The First Utility Scale Hybrid Plant in Europe
The Case of Haringvliet

Vazquez Pombo, Daniel; Raducu, George-Alin; Styliaras, Nikolaos; Sahin, Ozan; Thanopoulos, Sotirios ; Funkquist, Jonas; Shayesteh, Ebrahim

Published in:
Proceedings of 5th International Hybrid Power Systems Workshop

Publication date:
2021

Document Version
Peer reviewed version

Citation (APA):
Vazquez Pombo, D., Raducu, G.-A., Styliaras, N., Sahin, O., Thanopoulos, S., Funkquist, J., & Shayesteh, E. (2021). The First Utility Scale Hybrid Plant in Europe: The Case of Haringvliet. In *Proceedings of 5th International Hybrid Power Systems Workshop* Energynautics GmbH.

The First Utility Scale Hybrid Plant in Europe: The Case of Haringvliet

Daniel Vázquez Pombo[1,2], Alin George Raducu[1], Nikolaos Styliaras[1], Ozan Sahin[1],
Sotirios Thanopoulos[1], Jonas Funkquist[1], and Ebrahim Shayesteh[1]
[1] Research and Development - Vattenfall AB - Stockholm, Sweden
[2] Department of Electrical Engineering – Technical University of Denmark (DTU) - Risø, Denmark
Email: danielvazquez.pombo@vattenfall.com

***Abstract*—Hybrid Power Plants (HyPP) combine at least two traditional Renewable Energy Sources (RES) and/or an Energy Storage System (ESS) under the same Point-of-Common-Coupling (PCC). Among other advantages, they hold the potential to increase the profitability of RES in a subsidy free market while also supporting the grid similarly as traditional units. Haringvliet is the first utility-scale HyPP of Europe. It is compound by 22, 38 and 12 MW of Wind Farm, PVs and Battery Storage System (BSS) respectively which effectively represents a 50 MVA HyPP. Future plans involve the inclusion of a Hydrogen production unit. This paper discusses Vattenfall's motivation behind going hybrid, the plant's layout, and the controller's features; as well as the design process, lessons learned and future development stages. The simulation results confirmed that the developed controller provides a very good precision and the studied HyPP fulfils all needed requirements**

I. INTRODUCTION

Accelerated by environmental regulations and positive market conditions, RES penetration rates have exponentially increased over the past decades globally [1]. However, the economic subsidies applied to renewable plants are phasing out, thus straining their economic viability [2]. In addition, Transmission System Operators (TSO) increasingly demand further grid support capability from RES, which results particularly complex due to their dependency on random meteorological phenomena among other technical factors [3], [4]. Nevertheless, most of the technical challenges traditionally hindering RES deployment have been solved as presented in recent literature and pilot projects [5], [6].

Given the profit margin limitation caused by the subsidy withdrawal and increasing industry competitiveness, reducing the Levelized Cost of Energy (LCOE) is a matter of utter importance. There are several ways to approach it, being additional market participation and hybridization the two most important ones [5], [7]. The first one is related to engage not only in the day ahead and same day markets, but also in ancillary services and regulation markets like the intraday and frequency response [7]. The second involves over installation of generation units in order to maximize the utilization of the main point of connection [7]. When targeting Wind Farms (WF), this can be done by simply over installing turbines, while also, including PVs and/or ESS, like batteries. Furthermore, hybridizing presents two advantages when compared to simply over-installing. The first one is reducing the curtailment needs, since solar and wind resources are deeply decoupled; which means that windy and high irradiation periods are very unlikely to coincide; minimizing the necessary curtailment [5]. Additionally, the presence of an storage system allows for power smoothing and participation in markets like regulation and frequency provision, since it ensures a certain amount of energy or power to be delivered at will disregarding atmospheric phenomena.

This technology has gained attention within Vattenfall over the years since the company owns more than 50 WFs around 5 countries suitable for hybridization [8]. In fact, a set of papers about this topic have been published by Vattenfall R&D, with focus on the controller design [9], operation optimization [10], and frequency containment provision [7]. Once, the core knowledge was established within the team, Vattenfall aimed to build and operate the first utility-scale HyPP of Europe. Which is effectively a 50 MVA plant divided in 22, 38 and 12 MVA of WF, PV and BSS respectively. This has taken place in Haringvliet a site located near Rotterdam (Netherlands). Field deployment was expected during September 2020, although it was delayed several times due to the disruption caused by COVID-19.

The structure of this paper is as follows, Section II presents the motivation behind going Hybrid, while Section III presents Haringvliet's plant layout. Subsequently Section IV introduces the features and functionalities of the developed control system. Section V presents some insights related to project management. Furthermore, section VI presents a number of study cases aimed to present the controller's performance. Finally, Section VII concludes the paper with a summary of lessons learned.

II. WHY GO HYBRID?

A HyPP can potentially present a lower LCOE than its components would have by themselves when operating independently. This is due to a number of factors: [5], [11], [12]

- Increased Number of Equivalent Full Production Hours: Since there are a higher number of production units in the same PCC, the total production is simply higher.
- Improved efficiency (grid and PCC): Given the effective decoupling existing between wind and solar power, the significative increase in production allows to operate the

TABLE I: HyPP's Configuration.

Sub-plant	Size [MVA]	Manufacturer
WF	22	Nordex
SF	38	Huawei
ESS	12	BMW

substation and related equipment at a higher utilization rate.

- Generation Uncertainty Reduction: Given the increased generation capacity, by implementing different coordination schemes, it is possible to overcome random fluctuations with smooth control.
- Additional Revenue Streams due to flexibility: The uncertainty reduction also allows to participate in markets traditionally out of the scope of renewable plants, such as frequency regulation.
- Enhanced Grid Support Capabilities: The increased operational determinism of the plant allows to provide ancillary services such as black-start which is not provided by renewable units in general.
- Reduced Construction and Commissioning costs: The different sub-plants share part of the electrical apparel, therefore, the cost per W is lower.

Therefore, they represent a key element of the energy transition in its new subsidy-free stage.

III. HARINGVLIET

The so called Energy Park Haringvliet Zuid is located in the south-west of the Netherlands at roughly 25 km from the city of Rotterdam. It consists of 6 wind turbines, 115,000 solar panels and 12 shipping containers storing the batteries. The construction started on February 2020 with the installation of the WF, which took two months as according to the original schedule. On the other hand, the PVs installation was planned to start in April but it was not possible until June due to the incidence of COVID-19. Delaying the completion until late September. Subsequently the ESSwas installed after enduring some offsite testing. [13]

On a different note, it is also worth mentioning how Vattenfall has minimized the impact of the energy park by involving the local community in the design of the plant layout. In this way, bike paths have been built in order to attract visitors to the park, the PV height was limited at 1.5 m in order to allow walkers to see over them, and bee-hives were included. Additionally, a flock of sheep takes care of keeping the weeds height under check thus avoiding shadowing over the panels. [13]

A. Topology

The aforementioned plant configuration is presented in Table I, which also includes the manufacturers. Then, the balance of plant is presented in Figure 1, where it can be seen how the three sub-plants share the PCC in bus 2. Additionally, it should be noted how the WF is divided into two strings with 3 turbines each, whose control is assumed by the WF Controller (WFC), provided by the turbines' manufacturer. A similar set-up is applied to the SF and its Controller (SFC) which is divided into three strings. Lastly, the battery presents a single string connecting the Energy Management System (EMS) to the substation. Also, V_g and Z_g represent the Thevenin equivalent of the external grid.

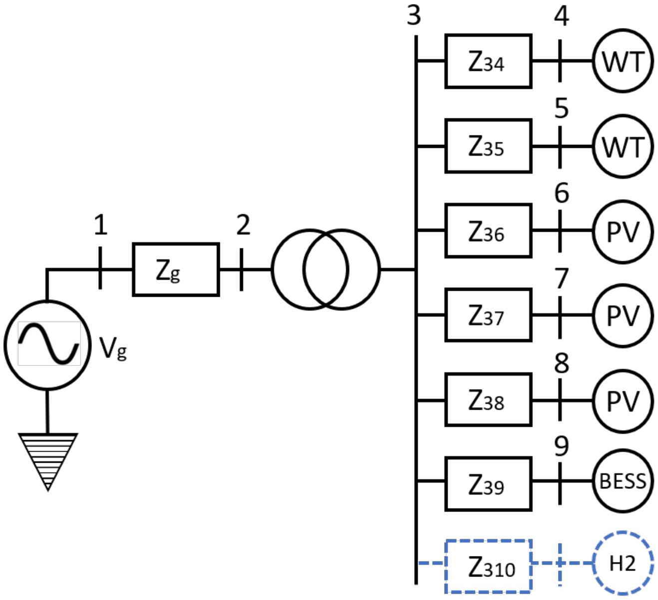

Fig. 1: HyPP's balance of plant.

Lastly, there is a Point of Connection (POC) reserved for a future inclusion of an electrolyzer aimed at Green Hydrogen production (noted with a dashed blue line in Figure 1).

B. Business case

Haringvliet is special in many ways, one of its particularities is the subsidy schema which supports solar but not wind production. In this way, the indicative prices can be 10 and 20 €/MWh for the WF and SF respectively. This obviously implies that generation from solar is prioritized over wind in periods when curtailment is necessary. This results counter intuitive as technically makes more sense to curtail solar over wind since WFs respond more slowly than SF when curtailing. On the other hand, Tennet, the TSO, has recently allowed BSS to bid in frequency provision markets. In the case of Haringvliet, the main use cases for the ESS is Frequency Containment Reserves (FCR) provision, whose qualification process of the battery was recently finalised successfully. In the future, its functionalities might be extended to other services. From an operational perspective, once an FCR bid is accepted, the plant must reserve certain capacity on the PCC to push or absorb power from the grid during the bid period. [14]

IV. HYBRID POWER PLANT CONTROLLER

Due to the rising relevance of the HyPP, an internal development of a suitable controller was initiated. The first delivered solution was a controller for Prinses Alexia Windpark [15], Netherlands in 2017. In that site, an existing 120 MW WF

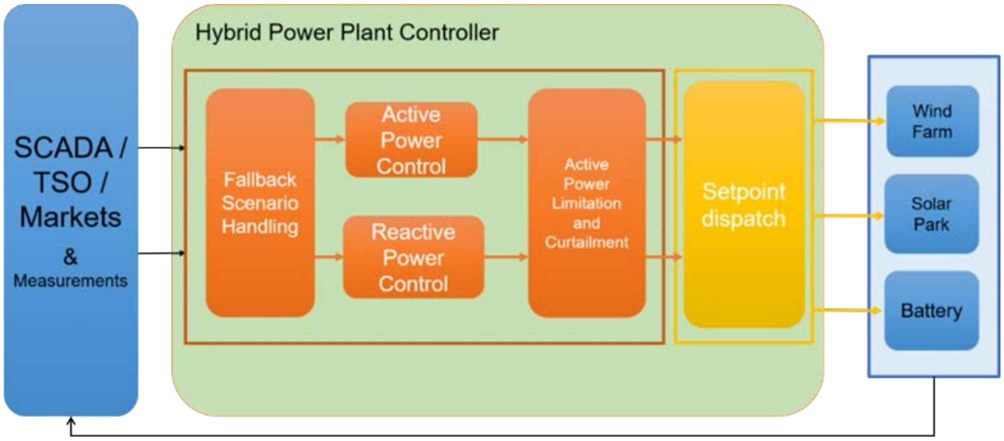

Fig. 2: HyPP's Communications Interface.

was hybridized with a 3 MW ESS. Although modest in size, this project launched the knowledge base of the Hybrid Power Plant Controller (HyPPC) team within Vattenfall. Subsequently in 2018 the Controller development for the Haringvliet took off.

A. *Objectives*

The objective of the HyPPC is to coordinate the different sub-plants, ensuring the correct prioritization between technical and market/economic objectives while at all times monitoring and securing the PCC's technical limitations and grid codes fulfillment. Those limitations are defined in terms of power factor, voltage level, active and reactive power, etc.

B. *Communication Architecture*

In the design of the HyPPC a bottom up approach was followed. This was necessary due to the fact that the WFC, SFC and EMS were black boxes from the design team perspective. Manufacturers keep locked the access to these elements which hinders the design of master controllers since the only possible communication is based on general set points and cascaded operation. Then, the particular sub-plant controller will decide by itself how to achieve the given set point.

Figure 2 presents an overview of the communication interface of HyPPC and how it is coupled with SCADA. This, is implemented in an industrial PC, coordinates the different controllers by exchanging information with them and retrieving measurements from the power quality monitor (Meter).

C. *Control Architecture*

Figure 2 also shows external signals coming from Vattenfall's Market Unit (VMU) or the TSO reaching HyPPC via SCADA. In this way, the steering parameters of the plant such as curtailment priority criteria are established. This information is then fed into the core of HyPPC, where those parameters are appropriately distributed and used in either the active or the reactive power control loop. The resulting operational points are then forwarded to the relevant sub-plant controller (WFC, SFC or EMS). In the active power loop, the process starts by deciding how much power should be generated. This is based on the signals coming from VMU, the TSO and the overall available power. Briefly, either the plant operates delivering maximum available power, or initiates curtailment.

Regarding the reactive power loop there are three modes of operation.

a) Set-point follower: HyPPC receives a certain amount of reactive power to generate inductive or capacitive power and distributes it to the sub-plants according to a certain priority signal.
b) Voltage Control: HyPPC receives a voltage set-point and coordinates the response in order to keep the desired value on the PCC.
c) Power Factor Control: HyPPC receives a cos(phi) set-point and it makes sure to maximize active power production while keeping the power factor at the desired value.

In the case of Haringvliet, the TSO requests to follow option c) [14], thus the other two functionalities are in place but not expected to enter into operation.

As an intermediate point, once the active and reactive power needs of the overall HyPP have been obtained, they are jointly compared with the available power in order to ensure that an unfeasible estate is not requested. Subsequently, the resulting corrected set-point is then distributed to two independent dispatch functions, again for active and reactive power respectively. It is in these dispatchers where the overall PCC active and reactive power set-points are distributed into the different sub-plants according to certain priorities. Lastly, these values are sent to the WFC, SFC and EMS respectively, which take care of implementing them. Additionally, there are of course a number of signals back-fed to SCADA in order to monitor the internal states of the plant.

D. *Future improvements*

HyPPC is still under ongoing development, just as the global Hybrid industry. In fact, given the potential of the HyPP concept of including multitude of different sub-plants, a

TABLE II: Scenario 1 – Reactive Power [MVAr] setpoints as step signals in second t.

t	0	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
Q	0	-5	-10	0	10	20	30	40	50	40	30	30

modular design has been followed. This will eventually allow for rapid prototyping of different configurations. Currently, HyPPC presents WF, SF, ESSand Electrolyzer sub-plants along with their controllers. However, it will probably include fuel cells and hydro in the near future. The possibilities are nearly endless.

On a different note, in upcoming subsidy free markets, FCR provision will represent a key ancillary service to be provided. HPPC integrates its coordinated provision as an enhanced optimization solution, selecting which component (or combination) will offer it in function of cost, energy spot prices, grid service prices, power availability, etc.

E. Development Tools

The most important tool employed was Matlab/Simulink as it represents the industry standard for model-based design and control development. Its graphical interface together with the automatic C++ coding allows for comprehensive and rapid prototyping. In addition, it also permits an easy delivery to the SCADA group which is the one in charge of mapping inputs and outputs, but also installing it on the field. The second key tool was TWINCAT, a windows based automation software by Beckhoff which can directly import and build C/C++ codes generated by Simulink Coder toolbox and deploy them directly into PLCs or Industrial Computers in a relatively easy way.

V. PROJECT HANDLING

The design and posterior development of such a controller is the product of a joined collaboration between different Vattenfall groups: R&D, Wind, Markets and SCADA which spawn across Denmark, Sweden, Germany, Netherlands and the United Kingdom . It was also necessary to align expectations and specifications with the manufacturers which were not always the best at stating what their product was or not capable to deliver and how. This is to be understood, as HyPP are a new technical reality that industry is yet to get ready for.

Apart from the general difficulties found in any project spawning internationally, there were others related to the differences in background between workers in each areas. At this level of complexity, it is crucial to find a common vocabulary that everybody agrees on its meaning (as network represents a grid of electrical connections for some while a system of interconnected telecommunication units for others for example). Therefore, it is key to document the development in two different ways, one meant for expert audience with high level of detail, and another more simplistic aiming to permit and boost the collaboration between groups.

Clearly, all the aforementioned makes HyPPC a complex endeavour where success can only be reached if all the parts collaborate effectively. Specially in this case as it was the first time a control system was developed within Vattenfall.

The foreseeable development of new HyPPs reveals the importance of rethinking the internal development processes; as the construction phase a HyPP project can not be treated similar as a single technology project.

TABLE III: Scenario 1 – Active Power [MW] setpoints as step signals in second t.

t	0	100	200	300	400	500	1600
P	0	10	20	30	40	50	50

TABLE IV: Scenario 2 – Available Power.

t		0	100	750	1500	1950	4000
S	WF	22,5	15	22,5	15	22,5	22,5
	SF	32	20	32	20	32	32

TABLE V: Scenario 2 – HyPP Active Power [MW] setpoints.

t	0	200	1000	1600	2200	4000
P	50	30	50	30	50	50

TABLE VI: Scenario 2 – HyPP Reactive Power [MVAr] setpoints.

t	0	2600	2700	2800	2900	3000
Q	0	-10	25	40	50	0

TABLE VII: Scenario 2 – Battery Offset setpoin [MW].

t	0	3050	3150	3300	3500	3600	3700
P	0	10	-11	0	8	-8	0

TABLE VIII: Scenario 2 – Battery's Negative FCR setpoint [MW].

t	0	100	700	800	1500	3800
P	0	10	0	12	0	0

TABLE IX: Scenario 2 – Battery's Positive FCR setpoint [MW].

t	0	1600	2300	2400	3000	3800
P	0	10	0	12	0	0

VI. CASE STUDY

In order to demonstrate the behavior under simulation environment of the developed platform, a study case is presented in this section. First, the scenario is defined; afterwards the results are presented and discussed.

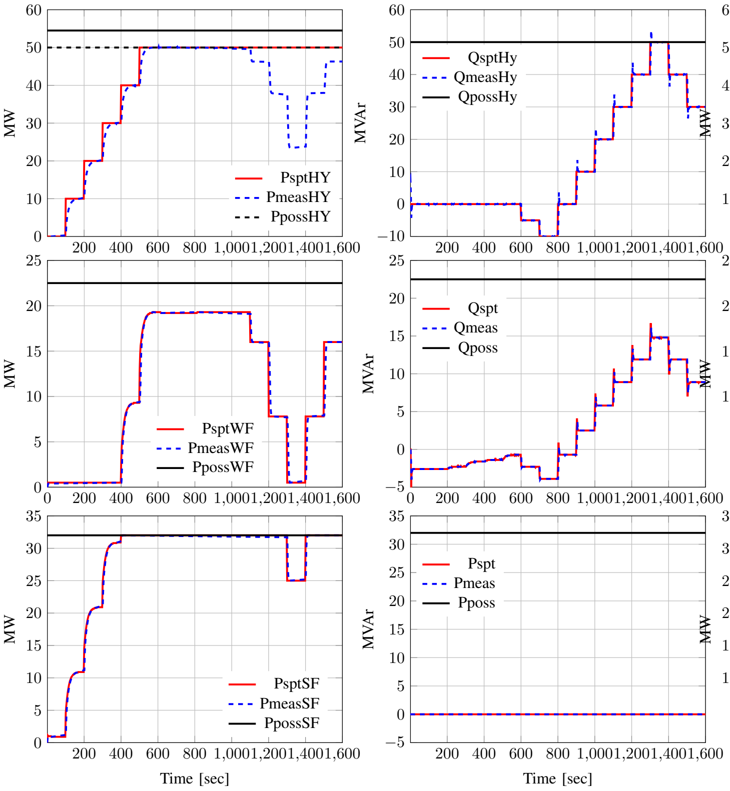

Fig. 3: Results of Scenario 1 – Active and Reactive Power Performance of the HyPP.

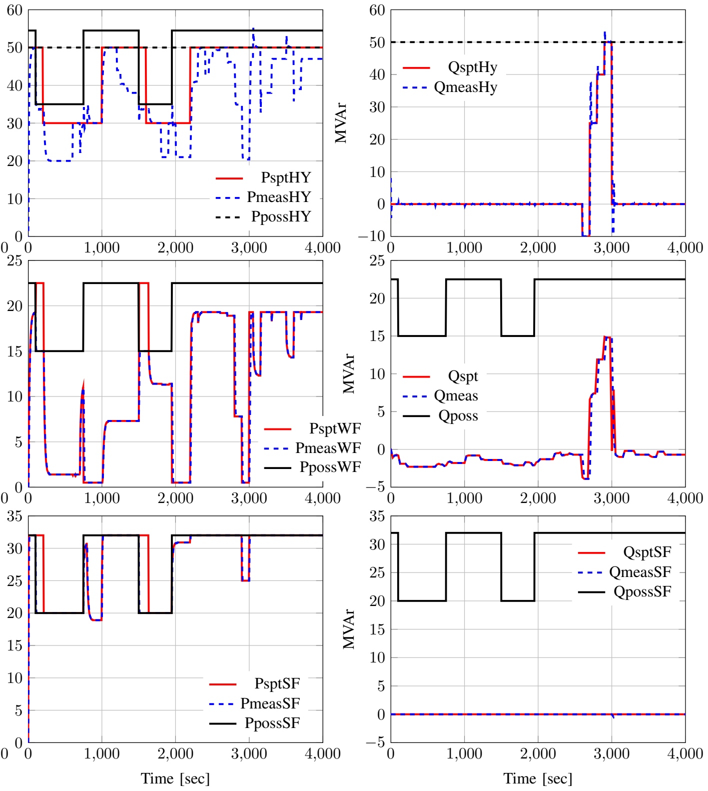

Fig. 4: Results of Scenario 2 – Active and Reactive Power Performance of the HyPP.

A. Scenario definition

The developed platform has ran an immense number of different tests, thus selecting meaningful scenarios was not a trivial task. Finally, it was decided to present two Scenarios that give an interesting overview over the main capabilities of the developed controller; that is:

1-P & Q setpoint following: A conceptually simple scenario in which different setpoints are independently fed to the HyPP's controller. This allows to see how the plant reacts to both, discriminates possible and impossible estates due to power availability limitation, etc. In this case, there is full power availability, the reactive power control mode is set to follow setpoints, and the priority determines to curtail wind if necessary. The reactive and active power setpoints are presented in Table II and III respectively, note that these are step signals.

2-FCR Activation: This scenario allows to visualize how the HyPP saves power capacity at the PCC in order to apply both positive and negative FCR. This is done under different grid frequency regimes. Table IV present the available power for both WF and PV. Then, Tables V and VI present the active and reactive power setpoints for the HyPP. While Tables VII to IX present the offset, positive, and negative FCR signals for the battery. Note that the offset signal is used as active power setpoint for either charging (negative) or discharging (positive).

B. Results

The results for Scenario 1 are presented in Figure 3. In the top row can be seen how the plant follows perfectly the reference signals for both active an reactive power. It should be noted how from second 1100 there is a reduction in active power production. This is due to the apparent power limitation of 50 MVA in the PCC, since the reactive power setpoint is prioritized over the active power as it accounts for technical restrictions during normal operation. Subsequently, in the second and third rows of the same picture it can be seen how the WF drives the reactive power production, even when it causes active power curtailment. It is only from second 1300 to 1400 that the PV needs to curtail as well in order to serve the required reactive power; which is still supplied by the WF.

The analysis of results of Scenario 2 is a little bit more complicated. Let's start from Figure 4c-f, which depicts the active and reactive power behavior of the HyPP in the PCC. There it can be seen how both WF and SF follow correctly the setpoint signal (yellow) unless there is not enough available power (blue). Then, in Figure 5, the behavior of the ESS is presented. It can be seen how the setpoints related to FCR provision (both positive and negative) and offset are perfectly followed. This causes the SOC to modify accordingly. Lastly, looking back to Figure 4a, now it can be easily checked how the magenta line corresponds to the combined action of the measured signal in Figures 4c, 4e and 5b.

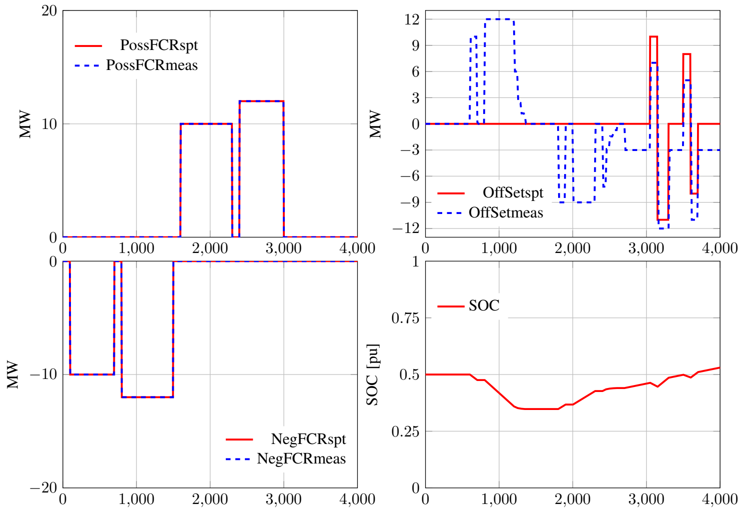

Fig. 5: Results of Scenario 2 – Battery Behaviour.

C. *Discussion*

The presented results represent a proof of concept of the HyPPC and its most important characteristics. The simulations show no steady state error and the only undesired oscillations are related to unrealistic setpoint transitions (as these plants are never operated so harshly). Additionally, another source for this oscillations are the plant's models and controllers, which have been recreated based on the brief descriptions provided by the manufacturers. Therefore, those excessive oscillations are not expected during field deployment. On the other hand, during deployment, there could be different source of noise and oscillations, like the measuring equipment, which are mitigated by using different filtering techniques.

VII. CONCLUSIONS

Current trends support the development of Hybrid Power Plants as the new active player in the energy transition. Given the current leading position of Vattenfall as green electricity producer it is crucial to stay ahead of the competition. The development of the HyPPC resulted challenging at first, but the platform's potential is outstanding, given its modularity.

In this paper, the particular case of Haringvliet has been presented, first, by discussing the plant's topology and business case. Then, the objectives, architecture, and expected future development of the HyPPC was presented along with the tools employed. Subsequently, a brief summary of the project's evolution was introduced. Followed by a case study focusing on two different scenarios: P-Q setpoint following, and FCR activation. This was used to demonstrate the main functionalities of the HyPPC in the case of a plant compound by WF, PVP and ESS such as Haringvliet. Without a doubt, the simulation results fulfil all requirements. We were hoping to present field results in this paper, however, due to the constant COVID-19 related delays, it has not been possible. Current plans for the HyPPC platform include integration of hydrogen production via electrolyzer, hydro, etc.

REFERENCES

[1] R. Hasan, S. Mekhilef, M. Seyedmahmoudian, B. Horan, and J. Jana, "Ren 21.(2017). renewables 2017: Global status report," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 1065–1080.

[2] M. Voogt, M. Boots, G. Schaeffer, and J. Martens, "Renewable electricity in a liberalised market–the concept of green certificates," *Energy & Environment*, vol. 11, no. 1, pp. 65–79, 2000.

[3] ENTSO-E, "High penetration of power electronic interfaced power sources," ENTSO-E, Tech. Rep., 2017.

[4] ENTSO-E, "Network code on load-frequency control and reserves," ENTSO-E, Tech. Rep., 2013.

[5] D. Vázquez Pombo, F. Iov, and D.-I. Stroe, "A novel control architecture for hybrid power plants to provide coordinated frequency reserves," *Energies*, vol. 12, no. 5, p. 919, 2019.

[6] P. Christensen, G. K. Andersen, M. Seidel, S. Bolik, S. Engelken, T. Knueppel, A. Krontiris, K. Wuerflinger, T. Bülo, J. Jahn *et al.*, "High penetration of power electronic interfaced power sources and the potential contribution of grid forming converters," 2020.

[7] C. Ionita, A. Raducu, and N. F. Styliaris, "Optimal provision of frequency containment reserve with hybrid power plants," in *17th Integration Workshop, Stockholm*, 2018.

[8] V. AS. (2020) What we do – our energy sources – wind power – wind energy – wind farms. [Online]. Available: https://group.vattenfall.com/what-we-do/our-energy-sources/wind-power

[9] A. G. Raducu, N. Styliaras, J. Funkquist, C. Ionita, and V. Ab, "Design and implementation of a hybrid power plant controller," in *Proceedings of the 3rd International Hybrid Power Systems Workshop, Tenerife, Spain*, 2018, pp. 8–9.

[10] C. Ionita, A. G. Raducu, N. Styliaras, and J. Funkquist, "Online optimization and control for renewable hybrid power plants."

[11] L. Petersen, F. Iov, and G. C. Tarnowski, "A model-based design approach for stability assessment, control tuning and verification in off-grid hybrid power plants," *Energies*, vol. 13, no. 1, p. 49, 2020.

[12] H. Li, P. Liu, S. Guo, B. Ming, L. Cheng, and Z. Yang, "Long-term complementary operation of a large-scale hydro-photovoltaic hybrid power plant using explicit stochastic optimization," *Applied Energy*, vol. 238, pp. 863–875, 2019.

[13] V. AS. (2020) Vattenfall's largest hybrid energy park is taking shape in the netherlands. [Online]. Available: shorturl.at/quIO8

[14] ACM-Tennet. (2020) "netcode elektriciteit," (in dutch). [Online]. Available: https://wetten.overheid.nl/BWBR0037940/2020-01-01

[15] V. AB, "Prinses alexia windpark," 2020. [Online]. Available: https://powerplants.vattenfall.com/prinses-alexia/