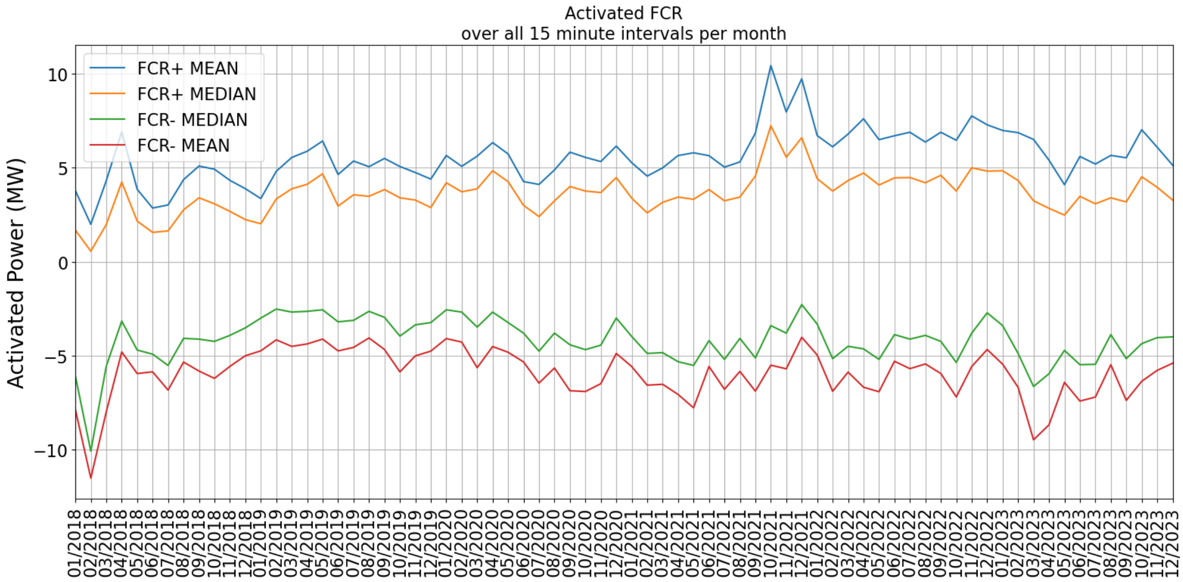

Figure 2 Activated positive and negative FCR in the APG region ([13]) between 2018 and 2023, mean and median values over all 15 minutes intervals per month.

Various controls strategies and hybridization options are proposed in literature for frequency response. In [11] for example, a filter control and fuzzy control logic were tested on a hybrid TG-unit in a RoR river. A double-layer Model Predictive Control (MPC) approach, we validate a novel strategy to enhance FCR capabilities and simultaneously reduce wear and tear is presented in [14]. Also in [15], an inner and outer layer optimization is proposed. Authors of [16], present a control strategy for avoiding the vibration zone of a hybrid HPP with the help of a BESS. Authors in [17] propose the hybridization with BESS and ultracapacitors to offer a very fast frequency response service in Pennsylvania-New Jersey-Maryland Interconnection Market.

In the next section, a hybrid system case study is presented with a 10 MW run-of-river TG-unit which has a response time of more than 30 seconds for full activation (1 MW). Hence, the TG-unit alone would not be able to qualify for the FCR-market. The TG-unit is hybridized with a 0.6 MW/0.6 MWh BESS and studied for a period of 1 month.
The performance of the hybrid system is then compared to a stand-alone BESS with 1.6 MW/1.6 MWh and considering also the evolution of frequency over the past years.

Scenario definition

In Figure 3, the simulation setup is presented. It consists of a non-hybrid TG-unit, a hybrid system (TG-unit and BESS) and a Standalone BESS system. A simplified turbine governor model was used in the study (PID governor, Servo motor model and waterway). This model with identical parameters is used both for the non-hybrid TG-unit and the hybrid system. The hybrid controller sends the setpoints to the hybridized TG-unit and a BESS 0.6 MW/0.6 MWh, considering the grid frequency. Furthermore, the SoC-Management of the hybrid system uses the hybrid TG-unit to ensure that the absolute SoC limits of the BESS are respected at all times.

A standalone BESS system with a size of 1.6 MW/1.6MWh was chosen according to [18], as a benchmark. Furthermore, the in the SoC-Management of the standalone BESS a lead time of 30 minutes to charge from the market is activated when violating 35% and 65% SoC.

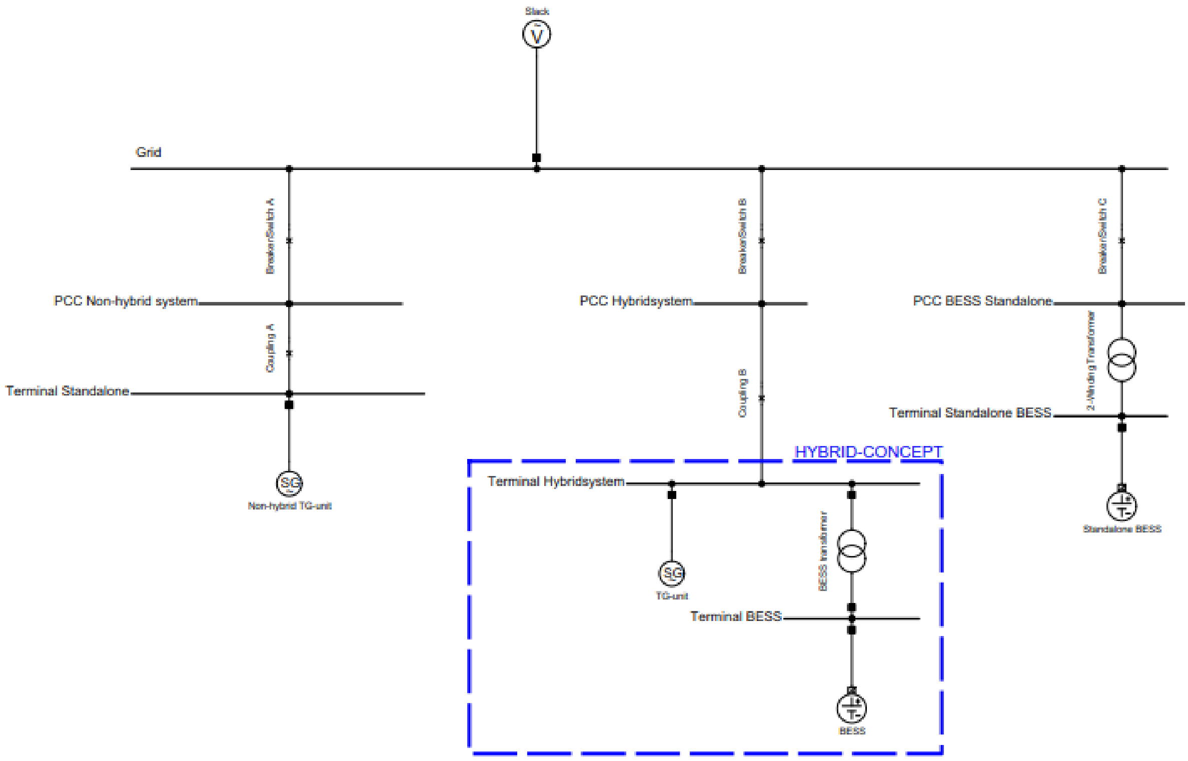

Figure 3 Simulation and benchmark setup – Non-hybrid TG-unit (left), Hybrid system (middle) and Standalone BESS (right).

In Figure 4, the response to a full activation (+200 mHz) of the non-hybrid and hybrid system are shown. The parameters of the turbine governor were chosen, to achieve that the non-hybrid unit is not fast enough to reduce its output by one MW within 30 s (blue curve). The lacking change in active power is thereby 0.18 MW. To still exploit the available flexibility of the unit, a BESS could be installed to compensate for the lacking power. Figure 4 (orange line) shows the response of a hybrid system with the identical TG-unit in combination with a BESS. Due to the sizing of the BESS, the hybrid system is fast enough, and the response of the hybridized TG-unit is slower than in the non-hybrid case. The control strategy in this work, splits the FCR setpoint to the BESS and the hybrid TG-unit, depending on the frequency deviation. Furthermore, the hybrid TG-unit is also used for the SoC-Management of the BESS.

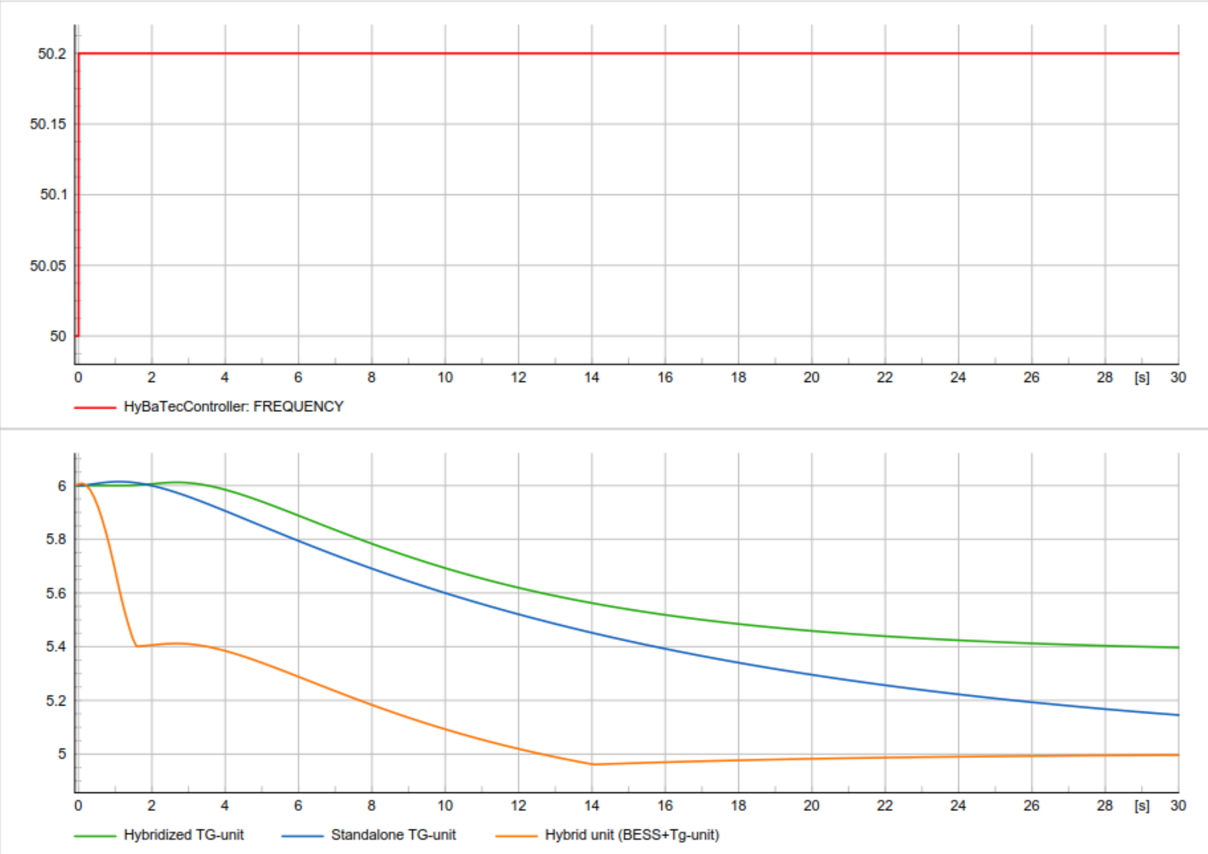

Figure 4 Response to a full activation (+200 mHz step test).

The dispatch setpoint of RoR-hydro power plants depends basically on the head and the discharge. Therefore, the dispatch setpoint changes when evaluating longer periods of time. In this work, a period of one month was studied. To focus solely on the impact of the hybridization, the dispatch setpoint of the TG-units was held constant during the investigated period. Therefore, the FCR provision is the only driver of the variation in the operating point.

In case of the standalone BESS; the required response with 1 MW within 30 s is reached easily. However, due to the standalone operation, the charging of the BESS has to be ensured via intraday trading which requires a lead time. A lead time of 30 minutes was considered, when the threshold SoC-levels are exceeded. Hence, when the SoC falls below 35% or rises above 65 %, a signal is generated to charge the BESS in 30 minutes.

Results

In this section, the results of the study are presented. First the evaluation of the operating conditions of the non-hybrid and hybrid TG-units is discussed. Second, the utilization of the two BESS is presented.

In Figure 5, the empirical cumulated distribution function (ecdf) of the operating points of the non-hybrid and hybrid TG-unit for a period of one month is depicted. Both TG-units are initially dispatched at 6 MW.

The non-hybrid unit operating in frequency control mode, shows practically no continuous operation on the dispatch setpoint. The active power output varies with the grid frequency. Because the non-hybrid TG-unit is slower than the FCR requirement, the minimum and maximum operating points are less extreme.

In case of the hybrid TG-unit, distinct operating points are observed (horizontal lines). Thanks to the BESS, the hybrid TG-unit is operating more than 80 % of the time on the dispatch setpoint. The second frequent operating point is at 5.9 MW and 6.1 MW, which is the power band of the BESS, which is reserved for the SoC-management.

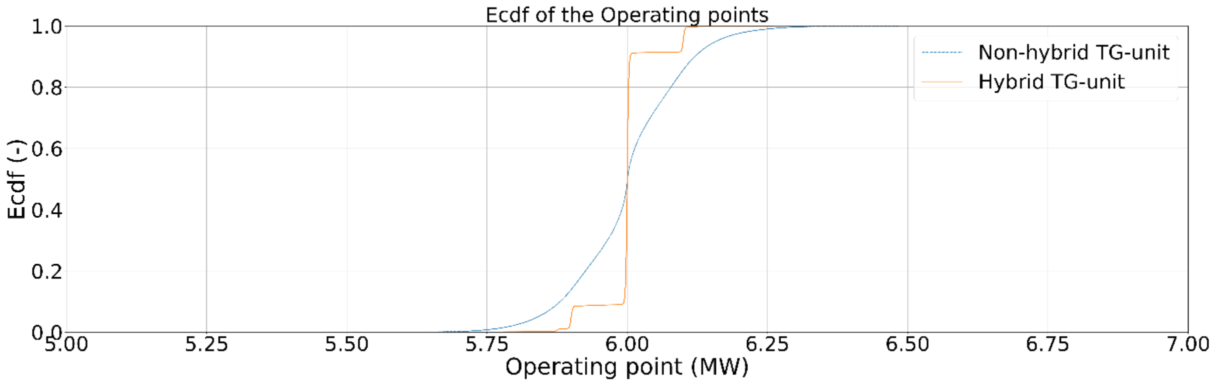

Figure 5 Empirical cumulated distribution function of the operating point of the hybrid and non-hybrid TG-unit.

In Figure 6, the required FCR characteristics is shown in orange. In general, the deviation of the operating points from this curve is evaluated in the FCR compliance. As depicted in Figure 6, the operating points of the non-hybrid on the P(f) pane differ significantly from the required FCR-characteristics (orange curve). In case of the non-hybrid TG-unit, the reason is that the unit is slower than the required FCR-response time. Still, several excursions are visible in the under-frequency range.

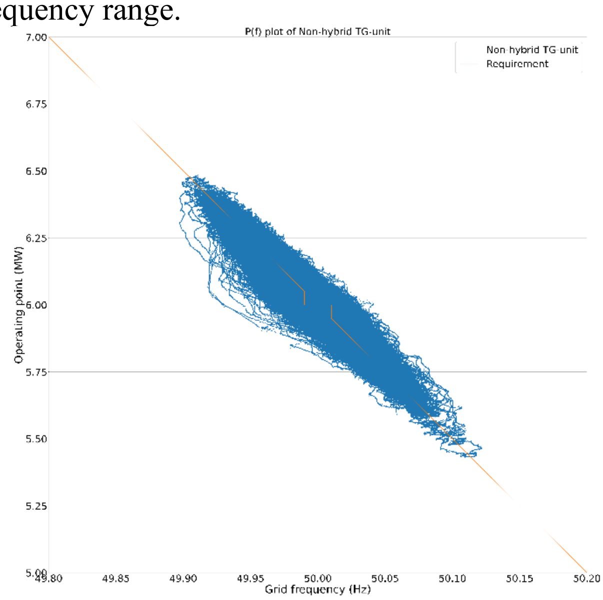

Figure 6 Comparison of the Operating points on the required P(f)-curve (orange) of the non-hybrid TG-unit (left).

The advantage of the hybridization is, that the operating points of the TG-unit can be decoupled from the grid frequency to a significant extent. The operating points of the hybrid TG-unit are less aligned to the required P(f) characteristics, as depicted in Figure 7 (right). The hybrid TG-unit shows a significant decoupling from the grid frequency. Around the operating point of 6 MW, no clear dependency on the grid frequency can be observed. The horizontal lines in the plot indicate setpoint changes for SoC-Management or the contribution of the hybrid TG-unit to the FCR provision. On the left plot in Figure 7, the response of the hybrid system (BESS + TG-unit) is shown, which shows a much better match of the required response compared to the non-hybrid unit (Figure 6).

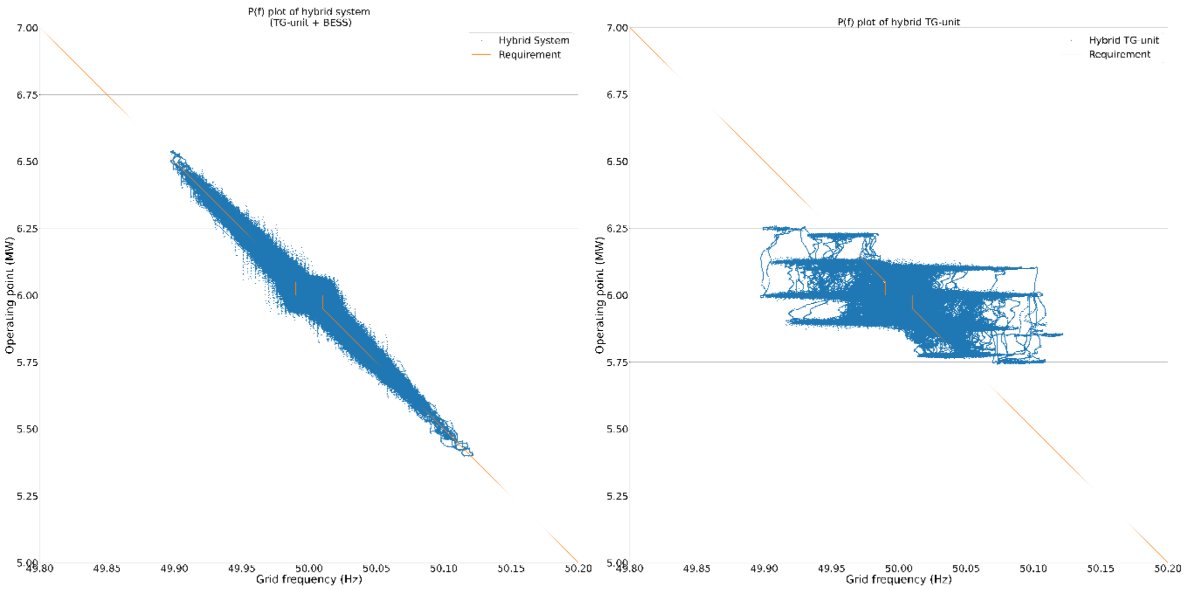

Figure 7 Comparison of the Operating points on the required P(f)-curve (orange) of the hybrid system, including the BESS (0.6 MW/0.6 MWh) and the hybridized TG-unit (left), and the hybrid TG-unit isolated from the BESS contribution (right).

Last but not least, Figure 8 shows the ecdf of the SoC of the Standalone BESS and the hybrid BESS. The SoC of the Standalone BESS (1.6 MW/1.6 MWh) varies during the simulation between 30 % and 70 % of SoC, because sufficient reserve has to be maintained in case of a full activation ([7]). To ensure sufficient reserves, the SoC-Management via intraday market requires sufficient lead time.

Contrary, for the hybrid BESS unit, the SoC utilization varies between 8.9% and 98 %which is much higher than the standalone BESS. However, during the investigated period of one month, the SoC of the hybrid BESS is 10% of the time higher and approximately 5% lower than in case of the standalone BESS.

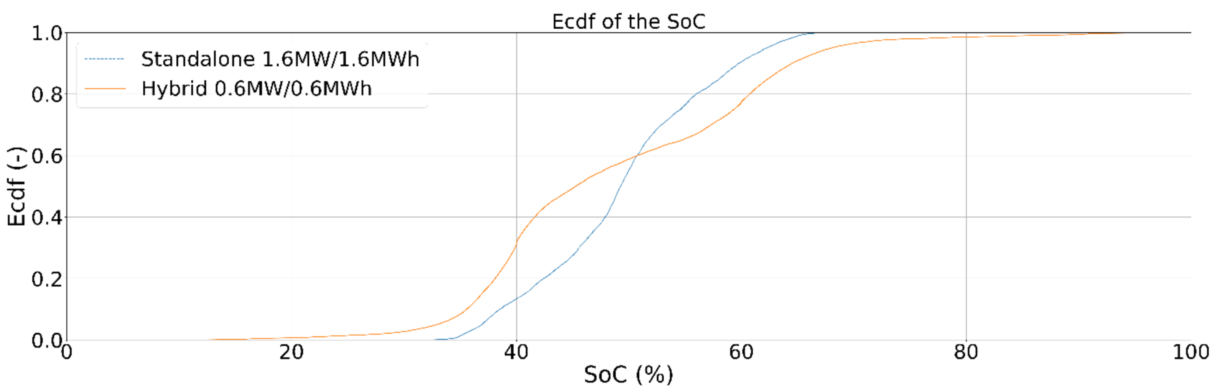

Figure 8 Empirical cumulated distribution function of the SoC of the standalone BESS (1.6MW/1.6MWh) and BESS of the hybrid system (0.6MW/0.6MWh).

Discussion and Outlook

The investigations demonstrates that the hybridization of TG-units that could provide flexibility, but insufficiently for FCR services, can be achieved with a smaller sizing than for standalone BESS systems.
Furthermore, the hybridization, with the aim of complementing existing TG-units with a BESS, has a minor impact on the operating scheme.
Moreover, BESS in hybrid operation benefit from the available energy generation capacity of the HPP.

The study was carried out with frequency data for a frequency time series of the continental European grid. The performance for primary control requirements in other power systems and markets (e.g. Nordics or United Kingdom) could serve as additional benchmark for control strategies and SoC-Management concepts.
In addition, the sizing of the BESS for the hybrid system has an impact on the contribution of the TG-unit on the FCR provision. While the power rating of the BESS is determined by the required response to a full activation, the storage capacity in MWh influences how often the TG-unit is activated for SoC-management.
An assessment of the wear and tear reduction between the two TG-units in this study would require that the non-hybrid unit is also qualified for the FCR provision. As the non-hybrid unit is too slow to qualify for the FCR market, a direct comparison of the hybrid and non-hybrid TG-units wear and tear reduction would be underestimated. However, the comparison of the ecdf plots show, that the non-hybrid unit rarely remains on its setpoint.

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Wolfgang Hofbauer made his PhD at the Vienna University of Technology in the field of controller optimisation for large gas engines. After some years of experience in the automotive business he joined ANDRITZ HYDRO in 2008. In his position as Product Manager he is responsible for the development of the digital turbine governor.