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WP8 intermediate progress report: software development and experimental results of multi-services demonstration following local tests

D8.3

EU-SysFlex

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AUTHOR (S)	Ye Wang (EDF), Victor Gomes (ENERCON), Antoine Breton (EDF), Claire Stefanelli (EDF), Héloise Baraffe (EDF), Lukas Holicki (ENERCON), Marcus Letzel (ENERCON), Ismet Zenuni (EDF), Bettina Lenz (ENERCON), Brice Youemto (ENERCON), Nikola Stankovic (EDF), Cristian Jécu (EDF)

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PARTNER	APPROVER
EDF	Marie-Ann Evans (Technical Manager)
EirGrid	John Lowry (Project Coordinator), upon PMB review

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ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
BESS	Battery Energy Storage System
BCS	Battery Control System
CG	Concept Grid
DC	Direct Current
DER	Distributed Energy Resources
DSO	Distribution System Operator
EDF	Electricité de France
EMS	Energy Management System
E-SCU	E-Storage Control Unit
EU-SYSFLEX	Pan-European System with an efficient coordinated use of flexibilities for the integration of a large share of Renewable Energy Sources (RES)
FACTS	Flexible Alternative Current Transmission System
FCR	Frequency Containment Reserve
FCU	Farm Control Unit
FFR	Fast Frequency Response
FRR	Frequency Restoration Reserve
GED	Grid Edge Device
ICT	Information and Communications Technology
IED	Intelligent Electronic Devices
KPI	Key Performance Indicators
LV	Low Voltage
MILP	Mixed Integer Linear Programming
MV	Medium Voltage
PHIL	Power-Hardware-In-the-Loop
PMB	Project Management Board
PoC	Point of Connection
PV	Photovoltaic
RES	Renewable Energy Sources
RRC	Ramp Rate Control
RT	Real-time
SCADA	Supervisory Control And Data Acquisition
SO	System Operator
SoC	State of Charge
STC	Short-Term Control
TSO	Transmission System Operator
VPP	Virtual Power Plant
VRG	Variable Renewable Generation
WF	Wind Farm
WP	Work Package

EXECUTIVE SUMMARY

In the context of the energy transition, the changes it imposes on European power systems and the consequent increase in flexibility requirements, an aggregation approach based on the concept of Virtual Power Plant (VPP) has been proposed in the Work Package (WP) 8 demonstration of EU-SysFlex H2020 project. This VPP aggregates a portfolio of decentralized assets, including wind and PV generation, a battery energy storage system as well as controllable loads, in order to provide not only energy but also ancillary services to the power system, such as frequency and voltage regulations as well as other flexibility solutions. Its approach is also innovative in the way that it can procure several services at the same time, which is technically possible and economically interesting, and from different controllable resources within the VPP including variable renewable generation, in a so called “multi-resources multi-services” concept.

Since the publication of D8.1 report in 2018 and according to the specifications defined in detail in this report, EDF and ENERCON, as the two partners involved in this work package, have worked jointly to prepare the set-up of the WP8 demonstration in 2019. They successfully implemented several hardware, software and a part of the ICT (Information and Communications Technology) infrastructure for the operation of the VPP. **In 2020, the WP8 team has focused on enhancing the functions of the EMS** (Energy Management System), which is the ‘brain’ of the VPP, **as well as on verifying the good operation of different services provision by individual resources through local experimentations**. The French demonstration work has globally well progressed in the past year thanks to the great effort and efficient cooperation made by EDF and ENERCON, despite the context of COVID-19 sanitary crisis which has led to repeated difficult working and test conditions.

Regarding the software development, a first release of an operational version of the EMS providing both day-ahead / intraday schedules and short-term program adjustment capacities was proposed in 2019. This first version could manage power flows of three resources: a BESS (Battery Energy Storage System), a wind farm and a PV (photovoltaic) farm. Based on either a deterministic or a stochastic approach, it allowed to perform VPP scheduling optimization for the provision of two services, which are:

- the energy arbitrage using all the resources, through day-ahead and ex post facto energy purchases/sales;
- a symmetrical FCR (Frequency Containment Reserve), provided by the BESS only.

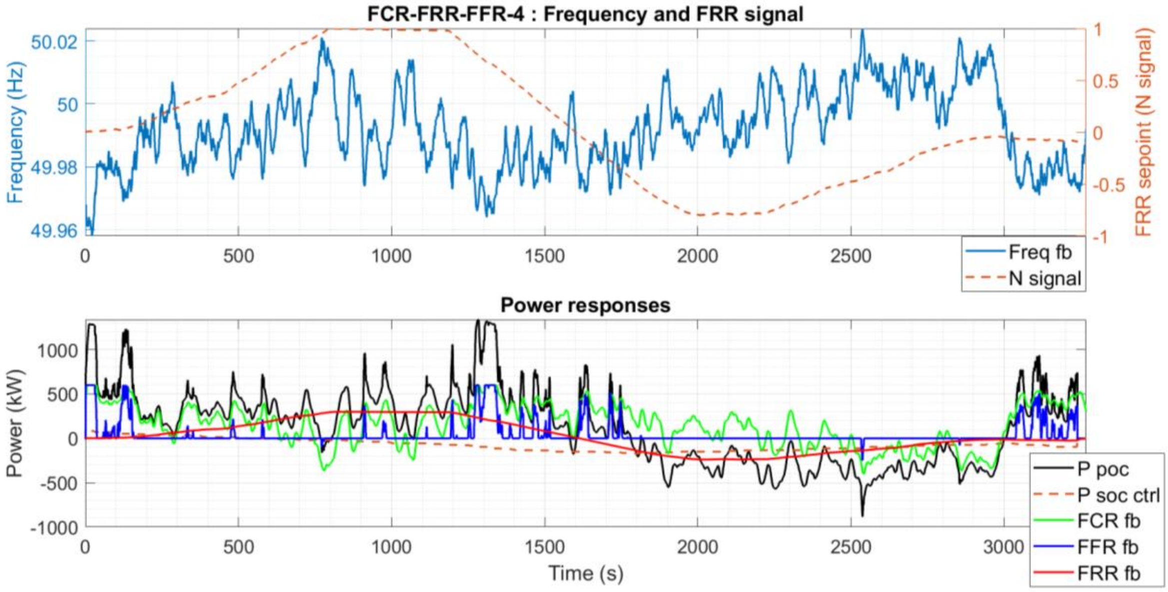
Since then, the performance of the operational planning scheduler has improved with the support of a large number of offline simulations performed on a specifically developed VPP simulation platform. **The first update made in 2020 was to take into account the SoC** (State of Charge) **deviations of the BESS, while providing FCR, in the modelling of uncertainties**, in addition to probabilistic PV and wind generation scenarios. In order to enhance the stochastic programming, SoC deviation scenarios were randomly generated by using the simulation results of a BESS, providing different quantities of FCR in response to 1-second time series of registered real grid frequency. However, the first simulation results showed some limitations of the scenarios generated with respect to the uncertainty that was expected to be modelled. The problem came mainly from the ability to only take into account a small number of SoC deviation scenarios due to limited computation capacity of the current version of

the scheduler, which seemed insufficient to represent correctly the stochastics of the SoC while the storage is providing the FCR service.

Another important update of the operational planning scheduler concerns the modelling of the frequency containment reserve provided by wind generation, in addition to the FCR provision by storage. The wind FCR was modelled in the way that the allocation of upward reserve would lead to curtailment of wind power, whereas the constitution of downward reserve would not necessarily change the wind generation output. The total FCR of the VPP is modelled to be symmetrical or asymmetrical depending on user-defined parameters and corresponds, at all times, to the amount of reserve defined by the services schedule. However, the distribution of FCR between the wind farm and the BESS is not always equal. The optimal allocation depends on the wind generation forecasts at different timescales as well as on the availability of the storage, and can be modified following the intraday rescheduling.

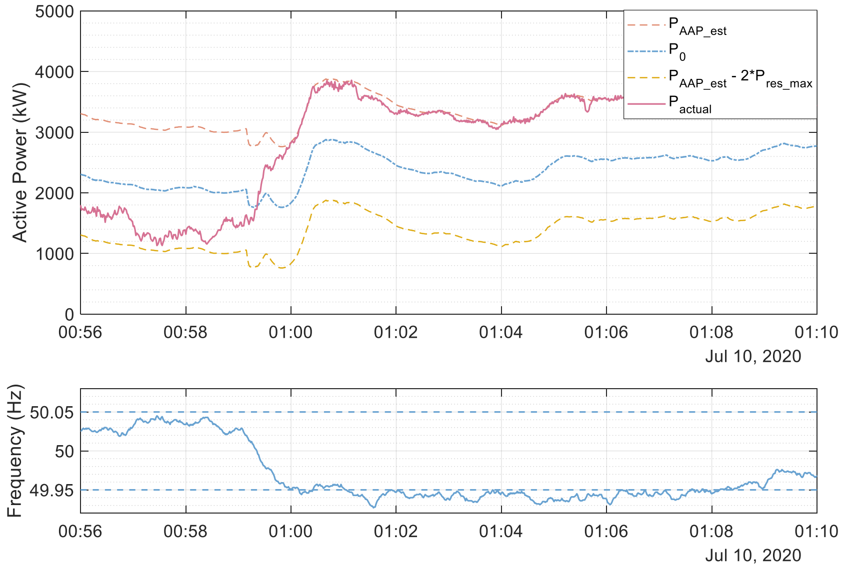
Besides the software updates, experiments of services provision in real conditions were also started in 2020. Indeed, before demonstrating the full-chain operation of the whole VPP, it is essential to first test and to verify the individual services provision by each controllable resource within the VPP. Therefore several tests were carried out on the BESS by activating different services through the real-time storage controller E-SCU (E-Storage Control Unit), as well as on the wind farm by activating FCR provision through the on-site wind controller FCU (Farm Control Unit). These real-time tests were performed locally as a first step, with very limited interactions with the top layers of the centralized EMS of the VPP comprising day-ahead and intraday optimization processes.

Local experiments on the services of the storage were performed by using a specifically built testing platform implemented in the real-time simulator of EDF Concept Grid. Following the successful trials of some basic scenarios (manual mode and state of charge control), several active power services including FCR, FFR (Fast Frequency Response), FRR (Frequency Restoration Reserve) and RRC (Ramp Rate Control) were first activated individually to verify their good operation, and then simultaneously to demonstrate the multi-services provision scheme. As illustrated by the following figure, the storage responded correctly to the services activation signals (grid frequency measured and historical N-signal of FRR) and effectively provided different ancillary services according to the pre-set control parameters. **The obtained experimental results were very satisfactory and showed good performance of various services offered by the storage system within the French VPP**, compared to the requirements that would be demanded by system operators.



The similar approach of local tests was also applied to the Anglure wind farm so as to assess to what extent wind generators can provide FCR and to evaluate the performance of this service when it is offered by non-conventional and variable generation. The wind reserve constitution was first investigated and it was revealed that the **ability of estimating in real time the maximum available active power,** or the so-called wind AAP, **is essential to allow wind FCR provision**. Depending on the wind speed and/or pitch angle, two different methods were used during the tests to enable wind AAP estimation throughout the whole operating zone of a turbine. The combination of both methods can ensure a relatively good accuracy of AAP estimation for FCR provision according to both empirical and operational experiences.

Experiments of tens of hours were performed in the 12-MW Anglure wind farm in order to verify the quality of FCR provision. An extract of the experimental results from one of the complete tests, shown in the following figure, clearly demonstrates the capability of the tested wind farm to deliver downward and upward power reserve around its baseline operating point (which can be defined while knowing the estimated available wind power without reserve provision), when the grid frequency goes respectively higher and lower than the reference value of 50 Hz.



More generally, the obtained results show that **although wind generation is of variable nature, it is technically capable of providing effective FCR service** when equipped with a dedicated AAP estimator and an FCR controller. Furthermore, the knowledge of the estimated AAP makes it possible to monitor the performance of wind FCR response in a continuous manner during the operational phase, through the assessment of the FCR gain. The analyses show that **the actual wind FCR performance is globally compliant with the current TSO's requirements in terms of dynamics and gain**, although over-estimation of wind AAP could lead to occasional under-performance. It should also be noted that the quality of wind FCR provision would be further enhanced when the service is provided by a large-scale wind generation fleet or a system-sized virtual power plant.

As the final year of the French demonstration, 2021 will be essential to complete the expected simulations and experiments as defined in the WP8 specifications. Regarding the development perspectives, one of the most important targets in the next months will be to fully implement and commission the whole ICT infrastructure of the VPP, allowing a remote control of all the distributed resources from the EMS, thus enabling the operation of the full-chain VPP. Additional local tests will also need to be performed, especially to evaluate the provision of voltage control services. In parallel, further developments of software will be carried out by means of simulations over long durations, to improve the performance of the developed algorithms and to enhance the functions of the VPP's EMS. Last but not least, it is expected to assess the KPIs (Key Performance Indicators) of the French demonstration based on experimental and simulation results of the full VPP operation, as well as to provide useful technical inputs and key messages for the development of the EU-SysFlex flexibility roadmap.

1. DESCRIPTION OF THE WP8 DEMONSTRATION

1.1 BACKGROUND

In the context of operating power systems with high penetration rates of variable renewables, higher reserve and new flexibility requirement would be necessary to ensure power system security and reliability [1]. The provision of ancillary services – so far mainly supplied by conventional synchronous units – could also be required for VRG (Variable Renewable Generation) connection or supplied by storage [2]. These decentralized resources can technically provide various services including voltage and frequency regulations. However, when offered individually, they mobilize only a part of the whole power/energy capacities of the resource and do not generate enough revenue to reach profitability. Besides, as resources have their own operational limits (e.g., wind/PV generation depends on the local weather conditions, and maximum charge/discharge of a battery on its current state of charge), they are generally not available at the same time to provide a given service.

In this context, an aggregation approach based on the concept of **Virtual Power Plant (VPP)** has been proposed in the Work Package 8 (WP8) demonstration of EU-SysFlex H2020 project, which aims at developing and experimenting an innovative **multi-services, multi-resources control approach**. From a local point of view, it is expected to enhance the performance and reliability of the services procured from the VPP and to help increase the economic gain for the VPP's operation thanks to additional revenue streams, from one or, more likely, from several levels of the electricity value chain. The partners involved in this demonstration are EDF R&D, including several research teams, and ENERCON, with also several branches cooperating for the needs of the demonstration work.

The main objectives of the WP8 demonstration are to:

- **demonstrate the technical feasibility** of performing optimal management and coordinated control of the multi-resources aggregator to provide multi-services to the power system;
- **assess the performances of different services and flexibility solutions** that can be procured from the aggregator by considering the grid codes' requirement.

1.2 MAIN COMPONENTS AND SERVICES PROVISION

The main facilities and testing means for the demonstration are shown in Figure 1. The portfolio of resources comprises a 12-MW wind farm, a 2MW/3MWh lithium-ion BESS (Battery Energy Storage System), photovoltaic panels and a variable load test bench, combined with power amplifiers and a real-time (RT) simulation platform. The demonstrator is mainly implemented at EDF privately owned Concept Grid (CG), with the exception of the wind farm being at a location of 150 km away, and connected to the French public distribution grid.

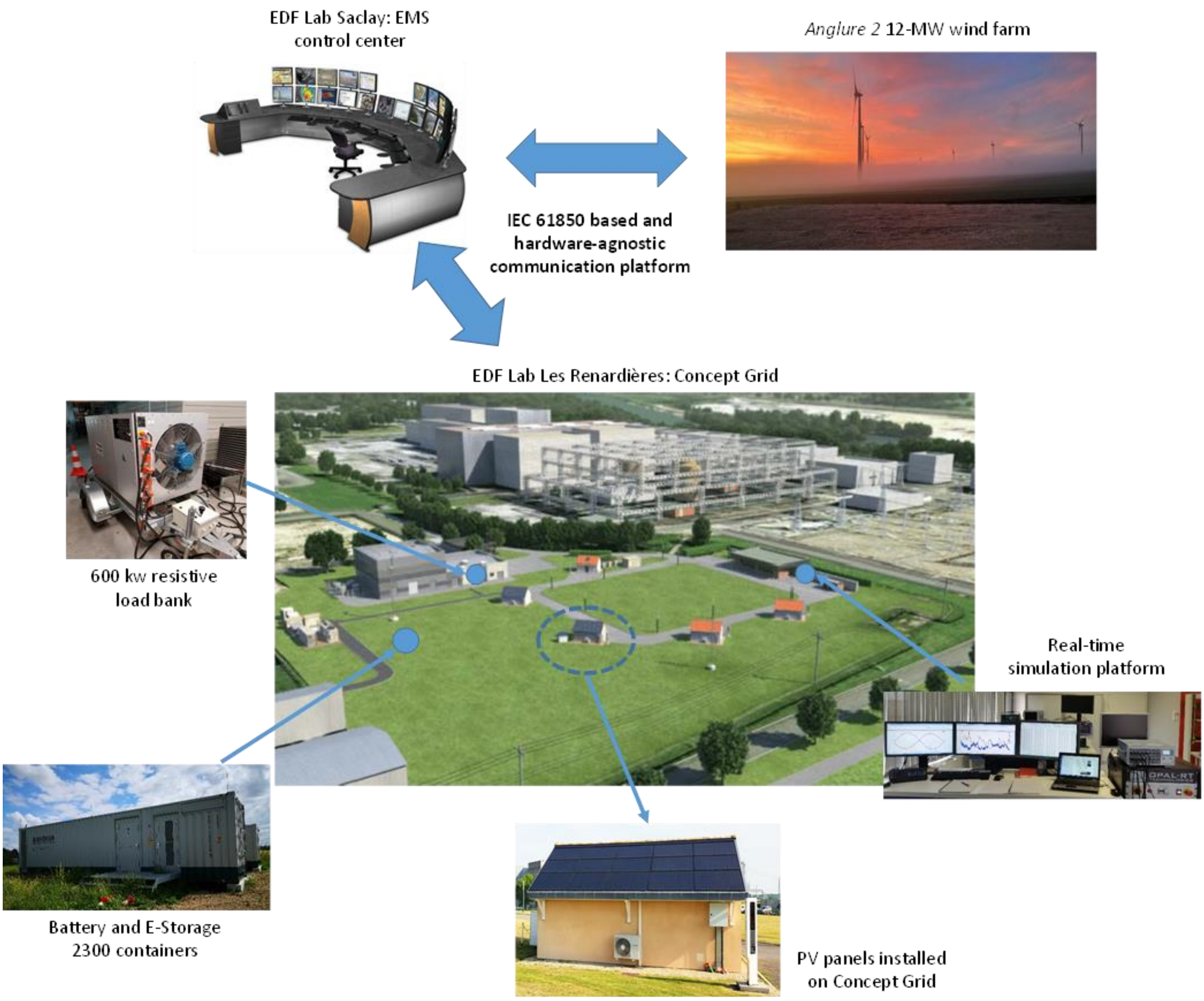


FIGURE 1. MEANS AND FACILITIES OF THE MULTI-RESOURCES MULTI-SERVICES DEMONSTRATION

Concept Grid

Concept Grid has been set up by EDF R&D in the site of Les Renardières south-east of Paris. It was developed to study the integration of renewable energy resources (RES) in the electric system as well as new uses such as electric vehicles or heat pumps [3]. Fed by a fully dedicated 63/20 kV transformer, Concept Grid includes 3 km of MV (Medium Voltage) network (overhead lines, underground cables) supplying 7 km of LV (Low Voltage) network. One of the goals is to replicate the real conditions of an electric system operation. Representativeness is also brought by a residential neighbourhood of five 20 m² houses, fitted with state-of-the-art equipment: smart meters, remote controlled household appliances, reversible heat pumps, PV panels, terminal for electric vehicles, etc. Concept Grid is designed to take place half-way between laboratory tests and experiments in the field, where it is possible to conduct, in complete safety, complex testing campaigns that would be difficult to be performed in a real system.

For the demonstration purpose, the equipped kW-size PV panels as well as the resistive load banks will be used to emulate respectively the generation of a real MW-size PV farm and the behaviour of an industrial load, through a powerful four-quadrant amplifier (120 kVA source / 60 kVA load) coupled with a real-time (RT) simulation platform. RT simulation is a complementary tool to conventional offline simulation programs for power system studies [4]. With much more computational power, real-time simulators are able to simulate very complex and large models in real-time or faster [5]. Moreover, with this infrastructure, step-by-step power-hardware-in-the-loop (PHIL) experiments[1] from fully simulated demonstration platform to fully real-life tests can be performed. This approach allows fast and secure development of models as well as controllers, and de-risks as much as possible the entire control system thus minimizes the costs.

Anglure wind farm

For the purpose of demonstration, ENERCON will make available the owned wind farm *Anglure 2*, located in the department of "Marne", in the community of Saron-Sur-Aube, about 120 km south-east of Paris. Commissioned in September 2015, *Anglure 2* is generating 30 000 MWh/year and comprises 6 x 2000-kW turbine of type E82 for a total installed power of 12 MW. Each wind turbine is based on a full converter technology with FACTS (Flexible Alternative Current Transmission System), which is a suitable solution for integration into the grid.

An enhanced wind farm (WF) control unit dedicated to providing grid services has been developed and equipped, allowing much faster response time of the WF while keeping the capability of responding to the eventual requests from the French Distribution System Operator (DSO) ENEDIS (e.g. active power curtailment, WF disconnection, etc.) through a dedicated communication interface [6].

Battery storage – E-Storage 2300

A full storage system including a 2MW/3MWh lithium-ion battery based on graphite-NMC as well as a newly developed ENERCON E-Storage 2300 power conversion system have been installed at EDF CG and used for the EU-SysFlex demonstration. The Li-Ion-battery is located in a 45-foot container, consisting of 42 racks. Based on proven ENERCON power components, the E-Storage 2300 consists of a bidirectional inverter within a 40-foot container and serves as an intelligent interface technology for DC-batteries of all kind. Together with a battery and an ENERCON controller, the E-STORAGE 2300 can provide system services – such as frequency controls and ramp rate reduction of active power variations from wind farms.

Services provision

The services that can be procured from the VPP are well aligned with the power system scarcities at high RES (Renewable Energy Sources) penetration rates, in terms of future needs of ancillary services, as well as additional requirements on flexibilities
[7]. These services are classified into 4 categories as summarized in Table 1[2].

[1] This concept means that part of a model or a system is simulated in real time and connected to real power devices through sensors and amplifiers.
[2] Detailed description of each service as well as their operating principles can be found in Chapter 1 of D8.1 report of EU-SysFlex project [9].

Categories	Services
Frequency support services	Fast Frequency Response (FFR)
	Frequency Containment Reserve (FCR)
	Frequency Restoration Reserve (FRR)
Flexibility solutions	Ramp-rate control
	Peak shaving
Reactive power services	Local voltage support
	Dynamic reactive response
Energy arbitrage as an aggregator	

TABLE 1. SERVICES PROVIDED BY THE WP8 MULTI-RESOURCES VPP

1.3 OPERATING PRINCIPLE AND ARCHITECTURE

As presented in detail in the previous report [9], to operate the demonstrator composed of multi-resources of different nature as a whole and to ensure the optimal coordination of multi-services provision, centralized control functions need to be built, including renewable generation forecasting tools as well as the Energy Management System (EMS) providing both day-ahead / intraday schedules and short-term program adjustment capacities. An advanced communication infrastructure also needs to be implemented to ensure fast, accurate and reliable information and data exchange between the EMS and each of the assets.

1.3.1 OPERATING PRINCIPLE AND CONTROL LAYERS

The operation of the demonstrator is achieved using a dedicated three-level supervisory control as illustrated in Figure 2.

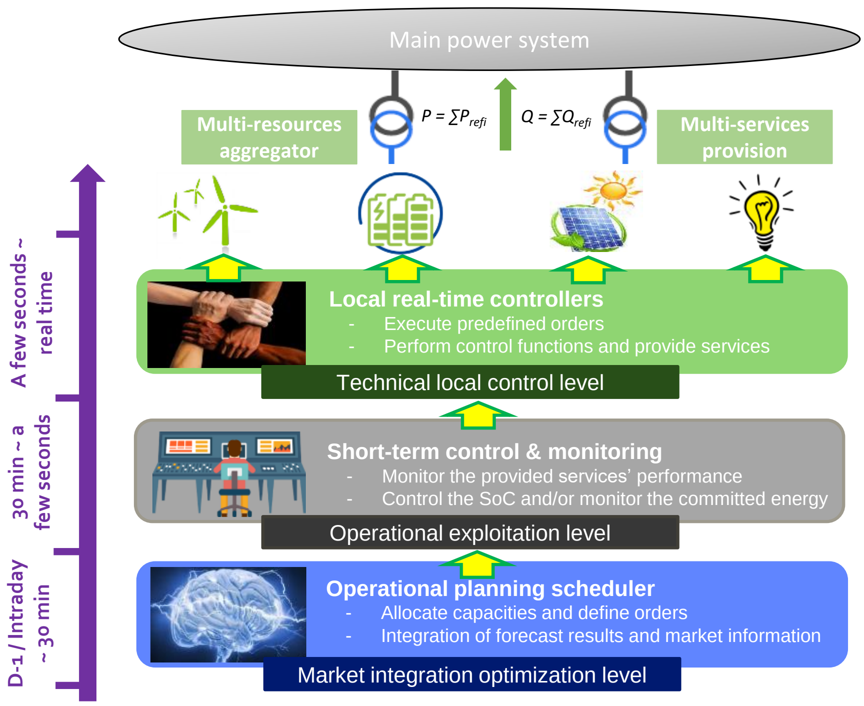


FIGURE 2. GENERAL CONTROL LAYERS OF THE WP8 DEMONSTRATION

First, a remote supervision will perform day-ahead scheduling of generation planning and services allocation to maximize profitability while satisfying different constraints (e.g., battery state of charge) and requests from the system operators. This function is performed through the layer of "operational planning scheduler" with a time resolution of 30 minutes or 15 minutes. It also performs intraday rescheduling of the operating programs in order to limit the impact of the deviations due notably to renewable generation forecasting errors.

Secondly, the layer of Short-Term Control (STC) is necessary to ensure the continuous and correct operation of the VPP by handling unexpected program deviations, or unsatisfying performance of the provided services. It will take appropriate actions within each scheduling time step to achieve, to the extent possible, the following goals: 1/ to control the state of charge (SoC) of the BESS according to the expected SoC reference at the end of each time step, which can be predefined by the scheduler allowing to optimize the use of the storage in the next scheduling time steps; 2/ to guarantee, , the energy engaged by the VPP in each time step to be sold in the energy market; 3/ to monitor, in accordance with the requirement of system operators (SO), the performance of the VPP in regard to the services that are being provided. The operational planning scheduler, together with the short-term control layer, constitutes the EMS (Energy Management System) of the VPP, which is the "brain" controlling and monitoring the operation of the whole system.

Ultimately, local controllers of each resource will autonomously manage the execution of the services allocated by the EMS and send active and reactive power references to the resources, according to local measurement such as frequency and voltage. This level of control will react in real time and generate power references for each asset according to the physical laws of the different services that are generally specified in grid codes by SO.

1.3.2 COMMUNICATION INFRASTRUCTURE AND INTERFACES

To ensure the communication within different control layers and assets, an IEC 61850-based and hardware-agnostic communication platform developed by EDF is used in this demonstration. This platform presents several advantages, such as the flexibility to manage the software, firmware and configurations on remote devices (e.g.: Intelligent Electronic Devices (IED) or grid edge devices (GED)) with an increased level of cybersecurity. Another important aspect is the evolutivity of the proposed platform since the evolutions of its software and hardware are mostly independent. This aspect allows to enhance the management of an increasing number of devices being deployed on the field for automation and of Distributed Energy Resources (DER) on all voltage levels. Furthermore, the developed software and platform are based on IEC core standards (such as IEC 61850, IEC 62351 and IEC CIM), which helps to improve the interoperability and replicability of the demonstrated solutions.

The overall communication architecture of the demonstration was first specified in 2018 [8] [9], then updated and adapted in 2019 to better consider the hardware constraints and demonstration needs [10]. As shown in Figure 3, Grid Edge Devices (GED) are introduced to assure the communication between each DER and the VPP's EMS[3]. This

[3] GED-W stands for the device dedicated to assuring the communication with the wind farm; GED-S with the storage and GED-PL with loads and PV.

solution allows the interaction with a wide range of DER using different protocols with advanced functions integrated, such as sending measurements, receiving control signals, managing alarms, storing information for a short period, giving priority to the orders provided by system operators, etc. The proposed architecture therefore intended to represent a real and global environment that can be used by a larger industrial-scale VPP to manage several resources.

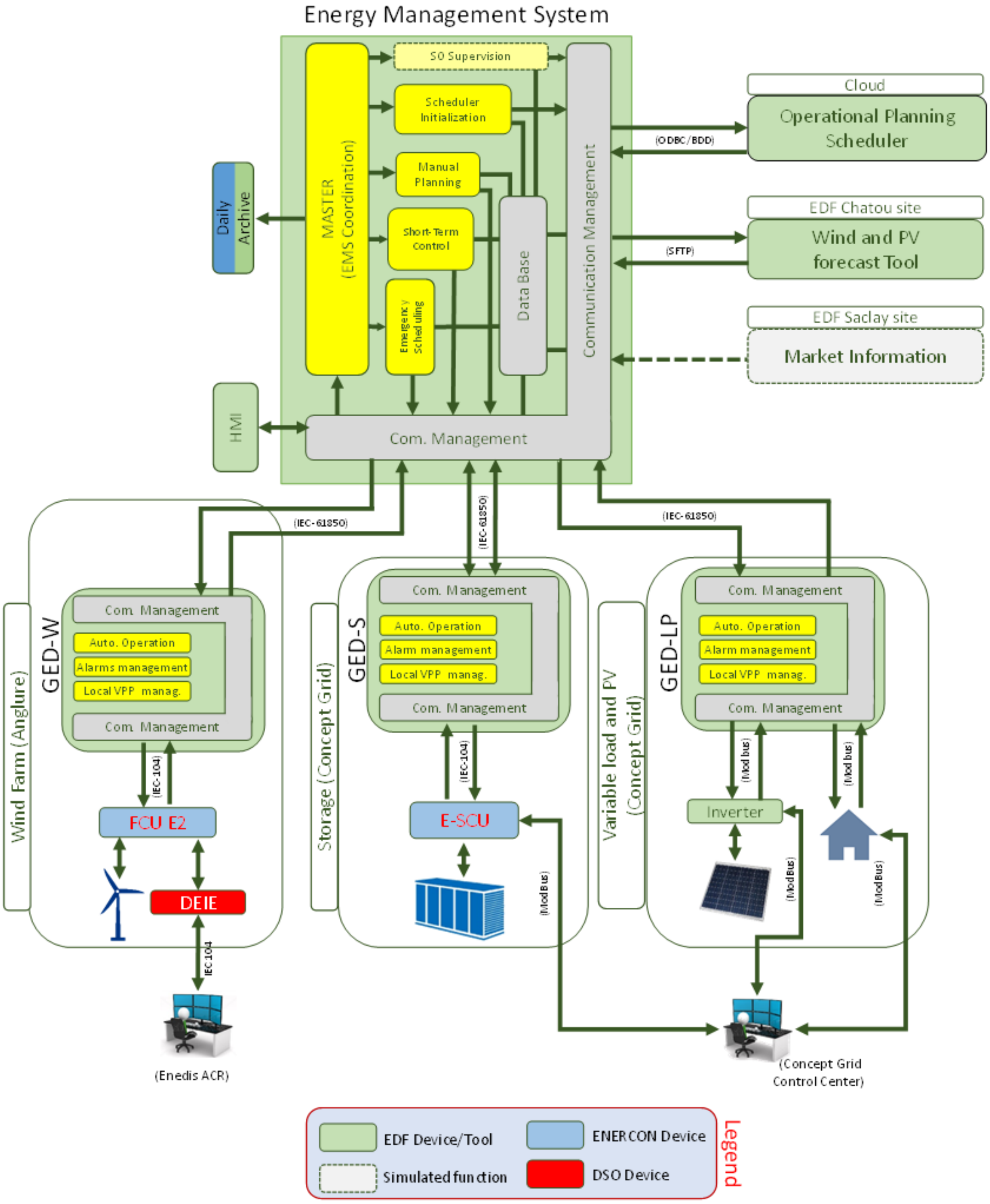


FIGURE 3. COMMUNICATION ARCHITECTURE OF WP8 DEMONSTRATION

1.4 WP8 REPORTS

An annual feedback report of WP8 is scheduled to be drawn up to present the development progress of the demonstration. D8.1 report published in October 2018 [9] described in detail the technical specifications, the operating principle as well as the system use cases of the WP8 demonstration, which was then set up according to the specifications and on the basis of the innovative approach of “multi-services provision by multi-resources”. D8.2 report published in November 2019 [10] presented the state of progress of the second year’s work in WP8, which mainly focused on the commissioning of the hardware components and several software / control modules, as well as on the implementation of the communication system to integrate DER in the VPP.

As the third annual technical report, the present document gives progress updates on the software and algorithm development of the VPP’s EMS (chapter 2) and presents analyses of some first experimental results obtained by performing local tests on the services provision of individual resources (chapter 3).

2. UPDATES ON THE OPERATIONAL PLANNING SCHEDULER

As mentioned in the previous chapter, the EMS of the aggregator is the “brain” controlling the operation of the VPP, which includes an operational planning scheduler that provides day-ahead / intraday service schedules. This chapter is dedicated to presenting the development progress of the operational planning scheduler.

2.1 OPERATING PRINCIPLE

The operational planning scheduler aims at defining the services to be provided by each resource within the VPP in the coming hours with a fixed sampling interval (e.g., in the following 48-36 hours with a 30-minute interval). More precisely, it determines the sequence of the service setpoints for all the resources and sampling intervals considered. For instance, it defines the upward and downward power reserves of the BESS from 8:00 to 8:30 if it is expected to deliver the FCR service.

The operational schedule of services is designed so as to maximize profitability while satisfying requests from stakeholders (e.g., wind power limitation demanded by the DSO) and a set of constraints (e.g., service parameter ranges, limits of assets, grid issues, regulatory framework, market closure…). To design such a schedule, the scheduler uses at least the following data:

- the wind and PV generation forecasts;
- the services prices forecasts;
- some data measured on the resources such as the state of charge of the BESS;
- a set of parameters provided by the user and related to the services and optimization algorithm considered.

This services schedule can then be updated by the scheduler several times a day, e.g., every 30 minutes, in order to consider the most recent forecasts and measures available.

For the French demonstration, which focuses on the development of technical solutions, some simplified market assumptions have been considered in the configuration of the scheduler. Especially:

- The gate closure time of the day-ahead markets is at 12:00, which means that the day-ahead services’ schedule of the VPP has to be committed by 12:00.
- To satisfy its day-ahead commitments (e.g., overall energy produced/consumed by the VPP, and level of FCR) and/or maximize its full income, the aggregator can adapt its services’ schedule in an intraday basis (e.g., every 30 minutes). Regarding the energy arbitrage, intraday (or ex post facto) energy sales or purchases are indeed possible at extra costs.
- PV and wind generation benefit no longer from specific feed-in tariffs as in today’s case, meaning that the VPP should sell produced energy to the French electricity energy market like conventional power plants.

In other words, **the operational planning scheduler provides**:

- **a generation program and a services’ schedule of the VPP for the next day** when it is run just before 12:00,
- **updates of the generation and service’s schedule** on the very day, running every 30 minutes.

These assumptions are considered to be accepted in the context of WP8 demonstration which is set up at a reduced scale in a dedicated laboratory-size power system. Neither service nor energy provided by the VPP will be sold to the real related markets in France. The objective of the work is to develop tools and software of which the operation can be technically demonstrated, but not to reproduce the exact real environment under strict regulatory and economic constraints. However, replicability and scalability issues are always under consideration to ensure that the developed technical solutions can be replicated in different parts of the system, and at an industrial scale.

2.2 STATE OF DEVELOPMENT

The operational planning scheduler is based on an existing planning software developed entirely by EDF R&D. This software is developed for multi-energy systems in C++ and can be used with different commercial or open-source solvers (e.g., the open-source solver COIN or the commercial solver XPRESS). It was also conceived to ensure that evolutions can be updated quickly.

The software has a graphical user interface, as illustrated in Figure 4, where the user can model the system of which the schedule has to be optimized. The elements of the system can be chosen from a library of various objects (battery, engine, cogeneration, boiler, etc. for different kinds of flows). In addition to this model, the user can provide a configuration file that gives optimization parameters, additional non-physical equations as well as the links between the parameters of the graphical elements and the values stored in a database.

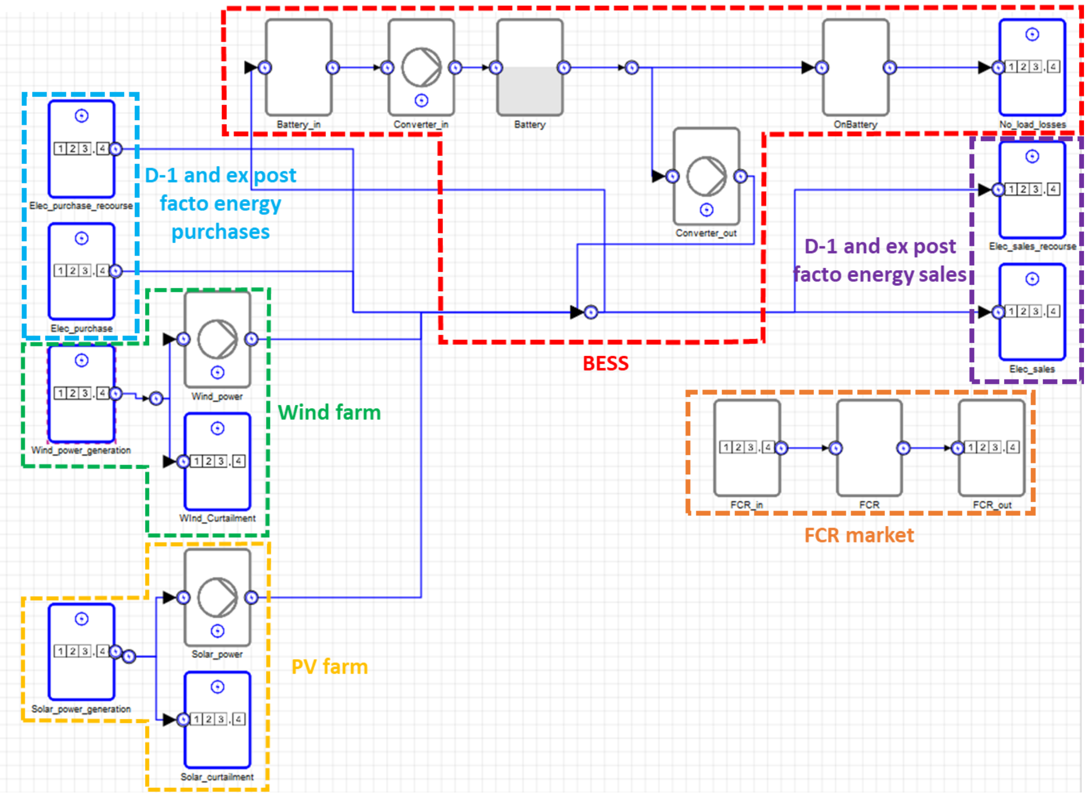


FIGURE 4. BASE MODEL OF THE VPP IN THE SCHEDULER SOFTWARE

Once started, the software writes the equations governing the elements and flows of the graphical model. For example, a battery is characterized by three continuous variables, which are the SoC, the charging and discharging power references, and one binary variable, which is the on/off status. Then, the software gives all the equations to a solver. The optimization method used is Mixed Integer Linear Programming (MILP). It is more efficient than non-linear programming but it implies that all the equations from the optimization problem are linear. For example, the battery losses have to be approximated by linear or piecewise-linear functions. Finally, the optimal solution obtained by the solver is written in a database.

At the beginning of the demonstration project in 2018, only deterministic optimization approaches were possible with the scheduler software. The forecasts of photovoltaic and wind generation could therefore be used in a deterministic way only, meaning that no generation forecast error was considered in the optimization process[4]. As detailed in D8.2 report [10], to overcome the limitations of classical deterministic optimization approaches regarding the modelling of uncertainties, **the operational planning scheduler software was improved in 2019 to enable stochastic optimization using probabilistic PV and wind generation scenarios**. These scenarios were randomly created using two types of data (illustrative examples of scenarios of variable renewable generation are given in Figure 5):

- the quantiles of the probabilistic generation forecasts (from the statistical generation forecasting model), which give information on the generation probability distribution at a given point of time,
- historical data of copula, which describe the dependence between the generation values at different points of time.

[4] More precisely, the generation uncertainty can be partly considered in a deterministic approach by limiting the BESS operation when designing the schedule. For instance, the SoC of the BESS can be planned to remain within a range of 20% to 80%, the unused capacity being used to compensate for forecast errors. Note however that the limits of SoC are set arbitrarily as no proper forecast error model can be considered in deterministic approaches.

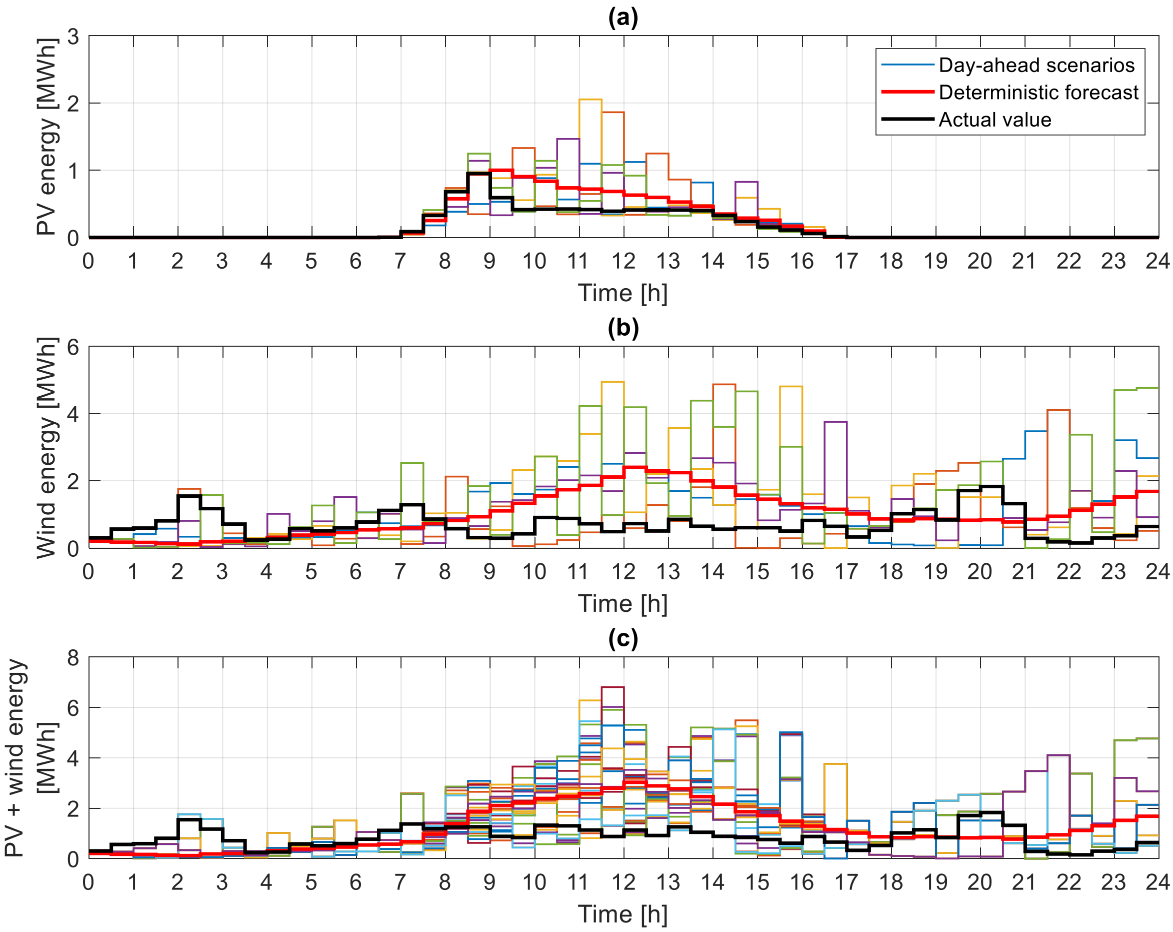


FIGURE 5. EXAMPLES OF STOCHASTIC SCENARIOS GENERATED FROM PROBABILISTIC GENERATION FORECASTS: (A) PV, (B) WIND, (C) PV + WIND

Based on the probabilistic generation scenarios, the optimization solution adopted was to use a two-stage stochastic programming approach:

- The first-stage decision is the VPP's commitment to the day-ahead markets, i.e., the day-ahead energy sales/purchases and the level of FCR. The commitment of the VPP is common to all the scenarios.
- The recourse decisions are the flexibilities of the VPP used to compensate for generation forecast errors, i.e., the BESS power, the curtailed renewable energy and/or the intraday (or ex post facto) energy sales/purchases. The recourse decision is specific to the scenario considered.

For instance, Figure 6 shows the day-ahead results when applying the operational planning scheduler to the stochastic scenarios depicted in Figure 5, in case the VPP performs "energy arbitrage" only:

- the potential overall energy of the VPP (coloured curves in Figure 6(a)), which is composed of: 1/ the day-ahead schedule to be committed (black curve in Figure 6(a)) and 2/ the potential ex post facto energy purchases/sales (gaps between the back curve and the coloured one in Figure 6(a));
- the potential state of charge of the BESS (coloured curves in Figure 6(b)) in different scenarios.

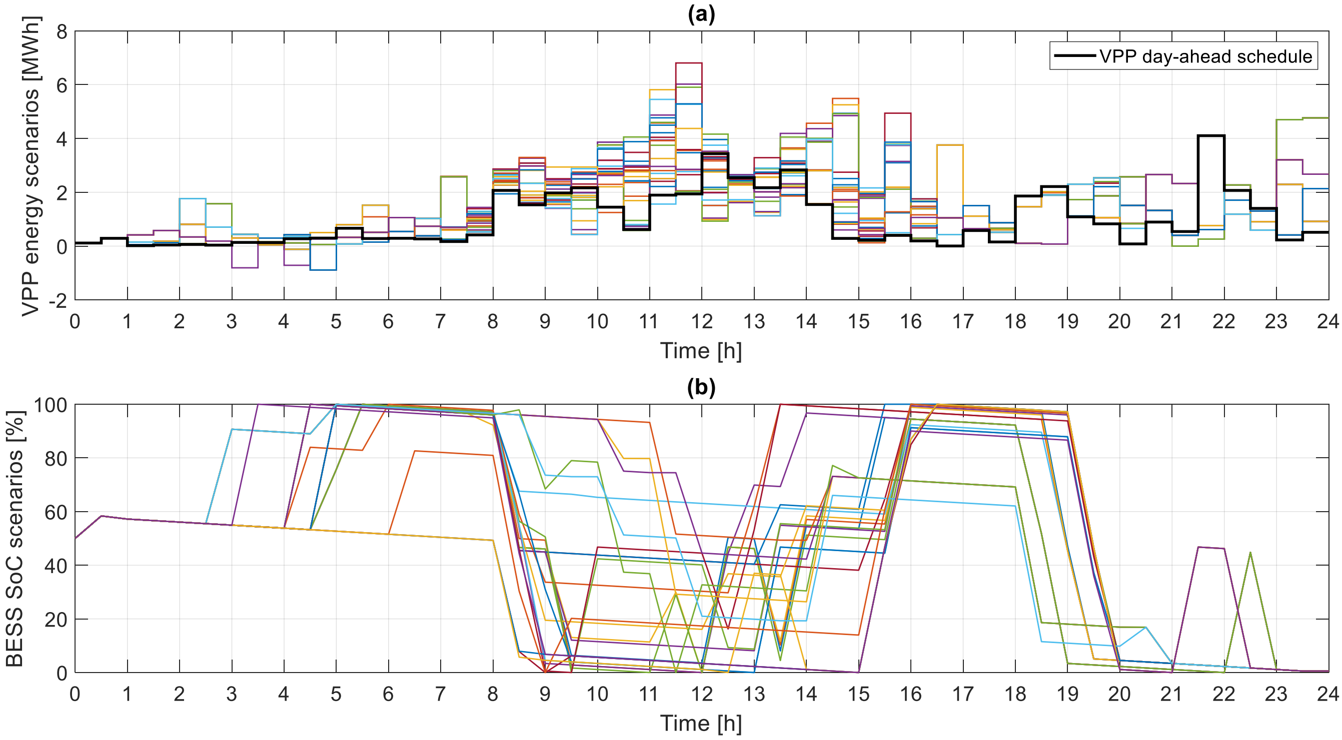


FIGURE 6. DAY-AHEAD SCHEDULE FOR THE VPP TO PROVIDE ENERGY ARBITRAGE WHEN CONSIDERING PROBABILISTIC GENERATION FORECASTS: (A) ASSOCIATED SCENARIOS OF INTRADAY ENERGY PURCHASES/SALES, AND (B) STATE OF CHARGE OF THE BESS

2.3 MODELLING OF SOC DEVIATION SCENARIOS

A first release of the scheduler was developed in 2019 and tested on the offline simulation platform that was especially designed for the EU-SysFlex demonstration [10]. This version of the scheduler could manage power flows of three resources: a BESS, a wind farm and a PV farm. It allowed to perform VPP scheduling optimization for the provision of two services, which are:

- the energy arbitrage using all the resources, through D-1 and ex post facto energy purchases/sales,
- a symmetrical FCR, provided by the BESS only.

The first update performed in 2020 was to take into account the SoC deviations of the BESS while providing FCR. Indeed, the provision of ancillary services (e.g., FCR) causes uncertainties on several electrical quantities such as the SoC, which needs also to be considered in a similar way as other uncertainties like the generation forecast errors. To do this, SoC deviation scenarios were randomly generated by using the simulation results of a BESS providing different quantities of FCR in response to 1-second time series of registered real grid frequency. Figure 7 shows the statistics of SoC deviations after 30 minutes of FCR activation, computed for one year using real frequency data of 2018. The mean and variance of this data was used to sample SoC deviations scenarios.

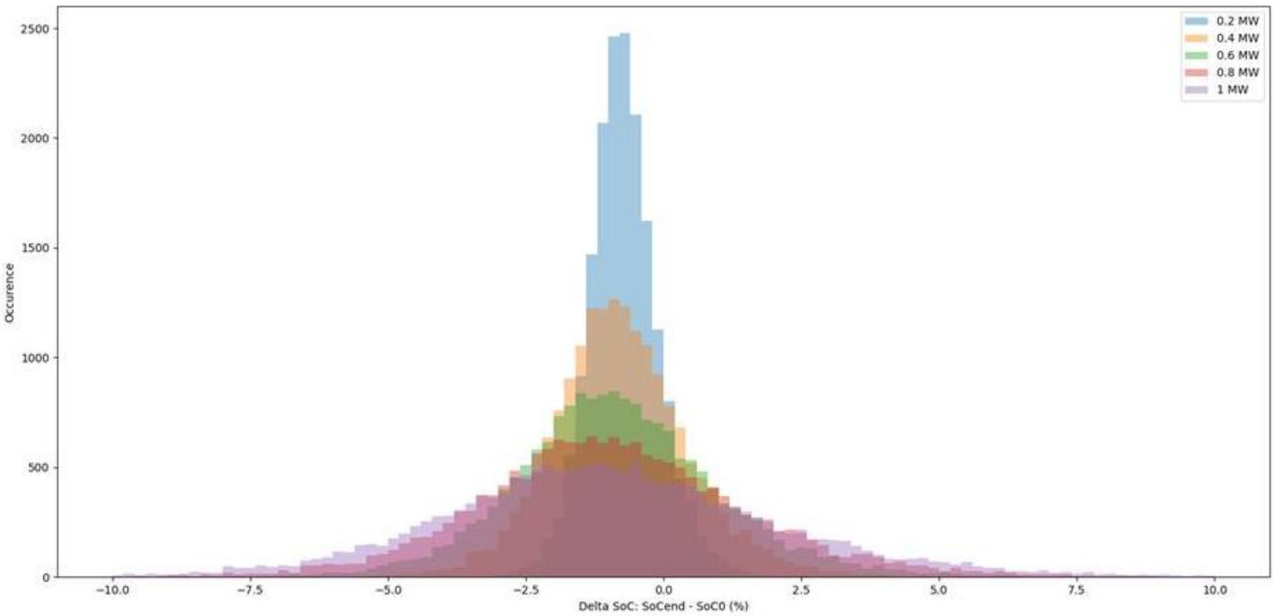


FIGURE 7. HISTOGRAM OF SIMULATED SOC DEVIATIONS AFTER 30 MINUTES OF FCR PROVISION AT DIFFERENT LEVELS

While performing stochastic optimization to generate the VPP's schedules, the probabilistic scenarios of SoC deviation are only activated when FCR is enabled, meaning that the SoC after half an hour of FCR provision will be uncertain and follow one of the possible scenarios. Besides, it is worthy to mention that the efficiency of the proposed stochastic optimisation process strongly depends on the considered scenarios. Especially, the number of scenarios has to be carefully chosen to reach a good trade-off between accuracy and speed.

The first simulation results showed some limitations of the scenarios generated with respect to the uncertainty that was expected to be modelled. Indeed, due to limited computation capacity, only 3 scenarios of SoC deviation can be considered in the current version of the scheduler software in addition to the respective probabilistic wind and PV forecasts scenarios, which is far from being representative to characterize the SoC variations from a statistic point of view. Imagine that at a given time step, if the SoC deviations were all positive in the 3 scenarios chosen, the BESS would be supposed to be charged (by absorbing power) after rendering the FCR service. The scheduler would then consider that the SoC level should be sufficient and 'encourage' the FCR provision by the storage. Nevertheless, in reality the grid frequency could vary in the opposite direction than that was represented by the scenarios considered. In this case, the provision of FCR would rather lead to a power discharge and a decrease in SoC. Thus, the consideration of 'wrong' uncertainties would have made the scheduler take inappropriate decisions.

The problem comes mainly from the ability to only take into account a very limited number of SoC deviation scenarios. One possible corrective solution would be to 'force' one scenario chosen to be in a different direction of variation than the others at each time step.

2.4 MODELLING OF WIND RESERVE

Another important update of the operational planning scheduler in 2020 concerns the modelling of the frequency containment reserve provided by wind generation, in addition to the FCR provision by storage. It was assumed that the VPP should participate in the FCR market as a whole by offering the sum of the quantities of FCR provided by both storage and wind generation. The total FCR of the VPP is modelled to be symmetrical or asymmetrical depending on user-defined parameters. The sum of the frequency containment reserves allocated on the BESS and on the wind farm corresponds, at all times, to the services schedule for the FCR service, however, the distribution between the two assets is not always equal and could be different from the original D-1 planning following an intraday rescheduling.

The wind FCR was modelled in the way that the constitution of upward reserve would lead to curtailment of wind power, whereas the generation of the wind farm would not change while providing downward reserve. In the latter case, the activation of downward FCR will reduce the VPP's energy sales in the SPOT market, compared to the originally planned quantity. Nevertheless, the impact is quite limited, as, in practice, the energy dedicated to FCR should only be a small part of the total wind generation and this sale loss could probably be financially compensated when symmetric FCR is provided by the VPP.

Seen from the scheduler, the volume of FCR that can be allocated on the wind farm depends strongly on the wind power forecasts, which is the absolute maximum power level considered in the scheduling process. To hedge against uncertainty, in addition to the stochasticity, some further rules have been added to model the wind farm FCR:

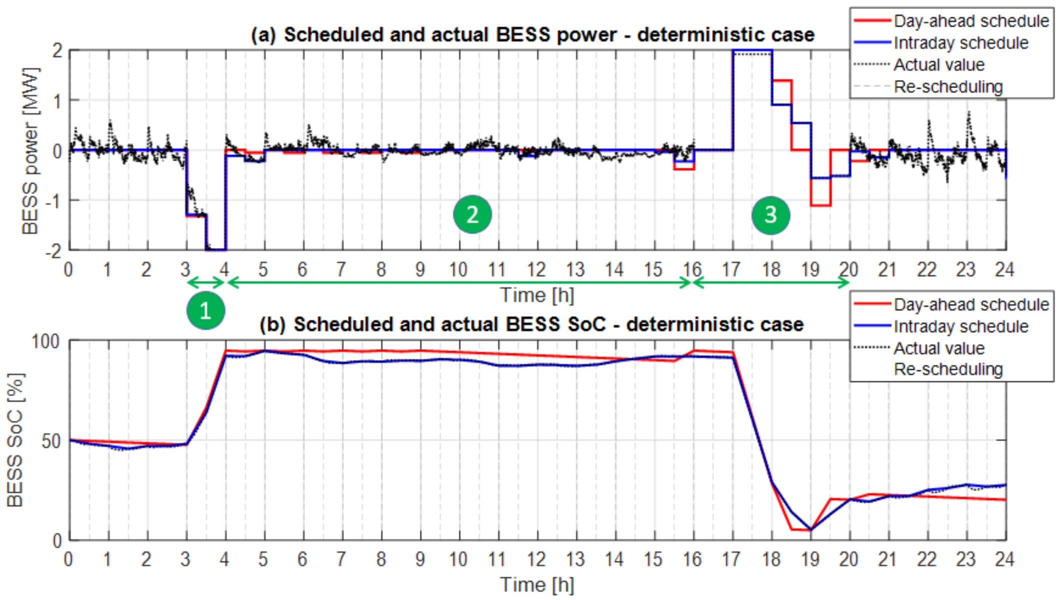
- The maximum level of FCR that can be provided is limited to a percentage of the forecasted wind power, the value of which can be defined by the user according to the requirement of system operators and to the technical capability of the wind farm considered.
- The wind farm is allowed to participate in the FCR market (i.e. the allocation of reserve is enabled) only if the forecasted wind power is higher than a certain minimum value (e.g.: 500 kW).

Furthermore, for some scenarios while applying the stochastic optimization, the possibility to have a total amount of FCR different from the scheduled quantity was allowed, but with a high penalty, to technically ensure that the calculations were 'feasible' even for the worst scenarios from an optimization point of view.

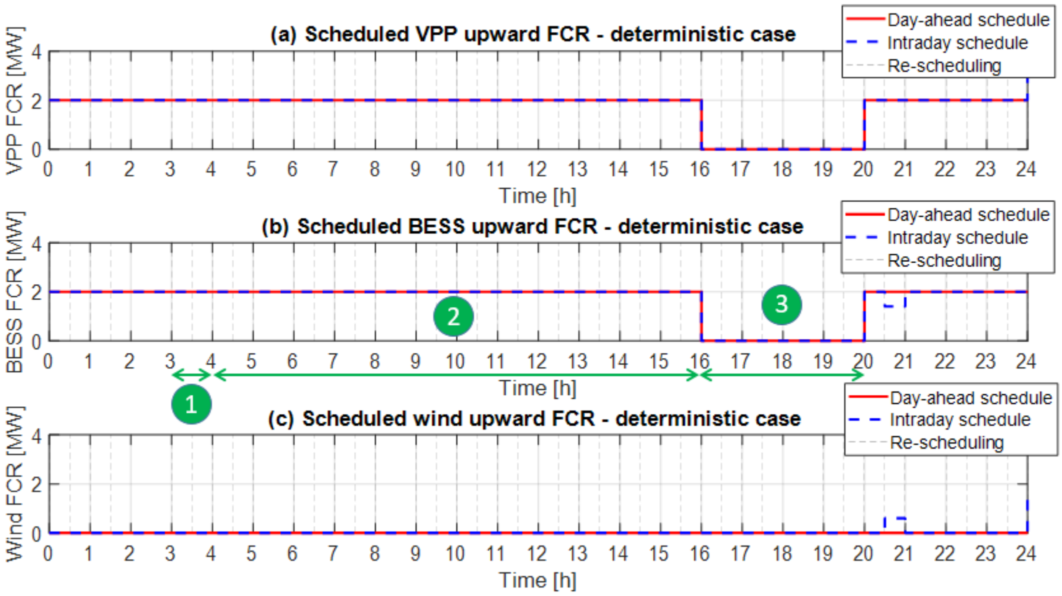
To illustrate how wind FCR provision is considered in the operation planning scheduler, simulation results over one particular day are given, using the dedicated offline simulation platform of the VPP. As described in detail in [10], this platform was specifically developed for intensive simulation tests for the EMS software development, which aims at capturing the main influences/interactions between the EMS/VPP components and ensuring that the whole system behaves as expected in all possible situations. Basically, this platform can be used to simulate precisely the behavior of the VPP, from one day to several months, in response to the services schedule, the short-term control adopted, and time series of electrical frequency and renewable generation.

Figure 8 ((I) (II) (III) (IV)) depicts an illustrative example of upward and downward FCR provision planning as well as the distribution between the assets of the VPP, based on the day-ahead and intraday renewable generation forecasts. To better understand the planned and actual activities of the VPP during the day, 3 operational periods can be identified:

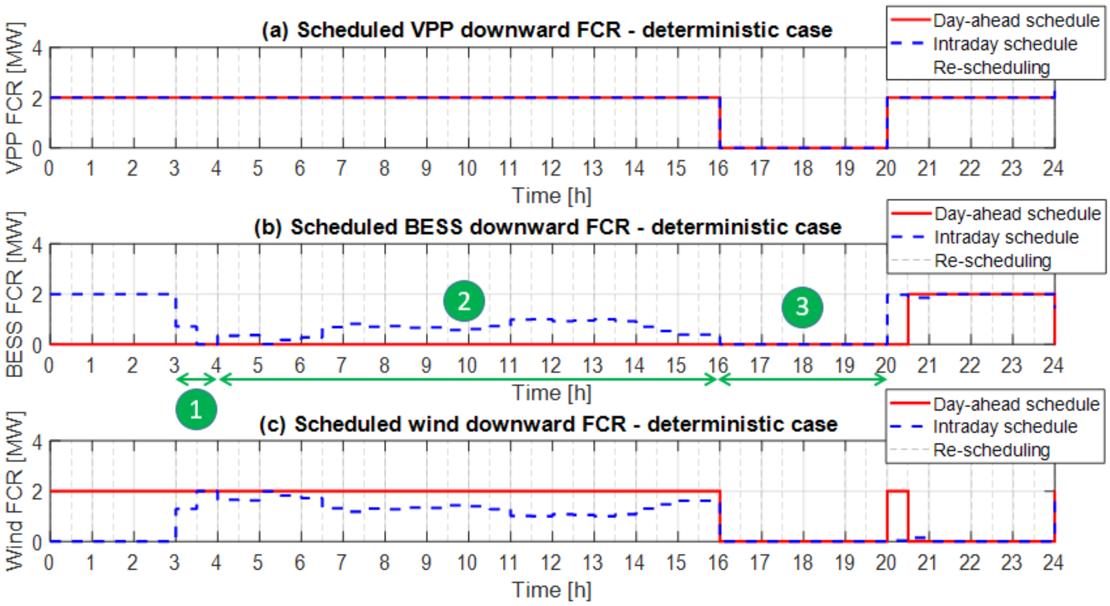
- From 3 am to 4 am (first period), the scheduler plans to charge the BESS using wind energy (Figure 8(I)). Since the electricity energy prices are relatively low in this hour, not only for purchases but also for sales, it is therefore economically more optimal to charge the battery using wind generation, instead of selling all the available wind energy to the electricity market for this period.
- From 4 am to 4 pm (second period), both upward and downward FCR reserve were originally planned to be fully provided by the wind farm the day before (Figure 8(II) and (III)), given the day-ahead forecasts as shown in Figure 8(IV). However, the intraday forecasts indicate that wind power will be lower than expected which may reduce the amount of FCR reserve the wind farm can provide (Figure 8(IV)). Thereby during this period a part of the downward reserve is reallocated on the BESS by the scheduler in order to fulfill the committed FCR service (Figure 8(III)). As illustrated by the curves of actual value in Figure 8(I) and in Figure 8(IV), the symmetrical FCR of the VPP is then delivered to the power system according to the real-time grid frequency.
- From 4 pm to 8 pm (third period), it is the on-peak prices period. The battery is discharged using up to 2-MW power (Figure 8(I)). Thus, it is not possible to provide FCR at the same time and the scheduler has only planned energy arbitrage on the SPOT market for this period.



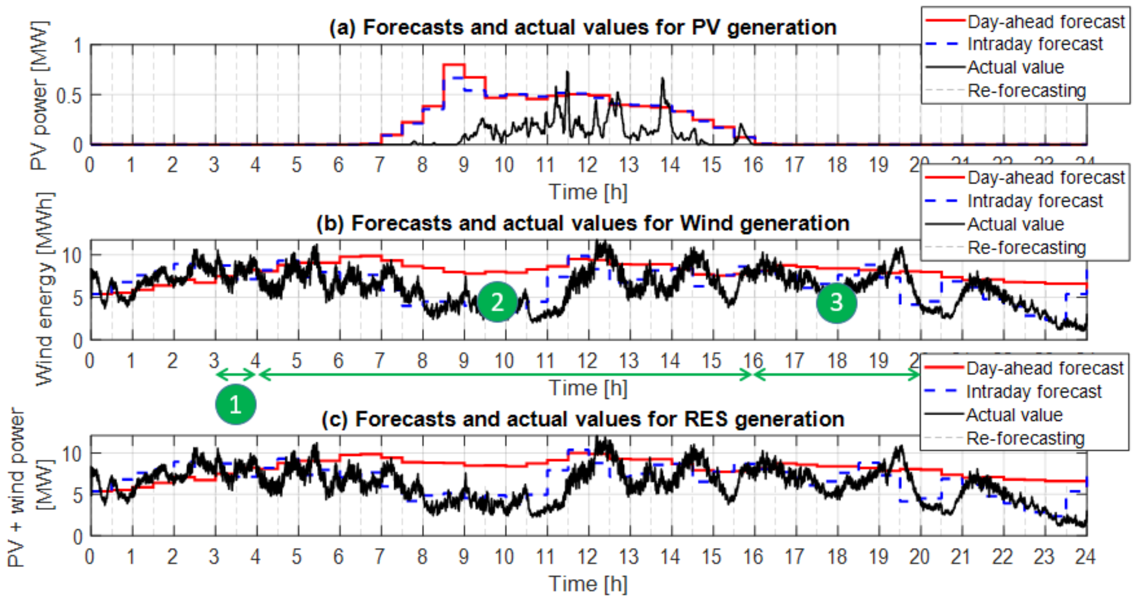
(I) Battery power and state-of-charge



(II) Upward FCR planning and distribution (MW)



(III) Downward FCR planning and distribution (MW)



(IV) Renewable generation forecasts in power (MW)

FIGURE 8. AN ILLUSTRATIVE EXEMPLE OF DAY-AHEAD AND INTRADAY RESCHEDULED FCR PLANNINGS

2.5 NEXT DEVELOPMENTS

Several technical issues have to be addressed in the development of the operation planning scheduler for the VPP of the French demonstration, which manages several resources for multi-services provision. The most significant issues are the following:

- Assessing the potential shortfall of the services schedule due to forecast errors.
- Defining rules of compatibility between different services provided by one or several resources.
- Defining appropriate risk measures for guiding the optimization process.

Up to now, development work mainly focuses on the first and second issues and especially on the modelling of different uncertainties in the optimization process of services scheduling. Some further developments should still be carried out in order to improve the performance of the stochastic programming, which, for now, has not yet proven to be more efficient than the classical deterministic approach.

First, the current overall scheduling process takes almost 30 minutes when considering 64 renewable generation scenarios (8 PV and 8 wind generation scenarios). There is a clear need to reduce the computation time without degrading the scheduling quality. A possible solution would be to **select only the most representative scenarios among a large number of random scenarios**, using reduction or clustering techniques (such as k-MILP [11] or the more simple k-means method).

Second, the current stochastic optimisation process is quite conservative as it optimizes the services schedule considering all the scenarios. **Appropriate risk measures could be added to guide the optimization process**. For instance, the optimization could compute a services schedule that would be feasible for only a percentage of scenarios (e.g., 95% of the scenarios).

3. LOCAL TESTS AND EXPERIMENTAL RESULTS ANALYSES

3.1 OBJECTIVES AND GENERAL APPROACH

Before demonstrating the full-chain operation of the whole VPP, it is essential to first test and to verify the individual services provision by each controllable resource within the VPP. Therefore the WP8 team started by carrying out several local tests on the storage system by activating different services through the real-time storage controller E-SCU (E-Storage Control Unit), as well as on the wind farm by activating FCR provision through the on-site wind controller FCU (Farm Control Unit). These tests were performed locally as a first step with very limited interactions with the top layers of the centralized EMS of the VPP comprising the optimization process.

In order to ensure the safety of the materials and to facilitate troubleshooting, the general approach shown in Figure 9 has been applied to perform the experimentations:

- First, fake signals such as simulated grid frequency as well as simplified parameters of the local controllers were applied to verify the behavior of the tested resource, compared to the expected response of each service activated;
- Secondly, based on the results analyses of the simplified tests, algorithms debugging and controllers tuning were achieved;
- Once the control algorithms were validated, tests in real conditions using grid-side measures were carried out, which then allowed data post-processing and analyses of full experimental results.

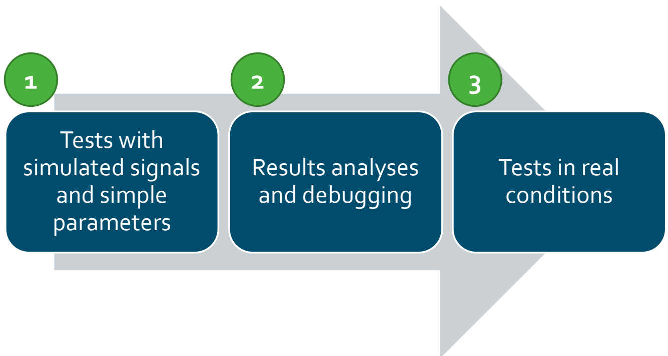


FIGURE 9. GENERAL APPROACH FOR LOCAL TESTS

3.2 LOCAL TESTS ON STORAGE: DEMONSTRATION OF MULTI-SERVICES PROVISION

Local tests on storage were carried out by EDF, with technical support of ENERCON, in the first semester of 2020 to accomplish the following missions:

- To verify the good operation of the storage local controller E-SCU built by ENERCON according to the technical specifications of different services;
- To validate and improve a part of the functionalities implemented by EDF in the Short-Term Control (STC) layer, especially the functionality of SoC (State of Charge) controls for different services when needed as well as the functional interfaces with E-SCU;

- To activate / deactivate storage services and set corresponding technical parameters in different testing cases considered as possible during the full VPP's operation;
- To analyze experimental results, investigate the performance of storage services and to learn lessons for future tests.

3.2.1 E-SCU CONTROLLER DESIGN AND LOCAL TEST PLATFORM

Composed of a 45-foot container containing a lithium-ion battery and a 40-foot container containing the energy conversion system, the ENERCON E-Storage system was commissioned at Concept Grid in January 2020. Detailed commissioning tests and process have been presented in D8.2 report [10].

FIGURE 10. COMPLETED BATTERY ENERGY STORAGE SYSTEM (BESS) INSTALLATION AT EDF CONCEPT GRID

The E-SCU is the superordinate controller that determines the power that should be set in the BCS (Battery Control System) to charge or discharge the energy storage system. By using external setpoints, and as well by using a local grid frequency measurement, the E-SCU activates the requested services through the BCS. The external setpoints can be emitted to the E-SCU either by the GED-S interface through an IEC80607-5-104 communication, or by the control room in Concept Grid through a Modbus communication. The E-SCU uses the voltage and current measurements at the point of connection of the BESS in order to evaluate electrical values such as active and reactive power, frequency, etc.

Moreover, as real frequency events are not 'controllable' and significant incidents triggering some services can be rare and hardly predictable, the E-SCU can as well receive from the GED-S a fake frequency signal allowing for 'forcing' the activation of certain frequency-dependent services.

Several operational modes of E-SCU had been developed and were validated through the local tests performed:

- Manual mode: this mode allows the operation of the battery with user-defined power setpoints. This enables the user, for example, to drive manually the battery to a desired SoC. When this is used, all other services are inhibited.

- Frequency Containment Reserve (FCR): in case of frequency deviations, the E-SCU can contribute to stabilize the grid frequency around the reference frequency by injecting/absorbing some active power proportionally to the frequency deviation.
- Fast Frequency Response (FFR): as for FCR, FFR responds to frequency deviation but in a much faster way (~1 s versus ~30 s)
- Automatic Frequency Restoration Reserve (aFRR): the aFRR service orders the storage system to produce an active power setpoint upon request of the System Operator (SO).
- Ramp Rate Control (RRC): this mode allows for the reduction of the active power variations of renewable resources (limitation of *dP*/*dt*).

Depending on the active mode, different logics are used by the E-SCU to calculate the power setpoints. It is noteworthy that, as a BESS system can react very fast (in the order of 250 ms), a special parameter *Tr* (time constant) was used for each mode in order to adapt the response time of the system.

In order to be able to control locally the storage without automatic management of the centralized VPP scheduler, a simplified testing platform including only a part of the STC functionalities has been developed and implemented in the real-time simulator of Concept Grid. As illustrated by Figure 11, this platform communicates with E-SCU using Modbus and ensures the security of local tests by enabling the monitoring of the dynamic behavior of the BESS.

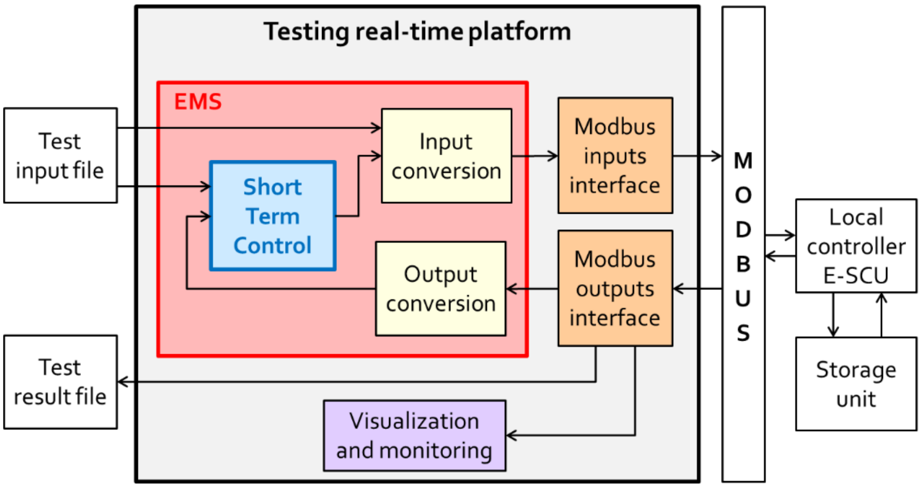


FIGURE 11. COMMUNICATION AND CONTROL CHAIN OF THE TESTING PLATFORM FOR LOCAL TESTS ON STORAGE

With this platform, it is convenient to change parameter settings and to switch from one testing scenario to another by adapting the preformatted input file. Key outputs of experiments can also be visualized in real time through a monitoring interface to ensure the safety and well-functioning of the tests, or can be archived for further analyses.

3.2.2 ACTIVATION OF STORAGE SERVICES

Local tests on storage were started by activating the manual mode by sending active and reactive power references as well as by performing the SoC control. The objective was to verify whether the BESS could correctly react to simple setpoints. It was generally found that the E-SCU active power controller design was based on an open-loop control, resulting in slight active and reactive power differences between the power measured at the PoC (Point of Connection) and the its setpoint, which correspond to power losses in the auxiliaries and in the MV transformer. The E-SCU controller can therefore be enhanced by applying a close-loop control to respect more precisely active power references.

Following the successful trial of some basic scenarios, the implemented E-SCU services were first activated individually to verify their good operation, and then simultaneously to demonstrate the multi-services provision scheme. As aforementioned, fake signals and simple parameters were first sent to the E-SCU controller mainly for the objective of debugging. These experimental results will not be detailed and only outputs of the tests performed in real conditions will be described in the present report.

3.2.2.1 ACTIVATION OF FCR SERVICE

FCR delivery consists in modulating the active power around a baseline power (P_0), with an additional power proportional to the frequency deviations from its reference value as shown in *Eq. 1*.

$$P_{ref}(t) = P_0(t) + k * \left(f_{ref} - f(t)\right) \qquad \textbf{EQ. 1}$$

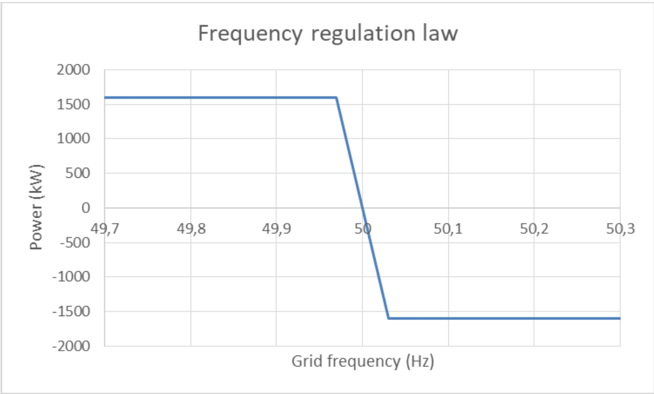
With:

k : FCR gain (in MW/Hz);

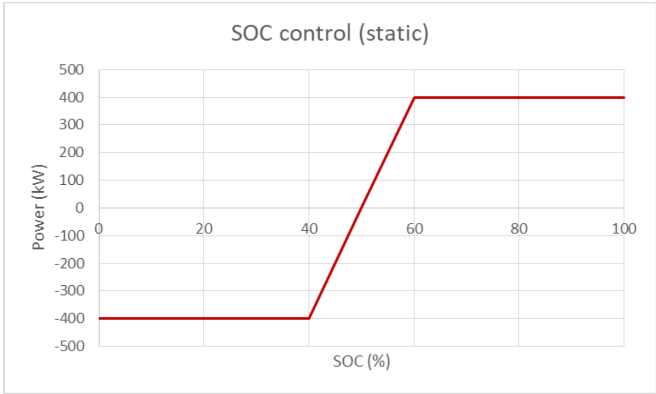
f_{ref} : reference frequency (50 Hz in Europe);

P_{ref} : actual active power reference.

Based on this principle, the FCR service was activated by applying the regulation law as illustrated in Figure 12(a). 1600 kW of symmetrical FCR reserve was allocated on the storage and was set to be fully delivered to the grid for ± 30 mHz of frequency deviation with a time response (at 99%) of 30s. In the current French power system, the full FCR should be provided at ± 200 mHz as required by the grid code. However, since such important frequency deviations are rarely observed in practice, a narrower frequency regulation band was applied during the local tests to evaluate the FCR performance in the full regulation area.



(a) FCR power frequency regulation law

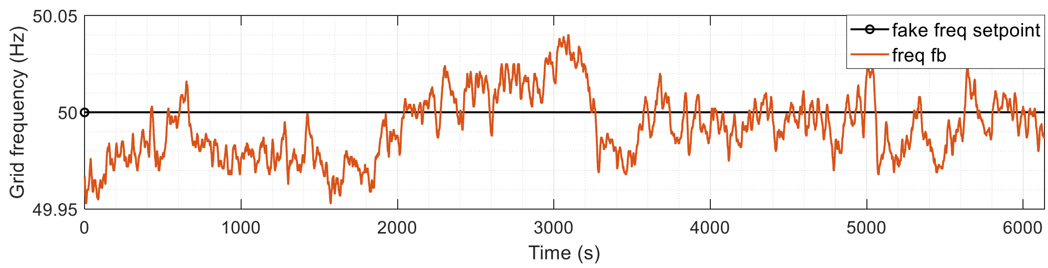


(b) SoC control law

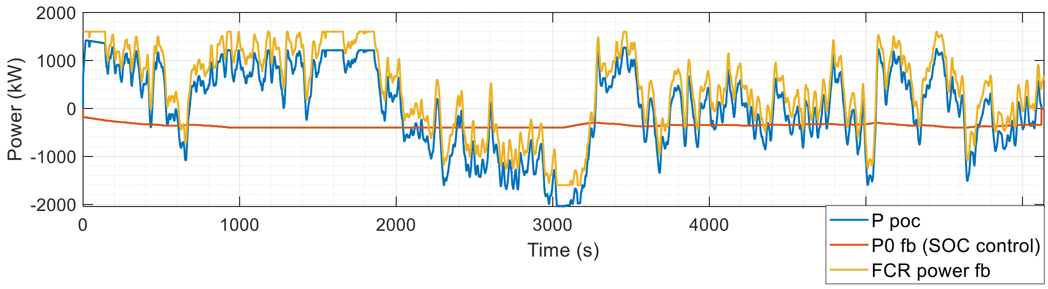
FIGURE 12. CONTROL PARAMETERS AND REGULATION LAW FOR BESS FCR PROVISION

In order to ensure a continuous FCR provision by storage, the control of its SoC is indispensable. When the BESS provides the FCR service, the P_0 setpoint (in *Eq. 1*) can be used to adjust the SoC level. A proportional linear function of P_0 as shown in Figure 12(b) was therefore implemented to regulate the SoC around a reference value, which was set at 50% during the FCR test, by following a dynamic slope of 40 kW/%. A maximum power of 400 kW was reserved for SoC control, which was activated in parallel with the FCR service.

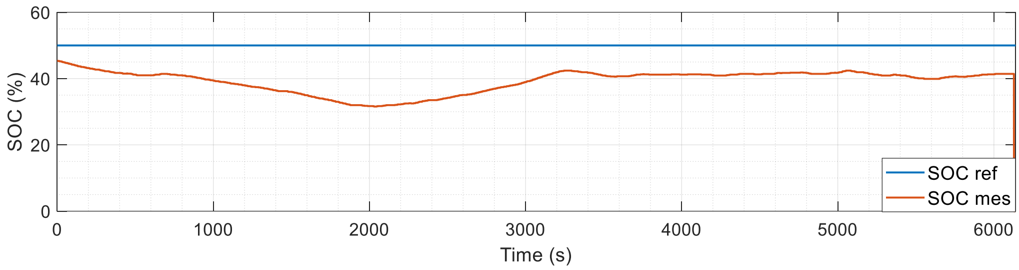
A 100-minute extract of the BESS dynamic behaviour while providing FCR is shown in Figure 13. The power measured at the PoC (blue curve in Figure 13 (b)) corresponds to the sum of the power allocated for FCR (yellow curve) and the power dedicated to SoC control (red curve). It can be observed that the FCR response was correctly delivered to the power system (Figure 13 (b)), in opposition to the frequency deviations (Figure 13(a)). 1600 kW of power reserve was effectively injected when frequency dropped below 49.97 Hz and absorbed when frequency goes beyond 50.03 Hz. The time response of the FCR was also coherent with the pre-set control parameter (full activation within 30s).



(a) Grid frequency



(b) Power at PoC, SoC control power and FCR power



(c) State of charge

FIGURE 13. PROVISION OF FCR BY STORAGE

The action of SoC control ((Figure 13 (c)) was coherent with respect to the defined control law, which successfully helped to maintain the SoC level by absorbing power from the grid to compensate energy loss. However, it should be noted that the SoC control gain and the dedicated power were "optimized" by considering the provision of the amount of allocated reserve quantity under the actual FCR regulation conditions (full activation at ± 200 mHz), but not sized for such important FCR gain applied during EU-SysFlex local tests (full activation at ± 30 mHz). For this reason, the SoC value was always kept lower than the reference value of 50% during the FCR provision period.

Besides the FCR response time, another important performance criterion focuses on the FCR gain (k in *Eq. 1*). According to RTE current rules [15], if one asset provides FCR with an actual gain differing by more than 20% from the contracted value, for more than 10% of the monitored period, the service is then considered as partially unavailable. In other words, to comply with RTE's requirements, the FCR gain assessed must mostly remain between 80% and 120% of the contracted value.

Two different methods were applied to estimate the FCR gain, by assuming that the exact value of the SoC control power P_0 was 'known' (method 1) or not (method 2) by the system operator while assessing the FCR performance. As can be seen from *Eq. 1*, when the value of P_0 cannot be used, assumptions should be made regarding the form of P_0 (e.g.: constant ramp-rate and continuous) to enable mathematically the estimation of the FCR gain k based on the measurement of the power at PoC as well as the grid frequency.

Figure 14 illustrates the comparison between the estimated FCR gain using both methods with the targeted value (provision of 1600 kW of FCR @ ± 30 mHz, i.e. K target = 1.6 MW/ 0.03 Hz = 53.3 MW/Hz) for the whole period of local test. The two dotted lines correspond respectively to the minimum (80%) and maximum (120%) authorized thresholds. It was observed that although the assessed FCR gain was lower than the expected value, which was partially due to the non-optimal SoC control, it remains globally within the allowable range regardless of the method used.

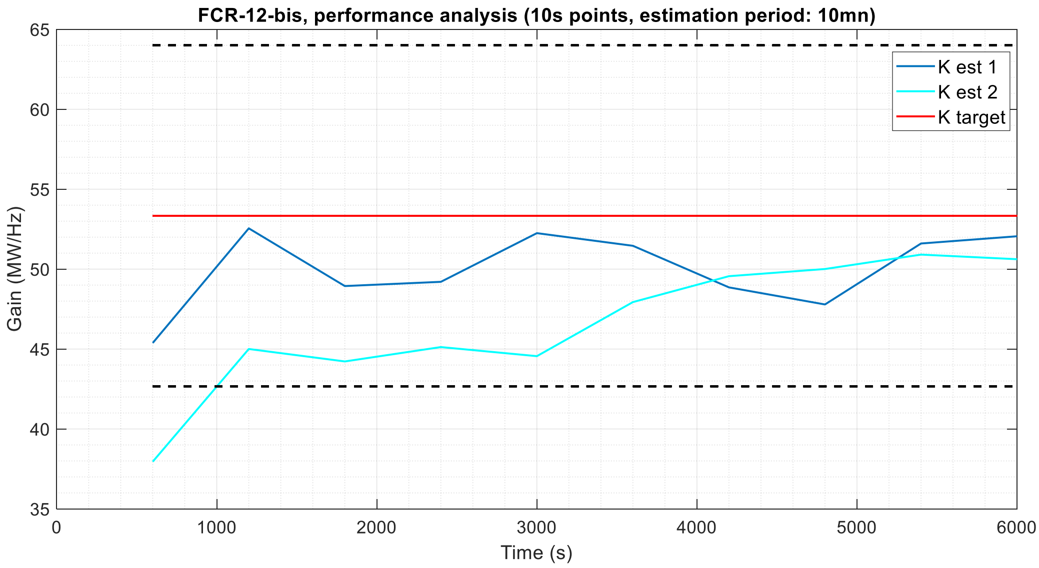


FIGURE 14. PERFORMANCE ASSESSMENT OF FCR GAIN

3.2.2.2 ACTIVATION OF FFR SERVICE

The FFR service is supposed to help the electrical system compensate the decreasing amount of inertia due to the increasing penetration of renewables [7]. This service is activated automatically based on the measurement of frequency and generally takes action before the FCR is activated. Regarding the control algorithm, the FFR is quite similar to FCR but with a major difference in terms of response time. The FFR responds significantly faster than the FCR and the time response can be tuned using the parameter *Tr*. The FFR power-frequency chart can be parameterized in the same way as that of FCR as depicted in Figure 15 and the power setpoints during over-frequency and under-frequency events can therefore be derived.

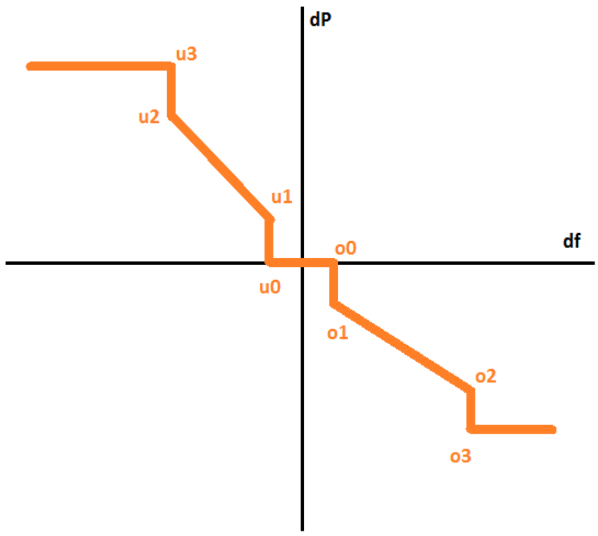


FIGURE 15. FAST FREQUENCY RESPONSE PARAMETER CHART

For the purpose of the FFR local test, the full rated power of the storage (2000 kW) was used as fast reserve and set to be entirely activated at ± 30 mHz of frequency deviation with a time response (at 99%) of 1s. A dead-band of 10 mHz around 50 Hz was defined during the test to avoid overusing the BESS during 'normal' grid disturbances. Another difference between the provision of FFR and that of FCR should be noted: while the FFR is provided, the activation of SoC control is not necessary, as this service only reacts on severe grid events and is not supposed to last long in practice, which therefore has little impact on the storage SoC.

The measurements plotted in Figure 16 show respectively the fast frequency response offered by the storage as well as the grid frequency. It can be observed that the contribution of BESS to FFR was coherent with the controller parameter settings. The time response measured was the one expected and the FFR service was triggered only when frequency deviations exceeded the dead-band of ± 10 mHz.

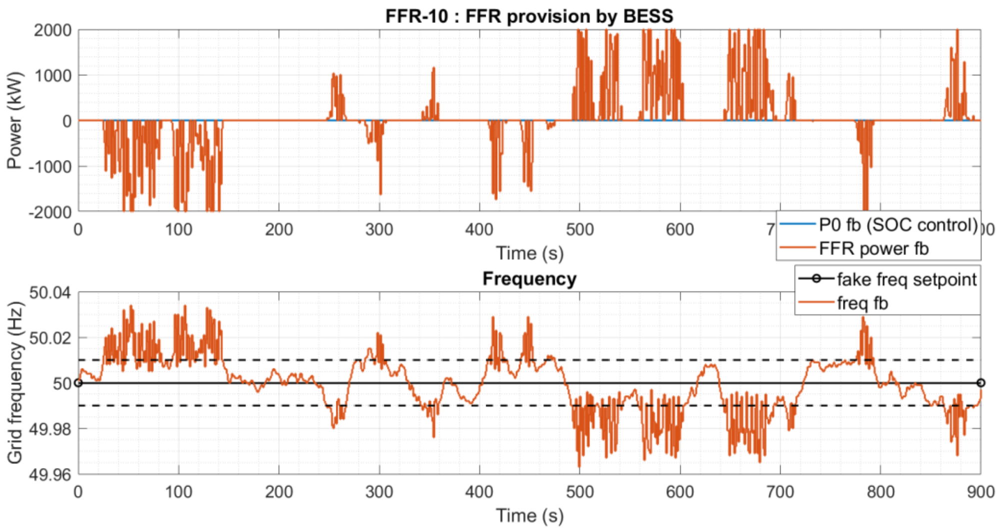


FIGURE 16. FAST FREQUENCY RESPONSE OF THE STORAGE

3.2.2.3 ACTIVATION OF FRR SERVICE

The aFRR service is activated automatically based on a signal sent by the TSO and must be fully activated within 5 minutes. In the French power system, this FRR activation signal corresponds to the "*N* signal" generated by the TSO RTE and sent to each power plant participating in FRR service [14]. The "*N* signal" is per unit and varies from -1 to + 1, meaning respectively the full activation of negative and positive FRR.

A historical N-signal profile, which lasted 3 hours as illustrated in Figure 17, was used to evaluate the aFRR provided by the BESS. 1 MW of the storage capacity was provided as FRR and a total power of 250 kW was dedicated to controlling the SoC. It can be observed in the same figure that the aFRR response followed correctly the requested reserve provision as derived from the N signal value at a given time.

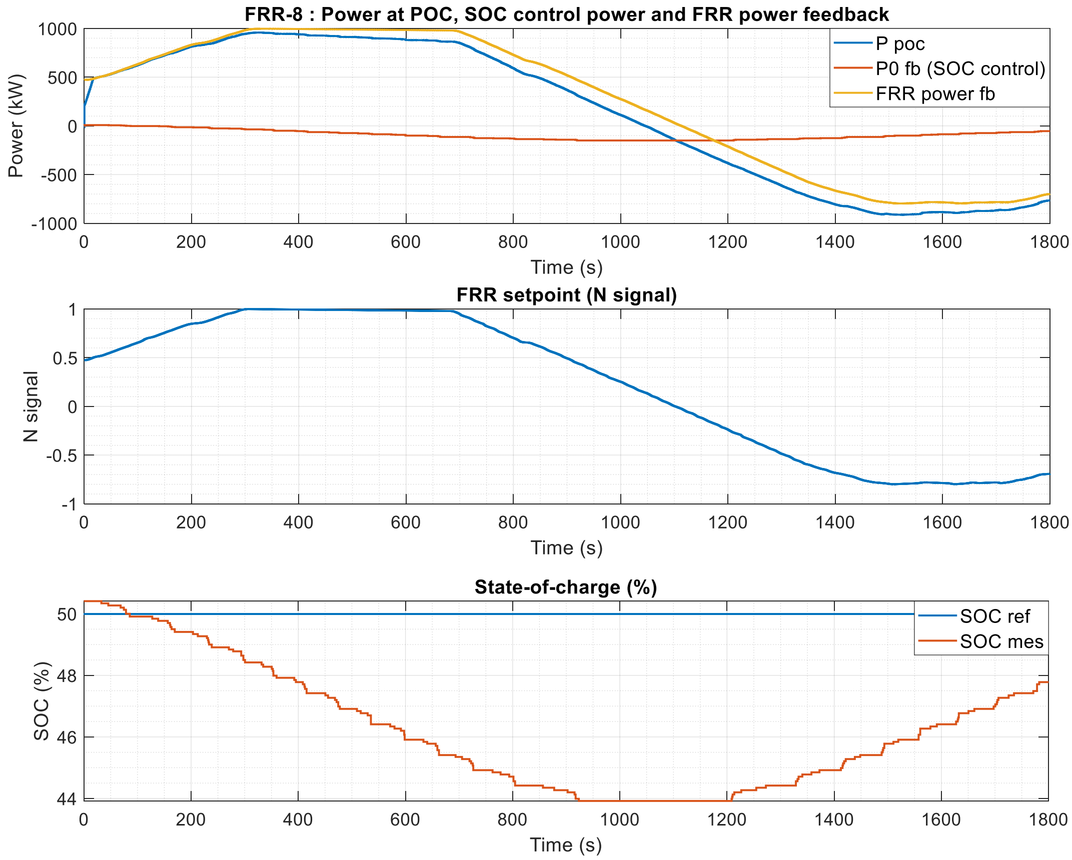


FIGURE 17. AUTOMATIC RESTORATION RESERVE PROVIDED BY THE STORAGE

It is also noteworthy to mention that the BESS in the EU-SysFlex French demonstration was not sized to provide continuously the FRR service. Indeed, in the current power system, the *N* signal could be maintained at -1 or +1 during several hours by the TSO for system needs. Therefore, a huge amount of energy capacity will be necessary to allow the storage to maintain successfully the FRR provision. Unlike FCR or FFR, the participation in aFRR does not seem to be a relevant use case for stand-alone batteries. The contribution of a VPP composed of controllable renewables and BESS, as designed in the French demonstration, could be a viable solution to overcome some technical and economic barriers for aFRR provision. For example, symmetrical FRR could be allocated on both storage and renewable generations considering the energy availabilities of each asset; or only positive aFRR is provided by storage while negative aFRR provision can be ensured by renewables. Different possible scenarios of the participation of the French VPP in the aFRR service will be further investigated through long-term simulations in the future EMS development.

3.2.2.4 ACTIVATION OF RRC SERVICE

The RRC service consists in limiting the power gradients of the total VPP generation by using the storage capacity to reduce renewable power variations. The E-SCU design of the RRC service consists of 2 cascaded control algorithms to define the power setpoint of the storage:

- As a first step, a gradient controller produces a BESS active power setpoint in opposition to the measured active power of renewable generation to maintain a desired power gradient. Figure 18 shows an example of how the gradient controller generates a power setpoint of the storage in order to comply with the gradient setpoint at the PoC. Light blue shows the area delimited between the ± gradient setpoint [kW/s].

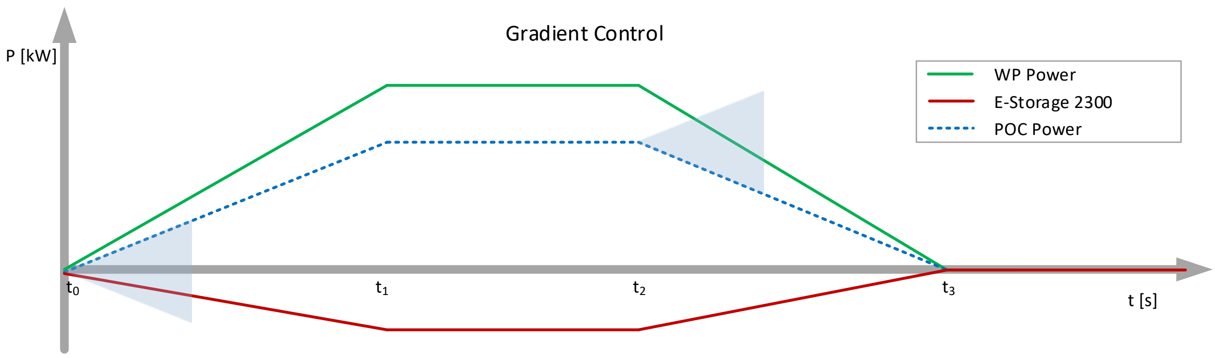


FIGURE 18. GRADIENT CONTROL ONLY OF THE RRC SERVICE

- Then a power controller, without affecting the power gradient at the PoC, reduces the power setpoint of the storage. In this way, the system reduces loss and minimizes the use of the battery. This is shown in Figure 19.

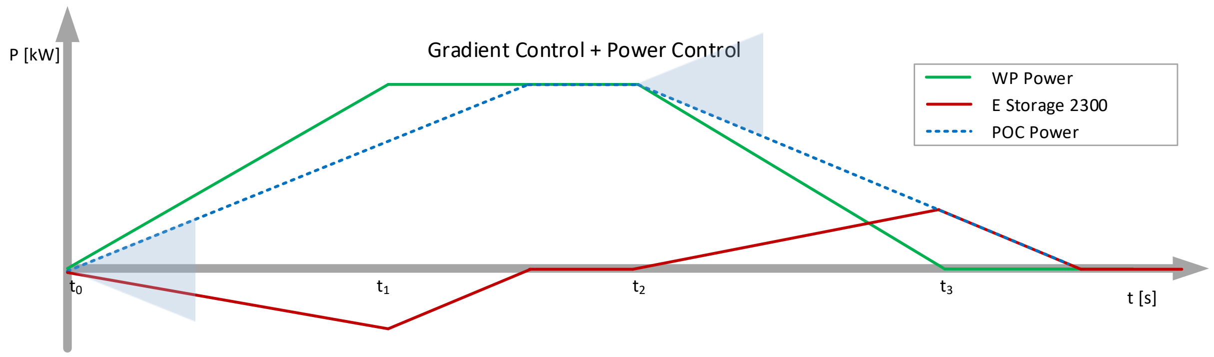


FIGURE 19. GRADIENT CONTROL + POWER CONTROL OF THE RRC SERVICE

The RRC service was tested locally by using a profile of historical Anglure wind farm generation to feed the E-SCU controller as renewable power input. Figure 20 shows the BESS behaviour as well as the power output of the wind-storage VPP when a ramping setpoint was fixed to 20 kW/s (i.e. 1200 kW/min), corresponding to a power variation of 10% of total installed wind capacity (12 MW) per minute. This ramping setpoint was determined according to an ‘expert’ opinion based on technical feedback of several international public tenders specifying similar requirements, as detailed specifications of ramping products of this type do not exist in the current French power system.

As can be seen from Figure 20, when the wind farm generation (the ‘P wind’ curve in blue) showed a too important positive variation of active power, then the BESS (the ‘P poc’ curve in red) created a negative variation of active power by absorbing the power; the resultant power variation at the VPP level (the ‘P vpp’ curve in yellow) was therefore contained. Conversely, when the wind power showed a too important negative variation, then the BESS created a positive variation of active power by injecting power; the resultant power variation of the VPP was also kept less than the targeted ramping setpoint.

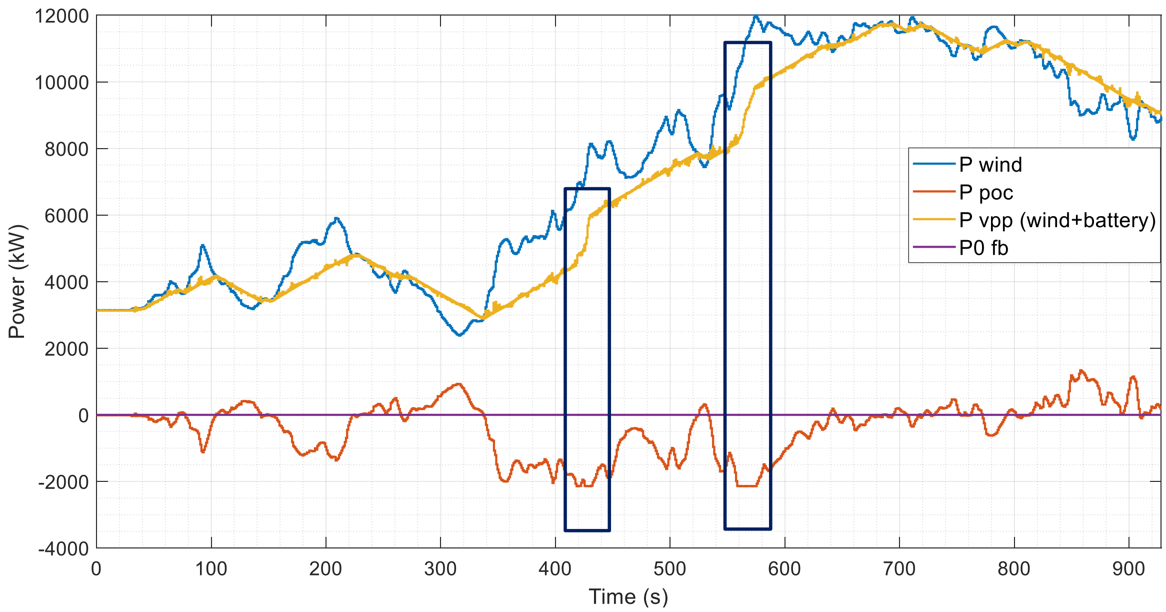


FIGURE 20. RAMP RATE CONTROL OF WIND GENERATION USING STORAGE

As for FRR delivery, the provision of the RRC service could have important consequences on the storage SoC, especially when a long lasting duration of the service needs to be ensured. Hence, the activation of a SoC control is indispensable while performing RRC. However, the dynamics of the additional power due to SoC control could influence the ramp rate of the global generation output. A poorly designed SoC control could therefore lead to unexpected non-compliance with the ramp rate setpoint at the VPP level.

For the EU-SysFlex local tests, a simplified approach of SoC control associated with the RRC service was applied. To respect the global power variation ramp rate (20 kW/s) including SoC control power, a more restricted ramp rate setpoint (15 kW/s) was sent voluntarily to the RRC controller, in order to leave a margin of 5 kW/s dedicated to controlling the SoC. It should be noted that this simple method works correctly by respecting the global ramp rate setpoint, however, it is not the optimal solution and further investigations on this topic will be needed to better design the SoC control strategy for the RRC service.

To assess the performance of the service, the 60-second sliding average of the ramp rate of the wind-storage VPP generation dP/dt_{VPP} was calculated according to *Eq. 2*:

$$dP/dt_{VPP}(t) = \frac{P_{VPP}(t) - P_{VPP}(t-60)}{t(t) - t(t-60)} \qquad \textit{EQ. 2}$$

Figure 21 shows the calculation outcome for the 15-minute observation period, based on the experimental results illustrated in Figure 20. It is clearly highlighted that the wind generation variation was much reduced with the help of storage and the ramp rate setpoint *RRmax* (20 kW/s i.e. 1200 kW/min) was globally well respected as long as the BESS does not reach its power and SoC limits (see boxes in Figure 20, which are examples of non-compliance in case of abrupt wind power ramps, while the maximum power capacity of the storage was already used for RRC).

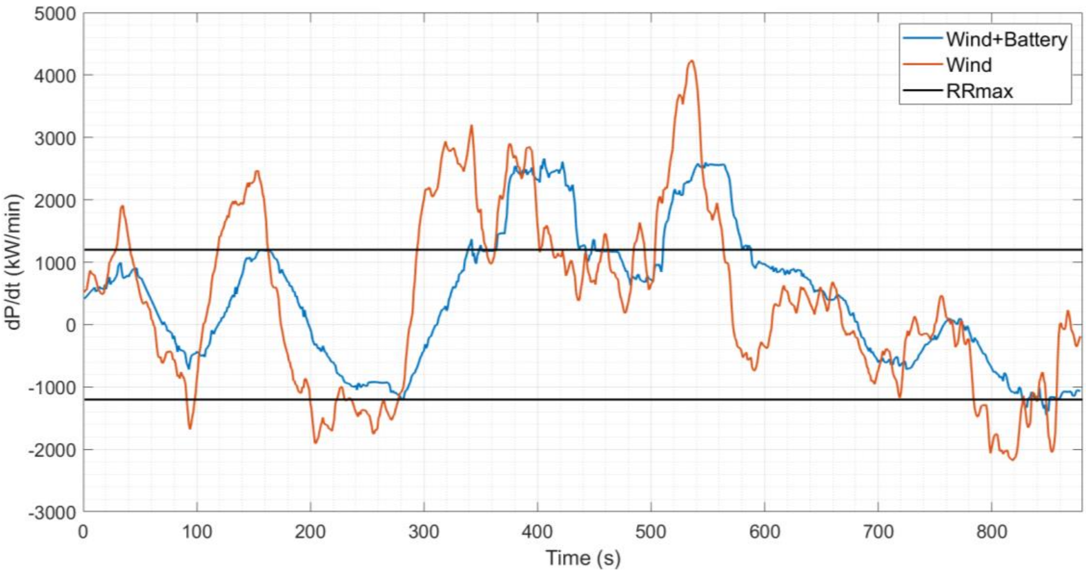


FIGURE 21. RAMP RATE OF WIND + STORAGE VPP V.S. WIND GENERATION ONLY

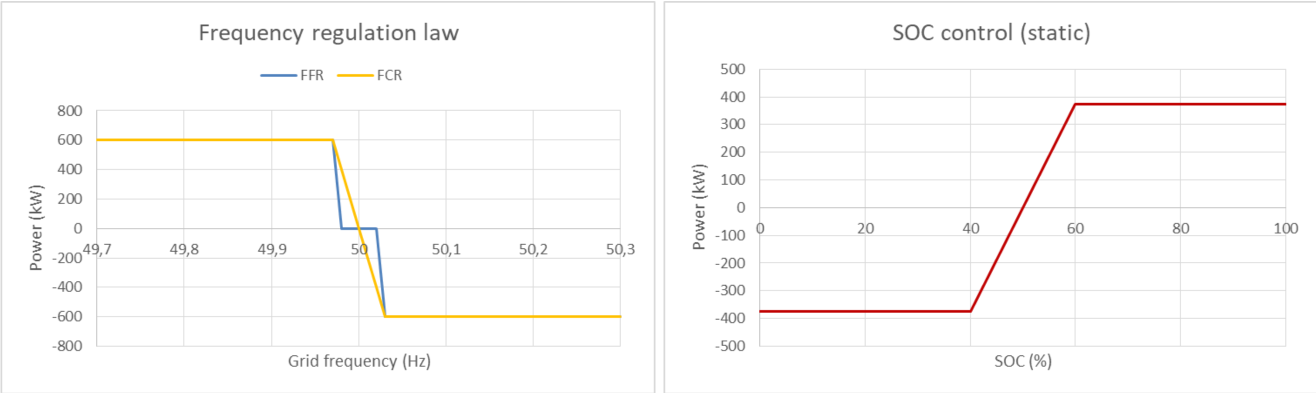
Table 2 shows further analyses on the percentage of the time when the calculated sliding average of the ramp rate was inside the expected maximum ramp rate of 1200 kW/min during the 15-minute observation period (success rate of RRC). One can therefore understand that the higher is the success rate, the better is the performance of the service. The results confirm the effective contribution of the storage to smooth the renewable generation variation and it can also be found that the activation of the SoC control managed to better ensure the availabilities of the BESS when needed, so as to improve the global performance of the ramp rate control.

Wind only	Wind + battery	Wind + battery with SOC control
50.8 %	71.7 %	83.6 %

TABLE 2. SUCCESS RATE OF RRC IN DIFFERENT CASES

3.2.2.5 ACTIVATION OF MULTI-SERVICES

As a final step of the local tests on the BESS, all the three ‘frequency services’ (FFR, FCR and FRR) were simultaneously activated to verify the technical capability of the storage system to provide “multi-services” to the power system when the needs appear. 600 kW of power reserve were allocated respectively as FFR and FCR. Adapted frequency – power regulation laws with smaller control ranges than that actually required by the French TSO, as presented in Figure 22(a), were defined, as real frequency measurement was used to trigger the activation of these services. Moreover, 600 kW of FRR was also provided by the storage by following a historical profile of *N* signals. To ensure the level of SoC during the provision of multiple services, the control law as shown in Figure 22(b) was implemented. A maximum power of 375 kW could be used for SoC control, by respecting a static droop of 37.5 kW/% and a dynamic ramp of 375 kW / 900 s.



(a) FFR and FCR power frequency regulation law **(b) SoC control law**

FIGURE 22. CONTROL PARAMETERS AND REGULATION LAW FOR MULTI-SERVICE PROVISION

Figure 23 shows the experimental results of the 1-hour test of the multi-services provision. It was observed that the three frequency services were appropriately and simultaneously activated according to the grid frequency and to the FRR activation signal, in parallel with SOC control. It was also found that through relevant controller design and feedback signals measurement, the resultant power at PoC could be decomposed of the powers dedicated to each service and the performance of different services can be assessed individually while they were simultaneously activated. This allows system operators to verify whether the storage provides effective contributions by responding correctly to the different indicators of power system needs (frequency, *N* signal, etc.) and will be key to enable the provision of multi-services in practice.

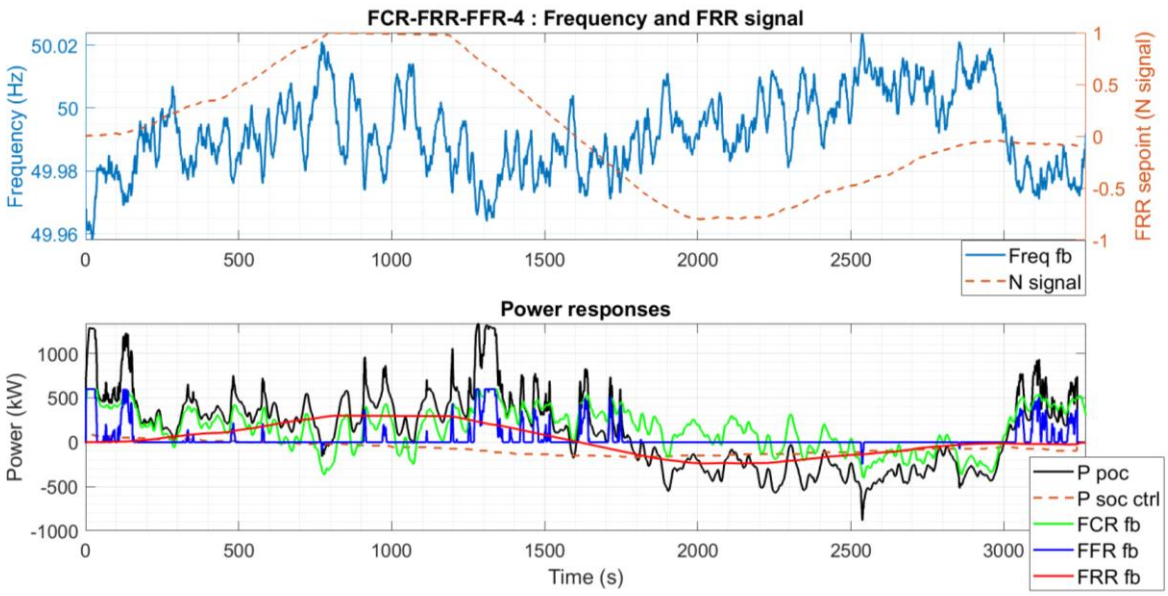


FIGURE 23. MULTI-SERVICE PROVISION BY BESS IN REAL CONDITIONS

During this phase of local tests on storage, the obtained experimental results were very satisfactory and showed good performance of various services offered by the storage system within the French VPP, compared to the requirements that would be demanded by system operators.

3.3 LOCAL TESTS ON WIND FARM: FCR PROVISION AND PERFORMANCE ASSESSMENT

Following the successful experimentations on the storage system, the WP8 team continued to carry out local tests of the wind services at the Anglure wind farm by applying a similar approach. The first tests performed in the year of 2020 focused on the FCR provision by wind generation, as to our knowledge, this service has not been fully investigated in the literature and still needed to be demonstrated in real grid conditions.

Indeed, in some European countries, wind farms already contribute to the frequency stability by providing 'Frequency Restoration Reserve (FRR)', either automatic (aFRR) or manual (mFRR), as well as 'Replacement Reserve' (RR), especially when asymmetrical (downward) reserve provision is allowed in the ancillary services market. For example, in 2015 in Belgium, an experimental project was conducted by the TSO ELIA and was aiming at testing the ability of a wind farm to provide downward aFRR. Based on accuracy and controllability criteria, the 81-MW wind farm "Estinnes", comprising 11 ENERCON E-126 wind turbines, was prequalified, and afterwards contributed successfully to the balancing market during a 2-month period [17]. Again in 2015, the four German TSO's (50Hertz, Amprion, Tennet, TransnetBW) agreed on a framework for mFRR provision by wind farms. Since then, after a period of implementation and testing, the first wind farms were pre-qualified (21 MW by Amprion and 60 MW by 50Hertz) and participated in the mFRR market until the end of 2019 [18] [19].

In practice, there are only a few countries where wind power penetration is high and in which wind farms participate in frequency controls to some extent. This is the case of Spain where a Royal Decree dated 2014 is in force to regulate rights and obligations of RES. Consequently, 13 GW and 7.5 GW of wind are now participating respectively to mFRR and aFRR in Spain [20]. In Ireland as well, wind farms can contribute to system services through the program of 'Delivering a Secure, Sustainable Electricity System' (DS3). Some of the services are dedicated to supporting frequency stability ranging from less than a second up to a few minutes [21].

In a nutshell, while many previous studies and pilot projects conducted at present have been addressing frequency restoration reserves, **local tests were first started by assessing to what extent wind power plants can provide FCR and by evaluating the performance of this service in regards to the requirements of the TSO**.

3.3.1 CONSTITUTION OF WIND RESERVE

As described in paragraph 3.2.2.1, the FCR service is generally activated around a baseline power (P_0). In case of conventional power plants participating in FCR service, P_0 is usually controlled by a fixed power reference during each commitment time step, and is inferior to their maximum available power, which ensures that upward (or positive) reserve can be allocated. The principle is different for wind farms, as in the current context they are operated to maximize their output, resulting, at a given instant, in a $P_0(t)$ equal to their maximum available active power level, known as wind 'AAP (available active power)' or P_{AAP}.

P_{AAP} level corresponds in theory to the maximum power that would have been produced by a wind farm without any generation curtailment and is continuously changing due to its wind dependency. When a wind farm participates in FCR provision, its P_{AAP} level can only be assessed through a specifically designed estimation approach, but cannot be directly measured on site. This could therefore lead to an estimation error, i.e. a difference between the estimated AAP (P_{AAP_est}) and the theoretical actual AAP level (P_{AAP}). Once the available power of a wind farm is assessed, to allow upward reserve, the wind farm must be operated below this estimated "maximum" generation P_{AAP_est}, leading to the baseline operating point $P_0(t)$ as calculated in *Eq. 3*.

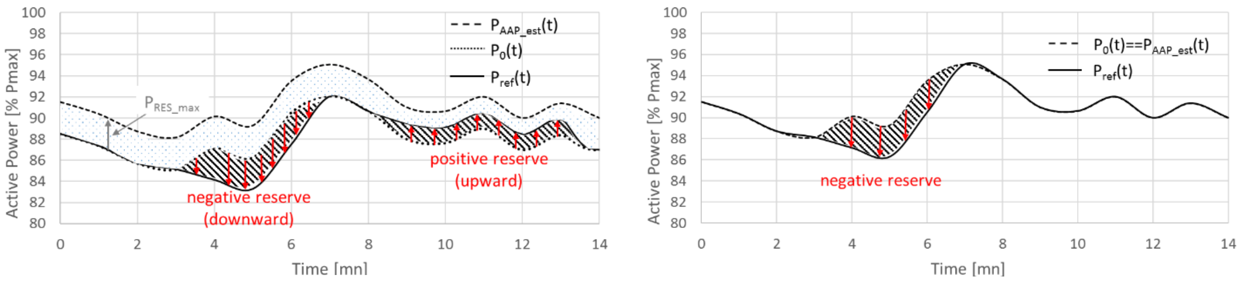
$$P_0(t) = P_{AAP\_est}(t) - P_{res\_max} \quad \textbf{EQ. 3}$$

With:

P_{AAP_est}: estimated wind available active power;

P_{res_max}: maximum allocated upward reserve.

However, the provision of positive and/or symmetrical reserve will result in a consistent energy loss as represented with the dotted area in Figure 24 (a). Without voluntarily curtailing the wind generation output, only downward reserve (i.e. asymmetrical reserve) can be provided as shown in Figure 24 (b). In this case, P_{res_max} can be set to zero, and P_0 turns out to be equal to the estimated $P_{AAP}(t)$.



(a) symmetrical reserve (b) asymmetrical reserve

FIGURE 24. ILLUSTRATION OF WIND RESERVE CONSTITUTION

In the following section, the available wind power estimation method that was used in the WP8 VPP experimentations is described.

3.3.2 WIND AAP ESTIMATION

For multiple purposes (FCR control setpoints definition and its performance evaluation, as well as quantification of wind energy losses), P_{AAP_est} must be estimated at every instant. The methodology used is arduous and its understanding requires recalling the relationship between wind power, wind speed, swept area and Betz factor. The aerodynamic power provided by a wind turbine is given by *Eq. 4*.

$$P_{aero} = \frac{1}{2}\rho A v_{wind}^3 C_p(\alpha, \lambda) \quad \textbf{EQ. 4}$$

With:

P_{aero}: aerodynamical power;

ρ: air density;

A: swept area;

v_{wind}: wind speed seen by the rotor;

C_p: Betz coefficient.

A parametric representation of the Betz coefficient C_p is given in Figure 25. It represents how much aerodynamic power can be taken from wind, and is characterized experimentally for a given wind turbine model. It is a function of the blade pitch angle α and of the blade tip speed ratio λ given as:

$$\lambda = \frac{2\,\pi\,R\,n_{rotor}}{v_{wind}} \qquad \textit{EQ. 5}$$

With:

n_{rotor}: rotor rotational frequency.

The modulation of the active power is technically implemented by modifying C_p while adjusting the collective pitch angle of the rotor blades and changing the rotor speed. But to operate at the maximum available power, an empirically determined operation trajectory λ=$f(\alpha)$ is used to maximize C_p, as depicted by the green curve in Figure 25.

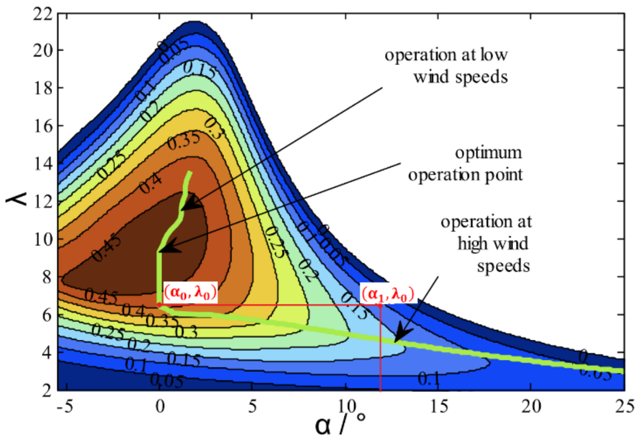


FIGURE 25. ILLUSTRATION OF THE BETZ FACTOR AS A FUNCTION OF BLADE PITCH ANGLE A AND BLADE TIP SPEED RATIO λ (MODIFIED FROM [12])

Hence, having an accurate wind measurement is a pre-requisite for estimating the available power. This could be achieved by the anemometer embedded in the turbine nacelle, which, in some cases, is doubled with another one to ensure redundancy. However, the measurements provided by these sensors have some limitations:

- As for practical reasons the anemometer is located on the nacelle, the measurement is hampered by the fact that the wind is very complex behind the rotor, leading to disturbed measurements requiring the use of a digital filter with a large time constant, which therefore implicates some delay in comparison to the reality;
- Due to the sensor location, the average wind speed 'seen' behind the rotor is always inferior to the one really experienced by the rotor, as the wind turbine extracts energy from the wind, thereby reducing the

wind's velocity. The consequence is a different average wind speed to which the anemometer is subjected in comparison to the real one at the rotor;

- The anemometer shows a reduced accuracy at low and intermediate wind speeds, as its calibration is optimized for the rated wind speed;
- The anemometer is by nature a measurement on a small spot (few square cm) while the energetically relevant wind is on the surface of more than 10.000 m^2.

Having said all this and based on operational feedback, the anemometer measures are of sufficient accuracy at higher wind speeds, and thus, large pitch angles. However, at lower wind speeds and/or pitch angles an alternative method must be used without the consideration of the wind speed measurement. In this partial-load operating zone at lower and intermediate wind speeds, which is the most frequent wind condition in central European sites, one can see from Figure 25 that the Betz coefficient (C_p) variations are greatly dependent on the pitch angle α and much less on tip speed ratio λ. Hence, independently from λ, and just by comparing C_p at the actual pitch angle to C_p at the available pitch angle, one can estimate P_{AAP_est} with:

$$P_{AAP\_est} = P_{actual} \frac{C_p(\alpha_0, \lambda_0)}{C_p(\alpha_1, \lambda_0)} \quad \text{EQ. 6}$$

With:

P_{actual} : Actual power (measured in real time);
α_1: actual pitch angle (measured in real time);
α_0: available pitch angle;
λ_0: empiric lambda value.

Therefore, depending on the wind speed and/or pitch angle, two different methods are combined to estimate wind AAP in the full operational wind speed range of a turbine. The latest method described, used for low and medium wind speeds, is known to provide a good accuracy for limited curtailments (< 50% P_{AAP_est}). For higher wind speeds and/or pitch angles, the method using the nacelle anemometer shows a better accuracy, having in mind that it still suffers from a certain degree of accuracy reduction, as a delay is introduced due to the required filtering. Such a lag may impact the quality of the service provided, especially when a very short response time is required, as it is the case for FCR, different to e.g. FRR.

3.3.3 WIND FCR EXPERIMENTATIONS AND PERFORMANCE ASSESSMENT

3.3.3.1 WIND FARM AND FCR CONTROLLER DESCRIPTION

Local tests on FCR provision were conducted in Anglure wind farm, which comprises 6 wind turbines of 2 MW each. In terms of control, as shown in Figure 26, a SCADA (Supervisory Control And Data Acquisition) server is managing the different wind turbines and receiving status and feedbacks that are recorded. Besides the SCADA, an FCU (Farm Control Unit) is ensuring an accurate and fast closed-loop control of the active and reactive power at the point of connection. Both SCADA and FCU are controlled remotely through a secured internet connection.

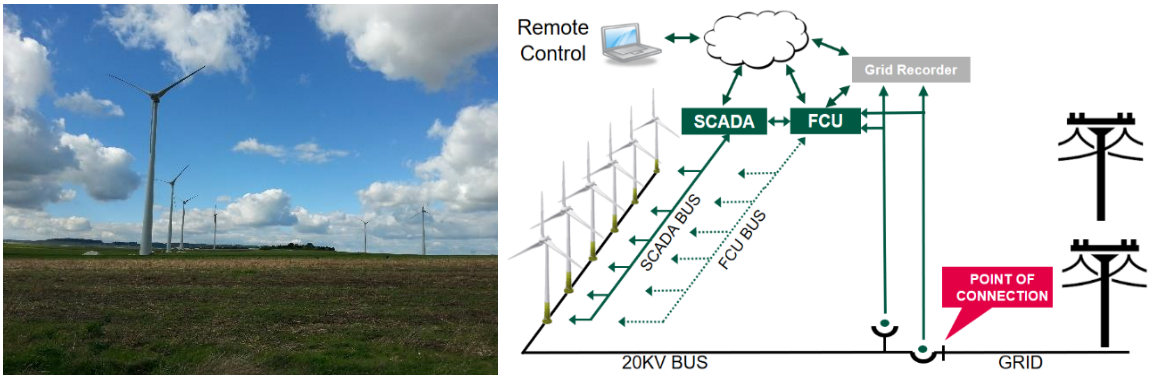


FIGURE 26. ANGLURE WIND FARM STRUCTURE

The FCU offers multiple advanced control functions but only the power/frequency *P*(*f*) function, designed specifically for the FCR experimentation, will be described in detail hereinafter. The control function was designed by carefully considering the compliance with the requirements specified in the European network code 'Requirement for Generators' (RfG) [13] in terms of FCR service. More precisely, the RfG code specifies the so-called 'Frequency Sensitive Mode' (FSM) which is *"…the active power output changes in response to a change in system frequency, in such a way that it assists with the recovery to target frequency"*.

Figure 27 is extracted from the RfG code, and describes the main features of the *P*(*f*) controller. The exact parameters of the control have to be fixed by each TSO, while considering the following RfG limits:

- Droop: in the range of 2-12%
- Positive and negative reserve: 1.5-10% of maximum power
- Deadband: 0-500 mHz

Additionally, the RfG specifies the following conditions:

- Activation time: < 2 s
- Response time: < 30 s
- Duration time: 15-30 minutes

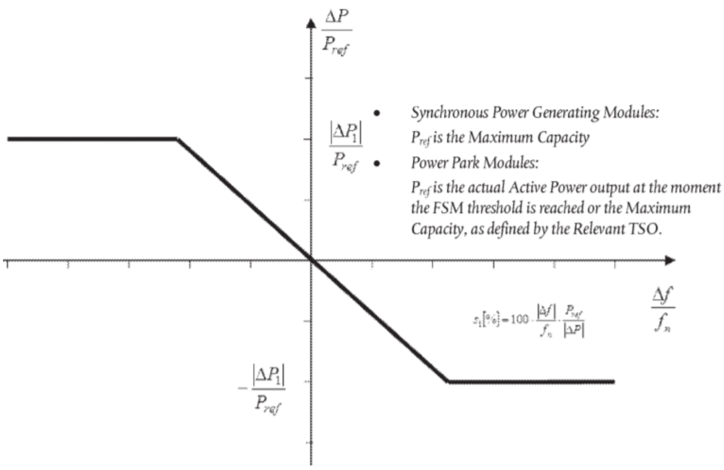


FIGURE 27. FREQUENCY SENSITIVE MODE (FSM/ EXTRACT FROM RFG CODE)

In the EU-SysFlex experimentations, the FCR technical parameter settings requested by the French TSO RTE were applied, as tests were conducted in the French power system. The procedure and the method recommended by RTE were also used as the reference to verify the performance of the FCR provision by the wind farm. In practice, the French TSO RTE verifies the quality of the service provided in two phases:

- In the qualification phase aiming at certification of assets for FCR provision, the tests consist in sending frequency step setpoints (±50 mHz and ±200 mHz) for a 15-minute duration as described in the technical reference document [14]. To obtain the FCR certification, the full reserve must be activated in less than 30 seconds (full activation delay criterion) and held for at least 15 minutes if the frequency deviation remains at 200 mHz. It should be noted that this holding time, required for the FCR provision of conventional power plants, seems complicated to be guaranteed for RES participation.
- In the second performance assessment phase, the TSO carries out a continuous evaluation of the service performance over the FCR contract lifetime based on the monitoring data. As the tests performed in EU-SysFlex cover wind FCR contribution in an operational mode based on real grid frequency, the following analyses refer rather to this performance assessment phase.

3.3.3.2 EXPERIMENTAL RESULTS AND ANALYSES

Two tests of 4 hours each were performed with the provision of 1 MW symmetrical wind FCR. In the test n°1, the wind farm was set to deliver the full FCR within a reduced range of frequency deviation, i.e. ±50 mHz. Although the current FCR activation conditions (total reserve delivery at ±200 mHz [15]) were not applied, this test allowed to verify the controller’s dynamic behaviour, in particular to observe the full reserve release when the frequency thresholds were reached. As shown in Figure 28, in this 14-minute extract from the complete test, the actual power P_{actual} reaches the estimated AAP (P_{AAP_est}) when the frequency drops to 49.95 Hz, thereby providing 1 MW of full FCR as expected. It was also observed that the wind farm could provide correctly full downward FCR when the frequency increased to 50.05 Hz by decreasing its power to the level of the estimated AAP minus twice the amount of FCR. Figure 28 also shows the capacity of the wind farm to provide FCR while the wind production is low. In the test n°1, the wind farm provides 1 MW (8.3% of P_{Max}) of FCR while the baseline production P_0 goes down to 2 MW (16.7% of P_{Max}).

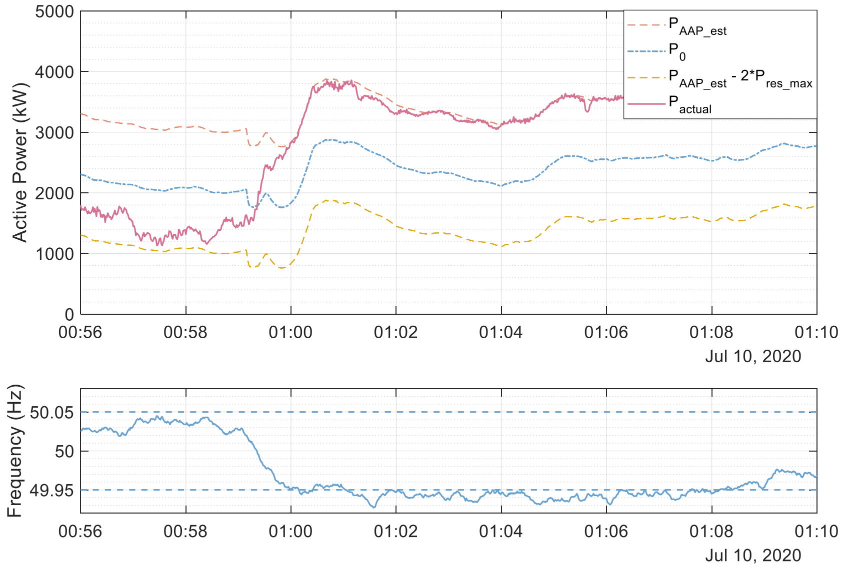


FIGURE 28. TEST N°1: WIND FCR DELIVERY OF 1 MW @ 50 MHZ (EXTRACTED DURATION: 14 MINUTES)

Regarding the FCR performance assessment, a first analysis concerns the dynamic response of the FCR regulation. As required from RTE's ancillary services rules [15], the response of the FCR regulation must remain within the area bounded by 2 curves: the expected 'instant' regulation ($k \cdot \Delta f$) and the expected regulation filtered by a first order filter with a 20-second time constant $(k \cdot \Delta f\ )/(1 + T_f.p)$. This dynamic criterion was checked through the data analysis of the test n°1 results. The 4-minute extract (Figure 29) allows to verify that the response of the wind farm is clearly located within the required boundaries. In fact, the equivalent constant time of the FCR regulation from the wind farm is around 1 second. Given this dynamics, the wind farm satisfies, without any difficulty, the full activation delay criterion of the qualification phase, which must be lower than 30 seconds, when the frequency drops to 49.8 Hz [15].

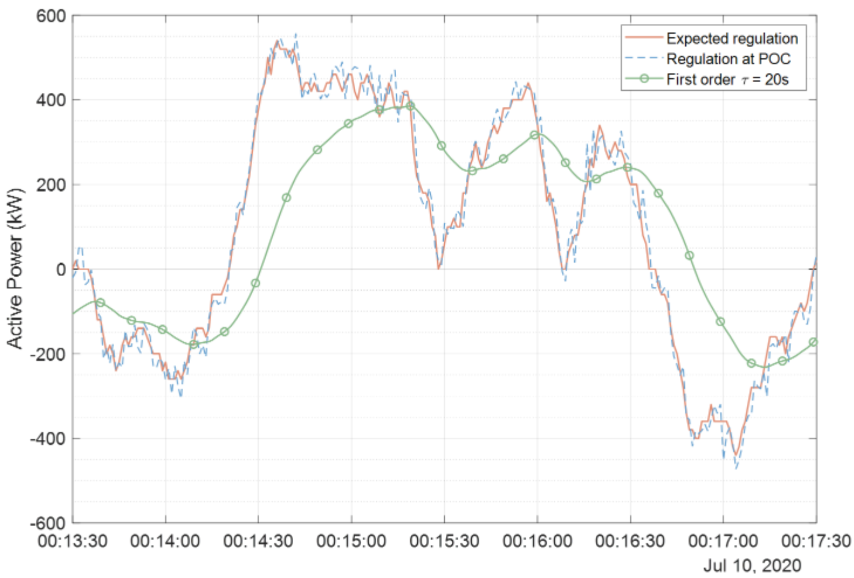


FIGURE 29. TEST N°1: FCR DYNAMIC PERFORMANCE (EXTRACTED DURATION: 4 MINUTES)

To evaluate if wind FCR could also satisfy the static criterion on FCR gain (see paragraph 3.2.2.1 for more details on this criterion), the test n°2 was carried out with parameter settings corresponding to real-life FCR activation conditions. In this test, the frequency deviation thresholds for full FCR delivery were set to ±200 mHz, as specified in the current grid codes [15]. In this testing scenario, the 'contracted' gain $k_{contracted}$ equals 5 MW/Hz, considering 1 MW of FCR that should be fully delivered for a frequency deviation of 200 mHz. Figure 30 shows a 30-minute extract from the full 4-hour test.

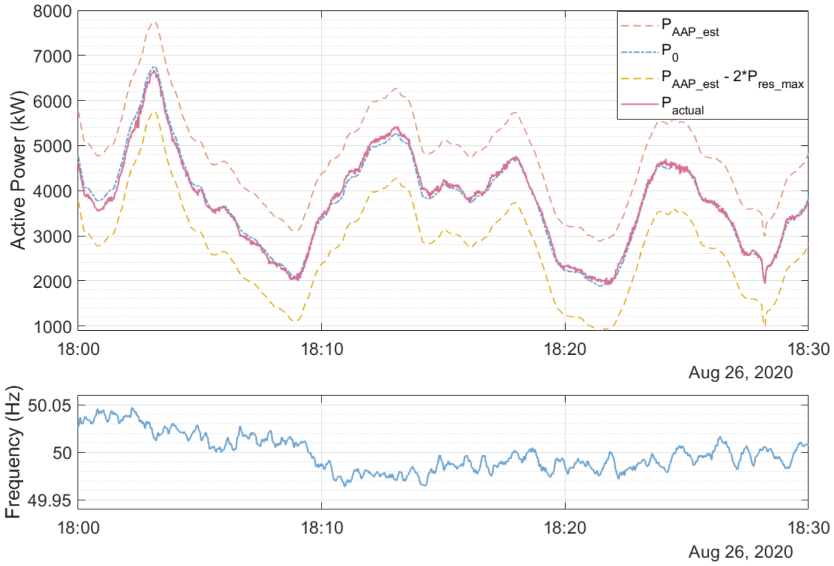


FIGURE 30. TEST N°2: WIND FCR DELIVERY OF 1 MW @ 200 MHZ (EXTRACTED DURATION: 30 MINUTES)

In order to assess the actual FCR gain *k*, the same method as recommended by RTE [16] was used. This method consists in estimating k and P_0 from *Eq. 1* at the same time by applying the least squares method on data of actual power and grid frequency acquired with a 10-second periodicity. This is possible for conventional power plants, for which the baseline operating point is almost constant piecewise at each scheduling time step. However, for wind generation, the baseline power P_0 varies continuously depending on wind conditions (see *Eq. 3*), which makes it complicated to dissociate the power variations due to the FCR regulation (i.e. frequency variations) and that from wind variability. The highly variable and – in the range of few seconds – unpredictable shape of the estimated AAP (as it can be seen in Figure 30) makes it mathematically impossible to get precise FCR gain assessment without knowing P_{AAP_est}. For this reason, the estimated AAP should be known by the TSO as an input while applying the least squares method for the estimation of the actual FCR gain *k*.

To better illustrate the FCR regulation error (i.e. difference between the actual gain *k* and the contracted gain $k_{contracted}$), the expected FCR response $P_{expected}$ was calculated by considering the contracted FCR gain ($k_{contracted}$) as shown in *Eq. 7*. This $P_{expected}$ value corresponds therefore to the 'ideal' wind FCR regulation, based on the estimated AAP, for a given frequency variation.

$$P_{expected}(t) = P_{AAP\_est}(t) - P_{res\_max} + k_{contracted} * \left(f_{ref} - f(t)\right) \qquad \textbf{EQ. 7}$$

Figure 31 shows the obtained results on FCR actual gain assessment: the difference between the actual and the expected power on the top; and the estimated FCR gain at the bottom. During this 4-hour test, the estimated FCR gain remained within the allowed range (4 and 6 MW/Hz, i.e. ±20% of the contracted gain equal to 5 MW/Hz) for 87.5% of the observation time. In the first 10-minute period, the FCR gain appeared to be twice as large as the contracted value of 5 MW/Hz.

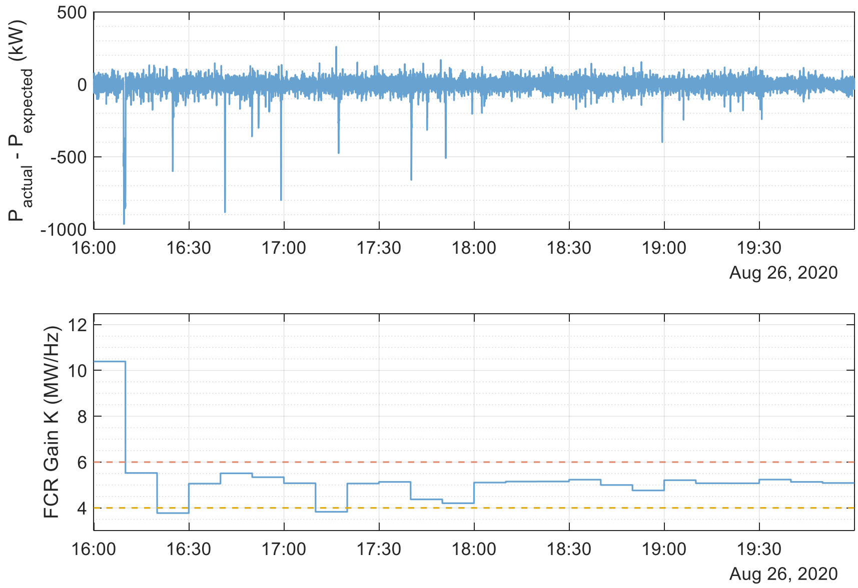


FIGURE 31. TEST N°2: FCR GAIN PERFORMANCE (FULL TEST N°2: 4 HOURS)

The top graph of Figure 31 also shows that a FCR regulation error of nearly 1 MW (i.e. difference between the actual power and the expected power) can be found in this period. Indeed, Figure 32 reveals that during about one minute, the wind power that was generated was much lower than P_0, whereas the grid frequency was merely above 50 Hz (i.e. little downward reserve should be activated in this time window). The unusual large power decrease comes from the overestimation of the AAP level, resulting in a misleading FCR gain assessment and consequently in a poor FCR performance. In contrast, an underestimation of the AAP leads to an over-curtailment of wind power for reserve constitution, and thus, to additional wind generation loss, but a priori, would not affect the gain assessment. During the EU-SysFlex experimentations, the overestimation of the AAP has been mainly observed when wind generation decreased.

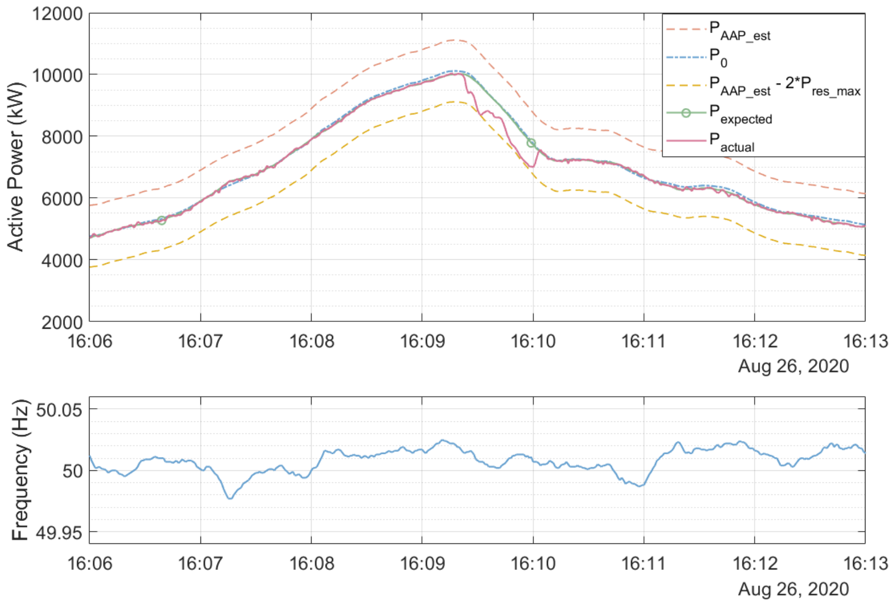


FIGURE 32. TEST N°2: AAP ESTIMATION ERROR IMPACTING FCR PROVISION PERFORMANCE (EXTRACTED DURATION: 7 MINUTES)

The two other periods when the estimated FCR gain is out of the allowed range are also linked to a saturation of P_{actual} due to the overestimation of the AAP. The effect on the gain estimation depends on the amplitude of the frequency deviation occurring at this moment. Indeed, for a difference between $P_{expected}$ and P_{actual} of 1 MW, the estimated gap on the gain will be twice as big for a frequency deviation of 50 mHz than for one of 100 mHz, although it is in opposition with the grid needs. The performance assessment method currently applied by the TSO may need to be reconsidered in order to take into account the relative impact of a regulation error on the network.

In a nutshell, the more renewables contribute to the power mix, the more they have to play an active role in frequency services provision to power systems. The local tests performed in 2020 at the Anglure wind farm investigated to what extent FCR can be technically provided from wind generation and whether wind FCR provision would satisfy the performance requirements of system operators. **The obtained experimental results globally demonstrated the capability of the wind farm to provide effective FCR service as pre-set by the *P*(*f*) controller in real conditions with requested performance.**

3.3.4 DISCUSSIONS AND OUTLOOK

One of the limitations of the performed analyses that were carried out is related to the accuracy of the available power estimation (P_{AAP_est}). Indeed, if the performance of the wind FCR service was shown to be mainly compliant with the TSO's requirements in the first experimentations, some occurrences of non-compliance were observed, and could be explained by an overestimation of P_{AAP_est}. In 3.3.2 were explained the reasons why measuring the wind velocity is not trivial. Since the accuracy of the available power estimation was already assessed as being essential for warranting the quality of the rendered services [17] [22], an alternative estimation approach providing a more reliable evaluation of the P_{AAP} was developed in the recent past (but not tested in the EU-SysFlex experimentations).

This new approach consists in considering the whole rotor as an anemometer itself by the means of a precise aerodynamic model using multiple parameters such as actual power, electrical losses, rotational speed, rotor inertia, and air density (while measuring air pressure and temperature). In this way, an equivalent effective wind speed can be deduced for the whole swept area. This method is therefore expected to provide a more reliable wind speed assessment.

Another factor affecting the quality of the estimation requires indeed a special attention to the “wake effect” at the wind farm level. Curtailing power on a turbine reduces the wake behind it, consequently the average wind speed in the wind farm rises. Each wind turbine would then report a slightly higher P_{AAP_est} signal, which will not be reached when the curtailment is suspended. Therefore, the wake effect needs to be taken into account using a wind farm-specific wake matrix, depending on wind speed and direction [23]. The consideration of this wind-farm effect, in combination with the new effective wind speed assessment method, would lead to an improved quality of estimation of the available power.

4. CONCLUSION AND PERSPECTIVES

Following the specification work in 2018, as well as the implementation of the necessary hardware, software and a part of the ICT (Information and Communications Technology) infrastructure in 2019, the global environment for the VPP's operation was set up. The WP8 team has focused in 2020 on updating the EMS algorithms of the VPP by integrating new services, as well as on verifying the good operation of different services provision by individual resources through local experimentations. The French demonstration work has well progressed in the past year thanks to the great effort and efficient cooperation made by EDF and ENERCON, despite the context of COVID-19 sanitary crisis which has led to repeated difficult working and test conditions.

4.1 MAIN ACHIEVEMENTS AND FINDINGS

Regarding the software updates, since the first release of an operational version of the EMS, the performance of the operational planning scheduler has been improved. **The first update performed was to take into account the SoC deviations of the BESS while providing FCR.** To enhance the stochastic programming, SoC deviation scenarios were randomly generated by using the simulation results of a BESS providing different quantities of FCR in response to 1-second time series of registered real grid frequency. However, the first simulation results showed some limitations of the scenarios generated with respect to the uncertainty that were expected to be modelled. The problem came mainly from the ability to only take into account a small number of SoC deviation scenarios due to limited computation capacity of the current version of the scheduler, which seemed insufficient to represent correctly the stochastics of the SoC in case of the FCR provision by storage.

In addition, on the basis of the first version of the operational planning scheduler which can only manage the FCR provision by the BESS, **an updated version has been developed in 2020 by integrating the frequency containment reserve provided by wind generation.** The wind FCR was modelled in the way that the allocation of upward reserve would lead to curtailment of wind power, whereas the constitution of downward reserve would not necessarily change the wind generation output. The total FCR of the VPP is modelled to be symmetrical or asymmetrical depending on user-defined parameters and corresponds, at all times, to the amount of reserve defined by the services schedule. However, the distribution of FCR between the wind farm and the BESS is not always equal. The optimal allocation depends on the wind generation forecasts at different timescales as well as on the availability of the storage, and can be modified following the intraday rescheduling.

Besides the software algorithms improvement, **local tests were also carried out to verify the individual services provision by each controllable resource within the VPP**, before demonstrating the full-chain operation of the whole system. Local experiments on the services of the storage were performed by using a specifically developed testing platform implemented in the real-time simulator of Concept Grid. Following the successful trials of some basic scenarios (manual mode and SoC control), the active power services (FCR, FFR, FRR and RRC), which were already implemented in the storage E-SCU controller, were first activated individually to verify their good operation, and then simultaneously to demonstrate the multi-services provision scheme. **The obtained experimental results were very satisfactory and showed good performance of various services offered by the**

storage system within the French VPP, compared to the requirements that would be demanded by system operators.

The similar approach of local tests was also applied onto the Anglure wind farm so as to assess to what extent wind generation can provide FCR and to evaluate the performance of this service when it is offered by a 'new' and non-conventional actor of the ancillary services market. The wind reserve constitution was first investigated and it was revealed that the **ability of estimating the maximum available active power in real time is essential to allow wind FCR provision**. Depending on the wind speed and/or pitch angle, two different methods were used to enable wind AAP estimation throughout the whole operating zone of a turbine. The combination of both methods can ensure a relatively good accuracy of AAP estimation for FCR provision according to both empirical and operational experiences.

Experimentations of tens of hours have also been performed in the 12-MW Anglure wind farm in order to verify the quality of FCR provision. The results show that **although wind generation is of variable nature, it is technically capable of providing effective FCR service** when being equipped with a dedicated AAP estimator and an FCR controller. Furthermore, the knowledge of the estimated AAP makes it possible to monitor the performance of wind FCR response in a continuous manner during the operational phase, through the assessment of the FCR gain. The analyses show that **the actual wind FCR performance is globally compliant with the current TSO's requirements in terms of dynamics and gain**, although over-estimation of wind AAP could lead to occasional under-performance. It should also be noted that the quality of wind FCR provision would be further enhanced when the service is provided by a large-scale wind generation fleet or a system-sized virtual power plant.

4.2 NEXT STEPS

One of the most important targets in the next months will be to fully implement and commission the whole ICT infrastructure of the VPP, allowing a remote control of all the distributed resources from the EMS, thus enabling the operation of the full-chain VPP. Indeed, as presented in paragraph 1.3.2, to ensure reliable and secured data exchanges between individual assets at local levels and the EMS at the centralised level, Grid Edge Devices (GED) was introduced in the global communication platform. The first GED device, the GED-S, was fully configured and tested to allow communications with the BESS. For the remote control / access of wind and PV generators, two more grid edge devices (GED-W and GED-LP) will still need to be implemented, which are being prepared and under configuration at the time of writing of this document.

Active power related services that were currently implemented in the E-SCU controller of the BESS were successfully validated through local tests. Controls for voltage services will still need to be developed and tested. Since these services based on reactive power regulations are not directly interfaced with the optimization process of the EMS, verification experiments can be performed locally at Concept Grid, where voltage incidents can be artificially created without affecting the stability of the main power system.

In parallel, further developments of software and controllers will also be carried out to improve the performance of the developed algorithms and to enhance the functions of the EMS, especially by increasing the efficiency of the stochastic optimization process and by modelling the remaining active power related services in the operational planning scheduler, as well as by integrating more advanced control modes into the short-term control layer. Simulations over longer durations with different variants / parameter settings of the EMS will be performed to support the algorithms development and to provide more conclusive results.

5. COPYRIGHT

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