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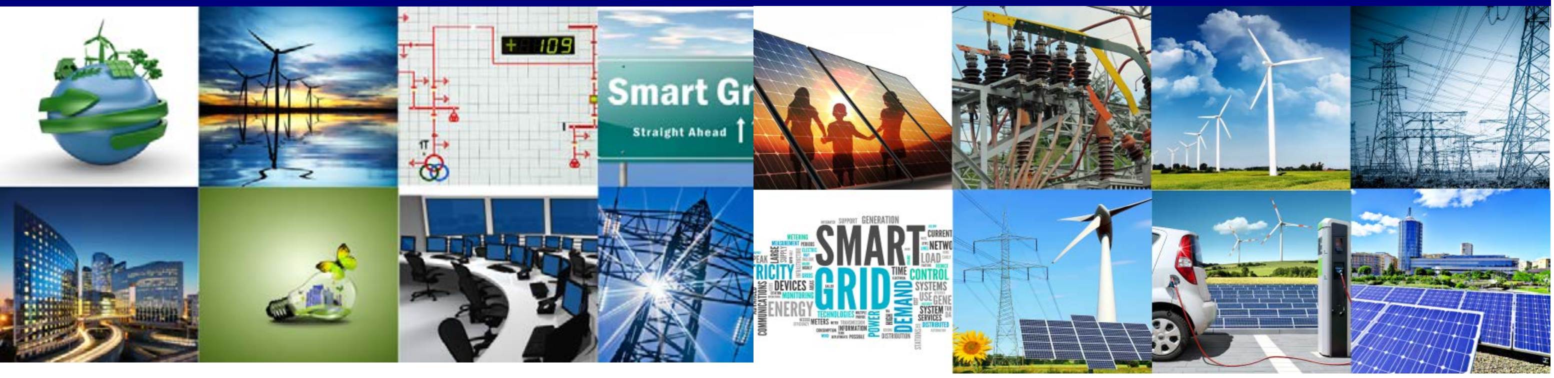
ELECTRA

European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids



WP 7

Integration and Lab Testing for Proof of Concept

Deliverable 7.2

Lessons learned from the ELECTRA WoC control concept evaluation and recommendations for further testing and validation of 2030 integrated frequency and voltage control approaches

08/04/2018

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Short description (Max. 50 words):		
This report presents the key findings and lessons learned obtained during the validation process of the so-called ELECTRA Proof of Concept, formed by six real-time control schemes for balancing and voltage management within a Web-of-Cells architecture. The limitations, problems and critical issues found in the laboratory experiments are also pointed out, as the basis for outlining the consequent future work. This document complements Deliverable D7.1, which describes in detail the evaluation criteria, set-ups and results.		
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Executive Summary

During the project ELECTRA, the Web-of-Cells concept has been defined as well as its voltage and balancing control schemes. The concept has been proved with successful results in a discrete set of scenarios for the different testing environments considered (pure simulations and Hardware-in-the-Loop platforms). Since testing setups and results are comprehensively reflected in a previous report (ELECTRA Deliverable D7.1), this document summarizes the experiences, key findings and lessons learned obtained during the validation process of the so-called ELECTRA proof of concept.

This deliverable is organised around three main pillars: (1) lessons learned on methodological aspects used during the validation stage, which can be exported to other projects as good practice, (2) description of the validation environments, emphasizing limitations and problems found, as well as possible technical improvements for evaluation of future power system architectures, and (3) key conclusions linked to the validation of different ELECTRA control function combinations.

A new methodology has been developed to allow the identification of requirements for the controllers to be tested within multiple laboratories. The procedure involves the mapping of the control functions and laboratory components into the Smart Grid Architecture Model, in order to identify the Key Performance Indicators for a consistent specification and planning of the validation experiments. Moreover, ELECTRA IRP has benefited from the ERIGrid methodology for specifying test cases in a rigorous manner; test case, test specification and experiment specification templates have been adapted to the validation needs.

The validation of balancing and voltage control functions of the Web-of-Cells concept has been performed in a structured manner by which pure simulation tests have been followed by co-simulation, Controller Hardware-in-the-Loop and Power Hardware-in-the-Loop implementations. This allowed for an increased realism in the experiments as well as an optimized prototyping of the final controllers.

Concerning simulations, in addition to the recognized CIGRE European MV distribution grid model, which has been partly modified for some of the experiments, a new powerful distribution network model has been produced for dynamic analysis. This new grid model has coped with the ELECTRA future grid assumptions (enormous penetration of RES/DER unit connected at all voltage levels), and has mitigated the current lack of grid models with non-conventional generators and dynamic controls. For the sake of laboratory feasibility and based on the analysis and selection of the grid models the number of cells in the validation environments was varied from small-scale (i.e., 1-3 cells) to medium-scale (i.e., 4-9 cells). *MATLAB/Simulink* and *DIgSILENT/PowerFactory* have dominated as the suitable power system simulation platforms.

Accurate experimental validation of the Web-of-Cells concept has proven to be challenging to be performed in a laboratory environment. The challenges emerge from the need to perform system level testing, due to the size of the electrical system required for validating such concepts, and at the same time, to consider the real hardware dynamics (speed of response, communication delays, measurement noise, etc.) for an accurate validation. Furthermore, complex control algorithms have to be integrated within the different simulations and hardware components at different levels requiring highly interoperable infrastructure. Nonetheless, progress has been made in advancing laboratory capability and systems level testing capability that will feed ongoing investigations.

Different balancing control use case combinations have been proven in simulation and experimental validation in laboratory environments, to effectively contain and restore the balance, prioritising the activation of the reserves in the cell with the imbalance and improving the short-term frequency stability of the power system. Besides, imbalance netting benefits (through “Balance Steering Control”)

in the Web-of-Cells have been demonstrated after successful negotiations between neighbouring cells, which resulted in correct deactivation of “Balance Restoration Control” reserves.

Pure complex simulations and Power Hardware-in-the-Loop-based experiments have shown that the implementation of a “Post-Primary Voltage Control” controller at cell level, running in the double corrective and proactive mode, restores the voltage to the safe-band in a very short time while minimizing the cell power losses. Besides, its proactive behaviour reduces the number of primary resource activations (such as “Primary Voltage Control”) and “Post-Primary Voltage Control” corrective triggers.

The experimental validation conducted has demonstrated under laboratory conditions that the proposed control schemes within the Web-of-Cells architecture are feasible for operating the future grid (i.e., Technology Readiness Level 4). Movement towards higher Technology Readiness Levels will have to analyse and solve a number of open issues like the validation of a complete control solution integrating balancing and voltage control functions, and scalability in terms of increased numbers of cells and numbers of concurrent events.

Terminologies

aFCC	Adaptive Frequency Containment Control
BRC	Balance Restoration Control
BSC	Balance Steering Control
CHIL	Controller Hardware-in-the-Loop
CHP	Combined Heat and Power
CIGRE	International Council on Large Electric Systems
DER	Distributed Energy Resource
DSL	DIgSILENT Simulation Language
DSO	Distribution System Operator
DuI	Domain under Investigation
EEGI	European Electricity Grid Initiative
EV	Electric Vehicle
FCC	Frequency Containment Control
FuI	Functions under Investigation
FuT	Functions Under Test
GAMS	General Algebraic Modelling System
HIL	Hardware-in-the-Loop
HV	High Voltage
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRP	(ELECTRA) Integrated Research Programme
IRPC	Inertia Response Power Control
KPI	Key Performance Indicator
LV	Low Voltage
MV	Medium Voltage
OPF	Optimal Power Flow
OuI	Object under Investigation
PHIL	Power Hardware-in-the-Loop
PMU	Phasor Measurement Unit
PoI	Purpose of Investigation

PPVC	Post-Primary Voltage Control
PVC	Primary Voltage Control
PV	Photovoltaic
RES	Renewable Energy Source
REX	(ELECTRA) Researcher Exchange Programme
RI	Research Infrastructure
RoCoF	Rate of Change of Frequency
RTDS	Real-Time Digital Simulator
SGAM	Smart Grid Architecture Model
SuT	System under Test
TRL	Technology Readiness Level
TSO	Transmission System Operator
WoC	Web of Cells

Table of Contents

List of Figures and Tables

Figures

Tables

1. Introduction

1.1 Scope and Purpose of the Document

One of the main activities in the last stage of ELECTRA IRP has been the evaluation at laboratory level of the proposed Web-of-Cells (WoC) real-time control approach and its six corresponding use cases for balancing and voltage control. Prior to a "Proof of Concept" validation, it is necessary to integrate within the laboratory environment a set of functions developed for each use case. Different use case combinations have been defined and a total of 15 experiments have been accomplished. The details of the different experiment set-ups and obtained results are reported in Deliverable D7.1 (validation results) [1].

Based on D7.1, Deliverable D7.2 extracts the main conclusions, lessons learned and key findings of the validation process, highlighting also the critical points and main problems found in the laboratory, and providing recommendations for further work when necessary.

1.2 Structure of the Document

This document is structured in the following way: after the Introduction, Section 2 summarizes the lessons learned on the methodologies employed during the validation process of the Proof of Concept, encompassing Key Performance Indicators and Test Case specification; Section 3 deals with the key findings from the validation environment, including the Validation Plan, grid models, simulation platforms, and experimental implementation in the laboratories; Section 4 concentrates on the experiences and issues found when evaluating the balancing and voltage control functions in the mentioned environments; after Section 5, where indications on open issues and future work can be found, Section 6 ends with the main conclusions of the validation task in ELECTRA. An Annex is also incorporated as complementary information for Section 2's testing specification.

2. Lessons Learned on Methodological Aspects

2.1 Technical Requirements and KPIs for Validation of the WoC Concept

This section describes the structured methodology adopted for determining experimental plans to validate future integrated balance and voltage control algorithms and associated technical Key Performance Indicators (KPI). This methodology is considered a lesson learned in ELECTRA and a recommended good practice for future collaborative activities on testing and validation of smart grid concepts across multiple laboratory environments. The methodology allows the identification of requirements for the controllers to be tested within a laboratory, an adequate representation of laboratory infrastructure based on which KPIs can be developed, and a consistent specification and planning of the validation experiments.

The Smart Grid Architecture Model (SGAM) reference framework has been considered a standard tool essential to identify the pragmatic implications on the information flows, communication systems and components of the power system that may arise due to the transition from the present day centralized power system architecture to the envisioned distributed control power system based on the new WoC concept.

However, in ELECTRA it was noted that there was no prior guidance available on how distributed control concepts like the WoC can be represented on SGAM and in undertaking this task a methodology has been developed and applied [2].

As reflected in Figure 2.1, the process from the development of the control solutions to their evaluation and testing is structured in three stages using SGAM (templates and examples have been developed to assist) [3], [4]:

- *Stage I: Consolidated functional descriptions:* mapping the identified control functions of the ELECTRA use cases to the SGAM Function Layer, and the information available (including data format and data exchange frequency) passing from one function to other to the SGAM Information Layer. This analysis was first done independently by all laboratories and then all laboratories working on the same use case combined their efforts to increase the process consistency.
- *Stage II: Laboratory implementation descriptions:* for each use case to be evaluated in the experimental infrastructure of a partner, the functions identified in Stage I along with the selected reference power system need to be mapped to individual laboratory components (including the communication protocols and data format) populating the SGAM Component and Communication Layers.
- *Stage III: Experimentation descriptions and KPIs:* narrative of the experimental scenario to be implemented in the laboratory for evaluation of use cases (individual and combinations), answering the research questions and specifying the required KPIs for the experiments (technical ones and those related to WoC integration advantages).

The specification of relevant KPIs of a system/process is not straightforward: first it is necessary to consider the goals to be achieved and then extract a parameter that shows how well the system/process is performing, allowing for a comparison between different scenarios. In ELECTRA different KPI definitions from different smart grid projects on grid control and operation (by CIGRÉ, EEGI, TERNA) have been analysed, leading to the following conclusions:

- There is no “one” formal method that can be used for KPI development.
- KPIs are usually divided into different categories.
- KPIs are often developed to be compared with a business-as-usual case, wherein defining and agreeing to a business-as-usual case is difficult.
- It is not feasible to compare the KPIs generated within different projects, as each project works towards solving a different challenge.

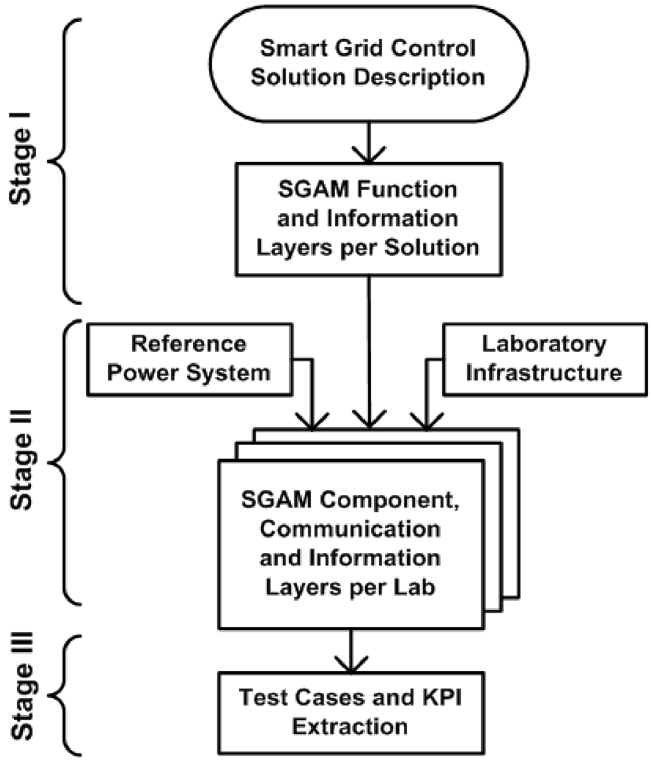

Figure 2.1: Structured methodology for validation of ELECTRA control concepts

Due to the particular objectives of the ELECTRA project, no use has been made of the above mentioned KPIs and new KPI definitions have been developed for the experimental validation of the ELECTRA control solutions. Since this evaluation is performed by diverse partner laboratories, the developed KPIs have taken into consideration the individual laboratory capabilities, ensuring that the developed KPIs can be measured at the facilities.

As a summary, for the first time a methodology has been developed to express distributed control schemes within SGAM. Extensive SGAM modelling exercises have been undertaken on experimental smart grid laboratories that have demonstrated the value of the methodology in communicating research infrastructure features for the integration of test equipment and algorithms. This procedure of mapping the functions and laboratory components into SGAM also assists the determination of the technical parameters that can be rigorously tested in the laboratory. This procedure allows successful identification of KPIs that can be analysed by individual laboratories for the Proof of Concept.

2.2 Test Case Specification

The validation process within ELECTRA is rooted in the general methodology developed in the European project ERIGrid [5]. This methodology is intended to create a general framework for the evaluation of smart grids solutions covering several domains (electric, heat, control, ICT) in a holistic manner, thus harmonizing the testing processes in different infrastructures which are not necessarily connected. The methodology tries to extend to the smart grids domain the culture of physical testing with formal and rigid specifications that come from the ICT culture. The summarized approach to conduct the holistic testing is shown in Figure 2.2.

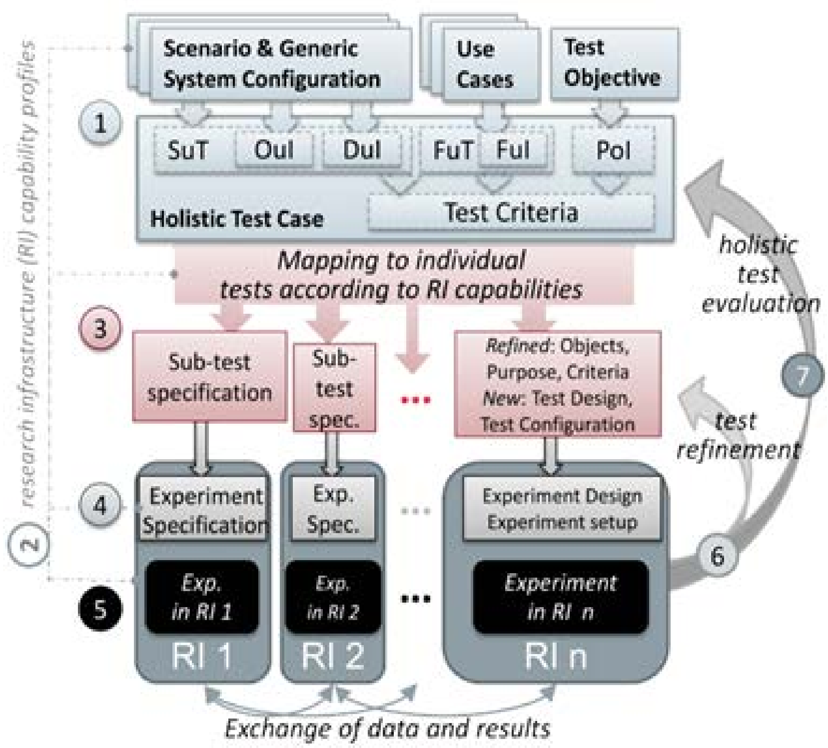

Figure 2.2: Holistic testing process

The ERIGrid test specification approach defines three incremental levels of test specification: (Holistic Test Case, Test Specification and Experiment Specification) each associated with a detailed specification template, as illustrated in Figure 2.3. The main objective is to do a full top-down approach from the Test Case to the more concrete Experiment Specification. For the application of this holistic testing process in ELECTRA, these templates have been slightly adapted.

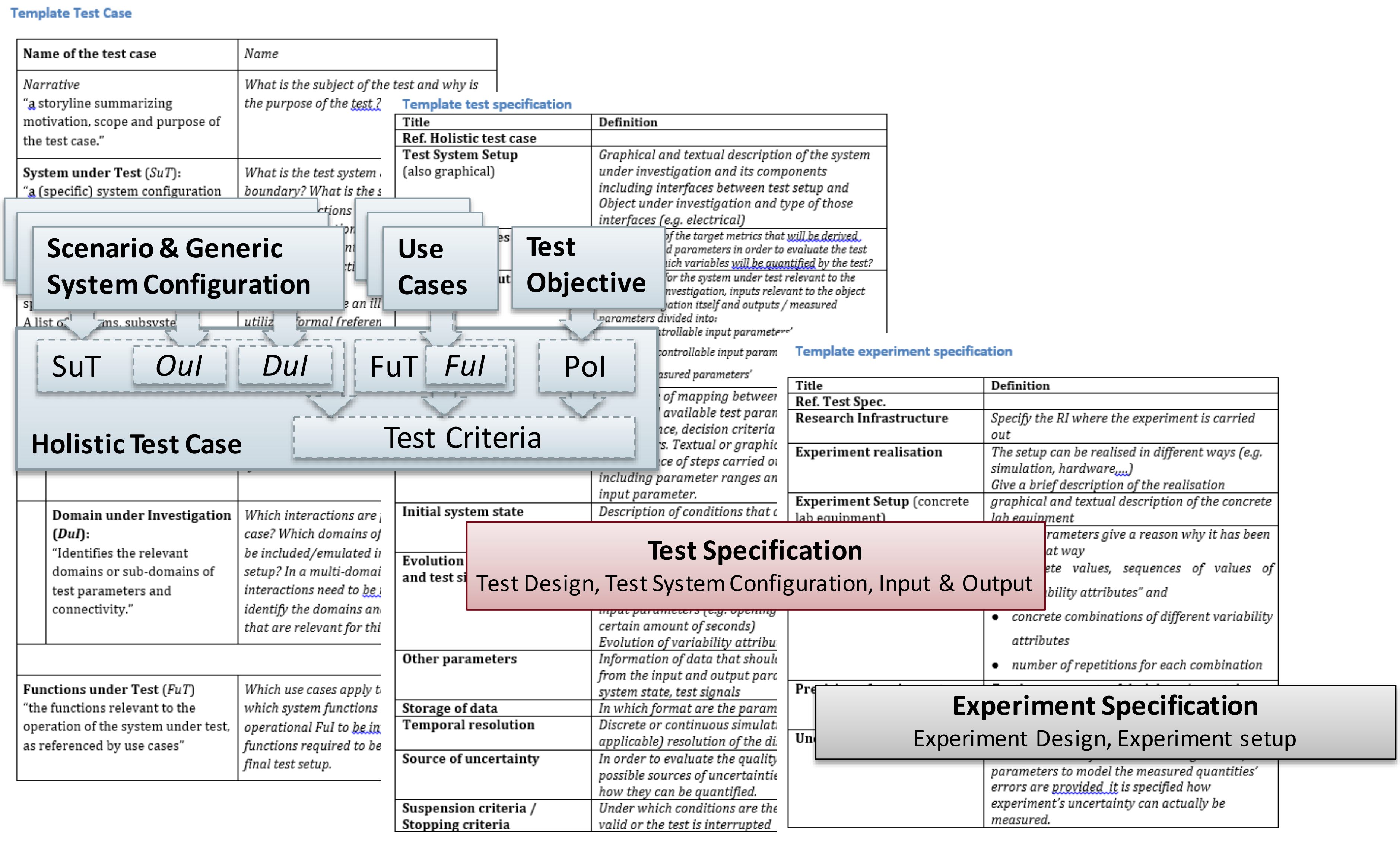

Figure 2.3: Overview of the ERIGrid templates for holistic test specification

The procedure starts with the definition of the *(Holistic) Test Case* that defines a test criterion for a test system configuration with a specific test objective. The Test Case tries to solve the fundamental questions such as what needs to be tested, why and how [6]. However, the test case specification is still general enough to not pose restrictions on the test setup and the test design. The main information about the test case is summarized in the narrative. The System Under Test (SuT) identifies the boundaries and all the components and interactions that need to be tested and encompass the Object under Investigation (OuI) and the Domain under Investigation (DuI). The OuI identifies the components or subsystems that are going to be characterized or validated while the DuI gathers the information about the different domains involved in the test and their connectivity. The Functions Under Test (FuT) are all those required in the operation of the test system and the enclosed Functions under Investigation (FuI) are those integrated or executed by the OuI. The Purpose of Investigation (PoI) is the test objective. With these main fields in the Test Case Specification template, also the Test Criteria are collected. The Test Criteria formalize the test metrics into: Target Criteria (a list of measures to quantify each test criterion), Variability attributes (input parameters and limits for their modification) and Quality attributes (measurements precision or maximum/minimum values of the Target Criteria).

The *Test Specification* defines the actual test system, the parameters that are going to be modified and checked for the evaluation of the test objective and how the test is going to be carried out (the test design). The Test System is the definition of how the OuI is embedded in a specific SuT, including the graphical and textual description and the interfaces between the test setup and the OuI. In the Test Specification template, the input and output parameters are also analysed. The inputs are those which are relevant for the OuI and can be both controllable or uncontrollable. Additionally, the Test Design defines the test sequence and the steps to obtain the target metrics through variation of the controllable or measured input parameters.

The *Experiment Specification* links a certain Test Specification to a determined research infrastructure (RI). It gives the additional information required to perform the test. Normally, there is one Experiment Specification per Test Specification. The Experiment Specification template gathers the information about the way to perform the test (pure simulation/pure hardware/hybrid) and a description about the realization. As it is more concrete, the simulation tools used as well as the concrete lab equipment involved have to be included (Experiment Setup). It also has to be included extra data such as the precision of the equipment, the measurement uncertainty, and the experimental design and justification (for every parameter which value has been selected and why).

In the Annex the templates for the Test Case specification, Test Specification and Experiment Specification used in ELECTRA can be found. The details about the information to be collected in each section are included.

As a supplementary to these three templates derived from the ERIGrid methodology, another one has been created to complete the reporting process in ELECTRA's validation of the WoC concept. This template (Experiment Reporting template) is shown in Table 2.1. The information in the Experiment Reporting template is intended to assess the validation of the Test Criteria (defined in Task T7.2. of ELECTRA) corresponding to the Experiment Specification. It is also planned for extracting the main conclusions from the testing concerning the results, lessons learnt and open issues.

Table 2.1: Experiment reporting template

Title	Definition
Ref. Experiment Specification	*Reference to experiment specification document (i.e., experiment specification Nº).*
Test Criteria	*Validation of test criteria as defined in Task 7.2 (corresponding Test Criteria Nº, KPI, etc.).*
Results	*Description of the achieved results (incl. figures/plots, tables).*
Discussion / Open Issues	*Discussion of the achievements in respect to the WoC and the covered integrated use case.*
Lessons Learned	*Lessons learned from the executed experiment (problems, open issues, necessary improvements, critical points during testing, etc.), addressing:* ● *WoC concept and covered integrated use cases (control/observable functions)* ● *Validation environment*

3. Proof of Concept Validation Environment

3.1 Validation Plan

Once the six individual use cases are specified within a WoC framework, developed by means of a set of control functions, and simulated/tested as stand-alone entities, they must be combined in the so-called Proof of Concept, and validated through simulations and lab experiments. The challenge at this point is to cope with a distributed laboratory implementation (multiple partners' labs involved in the same set of validation experiments) that needs good planning and coordination, and a common understanding of the evaluation goals.

To manage efficiently the validation activities, and considering the diverse criteria and tools and the distributed nature of the experiments developed my multiple partners, a Validation Plan is paramount. A spreadsheet has been used as an agile format to show at a glance planned and ongoing experiments and the progress of the activity. It is a living file that gathers the following main elements (see Table 3.1):

- Involved partners.
- Use Case combinations to be validated.
- Type of tool: simulation or/and lab experiment.
- Covered test criteria.
- Timeline of the validation (expected duration, completion).
- Link to associated reporting documents.
- Specific details/comments on the experiments.

Additionally, the spreadsheet has allowed the inclusion of references to activities carried out within the framework of the ELECTRA Researcher Exchange Programme (REX), whereby external researchers have participated in the validation experiments.

Table 3.1: Screenshot of the spreadsheet implementing the Validation Plan

Use Case Combination	Implementation and Validation by	Simulation experiment planned	Simulation experiment duration	Simulation experiment finished	Covered Test Criteria (TCR)/Case(s)	Lab experiment planned	Lab experiment duration	Lab experiment finished	Covered Test Criteria (TCR)/Test Case(s)	Experiment validation report available?
FCC+BRC+BSC	USTRATH	yes	10-12/2017	yes	TCR01, TCR04, TCR17, TCR19	no	---	---	---	simulations
	CRES	yes	09-10/2017	yes	TCR16, TCR17, TCR19, TCR24	yes	11-12/2017	yes	TCR16, TCR17, TCR19, TCR24	simulations and experiments
	~~DTU~~	~~yes~~	~~10-11/2017~~	~~no~~	~~TCR01, TCR02, TCR20~~	~~yes~~	~~11-12/2017~~	~~canceled~~	~~(planned) TCR07, TCR02, TCR18, TCR22,TCR23 (see 4b.2)~~	
FCC+BRC	USTRATH	yes	01-08/2017	yes	TCR01, TCR04	yes	10-12/2017	yes	TCR04, TCR08	partly
	ENEA	yes	06-09/2017	yes	TCR04	no	---	---	---	yes
	INESC	yes	09-11/2017	yes	TRC01, TRC03, TRC04	no	---	---	---	partly
	DTU	yes	12/2016	yes	TCR01, TCR09, TCR16	yes	02-03/2017	yes	TCR04, TCR08	TPS journal paper
	RSE	no	---	---	---	yes	10-12/2017	yes	TCR01,TCR04	yes
	LABORELEC	eled due to resource and equipment issues								
IRPC + FCC	IEE/DERlab	yes	10/2017	yes	TCR10, TCR11, TCR12, TCR14, TCR15, TC	~~yes~~	~~11-12/2017~~	~~no~~	~~TCR10, TCR12, TCR14, TCR15, (TCR11)~~	yes
	CRES	yes	06-07/2017	yes	TCR10, TCR11, TCR12, TCR14, TCR15	no	---	---	---	simulations results available
	DTU	yes	1/2017	yes	TCR10, TCR14, TCR15	yes	04-05/2017	yes	TCR10, TCR14, TCR15	applied energy journal
PVC + PPVC	AIT	yes	01-06/2017	yes	TCR30, TCR34	yes	10-12/2017	yes	TCR30, TCR34	reporting documents
	SINTEF	yes	06-11/2017	yes	TCR28	yes	09-11/2017	yes	TCR30, TCR31	reporting documents
	TECNALIA	yes	up to 11/2017	yes	TCR28, TCR30, TCR31	no	---	---	---	reporting documents
	TÜBİTAK	yes	06-10/2017	yes	--	no	---	---	---	---
	VTT	yes	01-10/2017	yes	TCR27, TCR30, TCR31, TCR32	no	---	---	---	reporting documents

3.2 Validation environment

Deliverable D7.1 [1] includes a comprehensive description of the range of environments used by the different partners for the validation of the new balancing and voltage control concepts within a WoC structure. The evaluation platforms are based on pure simulation, pure hardware and hybrid Controller Hardware-in-the-Loop (CHIL) and Power Hardware-in-the-Loop (PHIL) systems, to exploit the corresponding advantages of the environments matched to the different stages of development of the concepts, as they get closer to real-world conditions. Table 3.2 summarizes the ELECTRA Proof of Concept Validation Environment:

Table 3.2: An overview of the validation environment in ELECTRA

Environment	Partner	No of Cells	Details
Pure Simulation Environment	VTT	3	Modified CIGRE European MV distribution network model in *MATLAB/Simulink/SimscapePower* and *Matpower*
	IEE/DERlab	4	Modified CIGRE European MV distribution network model in *MATLAB/Simulink/SimscapePower*
	CRES	4	Modified CIGRE European MV distribution network model in *MATLAB/Simulink/SimscapePower*
	USTRATH	5	Reduced Great Britain power network model within RSCAD (RTDS) and *PowerFactory* with *MATLAB/Simulink*
	ENEA	6	Modified CIGRE European MV distribution network model within *PowerFactory*
	INESC_P	3	Modified CIGRE European MV distribution network model in *MATLAB/Simulink*
	TECNALIA	9	FLEXTEC ad-hoc developed grid model (LV/MV distribution grid; conventional and RES/DER units: 60% RES penetration) *PowerFactory* with Python scripts
Pure Hardware Environment	CRES	2	Experimental LV microgrid (controllable and uncontrollable DER: photovoltaics, batteries, battery inverters, loads)
	RSE	3	RSE microgrid (Distributed Energy Resources Test Facility-DERTF): controllable loads, PV, wind, CHP
	DTU	3	SYSLAB experimental facility (meshed configuration with the ability of opening tie-lines forming a radial network; resources: PV, wind, EVs, vanadium-redox battery, diesel, loads)
Hybrid Environment: Controller and Power Hardware-in-the-Loop	SINTEF	2	PHIL platform with CIGRE European MV distribution network (Opal-RT simulator; EGSTON 200 kW grid emulator; 2x 60 kW converter units; RT-Lab, *MATLAB* and *GAMS* software)
	AIT	3	SmartEST Lab: coupled HIL co-simulation with CIGRE European MV distribution network; *PowerFactory* with *Python* scripts; ASG converter (emulated power electronics + real converter controller); Typhoon HIL real-time simulator

Environment	Partner	No of Cells	Details
	USTRATH	5	Dynamic Power Systems Laboratory (DPSL). 2 Cells emulated with real lab equipment and 3 within RSCAD (RTDS)

A close examination of the selected controllers reveals that most of them (specifically for balancing control) act based on the state of the cell boundaries (tie-lines). Therefore, the environments selected for the validation of the control function combinations had to incorporate at least two cells, without any upper limit. However, for the sake of feasibility and based on the analysis and selection of grid models, the number of cells in the validation environment was selected to 3-5, with some experiments going up to 9. In the validation process, each involved partner was free to select the model of their preference based on simulation and laboratory capabilities and limitations. Hence, the diversity in the selection of the validation environments and grid setups enhances the validation of the controllers since it shows their feasibility of different implementations while the control objectives were fulfilled.

The validation of balancing and voltage control functions of the WoC concept has been performed in a structured manner by which pure simulations tests have been followed by co-simulation, CHIL and PHIL implementations. This allowed for an increased realism of the experiments as well as an optimized prototyping of the final controllers. This iterative development where experiences from (co-)simulations and experiments fed back into refinements of the methodology, eventually led to generally applicable solutions that are not tied to specific setups.

3.3 Simulation Platforms

Grid Models

The accuracy and results on the validation of the ELECTRA control schemes highly rely on the grid model and the input data available. The data includes the electrical properties and parameters of the components belonging to a certain grid model. Generally, neither real grid models nor grid data are publicly available. The most commonly used benchmarks with open data free for research purposes, such as the IEEE sets, are mainly high voltage grids with synchronous generation.

The very well-known *CIGRE benchmarks (MV and LV grids)* [7] have been the initial options for the validation of several control mechanisms despite its limitations for dynamic studies. These limitations (underrepresented ratio of non-manageable energy sources and limited dynamic controls) were overcome for the testing and validation of specific control mechanisms. The CIGRE MV reference grid has been adapted to accommodate the needed flexibility (type and location of resources in the cells) in a meshed topology.

One partner also used the so-called “reduced Great Britain model” (Great Britain transmission system including lower voltage distribution system models based on the University of Strathclyde PNDC test system), which proved very useful in terms of evaluating the frequency dynamics with the use of Adaptive Frequency Containment Control (aFCC) and Balance Restoration Control (BRC) mechanisms. Each cell contained controller models which act independently, solving active power imbalances locally by reserve activations when the imbalance event occurs within the local cell.

In order to accurately test the WoC voltage control schemes, it has been necessary to develop a dedicated MV/LV distribution grid model with a high penetration of distributed resources and the corresponding dynamic controls for the generation sources. This grid, called *FLEXTEC*, can faithfully represent the WoC control architecture and the future grid scenarios assumed in ELECTRA. It is also intended to serve as a flexible basis for further developments. The high number of distributed energy resources, many of them coming from renewable energy sources, also allow the testing of a wide range of scenarios and the analysis of the added-value of resource flexibility. Details can be found in Deliverable D7.1 [1].

Balancing Control

Pure simulations performed with Simulink proved to be useful for the validation of the individual balancing control functions under relatively small power system models. For the purpose of increasing the power system size under a more user-friendly environment for that aim, DIgSILENT/PowerFactory has also been used. DIgSILENT PowerFactory allows the integration into power system models of controller models, which have been designed in the MATLAB/Simulink design environment. The method, based on DIgSILENT Simulation Language (DSL), is cumbersome and causes extremely long simulation run times. This is the case when the complex fuzzy logic function of the Frequency Containment Control (FCC) had to be implemented as a DSL within PowerFactory. As a result, two different approaches were taken: 1) a co-simulation approach by which the Simulink implementation of the fuzzy logic controller was available into PowerFactory using a new method developed for accelerated model exchange between both simulation platforms [8], and 2) a simplification of the fuzzy logic algorithm by using a 0/1 logic.

In terms of implementation environments, the selected simulation models with 4 or 5 cells proved sufficient for the validation of the functions and, in particular, for the selected test scenarios. In particular, the selected CIGRE MV grid was an appropriate choice in terms of Balance Steering Control (BSC) validation due to the complex connectivity between at least two cells with multiple tie-lines. Also, the use of the “reduced Great Britain model” proved very useful in terms of evaluating the frequency dynamics with the use of aFCC and BRC. The implementation platforms, namely MATLAB/Simulink and DIgSILENT/PowerFactory, also proved to be good choices because they facilitated the exchange of data not only for this combination of use cases but also with all other tests.

Voltage Control

The pure simulation experiments within ELECTRA have been accomplished using a combination of DIgSILENT/PowerFactory together with automatization scripts programmed in Python. The challenges behind the simulation of the full voltage control scheme are related with the need to combine two simulation modes into a single sequence: “RMS” for the events and the corrective mode (Primary Voltage Control -PVC- and corrective Post-Primary Voltage Control -PPVC-) and “Quasi-Dynamic” for the long-term simulation of the proactive window (proactive PPVC). From the point of view of the simulation program these two simulation modes have different objectives and they need to be modelled separately. However, this is not consistent with the real operation of the grid, where the two modes have to be necessarily coupled if reproducing the real behaviour of an integrated voltage control algorithm. The Python script has been designed with that objective: combining the RMS with a Quasi-Dynamic simulation based on subsequent Optimal Power Flows (OPFs) for the proactive window, trying to overcome the limits of the simulation program to represent the full capabilities of the PVC+PPVC scheme.

3.4 Experimental Laboratory Implementations

Accurate experimental validation of the WoC concept has proven to be challenging to be performed in a laboratory environment. The challenges emerge from the need to perform system level testing, due to the size of the electrical system required for validating such concepts, and at the same time, to consider the real hardware dynamics (speed of response, communication delays, measurement noise, etc.) for an accurate validation. Furthermore, complex control algorithms have to be integrated within the different simulations and hardware components at different levels requiring of highly interoperable infrastructure.

Limitations and possible improvements of validation environments for system testing of the WoC

The validation under the challenging laboratory systems testing situation has led to the identification of a number of limitations for the testing of the WoC concept, some of which have been resolved bringing on new technical advancements towards systems testing procedures. Despite these issues, it was still possible to implement and validate the WoC control functions in a relevant lab environment.

Execution/Control Timing

For the further validation and testing of the performance of the controllers, CHIL testing has been also performed. CHIL technique has proven valuable as it provides a more realistic validation tool compared with control algorithms developed as simulation only. By using this technique some implementation issues of the algorithm were detected. For instance, the BRC controller developed in simulation had to be optimized in order to run at a different time step required by the real hardware device where the controller was implemented. Therefore, it is recommended to perform tests to the controllers running at different time steps if only simulations have been carried out, leading to an increased robustness of the developed controllers against environmental uncertainties and setup-specific limitations.

Scalability

The testing ability of the laboratories for scalability purposes under more realistic scenarios such as PHIL and CHIL is typically related to the limitations that real-time simulations models present for scalability purposes due to their limitation in the maximum number of nodes allowed for running in real time. In order to overcome this limitation, *aggregated dynamic equivalent models* could be used instead of detailed models, reducing the number of nodes and allowing for larger models to be run in real-time. This limitation has opened the possibility to pursue collaboration opportunities through the ELECTRA REX programme, leading to the publication of research in the area of aggregated dynamic equivalent models [9]. This is acknowledged as future work and as an enabler for the testing of systems such as the WoC in a more relevant environment.

Accuracy and Estimation Challenges

The experimental validation in the laboratory environment proved to be challenging due mainly to uncertainties in the operation of the involved RES (in particular PVs), inaccuracies in the estimation of the imbalance due to non-linearities in the controlled resources and communication delays.

Implementing a Rate of Change of Frequency (RoCoF) based controller, i.e., Inertia Response Power Control (IRPC) in a real system, where the RoCoF signal always differs from zero, requires the definition of a dead-band, which was not needed during the simulation studies. Similarly, employing series-produced Electric Vehicles (EVs) during the experimental validation as flexibility resources to provide synthetic inertia, showed some challenges/limitations that might occur. For example, even though EVs are converter connected units which in theory should be characterised by very fast response (in order of ms), a relatively slow response (around 2 s) was experienced due to some integrated controllers since EVs are not intended to provide ancillary services in first place.

Resilience through ensuring Measurement Quality

The fault analysis conducted within the project has been limited to simulations, however, a new method for accurately determining the reporting latency of a Phasor Measurement Unit (PMU) has been developed and demonstrated. This method operates in real-time, works passively for any existing PMU without requiring changes to the PMU hardware or software, and is very accurate: it provides a measurement uncertainty of <500 ns in many cases, significantly surpassing the 0.002 s accuracy requirement of the most recent IEEE Synchrophasor standard [10]. There are many emerging power system protection and control applications, which could benefit from faster-responding measurements and more accurate knowledge of the actual latency of the PMUs used to implement these schemes. It is particularly important to understand “full system” latency, including the impact of local and wide-area communications, rather than just the latency of the PMU device; the proposed method also supports such latency measurements. This advancement can be used to enable efficient, but realistic, cross-domain power system simulation studies which incorporate wide-area measurements and communications delays.

PHIL Implementation

The last part of the validation process was performed with the most realistic implementation, by which the controllers are implemented in hardware (as in the CHIL implementation) and additionally some of the devices to be controlled are also implemented as real hardware in a PHIL setup. This complex setup for the validation of FCC and BRC exposed a concern for the implementation of PHIL simulations when an important section of the power system is present in hardware. Mainly, stability issues for the initialization of the real-time simulation when performing the experiments, because the simulation is unable to initialize without that large area of the network. An initialization and synchronization technique with the use of a current source and a synchronized ramp system for the interconnection of the subsystems has been developed for such implementations.

During the PHIL implementation, there was overrun of simulations of the different blocks due to variable computational time needs. The electrical grid model was slower than the converter controller and the grid emulator controller. Hence, two different time steps were needed to assign to the system where the electric grid model is assigned to have larger time step than the rest of the system. Hence, such validation techniques need to consider the time the OPF algorithm (voltage control algorithm) takes and be prepared with contingency measures before laboratory implementations.

Instability was met in the PHIL test. This is due to introduction of noise (from the grid emulator or the converter hardware) in the feedback loop system. Eventually, the noise level increases to the level of instability of the test. This has been addressed by including filters to the measurements coming from the grid emulator.

There was time lag between the real-time and the actual test-time during the PHIL implementation. The time lag difference tends to increase as the test goes on. Nevertheless, as it was in the range where its impact is assumed to be minimal for voltage control applications, the results were presentable.

4. WoC Concept and Integrated Control Functions Validation

4.1 Validation of Balancing Control Functions

The use case *combination IRPC and FCC* has been proven in simulation and through experimental validation in a laboratory environment, to analyse its influence on the short-term frequency stability of the power system [11], [12]. The simulation approach was very helpful in order to prove the combined function of both controller functionalities. No issues were raised here.

IRPC provides contribution from decentralised resources to the overall power system inertia, which limits the RoCoF after disturbances and herewith the frequency nadir. The ability of IRPC to improve RoCoF/inertia time constant has been presented through simulations. In order to cope with a future power system with reduced system inertia also other implementations to provide inertia, such as virtual synchronous machines, need to be considered.

The ability of FCC to improve short-term frequency stability of the investigated networks has been shown. Implementations of FCC in simulation and hardware implementation showed improvements of frequency nadir and steady state frequency deviation after a disturbance. In addition, the ability of an adaptive FCC to improve frequency stability metrics was proven. The presence of aFCC always slightly worsens the dynamic frequency deviation, fact attributed to the non-optimized design of the fuzzy controllers. Otherwise, the controller effectively modifies the droop slope of all FCC reserves in order to increase the contribution of the faulty cell and decrease that of its neighbours, where no disturbance happened; as a consequence, the balance of the neighbouring cells is less disrupted.

No inherent controller conflict between both control functions, IRPC and aFCC could be determined. Besides, the impact of IRPC and FCC on the voltage variations is rather small. A reduced overall system inertia has negative impact on frequency stability measures like nadir and RoCoF. Therefore, a minimum required system inertia needs to be defined and also provided to ensure power system stability.

It is noteworthy that with the use of aFCC instead of fixed droop, the risk of controller conflict can significantly be reduced. This is due to the fact that aFCC curtails the droop slope of reserves in cells outside the cell of imbalance. This way, less power is used during frequency variations by the local droop controller and, hence, more power is available for use by IRPC.

From the WoC functions validation point of view the implemented tests showed that the control functions of the *combination FCC and BRC and BSC* effectively without deteriorating the stability of the system. In terms of FCC and BRC implementations, both controllers achieved two important things: to contain and restore frequency and balance effectively and to do this by prioritising the activation of the reserves in the cell with the imbalance. The implementation of BSC proved to be successful too in both the simulation and laboratory environments. As a result, the BSC controllers of the cells in the selected scenarios managed to exchange the correct signals even for more complicated interconnections among them. The successful negotiations resulted in correct deactivation of BRC reserves thus exploiting the imbalance netting effect in the WoC, even in the case of unequal imbalances in neighbour cells, congestion of one tie-line capacity or communication delay. Any change in the tie-lines setpoint was also done in a grid-secure manner since frequency stability was always maintained thanks to the good design of the selected BRC control [13], [14].

Despite the good performance of all three use cases which, in principle, validates the WoC concept, there were several issues related to this combination that were not comprehensively addressed in this test campaign and are deemed as topics for potential future work. The first issue is related to the action of BSC and BRC on the individual tie-lines power profile. Specifically, BRC uses the net imbalance error in order to correct deviations in the import/export scheduled power of a cell. BSC on the other hand utilises the individual capacity and schedule of tie-lines in order to calculate the allowed modification of each tie-line setpoint. Despite the correct calculation of this adjustment, the setpoint values communicated to BRC result in the correct change in the net tie-line power but the individual tie-lines (in case of multiple connections between the two negotiating cells) take values that are not in accordance with the set-points. This issue can only be dealt with by using individual tie-lines control such as voltage control in order to correct the power flow of the tie-lines. Since the selected scenario did not involve the use of voltage control in the setup, the latter could be part of a future analysis in which all use cases could be combined in one setup.

The second important issue that was pinpointed during the tests was the fact that Adaptive FCC and BRC present a “rather competitive” behaviour in terms of frequency dynamics in the sense that BRC is designed to eliminate as much as possible the frequency dynamics of the system, whereas aFCC in order to obtain a more local use of reserves reduces the droop slope of neighbouring cells, thus, leading to slightly worsen frequency dynamics. In order to deal with this issue an optimisation of the fuzzy controller used as aFCC should be followed. This optimisation method is also deemed as part of potential future work.

Besides, there is still an outstanding need for further development of the BRC controller in order to address the scenario where insufficient reserve action can be achieved in the problem cell to fully rectify the imbalance. This means that there will have to be some control logic and negotiation between cells which allows a neighbouring cell to participate in the frequency recovery through use of its fast-acting reserves. Currently, the location identification portion of the controller only allows the problematic cell to participate with fast-acting reserves. Some work has been initially done in this area [15].

4.2 Validation of Voltage Control Functions

An investigation into the optimal cell configuration in terms of size and dimensioning of local resources, has been accomplished based on a clustering approach using the normalized electrical distance. It provides a promising tool for a preliminary identification of the ELECTRA cells with sufficient flexibility for voltage control, which could be extended to balancing control use cases as future work. In some of the PPVC validation approaches this method is used to divide the CIGRE MV network in to certain number of cells. See Deliverable D7.1 [1] for further details.

The implementation of a PPVC controller at cell level, running in the double corrective and proactive mode, restores the voltage to the safe-band in a very short time while minimizing the cell power losses. Besides, its proactive behaviour reduces the number of primary resources activations and PPVC corrective triggers.

From the voltage control perspective, there is no real-time coordination between the neighbouring cells but only common agreements in terms of reactive power exchanges in the tie-lines. That means that enough reactive power reserves within the cell must be ensured (otherwise, the OPF solution will not be feasible and in the system, and the optimal voltage profile will not be reached).

The simulation validation process for the voltage control functions involved a *MATLAB/Simulink* implementation of the CIGRE MV network with LV extension. The same network was implemented in *PowerFactory*. *Matpower* or *GAMS* were used for running the OPF to minimize the power losses and calculate the optimal setpoints of the grid resources. One difficult issue was to get the grid models in two simulation environments to be exactly the same, in order to be able to correlate results and exchange data. Nevertheless, the overall results are clear and acceptable enough to reach the conclusions.

In one of the validation activities, for obtaining the complete PPVC sequence incorporating the corrective and proactive modes, *PowerFactory* simulations and *Python* scripts were identified to be crucial to implement an automated and complete PPVC mechanism. Besides, the object-based realization utilized in the particular PPVC validation can be easily extended to larger test grids with more cells, anticipating scalability issues [16].

The next step towards real-world conditions involves real-time co-simulation with HIL coupling, which has been found to be a very helpful tool for carrying out the proof of concept evaluation using a real component controller. The HIL validation of the PPVC function has demonstrated a high number of possibilities and powerful flexibility for the simulation environment, where the complexity of a large-scale communication model will be simplified. However, the implementation of the voltage controllers in HIL platforms are far from being straightforward and needs to solve diverse complex technical issues, as described in the previous section [17], [18].

5. Open Issues and Future Work

During the project ELECTRA, the WoC concept has been defined as well as its voltage and frequency (balancing) control schemes. The concept has been proved with successful results in a discrete set of scenarios for the different testing environments considered (pure simulations and Hardware-in-the-Loop platforms). However, the tests have been carried out with some limitations that should be addressed in future works. These validation results for such a novel concept have also pointed out the needs for deeper investigation in some areas of interest.

One of the main challenges pointed out by the different partners in the project is related to the *lack of grid models* to accurately reproduce the complex behaviour of the WoC. This has been tried to be covered by the FLEXTEC grid, successfully checked in the validation of the PVC and PPVC schemes. The refinement of the distributed energy resource controllers and modifications, if needed, to fit with the balancing use cases remain as future work.

Specific improvements of single controllers have been also mentioned in previous section of this document. Extended laboratory experiments are needed to analyse the impact of a real ICT infrastructure (latencies) on the functioning of these controllers at a larger scale, including the real-time behaviour of a many reserves.

In the validation approach followed in the project, the interactions and potential conflicts due to the implementation of a *complete control solution*, considering both the combination of balance and voltage control functions have not been analysed. A more holistic approach in terms of assessing potential conflicts should include the use of all use case controllers employing the same cell available resources (which will receive set-points linked to different use case objectives).

To faithfully validate the WoC integrated control solutions, an analysis on how all core functions developed for the different control use cases can be combined into one system, as well as the development of a relevant operating scenario where the interactions can be accurately studied, should be performed. Regardless of the number of cells, the emphasis here should be given on the operating conditions, the complexity of the grid topology and the controllability of the reserves, more than in the number of cells itself.

Once the validation has been accomplished for a complete set of use cases in a relevant operation scenario, the scalability of the solution (in a simulation environment) should be evaluated to justify a more stochastic behaviour in a grid with a larger number of cells (tens/thousands). Scenarios and simulation approaches have to be properly selected to assess this stochastic behaviour of the WoC and to evaluate the performance of the balance control use cases (in particular IRPC, aFCC and BRC) in these conditions. The objective of this analysis should be to obtain a probabilistic measure of transient stability for the WoC instead of just verify the particular response of the frequency control schemes when facing a set of discrete disturbances (as it is done in a worst-case analysis), as well as the interactions with the voltage control schemes in these particular situations. Later, the integrated validation of the combined set of use cases has to be validated in a more-realistic environment (PHIL platform), as was already done during the project for the balance control use cases and voltage control use cases combinations separately.

Further work is also necessary in order to define more *concrete rules for defining cells*. This issue does not jeopardize the overall WoC structure concept and the associated control mechanisms, but clearly assistance in this aspect will help through its implementation. It is a fact that when presenting the WoC concept, it still demands the initial clarification on cell size and dimensioning of cell internal resources.

Scalability, both in terms of number of cells and events, remains to be more fully proven. More validation is needed to assess the overall stability and containment and restoration features in a very dense cell power system, with a continuous stream of balancing deviations in each of the cells (for example, due to local forecasting errors). However, the advances made in experimental and simulation infrastructure, including communications emulation, have provided the basis for ongoing expansion of the test cases that will better prove this.

Despite it is not strictly related to a laboratory validation task, a *benchmarking* of the WoC control concept against the reference control concept (centralized) would be highly advisable. This ambitious activity should be accomplished by means of rigorous simulations relying on improved TSO-DSO coordination and suitable future grid conditions, in terms of inertia, RES integration at all voltage levels, reduced central generation, large amount of reserves connected to the distribution grid, etc. The benchmark should be showing the number/amount of resource activations, mitigated losses and congestions, stability and resilience of the system, etc.

6. Conclusions

WoC based real-time control solutions have been successfully implemented in a number of ELECTRA laboratories, showing the benefits with respect to a conventional centralised control. The conducted experimental validation has demonstrated that the proposed control schemes within a WoC architecture are feasible for operating the future grid, under laboratory conditions (TRL4). This confirms the pure simulation results obtained in previous activities of ELECTRA, going a step forward closer to a real-world situation.

The exposure and immunity of the proposed controllers to communications asynchronicity, real-life measurements and control step resolution, noise sources, parameter uncertainties, and other factors not explicitly incorporated in the models were tested in the process. The deployment of the controllers on dedicated controller hardware enabled rapid prototyping, allowing for an efficient iterative development process by feeding back experiences made under real conditions into the theoretical method.

The validation process in ELECTRA has shown that the WoC concept and associated control systems successfully localise the reserve response by identifying whether the imbalance originates in a given cell, and if so, tailoring droop settings (aFCC) and activating fast-acting reserves (BRC) in that cell only. These actions result in fewer and smaller reserve activation in non-problematic cells and lower transmission boundary flows immediately following an event. The FCC and BRC operation are not impeded by, nor do they impede the operation of, imbalance netting through BSC control.

With the development of the balancing control (and to a lesser extent voltage control) functions and their validation in a laboratory environment, the promise of the WoC concept has been proven, i.e. the ability of a more decentralized operation of power system has been proven. Furthermore, the developed controls, in essence work towards the objective of solving local problems locally.

Beginning with the speculation of advantages of more local control, this exercise has proven some merits of prioritizing local response to a local imbalance, such as improved dynamic response, robust reserve activations and reducing the divergence from planned system conditions and hence minimizing the operational implications of the disturbance. In addition, the developed controls support enhanced scalability in the future grid given the autonomy of the approaches. It must be noted that the control schemes are (especially for the voltage control) not strictly bounded to a WoC structure.

According to the long-term nature of the ELECTRA IRP research, it must be clear that the WoC architecture and related balancing and voltage control concepts are still in a conceptual phase (even when validated at laboratory level), which corresponds to a low TRL level. No real-world devices exist at this stage and there is a technology gap before full implementation, which should be filled by means of other National or European projects moving the current concepts towards higher TRL levels.

Before a full roll-out of the WoC concept in the real grid is possible, further scaled-up (in terms of number of cells) validations and thorough investigation of the interaction of the different control functions has to be carried out. Some of the potential challenges, for example inter-cell loop flows, possible collaboration between neighbouring cells and alternative approaches for such collaboration [19] have been already identified in ELECTRA, and should be explored more deeply. Nevertheless, partial experimentation of the WoC concept can be started in selected demo sites (in this regard, C/sells project could be seen as a possible pilot experience), representing portions of distribution network functioning as cells. As it stands now, consideration of a DSO as a Cell System Operator may minimize the complication coming from the execution of local control functions. Initial steps for deploying the developed control mechanisms could be based on the implementation of the PPVC function as the most feasible control function that can be tested in a selected demo distribution network area, followed by the implementation of a BRC controller for a single cell that could be done without impacting the existing centralized control scheme.

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8. Disclaimer

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The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Commission.

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ANNEX: Templates to report ELECTRA Experiments

TEST CASE:

Name of the test case	*Name*
Narrative "a storyline summarizing motivation, scope and purpose of the test case."	*Include research questions for the test case.*
System under Test (*SuT*): *(power system & ICT boundaries): SRPS + CTL*	
Objects under Investigation (*OuI*) The component(s) (1..n) that are to be characterized or validated.	
Domain under Investigation (*DuI*): The relevant domains or subdomains of test parameters and connectivity.	*Which interactions are part of the test case? Which domains of expertise needs to be included/emulated in a potential test setup? In a multi-domain system, not all interactions need to be reflected in a test; identify the domains and/or sub-domains that are relevant for this test case.*
Functions under Test (*FuT*) List all functions required in operation of test system.	
Function(s) under Investigation (*FuI*) Reference to functions realized by the object under investigation.	*The function or sub-function that is operational in the OuI and subject to testing.*
Purpose of Investigation *(PoI)* "a formulation of the relevant interpretations of the test purpose (e.g. in terms of Characterization, Verification, or Validation)".	*What information will be gained by a successfully carried out test? What is the objective of this evaluation? List relevant KPI here.*
<u>**Test criteria**</u>**:** "the measures of satisfaction that a need to be evaluated for a given test to be considered successful." A formalization of the purpose of investigation wrt. SuT and FuT attributes.	*Number the specific test objectives/KPIs/PoIs: consider a bullet list or table., put TCR-ID here*
Target metrics (criteria) A list of measures to (quantify) each identified test criterion (use reference to criteria numbers above).	*What should be measured, and if so, with what should it be compared? Refer to TRC-ID / TCR number.*

	Variability attributes (test factors): Which of the system parameters and properties will be varied, and how much?	*Which system (input) parameters should we varied in order to disturb the OuI?* *What kind of faults should the system be subjected to?*
	Quality attributes (thresholds): In case of "validation" and "verification": define the maximum/minimum threshold for deciding the performance is acceptable In case of "characterization": what would be the minimum required measurement precision?	*In case of validation/verification: How, or how good, should the target metrics be quantified in order to decide the test outcome?*

TEST SPECIFICATION:

ID / Title	
Reference Test case	
Responsible Entity	*i.e. responsible partner(s)*
Experiment Type	*Simulation, (P/C)HIL, Lab, or Real-time simulator?*
Test System (also graphical)	*Graphical and textual description of the system under investigation and its components including interfaces between test setup and Object under investigation and type of those interfaces (e.g. electrical).*
Input parameters	*List of inputs for the system under test relevant to the object under investigation, divided into 'Controllable input parameters' and 'Uncontrollable input parameters'.*
Output parameters	*Outputs / measured parameters: 'Measured parameters'.*
Target measures	*Identify the Test criteria evaluated here (reference the TCR-numbers from TC above) and specify how the target metrics will be derived from measured parameters in order to evaluate the test objectives. Which variables will be quantified by the test? (formula and explanation).*
Test Design	*Test sequence, establishment of reference values (in case of BAU), decision criteria and controlled parameters.* *Textual or graphical description of the sequence of steps carried out during the test including parameter ranges and variation of input parameter.*
Initial system state	*Description of conditions that are prerequisites to actually run the test and initial choices of parameters.*
Evolution of system state and test signals	*Quantitative characterization of the temporal evolution of test events and evolution of the relevant test parameters, as adjustable by the input parameters (e.g. opening breakers after a certain amount of seconds); incl. variability attributes.*
Other parameters	*Information of data that should be tracked apart from the input and output parameters and system state, test signals.*
Storage of data	*In which format are the parameters stored?*
Temporal resolution	*Discrete or continuous simulation and (if applicable) resolution of the discrete time steps.*
Source of uncertainty	*In order to evaluate the quality of the test, the possible sources of uncertainties are given in how they can be quantified.*
Suspension criteria / Stopping criteria	*Under which conditions are the test results not valid or the test is interrupted.*

TEST EXPERIMENT:

Title	*Definition.*
Reference Test Specification	*Reference to test specification document.*
Research Infrastructure	*Specify the RI where the experiment is carried out.*
Experiment Realisation	*The setup can be realised in different ways (e.g. simulation, hardware,…): give a brief description of the realization.*
Experiment Setup (concrete lab equipment)	*Graphical and textual description of the concrete lab equipment and interconnections.*
Experimental Design and Justification	*For all parameters give a reason why it has been chosen that way concrete values, sequences of values of "variability attributes" and concrete combinations of different variability attributes number of repetitions for each combination.*
Precision of equipment	*For the components of the lab equipment the precision is given such that the experiment uncertainty can be derived.*
Uncertainty measurement	*Based on the precision of equipment of the lab instrument and of measurement algorithms, the parameters to model the measured quantities errors are provided it is specified how experiment uncertainty can actually be measured.*