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ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
ACSI	Abstract Communication Service Interface
BESS	Battery Energy Storage System
BMS	Battery Management System
CA	Common Attributes
CDC	Common Data Classes
CG	Concept Grid
DC	Direct Current
DEIE	Dispositif d'Échange d'Informations d'Exploitation
DER	Distributed Energy Resources
DMS	Device Management System
DO	Data Objects
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
FCI	Farm Control Interface
FCR	Frequency Containment Reserve
FCU	Farm Control Unit
FFR	Fast Frequency Response
FRR	Frequency Restoration Reserve
GED	Grid Edge Device
HMI	Human Machine Interface
IE	Inertia Emulation
IED	Intelligent Electronic Devices
KPI	Key Performance Indicators
LD	Logical Device
LN	Logical Nodes
IT	Information Technology
LV	Low Voltage
MILP	Mixed Integer Linear Programming
MMS	Manufacturing Message Specification
MPP	Maximum Power Point
MV	Medium Voltage
PHIL	Power-Hardware-In-the-Loop
PMB	Project Management Board
PoC	Point of Connection
PV	Photovoltaic
RES	Renewable Energy Sources
REST	Representational State Transfer

RRC	Ramp Rate Control
RT	Real-time
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SCL	Substation Configuration description Language
SO	System Operator
SoC	State of Charge
SOSD	System Operation Supervision Device
STC	Short-Term Control
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
VPN	Virtual Private Network
VPP	Virtual Power Plant
VRG	Variable Renewable Generation
WEC	Wind Energy Converters
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 conventional and “new” frequency and voltage controls as well as other flexibility solutions. Its approach is also innovative in the way that it can procure several services at the same time, while it is technically possible and economically interesting, in a so called “multi-services” concept.

Since the provision of the D8.1 report published 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 been working jointly to prepare the set-up of the WP8 demonstration. EDF has focused on the software and algorithm development as well as on the communication infrastructure implementation, while the ENERCON team has dedicated their effort on the set-up of the hardware and on the local experiments.

Regarding the development of software and tools for the operation of the demonstration, **a first version of the EMS (Energy Management System) of the aggregator, including an operational planning scheduler and a short-term controller, is now operational.** The developed scheduler allows to perform day-ahead scheduling and intraday rescheduling of generation planning and services’ allocation to maximize profitability, while satisfying different constraints and requests from system operators. Within each scheduling time, the layer of the short-term control ensures a continuous and correct operation of the VPP by taking appropriate actions to control the power delivered, or the state of charge of the storage. Some further control modes of the short-term controller are being developed and tested in order to enhance its functionalities and performances.

The development of the EMS was performed by means of 2 simulation platforms, specially built for the WP8 demonstration, representing the physical behaviour of the wind farm / storage aggregator:

- the offline platform dedicated to intensive tests through simulations over long periods,
- the real-time platform allowing to better understand dynamic aspects, and enabling power-hardware-in-the-loop at a later stage.

The performed tests allowed to validate the operation of the different software parts of the EMS and the implemented functions. **The first simulation results also proved the value of considering probabilistic generation forecasts and stochastic optimization for EMS development as well as intraday services rescheduling for the VPP’s operation.**

Regarding the hardware set-up and adaptation, **the full storage system was delivered in early January 2019 and fully commissioned in August 2019.** It consists of a 2.3 MW/1h Li-Ion battery container, a power interface E-Storage 2300 as well as a local controller, the E-SCU, specifically developed for the WP8 demonstration, with frequency services functions embedded. The commissioning test procedure of the storage system was carried out

following installation and proper connection of the E-Storage 2300 (power converter) and the battery containers. **On the wind farm side, the existing local controller RTU-C was replaced in September 2019 by the new controller FCU-E2, which offers advanced controls in terms of voltage and frequency services and also enhances the response time of the wind farm.** Several functions of this new controller were developed specifically for EU-SysFlex. Additionally, each wind turbine inside the Anglure wind farm was also upgraded in October 2019 to be compatible with the new FCU-E2 controller. At the time of writing this report, local individual tests of wind ancillary services are being conducted.

To enable reliable and secured data exchanges within the VPP and between different tools, software and controllers, an IEC 61850-based and hardware-agnostic communication platform as well as corresponding IT architecture and solutions were developed and started to be implemented for the purpose of demonstration. Grid Edge Devices (GED) based on the proposed solution were introduced to assure the communication between individual assets of the VPP and the EMS at the centralised level. The first GED device, the GED-S, was fully configured and tested in 2019 and has been qualified for the communication with the storage controller E-SCU following successful mapping tests and interface configurations verification.

Finally, before starting the experiments in the overall environment of the aggregator, **the capability of the installed storage system to provide individually frequency services was demonstrated locally at Concept Grid in 2019.** Each of the frequency control modes has been tested first separately with emulated frequency signals, and then in combination to prove the operation of the local controller delivering consecutively multiple services. The successful demonstration formed a good basis for the investigation of the proposed approach of ‘multi-services from multi-resources’ in WP8, expected to be performed next year.

Until the beginning of 2020, EDF and ENERCON will focus on integrating progressively the different assets into the final ‘virtual power plant’ environment:

- Although storage services have been validated separately, the communication interface with the centralized controller, GED-S, will need to be integrated into the testing chain in the next step to allow the **management of the asset through the EMS**. Moreover, now that the frequency services have been implemented into the storage controller, **controls for voltage services** need to be considered as well, and it is planned to work on this aspect early in the first quarter of 2020.
- Similar to the approach applied onto the storage, experiments of **wind services** through local activation are being prepared. The different services will be tested one by one until the end of the year, allowing for the detection and correction if required, of any unexpected behaviour of the wind FCU-E2 controller. At the same time, a remote Internet connection between the Cloud, where the EMS of the VPP is implemented, and the wind farm will have to be established.
- The whole **IT and communication platform** for the VPP operation will be entirely set up in 2020 with two more grid edge devices (GED-W and GED-LP) configured and tested, allowing the communication and

data exchange of the wind farm, the PV panels and the controllable loads with the centralized EMS. Then, as expected in the WP8 demonstration specifications, a **final integration of all the distributed resources** as well as different controllers and tools into the ‘virtual power plant’ will be targeted by the end of the first semester of 2020. Once the VPP or aggregator is operational, the multi-services provision through coordinated and optimized management of different assets will be tested and demonstrated. Post-processing feedback of the experimental results, as well as lessons learnt and suggestions will be given in the next reports of WP8.

In parallel, further development 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, by increasing the efficiency of the proposed stochastic optimization process, by modelling more services in the scheduling tool and by integrating more advanced control modes into the short-term control layer.

Further simulations over longer durations, with different variants/settings of the EMS, will be performed to support the reinforcement of the latter and to provide more conclusive results. Furthermore, the hardware-in-the-loop approach, along with real-time simulations, will be used to verify the operation of the VPP as well as different controllers, in some complex or risky scenarios that are not going to be specifically created in real life for the purpose of experimentation.

1. BRIEF 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. It is already the case in several power systems such as in Ireland [2].

Facing the constant evolution of European power systems and the growing demand of flexibility requirement, an aggregation approach based on the concept of Virtual Power Plant (VPP), allowing the aggregator to provide multiple services and flexibility products to the power system, has been proposed in the Work Package 8 (WP8) demonstration of EU-SysFlex H2020 project [3]. 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 D8.1 report [4] published in 2018 described in detail the technical specifications of the demonstration, which aims at coordinating the operation of a portfolio of distributed resources for multi-services provision to the power system. This VPP aggregates decentralized assets: wind and PV generation, a battery energy storage system (BESS) as well as controllable loads. The services that can be procured from the aggregator are well aligned with the power system scarcities at high RES (Renewable Energy Sources) penetration rates, identified in WP2 and in WP3 of the EU-SysFlex project, in terms of future needs of ancillary services such as frequency and voltage controls, as well as additional requirements on flexibility solutions [1] [5]. These services are classified into 4 categories as summarized in Table 1¹.

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 AGGREGATOR

¹ Detailed description of each service as well as their operating principles can be found in the D8.1 report of EU-SysFlex project (Chapter 1).

Decentralized resources can generally 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. That is why the WP8 demonstration proposes to develop and experiment an innovative multi-services, multi-resources control approach. From a local point of view, it is therefore expected to enhance the performance and reliability of the services procured from the VPP and to help increase the economic gain for the aggregator's operation thanks to additional revenue streams, from one or, more likely, from several levels of the electricity value chain.

For these purposes, WP8 demonstration is being built in order 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 OF THE DEMONSTRATOR

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 2.3-MW/1h lithium-ion BESS, photovoltaic panels and a variable load test bench, combined with power amplifiers and a real-time 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 150 km away, and connected to the French public distribution grid.

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 in the electric system as well as new uses such as electric vehicles or heat pumps [6]. 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 [7]. With much more computational power, real-time simulators are able to simulate very complex and large models in real-time or faster [8]. Moreover, with this infrastructure, step-by-step power-hardware-in-the-loop (PHIL) experiments² 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.

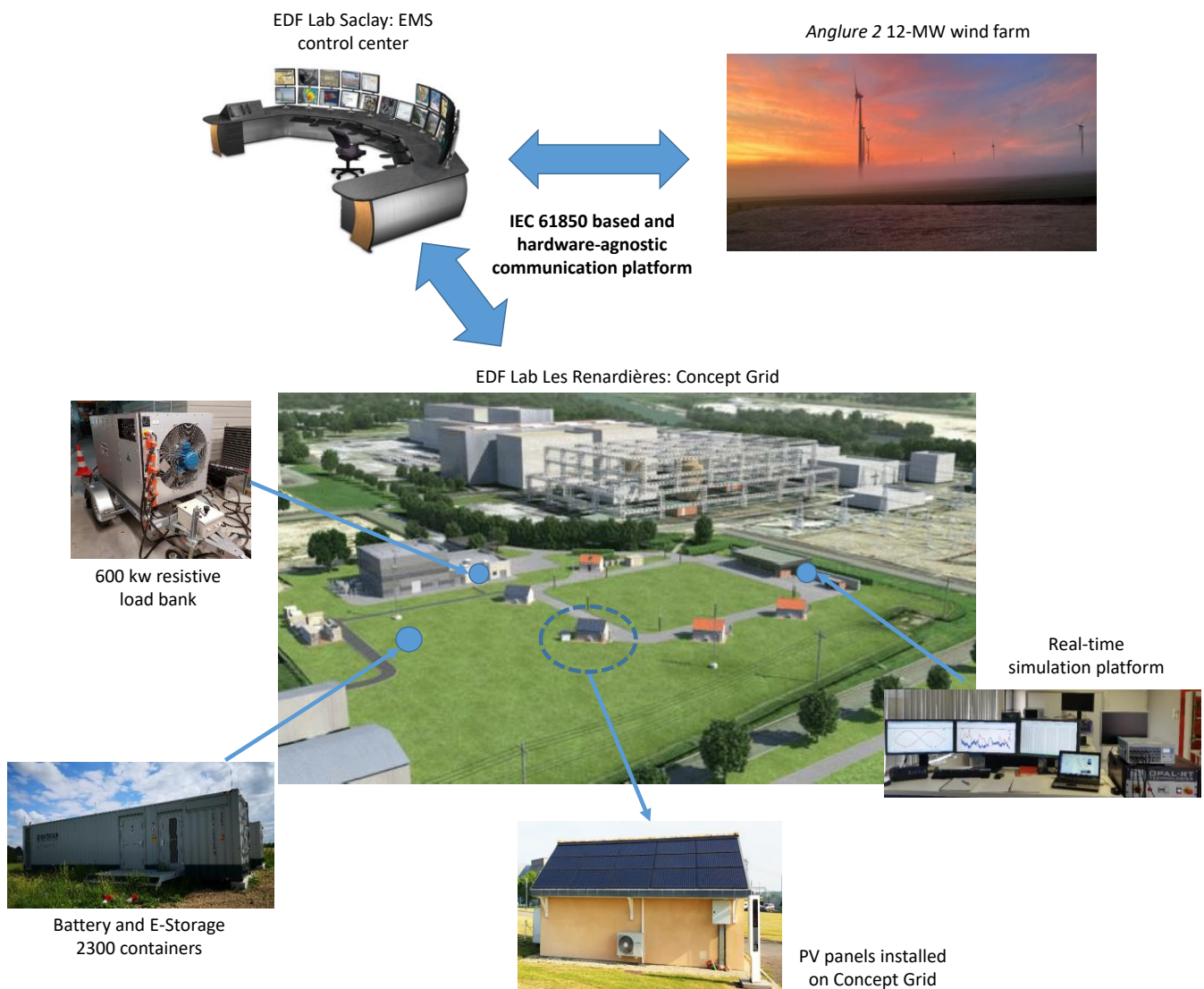


FIGURE 1. MEANS AND FACILITIES OF THE MULTI-RESOURCES MULTI-SERVICES DEMONSTRATION

² 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.

Anglure wind farm

For the demonstration, ENERCON will make available an 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 is being developed and equipped (cf. Chapter 3.2 for more details), 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 [9].

Battery storage – E-Storage 2300

A full storage system including a 2.3-MW/1h 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 (cf. Chapter 3.1 for more details). 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 primary frequency control and ramp rate reduction of active power variations from wind farms.

1.3 ARCHITECTURE OF THE DEMONSTRATOR

As presented in detail in the previous report [4], 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 will be achieved using a dedicated three-level supervisory control as illustrated in Figure 2.

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 the following main 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 is predefined by the scheduler of the upper layer allowing to optimize the use of the storage in the next scheduling time steps for the purpose of maximizing the global operational gain of the whole scheduling period; 2/ to guarantee, by using storage capacities and to the extent possible, the energy engaged by the VPP in each time step to be sold in the SPOT market facing the short-term variabilities of renewable generation; 3/ to monitor, in accordance with the requirement of system operators, the performance of the VPP in regard to the services that are scheduled to be provided.

More advanced functions can also be integrated in this control layer including, for example, the management of emergency events that occur within each scheduling time step, following the loss of a resource or the loss of communication. In this case, the STC can monitor the state and availability of the system and, if necessary, switch to another operational scenario in case of unexpected events. However, it should be noted that some of the abovementioned control objectives cannot be achieved simultaneously, due notably to the limited flexibilities that can be mobilized in practice inside a VPP in a short-term period of tens of minutes. Sometimes several objectives are even not compatible: for instance the SoC reference cannot be guaranteed while ensuring the engaged energy generated, as the storage use and the corresponding SoC control target could be totally different in these two cases. Therefore a priority of the STC objective should be set according to the VPP's operational strategy and can evolve between different control modes during the operation.

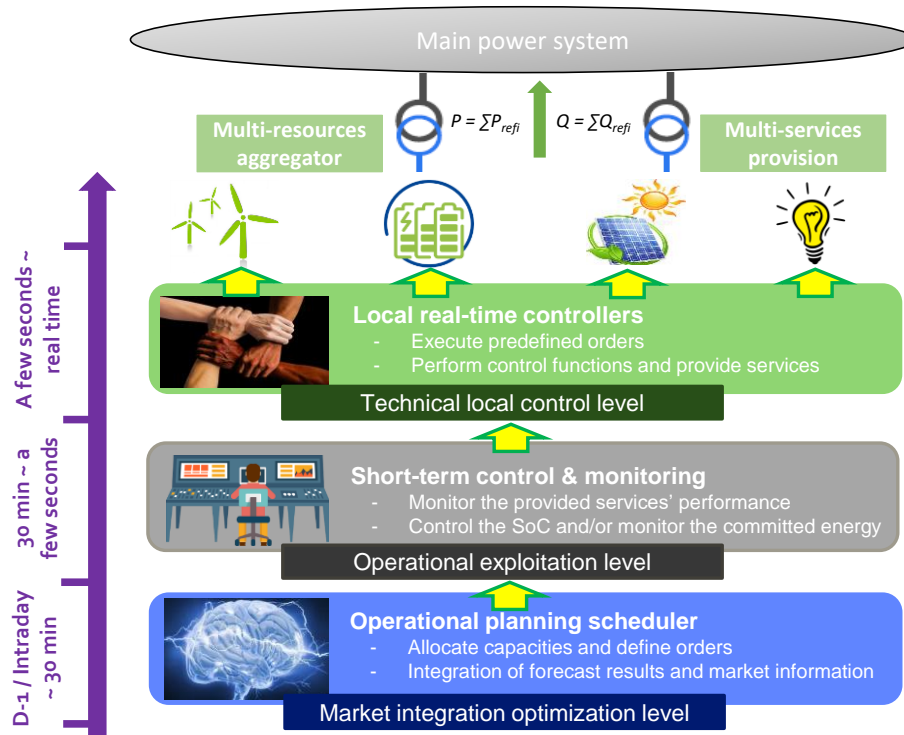


FIGURE 2. GENERAL CONTROL LAYERS OF THE WP8 DEMONSTRATION

The short-term control as well as the operational planning scheduler form together the EMS of the aggregator, which is the “brain” controlling the operation of the whole system. In the EU-SysFlex WP8 demonstration, EDF is in charge of developing the EMS of the aggregator. The detailed development work of the first year as well as the validation work through offline simulations will be presented in Paragraph 2.1 of the report.

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, depending on 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 by the system operators (SO) in the grid codes. As in practice these local controllers are implemented in the individual resources and quite linked with the nature and the physical limits of the controlled assets, in this demonstration, the design and the development of this level of control are ensured by ENERCON. Individual models of the distributed resources, including their controllers for ancillary services provision, were first developed, allowing EDF to run the simulations and to better understand the control logics for the purpose of EMS development (see Paragraph 2.2). Then experimentations were also performed locally to test and validate in real life the expected behaviour of the local controllers (see Paragraph 5.2).

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 such as 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 first version of the overall communication architecture of the demonstration was specified in 2018 [10] and is presented in Figure 3. The proposed architecture intended to represent a real and global environment that can be used by larger industrial-scale aggregator to manage several resources.

Grid Edge Devices (GED) based on the proposed solution are introduced to assure the communication between each DER and the aggregator’s EMS. This 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 one day, giving priority to the orders provided by system operators, etc. The

Device Management System (DMS), allows the update of firmware and configuration of the algorithms in the GEDs. The DMS is used for maintenance purposes in real equipment. In the present demonstration, the DMS was proposed to be added in order to test different algorithms and parameter settings which can be deployed in the GEDs remotely.

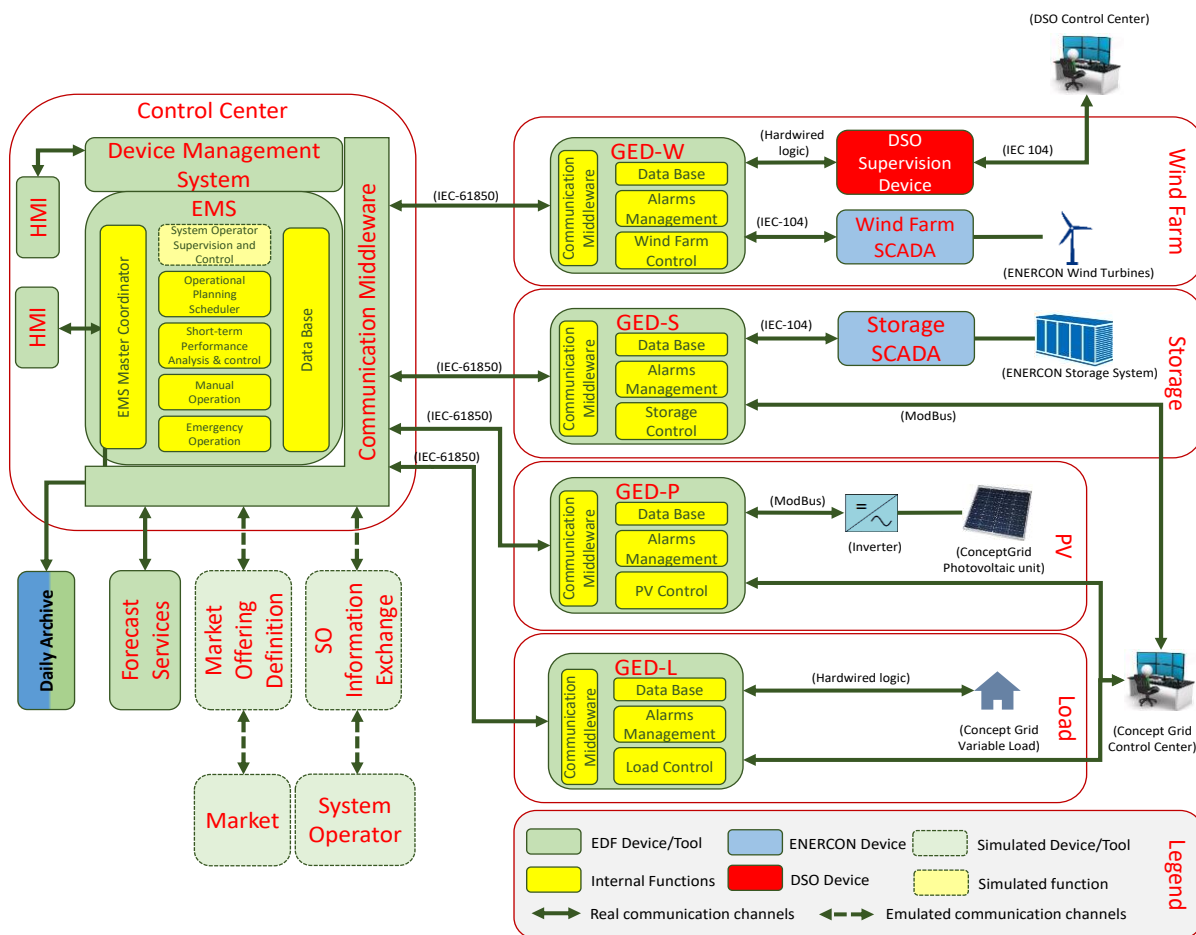


FIGURE 3. DEMONSTRATION COMMUNICATION ARCHITECTURE – FIRST VERSION SPECIFIED IN 2018

This first version of the communication infrastructure specification has evolved during the second year's work with necessary updates and several light modifications in order to be more adapted to the demonstration needs and to better consider the hardware constraints. These updates as well as the communication system implementation work will be presented in detail in Chapter 4.

1.4 ORGANIZATION OF THE REPORT

The D8.2 report presents the state of progress of the second year's work in WP8 of EU-SysFlex project. The main tasks consist of setting up the hardware components and implement the communication system to build the demonstration, as well as developing and integrating different software and tools allowing its operation.

- In Chapter 2 of the report, the operating principle and the algorithm development of the EMS and of the local controllers will be detailed. This work was performed with the help of both offline and real-time simulation platforms representing the behaviour of the aggregator. Obtained simulation results will also be presented in the same chapter.
- The main work regarding the hardware preparation in the year of 2019 was concentrated on the storage installation and connection at Concept Grid, as well as the necessary adaptation and updates inside the Anglure wind farm. This part of work will be presented in Chapter 3.
- Chapter 4 will give an overview of the IT (Information Technology) and communication architecture set-up, including the development of the IT solutions for the demonstration, the configuration of communication systems as well as the first version of HMI (Human Machine Interface).
- In the following chapter 5, some first experimental tests that were successfully performed at a local level, notably by using the installed storage system, will be shown.
- Conclusions and next steps of WP8 development will finally be given at the end of the report.

2. SOFTWARE AND ALGORITHM DEVELOPMENT

2.1 EMS DEVELOPMENT

As mentioned above, the EMS of the aggregator is the “brain” controlling the operation of the VPP. It is composed of two control layers:

- an operational planning scheduler that provides day-ahead / intraday service schedules,
- a Short-Term Control that provides short-term program adjustment capacities.

This section is organised as follows. First, Paragraphs 2.1.1 and 2.1.2 present the development progress of the operational planning scheduler and the short term control respectively. Then, Paragraph 2.1.3 details an offline simulation platform dedicated to intensive tests for the EMS software development. Finally, some simulation results over one particular day are given in 2.1.4 to illustrate the operation of the different layers of the EMS.

2.1.1 OPERATIONAL PLANNING SCHEDULER

2.1.1.1 GENERAL DESCRIPTION AND MAIN ISSUES

The operational planning scheduler aims at defining the services to be provided by each resource (PV farm, wind farm, BESS and controllable load) 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.

Several issues have to be addressed when designing the scheduler. The most significant ones are the following:

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

Up to now, development work mainly focuses on the first issue and especially on the consideration of the generation uncertainty in the optimization process of services scheduling.

2.1.1.2 EXISTING DEVELOPMENT BEFORE EU-SYSFLEX PROJECT

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 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.

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.

Note that only deterministic optimization approaches were possible with the scheduler software before the EU-SysFlex project. 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 process³.

2.1.1.3 BASE MODEL OF THE VPP FOR THE SERVICES SCHEDULING OPTIMIZATION

The first task was to model the power flows within the VPP, and between the VPP and the different markets, using the user graphical interface of the scheduler software (Figure 4). The current model includes three resources: a BESS, a wind farm and a PV farm. It allows to perform services scheduling optimization in case the aggregator provides at most 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.

³ 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.

In addition to this graphical model, which gives the power flow equations to be satisfied during the optimization process, a configuration file has been created to provide additional equations, corresponding data (prices, wind and PV generation), the period of optimization, the sampling interval size and other optimization parameters.

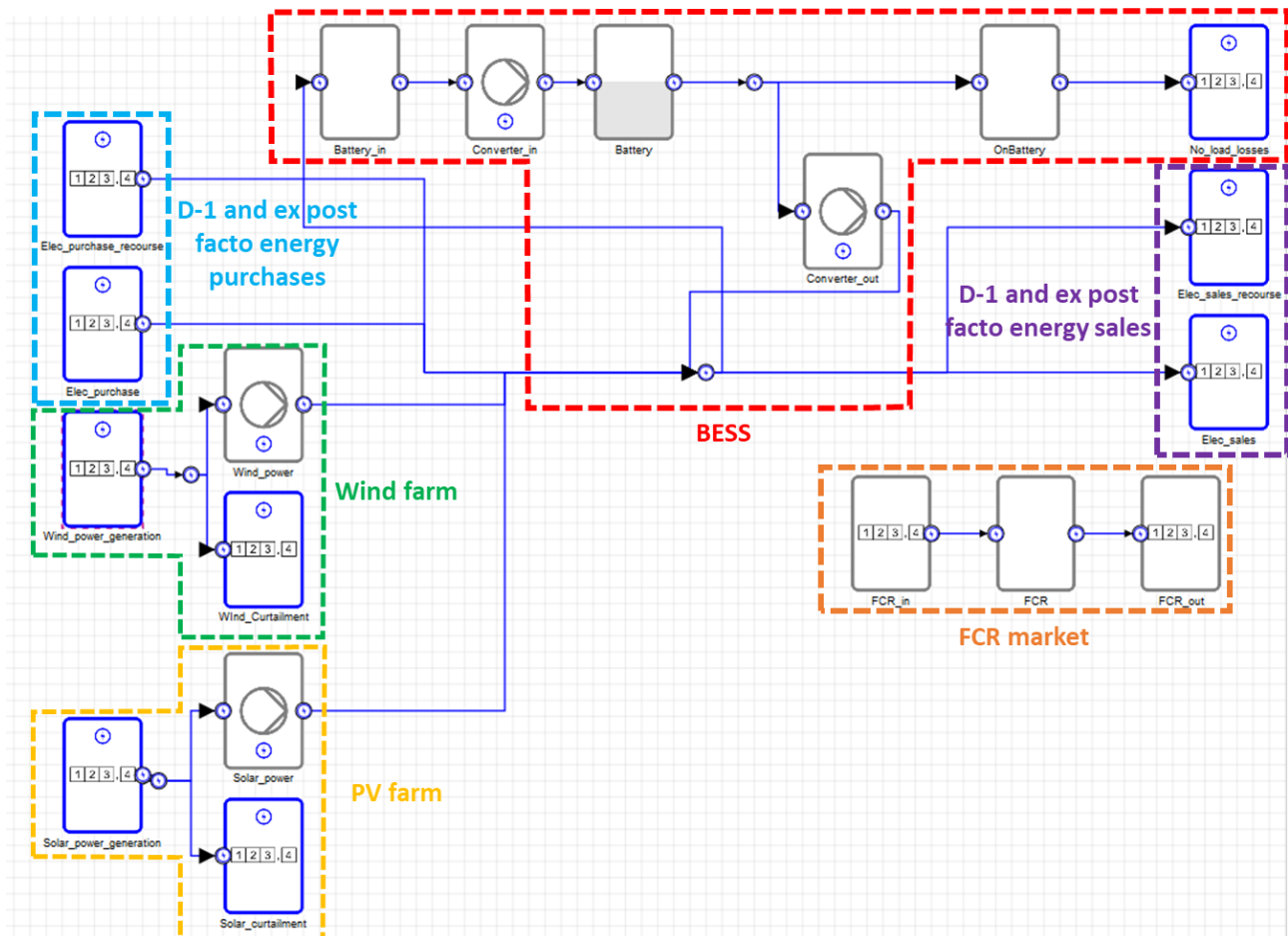


FIGURE 4. BASE MODEL OF THE VPP IN THE SCHEDULER SOFTWARE

Some of the additional equations are related to the simplified market assumptions adopted in the demonstration project. 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.

2.1.1.4 STOCHASTIC OPTIMIZATION OF THE SERVICES SCHEDULING

Classical deterministic optimization approaches show some limitations regarding how uncertainties like renewable generation forecast errors can be taken into account. Using stochastic optimization algorithms can overcome this. Within the EU-SysFlex project, the operational planning scheduler software was improved to enable stochastic optimization using probabilistic PV and wind generation scenarios.

The solution adopted was to remain simple and to use a two-stage stochastic programming approach. The general paradigm is that a decision needs to be made prior to observing uncertainty (first-stage decision), while another can be made after uncertainty has been revealed (second-stage or recourse decision). The optimal policy from such a model is a single first-stage policy and a collection of recourse decisions that define which second-stage action should be taken in response to each uncertain outcome. In the case of the operational planning scheduler:

- The first-stage decision is the aggregator's commitment to the day-ahead markets, i.e., the day-ahead energy sales/purchases and the level of FCR. The aggregator's commitment 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.

In addition to the two-stage stochastic optimization algorithm, another algorithm has been developed to randomly create PV and wind generation scenarios using two types of data:

- 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,
- copula historical data, which describe the dependence between the generation values at different points of time.

At present, stochastic optimization of services scheduling is done using 25 random generation scenarios (5 for wind generation and 5 for PV generation). Some examples of generation scenarios and stochastic optimization results are given in 2.1.4.

2.1.1.5 NEXT DEVELOPMENT

A first release of the scheduler was developed and is currently being tested on an offline simulation platform that has been especially designed for the EU-SysFlex demonstration (Paragraph 2.1.3). The current scheduler provides an optimal services schedule for the VPP in the next 36 hours with a sampling interval of 30 minutes. Especially, it provides the day-ahead commitment schedule at 12:00 for the next day, and can update this schedule (using a recourse market that corresponds to intraday or ex post facto energy sales/purchases) every 30 minutes the very day to compensate for contingencies like forecast errors.

Future work will focus on the following issues:

- First, the provision of ancillary services (e.g., FCR) causes uncertainties on several electrical quantities that have not been taken into account in the services scheduling process yet. Like the generation forecast errors, the uncertainty on the SoC of the BESS due to ancillary services could be considered using SoC deviation scenarios.
- Second, 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. There is therefore a clear need to reduce the computation time without degrading the schedule 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).
- Third, 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 services schedule could be optimized for a user-defined percentage of scenarios (e.g., 90% of the scenarios).
- Finally, all the frequency support and flexibility services listed in Table 1 should be modelled in the operational planning scheduler⁴. The main issues are the proper modelling of the services provided by the wind farm and the definition of appropriate services compatibility rules.

2.1.2 SHORT TERM CONTROL

As explained in part 2.1.2, the operational planning scheduler is run every 30 minutes to optimize the intraday services schedule of the VPP using the most recent renewable generation forecasts and the up-to-date SoC of the BESS. Especially, for the next 30-minute interval, the operational planning scheduler computes the amount of energy that the VPP needs to produce/consume as well as the power to reserve on the FCR market.

⁴ The reactive power services will not be included in the scheduler, as no specific optimization process will be needed to allocate the reactive power reserves and only the limits on the total apparent power will be considered in the scheduling parameters. Nevertheless, the reactive power services will be tested under real conditions at Concept Grid, with/without other services activated at the same time.

However, because of its resolution time, the operational planning scheduler does not consider what happens within each 30-minute interval and therefore does not take any appropriate follow-up action. For example, the performance control of the primary frequency regulation requires an assessment of the power on a second-time basis. Also, the loss of a resource or the loss of communication cannot be managed by the scheduler. That is why a layer of STC is necessary to ensure the continuous and correct operation of the VPP by handling unexpected schedule deviations or unsatisfying performance of the provided services. The goals of the STC could be as follows:

- **Managing emergency events**

The STC can monitor the state and availability of the different assets of the VPP and, if necessary, switch to another operational scenario in case of unexpected events (e.g., loss of a resource or communication).

- **Monitoring the performance of the provided services**

The provision of grid services involves ensuring a certain level of performance. For example, for the primary frequency regulation, the French Transmission System Operator (TSO) requires the assets to maintain their control gain in a certain range around the value specified by the contract with the TSO, on penalty of a partial remuneration. This means that during operation, the STC has to analyze the output power of the different resources in order to monitor the real-time performance of the aggregator. Therefore, the STC can put in place any remedial action if the measured performance is far from the required one.

- **Ensuring the commitment on the markets**

As mentioned previously, every 30 minutes for the next 30-minute interval, the operational planning scheduler computes at least the energy to sell in the electricity market and the amount of reserve to provide on the ancillary services market. However the STC has to face the short-term variabilities of renewable generation and should therefore mobilize the available flexibilities inside the VPP (e.g. BESS or controllable loads) to meet the commitment to the different markets.

It should be noted that some of the abovementioned goals are mutually incompatible. For example, guaranteeing the performance of frequency regulation services may lead to using the BESS for more margins. These energy reserves placed on the BESS are synonymous with less flexibility in order to face short-term renewable generation deviations. Because some objectives of the STC are conflicting, priorities should be established within the different control modes.

Figure 5 depicts the timeline of the EMS and especially the task performed by the STC. Based on the instructions provided by the operational planning scheduler for the ongoing 30-minute interval, the STC sends setpoints every second to each resource by taking into account the deviation between forecasted and actual renewable powers seen on this second-time basis, the performance of the provided services and potential emergency events.

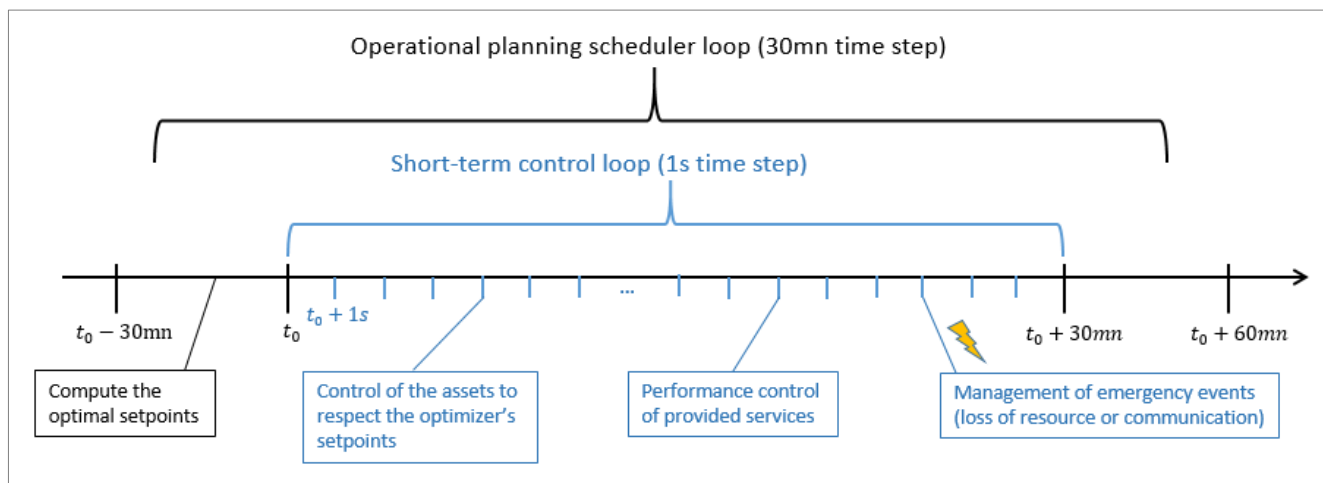


FIGURE 5. OPERATION OF THE SHORT TERM CONTROL WITHIN THE EMS TIMELINE

For now, first versions of some control modes have been developed and are being tested in the offline and real-time simulations. More specific control strategies along with different priority scenarios, as well as the appropriate methods of performance control for frequency regulation services, will need to be further developed and integrated into the short-term control.

2.1.3 OFFLINE SIMULATION PLATFORM

The different hardware and software components of the VPP are closely interlinked and may therefore impact the development of each component of the EMS. For example, the SoC of the BESS at a given time depends on the services' schedule provided by the operational planning scheduler, the mode of the STC as well as field measurements (e.g., electrical frequency, renewable generation, and local voltage). Conversely, the operational planning schedule updates the schedule of the BESS based on the most recent measure of SoC available. Therefore, optimising each component of the EMS separately, without considering the interactions with other EMS or VPP components, does not mean that the operation of the whole system will be optimal. On the contrary, it may lead to unexpected or even undesirable behaviour of the whole system.

That is why an offline simulation platform, **dedicated to intensive tests for the EMS software development**, has been developed for the demonstrator. This platform 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 the dynamic behaviour of the VPP in response to the services schedule (provided by the operational planning scheduler), the short-term control adopted, and time series of electrical frequency and renewable generation. For example, the behaviour of the VPP can be studied in the following cases:

- In normal conditions, to study the deviations from the services schedule, resulting from the generation forecasts errors, the unpredictable consequences of certain services (e.g., the deviation of SoC caused by the provision of FCR), etc.
- With intraday services rescheduling based on the most recent forecasts and measures available.

- When a contingency occurs and makes it impossible to completely meet the last services schedule provided by the operational planning scheduler.
- Over long periods, from a few days to several months.

The offline simulation platform is a useful tool to test and enhance the EMS before coupling it to hardware components. For instance, the platform can help us assess how compatible two services are, and thus identify the compatibility conditions to be satisfied by the operational planning scheduler. More generally, the platform allows us to carry out sensitivity analyses on specific parts of the control system, e.g., the short term control mode or on certain services. Consequently, the different software parts can be jointly tuned to **improve the global performance and robustness of the EMS**. An example of results from the offline simulation platform is given in Paragraph 2.1.4.

As shown in Figure 6, the offline simulation platform is mainly composed of three components: the operational planning scheduler itself, a Simulink model of the short term control, local controllers and resources, and a MATLAB script corresponding to the “EMS core”, which makes the first two ones work together. It performs several tasks as frequently as may be necessary to obtain the simulation results over the period asked by the user, such as writing the last forecasts and measures in the database of the operational planning scheduler or processing the schedule and sending appropriate setpoints, parameters and inputs to the Simulink model.

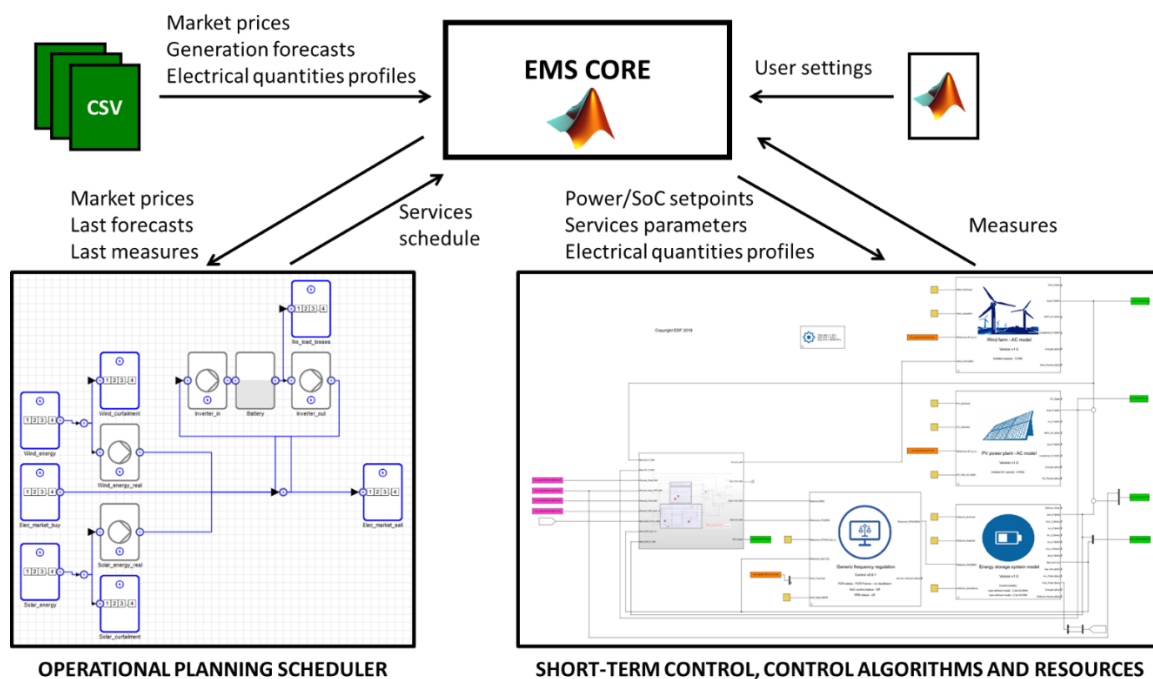


FIGURE 6. THE OFFLINE SIMULATION PLATFORM

The Simulink model is detailed in Figure 7. It aims at simulating the “real-time” behaviour of the VPP (with a 1-second interval for example) in response to a given services schedule (magenta blocs in Figure 7) and to time series of electrical quantities such as renewable generation and electrical frequency (orange blocs in Figure 7).

The current model includes three kinds of components:

- the first version of short-term control,
- the local controller of the BESS enabling FCR and SoC controls,
- three generic resources, which are a wind farm, a PV farm and a BESS.

Different outputs of the Simulink model (green blocs in Figure 7) can be “measured” and then considered by the operational planning scheduler: actual power and SoC of the BESS, actual power of the PV and wind farms, actual power of the VPP, etc.

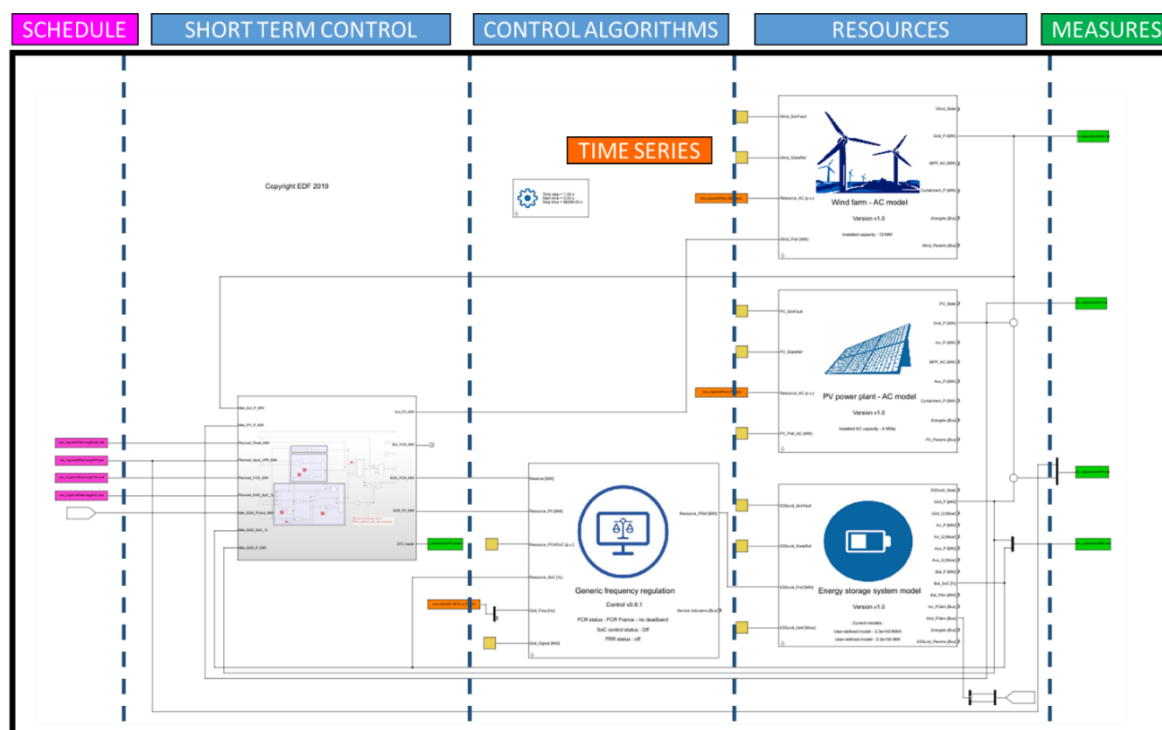


FIGURE 7. THE SIMULINK MODEL: SHORT-TERM CONTROL, CONTROL ALGORITHMS AND RESOURCES

Note that some components of the demonstrator are modelled in a simplified way, as their detailed models are not necessary for the EMS development. For instance, only the communication delay between components is modelled as a pure delay in the Simulink model but the whole communication architecture and devices are neglected in the offline simulation platform.

2.1.4 FIRST SIMULATION RESULTS

Some simulation results over one particular day are given in this section to illustrate the operation of the different software parts of the EMS. Paragraphs 2.1.4.1, 2.1.4.2 and 2.1.4.3 show examples of day-ahead services schedules when applying the operational planning scheduler to deterministic then probabilistic generation forecasts. Some economic figures based on simple assumptions are given to highlight the value of performing a scenario-based

optimization when renewable generation is hardly predictable. Paragraph 2.1.4.4 presents the evolutions of the intraday services schedule over 24 hours using the offline simulation platform of the EMS.

The following assumptions are made for all the examples presented in this section:

- The VPP comprises three resources, which are a 12-MW wind farm, a 6-MW photovoltaic farm and a 2.3-MW/1h BESS.
- The aggregator provides at most two services, which are:
 - o the energy arbitrage, by exploiting all the resources,
 - o the FCR, provided by the BESS only. If provided, the FCR is assumed to be constant for 4 hours (which corresponds, in general, to practical cases).
- The net energy provided/consumed by the VPP has to be sold/purchased on the electricity market. There is no guaranteed feed-in tariff for the PV and wind farms.
- The service price forecasts are assumed to be perfect.
- To make the examples easier to understand, the aggregator is assumed to provide its day-ahead schedule at midnight. The schedule is then optimized for the next 24 hours with a 30-minute interval.⁵ In this way, the SoC of the BESS at the beginning of the considered day is the same for all the examples, and the expected D-1 income is optimized using only the forecasts for this day.
- Due to its high complexity, the intraday electricity market is not considered. In other words, the aggregator intends to meet its day-ahead schedule. Deviations from this schedule are valued at the positive/negative imbalance settlement prices.
- The initial SoC of the BESS is set to 50%.

2.1.4.1 DAY-AHEAD SCHEDULING USING DETERMINISTIC FORECASTS

The purpose of this part is to illustrate through two simple examples the potential value that an EMS may provide to an aggregator. The focus is on the day-ahead schedule provided by the EMS using deterministic generation forecasts. In other words, the additional gain shown in this part is actually achieved provided there are neither forecast errors nor contingencies. The impact of the forecast errors on the full income will be illustrated in the following part (2.1.4.2).

Example n°1 - the aggregator provides energy arbitrage only:

First, the considered case is that an aggregator seeks only to maximize its earnings on the day-ahead electricity market ("energy arbitrage" service). To do so, the aggregator has to commit to a daily energy schedule, which is created the day before, using the most recent forecasts available. Figure 8 depicts the corresponding schedule generated by the operational planning scheduler of the EMS when considering perfect forecasts for the day-ahead market prices (Figure 8.a) and the renewable generation (dashed black line in Figure 8.b). As expected, the EMS schedules the BESS operation so as to maximize the earnings of the VPP on the electricity market. Indeed,

⁵ For the field experiments, the aggregator will be assumed to provide its day-ahead schedule at noon the day before. The schedule will therefore be optimized for the next 36 or 48 hours with a 30-minute interval.

renewable energy is stored in the BESS when the prices are the lowest (from 4:00 to 5:00 and from 15:00 to 16:00) and reinjected when they are the highest (from 8:00 to 9:00 and from 18:00 to 19:00).

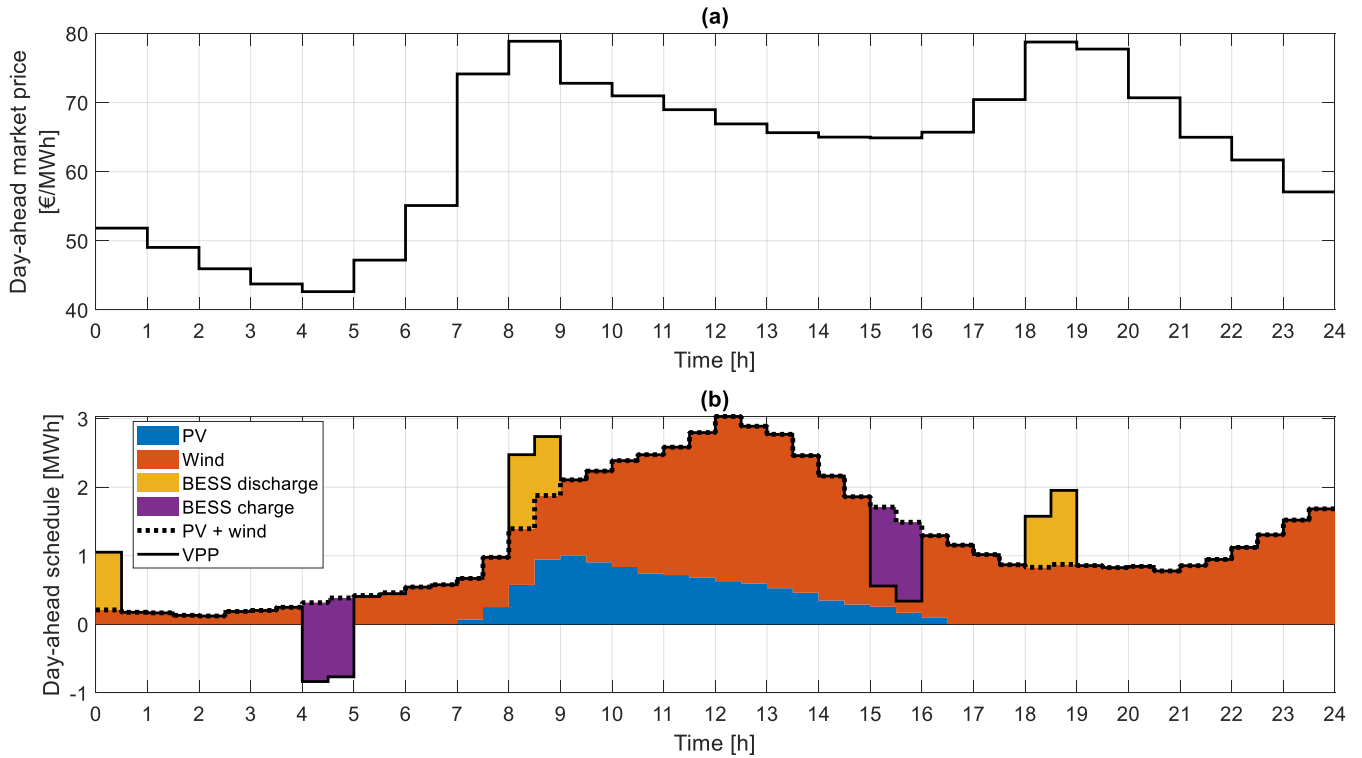


FIGURE 8. (A) DAY-AHEAD MARKET PRICE. (B) CORRESPONDING DAY-AHEAD SCHEDULE FOR THE VPP TO PROVIDE ENERGY ARBITRAGE WHEN CONSIDERING DETERMINISTIC GENERATION FORECASTS

As shown in Figure 9, the day-ahead schedule proposed for the BESS meets its power and energy capacities. **For this particular day, the use of the EMS would result in an additional gain of 91 euros on the day-ahead electricity market.** Note that this additional gain is limited by the BESS size considered (2.3-MW/1h).

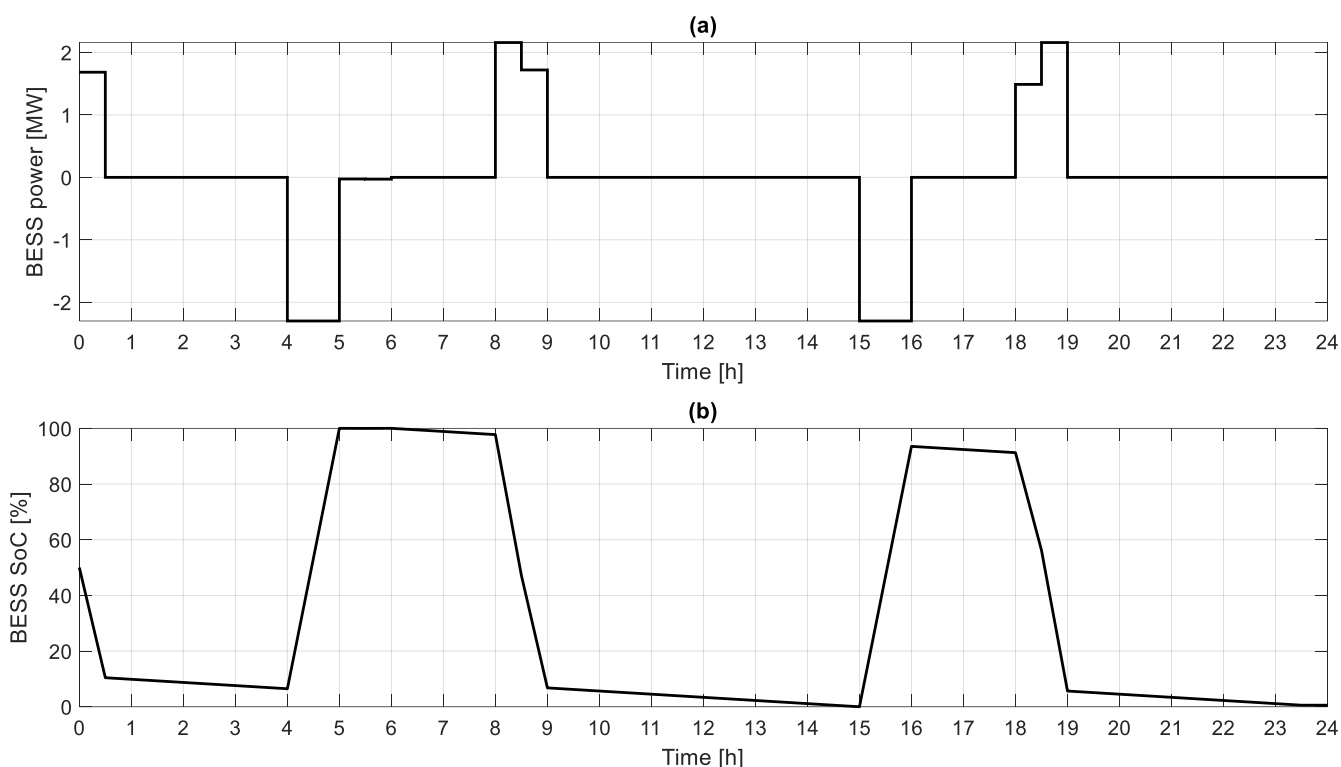


FIGURE 9. DAY-AHEAD SCHEDULE OF THE BATTERY: (A) POWER, AND (B) STATE OF CHARGE

Example n°2 - the aggregator provides Energy arbitrage and/or FCR:

Now, the considered case is that an aggregator seeks to maximize its earnings by combining energy arbitrage with the provision of FCR by the BESS. If the FCR price is arbitrarily assumed to equal 10 €/MW/h, then the operational planning scheduler provides the day-ahead schedule shown in Figure 10. The BESS is almost always used for providing FCR since this service is more profitable than energy arbitrage. Small charges of the BESS (not visible in Figure 10) are planned to compensate its operating losses.

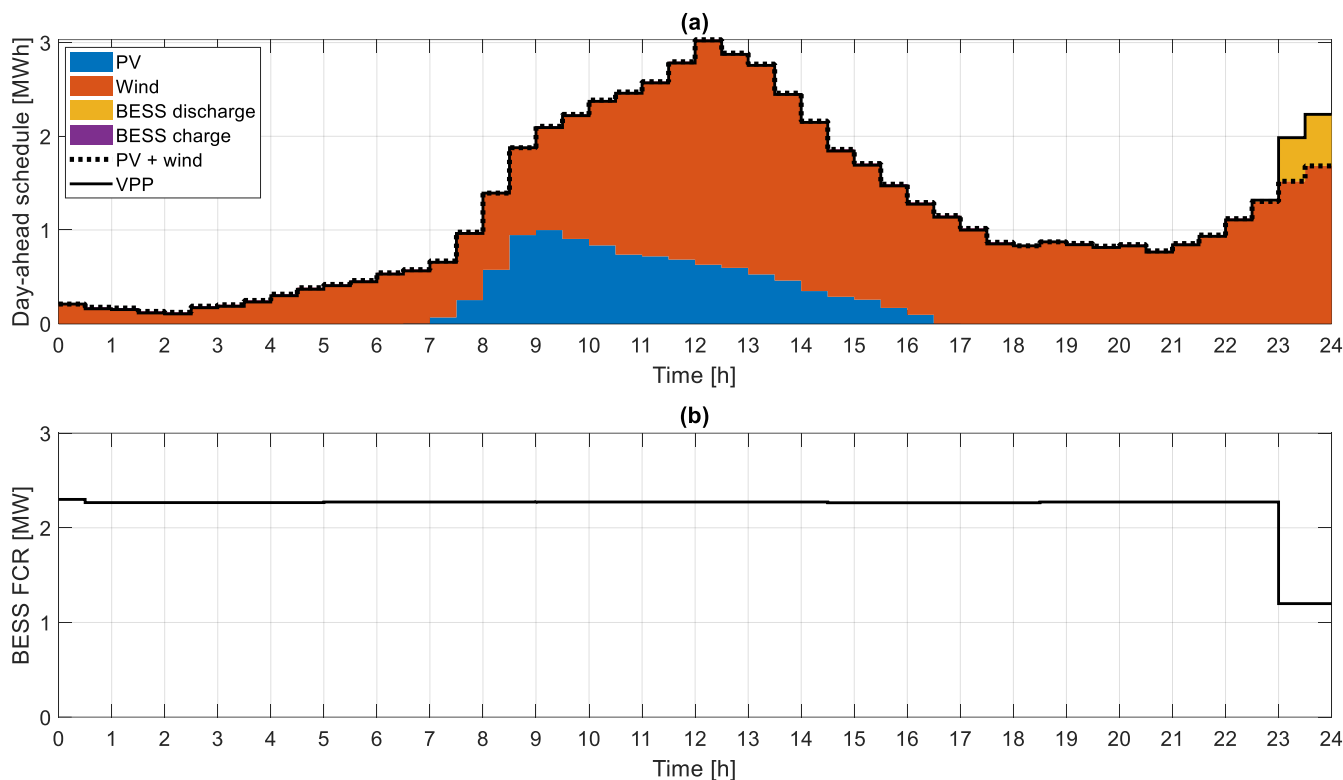


FIGURE 10. DAY-AHEAD SCHEDULE FOR THE VPP TO PROVIDE ENERGY ARBITRAGE AND FCR WHEN CONSIDERING DETERMINISTIC GENERATION FORECASTS: (A) ENERGY SCHEDULE FOR THE VPP, AND (B) FCR FOR THE BESS

Note that the BESS discharge at 23:00 is due to the period covered by the scheduling optimization process (24 hours); it would not occur in case of a longer optimization period combined with intraday services rescheduling.

For this particular day, the expected additional gain is 556 euros, i.e., 465 euros more than the previous schedule (without FCR provision).

2.1.4.2 IMPACT OF THE FORECAST ERRORS ON THE FULL INCOME

The additional gain mentioned in Paragraph 2.1.4.1 is the expected value provided by the EMS when any contingency occurs this very day. The reality is that hardware failure and even forecast errors may strongly impact the full income of the aggregator. In particular, day-ahead generation forecasts are often inaccurate as depicted in Figure 11⁶.

⁶ It should be noted that in this figure, cumulated energy deviations between the forecasts and the real generation are shown.

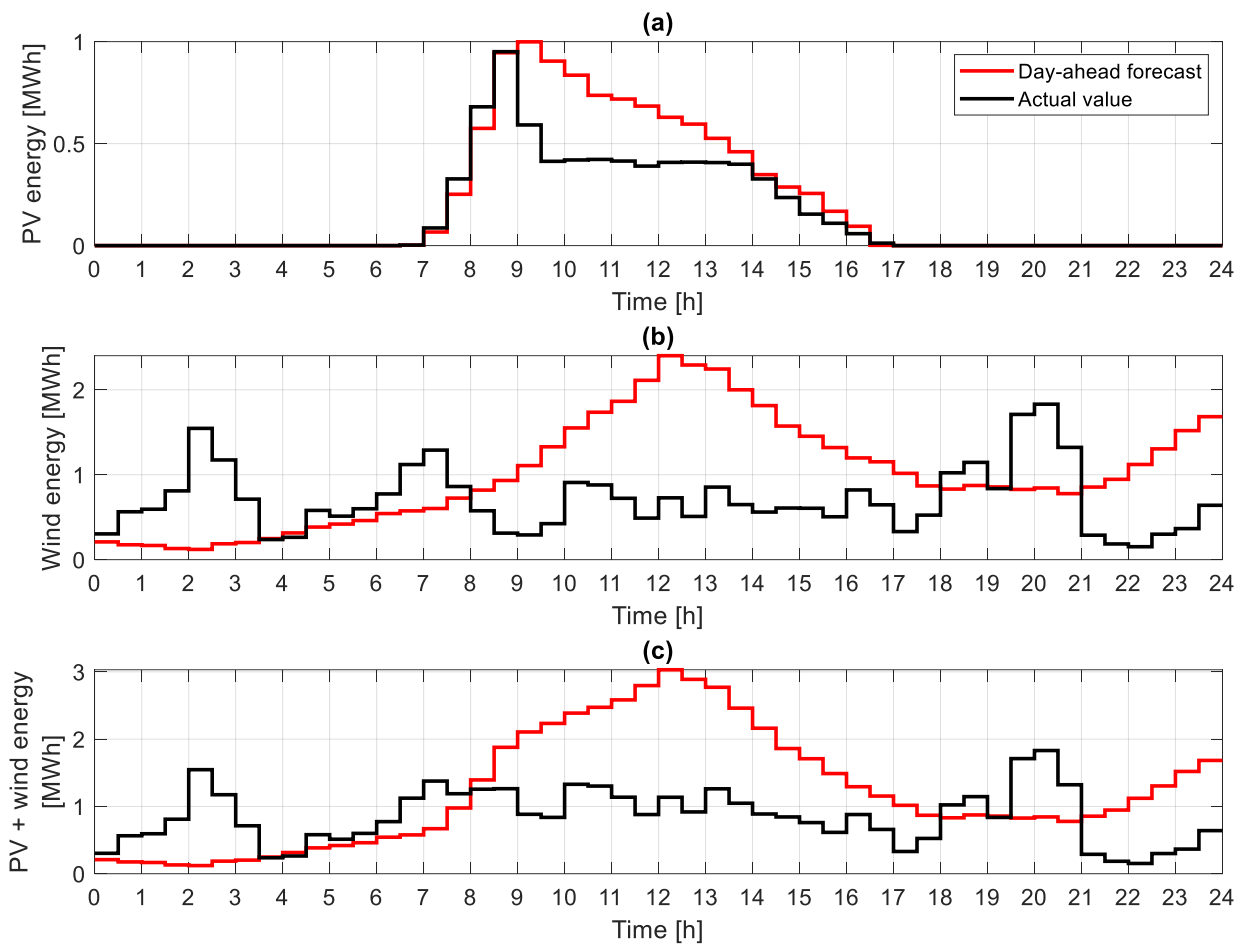


FIGURE 11. DETERMINISTIC DAY-AHEAD FORECAST AND ASSOCIATED GENERATION: (A) PV, (B) WIND, AND (C) PV + WIND.

This results in significant gaps between the day-ahead schedule of the VPP and its actual injected/consumed energy. For example, Figure 12.b highlights these gaps when the aggregator performs “energy arbitrage” only (Figure 8.b), assuming that: (1) the BESS keeps to its day-ahead schedule and (2) no intraday schedule updates are made⁷. As the aggregator does not meet its day-ahead schedule, the full income must include not only the gain on the day-ahead electricity market but also two other components:

- the loss caused by a lack of energy over any 30-minute interval (green area in Figure 12.b),
- the gain resulting from an excess of energy (blue area in Figure 12.b).

Note that **the real full income of the VPP is necessarily lower than the theoretical maximum day-ahead income of the VPP (obtained from perfect forecasts)** since:

- the negative imbalance settlement price is equal or higher than the day-ahead market price,
- the positive imbalance settlement price is equal or lower than the day-ahead market price (Figure 12.a).

⁷ These assumptions allows us to compute the actual energy of the VPP the very day without using the offline simulation platform.

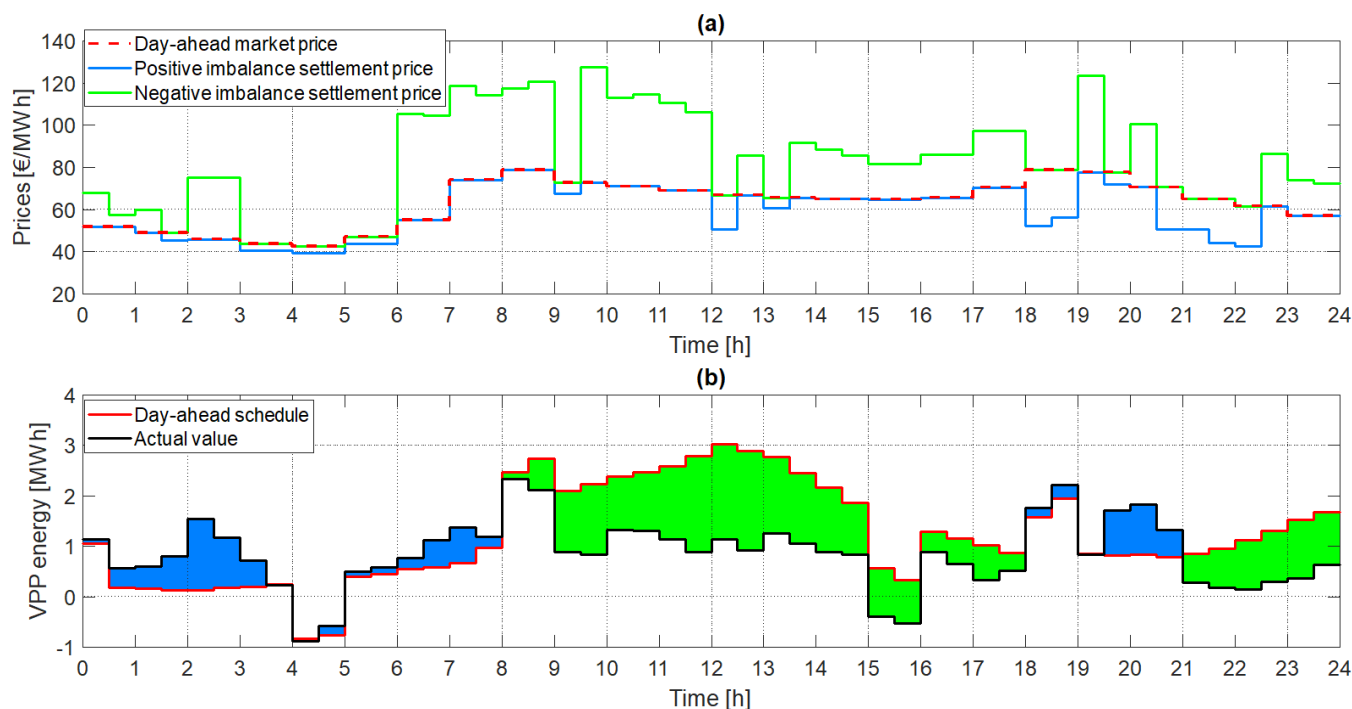


FIGURE 12. (A) PRICES OCCURING IN THE VPP FULL INCOME. (B) DAY-AHEAD SCHEDULE VERSUS ACTUAL ENERGY OF THE VPP

For instance, the costs and benefits for the considered study case are detailed in Table 2. It turns out that the forecast errors cause a loss in earnings of 13% for this particular case.

	Perfect forecasts	Deterministic forecasts
Day-ahead income	+2764 €	+4036 €
Expected positive imbalance settlement gain	0 €	+524 €
Expected negative imbalance settlement loss	0 €	-2425 €
Expected full income	+2764 €	+2135 €

TABLE 2. EXPECTED COSTS AND BENEFITS WHEN PROVIDING “ENERGY ARBITRAGE” SERVICE OVER ONE PARTICULAR DAY, WITH PERFECT AND DETERMINISTIC GENERATION FORECASTS, WITHOUT INTRADAY RESCHEDULING

2.1.4.3 DAY-AHEAD SCHEDULING USING PROBABILISTIC FORECASTS

Renewable generation uncertainty should be taken into account in the services scheduling in order to maximize the full income. This can be done by considering probabilistic generation forecasts. Probabilistic forecasts result from the same statistical model used to build deterministic forecasts, and also include the distribution of the forecast errors of this model over the training period. As shown in Figure 13, probabilistic forecasts are composed of several quantiles (5%, ..., 95%) that give information on the generation probability distribution at a given point of time. Specifically, the X%-quantile corresponds to the probability of the generation being less than or equal to X%.

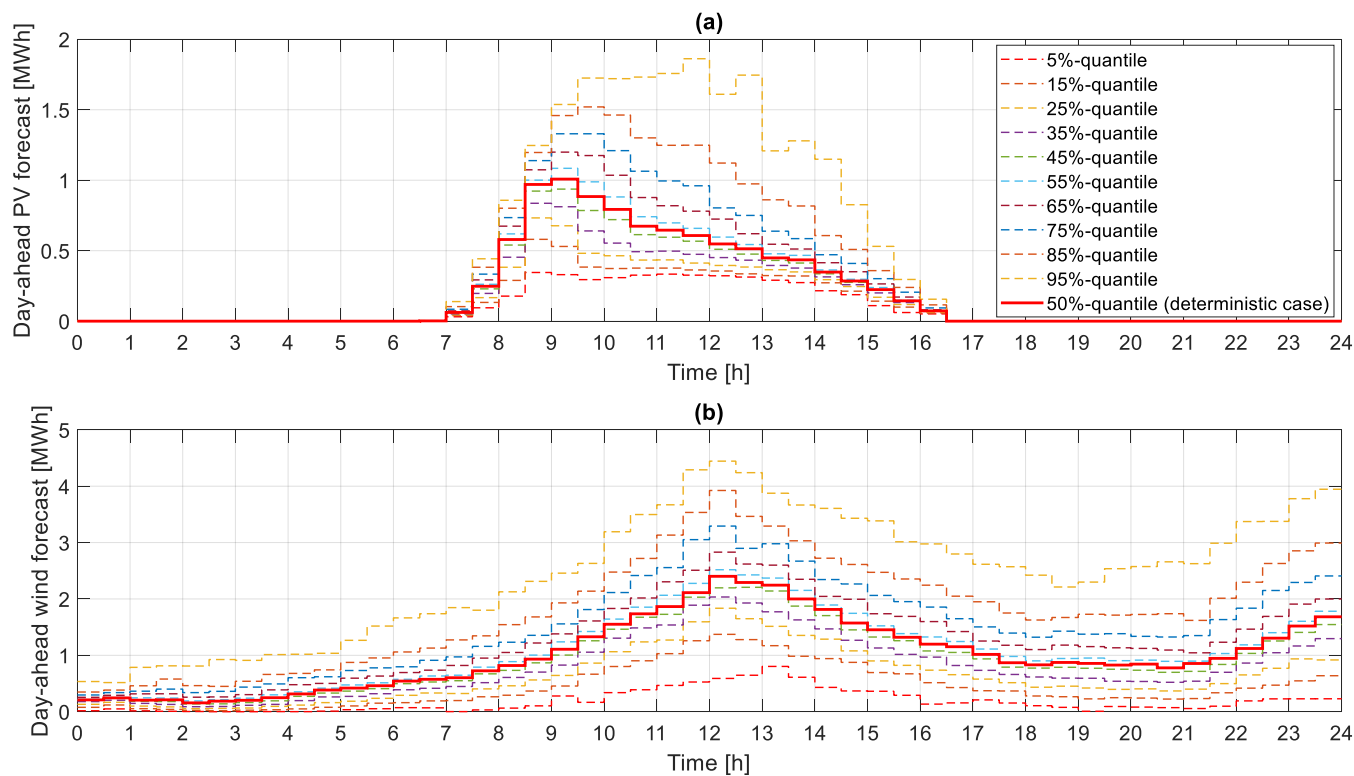


FIGURE 13. DAY-AHEAD PROBABILISTIC GENERATION FORECASTS

Using these quantiles as well as copula historical data (which describe the dependence between the generation values at different points of time), it is possible to create stochastic generation scenarios as depicted in Figure 14. The generation uncertainty can therefore be addressed in the services scheduling process using a large number of scenarios.

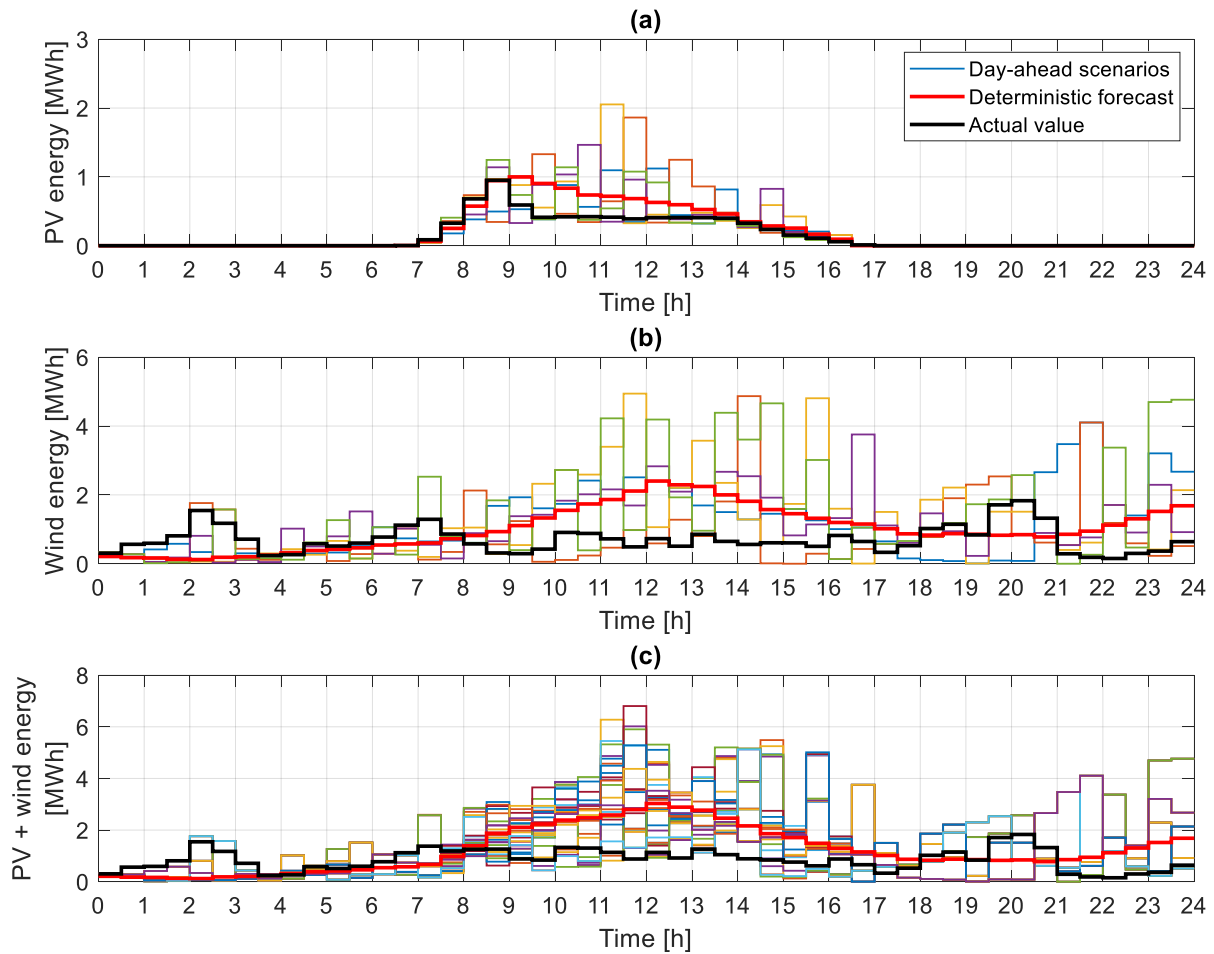


FIGURE 14. EXAMPLES OF STOCHASTIC SCENARIOS GENERATED FROM PROBABILISTIC GENERATION FORECASTS: (A) PV, (B) WIND, (C) PV + WIND

Given these various scenarios, the operational planning scheduler has to provide a unique day-ahead schedule for the VPP. The choice has been made in the optimisation process to generate a day-ahead schedule for the VPP common to all the scenarios and to fill the gap between this schedule and the renewable energy, which is specific to each scenario, by using two flexibilities: (1) the BESS charging/discharging, and (2) ex post facto energy purchases/sales on an intraday market or through the imbalance settlement mechanism. If provided, the FCR service has to be the same for all the scenarios too.

For instance, Figure 15 shows the day-ahead results when applying the operational planning scheduler to the stochastic scenarios depicted in Figure 14, in case the aggregator performs “energy arbitrage” only:

- the potential overall energy of the VPP (coloured curves in Figure 15.a), which is composed of: (1) the day-ahead schedule to be committed (black curve in Figure 15.a) and (2) the potential ex post facto energy purchases/sales (gaps between the black curve and the coloured one in Figure 15.a);
- the potential state of charge of the BESS (coloured curves in Figure 15.b).

It is worth noting that:

- In most scenarios, the BESS is expected to be fully charged from 6:00 to 8:00 and from 16:00 to 18:00, which allows injecting energy to the grid when the day-ahead market prices are expected to be the highest.
- A unique day-ahead schedule for the BESS cannot be easily defined when a scenario-based stochastic optimisation of the services scheduling is considered. That is why the operational planning scheduler demands the same operation of the BESS during the first hours of all the scenarios (from 0:00 to 1:00 in this example). This requirement allows us to define a short-term power/energy target to be achieved by the BESS (on an intraday basis with the short term control), regardless of the generation uncertainty.

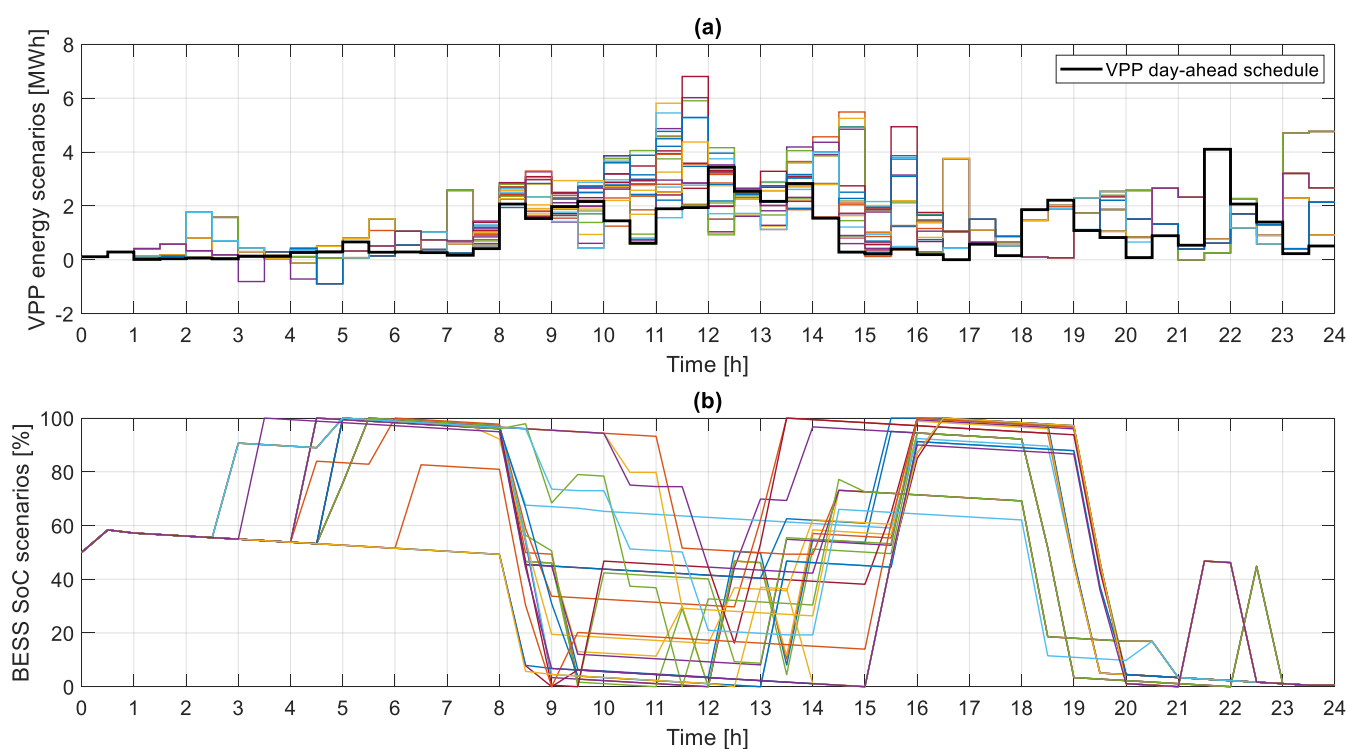


FIGURE 15. DAY-AHEAD SCHEDULE FOR THE VPP TO PROVIDE ENERGY ARBITRAGE WHEN CONSIDERING PROBABILISTIC GENERATION FORECASTS: (A) ASSOCIATED SCENARIOS OF INTRADAY ENERGY PURCHASES/SALES, AND (B) STATE OF CHARGE OF THE BESS

As shown in Table 3, a **scenario-based stochastic optimisation of the services scheduling succeeds in increasing the full income of the VPP (+12% in average)** for the considered study case⁸.

⁸ As mentioned in Paragraph 2.1.4.2, the expected intraday costs and benefits have been computed by assuming that: (1) the BESS keeps to its day-ahead schedule and (2) no intraday schedule updates are made. In case of probabilistic forecasts, as the day-ahead schedule for the BESS depends on the considered scenario, the expected costs/benefits have been computed for each scenario and then averaged over all the scenarios. These assumptions allow us to compute the actual energy of the VPP the very day without using the offline simulation platform.

	Perfect forecasts	Deterministic forecasts	Probabilistic forecasts ⁹
Day-ahead income	+2764 €	+4036 €	+3226 €
Expected positive imbalance settlement gain	0 €	+524 €	+1002 € (± 1%)
Expected negative imbalance settlement loss	0 €	-2425 €	-1827 € (± 3%)
Expected full income	+2764 €	+2135 €	+2402 € (± 2%)

TABLE 3. EXPECTED COSTS AND BENEFITS WHEN PROVIDING “ENERGY ARBITRAGE” SERVICE OVER ONE PARTICULAR DAY, WITH PERFECT, DETERMINISTIC AND PROBABILISTIC GENERATION FORECASTS, WITHOUT INTRADAY RESCHEDULING

2.1.4.4 IMPACT OF THE INTRADAY SERVICES RESCHEDULING

In the previous parts, the services schedule is performed on a day-ahead basis. Intraday services rescheduling may improve the performance of the aggregator by using the most recent forecasts and field measures available. For example, this part shows the results on the considered day using the offline simulation platform described in Paragraph 2.1.3, when the services schedule is updated every 4 hours and when the short-term control simply consists in meeting the BESS power schedule.

As shown in Figure 16, intraday 50%-quantile forecasts (blue curves) are generally closer to the real generation (black curves) than day-ahead 50%-quantile forecasts (red curves). Taking into account intraday forecasts in the scheduling process should allow a better use of the flexibilities, i.e., the BESS charging/discharging, and ex post facto energy purchases/sales, to comply with the day-ahead services schedule of the VPP.

⁹ The costs and benefits displayed for the “probabilistic forecasts” case are the average values over the scenarios depicted in Figure 14. The percentage values give the range of the costs/benefits for all the considered scenarios.

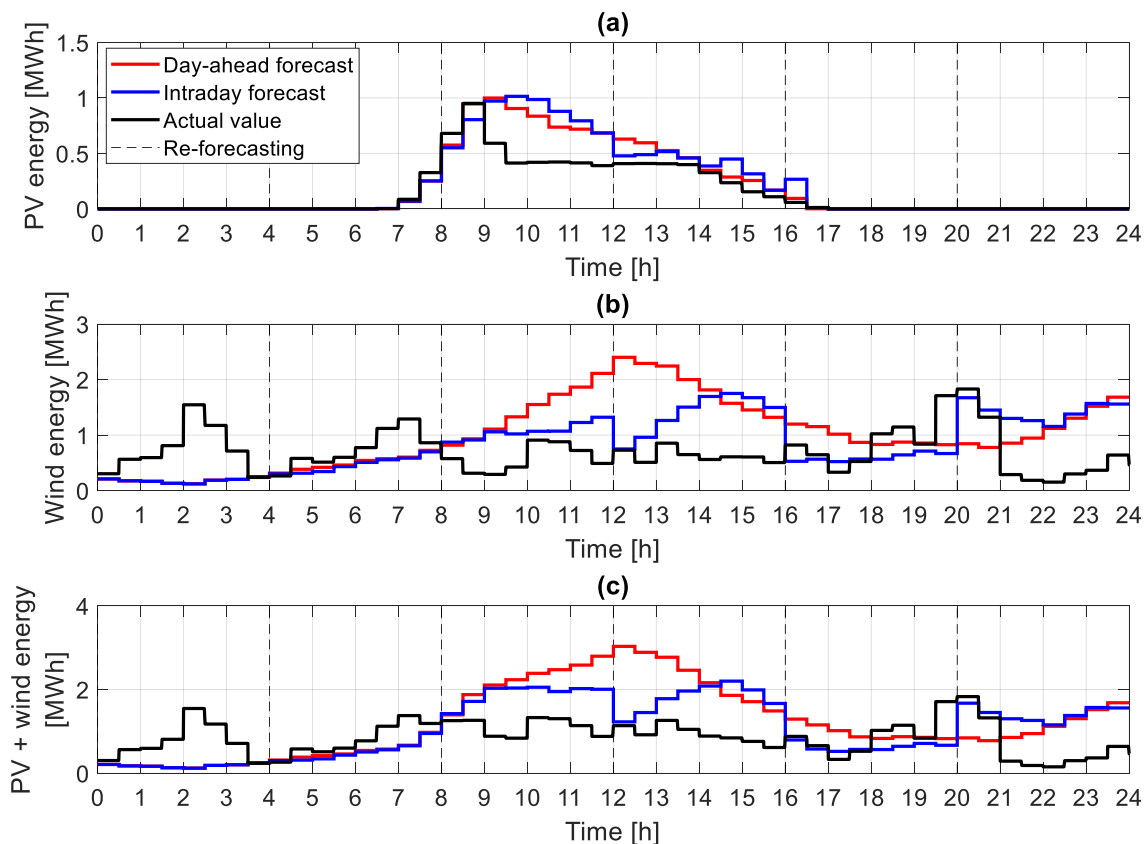


FIGURE 16. DAY-AHEAD AND INTRADAY DETERMINISTIC (OR 50%-QUANTILE) FORECASTS AND ASSOCIATED GENERATION: (A) PV, (B) WIND, AND (C) PV + WIND.

For example, Figure 17 shows the corresponding day-ahead and intraday schedules of the BESS, in case the aggregator performs “energy arbitrage” only using deterministic generation forecasts. On the basis of the most recent SoC measure and forecasts available at 8:00 (at 16:00, respectively), the operational planning scheduler decides to strongly change the BESS schedule from 9:00 to 12:00 (from 16:00 to 20:00, respectively).

Note that the slight difference between the intraday schedule (blue curve) and the real operation of the BESS (dotted black curve) is due to different modelling of the BESS energy losses in the scheduling process (linearized model) and in the offline simulation platform (more “realistic” model).

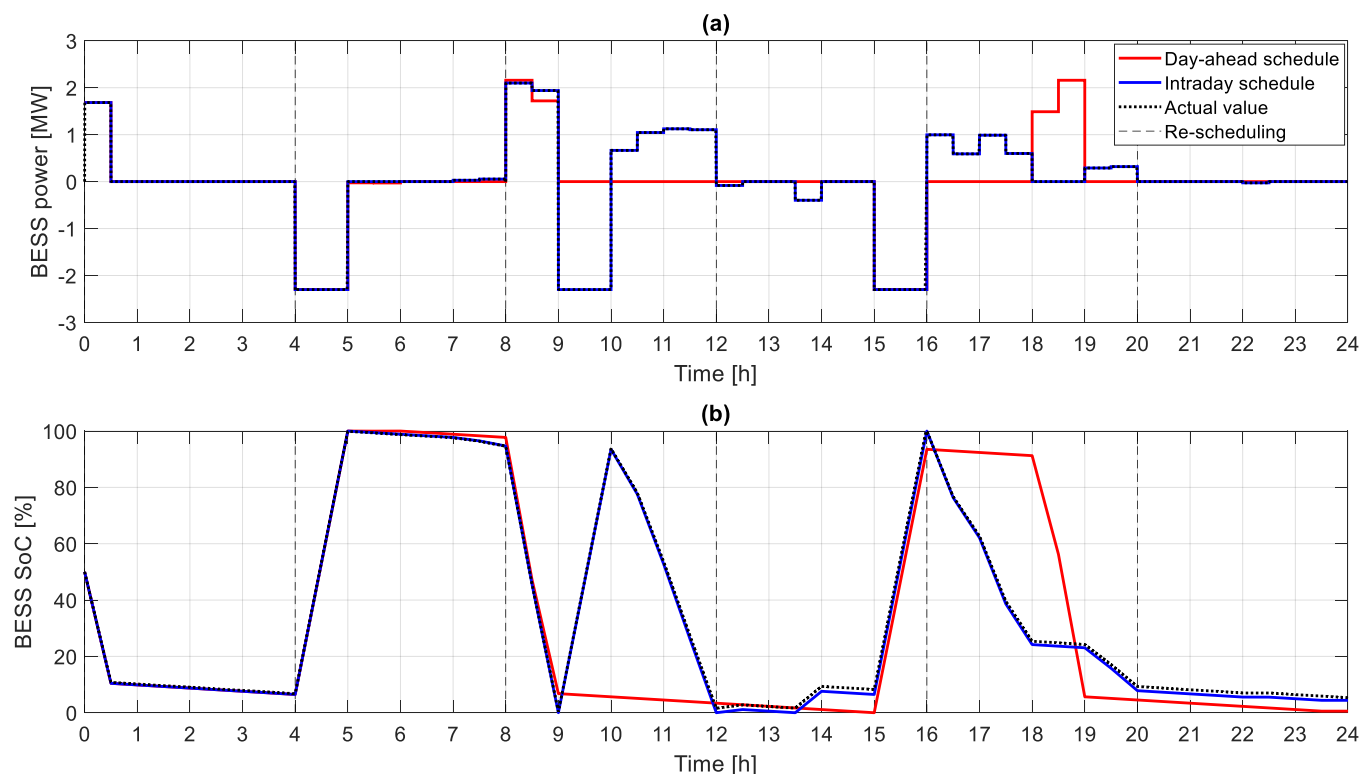


FIGURE 17. DAY-AHEAD AND INTRADAY DETERMINISTIC SCHEDULES AND ACTUAL OPERATION OF THE BATTERY: (A) POWER, AND (B) STATE OF CHARGE

The corresponding day-ahead and intraday energy schedules for the VPP are depicted in Figure 18. It is worth noting that the intraday scheduled energy is sometimes higher or lower than the day-ahead one, which means that the operational planning scheduler provides for intraday (or ex post facto) energy sales or purchases. Two reasons may account for this: (1) the BESS capacity is insufficient to offset the gap between the day-ahead and intraday forecasts, and/or (2) additional energy sales/purchases are expected to be more attractive than discharging/charging the BESS.

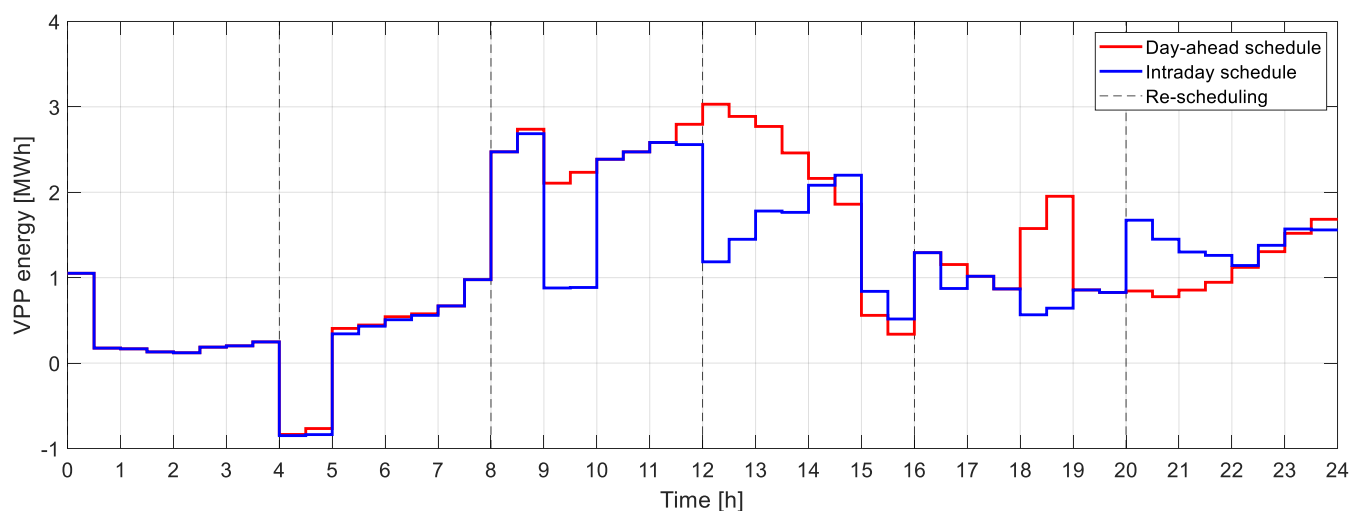


FIGURE 18. DAY-AHEAD AND INTRADAY DETERMINISTIC ENERGY SCHEDULES OF THE VPP

As shown in Figure 19, despite intraday rescheduling, there is still a difference between the intraday schedule of the VPP and its actual energy. This is due to the intraday forecast errors as well as the use of a simple short term control mode consisting in meeting the BESS intraday schedule regardless of the actual renewable generation.

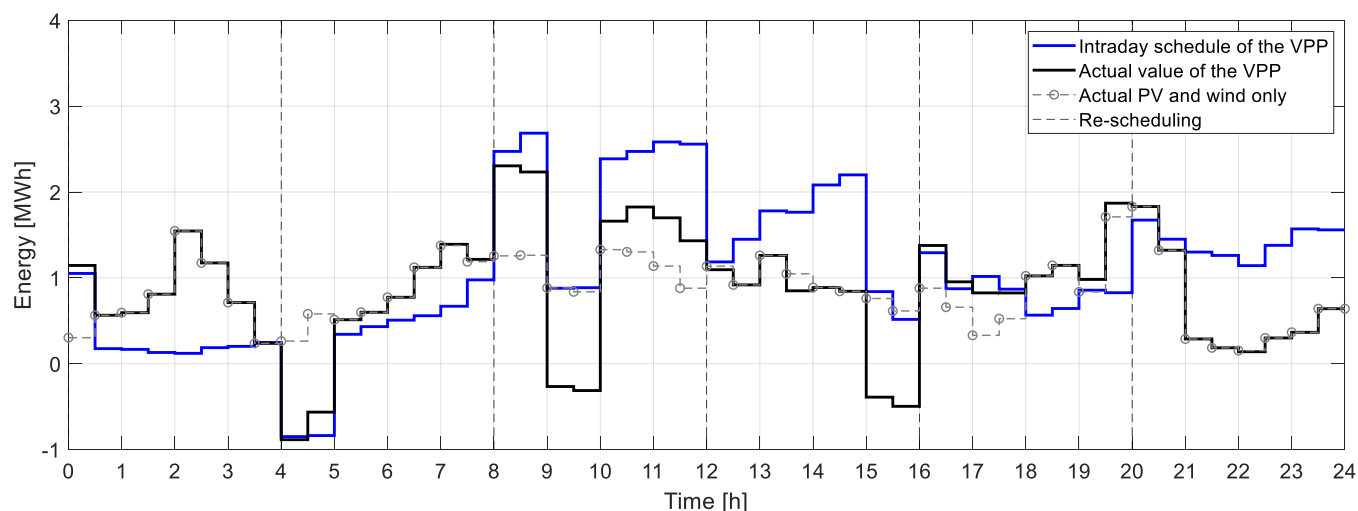


FIGURE 19. INTRADAY DETERMINISTIC SCHEDULE OF THE VPP, ACTUAL OPERATION OF THE VPP AND ACTUAL RENEWABLE GENERATION

As depicted in Table 4, intraday services rescheduling allows increasing the full income of 1% for this particular day.

	Deterministic forecasts	Probabilistic forecasts
Full income without intraday rescheduling	+2135 €	+2398 €
Full income with 4-hour rescheduling	+2153 €	+2414 €

TABLE 4. FULL INCOME OF THE VPP WHEN PROVIDING “ENERGY ARBITRAGE” SERVICE OVER ONE PARTICULAR DAY, WITH DETERMINISTIC AND PROBABILISTIC GENERATION FORECASTS, WITH INTRADAY RESCHEDULING

The first simulation results above illustrate the operation of the different software parts of the EMS, with and without using the offline simulation platform, and show the aggregator’s interest to consider probabilistic generation forecasts and intraday services rescheduling. Note however that the use of probabilistic forecasts and/or intraday rescheduling do not necessarily lead to better daily full income. For instance, if the day-ahead deterministic forecasts are quite precise, the deterministic day-ahead schedule may obtain lower imbalance settlement loss and thus better full income than the stochastic intraday one. In addition to the future work listed in Paragraphs 2.1.1.5, 2.1.2 and 2.1.3, simulations over a longer duration (e.g., one month) with different variants/settings of the EMS should therefore be performed to provide more conclusive results.

2.2 REAL-TIME SIMULATION PLATFORM DEVELOPMENT

The real time simulation plays a crucial role in testing the electrical equipment (e.g., controllers, protection relays, power converters) by interfacing that equipment with a numerical model (e.g., electrical drive, grid) through inputs/outputs and/or a power interface. Such a testing method provides high fidelity results and allows scenarios that would be otherwise difficult, expensive or potentially unsafe (see Figure 20).

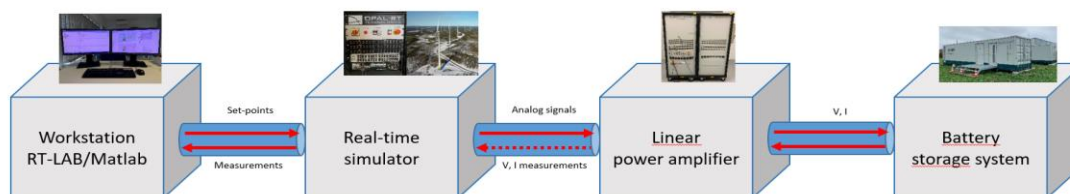


FIGURE 20. REAL-TIME SIMULATION SET-UP FOR TESTING BATTERY STORAGE SYSTEM

The wind farm that will be used in the WP8 demonstration is already operational on the grid. Therefore, for security and economic reasons, the use of the wind farm will be limited. Due to limited amount of time available for each test, real-time analysis reduces the risk and the overall development time required to complete the system. Using real-time simulation is also essential to better understand the dynamic behaviour of different resources providing system services, since many test scenarios can be performed without taking any risk for the equipment.

In this demonstration, real time simulation is used firstly to simulate the interaction between three key elements for the multi-service provision with distributed resources: wind farm, battery storage system and the aggregator's short-term control that coordinates these resources. PV panels as well as controllable loads will be modelled and added in the global simulation platform in a second time.

Specifically for the WP8 demonstration, ENERCON developed two models suited for real-time simulations. One model for the BESS and another one for the wind farm Anglure. Each model is described in the following sections. These models were then integrated by EDF into the aggregator's model including a short-term control.

2.2.1 REAL-TIME STORAGE MODEL AND INDIVIDUAL SIMULATIONS

The provided model of the BESS can be seen as the association of three elements:

- The battery management and converter control models.
- The E-SCU (E-Storage Control Unit) controller model, which monitors and regulates the Point of Connection (PoC) by controlling the battery.
- The unit transformer.

The first two elements are represented as black-box models whereas the transformer and other grid elements are modelled using Simscape™ Power Systems™ Toolbox (Specialized Technology). Figure 21 presents a model overview.

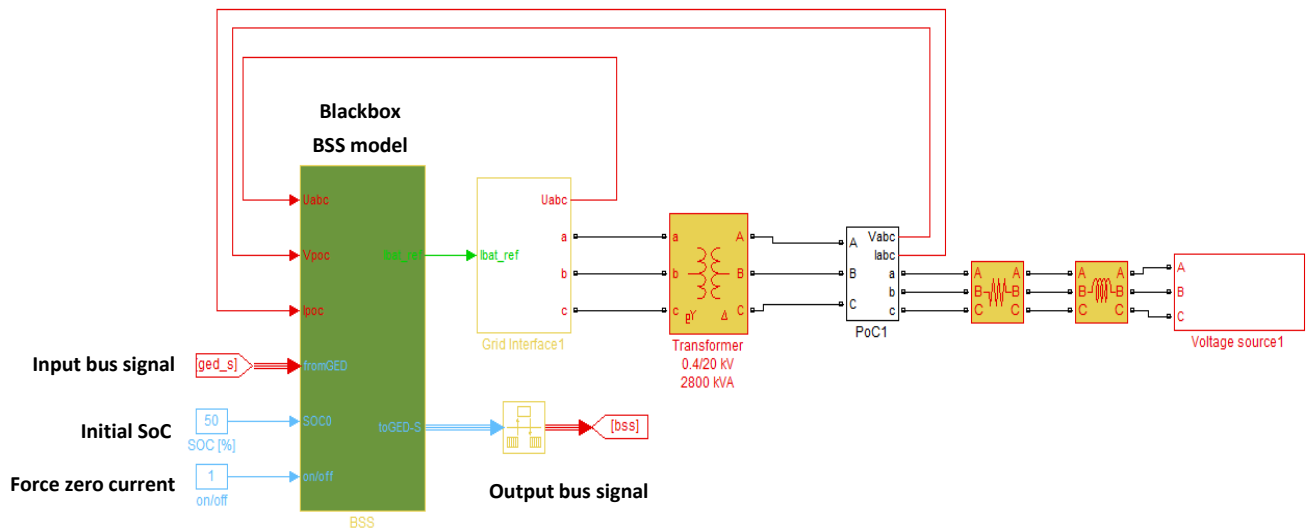


FIGURE 21. STRUCTURE OF THE BESS MODEL

The model has also been developed with the specific application in mind of demonstrating system services related to active power. In the current model version, reactive power can only be injected in manual mode, which immediately disables the system services features. The main features implemented in the BESS model are the active power control, fault ride through, and protections.

Before performing simulations in the whole environment representing the global behaviour of the aggregator, separate simulations have been performed to ensure that the models respond as desired. Therefore, in the following are presented the results of different testing cases.

- Fast Frequency Response (FFR)

In this simulation, the FFR is activated due to an over-frequency event (at $t \sim 60$ s) and then due to an under-frequency event (at $t \sim 180$ s). The results of the 'expected' provision of a negative and positive reserve under these events are shown in Figure 22.

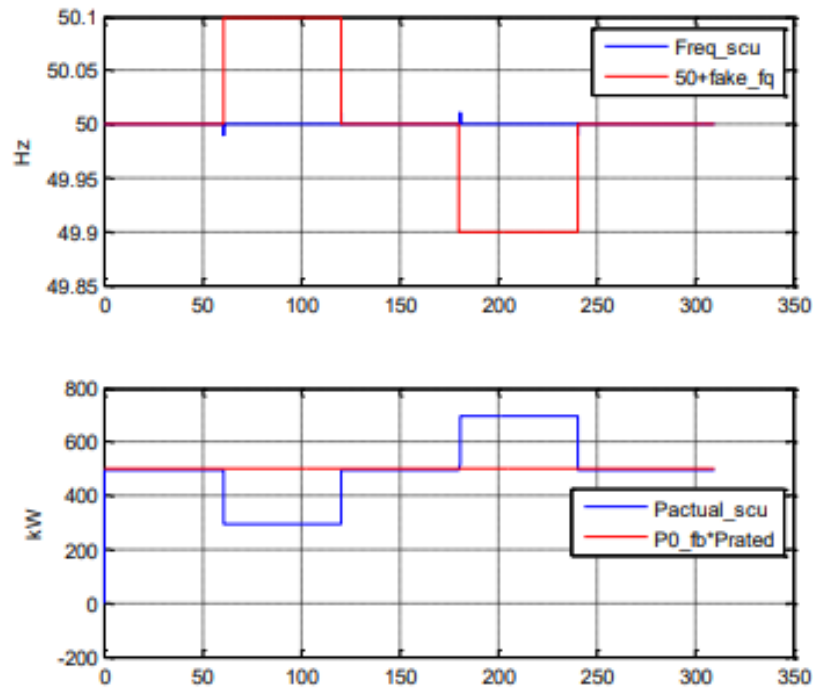


FIGURE 22. INDIVIDUAL SIMULATION: FFR PROVIDED BY THE BESS

- Frequency Containment Reserve (FCR)

Similarly to FFR simulation, the FCR controller responds here to over-frequency and under-frequency events (Figure 23). The major difference with FFR is the response time of the service (in the range of 30 s for FCR as required by the current ENTSO-E grid code).

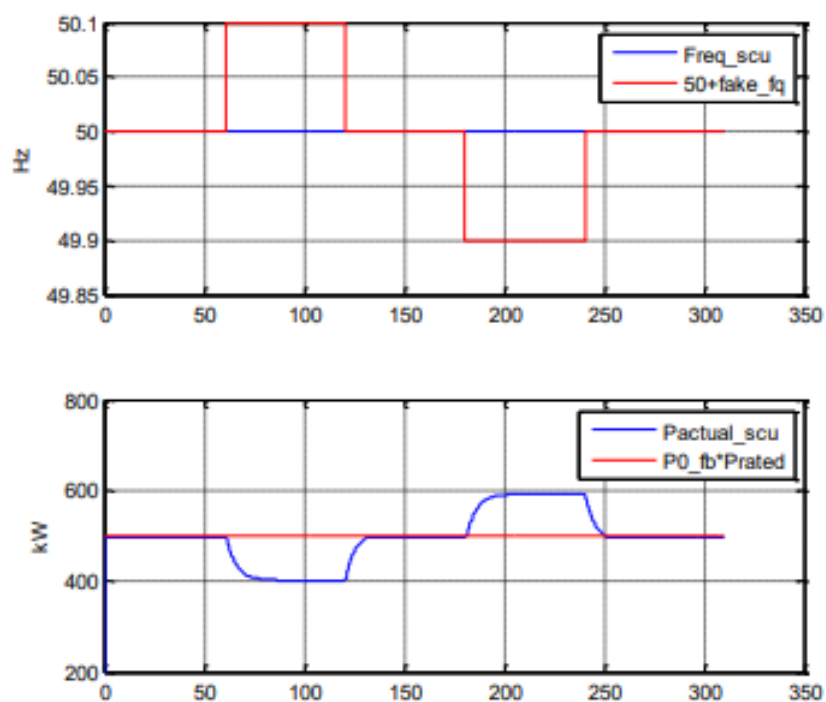


FIGURE 23. INDIVIDUAL SIMULATION: FCR PROVIDED BY THE BESS

- Frequency Restoration Reserve (FRR)

In this simulation, the BESS responds to an external request of restoration reserve signals emulated to be sent by system operators [12] as illustrated in Figure 24. General requirement in terms of FRR response time is slower than 2-5 minutes and the storage FRR can meet this requirement without any difficulty.

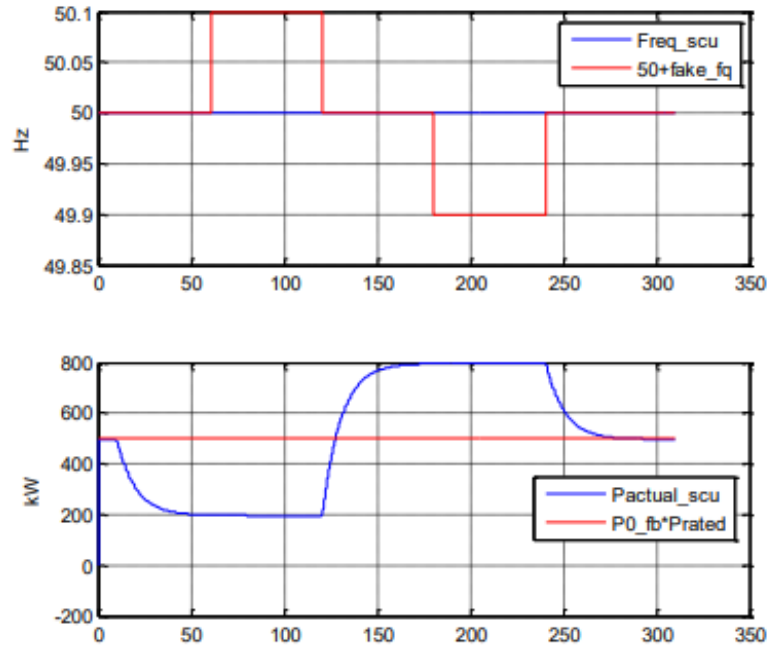


FIGURE 24. INDIVIDUAL SIMULATION: FRR PROVIDED BY BESS

- Ramp Rate Control (RRC)

In the following, the benefit of combining a BESS with a wind farm to reduce its variability is verified. The active power setpoint sent to the BESS opposes the variation of the measured wind generation so that the total aggregated power respects the pre-set power gradient (dP/dt) reference. The active power variations induced naturally by the wind farm are therefore limited by the RRC capability of the BESS controller (Figure 25).

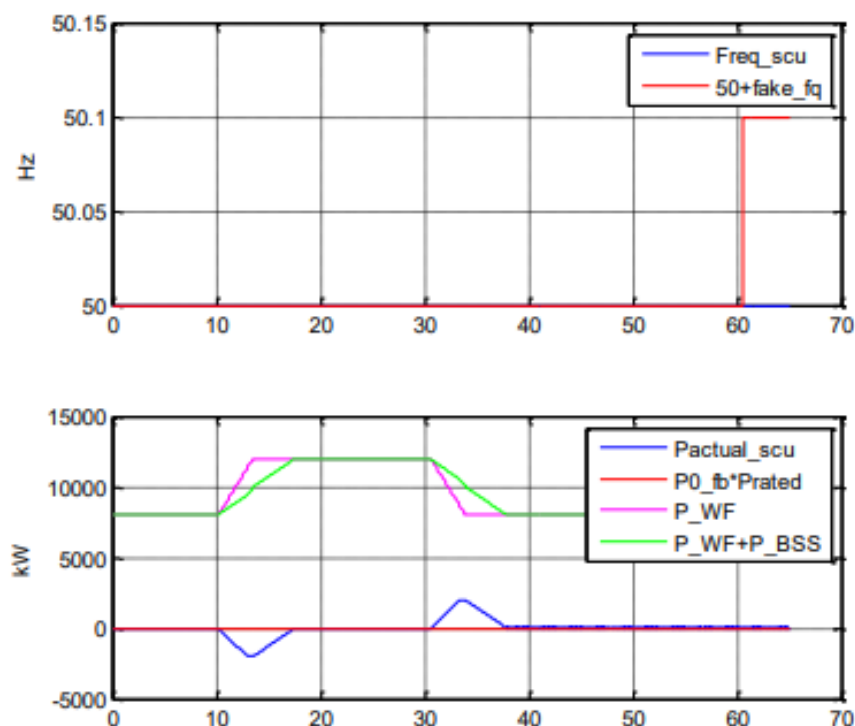


FIGURE 25. INDIVIDUAL SIMULATION: RRC PROVIDED BY THE BESS

2.2.2 REAL-TIME WIND MODEL AND INDIVIDUAL SIMULATION

A MATLAB® Simulink® model was prepared exclusively for the EU-SysFlex project and comprises the representation of the wind farm “Anglure - Les Vignottes 2”, which consists of 6 ENERCON type E-82 FT 2.0 MW Wind Energy Converters (WEC). The model can be seen as the association of three elements:

- the equivalent WEC model representing the 6 turbines from the wind farm;
- the Farm Control Unit (FCU) model, which monitors and regulates the PoC by controlling the WEC;
- the power system from WEC terminals to the reference voltage source (including unit transformer equivalent, WF cables equivalent and grid impedance).

Figure 26 presents a model overview.

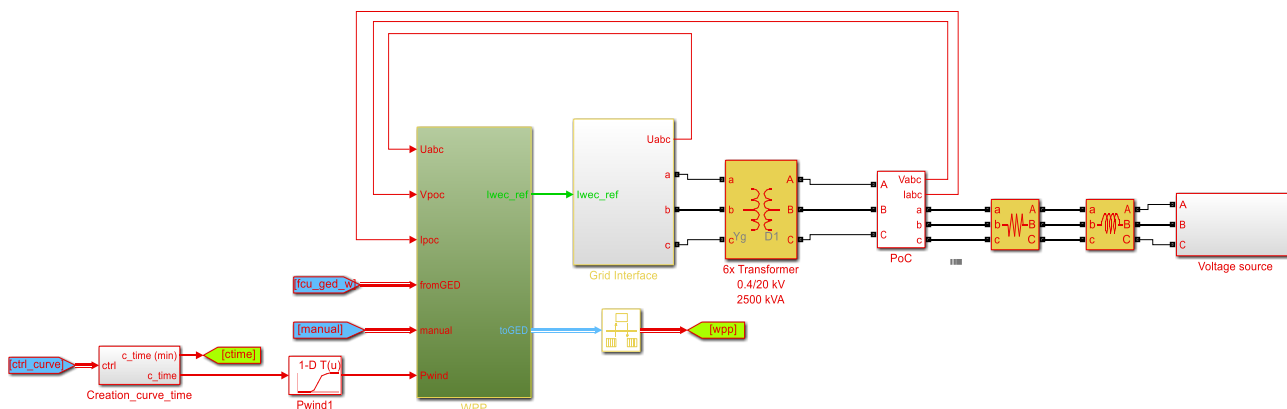


FIGURE 26. WIND FARM MODEL OVERVIEW

The model uses a fixed simulation time step of 50 μ s, although some internal control loops may use higher sample times. It has also been developed with the specific application in mind of demonstrating system services related to active power, which led to considerable simplification of the reactive power control loops. There is however no risk of active power limitation due to reactive power/voltage control since in normal operation the WEC will prioritize the injection of active power (reactive power will be limited if necessary).

Fault Ride Through modes are implemented but also considerably simplified. The protections that may trip the WEC in case of severe grid events have been represented. The procedure to restart the WF after such grid events (or manual disconnection) has been simplified.

Wind Energy Converter

The main features implemented at the WEC level are the active power limitation, fault ride through, inertia emulation, protections, and start/stop power ramp.

Wind farm Model

A lumped model of the six available Wind Energy Converters (WEC) represents the wind farm. The WEC transformers are modelled separately also as a lumped model. The WF collector system cables have been represented by equivalent impedances calculated as proposed by WECC [13]. Such simplification is required in order to create a system suitable for real time simulations and is reasonable since the different behaviour of each WEC is not relevant.

The WEC availability has been considered in the model in a very simplified way. The user may modify the number of available WEC (by setting a number between 0 and 6). The model accepts the user-defined number only if there are no WEC ramping power-up as part of the start-up procedure.

Farm Control Unit (FCU)

At the core of the FCU are the active and reactive power controllers. The active power reference at the PoC is determined by the equation $[P_{ref} = \min(P_{set}, P_{available}) - P_{reserve}]$ which subtracts $P_{reserve}$ from $P_{available}$ (estimated available wind power at a given time) after being limited by the external setpoint signal P_{set} . The volume of $P_{reserve}$ depends on the active reserve mode as well as on the upstream optimization calculation of the scheduler. If FCR is active, this volume of reserve will be delivered to the grid depends on the frequency as illustrated in Figure 27.

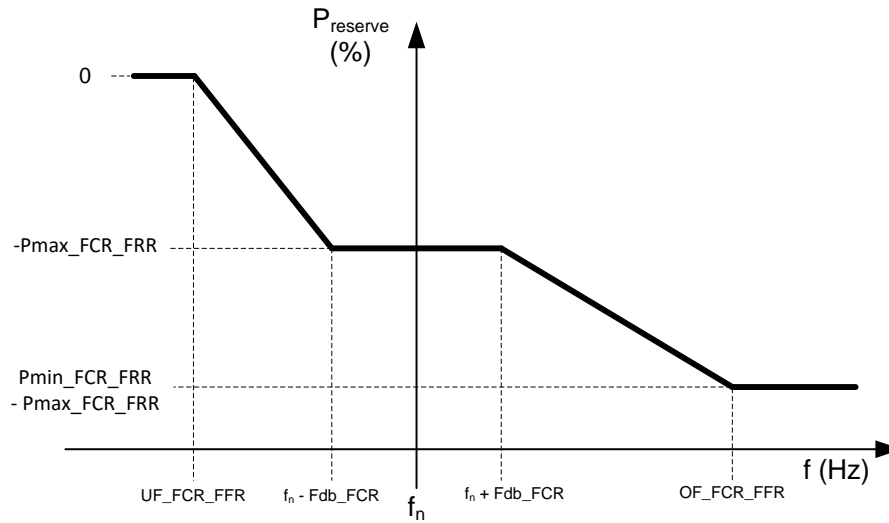


FIGURE 27. ILLUSTRATION OF THE FCR CURVE SETPOINTS

If FRR is active, $P_{reserve}$ is given by the external control signal P_{res_ext} . It should be noted that the current version of wind farm model does not allow the simultaneous activation of FCR and FRR.

Before performing simulations in the whole environment, separate simulations have been performed in order to ensure that the models respond as desired. In the following the results of different test cases are presented.

- Inertia Emulation (IE)

In this simulation (Figure 28), the IE is activated (at $t \sim 90$ s) when the frequency goes below 49.7 Hz. An active power boost is provided during a few seconds. Afterwards, an inertia recovery period (from $t \sim 105$ s to $t \sim 140$ s) is necessary to restore the wind operating point.

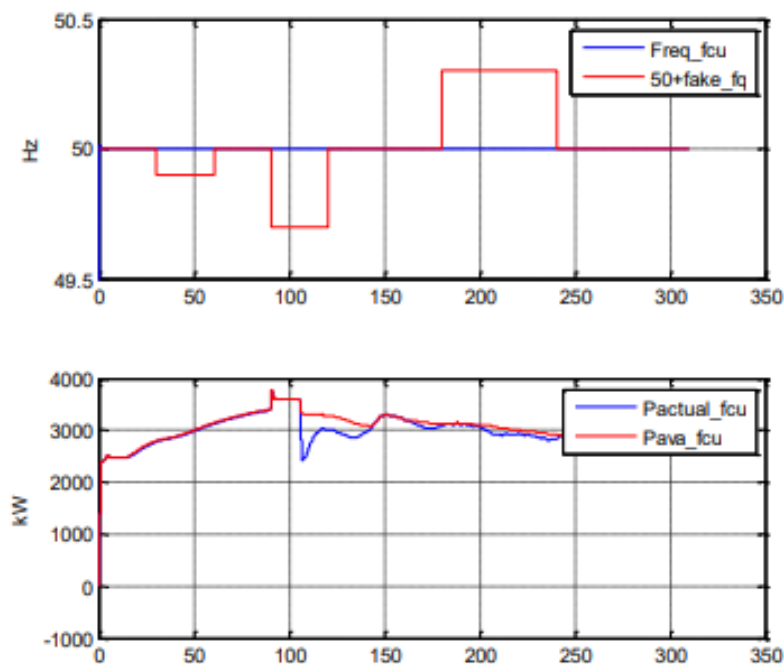


FIGURE 28. INDIVIDUAL SIMULATION: INERTIAL EMULATION OF WIND FARM

- Frequency Containment Reserve (FCR)

In the simulation below, the FCR service is activated. In case of under-frequency, a positive reserve is provided. Conversely, a negative reserve is provided in case of over-frequency (Figure 29).

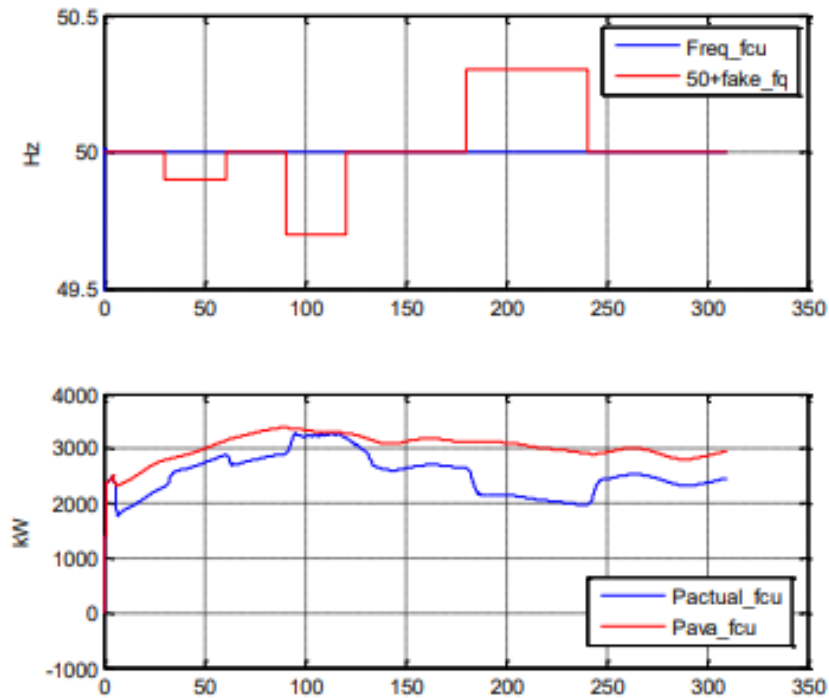


FIGURE 29. INDIVIDUAL SIMULATION: FCR FROM WIND FARM

- Frequency Restoration Reserve (FRR)

In the following simulation, FRR is activated by the consideration of an external reserve setpoint (P_{res_ext}). Positive and negative reserves are tested (Figure 30).

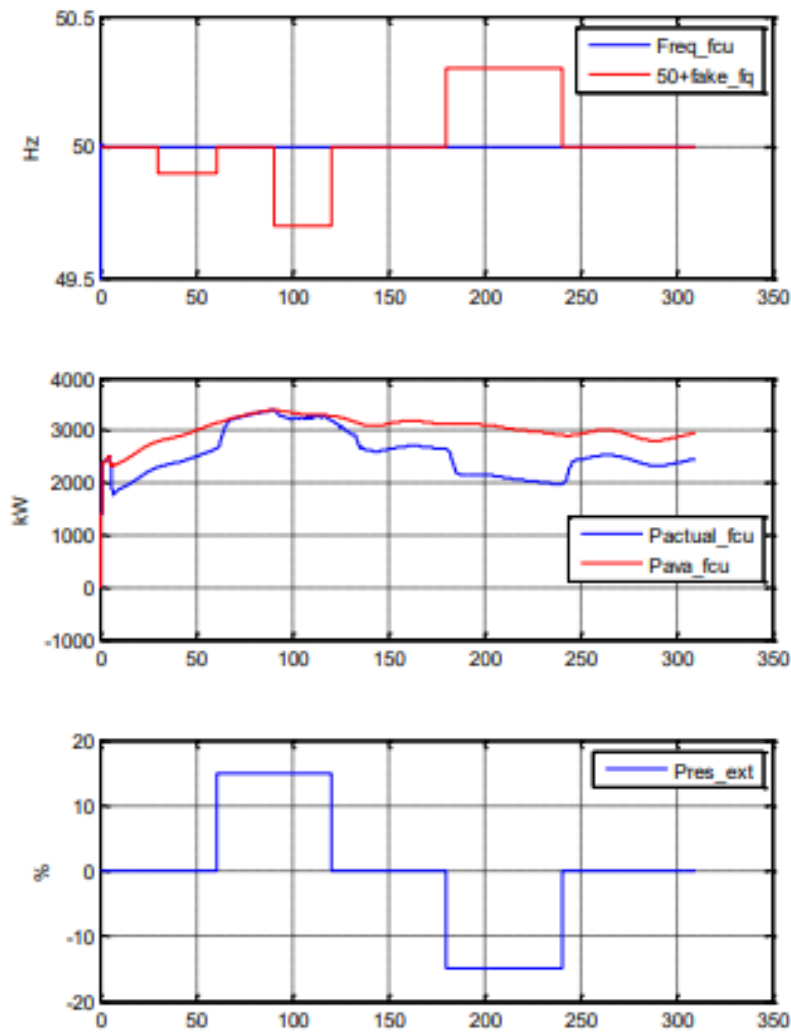


FIGURE 30. INDIVIDUAL SIMULATION: FRR FROM WIND FARM

2.2.3 INTEGRATION INTO THE GLOBAL SIMULATION PLATFORM OF THE AGGREGATOR

As presented previously, each element of the aggregator is firstly modelled and simulated independently. Wind power plant and storage models are developed by ENERCON, while the model of the aggregator's short-term controller (STC) is developed by EDF R&D. The three models are then integrated together by using RT-lab software, which runs MATLAB Simulink modelling environment. Such an integrated model is tested on the EDF Concept Grid's real-time simulation platform. One CPU core was sufficient to run such a model at 50- μ s time step (Figure 31 shows the model structure). In the next steps, the BESS model will be replaced with the real battery, while the rest of the system will be simulated, allowing the power-hardware-in-the-loop (PHIL) approach as presented in [4]. For this set-up, high-bandwidth linear power amplifiers will be used as the power interface. Signal exchange between the amplifier and the model is managed by an FPGA, which is integral part of the real-time simulator.

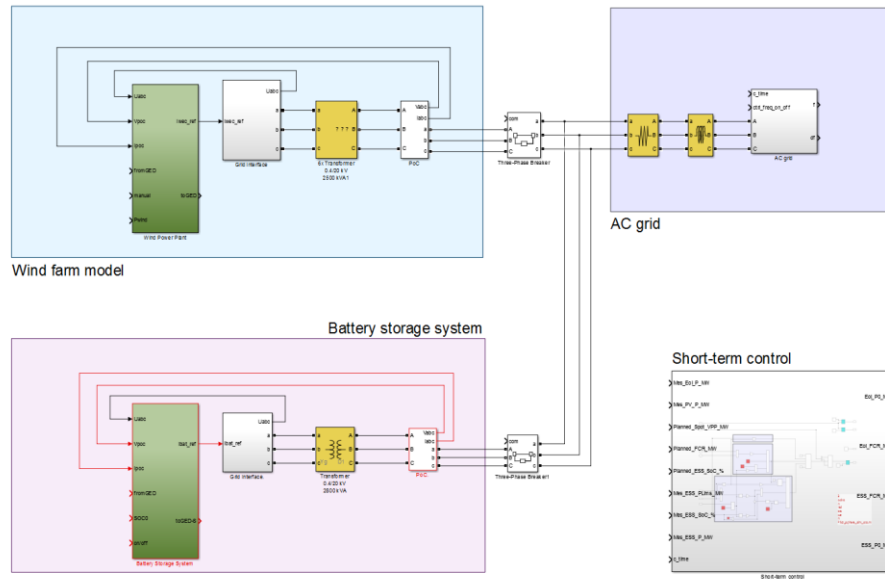


FIGURE 31. REAL-TIME SIMULATION OF THE BATTERY STORAGE SYSTEM, WIND FARM AND THE SHORT-TERM CONTROL

To better understand the dynamic behaviour of individual services provision from the storage and from the wind as well as to validate the interactions between the distributed resources and the STC, several scenarios, supported by real data, were simulated.

The goal of the real-time simulation platform is to shed light on the following aspects:

- data exchange between the assets (data format, necessary precision, units, required bandwidth of the data transfer, etc.);
- characterization of the response of the energy storage system and the wind farm to the aggregator's demands (time response, accuracy, dynamics, etc.);
- type of instructions that need to be sent from the short-term control (logic conditions, format, protection scenarios, etc.).

Several versions of the models were tested and compared giving some first results which allowed us to better understand operational limits proposed by ENERCON controllers (FCR, FRR, etc.). Some simulation results are provided in Figure 32, Figure 33 and Figure 34.

In Figure 32, the VPP or the wind farm / storage aggregator sells produced energy in the electricity market based on power setpoints given at the interval of 30 minutes ("energy arbitrage"), without any other activated grid service. The wind power plant operates at its maximum power point, and the battery is controlled in the way that the nominal power of the VPP (sum of the power provided by the battery and by the wind farm) provides the required power at each instance of time: $P_{ESS}(t) = P_{setpoint}(t) - P_{wind}(t)$. As shown in Figure 32, the setpoint is well respected all the time except for the period when the battery reaches its SoC or rated power limits.

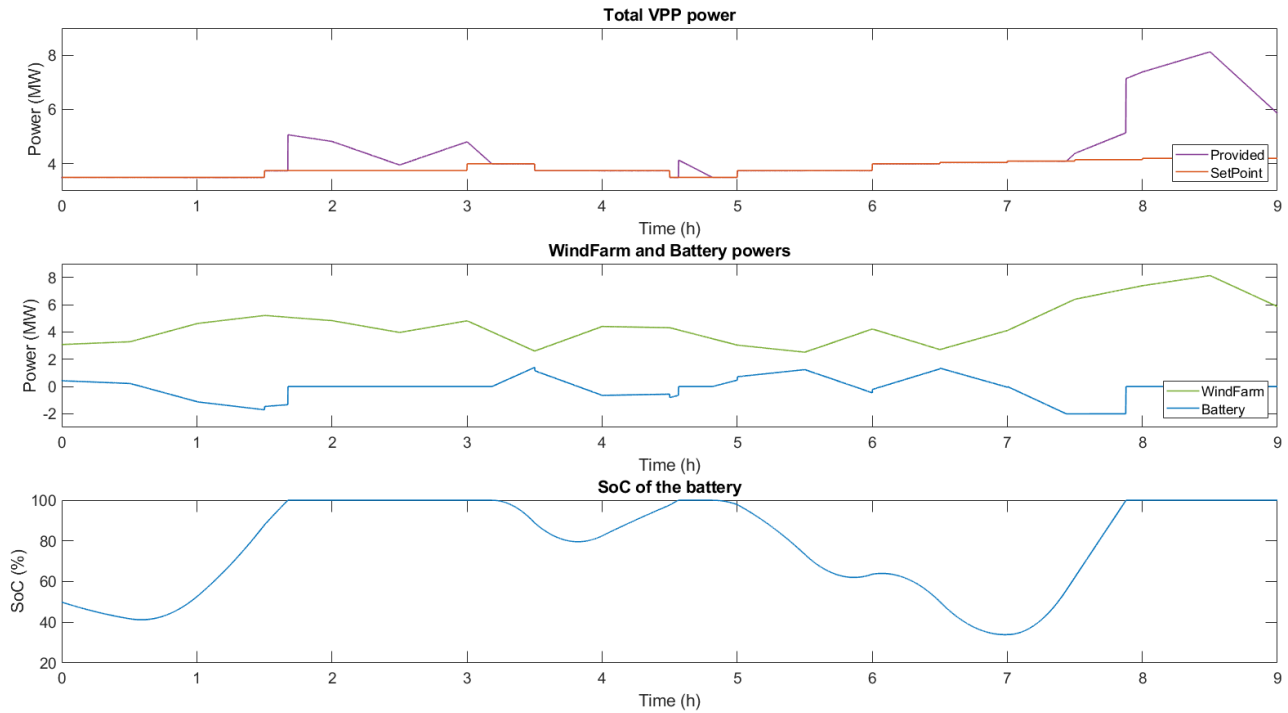


FIGURE 32. RT SIMULATION OF ENERGY ARBITRAGE OF THE VPP / WIND + STORAGE AGGREGATOR

In the second test, the energy arbitrage option is disabled, and the short-term control activates primary frequency regulation (FCR) with the allocation of reserve only on the storage. During the first two hours, the reserve setpoint is 1 MW, then is stepped up to 2 MW for the next two hours. With SoC control disabled, the battery follows the setpoint as defined in the equation: $P_{ESS}(t) = K(50 - f(t))$, where $K = 5 \text{ MW/Hz}$ during the first two hours, and 10 MW/Hz after that. The simulated results provided in Figure 33 show that the battery reacts as expected.

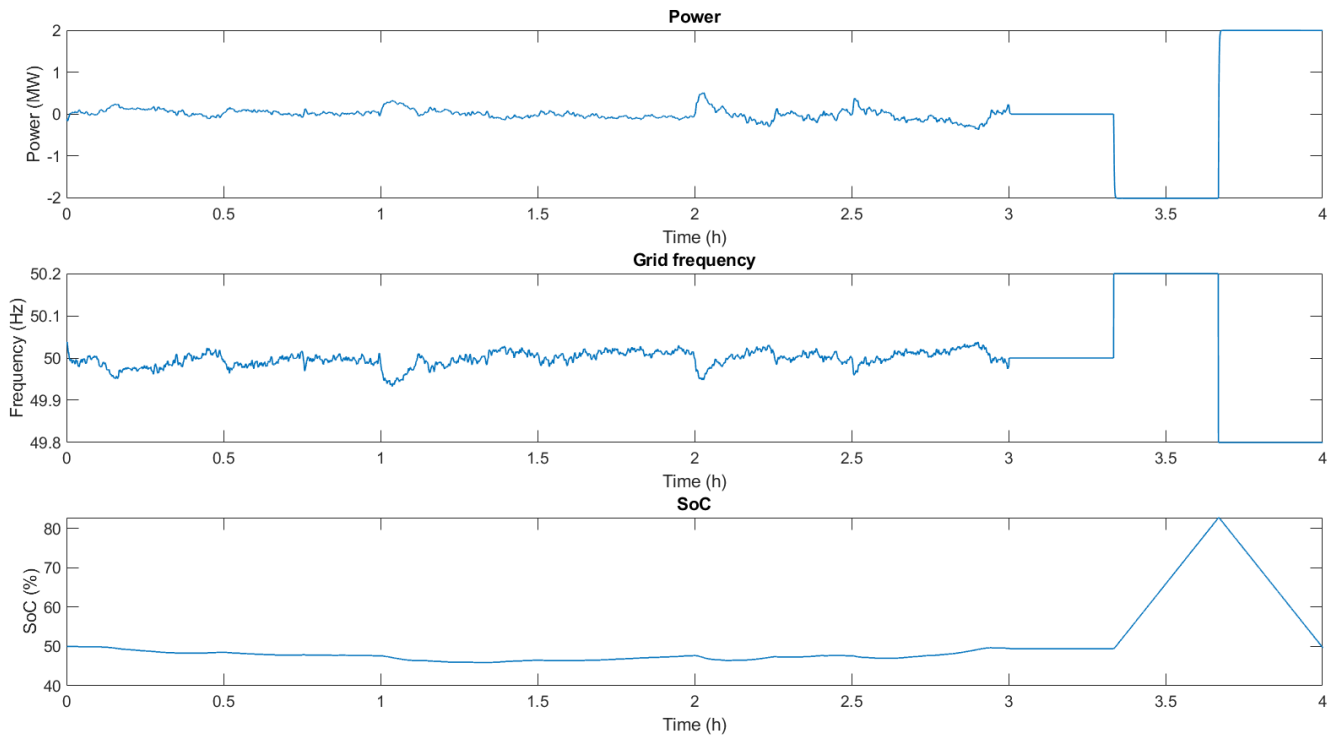


FIGURE 33. RT SIMULATION OF THE FCR SERVICE PROVIDED BY THE ENERGY STORAGE SYSTEM

In the third test, the wind farm provides the FCR service based on the same frequency data. During the first two hours, the setpoint for the reserve is 1 MW, then it is changed to 0.5 MW. The obtained results (shown in Figure 34) confirm that the wind farm is capable of providing required service around a reference power P_0 which is determined by subtracting the volume of reserve (1MW or 0.5 MW in this example) from the estimated Maximum Power Point (MPP) of the wind farm at a given time (MPP estimated).

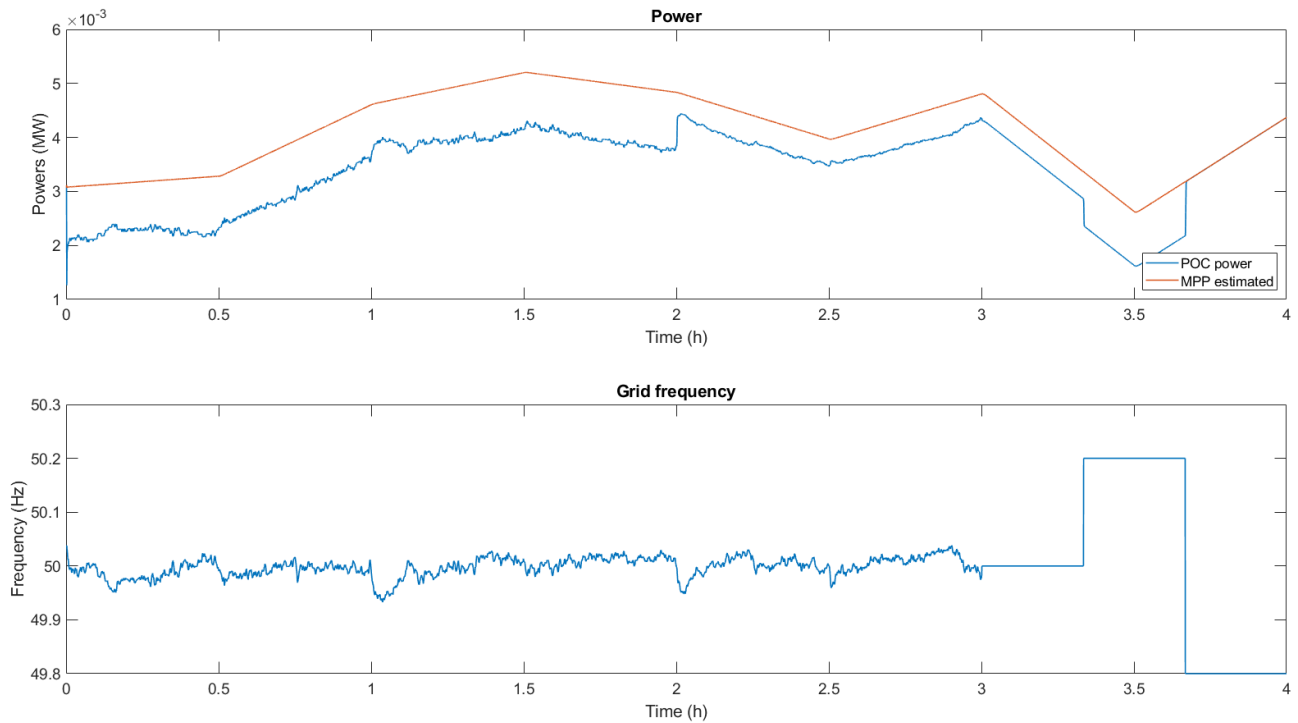


FIGURE 34. RT SIMULATION OF THE FCR SERVICE PROVIDED BY THE WIND POWER PLANT

The performed tests allowed to validate the correct operation of the very basic functions of the STC as well as the behaviour of the global real-time simulation platform representing the aggregation of wind farm and storage. Based on these first results, further work will be performed using the developed RT simulation platform, including hardware-in-the-loop for the simulation of more complex or risky scenarios as well as validation of more advanced functions of the STC.

3. HARDWARE PREPARATION AND IMPLEMENTATION

According to the agreed hardware implementation procedure of WP8 demonstration, the 2019 work was focused on the storage installation and connection onto EDF Concept Grid as well as on the necessary on-site wind farm adaptation at Anglure.

3.1 BESS INSTALLATION

3.1.1 STORAGE SYSTEM DESIGN AND DELIVERY

The installation of the BESS took place in January 2019. ENERCON provided the E-Storage 2300 and Hoppecke a German supplier of stationary battery solutions provided the battery container. LGChem a Korean manufacturer of secondary Li-Ion battery cells provided the battery modules. Figure 35 shows a schematic overview of the BESS.

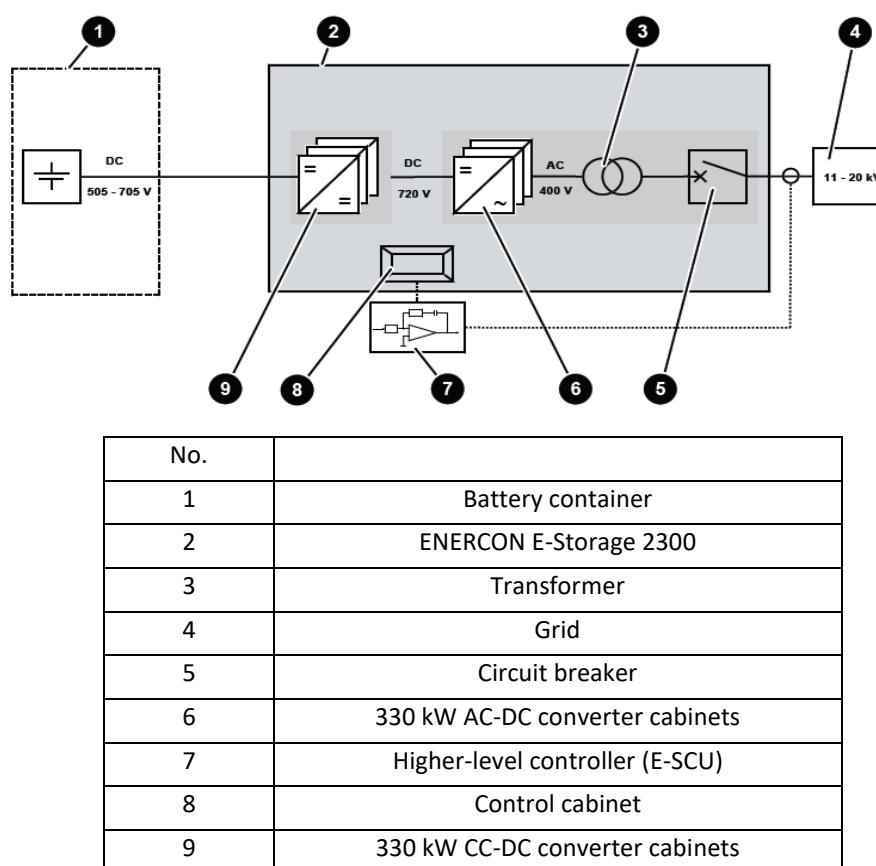


FIGURE 35: SCHEMATIC OVERVIEW OF THE BESS

Design of the E-Storage 2300

The E-Storage 2300 consists of a medium voltage (MV) room and a low voltage (LV) room. In the MV room components as the transformer (1), the MV switchgear (2), the oil catch pan (3) and the outlet to the MV grid (4) are allocated. Figure 36 shows a schematic description.

The transformer converts the voltage present at the output of the power cabinets (inverters, 400 V) to match the level of the MV (in concept grid 20 kV) grid and vice-versa. The transformer assembly comprises (among others) components like a heat exchanger, a circulation pump and fans.

When the MV grid is disconnected, a very hot electric arc is created within the MV switchgear; this electric arc is suppressed by insulating gas. The insulating gas expands due to the heat dissipation. If the pressure is too high, the insulating gas is directed to the outside through the venting outlet. The MV switchgear connects the transformer to the MV grid. It disconnects the system in the event of overcurrents from the grid. The MV switchgear can be connected/disconnected on site or using the medium-voltage switchgear remote control unit in the LV room.

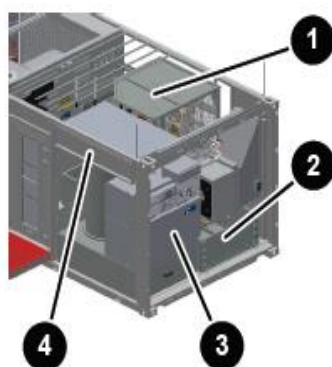
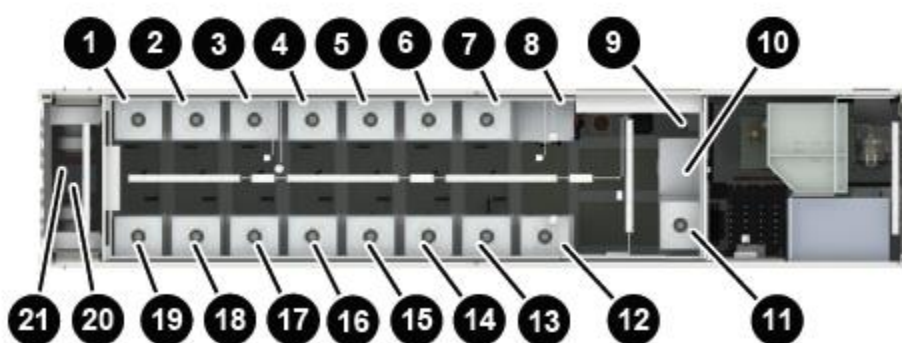


FIGURE 36: COMPONENTS IN THE MV ROOM

Figure 37 shows a schematic overview of the LV room.



No.	
1-7	DC-DC converter cabinet 1-7
8	Control cabinet
9	ETFS, optical fibre splice box
10	Secondary systems cabinet
11	LV distribution system
12	UPS cabinet
13-19	Power cabinet (AC-DC) 1-7

20	Frequency converter
21	Fan (6x)

FIGURE 37: COMPONENTS IN THE LV ROOM

The DC-DC cabinets convert the fluctuating direct voltage from the battery container to a direct voltage that can be used by the power cabinets and vice-versa. The control cabinet controls and monitors the components in the LV room. The system is operated from the control cabinet.

The control cabinet contains the monitoring unit for the grid safety circuit. The ETFS monitors the oil pressure and oil level of the transformer. If a drop indicator relay is triggered, the message is displayed in plain text on the relay and the MV switchgear disconnects the transformer from the grid. The transformer is oil-cooled. Too little oil reduces the heat dissipation and can result in overheating of the transformer. If the oil pressure is too high, it can lead to the transformer temperature being too high, even when the oil level is correct. If the oil pressure is too high, the transformer can be damaged.

The secondary systems cabinet and control cabinet serve for communication. Fiber-optic cables transmit the signals for the grid, ENERCON SCADA and between the ENERCON storage control unit and the battery container. The frequency converter controls the speed of the fans in the low voltage room.

The power cabinets transform the alternating current coming from the transformer into direct current. The direct current coming from the DC-DC cabinets is transformed into alternating current. The alternating current thus produced is a three-phase current whose voltage curve and phase position conform to the power grid. Any reactive power that may be required is produced by a phase shift in the fed-in current vis-à-vis the phase position of the grid voltage. The LV distribution system serves as an interface between the LV components and the transformer. A fuse switch disconnecter is located in the LV distribution system. The fuse switch disconnecter isolates the control cabinet. The circuit breakers are located in the LV room in the LV distribution system (7x) and in the control cabinet (1x).

The power cabinets are isolated by the circuit breakers. The secondary systems cabinet contains the grid hardware and the 24 V power supply to the components like the emergency switching off system, the SCADA interface and the battery interface.

The UPS cabinet serves to supply the control system with power in the event of grid faults. The UPS allows the control system to send a status message via the ENERCON SCADA system in the event of a complete failure. The UPS receives its power from the DC link between the power cabinets and the DC-DC cabinets. There are 3 vertical fans to the left and right of the LV room swing door to cool the components.

Design of the Battery container sun systemizer scalecube

The battery storage container is a modular stationary storage system, which was designed individually according to the requirements of the costumer. The sun systemizer scalecube consists of a 45 feet container with the components listed in Figure 38.

The battery container serves as a DC storage unit for the E-Storage 2300 and is designed accordingly. The envisioned applications are frequency controls (FFR, FCR, FRR), reduction of ramp rates (RRC) and participation in electricity trading.

The UPS supplies all the components with, needed for safe and proper operation during grid outages as the fire alarm system, the fire extinguishing system, the communication system to the E-Storage 2300 and the fans for cooling of the battery racks.

There are 2 access doors (panic doors) as shown in Figure 38.

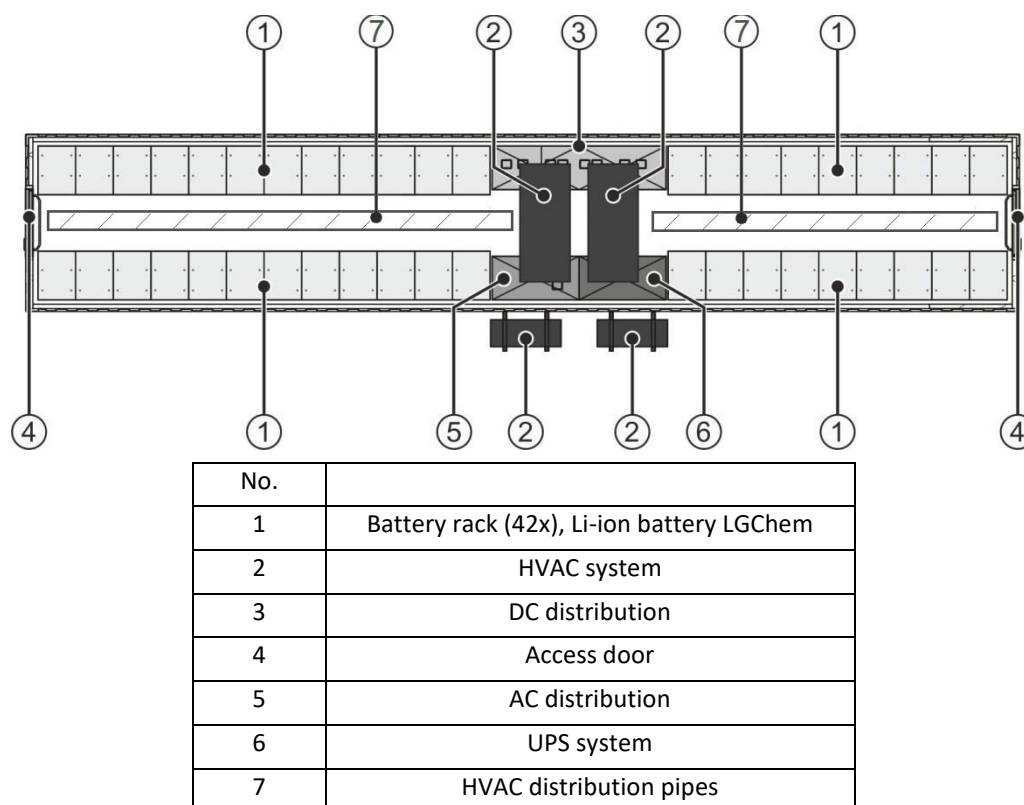


FIGURE 38: COMPONENTS IN THE BATTERY CONTAINER

The interfaces to the E-Storage 2300 are auxiliary voltage supply, interface boards (2x), converters from POF cables to copper cables, DC-cabling between the battery racks and the DC-DC converter cabinets and copper connection tabs.

```

graph TD
    BSM[Battery System Monitor] --- EMS[EMS]
    BSM --- BankBMS1[Bank BMS]
    BSM --- BankBMS2[Bank BMS]
    BSM --- BankBMS3[Bank BMS]
    BankBMS1 --- RackBMS11[Rack BMS]
    BankBMS1 --- RackBMS12[Rack BMS]
    BankBMS1 --- RackBMS13[Rack BMS]
    BankBMS2 --- RackBMS21[Rack BMS]
    BankBMS2 --- RackBMS22[Rack BMS]
    BankBMS2 --- RackBMS23[Rack BMS]
    BankBMS3 --- RackBMS31[Rack BMS]
    BankBMS3 --- RackBMS32[Rack BMS]
    BankBMS3 --- RackBMS33[Rack BMS]
    RackBMS11 --- ModuleBMS11[Module BMS]
    RackBMS11 --- ModuleBMS12[Module BMS]
    RackBMS11 --- ModuleBMS13[Module BMS]
    RackBMS12 --- ModuleBMS14[Module BMS]
    RackBMS12 --- ModuleBMS15[Module BMS]
    RackBMS12 --- ModuleBMS16[Module BMS]
    RackBMS13 --- ModuleBMS17[Module BMS]
    RackBMS13 --- ModuleBMS18[Module BMS]
    RackBMS13 --- ModuleBMS19[Module BMS]
    RackBMS21 --- ModuleBMS20[Module BMS]
    RackBMS21 --- ModuleBMS21[Module BMS]
    RackBMS21 --- ModuleBMS22[Module BMS]
    RackBMS22 --- ModuleBMS23[Module BMS]
    RackBMS22 --- ModuleBMS24[Module BMS]
    RackBMS22 --- ModuleBMS25[Module BMS]
    RackBMS23 --- ModuleBMS26[Module BMS]
    RackBMS23 --- ModuleBMS27[Module BMS]
    RackBMS23 --- ModuleBMS28[Module BMS]
    RackBMS31 --- ModuleBMS29[Module BMS]
    RackBMS31 --- ModuleBMS30[Module BMS]
    RackBMS31 --- ModuleBMS31[Module BMS]
    RackBMS32 --- ModuleBMS32[Module BMS]
    RackBMS32 --- ModuleBMS33[Module BMS]
    RackBMS32 --- ModuleBMS34[Module BMS]
    RackBMS33 --- ModuleBMS35[Module BMS]
    RackBMS33 --- ModuleBMS36[Module BMS]
    RackBMS33 --- ModuleBMS37[Module BMS]
  
```

Table 5 gives the technical data of the battery on module, rack, bank and container level.

TABLE 5: TECHNICAL DATA OF THE BATTERY CONTAINER

Safety related equipment

The following safety related equipment is located in the sun systemizer container:

- Emergency stop push button

Execution of the emergency stop push button leads to disconnection of the lithium ion battery banks from the DC bus bar, in addition the DC contactor in the rack BMS opens. To reconnect the emergency stop push button must be unlocked and the reset button in the sun systemizer as well as the reset button in the E-Storage 2300 must be unlocked manually.

- Fire alarm system and fire extinguishing system

The fire alarm system consists of two smoke detectors (CO and CO₂). After detection of the gases, the fire extinguishing system is activated and acoustic and visual alarms are notable. The fire alarm system can also be activated manually.

As the Lithium ion battery is a hazardous material, the modules must be packaged in special boxes and are transported separately to the electrically fully equipped container housing. The container was equipped with the battery modules onsite by specially trained personnel (working under voltage).

3.1.2 GROUND PREPARATION AT CONCEPT GRID

As the equipped battery container and the E-Storage container are very heavy (together more than 70 tons), the underground and the foundation must be prepared carefully according to suppliers' requirements. The EDF concept grid team took care of foundation preparation according to ENERCON's and Hoppecke's requirements.

Figure 40 shows the dimensions and the requirements for foundation of the sun systemizer container. The foundation must consist of 4 strip foundations, evenly prepared to hold the container weight safely.

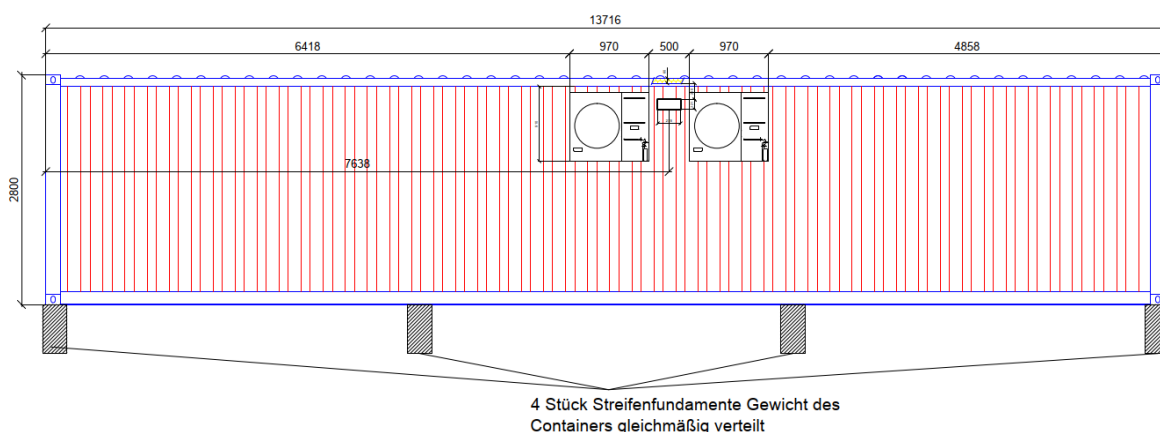


FIGURE 40: HOPPECKE'S REQUIREMENTS FOR FOUNDATION OF SUN SYSTEMIZER, SIDE VIEW

Figure 41 shows the requirements in terms of size and dimension for the foundation of ENERCON's E-Storage 2300 container. As already stated for the sun systemizer container the strip foundation must be plane and ensure proper container support during the project duration.

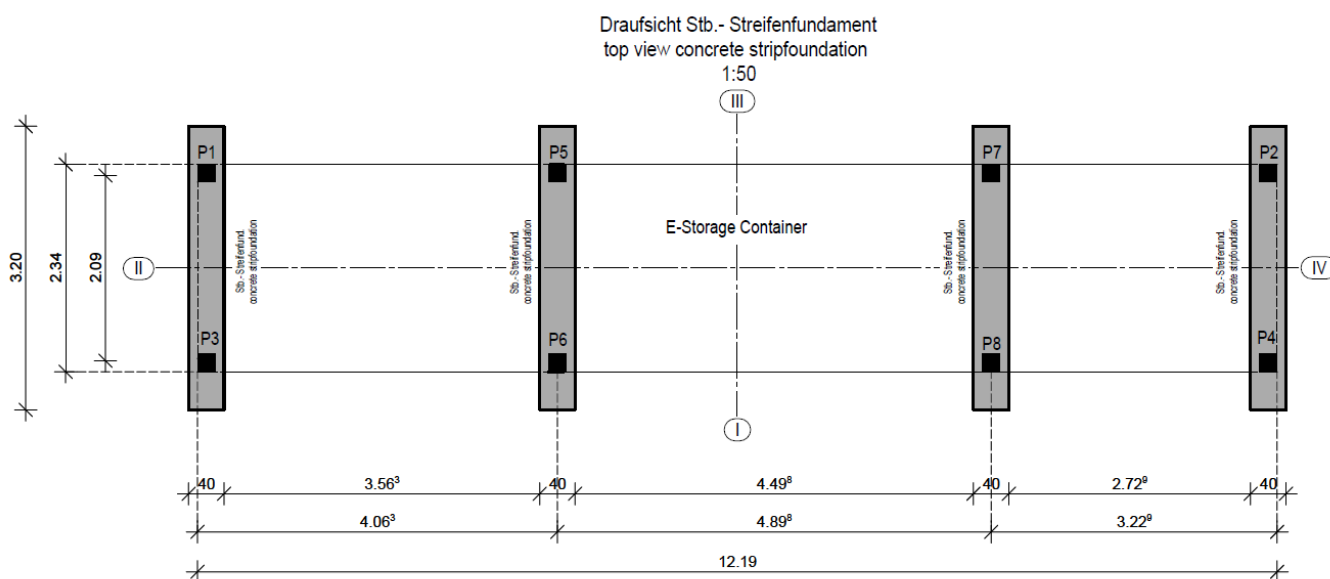


FIGURE 41: ENERCON'S REQUIREMENTS FOR FOUNDATION OF THE E-STORAGE 2300, TOP VIEW

The foundation for the E-Storage and batteries containers have been done in December 2018. The grounding preparation has been required to make 4 foundation beams and to install 4 concrete studs for each container according to ENERCON's requirements.

The foundations are illustrated on the following figure:



Foundations
before the
concrete strips
installation

FIGURE 42: PREPARATION OF GROUND FOUNDATIONS AT EDF CONCEPT GRID

The eight concrete strips have been manufactured at the factory and transferred on EDF site as shown in Figure 43. The concrete strips have been installed and raised at 20-30 cm from the ground in order to facilitate the cables insertion to the containers.



FIGURE 43: INSTALLATION OF CONCRETE STRIPS AT EDF CONCEPT GRID

A week after, the tubes for AC and DC cables insertion and the equipotential rings have been installed between each container and from the secondary substation as shown below:

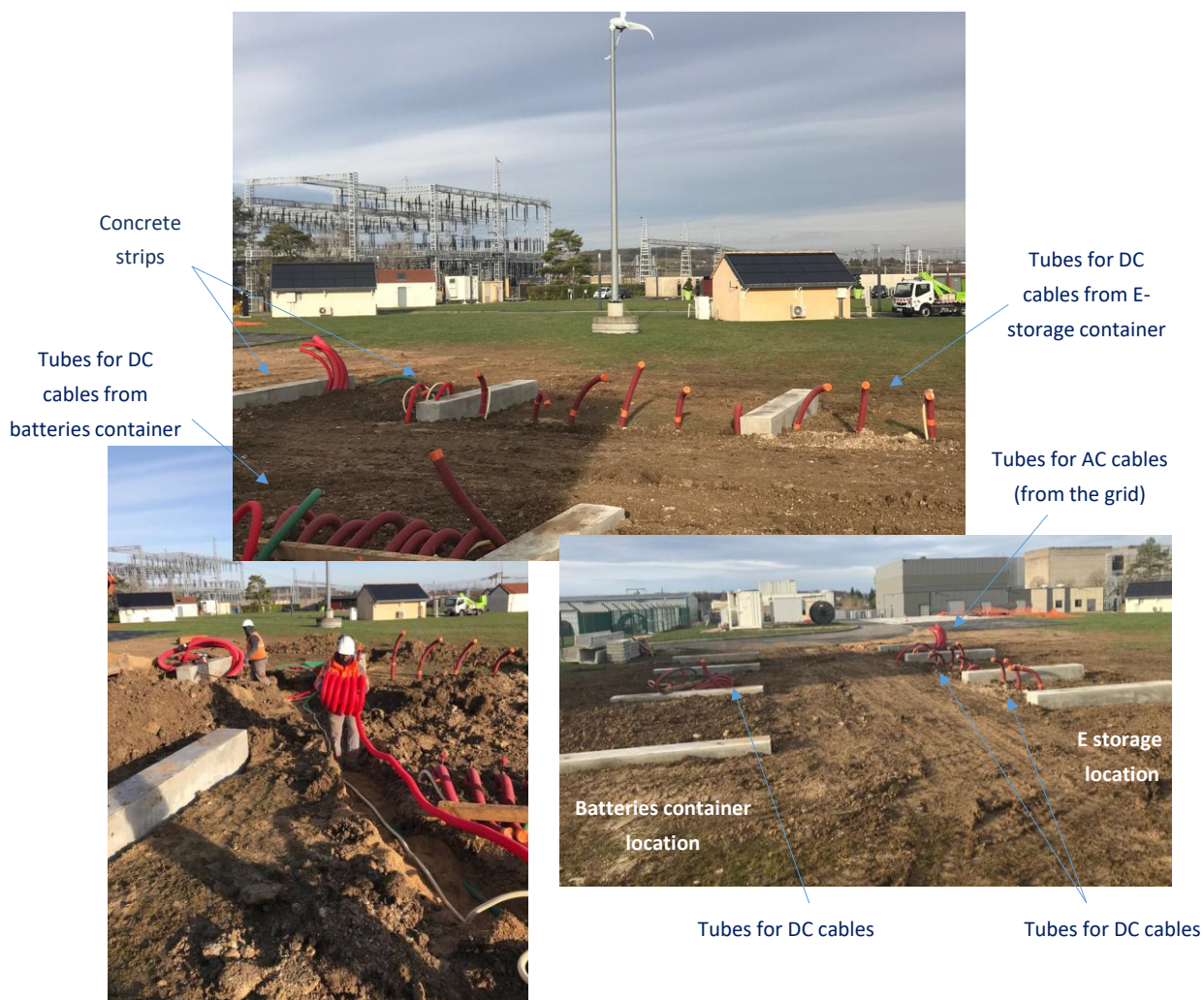


FIGURE 44: INSTALLATION OF AC AND DC CABLES AND EQUIPOTENTIAL RINGS

3.1.3 BESS INSTALLATION AND CONNECTION

ENERCON and EDF jointly worked to prepare all the operations for the containers installation and the connection to the grid with the support of the crane supplier and the project partners as illustrated on the following pictures:



FIGURE 45: UNLOADING OF THE UNEQUIPPED SUN SYSTEMIZER CONTAINER (45 FEET CONTAINER), NO.1



FIGURE 46: UNLOADING OF THE UNEQUIPPED SUN SYSTEMIZER CONTAINER (45 FEET CONTAINER), NO.2



FIGURE 47: UNLOADING OF THE UNEQUIPPED SUN SYSTEMIZER CONTAINER (45 FEET CONTAINER), NO.3

The photo sequence presented in Figure 45 to Figure 47 shows the unloading procedure of the battery sun systemizer container with a large crane. Using the crane the container was put precisely on the prepared foundation with existing DC-cabling.

Figure 48 shows the unloading of the E-Storage 2300 container, it can be seen that the container is placed precisely on the prepared foundation with existing DC-cabling.



FIGURE 48: UNLOADING OF THE E-STORAGE 2300 CONTAINER

In January 2019, the two containers were successfully installed at Concept Grid.



FIGURE 49: COMPLETED BESS INSTALLATION

3.2 WIND FARM CONTROL ADAPTATION

3.2.1 UPDATES OF THE EXISTING WIND FARM CONTROLLER

Since its commissioning in September 2015, the wind farm Anglure has been using the ENERCON standard RTU (Remote Terminal Unit) controller. This controller is usually installed in every wind farm connected to the distribution grid. Its main role is about monitoring and controlling the electrical values at the PoC of the wind farm.

More precisely, it allows for:

- Monitoring remotely electrical values such as voltage, current, active and reactive power at the PoC;
- Ensuring a closed-loop control of the maximum injected active power (as per limited by the system operator) and a closed-loop control of the injected reactive power (typically a $\tan(\varphi)$ control as per requested by the system operator);
- Finally yet importantly, it ensures a communication interface between the grid operator and the wind farm.

In some rare projects, this controller is used as well as a voltage-droop controller when a wind farm is connected to a feeder mixing producers and consumers.

Having said this, the RTU is inadequate for enhanced services such as the ones claimed to be tested in the case of EU-SysFlex WP8 demonstration (RTU's typical response time is approximately 30 seconds). Therefore, the RTU had to be replaced by a more advanced controller - the ENERCON FCU E2. One can refer to the report D8.1 for having more details about the FCU E2 features.

As described in [4], the FCU E2 controller offers advanced controls in terms of voltage and frequency regulations, but as well in terms of response time. This ability to react fast is conferred by an embedded powerful microcontroller, but as well by the set-up of a direct communication between the FCU and the wind turbines, as illustrated in Figure 50 (contrary to the RTU through which the SCADA is an intermediate to communicate with the wind turbines).

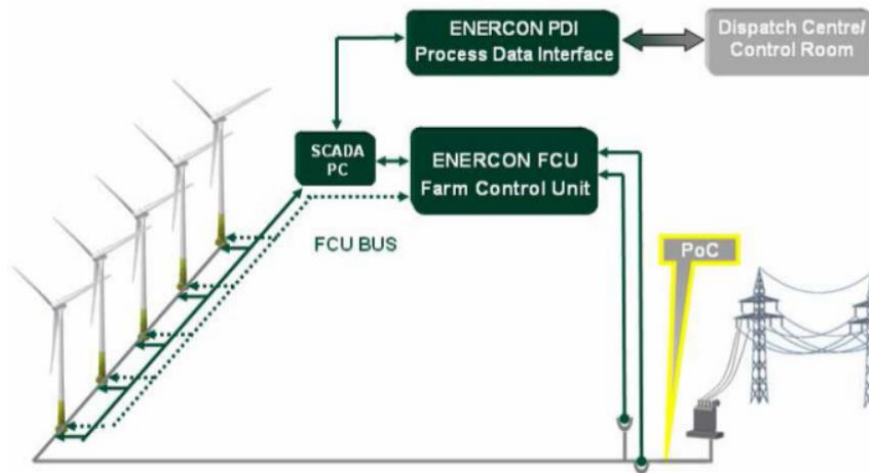


FIGURE 50. OVERVIEW OF DIRECT COMMUNICATION BETWEEN THE FCU AND THE WINDTURBINES (DOTTED LINE)

3.2.2 INSTALLATION PHASES

The installation process of FCU E2 involved 3 main steps.

Phase 1: FCU E2 installation

As a first stage, after its delivery on site, the FCU E2 cabinet was installed in September 2019 as illustrated in Figure 51. The Human Machine Interface (HMI) of the controller can be seen in Figure 52.



FIGURE 51. FCU E2 CABINET INSIDE ANGLURE WINDFARM

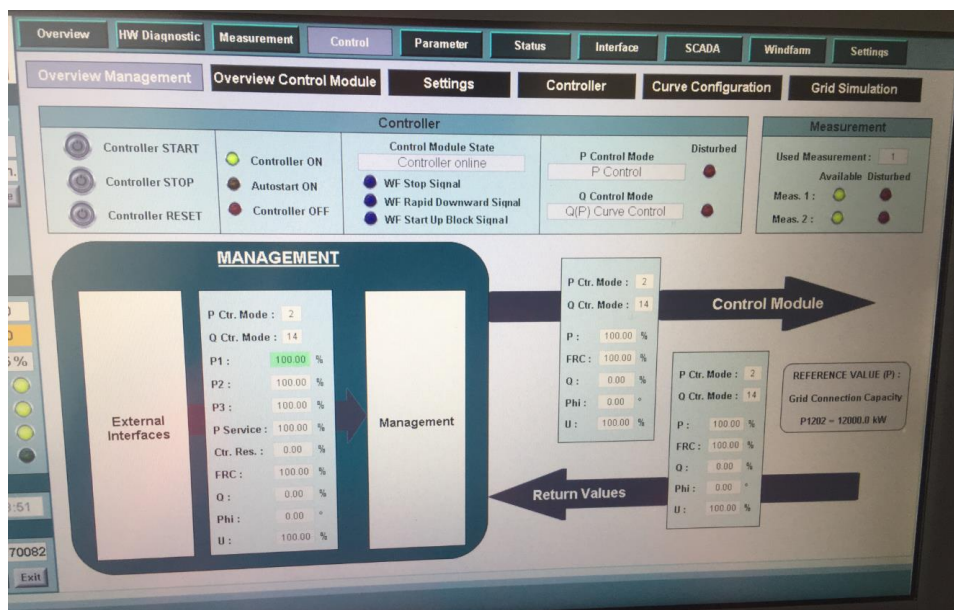


FIGURE 52. HMI OF THE FCU E2 CONTROLLER

The installation consisted on:

- installing the FCU cabinet inside the substation SCADA room
- connecting the FCU (power supplied by 230V AC and measurements issued from the voltage and current transformers)
 - o to the existing intermediate interface (SI) of the system operator
 - o to the ENERCON network for enabling a remote access
- leaving the FCU in standby mode, waiting for phase 2 finalization.

Phase 2: Wind turbines upgrade

During the second phase, each wind turbine had to be upgraded in order to confer them the ability to communicate directly with the FCU. For this purpose, an interface named FCI (Farm Control Interface) was installed on each wind turbine (Figure 53). With it, the direct communication between the wind turbines and the FCU controller is possible by the mean of the optical fiber already distributed within the wind farm. This entire work was conducted during September 2019.

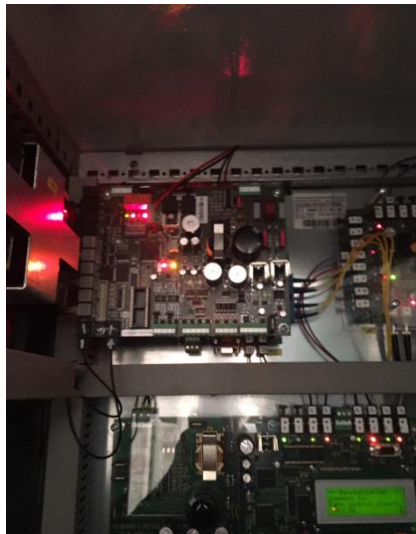


FIGURE 53. WIND FARM FCI BOARD (TOP LEFT)

Phase 3: activation of the FCU control

The third stage was to activate the FCU E2 control.

- Firstly the FCU control was activated in order to take over RTU's control:
 - Active power limitation was activated to the limits given by the system operator (12MW) and so was the reactive power control (set to $\tan(\varphi)=0.05$).
 - The activation of the communication FCU<SI>system operator.
- And then the RTU was disconnected.

At the time of writing this report, the last step of pre-commissioning is in the way: it consists on recording at least one week of 10-minute data measurement (P and Q) and then verifying that the requirement imposed by the utility is still fulfilled with the new controller.

To completely end the commissioning of the new controller adapted for WP8 demonstration, the remaining work will be to test locally every single service (FFR, FCR, and FRR) that can be provided by the wind farm. These tests are planned to be performed in November 2019.

4. IT AND COMMUNICATION INFRASTRUCTURE IMPLEMENTATION

With a better understanding on the relevance of the necessary IT and communication infrastructure enabling the operation of the WP8 demonstration, some detailed updates have been proposed during the second year's work regarding the global communication architecture specified in the D8.1 report [4] and previously illustrated in Figure 3:

- Each GED (Grid Edge Device) has a buffer to store data in case of communication failure, and no longer needs a local database.
- Integration of the Device Management System (DMS)¹⁰ has been removed from the target architecture. The role of the DMS is to provide the configuration, supervision, asset management as well as maintenance and administration functions for a set of IEC 61850 systems. Initially in the EU-SysFlex WP8 demonstration, the functionality expected by the DMS was only for devices' configuration deployment. Other functionalities are not used or can be provided elsewhere (e.g.: supervision will be assured thanks to the web HMI and administrative tasks will be done manually through a remote SSH connection). As the implementation of DMS is not mandatory for communications between the EMS and GEDs, it was decided to put on hold its implementation due to the low number of IEC 61850 systems to manage.
- The GED-P and the GED-L are merged into a single physical device named "GED-LP", as the PV panels and the controllable loads are geographically located at the same place (Concept Grid).
- The servers will not be in EDF's lab (A²R) but in an external cloud provider.

A newly proposed global communication architecture of the demonstration with the above-mentioned updates integrated can be seen in Figure 54.

¹⁰ The Device Management System is the subject of the IEC 61850-90-16. This standard is still in a draft version (the IEC 61850-90-16 reference indicates that discussions are still in progress).

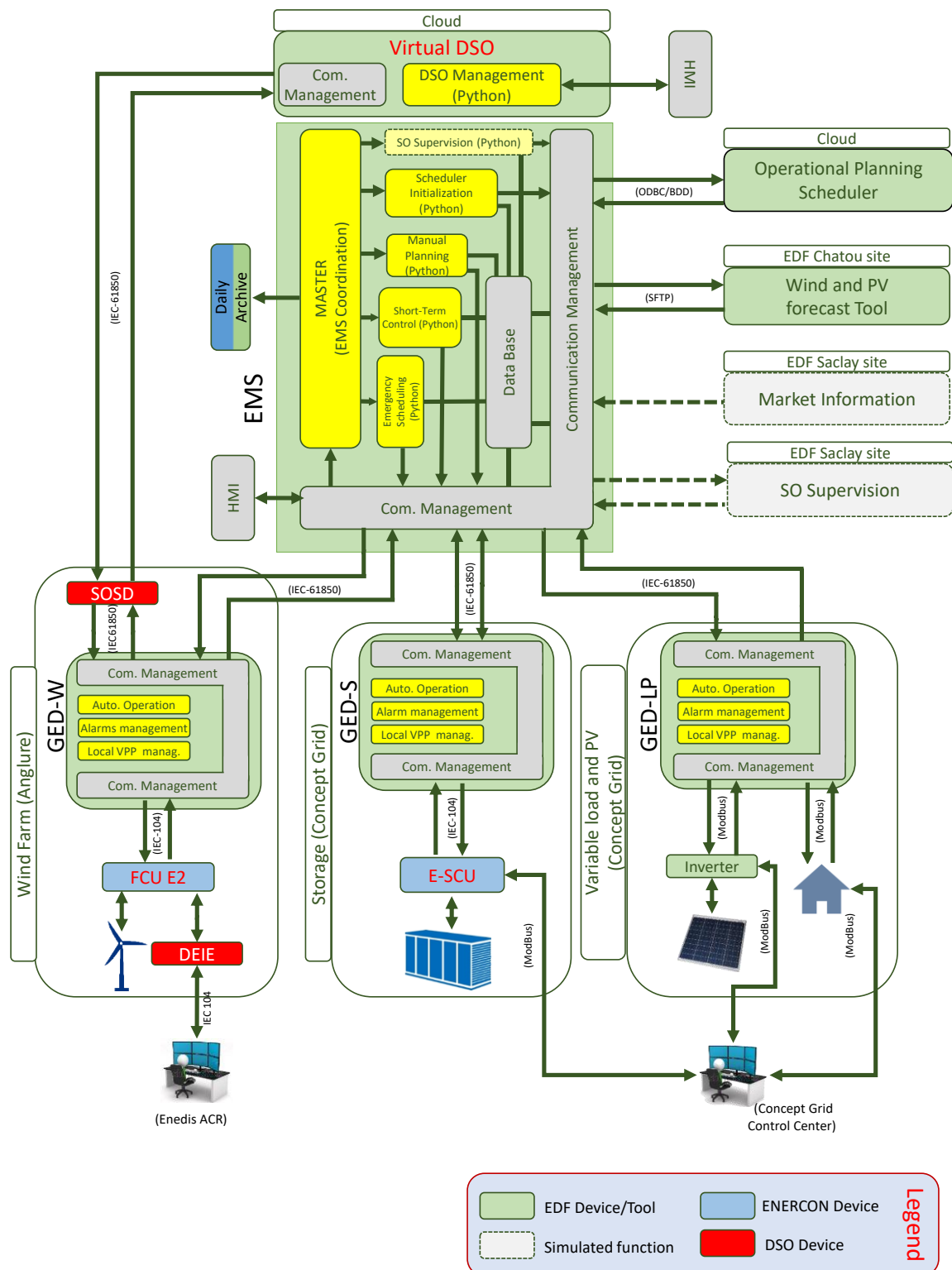


FIGURE 54. UPDATED COMMUNICATION ARCHITECTURE OF THE DEMONSTRATION

4.1 IT INTERFACES AND SOLUTIONS

The demonstration assets are located in two different sites (Anglure wind farm and Concept Grid). Concerning the IT infrastructure, there is a GED for the communication of each asset with the EMS (except for load and PV where the same GED will be used)¹¹.

The used servers have been installed in a datacenter, directly connected to the Internet. EDF network filters communication between internal network and the Internet. Industrial protocols are not allowed to pass from one network to the other. For this reason, the EMS was chosen to be put on the Internet. Servers are cyber-secured and the EMS is only accessible by pre-defined IP addresses. All communications carrying the assets measurement or control signals must use an encrypted protocol while transiting on the Internet. Therefore IPSec tunnel will be established from the wind farm to the EMS, so as from Concept-Grid to the EMS.

At present, the first VPN (Virtual Private Network) connecting the Concept Grid firewall/gateway to the cloud provider firewall is operational, allowing transparent communication between the EMS and GED-S / GED-LP. The second VPN connecting the cloud provider firewall directly to the GED-W is not yet deployed because it is still under configuration and not yet installed in the wind farm.

The use of a VPN tunnel was not only motivated by the need to secure the connection between field assets and the cloud, but also due to the fact that the MMS (Manufacturing Message Specification) industrial protocol does not support encryption natively. Indeed, the GED communicates with the assets by using the protocol expected by each asset supplier. Between the GED and the EMS, IEC 61850/MMS has been chosen. This protocol is richer than IEC 60870-5-104 or Modbus, and is well-known on grid installations. However, MMS packets are not encrypted and the encryption functionality is defined in the IEC 62351 standard. This cybersecurity layer is therefore not included inside the GEDs, whereas the encapsulation in an IPSec VPN brings the same level of security as the solution suggested in IEC 62351.

An exception is made for the connection of the forecast tool server, which relies on EDF Internal network (EDF Chatou site) for this demonstration. Indeed, this server is also used for other EDF projects, therefore it has to stay connected to EDF network. File transfer between the forecast tool server and the EMS will be based either on (s)FTP or SCP. Figure 55 shows a simplified view of the IT architecture of the demonstration.

¹¹ Indeed, as the battery, load and PV are on the same site, technically we could also have embedded all three GED in the same hardware.

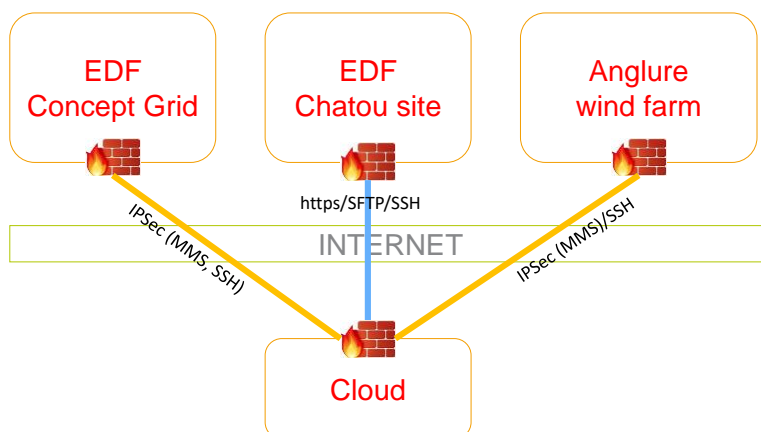


FIGURE 55. DEMONSTRATION UPDATED IT ARCHITECTURE (SIMPLIFIED VIEW)

4.2 COMMUNICATION INFRASTRUCTURE CONFIGURATIONS

The GED communications and modelling layers are based on the IEC 61850 international standard as explained previously. The IEC 61850 standard describes communication services and data mediatization structure for the control-command of electrical grid systems implemented in Intelligent Electronic Devices (IED). Initially intended for substations with the publication of the IEC 61850 edition 1 in 2004, the standard is subsequently extended to equipment outside substation since the IEC 61850 edition 2 in 2011. This version upgrade now also encompasses Distributed Energy Resources (DER) assets used for the management and control of wind and solar farms, battery bench or load bank.

The general scope of the standard is to provide a set of services and data model to support information exchange between two or more IEDs from different vendors. This interoperability is achieved thanks to a common data model which describes all functions of an electric system at all levels of an installation in an object-oriented way.

As illustrated in Figure 56, specific function are modelled into Logical Nodes (LN) and are used as basic "class" to build a full Logical Device (LD). LDs are therefore composed of the relevant LNs so as to provide the information needed for a particular device. The LNs are themselves composed of a set of predefined grouping of Data Objects (DO) of which the meaning and type are framed by the standard. The last level of modeling is the Data Attribute (DA) which contains the data to be read or set. DAs are instantiations of multiple Common Attributes (CA) such as the timestamps, the quality or magnitude using standard data types (Boolean, integer, floating point, etc.) and grouped under Common Data Classes (CDC). CDCs can be defined as the type or format of DOs.

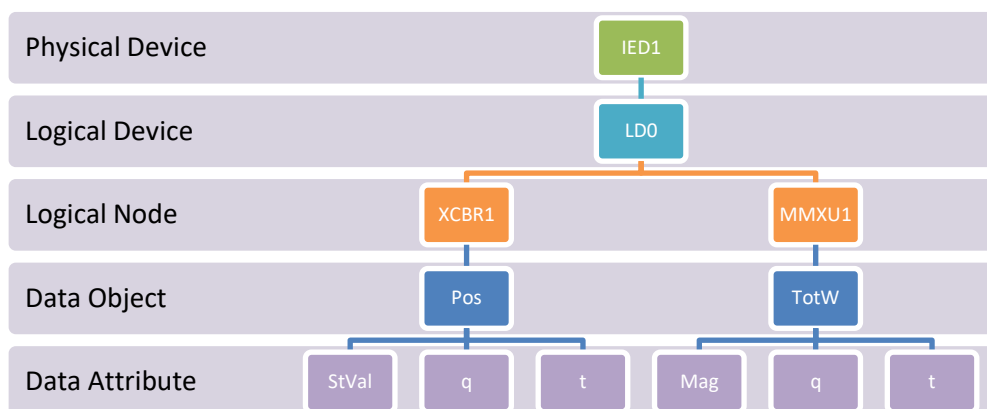


FIGURE 56. IEC 61850 MODELING STRUCTURE EXAMPLE

Access to the data from the IEC 61850 model is performed by Abstract Communication Service Interface (ACSI) services mapped to industrial protocols such as MMS, IEC 60870-5-104, Modbus, OPC DA, etc. This mapping can also be done with non-industrial protocols such as MQTT, Kinesis (AWS), Kafka or HTTP/REST. ACSI services not being dependent to a specific communication protocol, makes the IEC 61850 standard highly future-proof. DA to be accessed by ACSI services are referenced by a functional constrained data attribute (FCDA) whose semantics and terminology are fixed by the standard.

The IEC 61850 standard thus provides a common language for data medialization and exchanges services for substations and DER assets.

4.2.1 INTERFACES MODELLING AND NOMENCLATURE

The implementation of the IEC 61850 standard within the GEDs is ensured by an internal software solution to EDF R&D: GeneSys. The solution includes a set of generic, modular and configurable libraries, based on the IEC 61850 standard, that interface with each other to compose a communicative, intelligent and standardized application to meet the needs of assets in the electric utility field.

GeneSys includes several software components in order to retrieve, standardize and report data from field assets to a centralized EMS. In this context, a GeneSys eCore is deployed on each of the GEDs to perform the data retrieval functions as well as to send the command and setup instructions for the operational process of the DERs. The GeneSys eCore consists of a protocol gateway based on the IEC 61850 standard which makes it possible to interface different industrial and non-industrial protocols with the GEDs.

The first step of the IEC 61850 modelling is to best match each data of the asset which is going to be considered with a DO of the standard. In the case where a DO is not pre-defined in the standard, it is possible to define a new one by following strict terminology and semantics rules.

Once all data have been identified within the standard, writing of the model is done with the Substation Configuration description Language (SCL) defined by the IEC 61850 standard itself. The SCL data medialization file

in based on XML format and can either be written directly or with the help of dedicated tools. The use of an SCL file editor is however strongly advised because of the complexity of the task and to avoid errors. The SCL file then goes through a validation tool that verifies that the syntax matches the requirements of the standard.

4.2.2 INTERFACES MAPPING

The GeneSys eCore needs a configuration mapping file in order to match references of the target communication protocol with the FCDAs of the IEC 61850 data model. This process is not standardized and is done with the help of an Excel file which lists all data to be considered with their type, addresses, description, access mode (read/write), etc. This file is specified collaboratively by ENERCON and EDF in the case of the GED-S and GED-W and is produced internally by EDF R&D for the GED-LP.

In the case of the GED-S, the communication being done by the IEC 60870-5-104 with the E-SCU (Battery Control Unit), the mapping of the IEC 61850 FCDAs with the IEC60870-5-104 IOA addresses allows data setpoint and measurement to be exchanged.

More specifically, it is up to EDF R&D engineering team to find the DOs matching as closely as possible to the IEC 60870-5-104 data. The IEC 61850 standard provides a dictionary of predefined LNs which list functions by categories. Each data being assigned to a LN that produces or consumes the values of this DO. For example, data consisting of calculated values of current and voltage are assigned to the LN "measurement unit" which provides the "TotW" DO for the total power output measurement of a DER. When the needed DO is not defined by the standard, a new DO must be added to a LN according to the semantics rules of the standard.

4.2.3 CONFIGURATION OF GED-S AND COMMUNICATION TESTING WITH E-SCU

The configuration of a GED can be split into two parts, network interface settings and GeneSys eCore configuration. The first one is done by fixing the IPv4 address in the GED network interface configuration file. The IP address indicated must be configured at the firewall/router level so that it can communicate with the EMS in the cloud through the secured VPN tunnel. On the other hand, the GeneSys eCore configuration is written and tested before deployment within the EDF R&D laboratory. This configuration mainly consists of two files:

- IEC 61850 SCL modelling file: XML file written according to SCL language specification that describes IEC 61850 data model of an asset.
- GeneSys eCore configuration file: XML file for the settings of the GeneSys eCore parameters and the protocol mapping.

The GED-S is already configured and has been tested and qualified for communication with the E-SCU. The test consisted of sending emulated commands and reading measurement to/from each IOA addresses of the E-SCU listed by ENERCON using a script with the GeneSys eCore python API. The IT infrastructure used during the test is illustrated in Figure 57.

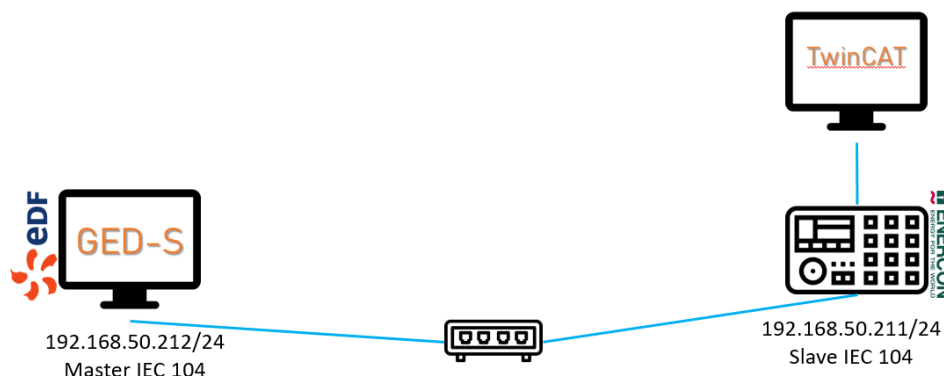


FIGURE 57. IT INFRASTRUCTURE USED DURING THE GED-S – E-SCU COMMUNICATION TEST

The communication between the GED-S and the E-SCU uses the IEC 60870-5-104 protocol. At the same time, the GED-S has to transfer information from and to the EMS using another protocol (IEC 61850). A mapping is therefore mandatory as mentioned previously. The performed communication test allowed to verify that IEC 60870-5-104 interface configurations are similar on both sides of GED-S and E-SCU and the mapping in the GED-S is correct (same scale, same positive/negative sign, same precision, etc.). The test was performed for every setpoint tag and feedback tag that needs to be exchanged between both equipments.

The GED-S is the first GED developed in the demonstration work. The configuration of GED-W and GED-LP will be finalized in the year 2020. As mentioned previously, the use of a centralized device management system has been ruled out due to the simplicity of the deployment environment which only contains 3 GEDs to be administered. This task will be handled through command line instruction directly on the targeted GED through a secure SSH connection. Once all VPN connections are set, all GEDs will be available for remote configuration update and system administration.

4.3 PREPARATION OF THE DATABASE

Before launching experimental tests, an appropriate database should be configured in order to store and archive all the necessary data for eventual postprocessing. In this demonstration at a reduced scale, the data traffic should normally be manageable with a SQL database such as “MariaDB” or “PostgreSQL”. However, if much more power plants or load sites are aggregated in a VPP and controlled by an EMS, limits of this type of database will be reached. Therefore, the database management system “Apache Cassandra” has been chosen for the concern of scalability of the demonstrated solutions. This NoSQL database is dedicated to manage large amount of data with a considerable scalability ability, for example, by dispatching data on several nodes. Another interesting characteristic of this database is the internal schema. It is a key-value database, column oriented. This particularity allows us to add new data point/flag without restructuring the table schema, even if it is not normalized data.

At the time of writing, one keyspace (Cassandra name for “database”) has been created with one column family (Cassandra name for “table”). The database is managed by an HMI backend. This backend keeps data from the

EMS communication management interface and sends them to Cassandra. This database is accessible directly or through the HMI backend.

4.4 HMI DEVELOPMENT

An HMI has been developed to monitor, control and supervise the EMS, which is installed in the cloud's servers. The HMI is a web interface, built with Javascript, HTML5 and CSS3. As shown in Figure 58, a backend has been developed to offer the HMI the capacity to keep, at the same time, real-time data embedded in the Communication Management and historical data embedded in the database. Information are available through an REST (Representational State Transfer) API, allowing a partner to develop its own HMI and to plug it to the API if necessary¹².

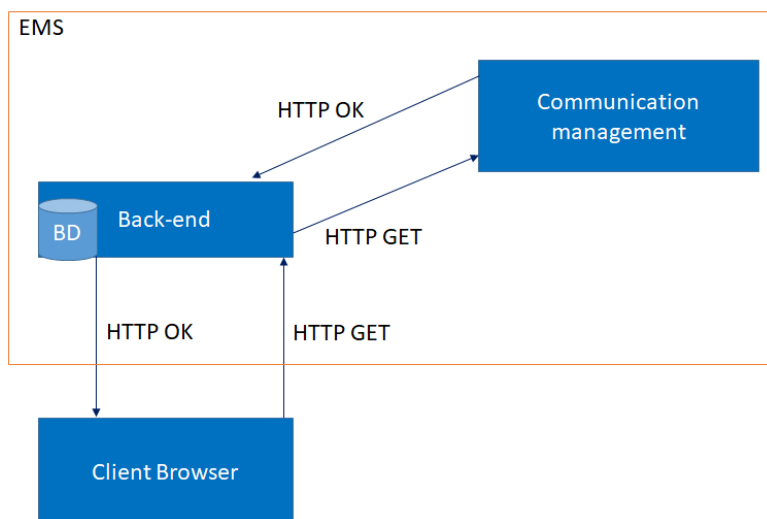


FIGURE 58. BACK-END INFRASTRUCTURE AND REQUEST-RESPONSE PATH

In the following section, the main pages representation of the current version of the developed HMI is presented. First, to enter in the HMI, the user indicates a login and a password as illustrated in Figure 59.

¹² The REST API will not be describe in this document.



FIGURE 59. LOGIN PAGE OF THE DEMONSTRATION HMI

The application is split in 5 tabs:

- **Dashboard:** it is the main view, giving all the main information about the assets, based only on live information (Figure 60). At a glance, the users can have access to the most important KPI (Key Performance Indicators) and the states of the assets. Historical information are available in the Graph tab, of which the display needs a database export.

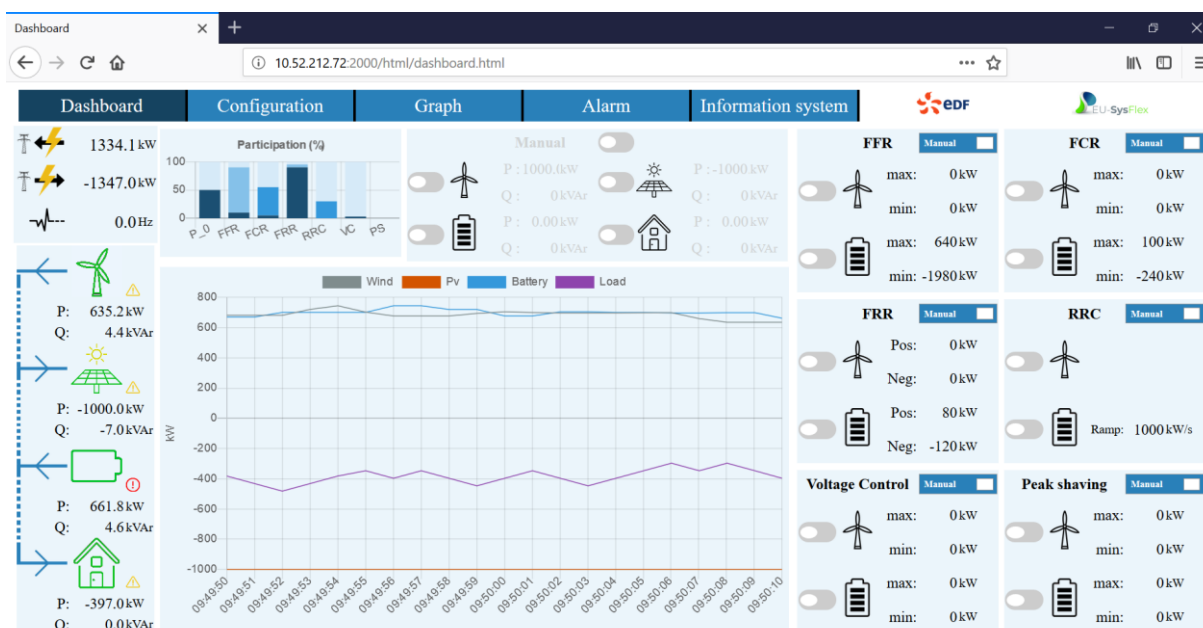


FIGURE 60. DASHBOARD PAGE OF THE HMI

- **Configuration:** it is the page to get running asset's configuration parameters (only the ones that are accessible remotely), and to modify them in case of necessity (Figure 61). This page will be completed with respect to further GEDs deployment.

Dashboard	Configuration	Graph	Alarm	Information system																																																																
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FIGURE 61. CONFIGURATION PAGE OF THE HMI

- **Graph:** In the Dashboard, the users have access to live information. The Graph page here offers the ability to visualize historical data through interactive graphs and to perform basic comparisons (Figure 62). More complex analyses could be done with ad-hoc tools, based on an extraction of the EMS' database.

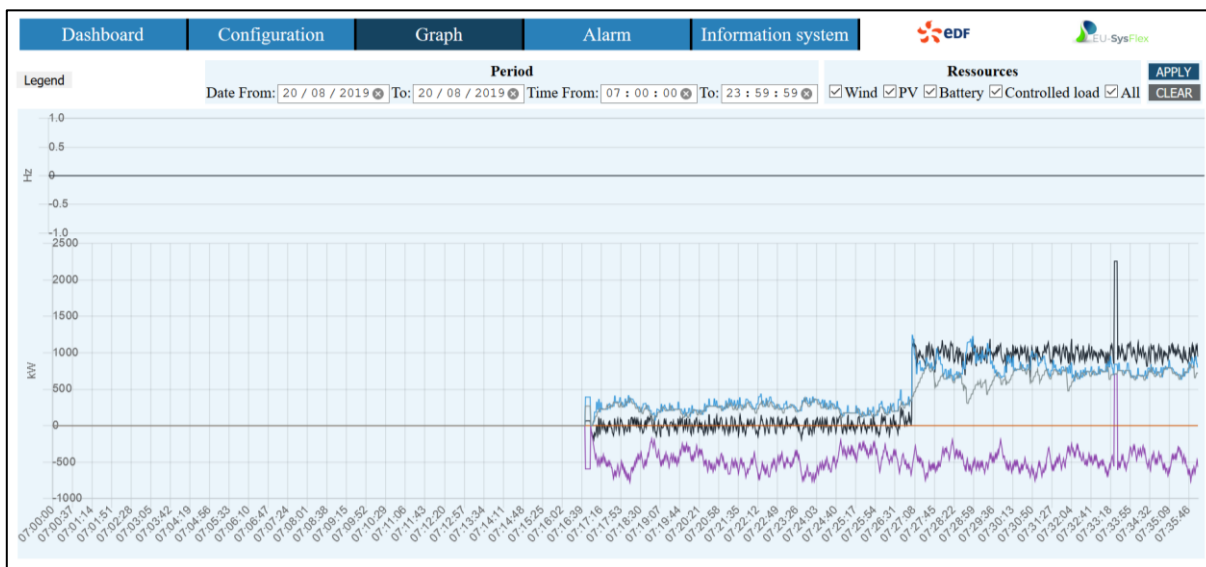


FIGURE 62. GRAPH PAGE OF THE HMI

- **Alarm:** this view is not completely developed in the current version. IT alarms will be displayed when all the infrastructure is fully deployed (Figure 63).

Dashboard	Configuration	Graph	Alarm	Information system	edf	EU-SysFlex
Period From : 13 / 08 / 2019 To : 13 / 08 / 2019 From : 07 : 00 : 00 To : 23 : 59 : 59		Criticality Choose an option	Equipment Choose an option	Label Choose an option	State Choose an option	Acknowledgment Choose an option
		APPLY	CLEAR			
Time	Criticality	Equipment	Label	State	Acknowledgment	
2019-08-13 13:46:38	Warning	Pv	Label	✗	Not ack	
2019-08-13 13:46:33	Info	Load	Label	✓	Ack	
2019-08-13 13:46:28	Info	Load	Label	✓	Ack	
2019-08-13 13:46:23	Info	Load	Label	✓	Not ack	
2019-08-13 13:46:18	Debug	Pv	Label	✓	Ack	
2019-08-13 13:46:13	Info	Wind	Label	✓	Ack	
2019-08-13 13:46:08	Debug	Pv	Label	✗	Ack	
2019-08-13 13:46:03	Fatal	Pv	Label	✗	Not ack	
2019-08-13 13:45:58	Info	Load	Label	✓	Not ack	

FIGURE 63. ALARM PAGE OF THE HMI

- **Information system:** this view gives the state of the IT infrastructure (Figure 64).

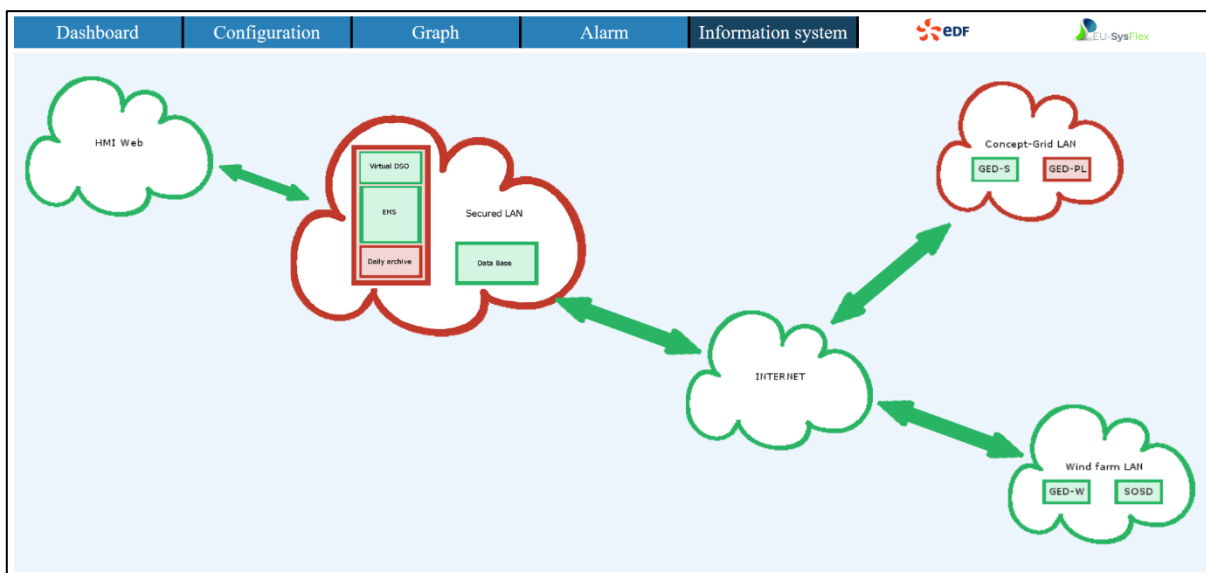


FIGURE 64. INFORMATION SYSTEM PAGE OF THE HMI

The developed HMI will help to perform experimental tests expected in 2020 more easily, as it not only allows a visual supervision of the general state (on/off, power output, services provided, etc.) of each asset of the demonstration as well as of the IT connections, but also enables remote control parameters setting during experimentations. Further development of the HMI will be performed in 2020 to better adapt the functionalities and the display of the HMI to the evolutionary needs of the demonstration.

5. FIRST EXPERIMENTAL TESTS

Before starting the experiments in the overall environment of the aggregator, it was necessary to test more 'locally' the capability of different assets (BESS, wind farm, etc.) to provide individually ancillary services. The aim of this chapter is to describe the experimental tests conducted until September 2019. At the time of writing this report, the integration tests considering the overall environment (multi-services provision from different assets managed by the scheduler through remote activations) are under preparation and planned to start before the end of the year.

5.1 COMMISSIONING TESTS OF THE BESS

After erection and proper connection of the E-Storage 2300 and the sun systemizer containers, a comprehensive commissioning and test procedure was carried out. That was an integrated collaborative work of LGChem, Hoppecke and ENERCON, together with EDF.

Table 6 shows an excerpt of the LGChem commissioning protocol.

No.	Instruction	Completed By(initials/Date)	Corrective Action Taken? (Y/N)
1	Check the Battery Installation Check List completed by installer.	<input type="checkbox"/> 17.Jan.2019	N
2	Perform a complete visual inspection of ALL equipment for damaged components, materials, etc.	<input type="checkbox"/> 17.Jan.2019	N
3	Check the bolted power cables on each rack that they are marked with a permanent marking.	<input type="checkbox"/> 17.Jan.2019	N
4	Check auxiliary power cable connection in each rack.	<input type="checkbox"/> 17.Jan.2019	N
5	Check auxiliary power switch in each rack is ON.	<input type="checkbox"/> 17.Jan.2019	N
6	Check the communication cable connections between MBMS in each rack.	<input type="checkbox"/> 17.Jan.2019	N
7	Check the communication cable connections between RBMSs.	<input type="checkbox"/> 17.Jan.2019	N
8	Check the communication cable connections between RBMS and BBMS.	<input type="checkbox"/> 17.Jan.2019	N
9	Check the communication cable connection between BBMS and EMS.	<input type="checkbox"/> 17.Jan.2019	N
10	Ground Check	<input type="checkbox"/> 17.Jan.2019	N

TABLE 6. EXCERPT FROM COMMISSIONING PROTOCOL PRIOR TO TESTING

Table 7 and Table 8 give an overview of the performed battery diagnosis tests. As this is relevant for safe and proper operation of the BESS, these tests are performed prior to any charge/discharge measurement. In the EU-SysFlex WP8 case, all tested functions worked well.

No.	Diagnostic Name	High Diagnosis Setting (Default)	High Release Setting (Default)	Low Diagnosis Setting (Default)	Low Release Setting (Default)	Check reset the diagnostic condition back to standard
1	Cell Voltage Warning	CV - 100mV	CV - 200mV	CV + 100mV	CV + 200mV	OK
2	Cell Voltage Fault	CV - 100mV	N/A	CV + 100mV	N/A	OK
3	Current Warning	5A	2A	-5A	-2A	OK
4	Current Fault	5A	N/A	-5A	N/A	OK
5	Over Power Limit Warning	5%	2%	5%	2%	OK
6	Over Power Limit Fault	5%	N/A	5%	N/A	OK
7	SOC Alarm	CV - 2%	CV	CV + 2%	CV	OK
8	Cell Voltage deviation Warning	CV - 10mV	0	N/A	N/A	OK
9	Cell Voltage deviation Fault	CV - 10mV	N/A	N/A	N/A	OK
10	Temperature Warning	CV - 0.5°C	CV - 1°C	CV + 0.5°C	CV + 1°C	OK
11	Temperature Fault	CV - 0.5°C	N/A	CV + 0.5°C	N/A	OK
12	Temperature deviation Warning	CV - 0.5°C	CV - 1°C	N/A	N/A	OK
13	Temperature deviation Fault	CV - 0.5°C	N/A	N/A	N/A	OK
14	Over Average Temperature Warning	CV - 0.5°C	CV - 1°C	N/A	N/A	OK
15	Over Average Temperature Fault	CV - 0.5°C	N/A	N/A	N/A	OK
16	Over Temperature Warning Long Term	CV - 0.5°C	CV - 1°C	N/A	N/A	OK
17	Over Temperature Warning Long Term	CV - 0.5°C	N/A	N/A	N/A	OK

TABLE 7. EXCERPT FROM COMMISSIONING PROTOCOL PRIOR TO TESTING, BATTERY DIAGNOSIS TEST

No.	Diagnostic Name	Action at High diagnosis	Action at high diagnosis release	Action at low diagnosis	Action at low diagnosis release	Completed By(initials/Date)	Corrective Action Taken? (Y/N)
1	Cell Voltage Warning	4.25V	4.2V	2.7V	2.9V	<input checked="" type="checkbox"/> 18.Jan.2019	N
2	Cell Voltage Fault	4.28V	N/A	2.4V	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
3	Over Current per Rack Warning	155.3A	145.3A	-155.3A	-145.3A	<input checked="" type="checkbox"/> 18.Jan.2019	N
4	Over Current per Rack Fault	172.5A	N/A	-172.5A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
5	Over Power Limit Warning	110%	100%	110%	100%	<input checked="" type="checkbox"/> 18.Jan.2019	N
6	Over Power Limit Fault	120%	N/A	120%	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
7	SOC Warning	99.5%	99%	2%	2.5%	<input checked="" type="checkbox"/> 18.Jan.2019	N
8	Cell Voltage deviation Warning	120mV	100mV	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
9	Cell Voltage deviation Fault	250mV	N/A	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
10	Temperature Warning	53	48	0	5	<input checked="" type="checkbox"/> 18.Jan.2019	N
11	Temperature Fault	58	N/A	-10	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
12	Temperature deviation Warning	8	6	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
13	Temperature deviation Fault	10	N/A	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
14	Over Average Temperature Warning	35	34	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
15	Over Average Temperature Warning	38	N/A	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
16	Over Temperature Warning Long Term	40	35	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N
17	Over Temperature Warning Long Term	45	N/A	N/A	N/A	<input checked="" type="checkbox"/> 18.Jan.2019	N

TABLE 8. EXCERPT FROM COMMISSIONING PROTOCOL PRIOR TO TESTING, BMS CHECK LIST

After a check of the whole safety related functions of the BESS, initial charge and discharge procedures were carried out. The procedures are described in Table 9.

Step	Battery State	Condition	Completed By (initials/Date)	Corrective Action Taken? (Y/N)
1	Initial Discharge	300kW Discharge(AC) till the SOC 2%	21~24.May.2019	N
2	Rest	Rest for 45 min		
3	Charge	300kW Charge (AC) till the SOC 99%.		
4	Rest	Rest for 45 min.		
5	Discharge	300kW Discharge (AC) till SOC 2%.		
6	Rest	Rest for 45 min		
7	Repeat	Repeat at least 2times if needed		

TABLE 9. OVERVIEW OF BATTERY FULL CHARGE/DISCHARGE TESTS

The results of the tests are shown in the following figures. The data logs of the discharge procedures are shown in Figure 65 to Figure 68 whereas Figure 69 to Figure 72 show the charge direction. All tests were carried out at a C-rate of 1 (that means the whole capacity is withdrawn or injected during 1 hour).

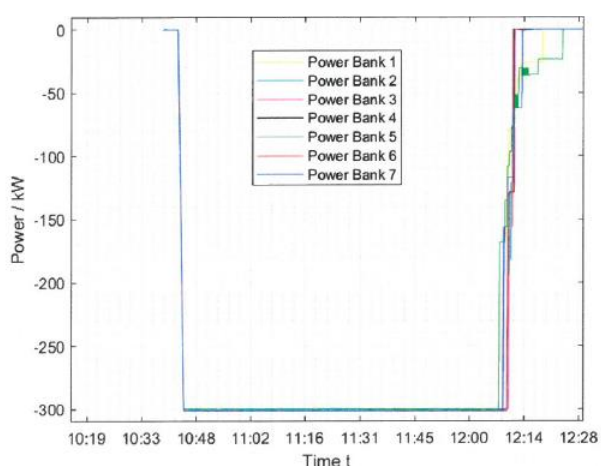


FIGURE 65: DISCHARGING@1C, POWER ON BANK LEVEL

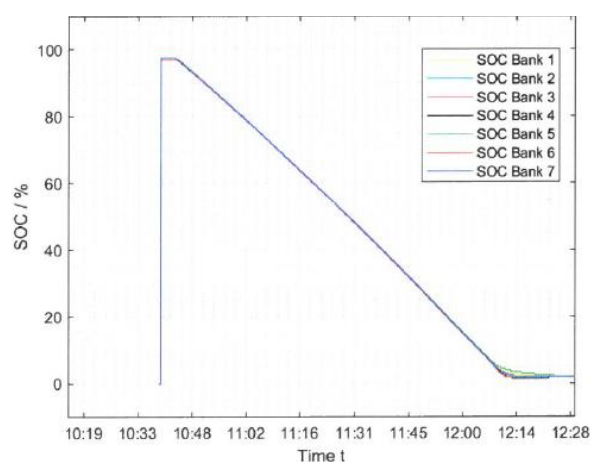


FIGURE 66: DISCHARGING@1C, SOC ON BANK LEVEL

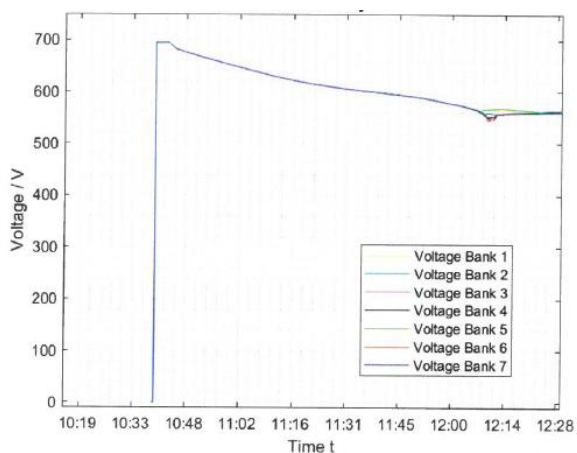


FIGURE 67: DISCHARGING@1C, VOLTAGE ON BANK LEVEL

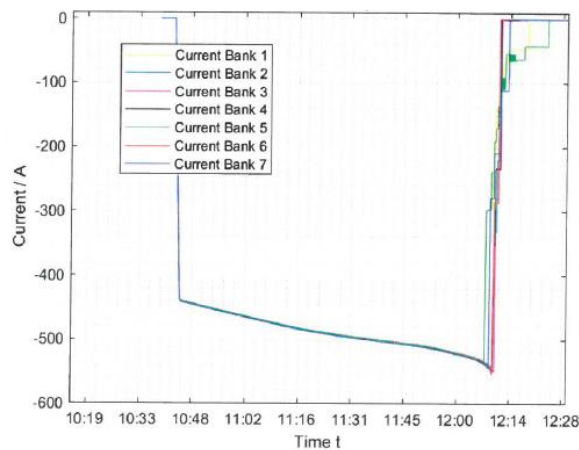


FIGURE 68: DISCHARGING@1C, CURRENT ON BANK LEVEL

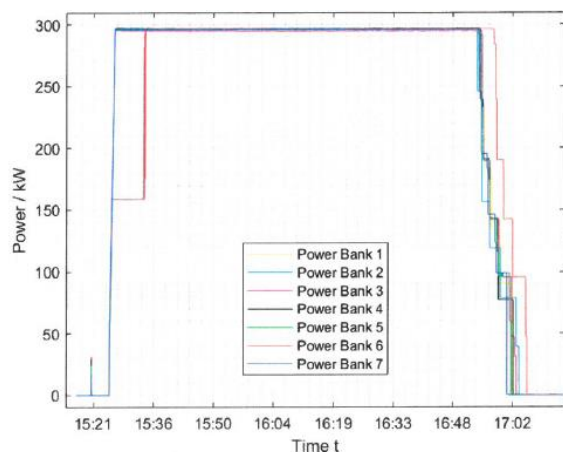


FIGURE 69: CHARGING@1C, POWER ON BANK LEVEL

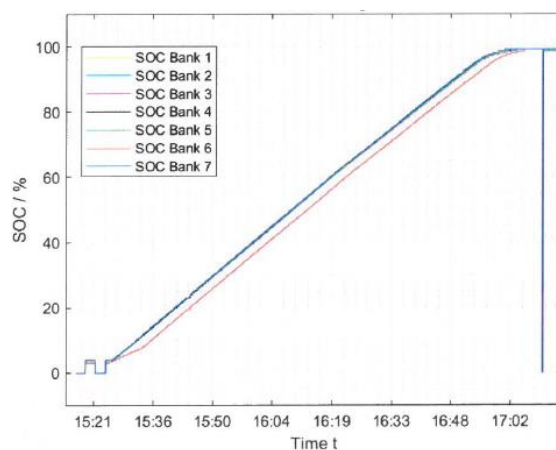


FIGURE 70: CHARGING@1C, SOC ON BANK LEVEL

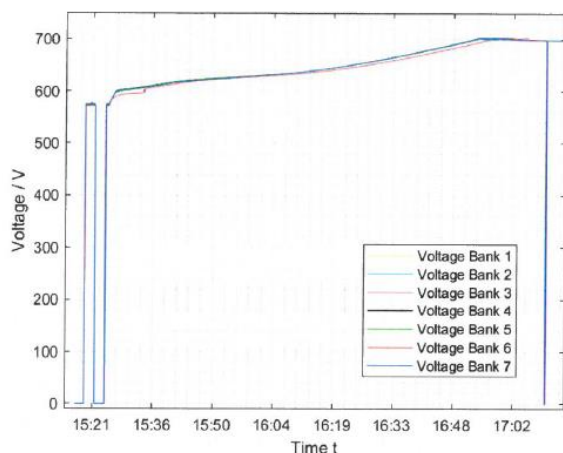


FIGURE 71: CHARGING@1C, VOLTAGE ON BANK LEVEL

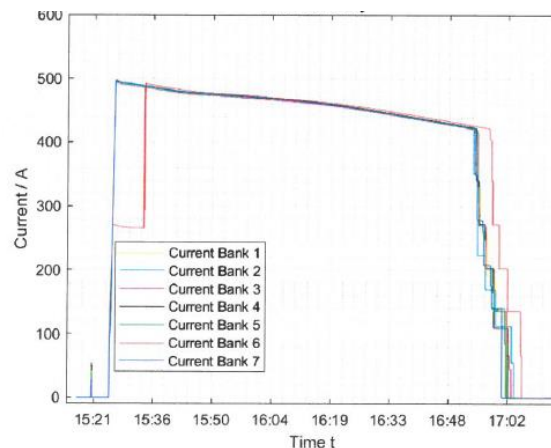


FIGURE 72: CHARGING@1C, CURRENT ON BANK LEVEL

In the following paragraph, the results are explained in more detail.

Figure 65 gives the power of each battery bank during discharging from a SoC of 98 % to a SoC of 3 % (which are the recommended limits by LGChem). While reaching the limits the power is reduced step by step whereas the weakest module determines the behaviour of the battery bank. Figure 66 shows the corresponding SoC values of each battery bank.

Figure 67 shows the voltage level during discharging of each battery bank, the 7 battery banks are installed in parallel to add up to the overall power of the BESS. Finally, in Figure 68 the current of each battery bank is shown during discharging procedure.

As noted before, Figure 69 to Figure 72 show the same parameters during charging at 1C from a SoC of 3 % to a SoC of 98 %. Derating can be seen in Figure 69 and Figure 72 while approaching the SoC limits, again the weakest module determines the behaviour of the battery bank.

During the test it turned out that 4 of the 504 modules were not conformal in terms of voltage deviation. The modules were replaced with spare parts. After repetition of the test series, the installation was conformal and commissioning was passed. The average round trip efficiency during the test turned out to be 96.6 % at an energy content of 2.9 MWh. At lower C-rates it is expected that efficiency increases, and therefore the available capacity increases as well.

5.2 ACTIVATION OF INDIVIDUAL STORAGE SERVICES

As described in the D8.1 report, several different operational modes have been developed. These modes are the following:

- Manual: 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.
- Ramp Rate Control: this mode allows for the reduction of the active power variations (limitation of dP/dt).
- Frequency Restoration Reserve: the FRR service orders the storage system to produce an active power setpoint upon request of the System Operator (SO).
- Frequency Containment Reserve: 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: as for FCR, FFR responds to frequency deviation but in a much faster way (~ 1 s versus ~ 30 s)

Depending on the active mode, a different logic is used by the E-SCU to calculate the power setpoints.

5.2.1 E-SCU CONTROLLER DESIGN AND IMPLEMENTED LOCAL SERVICE CONTROLS

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.

It is noteworthy that, as a BESS system can react very fast (in the order of 250 ms), a special parameter T_r (time constant) was used for each mode in order to adapt the response time of the system.

5.2.2 REMOTE TEST RESULTS

Before a more complete integration test taking into consideration the GED-S interface as well as the EMS calculations, separate tests were conducted manually and remotely through an internet VPN connection between the storage and ENERCON laboratory. Each of the modes has been tested firstly individually, and then in combination, to validate the performance of different control modes.

Manual mode

Table 10 and Figure 73 show the active power at the point of connection (P_{kw} in kW) when there is an increase in the setpoint (P_{sp_kw} in kW).

P_{sp_kw}	0	100	200	300	400	500	700	1000	1200	1400	1600	1800	2000
P_{kw}	0	97	198	301	402	503	709	1008	1212	1413	1611	1812	2009

TABLE 10 : TEST OF MANUAL MODE – POSITIVE ACTIVE POWER

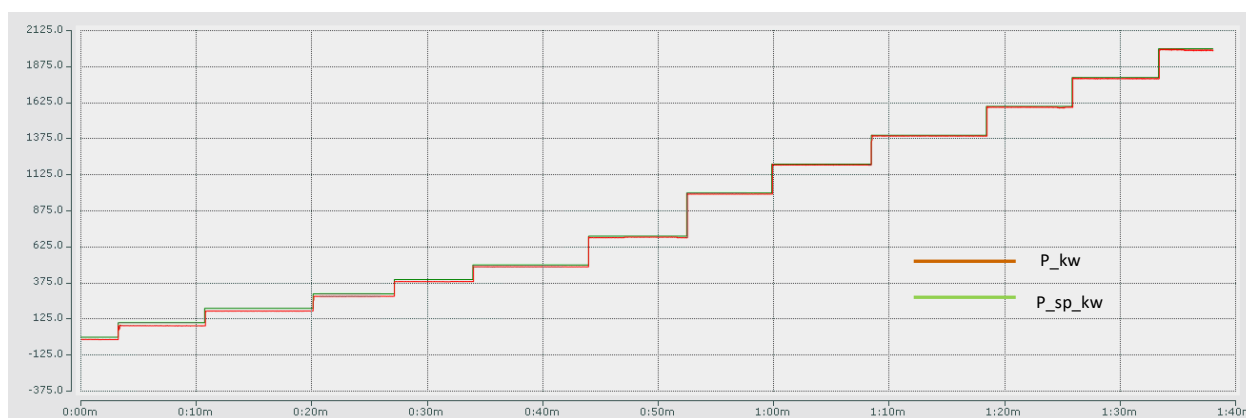


FIGURE 73. TEST OF MANUAL MODE – POSITIVE ACTIVE POWER

Table 11 and Figure 74 show the active power at the point of connection (P_{kw} in kW) when there is a decrease in the setpoint (P_{sp_kw} in kW).

P_{sp_kw}	0	-100	-200	-300	-400	-500	-700	-1000	-1200	-1400	-1600	-1800	-2000
P_{kw}	0	-105	-204	-301	-402	-498	-699	-999	-1212	-1400	-1602	-1807	-2009

TABLE 11 : TEST OF MANUAL MODE – NEGATIVE ACTIVE POWER

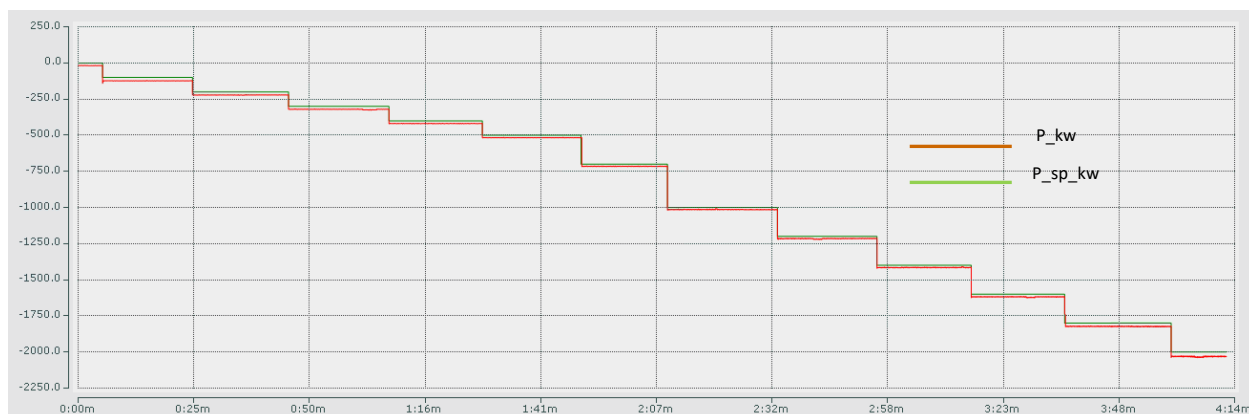


FIGURE 74. TEST OF MANUAL MODE – NEGATIVE ACTIVE POWER

Ramp Rate Control

The Ramp Rate Control consists of two different control cascaded algorithms to define the power setpoint of the BCS: the Gradient Control and the Power Control.

- Gradient Control: the gradient controller produces an active power (P) setpoint in opposition to the WF active power to maintain a desired power gradient. Figure 75 shows an example of how the gradient controller generates a power setpoint of the BCS in order to comply with the gradient setpoint at the PoC. Light blue shows the area delimited between the \pm gradient setpoint [kW/s].

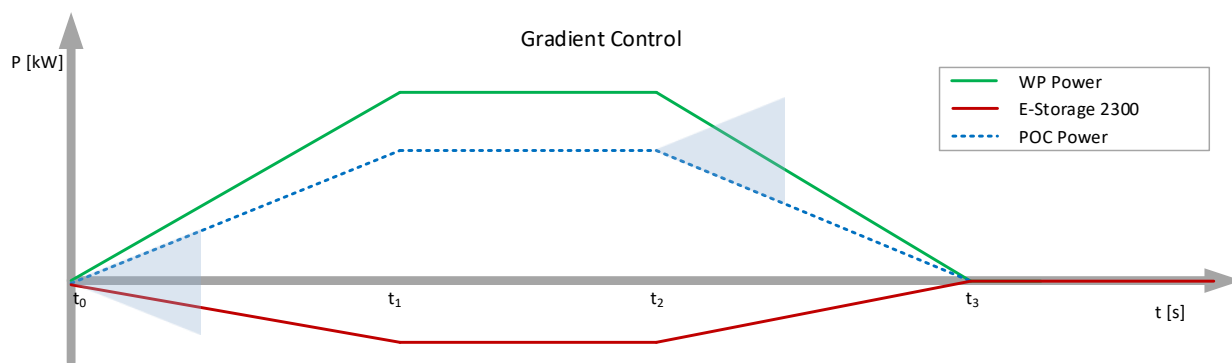


FIGURE 75. GRADIENT CONTROL ONLY

- Power Control: the power controller, without affecting the power gradient at the PoC, reduces the power setpoint of the BCS. In this way, the system reduces loss and minimizes the use of the battery. This is shown in Figure 76.

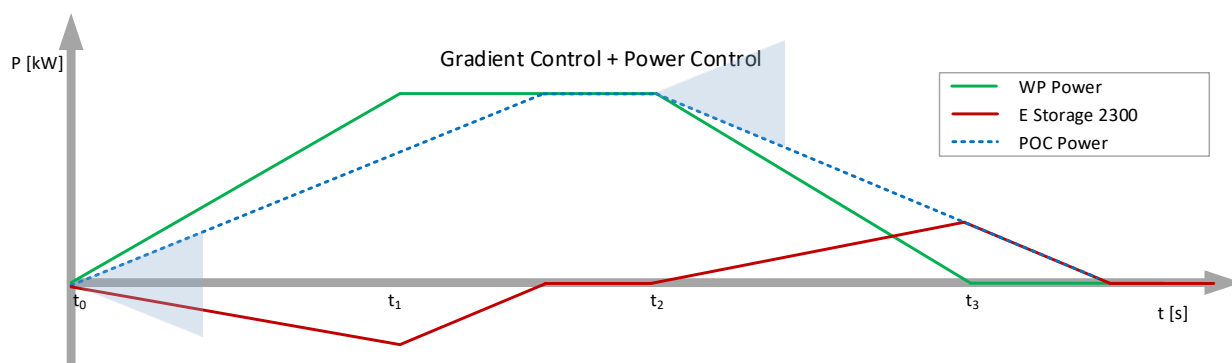


FIGURE 76. GRADIENT CONTROL + POWER CONTROL

Figure 77 shows the real behaviour when a ramping setpoint is fixed to 20 kW/s. When the emulated wind farm output shows a too important positive variation of active power, then the BESS creates a negative variation of active power by absorbing the power; the resultant power variation at the PoC is contained. Conversely, when the power plant shows a too important negative variation of active power, then the BESS creates a positive variation of active power by injecting power; the resultant power variation at the PoC is also contained.

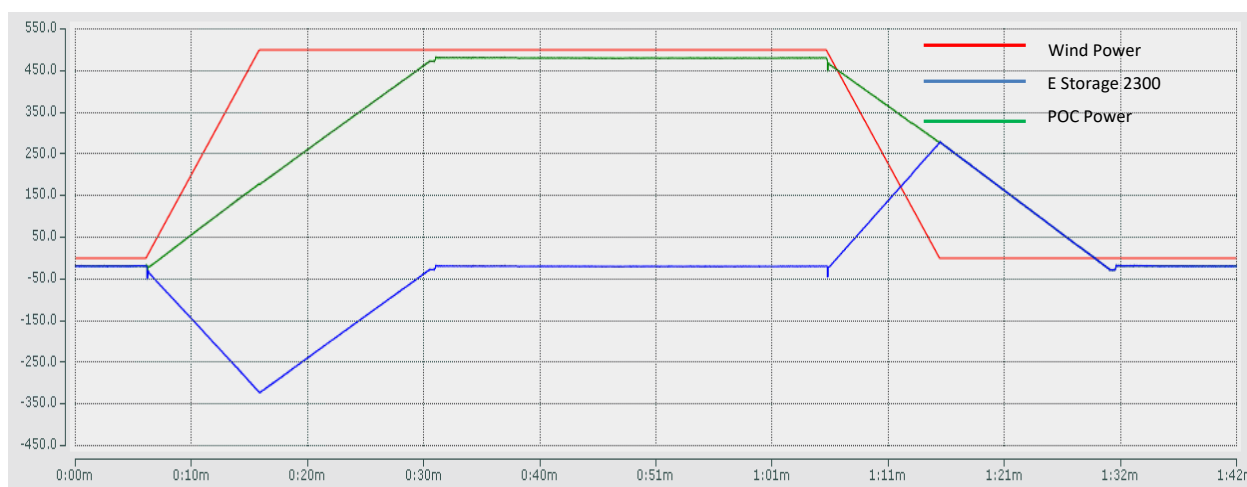


FIGURE 77. TEST OF RRC MODE WITH RAMPING SETPOINT=20 KW/S

Frequency Restoration Reserve

Figure 78 shows the BESS response (P_{kw}) to a request of positive restoration reserve provision, which is represented by an emulated incremental active power reference steps (P_{sp}). In practice 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].

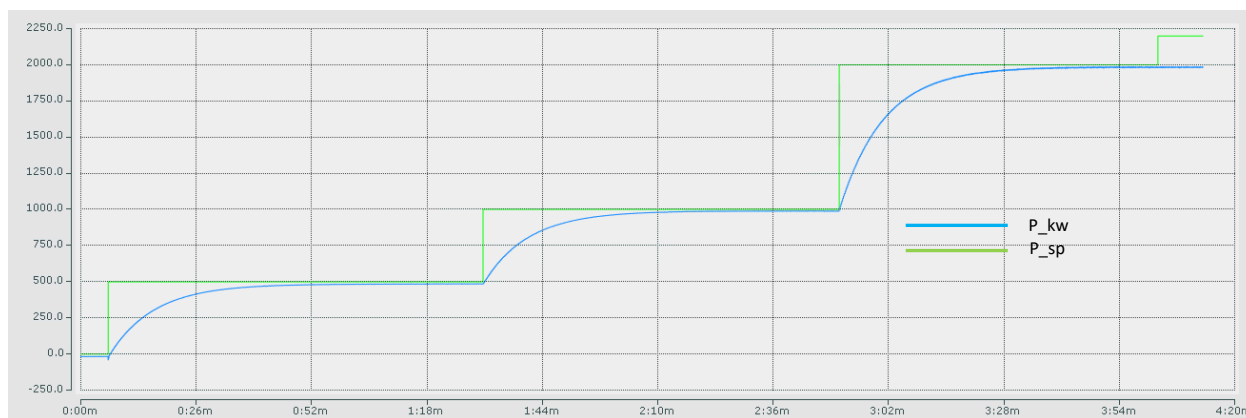


FIGURE 78. TEST OF FRR MODE – POSITIVE ACTIVE POWER

In the same way, the measurement below (Figure 79) shows the BESS response to a request of negative restoration reserve provision.

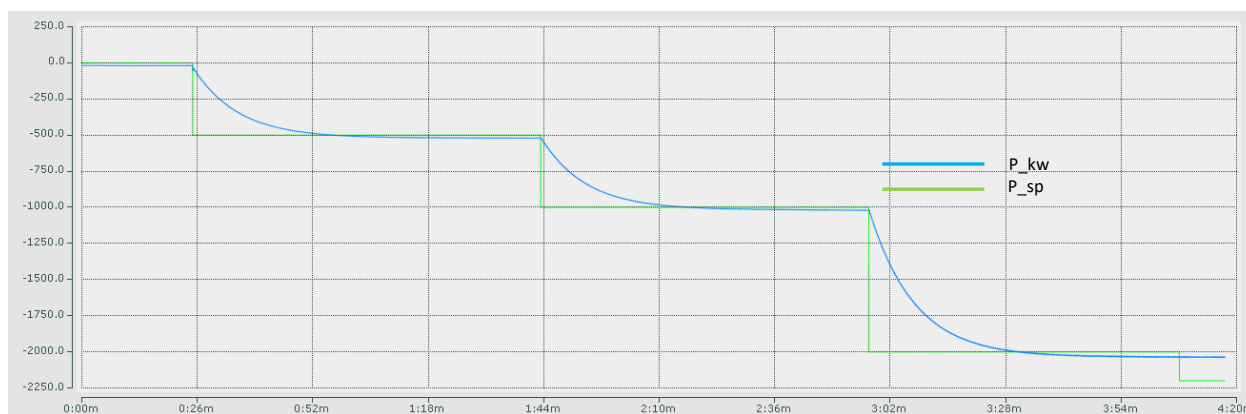


FIGURE 79. TEST OF FRR MODE – NEGATIVE ACTIVE POWER

The response time of the BESS while providing FRR is shown below.

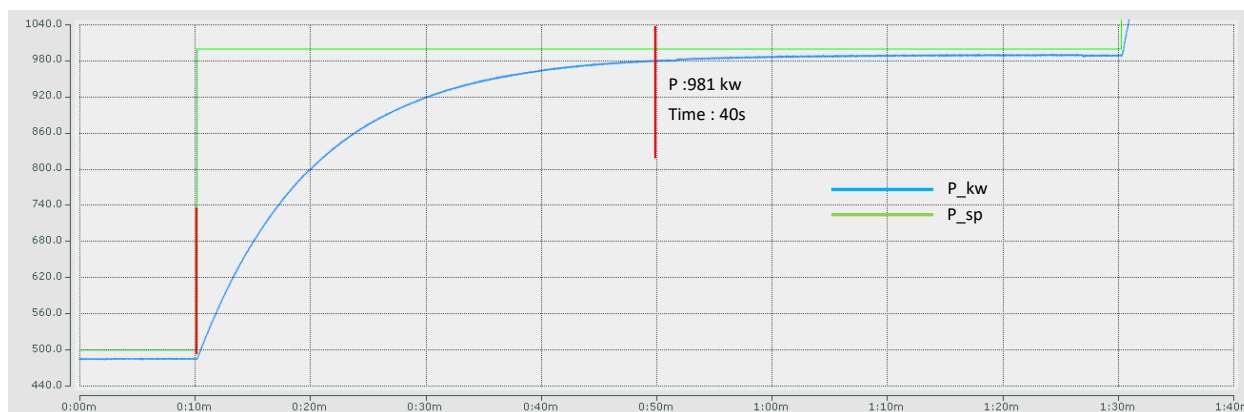


FIGURE 80. TIME RESPONSE OF FRR

Figure 80 shows how fast the FRR service responds. According to the figure, the BESS needs ~40 s to reach $\pm 2\%$ of the BCS setpoint. This response time was set below the typical requirement for FRR response dynamics (generally < 10 min) and above FCR requirement (< 30 s).

Frequency Containment Reserve

As explained before, the FCR chart of the storage can be parameterized over either the IEC 60870-5-104 Communication interface (GED-S) or the Modbus communication (Concept Grid control center). All the points shown in Figure 81, corresponding to a typical FCR power – frequency control curve, are parameters to be set.

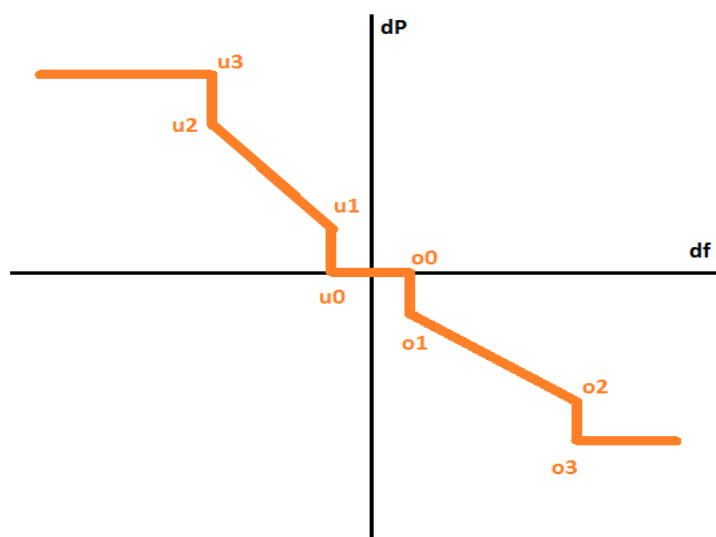


FIGURE 81. FREQUENCY CONTAINMENT RESERVE PARAMETERS CHART

For the purpose of the FCR service test, the parameter setting proposed in Table 12 has been used to perform the corresponding experimentations.

Parameter setting of $P(f)$ curve											
f_fake_Hz	49.75	49.8	49.85	49.9	49.99	50	50.01	50.1	50.15	50.2	50.25
P_sp_%	100	100	50	25	0	0	0	-25	-50	-100	-100

Test											
P_kw	1984	1982	985	480	-18	-18	-18	-520	-1017	-2039	-2039
P_diff_kw	-2	0	-3	2	18	18	18	-2	1	-21	-21

TABLE 12 : PARAMETER SETTING FOR FCR PROVISION

The measurements below (Figure 82 and Figure 83) show respectively the response of the BESS when under-frequency and over-frequency events are emulated.

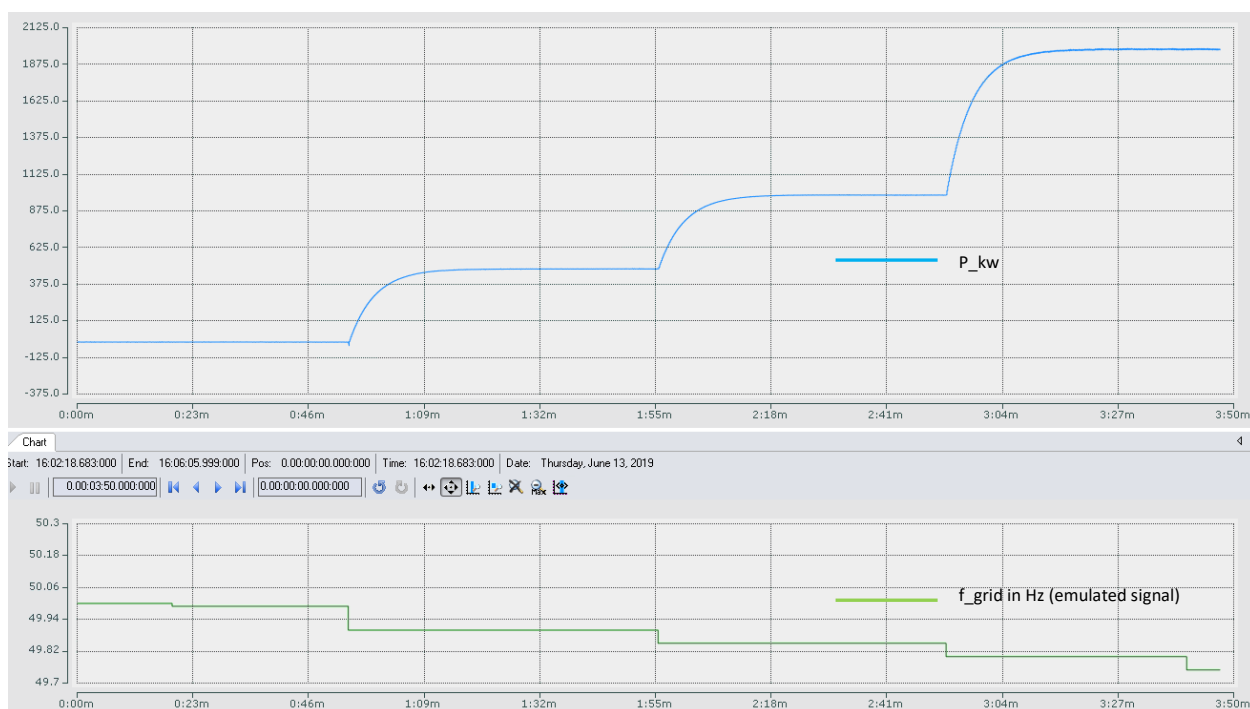


FIGURE 82. STORAGE FCR TEST: UNDER-FREQUENCY EVENT

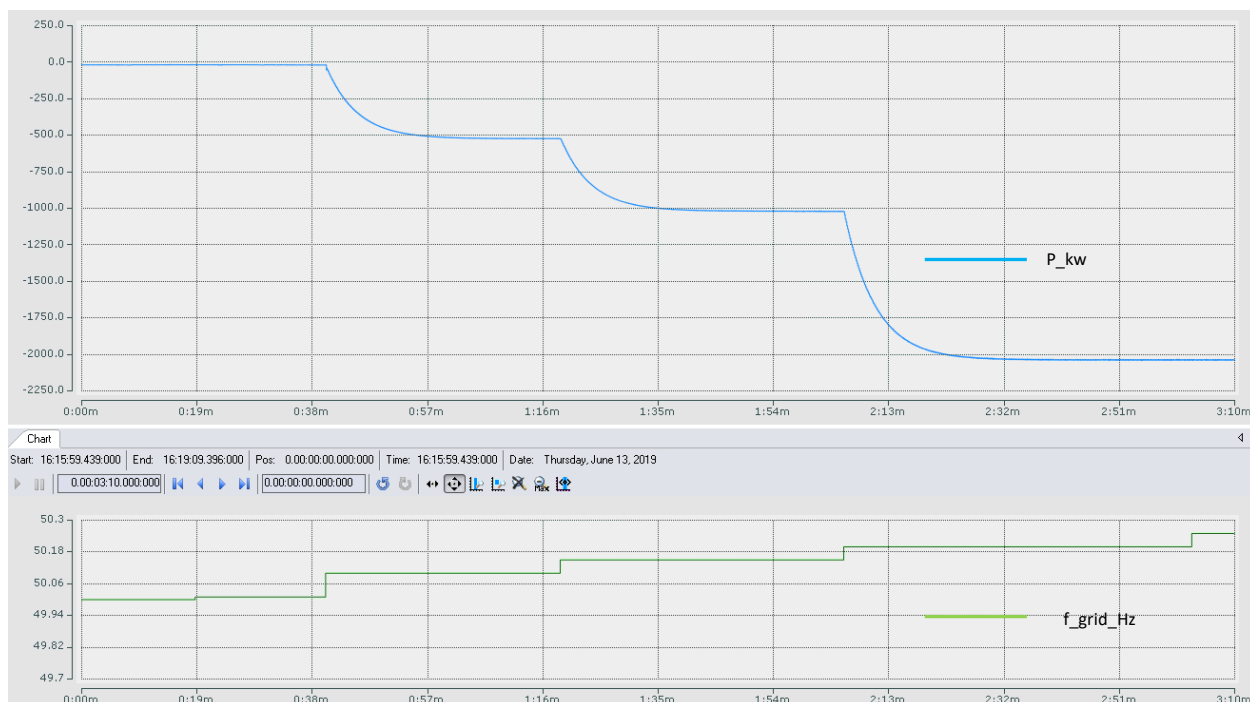


FIGURE 83. STORAGE FCR TEST: OVER-FREQUENCY EVENT

Figure 84 shows how fast the storage FCR service reacts under a pre-set time response configuration. According to the obtained test results, the BESS needs ~ 20 s to reach $\pm 2\%$ of the BCS setpoint, which is in accordance with typical FCR requirement [12].

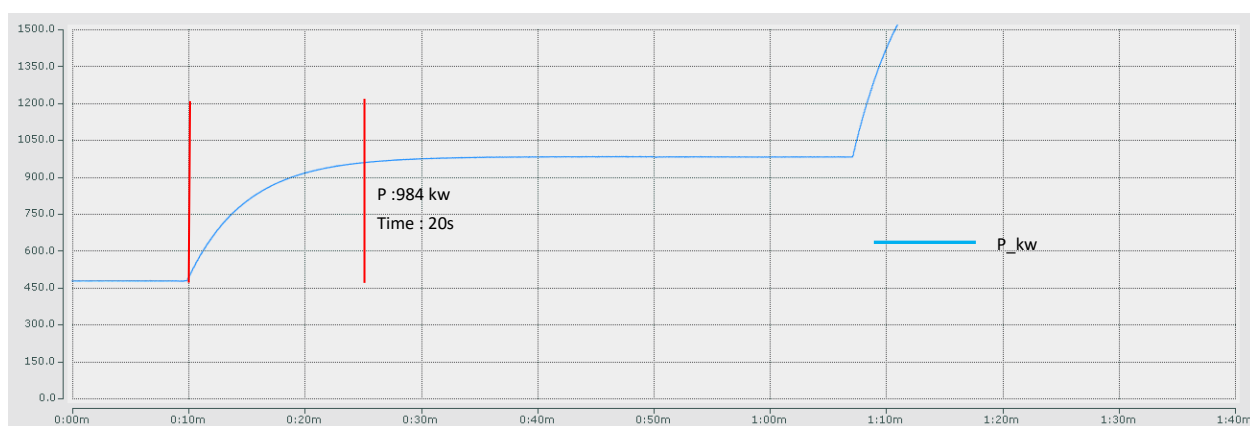


FIGURE 84. STORAGE FCR TIME RESPONSE

Fast Frequency Response

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 (~ 150 ms versus 30 s). The FFR power-frequency chart can be parameterized in the same way as that of FCR as illustrated in Figure 85 and the power setpoints during over-frequency and under-frequency events can therefore be derived.

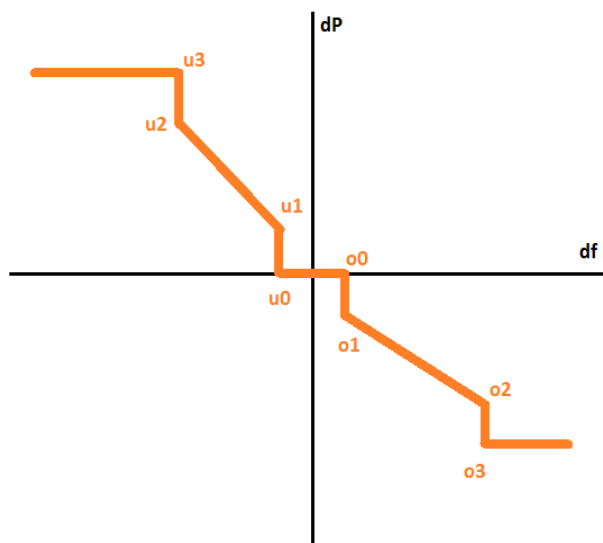


FIGURE 85. FAST FREQUENCY RESPONSE PARAMETER CHART

For the purpose of the FFR service test, the parameter setting of the controller given in Table 13 was used.

f_fake_Hz	49.8	49.85	49.900	49.99	50	50.01	50.1	50.15	50.2
P_sp_%	100	60	30	0	0	0	-30	-60	-100
Test									
P_kw	1976	1187	582	-18	-18	-17	-616	-1213	-2026
P_diff_kw	6	-5	0	18	18	17	-2	-5	8
Tr_ffr_s	1								

TABLE 13. PARAMETER SETTING OF FFR TEST

The measurements plotted in Figure 86 and Figure 87 show respectively the response of the storage system when over-frequency and under-frequency events are emulated.

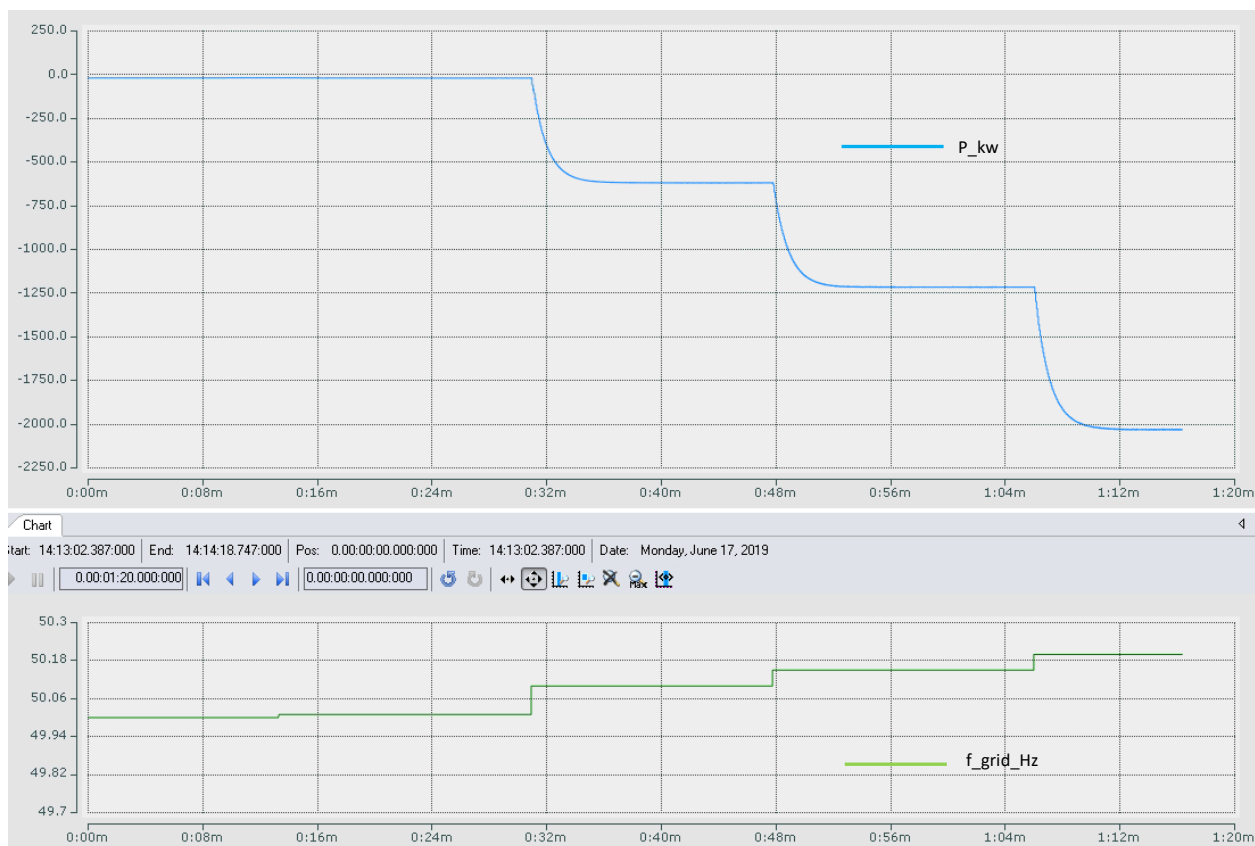


FIGURE 86. STORAGE FFR TEST: OVER-FREQUENCY EVENT

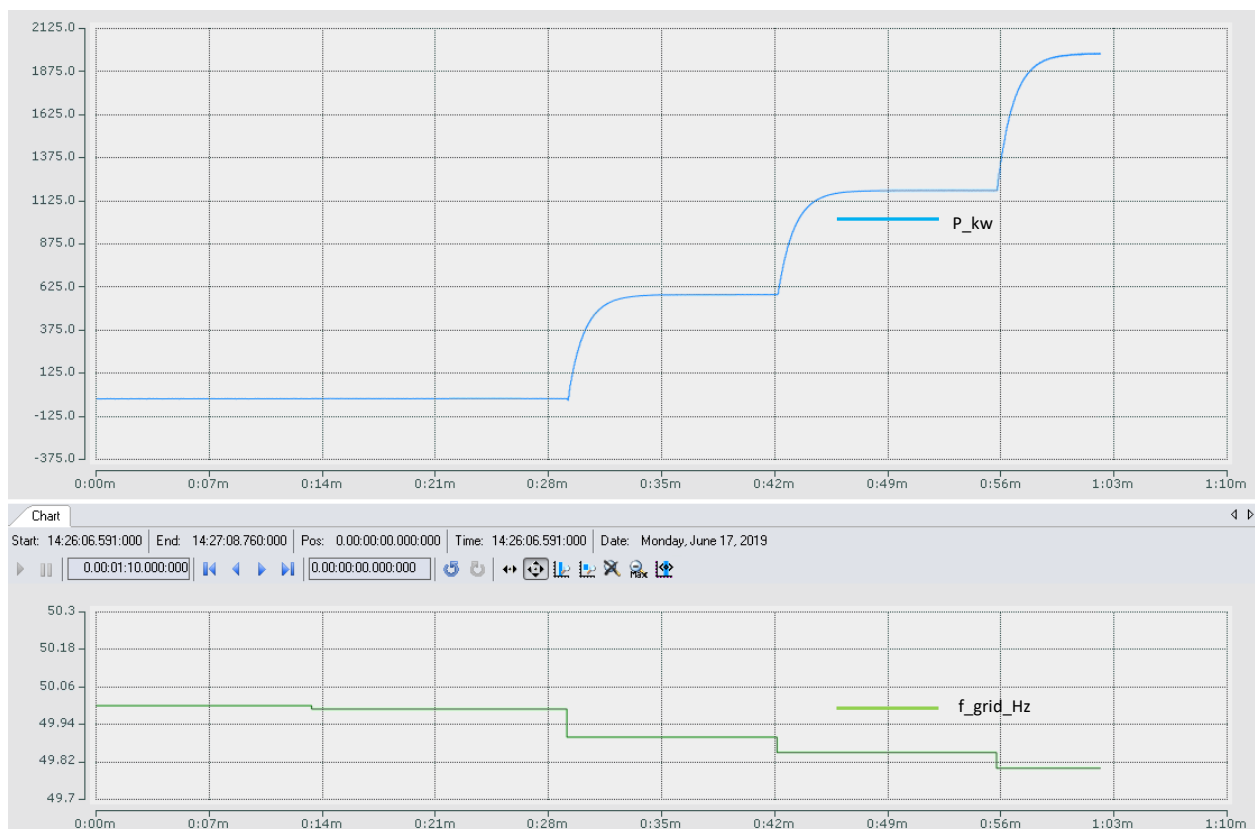


FIGURE 87. STORAGE FFR TEST: UNDER-FREQUENCY EVENT

Figure 88 shows how fast the FFR service responds. According to the experimental results, the BESS needs ~ 4 s to reach $\pm 2\%$ of the BCS setpoint. The typical dynamic requirement for FFR service is generally faster than 2 s. Therefore, during the integration tests of the aggregator, the time constant parameter T_{r_ffr} will be modified from 1s to ~ 0.25 s in order to respect a response time of about 1 s.

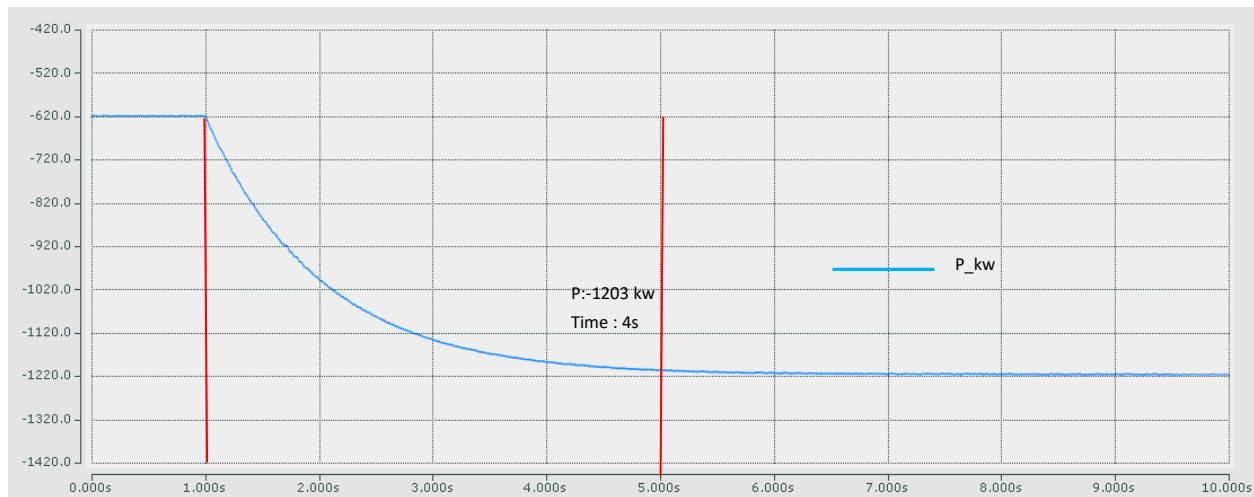


FIGURE 88. STORAGE TIME RESPONSE

Consecutive activation of multi-services: FRR+FCR+FFR+RRC

The last experimentation conducted on the storage was dedicated to verify the ability of the BESS to provide multi-services. Therefore was tested the activation of FRR followed by FCR, FFR and RRC consecutively. During this test, the whole capacity of the storage ($P_n = 2$ MW) was considered as effective symmetrical reserve, which means that 1 MW of upward reserve and 1 MW of downward reserve were available.

- Phase 1: activation of FRR $\rightarrow P = -536$ kW
An external order was given to release the downward FRR equal to 25% of the storage nominal power, i.e., 500 kW of power reduction from the initial operating point (~ 0 kW). The storage output has stabilised at around 536 kW.
- Phase 2: FCR $\rightarrow P = -17$ kW
An emulated frequency equal to 49.9 Hz was given and, according to the pre-set power – frequency FCR parameter chart, the storage should deliver 50% of the total upward reserve, which corresponds to a power increase of 500 kW from the end point of the phase 1. Finally the storage output has stabilised at around -17 kW.
- Phase 3: FFR $\rightarrow P = 564$ kW
According to the emulated frequency setpoint, the storage should further deliver 30% of upward FFR reserve (≈ 600 kW) from the end point of the phase 2. Finally the storage output has stabilised at around 564 kW.

- Phase 4 : RRC → ramping setpoint = 20 kW/s

During the last phase, the storage was used to reduce power variations of an emulated wind farm output, by respecting the ramping setpoint of 20 kW/s, similarly to the individual RRC test that was presented previously.

Figure 89 shows the results of the above-described tests.

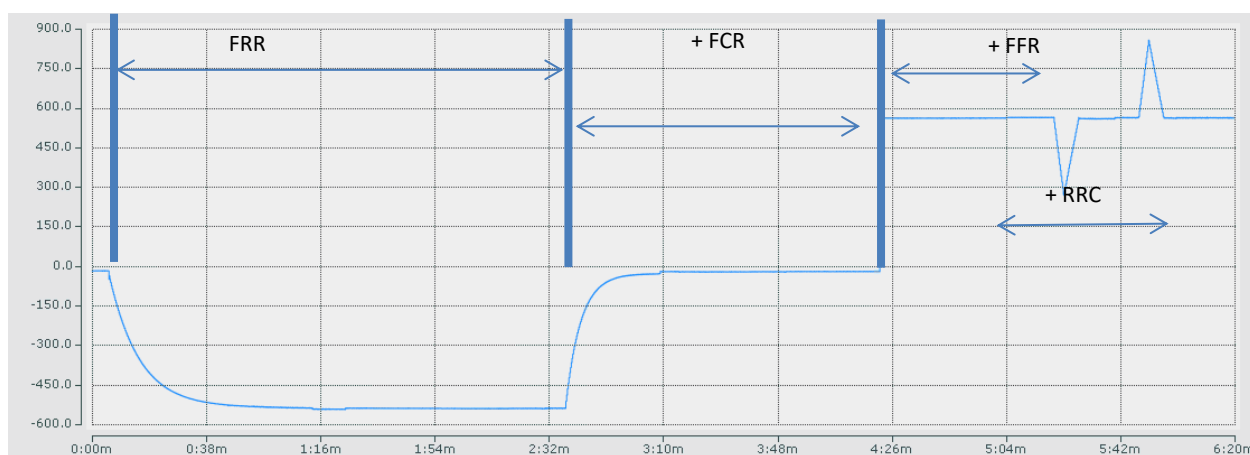


FIGURE 89. STORAGE SERVICES STACKING

In practice, the FFR could be activated automatically in the second following a severe frequency event, and the FCR service will also be triggered when the frequency deviates from the reference value (50 Hz in Europe). TSOs will then mobilize the FRR reserves in the power system to restore the frequency as well as the FCR capacities. This “natural” order of activation (FFR - FCR - FRR) of the different reserves was not respected during the experimentation for the reason of practicability. However, the performed tests proved the capability of the storage system to deliver consecutively multiple services according to their proper specifications. This successful demonstration formed a good basis for the investigation of the proposed approach of ‘multi-services from multi-resources’, expected to be performed next year.

6. CONCLUSION AND PERSPECTIVES

Since the provision of the D8.1 report in M12 and according to the specifications of the demonstration defined in this report, EDF and ENERCON teams have been working jointly to prepare the set-up of the WP8 demonstration. EDF has focused on the software and algorithm development as well as on the communication infrastructure implementation, while ENERCON team has concentrated their effort on the set-up of the hardware and on the local experiments.

6.1 CONCLUSION AND MAIN RESULTS

Regarding the development of software and tools for the operation of the demonstration, **a first version of the EMS of the aggregator, including an operational planning scheduler and a short-term controller, is now operational.** The developed scheduler allows to perform day-ahead scheduling and intraday rescheduling of generation planning and services' allocation to maximize profitability, while satisfying different constraints and requests from system operators. Within each scheduling time, the layer of the short-term control can ensure a continuous and correct operation of the VPP by taking appropriate actions to control the power or state of charge of the storage.

The development of the EMS was performed by means of 2 simulation platforms, intentionally built for WP8 demonstration work, representing the physical behaviour of the wind farm / storage aggregator: the offline platform dedicated to intensive tests through simulations over long periods, as well as the real-time platform allowing to better understand dynamic aspects, and enabling power-hardware-in-the-loop at a later stage. The performed tests allowed to validate the operation of the different software parts of the EMS and the implemented functions. **The first simulation results also showed the interest to consider probabilistic generation forecasts and stochastic optimization for EMS development as well as intraday services rescheduling for the VPP's operation.**

Concerning the hardware set-up and adaptation, **the full storage system was delivered in early January 2019 and fully commissioned in August 2019.** It consists of a 2.3 MW/1h Li-Ion battery container, a power interface E-Storage 2300 as well as a local controller, the E-SCU, specifically developed for the WP8 demonstration, with frequency services functions embedded. The commissioning test procedure of the storage system was carried out following erection and proper connection of the E-Storage 2300 and the sun systemizer containers. **On the wind farm side, the existing local controller RTU-C was replaced in September 2019 by the new controller FCU-E2, which offers advanced controls in terms of voltage and frequency services and also enhances the response time of the wind farm.** Several functions of this new controller were developed specifically for EU-SysFlex. Additionally, each wind turbine inside the Anglure wind farm was also upgraded in October 2019 to be compatible with the new FCU-E2 controller. At the time of writing this report, local individual tests of wind ancillary services are being conducted and are still at the preparation stage.

To enable reliable and secured data exchanges within the VPP and between different tools, software and controllers, an IEC 61850-based and hardware-agnostic communication platform as well as corresponding IT

architecture and solutions were developed and started to be implemented for the purpose of demonstration.

Grid Edge Devices (GED) based on the proposed solution were introduced to assure the communication between individual assets of the VPP and the EMS at the centralised level. The first GED device, the GED-S, was fully configured and tested in 2019 and has been qualified for the communication with the storage controller E-SCU following successful mapping tests and interface configurations verification.

Finally, before starting the experiments in the overall environment of the aggregator, **the capability of the installed storage system to provide individually frequency services was demonstrated locally at Concept Grid in 2019.** Each of the frequency control modes has been tested first separately with emulated frequency signals, and then in combination to prove the operation of the local controller delivering consecutively multiple services. The successful demonstration formed a good basis for the investigation of the proposed approach of ‘multi-services from multi-resources’ in WP8, expected to be performed next year.

6.2 NEXT STEPS

Until the beginning of 2020, EDF and ENERCON will focus on integrating progressively the different assets into the final ‘virtual power plant’ environment:

- Although storage services have been validated separately, the communication interface with the centralized controller, GED-S, will need to be integrated into the testing chain in the next step to allow the management of the asset through the EMS. Moreover, now that the frequency services have been implemented into the storage controller, controls for voltage services need to be considered as well, and it is planned to work on this aspect early in the first quarter of 2020.
- Similar to the approach applied onto the storage, experiments of wind services through local activation are being prepared. The different services will be tested one by one until the end of the year and will allow detecting and correcting, if required, any unexpected behaviour of the wind FCU-E2 controller. At the same time, a remote Internet connection between the Cloud, where the EMS of the VPP is implemented, and the wind farm will have to be established.
- The whole IT and communication platform for the VPP operation will be entirely set up in 2020 with two more grid edge devices (GED-W and GED-LP) configured and tested, allowing the communication and data exchange of the wind farm, the PV panels and the controllable loads with the centralized EMS. Then, as expected in the WP8 demonstration specifications, a final integration of all the distributed resources as well as different controllers and tools into the ‘virtual power plant’ will be targeted by the end of the first semester of 2020. Once the expected VPP or aggregator is operational, the multi-services provision through coordinated and optimized management of different assets will be tested and demonstrated. Post-processing feedback of the experimental results as well as lessons learnt and suggestions will be given in the next reports of WP8.

In parallel, further development 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 proposed stochastic optimization process, by modelling more services in the scheduling tool and by integrating more advanced control modes into the short-term control layer. Further simulations over longer durations with different variants/settings of the EMS should therefore be performed to support the reinforcement of the latter and to provide more conclusive results. Furthermore, the hardware-in-the-loop approach, along with real-time simulations, will be used to verify the operation of the VPP as well as different controllers, in some complex or risky scenarios that are not going to be specifically created in real life for the purpose of experimentation.

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8. BIBLIOGRAPHY

- [1] A. Rousis *et al.*, "State-of-the-Art Literature Review of System Scarcities at High Levels of Renewable Generation", *D2.1 report of EU-SysFlex project*, 2018. [Online]. Available: <http://eu-sysflex.com/>.
- [2] EirGrid Grid Code v6.0, Eirgrid, 22nd July, 2015. [Online]. Available: <http://www.eirgrid.com>.
- [3] EU-SysFlex project official website: <https://eu-sysflex.com/>.
- [4] Y. Wang *et al.*, "WP8 Demonstration Specification for Field Testing: Aggregation Approaches for Multi-services Provision from a Portfolio of Distributed Resources", *D8.1 report of EU-SysFlex project*, 2018. [Online]. Available: <http://eu-sysflex.com/>.
- [5] S. Nolan *et al.*, "Product Definition for Innovative System Services", *D3.1 report of EU-SysFlex project*, 2019. [Online]. Available: <http://eu-sysflex.com/>.
- [6] B. Puluhen, A. Pelletier, L. Joseph-Auguste, T. Pelinski, 2015, "Concept Grid: a new test platform for smart grid systems general presentation & experiments", *Proceedings CIRED conference*, Lyon, 15-18 June 2015.
- [7] Y. Wang, G. Delille, X. Guillaud, F. Colas and B. François, "Real-time simulation: The missing link in the design process of advanced grid equipment," *IEEE PES General Meeting*, Providence, RI, 2010, pp. 1-8.
- [8] W. Li, G. Joos and J. Belanger, "Real-Time Simulation of a Wind Turbine Generator Coupled With a Battery Supercapacitor Energy Storage System," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1137-1145, April 2010.
- [9] ENEDIS, "Présentation du Dispositif d'Échange d'Informations d'Exploitation (DÉIE) entre Enedis et un Site Producteur raccordé en HTA sur le Réseau Public de Distribution", March 2017. [Online]. Available: https://www.enedis.fr/sites/default/files/Enedis-NOI-RES_14E.pdf.
- [10] Y. Wang *et al.*, "The EU-SysFlex French industrial-scale demonstrator: coordinating distributed resources for multi-services provision", *Proceedings CIRED conference*, Madrid, 3-6 June 2019.
- [11] M. Zatti *et al.*, "k-MILP: A novel clustering approach to select typical and extreme days for multi-energy systems design optimization", *Energy*, 181, pp 1051-1063, 2019.
- [12] ENTSO-E, "Commission regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation", 2 August, 2017. [Online]. Available: <https://www.entsoe.eu/>.
- [13] E. Muljadi, C.P. Butterfield, A. Ellis, J. Mechenbier, "Equivalencing the Collector System of a Large Wind Power Plant.", *IEEE Power Engineering Society General Meeting*, Montreal, Quebec, Canada, 2006.
- [14] RTE, "Documentation technique de référence", 5 July, 2018. [Online]. Available: <https://www.rte-france.com/>.