New Frequency Control Philosophy for Future Hybrid Power Plants

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***Abstract*—Global energy markets trend towards a subsidy free paradigm, where renewable energy sources (RES) must improve their levelized cost of energy. Furthermore, power system operation is increasingly challenged by weather related uncertainty and inertia loss. Thus, RES must adapt to facilitate their integration. In this context, hybrid power plants result more efficient and flexible. Vattenfall is at the industry's forefront in the deployment of utility scale Hybrid Power Plants (HyPP) of different configurations. In this work we present a HyPP frequency support strategy coordinating wind, solar, and batteries under the same point of common coupling. In addition, we present measurements from a number of tests performed in Haringvliet, a 50 MW HyPP, currently fully operational in the Netherlands.**

I. Introduction

Combinations of different renewable energy sources (RES) under the same point of common coupling (PCC), battery energy storage systems (BESS) and/or demand responsive units are defined as Hybrid Power Plants (HyPP). Such modern concept aims to increase the profitability of RES by exploiting the synergies among the different technologies. Among their advantages one can mention their increased efficiency as they improve the utilization of the substation and PCC, their larger number of equivalent full power hours, and their suitability to provide ancillary services traditionally reserved to synchronously coupled units, which in turn generates additional revenue streams. Furthermore, inherent RES uncertainty is reduced due to flexible coordination schemes effectively aggregating the units and reducing steering deviations. Lastly, construction and commissioning costs are lowered as the different units share different parts of the infrastructure, such as cables. characteristics reinforce the capacity of RES to remain profitable in subsidy-free markets as they directly reduce the levelized cost of energy. The HyPP concept is suitable not only for planning completely new installations, but also for hybridization of already existing plants by adding new technologies. The latter approach is particularly common by integrating BESS in wind farms (WF) or solar farms (SF) in order to participate in frequency regulation markets or to perform power smoothing strategies. Therefore, it has gained increasing attention over the last decade from the industry. For instance, Vattenfall has identified more than 50 WFs as suitable for different types of hybridization [1]. Accordingly, much effort has been spent in the development of different tools aiming to investigate and deploy HyPP. For instance, a generic controller design for HyPP was published in 2018 by Vattenfall R&D [2] along with initial research covering frequency containment provision [3]. Then, in 2019, the proposed platform was expanded to include online operational optimization [4]. The first operational HyPP developed by Vattenfall was the hybridization of Princess Alexia WF in 2018 by including a BESS battery in order to provide frequency support services. There, the HyPP controller was first deployed to coordinate these two assets. A couple of years later, the market had evolved making the original use case less profitable. Therefore, it is planned to review the HyPP controller in order to unleash new functionalities such as load shifting. The subsequent project was even more ambitious, building the first utility scale HyPP from scratch, combining 22, 38 and 12 MW of WF, SF and BESS under a 50 MVA PCC [5]. However, due to local TSO regulations, only the BESS were allowed to provide frequency containment reserve (FCR). This plant, called Energy Park Haringvliet Zuid, is located in the Netherlands, has been in operation since January 2021. Future plans for the HyPP platform include the inclusion of hydrogen technologies, hydro power, and implementation in both new plants and hybridizations of existing WFs. In this paper we first present an architecture for coordinated FCR provision on HyPP level, along with simulation results for different scenarios to assess the functionality of the proposed methodology. Secondly, measurement results from field tests at the Haringvliet HyPP are presented, collected under various operating conditions in order to analyse the performance of the HyPP controller.

II. Coordinated Frequency Containment Reserve

This section is focused on the FCR functionality as part of the active power control (APC) loop of the Hybrid Power Plant Controller (HPPC). A block schematic representation of the overall system is provided in Figure 1, depicting the main components and their interconnections. The black arrows represent data flow (setpoints, power capabilities, etc.) and the blue ones – measurement signals. The HPPC receives commands from different external units (Markets, surveillance centre, TSO) through the SCADA system, and measurements from a number of smart meters. Such commands can be, for instance, active and reactive power setpoint at the PCC, and FCR volumes that have been traded and need to be reserved. The measurements include active and reactive power at asset level, i.e., WF, SF and BESS, and at the PCC, as well as

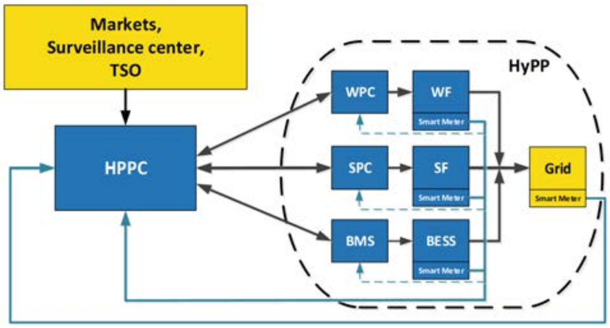

Fig. 1: Communications and measurements diagram

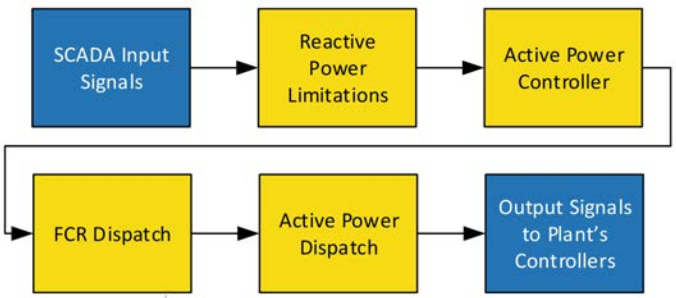

Fig. 2: Active power loop diagram

frequency and voltage. To track the external power setpoints at the PCC, the HPPC determines active and reactive power setpoints for each asset and communicates these to the asset level controllers: wind plant controller (WPC), solar plant controller (SPC) and battery management system (BMS). The asset controllers ensure that the power outputs of the assets track the HPPC setpoints.

A. Architecture

To highlight the functionality of the FCR controller, a high-level description of the APC loop of the HPPC is provided in this section. It consists of different blocks that aim to determine an overall active power setpoint at the PCC and dispatch it to the different HyPP's assets. Figure 2 illustrates the main components of the APC loop. An overview of the functionality of each block is provided below.

The SCADA block provides the interface between external units (individual assets' controllers, measurement equipment, market unit, TSO, surveillance center) and the HPPC controller. It communicates a range of signals to the HPPC, such as measurements at the PCC, available powers of the different assets, traded FCR volumes by the market unit, and external power setpoints. Reactive power limitation block prioritizes the reactive power supply over the active power to facilitate the compliance with the grid code requirements in different operation modes. When reactive power is being provided by the HPPC, the possible active power setpoint might get limited by this block to ensure that the apparent power at the PCC does not exceed the operational limits. The active power controller, schematically depicted in Figure 3, is responsible for determining the total active power setpoint for all assets in such a way that it complies with the actual capabilities of the individual assets and limitations at asset and PCC level. In this process, the APC attempts to reserve the FCR volume that has been committed by the market unit, and secure the activation when the frequency measured at the PCC deviates from the nominal value of 50 Hz. To this end, an active power setpoint at the PCC is derived from the "FCR Look-up-Table" block in Figure 3 as the sum of two terms: baseline (wholesale market) power setpoint and FCR activation power setpoint. To enable compliance with the requirements from different grid codes, including symmetric and asymmetric positive and negative FCR volumes, the FCR power response curve is implemented generically in the form of a look up table. Figure 4 depicts two examples of such FCR power response curves in accordance with different grid codes. The maximum power capacity is determined based on the available wind and solar power, the PCC power rating, and taking into account the worst-case connection losses between the individual assets' measurements and the PCC measurement. The baseline production level is determined such that the whole FCR volume traded by Markets can be realized at the PCC if the frequency drops below f_1 in Figure 4, regardless of the losses. In the current implementation, the battery does not participate in the baseline power production but only contributes to the FCR provision. When no FCR volume has been traded, the active power setpoint at the PCC can be set externally (through the SCADA interface) or equals otherwise sum of the available powers of the wind and solar farms so as to maximize their power production. This is visualized by the switch block in Figure 3. Furthermore, in order to properly deal with any connection losses between the different assets and the PCC, a PI controller is used to construct an active power setpoint for the HyPP as a whole that ensures, under stationary conditions, the right amount of power at the PCC. This PI controller acts on the difference between the active power measurement at the PCC and its setpoint and employs an anti-windup implementation that takes into account all limitations in terms of active power magnitude and rate of change at both assets and PCC level. Finally, the HyPP active power setpoint is split into baseline and FCR activation setpoints for the HyPP, which are then sent forward to the subsequent dispatch blocks (see Figure 2).

FCR dispatch block in Figure 2 consists of an algorithm that distributes the required FCR volume to be reserved or activated at any moment of time among the different assets. The reservation term represents the FCR volume that will be deducted from the assets' capabilities. This has been implemented in order not to exceed the assets' limitations, and to allow producing the required FCR volume anytime. The activation term, on the other side, is the actual amount of active power that needs to be supplied due to frequency deviations. The activated amount of FCR is a function of grid's frequency while the reserved amount is a fixed volume that is committed based on the trading agreements. Accordingly, two main states are developed as a part of the FCR state flow: reservation and activation states. Two conditions trigger the

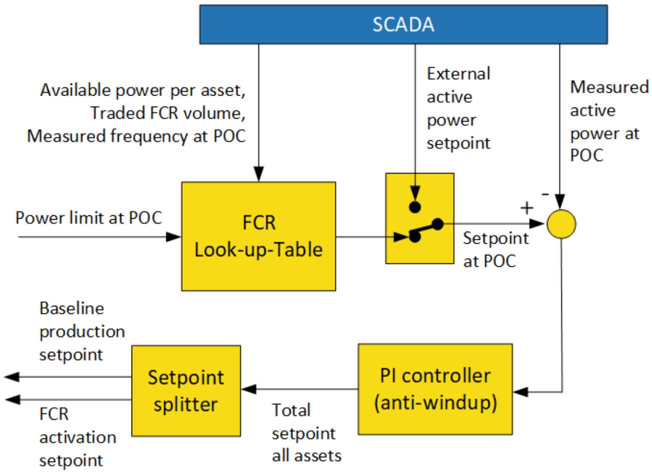

Fig. 3: Active power controller

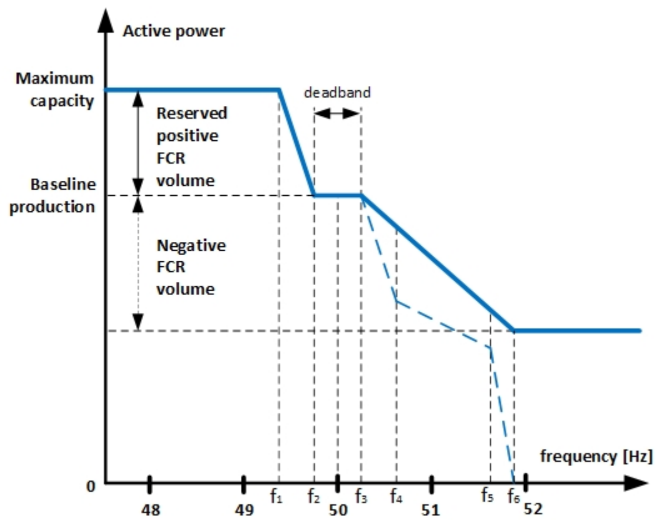

Fig. 4: Examples of FCR power response curves

transition between the substates, namely the priority signal of FCR that defines the distribution strategy of the FCR volume between the assets, and the activation signal that indicates if there is an under-frequency event that demands an active power production. For simplification purposes, the battery is considered to have the highest priority in supplying the FCR volume, and the priority signal specifies if WF or SF will be first to support the BESS, both for the reservation and activation states. The block diagrams in Figures 5 and 6 show the main states and substates of the FCR dispatch logic.

Taking the dynamics of the WF and the long restart time of the turbines into consideration, whole capability reservation is avoided. Instead, preconfigured minimum setpoints will be dispatched to ensure continuous running of the turbines. These will be the lower limits of the reservation state. The "no activation" state is in operation as long as no under frequency event is occurring. An under-frequency measurement below the defined dead band by the TSO requirements will trigger

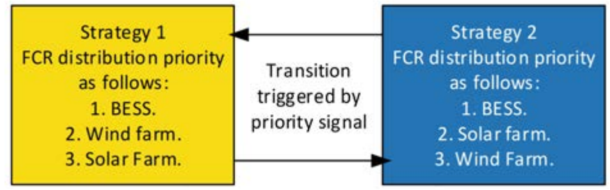

Fig. 5: Reservation state block diagram

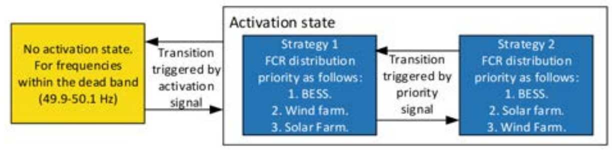

Fig. 6: Activation state block diagram

the transitional condition to run the "activation" state. The distribution strategy of the instantaneous required FCR volume is applied in the "activation" state following the aforementioned priority signal. Finally, active power dispatch block (see Figure 2) distributes the baseline power production setpoint to the individual assets by following prespecified priority rules. In the context of FCR services, this block handles the curtailment of either WF, SF or both in case of over-frequency measurements. Baseline power setpoints are then combined with the FCR output signals to result in the final active power setpoints to be communicated to the asset's controllers as output signals from HPPC. This block deals with the curtailment requirements in over-frequency events where the down FCR product needs to be activated.

B. Study Case

To illustrate the performance of the FCR algorithm, simulation results under different scenarios are presented in this section. Each scenario shows dispatching performance considering different set of input parameters, such as frequency variations, reserved FCR volume, assets' capabilities, etc. It should be highlighted that the simulation scenarios are based on the Swedish FCR-D requirements. Additionally, symmetrical up and down product scheme is considered in these simulations, meaning that FCR-D up and down products have the same volume. A common parameter between different scenarios is the frequency. A set of frequency values has been designed to cover the whole frequency range of interest in studying the FCR product (from 49.5 Hz up to 52 Hz). These values require different FCR active power production, 100% FCR-D up production for f $\leq$ 49.5 Hz, 100% FCR-D down production for f $\geq$ 50.5 Hz and linear in between with a dead band for 49.9 $\leq$ f $\leq$ 50.1 Hz. The frequency signal varies in a way to represent under and over frequency events along with values that fall within the dead band that does not require FCR production based on the grid code requirements. The FCR functionality considered is based on the Swedish TSO's (Svenska Kraftnät - SvK) requirements for FCR-D [6], which has the form of the solid curve in Figure 4 with frequency

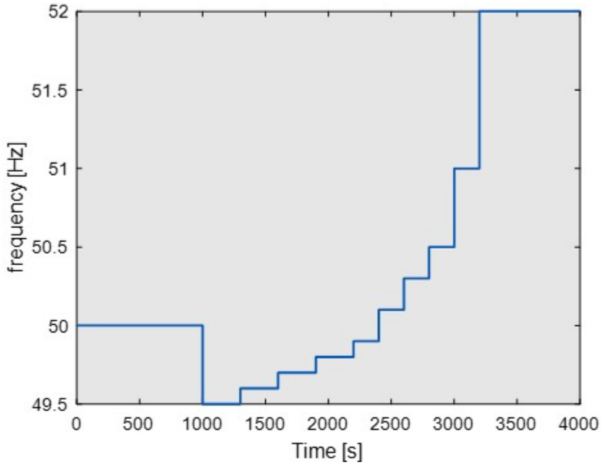

Fig. 7: Considered frequency deviations.

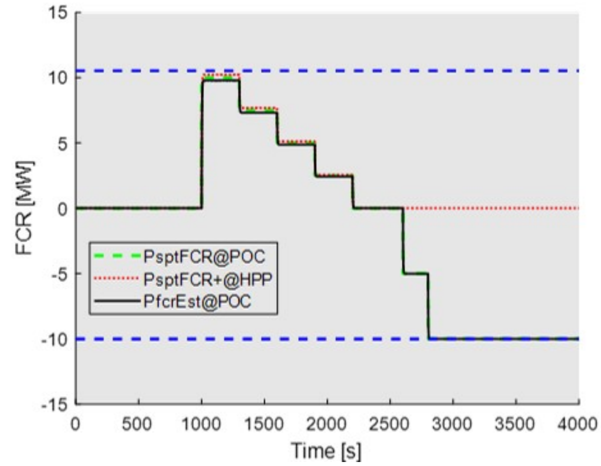

Fig. 8: Required FCR volumes for scenario 1

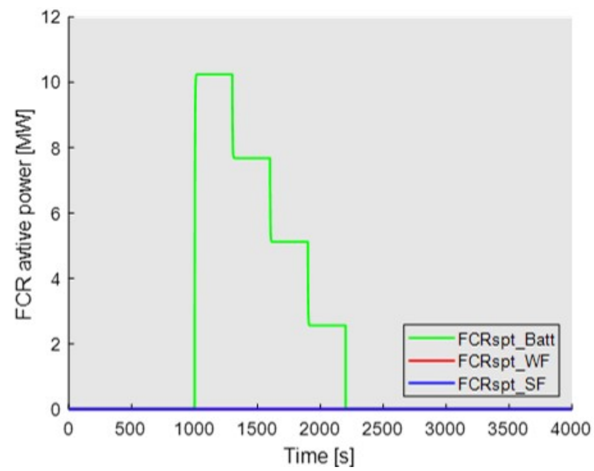

Fig. 9: Scenario 1 FCR dispatch setpoints for all assets.

points $f_1 = 49.5$, $f_2 = 49.9$, $f_3 = 50.1$, and $f_6 = 51.7$ Hz. Figure 7 shows the frequency variations adopted for different scenarios.

First scenario is designed to test the dispatching algorithm while relatively small FCR volume is demanded. Wind and solar capabilities are set to 20 MW each while battery's capability is 12 MW in this scenario. Capability term corresponds to the maximum power that can be supplied from each asset separately. Priority signal is defined to prioritize wind over solar in supporting the FCR production with the BESS. Contracted FCR volume is assumed to be 10 MW, represented by the dashed blue line in Figure 8. The required FCR volume to be activated at the PCC as output from the APC block is given by the green dashed line in the figure. The red dotted line represents the corresponding positive FCR setpoint at HyPP level that needs to be distributed between the assets, which is slightly higher than the setpoint at the PCC to overcome the connection losses. Also given in the figure is an estimate of the actual FCR volume at the PCC (black solid line) calculated as the difference between the total power produced at the PCC and the baseline power production setpoint at the PCC.

Notice that, for under-frequency values, the activated volume of FCR varies from 100% for 49.5 Hz and decreasing linearly with the frequency, reaching 0% activation at 49.9 Hz. This complies with the Swedish TSO FCR-D requirements. Negative FCR is activated in the form of production curtailment in the over-frequency range following the same set of requirements.

The positive FCR setpoints of all the assets are presented in Figure 9. Since the FCR volume is less than the battery's capacity, the reservation of the whole positive FCR volume is conducted from the BESS alone and there is no contribution from the other assets in supplying the FCR demand. In the current model setup, the battery's production is of interest only in terms of FCR production. Accordingly, the battery capability for baseline power production is set to zero after applying the reservation algorithm to avoid participating in the baseline energy production. HyPP's assets capabilities before and after FCR volume reservation are presented in Figure 10. Wind and solar operate at maximum power production.

Referring to Figure 8, in over frequency periods where negative (down) FCR is required, curtailment of the assets is conducted. There is a separate signal that specifies the curtailment priority based on business case requirements and other different factors. It has been set to curtail the wind asset first followed by solar if needed, while the battery is not considered. Figure 11 demonstrates the conducted curtailment of the wind during the over frequency occurrence, while solar is maintained at maximum production since the wind asset is sufficient to supply the required -10 MW.

Second scenario considers a higher FCR volume that requires, aside from BESS, an FCR provision form the WF as well. This scenario represents the concept of developing a frequency controller on a plant level. Other parameters, i.e., frequency, priority signal, assets' capabilities are kept similar to the first scenario. However, FCR volume is set to be 20 MW now. Following the same frequency variations shown in Figure 7, the activated FCR signal is given in Figure 12.

The figure demonstrates different volumes of FCR activation

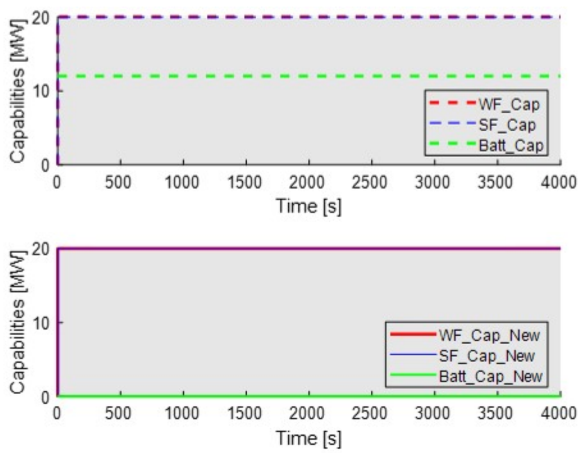

Fig. 10: HyPP's assets capabilities before and after the reservation process in scenario 1.

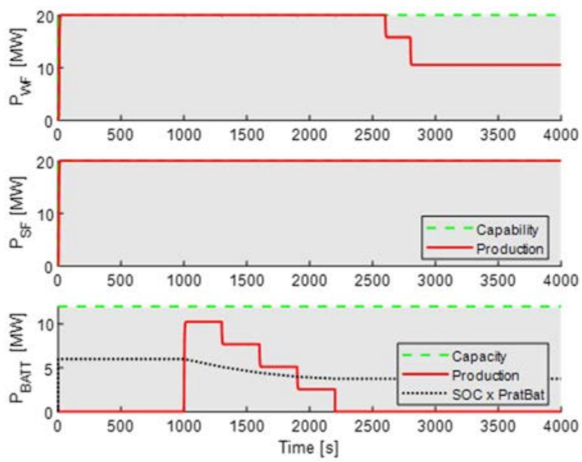

Fig. 11: Active power production from WF, SF, and BESS for scenario 1.

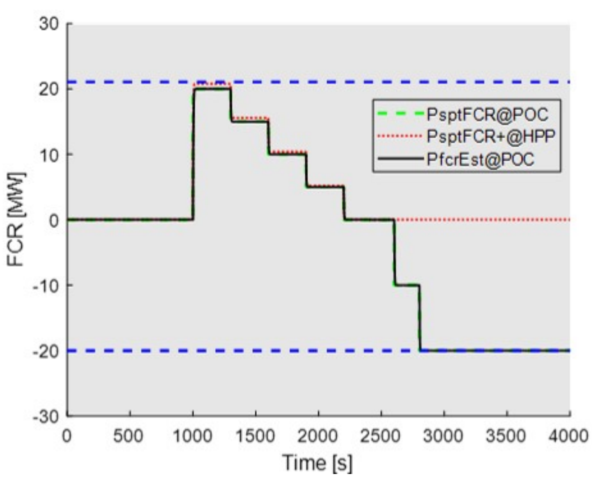

Fig. 12: Required FCR reservation/activation volume for scenario 2.

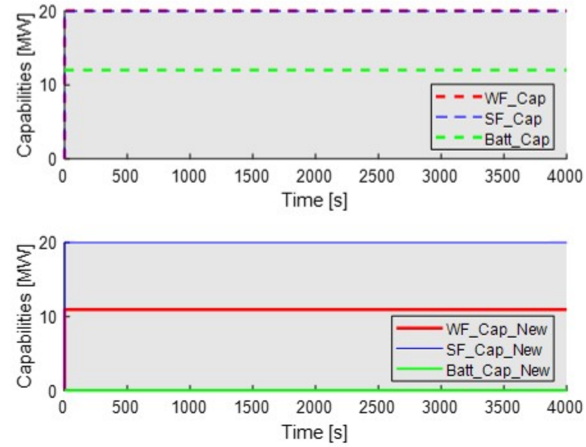

Fig. 13: HyPP's assets capabilities before and after the reservation process in scenario 2.

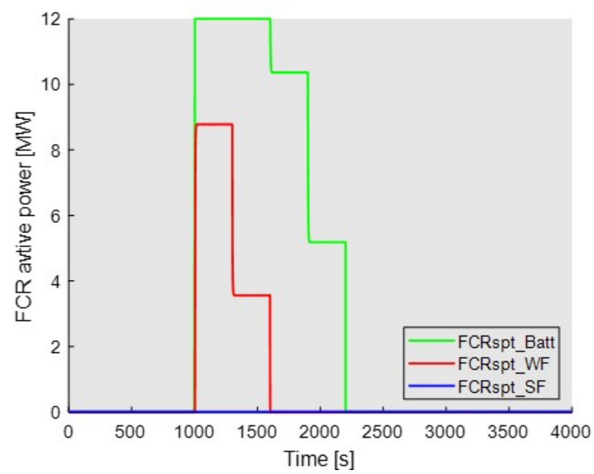

Fig. 14: Scenario 2 FCR dispatch setpoints for all assets.

following the simulated frequency deviations. Due to the need of compensating the possible connection losses, the FCR volume at HyPP level is slightly higher, around 21 MW. Since the whole volume will be reserved from the assets, and the FCR priority signal makes the WF in the second position after the BESS in providing FCR supply, the 21 MW is distributed as 12 MW from BESS and 9 MW from wind. New assets' capabilities upon the reservations of the aforementioned values are shown in Figure 13.

The wind's capability for baseline power production becomes 11 MW after the FCR volume reservation. The activated FCR is supplied from the BESS up to 12 MW with the remaining part filled in by the WF. During the 100% and 75% FCR activations, both BESS and wind act to meet the FCR demand, while 50% and lower activations can be satisfied by the BESS reservation alone. FCR dispatch setpoints for the three assets are shown in Figure 14.

Similar to scenario 1, curtailment of the production is conducted in over-frequency events. For full activation of the negative FCR volume, the curtailment is applied on both wind

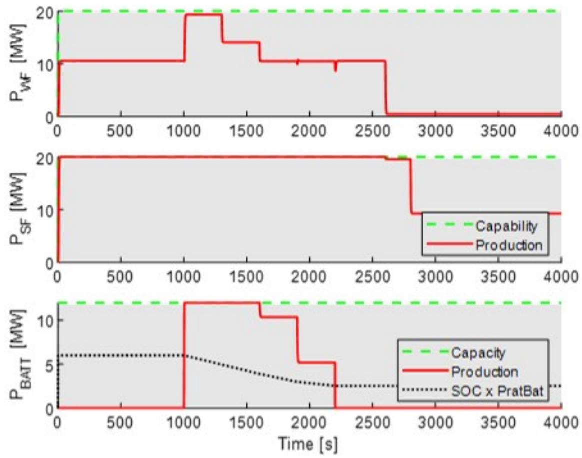

Fig. 15: Active power production from WF, SF, and BESS for scenario 2.

and solar assets since, due to the positive FCR reservation, the wind farm alone is not sufficient to provide the whole negative volume of -20 MW. Accordingly, the remaining negative FCR down volume after curtailing the wind farm to its minimum production (which is nonzero to avoid shutting down the turbines) is provided form the solar farm. Active power production for all the assets is shown in Figure 15.

At time 2800 s when the frequency increases to 50.5 Hz, the drop in production of 20 MW is noticed. Wind is curtailed first followed by the solar production as previously explained. This is conducted in the active power dispatch block presented in Figure 2.

Moving to third scenario, due to the intermittency of the renewable assets, the scenario is designed to test the dispatch algorithm in case of a shortage in the assets capabilities to supply the required FCR demand. In this scenario, the FCR volume traded by the market unit is set to be 30 MW while the wind and solar capabilities are just 5 MW each. Frequency and FCR priority signals remain the same as in scenario 1.

The APC attempts now to reserve the maximum amount of FCR volume in order to minimize the FCR reservation shortage. Due to the limited capabilities, instead of having 30 MW activation at 49.5 Hz, the activated FCR volume is around 20 MW, as seen from Figure 16. This is lower than the sum of the capacities of the three assets in this scenario (12+5+5 MW) because of the connection losses, but also because the maximum FCR volume that is reserved by the WF and SF is lower than their actual capacity. This is done to avoid shutting these assets completely down, which would result in an unacceptable activation delay once FCR needs to be suddenly supplied. The resulting FCR volume shortage (see Figure 18) can be communicated back the market unit and accordingly, take the necessary actions to compensate for it on a portfolio level, for instance.

In the over-frequency range, the FCR volume has been set to zero as the assets baseline production capabilities are set to the minimum values and cannot be further curtailed. Corre-

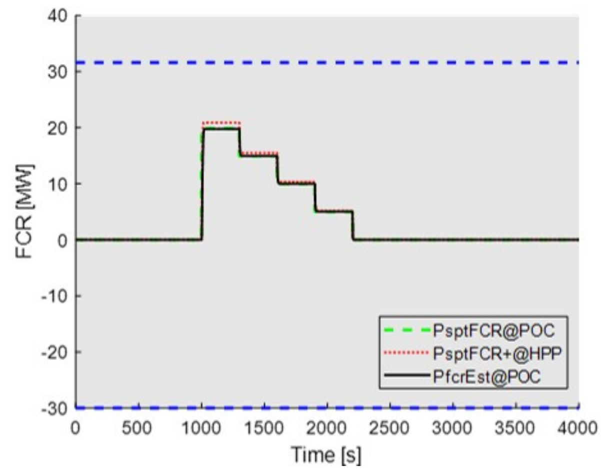

Fig. 16: Required FCR reservation/activation volume for scenario 3.

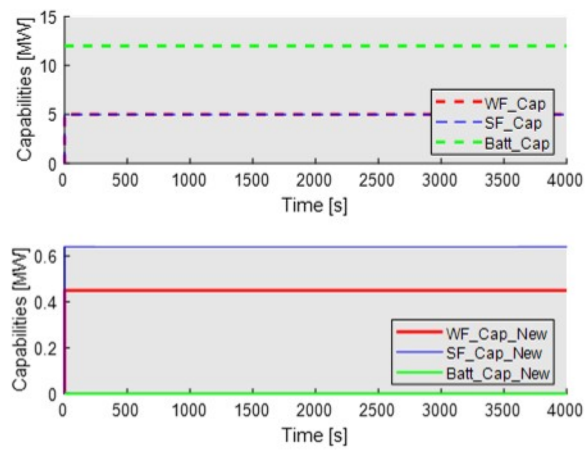

Fig. 17: HyPP's assets capabilities before and after the reservation process in scenario 3.

sponding capabilities of the assets upon the FCR reservation is shown in Figure 17.

The received activated FCR is distributed among the available assets as previously done in the first two scenarios. BESS acts first, followed by wind and solar respectively. FCR dispatch signals are shown in Figure 19.

The overall production for the HyPP's assets including baseline and FCR volumes are shown in Figure 20.

The three study cases presented in this section show successful implementation for FCR controller on a plant level, i.e. where all assets contribute to supplying FCR support. In the next section, measurement data from an operational HyPP will be presented, namely Energy Park Haringvliet Zuid, where the FCR provision is supplied only by the BESS.

III. Field Tests From Haringvliet

Upon commissioning the generation units and the controller itself at the Haringvliet renewable park, a Site Acceptance Test (SAT) is carried out to verify the performance of various

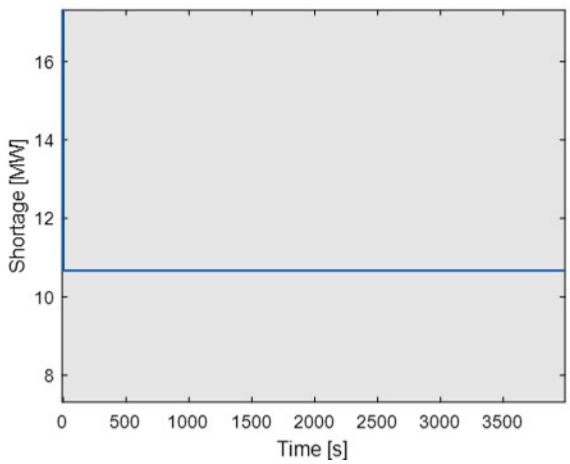

Fig. 18: FCR reservation shortage in scenario 3.

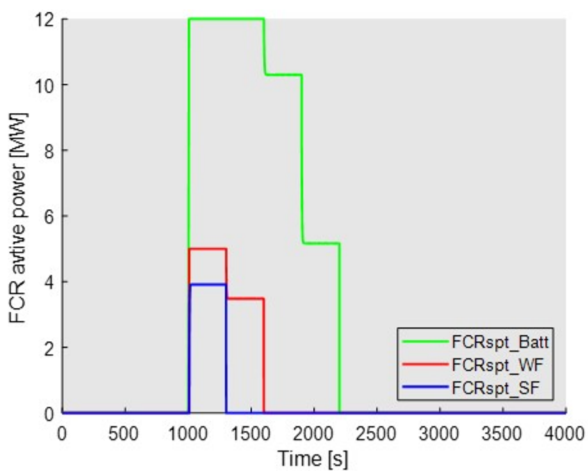

Fig. 19: Scenario 3 FCR dispatch setpoints for all assets.

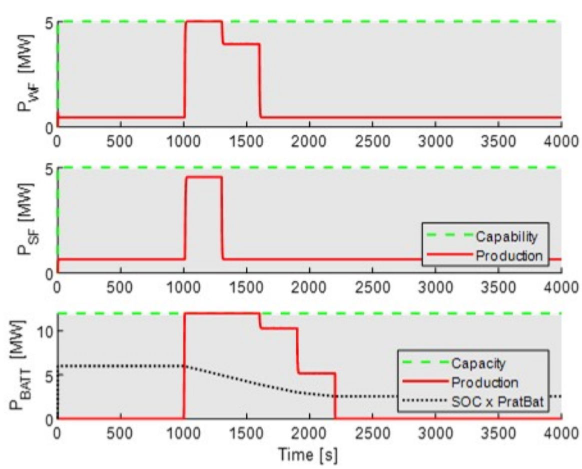

Fig. 20: Active power production from WF, SF, and BESS for scenario 3.

TABLE I: Configuration of Haringvliet Hybrid Park.

Sub-plant	Capacity [MVA]
WF	22
SF	32
BESS	12

functionalities of the controller. The site is comprised of the following assets with their respective active power capacities:

As mentioned in the previous sections, the battery unit is only used for FCR delivery and it does not participate in the baseline energy production. Since a full activation of all assets, where both baseline energy production from wind and solar assets as well as FCR delivery from battery units can overburden the point of grid connection, which has a rating of 50 MW, an amount equal to reserved FCR volume is constantly deducted from the active power setpoint. It should be noted that, although a specific FCR amount is reserved through a market mechanism, the actual percentage of delivery of this reserved amount is dependent on the scale of imbalance on the frequency and the actual capabilities of the assets.

The following tests have been performed:

- Active power setpoint tracking
- Switching active power curtailment priority between different assets
- Reactive power setpoint tracking
- Switching reactive power curtailment priority between different assets

During all the tests, a constant 12 MW FCR volume has been reserved.

A. Methodology

The HPPC is located between the SCADA system and the separate plant controllers, where the SCADA system sets the setpoint commands as well as the FCR volume. These commands then are sent to the HPPC for processing through the control algorithm, which is embedded in a PLC and dispatched to the plant controllers accordingly. This communication process can also be seen visually on Figure 1.

B. Active Power setpoint tracking

In this test, the active power setpoint is gradually dropped from 50 to 10 MW and back to 50 MW again in steps of 10 MW each. WF is prioritized to curtail before SF or BESS in case the setpoint is less than the sum of the asset capabilities.

Top side of Figure 21 shows the active power setpoint (W_spt) along with the reading from the meter at the point of grid connection (W_out). An additional line is shown ($W_out + FCR$ reserve) to illustrate the effect of the reserved amount. The bottom plot is showing the HPP capability, (which is the sum of wind and solar capabilities since BESS is only used for FCR services) and the actual activated amount of FCR from the BESS (notice the y-axis on the right).

When the controller gets a setpoint value of 50 MW, which equals the PCC rating, due to the 12 MW FCR reserved with the battery only 38 MW baseline production command is sent

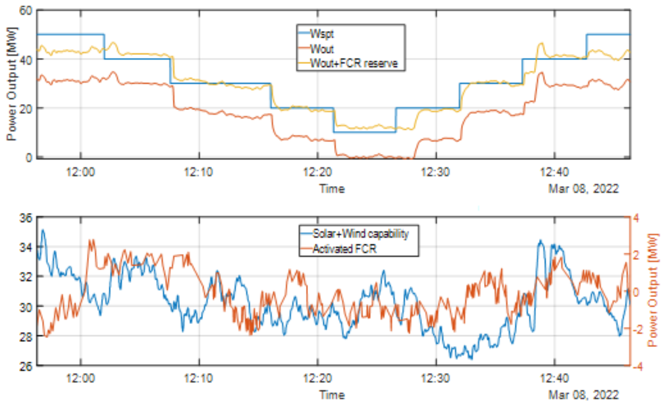

Fig. 21: SAT 1: Active power setpoint tracking

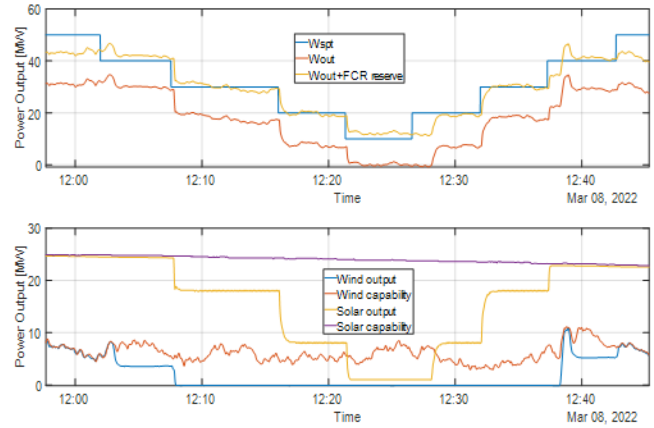

Fig. 22: SAT 2A: Active power curtailment with WF as curtailment priority

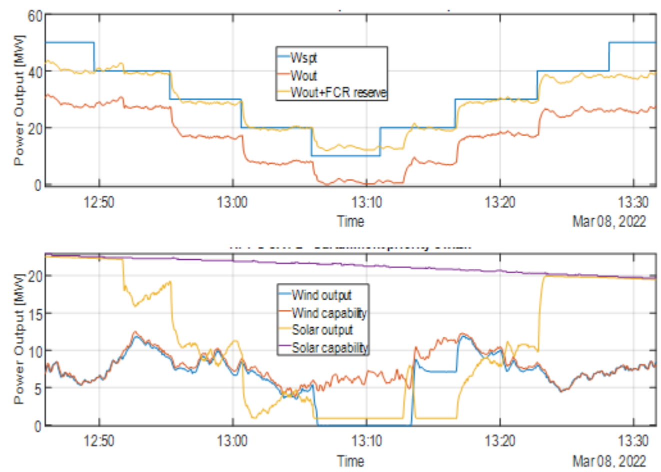

Fig. 23: SAT 2A: Active power curtailment with SF as curtailment priority

to WF and SF. However, this setpoint is not reached by the assets since the production is limited by the sum of their capabilities.

For the 40, 30 and 20 MW setpoint commands (corresponding to a total of 28, 18 and 8 MW for the solar and wind assets), the desired output is reached since these levels are below the sum of WF and SF capabilities. The measured power signal shows some variations around the desired setpoint, which are attributed to the FCR contribution and the dynamic changes on the WF and SF capabilities due to changing external conditions.

Once a 10 MW setpoint is received, a 0 MW command is sent to wind and solar assets since the FCR volume itself exceeds this setpoint. However, it is observed that the meter still measures active power values up to 2 MW, which is due to 2 main reasons: FCR contribution, and the fact that the SF always keeps 5 cells running at maximum capacity (1 MW), regardless of the setpoint, to measure the solar plant capability at all times.

It is also noted that the system needs time to catch up once the setpoint is raised to 20 MW, since the wind turbines require time to go back from idling to operating state.

C. Curtailment priority test

The first part of the curtailment priority test examines the performance when the WF is prioritized over the SF. To this end, the measurements from the SAT 1 test in Section B are used. Figure 22 shows the SAT 1 results from the perspective of curtailment priority of assets. When a 40 MW setpoint is sent to the controller (28 MW for solar and wind assets), the WF controller curtails its output to match the required power output. Eventually, for the setpoints of 30 MW and lower, wind park goes idle and SF is curtailed to control the active power setpoint.

Next, the same test as described in section B is repeated, only this time the SF are set to curtail first in case the setpoint is less than the sum of the asset capabilities. Figure 23 shows the results for this test. For the same commands of setpoints of the previous test, it can be clearly observed that, until a 10 MW setpoint is sent, the WF controller follows its capability quite accurately and the SF curtail itself to match the setpoint. After the 10MW setpoint the wind farm is shut down and the solar farm is operated at its minimum capacity of 1 MW, as explained above. At this stage, one should observe the distinction between the ongoing implementation explained in the previous sections and the SAT implementation where there is no lower bound is defined for the wind park setpoint, leading to shutdowns when a 0 setpoint is sent, an issue that is avoided in the current setup. Once the setpoint gets back to 20MW, the WF controller is unable to follow its capability for some time (around 13:15 in the figure), which is due to the startup process of the wind turbines. D. Reactive Power setpoint tracking In this test, reactive power setpoints of 2, 4, -2 and -4 MVAr are sent as commands, where the reactive power dispatch priority is set in the order WF, SF and the BESS.

Independent from the weather conditions and the active power capabilities, the wind park and the solar cells have 9 MVAr and 17 MVAr of reactive capabilities, respectively.

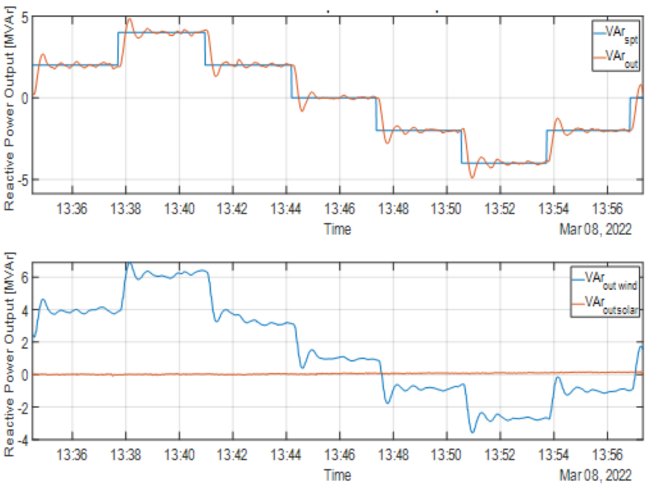

Fig. 24: Reactive power setpoint tracking prioritizing WF.

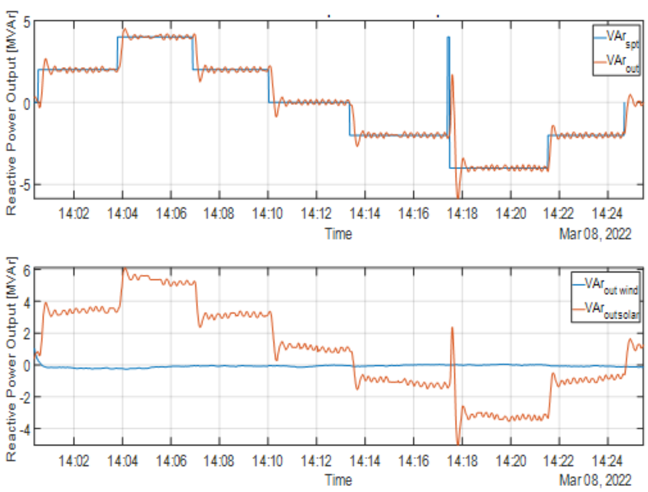

Fig. 25: Reactive power setpoint tracking prioritizing SF.

Figure 24 shows the test result, where the wind asset fulfills the setpoints alone without any contribution of SF. One can also note the slight overshoot and oscillations after each step which, even though the response is considered acceptable, indicates that the reactive power control performance may be improved by further fine-tuning.

D. Reactive Power curtailment priority test

Here, the same test as in section D is repeated, only this time, SF is set to have the dispatch priority, followed by WF and the BESS.

As seen on Figure 25, the SF alone fulfills the required setpoints. The spike around 14.18 is caused by an abrupt, though unintended, setpoint which the SF responds well to. Even though they have slightly lower overshoot compared to the WF, SF exhibits more oscillations around the setpoint.

IV. Conclusion

This paper presented the development of an FCR controller on a plant level, meant to support the business case of future hybrid power plants. Considering the ongoing trends towards subsidy-free markets for renewables, this feature provides several benefits:

- it can enable secondary revenue streams
- contribute towards a more stable FCR supply due to the redundancy between different assets on a plant level
- enhance flexibility to comply with specific TSO requirements for the selected assets to participate in FCR production.

Inclusion of other technologies such as hydrogen production units and/or hydro power plants can be further integrated into the existing solution and their contribution towards a coordinated FCR supply can be investigated. Additionally, SAT results are presented , which demonstrate the operation of HPPC in the Haringvliet hybrid power plant. The field results show that the controller can follow the SCADA setpoints dynamically while distributing them correctly to the desired generation assets. Depending on the need, the controller can also dynamically switch the curtailment priority both for active and reactive power dispatch.

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