No 727481 RESERVE

D1.6 Adaptation of Research Concepts based on Simulation, Live ICT Tests and Field Trial Results, V2

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Abstract

This report discusses the procedures for validating the frequency and voltage control concepts that were developed in RESERVE. The procedures extend from the software simulations of simple networks, to the simulations of real networks, and to the field trials. The procedures served as a way to build confidence in the performance and applicability of the control concepts. The procedures also led to updates in the control concepts and their respective system-level requirements. This deliverable also reports these updates, which were collected every 6 months since the 18th month of the project.

Keyword list

Electricity System Requirements, 100% RES Electricity Networks

Executive Summary

New control concepts were developed in RESERVE for electrical systems with up to 100% Renewable Energy Sources (RES). Each concept provides either frequency control or voltage control. This deliverable gives the reader an overview of the procedures for investigating these new control concepts. The investigations include offline and real-time simulations, ICT tests, and field trials. These investigations aim to 1) validate the concepts, and 2) give the industry the confidence that the concepts will work in real systems.

The new control concepts require power system components and functions. These components and functions are collectively referred to as system-level requirements in this deliverable. This deliverable contains the list and definitions of the system-level requirements. It also contains the changes in these requirements since the submission of D1.2 in Month 12, where the requirements were initially listed and defined.

In RESERVE, the system-level requirements of the new control concepts are studied using four scenarios – two scenarios for frequency control and two scenarios for voltage control.

The two scenarios for frequency control are the following:

- **Sf_A:** Mixed Mechanical-Synthetic Inertia
- **Sf_B:** Full Synthetic Inertia

The two scenarios for voltage control are the following:

- **Sv_A:** Dynamic Voltage Stability
- **Sv_B:** Active Voltage Management

These scenarios were initially defined in D1.2. The updated and refined scenario descriptions can be found in this deliverable.

Moreover, the investigations for the control concepts across the scenarios are summarized as follows:

Sf_A:

For Sf_A, the investigations focused on the following concepts:

- Fast frequency response (FFR), RoCoF (a.k.a. inertial) and primary frequency control (PFC) provided by the Distribution System (DS)
- RoCoF/inertial, FFR and PFC provided by ESSs
- Definition of Frequency Makers and Frequency Takers
- Including Virtual Power Plants in the Secondary Frequency Control
- Frequency control of grid-connected microgrids

These concepts have been investigated using both offline and real-time simulations. Initially, the simulations have considered a simple approximation of the Western System Coordinating Council (WSCC) 9-bus test system. In the latter parts of the project, the simulations have been based on the Romanian and the Irish Transmission Grids modeled inside different software tools (DOME, EUROSTAG, and OPAL-RT).

Sf_B:

For Sf_B, the investigations were focused on the use of the Linear Swing Dynamics (LSD) concept in the control of DC (HVDC) and RES-tied converters to achieve the following features:

- System synchronization and coherency
- Provisions for virtual inertia
- Consistent performance in frequency control and regulation

The investigations in Sf_B validated both the centralized and the decentralized implementations of LSD for multimachine systems using offline simulations.

The effects of the frequency control concepts are widespread and cannot be isolated. Therefore, it should be noted that the new frequency control concepts cannot be investigated in the field (i.e. on actual transmission systems). Therefore, for both Sf_A and Sf_B, no field trials were done. In contrast, the voltage control concepts can be tested in smaller systems. Thus, field trials were done for testing several voltage control aspects.

Sv_A:

The investigations for Sv_A focused on the use of Wideband System Identification (WSI) and Virtual Output Impedance Control (VOI) in distribution systems. These concepts prevent dynamic instability in systems with many power converters.

The investigations for Sv_A proceeded from software simulations, into hardware-in-the-loop simulations, into laboratory trials with the new converter in RWTH Aachen. Field trials in the Irish low-voltage distribution network were also planned.

Sv_B:

The investigations for Sv_B focused on the use of Active Voltage Management (AVM) concept. This concept aims to maintain the effective (a.k.a. RMS) values (e.g. 220 Volts, 110 Volts) of system voltages within allowed values. It also minimizes the power losses or voltage unbalance in the system.

The investigation for Sv_B proceded from software simulations into field trials in the actual Irish low-voltage network. Four separate field trials were done – one for each of the following technologies: vehicle-to-grid chargers, photovoltaics, battery storage, and air-sourced heat pumps.

The system-level requirements for the four different scenarios were listed in D1.2. However, the investigations of the different control concepts have led to some updates to these requirements. The updates on the requirements were collected under WP1 of RESERVE. The final definitions of the requirements are reported here in D1.6.

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1. Introduction

The project RESERVE aims to demonstrate the applicability of the new control concepts developed during the project. The demonstrations aim to increase the confidence of the network operators that the new concepts will be effective in future electricity systems.

In summary, there are four scenarios defined in the project from the system-level perspective. Different concepts for frequency and voltage control were developed and investigated across these scenarios. The scenarios and the control concepts are summarized below:

1. Sf_A (Mixed Mechanical-Synthetic Inertia): Sf_A is the scenario where synchronous generation (e.g. hydro, coal and nuclear power plants) is still present in the power system. This scenario also considers the transition to 100% penetration of RES where the only synchronous generation technology is hydro. As the penetration of RES increases, the overall mechanical inertia in the system decreases. With less inertia in the system, the frequency is less stable. Thus, the investigations in Sf_A focused on new concepts that stabilize frequency using distribution systems (DS), energy storage systems (ESSs), and virtual power plants (VPPs). The investigations also covered the participation of grid-connected microgrids in the frequency response of the transmission grid. It also covered the definitions of frequency makers and frequency takers. Furthermore, since the concepts in Sf_A are developed for systems with reduced mechanical inertia, the concepts will be applicable to systems with high penetration of RES, even if the penetration is not 100%.

2. Sf_B (Full Synthetic Inertia): Sf_B is a futuristic power system scenario with up to 100% penetration of non-synchronous generation. The power system in Sf_B has HVDC grids, hybrid AC/DC grids, and very low or no mechanical inertia. The investigations in Sf_B focused on the use of Linear Swing Dynamics (LSD) to stabilize the frequency.

3. Sv_A (Dynamic Voltage Stability): Sv_A is the scenario in the low-voltage part of the grid where numerous loads, distributed energy resources (DERs), and ESSs are connected to the system via power converters. These converters may cause dynamic voltage instability. Thus, the investigations in Sv_A focused on the application of the Wideband System Identification (WSI) in distribution systems to assess the system stability. Based on the assessment, the concept in Sv_A uses the Virtual Output Impedance (VOI) Control to maintain stability.

4. Sv_B (Active Voltage Management): Sv_B is the scenario where the loads and DERs, which are connected to the system via power converters, are used for Active Voltage Management (AVM). AVM minimizes voltage unbalance or power losses in the system by optimizing the reactive power support provided by RES and other sources of electricity.

1.1 Task 1.5

The expected system-level requirements to implement these concepts have been defined initially in D1.2. In Task 1.5, we regularly updated and refined the system level requirements of the control concepts, as well as the scenario descriptions. The updates and refinements may come from 1) the updates in the conceptual framework or 2) the results of simulations and tests of the control concepts. This deliverable report these updates.

1.2 Objectives of the Work Report in this Deliverable

In summary, the objectives of this deliverable are:

- To describe the procedures for validating the frequency and voltage control concepts for electric power systems with up to 100% RES; and
- To provide the updated system-level requirements for implementing the control concepts.

1.3 Outline of the Deliverable

Chapter 2 describes the procedures of validating the frequency control concepts for Sf_A and Sf_B. It also reports 1) the simulations and tests that were done and 2) the resulting updates in the system-level requirements.

Chapter 3 is the counterpart of Chapter 2 for voltage control. Chapter 3 describes the procedure of validating the voltage control concepts in Sv_A and Sv_B. It reports on the simulations and field trials for the developed voltage control concepts, and the resulting updates in the system-level requirements.

Both chapters 2 and 3 also give the reader the deliverable where the details of each test, including ICT tests, can be found.

Chapter 4 concludes the report, highlighting the main findings.

Furthermore, this deliverable includes one annex. This annex discusses the perspectives of using the solid-state transformer technology – a technology that came into the discussions during the project.

1.4 How to Read this Document

The investigation procedures described in this deliverable were done to validate the concepts for the different voltage and frequency scenarios in RESERVE. In addition to these procedures, ICT performance tests were also done to validate the behavior of ICT systems that will be needed to implement the scenarios in actual systems. The readers can refer to the following deliverables for the description of these ICT requirements and performance tests:

- Deliverable 2.5 and 3.7 describes the 5G and ICT requirements for frequency and voltage scenarios
- Deliverable 5.8 and 5.9 describes the 5G and ICT test cases, lab setups, and results.

In addition, for further reading about the concepts, test setups, and trial sites, the reader can refer to the following list:

- D2.1, D2.2 and D2.3 – in-depth discussions on the frequency control techniques that were developed in RESERVE
- D3.1 and D3.2 – theoretical background of voltage control and management concepts developed in RESERVE
- D4.1 and D4.2 – laboratory connection infrastructure and real-time solver used to test the frequency and voltage control concepts in RESERVE.
- D5.1, D5.2 and D5.3 – overview of the test set-ups and field trial sites for voltage control concepts.
- D5.4 and D5.5 – trials of frequency in the laboratory and validation of initial network codes and ancillary service definitions.

Figure 1-1 shows how this deliverable, D1.6, relates to the other deliverables in WP1 and the other work packages. D1.6 is the last installment of a series of reports. The reports in this series describe the procedures for validating and updating the control concepts using the simulations, setups, and trials coming from work packages WP2, WP3, WP4, and WP5. Each report is an updated version of the previous one – capturing the updates every 6 months from the 18th to the 36th month of the project.

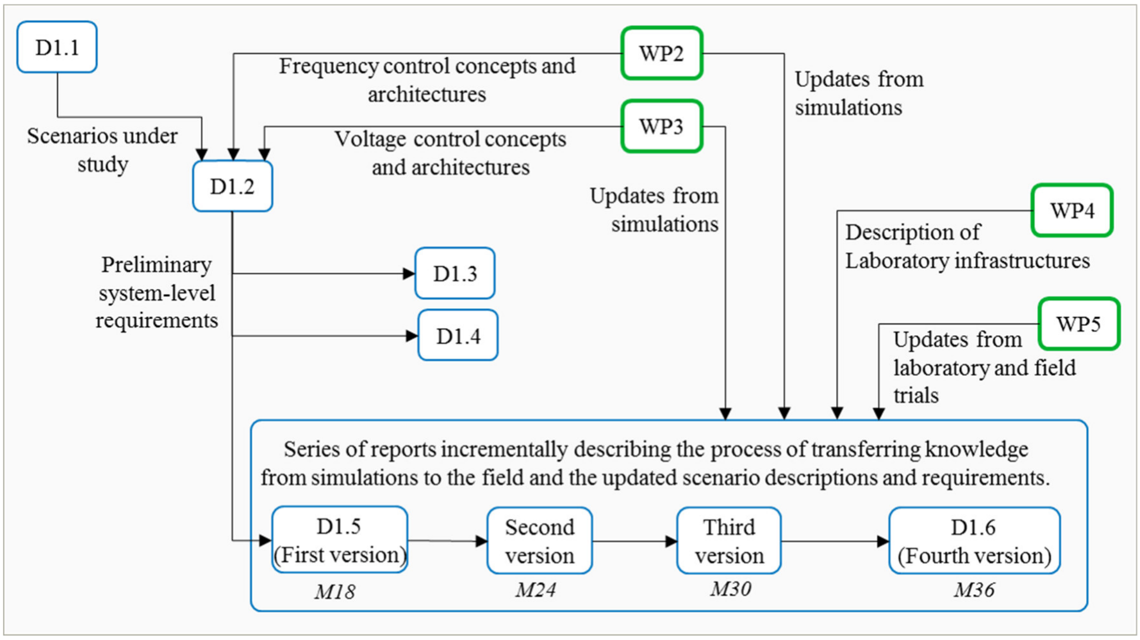

Figure 1-1. Relations between deliverable in WP1 and other work packages

1.5 Approach used to Undertake the Work

The project partners in WP2 and WP3 were regularly consulted for the updates in the system-level requirements since the submission of D1.2. Project partners working in WP4 and WP5 were also consulted for the details and status of the investigation procedures for the different control concepts. These results of these consultations were collected and used to update D1.5 every 6 months. The final version is this deliverable D1.6. All this work falls under Task 1.5 of RESERVE.

2. Frequency control concepts

Following the strategy of switching the power generation from large fossil-fueled power plants to small RES-based units, the mechanical inertia is drastically decreasing to dangerous values so that the frequency is no longer stabilized by the natural reaction of the mechanical systems of both the generation and load entities, as shown in deliverables D2.1 and D2.2.

As explained in D2.2, the frequency regulation is performed using a hierarchical architecture, including automatic and manual actions. In RESERVE, our focus is on automatic actions. The following control strategies are explored:

- RoCoF control (decentralised or distributed)
- Primary Control (decentralised or distributed)
- Secondary Control (centralised)

The entities involved at all the automatic control levels are illustrated in Figure 2-1.

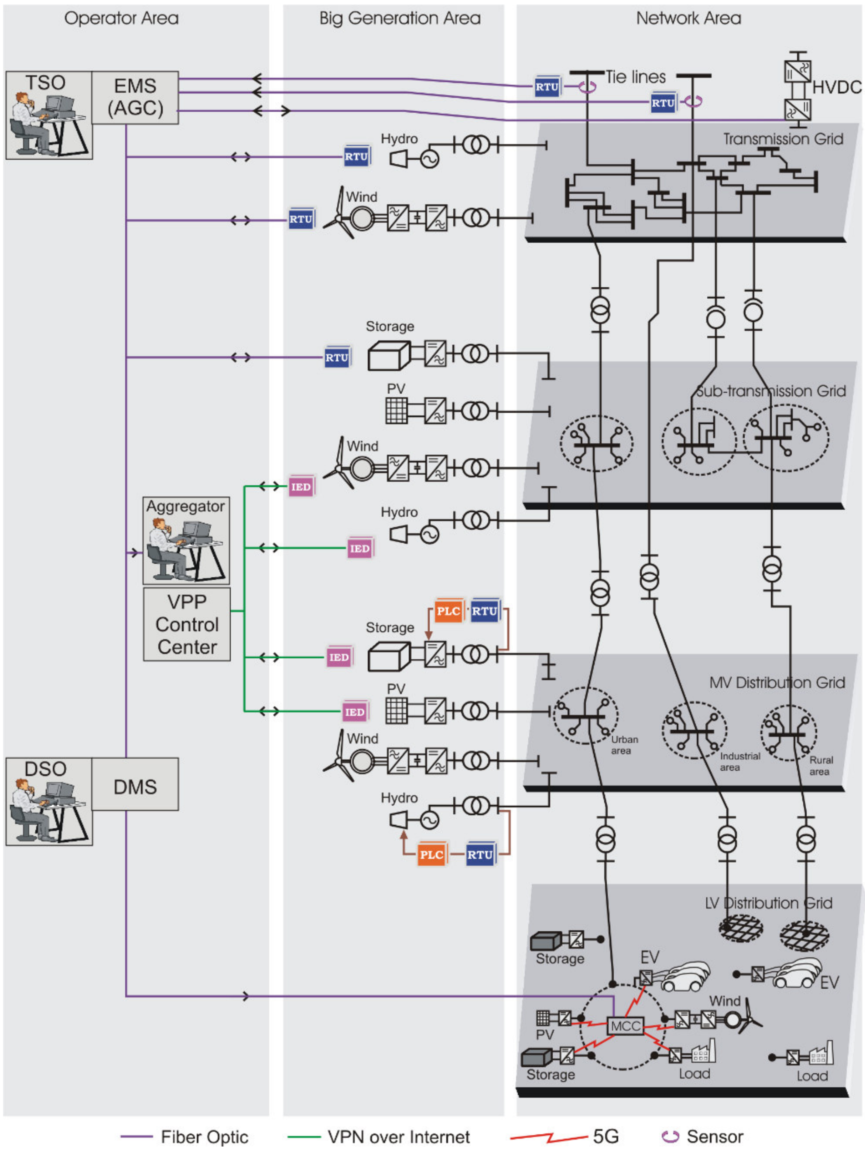

Figure 2-1. Overview of the system components and communication in the hierarchical frequency control

There are two scenarios studied in RESERVE for frequency control. The first is Sf_A, where it is assumed that certain mechanical inertia is available due to the presence of conventional power plants. The second is Sf_B, where it is assumed that 100% of the generation is provided by wind and solar plants, resulting in very little to no inertia in the grid.

2.1 Updated System-Level Requirements for Frequency Control

Table 2-1 shows the final definitions of these requirements for frequency control. The definitions in Table 2-1 were updated from their earlier versions in deliverables D1.2 and D1.5 based on the validation procedure followed in the project. The validation procedure for studying the frequency control concepts in Sf_A and Sf_B are respectively discussed in sections 2.2 and 2.3 of this report.

Table 2-1. Updated definitions of component and functional requirements for frequency control in Sf_A and Sf_B

System-Level Requirement	Updated Definitions	Changes with respect to the definitions in D1.2
Component		
Generating Units	1) Hydro Plants use electric power to produce electricity. Water storage can serve as an ESS as well as a means to regulate the flow of water. (Sf_B does not consider the presence of hydro plants). 2) Solar Plants (with or without storage): Solar plants convert electricity from energy radiated by the Sun. The solar plants considered are equipped with ESS, allowing them to provide frequency control support. 3) The wind plants are groups of wind turbines interconnected to a common utility system that converts wind power to electricity. These wind plants can provide frequency support by changing the angles of the turbines' blades. Wind plants with Double fed induction machines (DFIG) can also provide faster frequency response by means of its converter (mainly in over-frequency situations, i.e, when the wind turbine needs to reduce its power production. For under-frequency situations, power reserve is required). 4) Fossil-fuel and nuclear plants: These power plants produce electrical energy through synchronous machines and are not connected to the grid via electronic power converters. These plants also provide high mechanical inertia to the grid, which makes the frequency more stable. (Sf_B does not consider the presence of fossil-fuel and nuclear plants).	• Fossil-fuel and nuclear plants are included in the study of the transition to 100% RES (M24). • Minor changes in wording (M12, M24, M30).
Power Converters	The power converters provide the interface between the grid and the different RES and electrical ESSs. The power converters will provide AC/DC, DC/DC, or DC/AC conversion. These converters must be able to handle the high-power transfers required in RoCoF control	• Minor changes in wording (M30).
Energy Storage Systems (ESSs)	ESSs will release or absorb energy to provide support in the RoCoF, primary, and secondary control stages.	• Minor changes in wording (M30).

Tie Lines	Tie lines provide interconnections between different transmission grids. The use of tie lines will help maximize the utilization of available capacities from future RES and ESSs.	No changes
Local Meters	Each generating unit must include a meter that will provide frequency measurements.	No changes
Local Controllers	Each generating unit must have a local controller. Today, these local controllers house the primary control function, and perform it independently from one another. The local controllers will also house the RoCoF control.	No changes
Remote Terminal Units (RTUs)	Each generating unit must include an RTU. The RTUs relay the following information: frequency measurements from local meters to local controllers frequency measurements from local meters to RoCoF units control commands from RoCoF units to local controllers frequency measurements from local meters to supervisory controllers, microgrid controllers, or aggregators control commands from a supervisory controller or aggregator to the local controllers	• Minor changes in wording (M24).
RoCoF units	RoCoF units participate in distributed RoCoF control. In distributed RoCoF control, a RoCoF unit performs frequency measurements, frequency estimation, and RoCoF calculation. It sends control signals to the different controllers to adjust the power outputs of different generating units and ESSs.	
Supervisory controller	A control unit that houses the secondary control function.	No changes
VPP Controller (of DSO or Aggregator)	A control unit that facilitates the coordinated operation and response of aggregated units covered by the VPP.	No Changes
DC Grids	Parts of the transmission system that uses DC voltage (This requirement is only for Sf_B).	• DC grids are limited to transmission systems (M24).
Function		
RoCoF control (independent or coordinated)	i) Objective: Supply synthetic inertia to the power system following a disturbance to slow down the frequency dynamics. ii) Equipment rating: The power plants and ESSs should be capable of releasing energy fast enough to provide enough synthetic inertia to the	• It may also be referred to as "Inertial Control" (M18).

	power system right after disturbances to limit the rate of change of frequency. In this regard, SF_B requires higher power generation from the storage elements as compared to SF_A. iii) Timeframe: For SF_A, the research work assumes that the required timeframe for RoCoF control is from the beginning of fault up to 5 seconds. This timeframe includes the time needed for measurements and communications. Future field tests of the project need to evaluate the appropriateness of this timeframe. For SF_B, the researchers expect the required timeframe for RoCoF control is shorter compared to that of SF_A. One reason for the reduction in control duration is the faster response required by the faster dynamics due to the absence of inertia from generation. Another reason is that the power converters can provide control faster than the regulation provided by synchronous machine controllers. In SF_A and SF_B, the total response time for the control must be minimized. iv) Frequency Measurements and Estimation: Trade-offs between local frequency measurements and frequency estimation must be in place to maximize the benefits of RoCoF control. v) High granularity of Frequency Measurements: Meters and RoCoF units must have the appropriate granularity to capture the fast dynamics in frequency after the disturbance. Determining the optimal granularity is outside of the purpose of the project, but minimum time reactions have been determined in the simulations, which helps defining requirements for the granularity. vi) Manner: The controllers may perform the RoCoF control in a decentralized manner (i.e. individually based on local measurements and without the use of communications). The controllers may also perform the RoCoF control in a coordinated manner (with communications with other controllers and RoCoF units). vii) Coordination Requirements: In case used, communication infrastructure must be fast enough to allow RoCoF control.	• Minor changes in wording (M30).
Primary Control (independent or coordinated)	i) Objective: Contain the frequency within the allowed range and stabilize it on a certain quasi-steady state value ii) Maximum deviation of quasi-steady-state value: Like the present case, primary control in SF_A and SF_B should stabilize the frequency to a level that falls within the maximum permissible deviation of the steady-state value. The present value (± 180 mHz for Central Europe) in network codes must be reviewed if more stringent limits must be in place in the future. In SF_B, the limits may become less stringent, as the loads and	• Minor changes in wording (M30).

	generating units affected by grid frequency becomes fewer. iii) Maximum instantaneous frequency deviation: Primary control, together with the RoCoF control, should limit the instantaneous frequency within the maximum and minimum limits set by network codes. The current limits must be reviewed if more stringent or less stringent limits need to be in place in the future. If faster control is envisioned for SF_B compared to that of SF_A, then reserves must be sized accordingly. iv) Availability of reserves: Determination of the appropriate size of reserves available and used in primary control should consider the intermittency of generating units and the presence of ESSs. Availability of primary control reserves must be ensured always. This can be difficult to ensure using the presently available technologies. From the technical point of view, it is challenging to maintain unused energy for both the wind and photovoltaic power plants as 1-2% power reserve ready for the primary frequency control. This is because of the intermittency of the energy resource, which cannot guarantee reserve availability, especially for the upward regulation. v) Reliability: Primary control is expected to work without the need for automatic load-shedding or disconnection of generation in response to a frequency deviation. vi) Accuracy and measurement cycle of frequency measurements: The accuracy and granularity of frequency measurements must be high enough to capture the fast dynamics of the power system. The present accuracy requirement (e.g. 10 mHz for Central Europe [12]) and measurement cycles (typically 0.1 seconds to 1 second for Central Europe [12]) from network codes must be reviewed to check if they are appropriate for the future systems with faster dynamics. vii) Manner: The controllers may perform the primary control in a decentralized manner (i.e. individually based on local measurements and without the use of communications). The controllers may also perform the primary control in a coordinated manner (with communications with other controllers). viii) Controller sensitivity: Controllers must be sensitive enough to handle the faster changes in frequency. The present sensitivity requirements from network codes (e.g. 10 mHz for Central Europe) must be reviewed if they are still appropriate for future power systems ix) Time to deploy reserves: In cases where RoCoF control is not able to limit the RoCoF up to a certain value, then primary reserves will be deployed sooner following a disturbance. The	

	maximum deployment time required by network codes (e.g. 30s for Central Europe [12]) needs to be reviewed. Due to the anticipated faster response in SF_B, the maximum deployment times of primary reserves in SF_B will be shorter compared to that in SF_A. x) Responsibilities in the process: Both TSOs and DSOs may play an active role to ensure that generating units can perform primary control. This role is currently done by the TSO. However, the proliferation of RES in the distribution level may require the DSO to ensure that this requirement is met in the future. xi) Information exchange between TSOs/DSOs: Contribution of each connecting TSO, or DSO, must be reviewed to account the intermittency of generation and the presence of ESSs. Changes here will determine the information exchanges required among TSOs and DSOs in the future.	
Secondary Control (centralized)	i) Objective: Restore the frequency back to the nominal value. Also, restore the power exchanges among the transmission grids back to their desired values. ii) Secondary controller: A single automatic secondary controller must perform the secondary control for a control area. The definition of control area and its Area Control Error must be updated for possible cases where DSOs have their own secondary control.iii) Secondary controller characteristics: Measurement cycle times, integration cycle times, and controller cycle times must be coordinated within the control loop. The required control cycle time must be reviewed to check their appropriateness to the expected frequency dynamics. iv) Manual control capability: Like today's requirement, manual control of reserves must be allowed in case of deficiencies in the automatic secondary control v) Secondary control reserve: Secondary control reserves must be available to cover the expected fluctuations in demand and generation. Reliability criteria, intermittency of solar and wind, and the presence of ESSs must be considered when determining reserve requirements. vi) Availability and Reliability of the Control Function: Like today's requirement, the operation of the automatic secondary controller should be on-line and closed-loop. The controller must have a very high availability and reliability, with a back-system ready to take over the control action in case of outage or fault in the automation system providing secondary control [12]. Reliability of measurement transmission to the secondary	No changes

	controller must also be reliable (e.g. using parallel data links). vii) Metering and Measurement Transmission to other TSOs/DSOs: Usage and provisions for alternative measurement from neighboring control areas for comparisons and eventual backup must be in place. Required interactions among DSOs and TSOs to ensure an effective secondary control must be in place. viii) Data Recordings: Recordings of all values required for the control action of the secondary controller and for analysis of normal operation and incidents in the interconnected power systems. These values include frequency measurements, active power flows, and exchange set-point value.	

2.2 The Sf_A scenario

The Sf_A scenario assumes a power system with a mix of conventional synchronous generation (e.g., coal, hydro and nuclear), and non-synchronous generation (e.g., wind and solar). Additionally, for the purpose of power balancing and frequency stabilization, energy storage systems (ESSs) are considered.

The control concepts in Sf_A are developed for power systems with reduced mechanical inertia. This means that the control concepts are applicable to systems with high (up to 100%) penetration of RES.

2.2.1 Control Concepts in Summary

In the Sf_A scenario, it is assumed that certain mechanical inertia is available due to the presence of synchronous power plants. Simulations conducted and shown in D2.1 and D2.2 have revealed that the hydraulic units cannot totally replace the steam and gas turbines because of their lower inertia constant and because they are close to being fully exploited. For this reason, ESSs are extensively employed at all control levels.

The main concepts to be studied regarding Sf_A are the following:

Fast frequency response (FFR), RoCoF (a.k.a. inertial) and primary frequency control (PFC) provided by the Distribution System (DS)
RoCoF/inertial, FFR and PFC provided by ESSs
Definition of Frequency Makers and Frequency Takers
Including Virtual Power Plants in the Secondary Frequency Control
Frequency control of grid-connected microgrids

2.2.2 Validation Procedure

To validate the control concepts in Sf_A, the control concepts were simulated first using the simple Western System Coordinating Council (WSCC) 9-bus test system [1]. Then, the control concepts were simulated on a software model of the Romanian Grid and Irish Grid. Offline and real-time simulations are done for both test-systems (i.e. WSCC 9-bus system and the Romanian grid model). The offline simulations were done under WP2. The real-time simulations were done under WP5. In addition, the real-time simulations used a 5G-flight rack to investigate the communication requirements of Sf_A.

During the second year of the project, the main concepts that were studied regarding Sf_A are the following:

- **RoCoF/inertial and primary frequency control (PFC) provided by the Distribution System (DS)**

The increasing penetration of converter-based Distributed Energy Resources (DERs) in distribution systems will require the redefinition of the role of the Distribution System Operators (DSOs) in future frequency control procedures. To this aim, it is necessary first to study and quantify the capability of such DERs to provide RoCoF and primary frequency control. A distribution system with a variety of DERs capable of providing inertial control and PFC was first connected to the 9-bus system in the real-time simulator (RTS). The main studied aspects are:

i. the signals used as input to the frequency controllers;
ii. the level of coordination for the best performance (i.e., centralized, decentralized, distributed);
iii. impact of associated delays and noises in the signals;

The initial study of the inertial control and PFC provided by the distribution system was done from March 2018 until May 2018. After the initial study, this scenario was further studied considering also the Romanian Power System database.

- **RoCoF/inertial and primary frequency control provided by ESSs**

  ESSs have the potential to provide a large variety of ancillary services to the power system thanks to their capability to supply/absorb active and reactive powers very fast. While the capability of ESSs to provide primary control has been extensively studied in the literature (this is partially shown in D2.1), the concept of ESSs and RoCoF control at both transmission and distribution system levels needs a more in-depth study. This will help in defining the set of requirements for the connection of ESSs in future transmission and distribution systems. To this aim, a variety of ESS technologies, capacities, locations, and so on, were considered. Such studies were based on the All-island Irish Transmission Grid (AIITS) implemented in the software tool DOME, upon completion of the implementation and testing of such a grid. This task was completed between January-June 2018.

- **Definition of Frequency Makers and Frequency Takers**

  Currently, it is indirectly assumed that “frequency makers” are the synchronous machines installed in the system, whereas any other power system device is “frequency taker”. This classification is correct in the context of current power systems. However, the distinction of frequency “makers” and “takers” is not straightforward in systems with very large or full penetration of non-synchronous generation. This is crucial to properly define the set of required measurements and signals needed for a proper estimation of the system state and operation. This is because in power systems with 100% renewables, the generation units are no longer naturally synchronized, and thus adequate coordination is required. This concept will be initially studied and tested on the 9-bus system in DOME between January-June 2018, followed by a further study and validation considering the AIITS in later stages of the project.

- **Including Virtual Power Plants in the Secondary Frequency Control**

  The Secondary Frequency Control (SFC) is traditionally provided by large power plants, which meet certain flexibility criteria. The RES generation consists mainly in small entities distributed on wide geographical areas. While the large power plants are decommissioned, new solutions must be found to control the RES entities. In RESERVE, we will use the virtual power plant concept as a way of ensuring the required power reserve and providing frequency control in the SFC level. Simulations were performed on the Romanian power system database. This task will be developed between January and September 2018.

- **Frequency control of grid-connected microgrids**

  The concept of microgrid (MG) has received particular attention from the scientific community as it is generally considered the building block of the smart grid [19]. The MG is defined by the U.S. Department of Energy as: “A MG is a group of interconnected loads and DERs with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode". While there has been a considerable amount of research carried out on the control of single, often islanded, MGs and on the investigation of the penetration level of DERs, the research on the interaction between MGs, the market and its effect on the grid is limited. The ability of a MG to conduct policies of Demand & Response and its effect on the frequency control of the transmission system has not been taken into consideration so far. In the study carried out in RESERVE, the electricity market model is merged together with a hybrid dynamic and event-driven MG representation as well as a detailed electromechanical model of the system. The goal is to provide a dynamic model to study the coupling between the dynamics of the MGs, the power system and the energy market, with an emphasis on frequency regulation.

The Romanian Power System database, available in CIM and EUROSTAG format, considered in the simulation consists of:

load flow data, including the network topology and parameters
dynamic models of the hydro power plants, wind power plant, and PV power plant
information specific to the AGC system

Table 2-2 summarises all the offline and real-time simulations for Sf_A.

Table 2-2. Tests done for validating the concepts in Sf_A

Title (Timeline)	**Type**	**Objective**	**Deliverable containing the details**
Frequency Makers vs. Takers **(Month 24-36)**	Offline simulations considering the AIITS in DOME	Validate the definition proposed for frequency makers and takers	D2.7
Frequency Control of DERs in Distribution Networks **(Month 12-36)**	Offline and RT simulations considering the modified WSCC 9-bus system with the model of an Irish distribution grid in DOME and SIMULINK	Study the contribution of a number of different DERs installed at the distribution system level on the frequency response at the transmission system level	D2.4, D2.5, D2.6 and D.27
RoCoF, FFR and PFC of Converter-Interfaced ESSs in transmission Grids **(Month 1-30)**	Offline simulations considering the AIITS in DOME	Study the contribution of a number of different technologies of converter-interfaced ESSs on the frequency response at the transmission system level	D2.1, D2.2, D2.6 and D2.7
Primary and secondary frequency control in Eurostag **(Month 24-36)**	Offline simulations in Eurostag	Testing the performances of BESS control, VPP control, AGC control on Romanian power system database	D2.7

Primary and secondary frequency control in Simulink **(Month 24-36)**	Offline simulations in Simulink	Testing the performances of BESS control, VPP control, AGC control on the Dobrogea region	D5.7
Frequency Control of Grid-connected Microgrids **(Month 12-24)**	Offline simulations considering the New England 39-bus system in DOME	Study the coupling between the dynamics of the MGs, the power system and the energy market, with an emphasis on frequency regulation	D2.5, D2.6 and D2.7

In parallel to the tests in Table 2-2, ICT tests have also been done to validate the behavior (e.g. in terms of latency, reliability) of communication components that are required to implement the concepts. The details of these tests can be found in deliverables D5.8 and D5.9.

2.2.3 Overview of Findings and Milestones

Below are an overview of the most important findings and milestones in Sf_A.

- Month 12 to Month 18
    - Various simulations have been conducted on the 9-bus test system in DOME and RTS for RoCoF and primary frequency control;
    - The All-island Irish Transmission Grid database has been implemented in DOME and is almost ready for final verification;
    - The two-level secondary frequency architecture is under development; It will be tested in EUROSTAG and RTS;
    - ESSs are essential for frequency stability, at all levels; the importance of the time reaction as a replacement for the mechanical inertia will be evaluated for power systems of different size, i.e., the 9-bus test system and the Romanian power system.
- Month 18 to Month 24
    - A first version of the Dobrogea area of the Romanian power system (14-bus network) was implemented in Simulink. The file will be used for RTS.
    - The detailed model of a battery system was implemented in Eurostag. The model is under tests to tune the parameters.
- Month 24 to Month 30
    - The secondary frequency control scheme was successfully implemented in a 4-bus system. The simulation results show the expected dynamic response.
    - The dynamic models of one synchronous generator, several wind generation systems, storage systems have been implemented in the Simulink model of the Romanian power system (14-bus network). Tests are being performed to verify the functionality of the complete model.
    - Tests are also performed in Eurostag to adjust the BESS model against non-satisfactory results.
- Month 30 to Month 36
    - A definition of “Frequency Makers” and “Frequency Takers” to identify the key actors that must contribute to the frequency regulation in scenarios with very high penetration of non-synchronous RESs.

- A battery storage system was successfully tested in Eurostag. Simulations have been performed on the Romanian power system database with the battery being involved in both primary and secondary frequency control. Load connection and generator tripping were simulated to study the importance of BESS for frequency stabilization in low-inertia power systems.
- The Dobrogea region of the Romanian power system was implemented in Simulink. A VPP was also created. Several sets of simulations have been performed to prove the importance of storage systems in power balancing. Also, the simulations show the effectiveness of the models implemented.

These findings and milestones are reported in more details in the following deliverables:

- D2.7 „Drafting ancillary service and network code definitions, V2"D5.7 "Report on the 100% renewable Irish Scenario, V2"

2.2.4 Major changes in system-level requirements and test procedure

Below are the major changes in the system-level requirements and test procedures for Sf_A from Month 12 to the present. It doesn't include small refinements in word selection and phrasing.

- Month 12 to Month 17
  - No major changes.
- Month 18 to Month 24
  - Initially, Sf_A is defined to have a 100% RES, in which only hydro plants provide mechanical inertia. However, Sf_A will now also consider the transition to 100% RES. Therefore, the study in Sf_A will also consider the cases where fossil-fired and nuclear power plants are still present, albeit with reduced penetration.
  - Compared to the Romanian Grid, the Irish Grid has fewer interconnections to other grids. Therefore, the Irish Grid is deemed more appropriate for studying RoCoF and primary control in low-inertia systems. Consequently, the study for the RoCoF and primary controls in Sf_A will use the Irish Grid instead of the Romanian Grid.
  - The study in Sf_A now also considers frequency control of grid-connected microgrids containing loads, DER, and ESS. In this regard, the New-England 39-bus system has been used, as the WSCC grid was too small in terms of the number of buses and machines.
- Month 24 to Month 30
  - No major changes.
- Month 30 to Month 36
  - No major changes for RoCoF and fast frequency control concepts.

2.3 The Sf_B scenario

The Sf_B scenario assumes a power system with 100% of the generation provided by RES, limited to only wind and solar plants. Hydro power plants are not present in Sf_B, resulting in very little to no inertia in the grid. Instead, virtual inertia is provided from the storage-connected wind and power plants. Note that in Sf_B, small mechanical inertia might be present. This inertia is injected from the HVAC-connected neighbor network (country), which has mechanical inertia. Similarly to Sf_A, ESSs are also considered in Sf_B.

2.3.1 Control Concept in Summary

In Sf_B, the Linear Swing Dynamics (LSD) will be embedded in the control of DC (HVDC) and RES-tied converters. The objectives of doing so are as follows:

- provide a linear dynamical system, with the capability of providing RoCoF and primary frequency control.
- maintain system synchronization and coherency.
- enhance the system dynamic performance.

In Sf_B, the Synchronous Generator (SG) emulation control is considered, namely the Virtual Synchronous Generator (VSG). In this regard, the LSD concept will be integrated into the VSG control. Although the VSG is not listed as a requirement for Sf_B, however, their applicability will be studied under Sf_B.

The LSD control will be embedded into the VSG aiming to achieve the following features:

- System synchronization and coherency.
- Provisions for virtual inertia.
- Consistent performance in frequency control and regulation.

Hence, the aim of proposed LSD-VSG is to preserve the advantages of SG, e.g. system synchronization and inertia provision, and tackle its disadvantages represented by nonlinear characteristics. In this work, both decentralized (independent) and coordinated control are considered.

The latest descriptions of the LSD concept can be found in deliverable D2.6.

2.3.2 Updated System-Level Requirements

Table 2-1 in Section 2.1 shows the updated definitions of the system level requirements scenario Sf_B. The same requirements are also needed in Scenario Sf_B, which is discussed here in Section 2.3.

As specified in Table 2-1, the RoCoF and the primary control can be either decentralized or coordinated. In transmission systems, given the long distances and the reliability of measurements, decentralized primary control and RoCoF control are deemed more meaningful to inhibit de-synchronization and ensure system stability.

However, in distribution systems where measurements are characterized by higher levels of noise and other inaccuracies due to harmonics and unbalance, etc., coordinated control could give better performance.

Moreover, as for the secondary control requirements, it is the same as in conventional power systems; centralized and involves the transmission level. At this level, the communication only takes place between the control center and the resources. However, in a 100% converter-based system, communication among the new components can be used to enhance the performance of secondary frequency control. This concept of distributed secondary control has already been used for microgrids and its applicability in the future for 100% non-synchronous system is investigated in Sf_B as well. It is worth mentioning though, that the distributed secondary control is not listed as a requirement for Sf_B.

2.3.3 Validation Procedure

The LSD-VSG concept is tested and validated in a Single-Machine Infinite-Bus (SMIB) system, as reported in deliverable D2.6, in addition to an interconnected system consisting of three machines i.e. the WSCC 9-bus system, as reported in deliverable D2.7.

The case studies cover different scenarios, the SMIB system is used to validate:

- The LSD concept for both the transmission and distribution system in a SMIB setup.

The WSCC 9-bus system is used to:

- Validate the decentralized LSD concept in a multi-machine transmission system.

- Investigate the response of a 100% converter-based system to different grid events (i.e. large disturbances represented with load steps or generator disconnection in addition to topology change).
- Validate the applicability of distributed secondary control at the transmission level in a 100% nonsynchronous system.

These study cases represent a starting point for future NCs recommendations.

Table 2-3 summarises all the offline simulations for Sf_B.

Table 2-3. Tests done for validating the concepts in Sf_B

Title (Timeline)	Type	Objective	Deliverable containing the details
Centralized LSD in 4-bus system **(Month 18-24)**	offline simulations	Validate the centralized LSD concept for a multimachine system	D2.6
LSD in distribution networks for SMIB **(Month 18-24)**	offline simulations	Validate the LSD concept for resistive network	D2.6
LSD-VSG based HVDC converters **(Month 18-24)**	offline simulations	Compare the performance LSD-VSG based HVDC converters with the classical VSG based HVDC converters	D2.6
The MA-IFC scheme in grid-tied HVDC converters **(Month 18-24)**	offline simulations	Investigate the performance of the MA-IFC scheme in grid-tied HVDC converters to provide a systematic enhancement in frequency stability.	D2.6
Decentralized LSD in the WSCC 9-bus system **(Month 24-36)**	offline simulations	Validate the decentralized LSD concept for a multimachine system. Investigate the performance of LSD based converters in 100%	D2.7

		nonsynchronous system.	
Distributed Secondary Control **(Month 30-36)**	offline simulations	Validation of the applicability distributed secondary control at the transmission level in a 100% nonsynchronous system.	D2.7

In parallel to the tests in Table 2-3, ICT tests have also been done to validate the behavior (e.g. in terms of latency, reliability) of communication components that are required to implement the concepts. The details of these tests can be found in deliverables D5.8 and D5.9.

2.3.4 Overview of Findings and Milestones

Below are the findings so far from the completed tests for Sf_B:

- Month 12 to Month 18
    - From the theoretical point of view, the currently developed LSD-VSG can achieve LSD characteristics up to infinity, i.e. beyond the maximum power point. However, as observed in the simulation results, the LSD characteristics have been achieved up to a margin very close to the maximum power point. This is due to the standard voltage threshold, which cannot be exceeded in practice. This means that the control needs to ensure LSD characteristics without deteriorating the system voltage profile.
    - The details can be found in D2.3 and Chapter 5 of D2.6.
- Month 18 to Month 24
    - The linearity has been achieved not only for small power range around the actual operating point but over almost the whole power range. However, this does not cope with fault conditions, which are traditionally categorized as large-signal stability issues.
        - The reason is that the converters will operate in a current-limited mode under fault conditions. Hence, the linearity has been achieved for both small and large disturbances (that do not bring the converter into current-limited operating mode).
        - Note that in case of contingencies or specific large disturbances in classical power systems, the synchronous generators can still operate within a margin that goes beyond the SG limits, for a very short time. This is in contrast with future converter-based power systems, in which the converters should operate strictly and only up to their limits.
        - Therefore, it is to be stressed that the limits are not related to LSD performance, but are related to the inherent characteristics and design specifications of power electronics and future converter-based power systems.
    - The LSD concept has been validated at the 4-bus system and is being validated at the 9-bus system. (see D2.6 Chapter 5)
    - The concept of LSD is further developed for the system impedances having resistive and inductive parts, i.e. as applicable in distribution systems and is validated for a SMIB system. (See D2.6 Chapter 5)
- Month 24 to Month 30

- The MA-IFC scheme is developed and implemented in grid-tied HVDC converters to provide a systematic enhancement in frequency stability (particularly in the weak and disturbed ac grids) while maintaining a stable dc voltage profile.
  - The control setting, including frequency droop coefficient (α), should be changed by time based on: instantaneous generation and demand, technical specifications and constraints (e.g. existing inertia and damping) of each ac grid connected to HVDC system. Setting α means deciding the amount of active power participation (injection) by healthy ac grids to provide frequency support to the disturbed ac grid. This should be done in coordination with HVDC owners and respective transmission system operators.
  - The MA-IFC scheme has shown good robustness characteristics and performance under agent failure as well as communication delay.
  - The MA-IFC is scalable for any future network extension, and it is viable for all HVDC-connected ac grids, including weak and island ac grids

- The LSD-VSG is tested and compared with the classical VSG to show that the former has a better performance in terms of enhancing dc voltage stability profile as well as achieving linear power-angle characteristics in the HVDC converters
  - Achieving LSD (power-angle linearization) relies on ac voltage control, by exploiting the permitted ac voltage tolerance ($\pm$ % 5).
  - Control actions are done with local measurements, i.e. there is no need for coordination and communication with other HVDC converter stations.
- The decentralized LSD concept in a multi-machine system is developed and validated in the WSCC 9-bus system.

- Month 30 to Month 36
  - The performance of a 100% LSD-VSG based system under large disturbances represented with load steps in addition to topology change is investigated and compared with that of the classical VSG based system. The LSD-VSG based system has shown better performance in terms of the system frequency metrics as presented in deliverable D2.7.
  - Implementation and validation of the applicability distributed secondary control at the transmission level in a 100% nonsynchronous system.

2.3.5 Major changes in system-level requirements and test procedure

Below are the major changes in the system-level requirements and test procedures for Sf_B from Month 12 to the present. It doesn't include small refinements in word selection and phrasing.

- Month 12 to Month 18
  - No major changes
- Month 18 to Month 24
  - No major changes
- Month 24 to Month 30
  - The developed LSD-based control schemes (for both RES and HVDC) require only local information, and hence, there is no need for communication, except for the adaptive frequency control (MA-IFC) in HVDC systems, which uses communications to coordinate among other controllers via fiber optic cables.
  - The LSD concept is being tested in a multi-machine system. In this regard, only the 9-bus system is considered for concept validation, as the results and findings are the same for the larger (Romanian) 14-bus system.

  - Studies on hybrid ac/dc network are conducted via two case studies in which LSD-VSG and MA-IFC schemes are developed for HVDC systems (grid-tied HVDC converters) to participate in system frequency stabilization. These two studies substitute the case of two 9-bus systems coupled via HVDC link, as more valuable and coherent findings are obtained with the former two case studies.
  - The possibility of leveraging the communication between the converters and the applicability of distributed secondary control at the transmission level in a 100% non-synchronous system is investigated.
  - Due to the long geographical distances between the converters at the transmission level, fiber optic communication is deemed more appropriate. Hence, real-time simulations involving the 5G flight rack are not included in Sf_B.
- Month 30 to 36
  - No major changes

3. Voltage control concepts

3.1 Sv_A

3.1.1 Control Concept in Summary

Dynamic voltage instability may arise due to the high number of power converters in future distributions systems. The objective of the control concept in Sv_A is to maintain the dynamic voltage stability. It uses the concept of Wideband System Identification (WSI) to determine the present voltage stability margins of the system. Based on the measured grid impedance, the control concept in Sv_A embeds the Virtual Output Impedance (VOI) control in the inner control loops of the inverter to modify the inverters output impedance to maintain stability.

3.1.2 Updated System-Level Requirements

Figure 3-1 shows the schematic diagram of the system level and functional requirements to perform DVSM control in Sv_A. The updated definitions of the system-level requirements for Sv_A are shown in Table 3-1. Moreover, Table 3-1 shows the final definitions of these requirements for frequency control. The definitions in Table 3-1 were updated from their earlier versions in deliverables D1.2 and D1.5 based on the validation procedure followed in the project. The validation procedure for studying the voltage control concepts in Sv_A are discussed in Section 3.1.3 of this report.

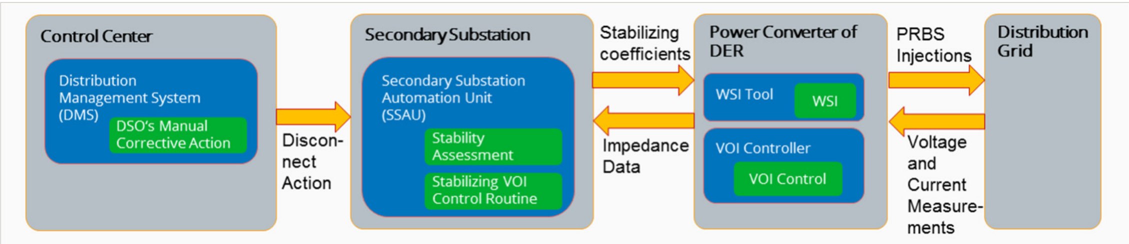

Figure 3-1. Overview of the system level and functional requirements of Dynamic Voltage Stability Monitoring in Sv_A

Table 3-1. Changes in the definitions of component and functional requirements for voltage control in Sv_A

Requirement	Updated Definition	Changes with respect to the definitions in D1.2
Component Requirements		
Power Converters	The power converters should be able to incorporate a WSI Tool and a VOI controller. Both can stay on the enclosure with the local controller. WSI tools will house the WSI function, while the VOI controller will house the VOI control function.	No changes
SSAU	The SSAU stays at the secondary substation and houses different control and automation functions for the DSO. For SV_A, it will both house the Stability Assessment and Stabilizing VOI Control Routine. It may also house the WSI tool.	Minor changes in wording (M24)

Distribution Management System	This system supports the decision making of personnel in the field and control room of the DSOs. It will be used to disconnect converters when stability cannot be guaranteed.	Minor changes in wording (M30)
Functional Requirements		
WSI	The WSI can be either implemented locally in the inverter or it can be moved to the SSAU. If WSI is located in the inverter, then the computation power of the inverter hardware needs to be high. However since the impedance data is compressed into coefficients, the data size is small. If WSI is located in SSAU, then the data size to be sent from the inverter is high.	Monitoring cycle is reduced to 2-5 minutes since the number of households per SSAU is reduced from 10000 to 400 to 500 households. Changes in the number of households were clarified by ESB in the meeting in Brussels (M30) Minor changes in wording (M30)
Compliance with Proposed Network Code	The WSI process needed for impedance measurements will affect the harmonic distortion in the power system and voltage flicker. Therefore, the process must comply with the network codes on power quality. An example standard related to this is Distribution Code from ESB	A minor change in the name of the requirement (M30) Minor changes in wording (M30)
VOI Control	Upon receiving instructions from the SSAU, VOI controllers must be able to adjust the output impedance of the power converters to maintain the desired stability margins of the power system. Receives stabilizing VOI coefficients from the SSAU.	Minor changes in wording (M30)
Stability Assessment	The SSAU must receive the impedance information from the WSI tools as soon as possible. The SSAU is responsible for the stability assessment of the power system based on the impedances.	A minor change in the name of the requirement (M30) Minor changes in wording (M24, M30)
Provision for Stability Margins	Future network codes must contain provisions about the required stability margins (gain and phase) in the power system.	No changes

Stabilizing VOI Control Routine	This is a function done by the SSAU to calculate the desired output impedance of a converter to maintain the stability. It uses the measured grid impedance to determine the appropriate VOI control coefficients.	A minor change in the name of the requirement (M24) Minor changes in wording (M24, M30)
DSO's Manual Corrective Action	This is not done by the automation system, but it plays a role in maintaining dynamic stability. In cases where the stability assessment from the SSAU shows an unstable situation, then the DSO must perform corrective action through the DMS	Minor changes in wording (M24, M30)

3.1.3 Validation Procedure

3.1.3.1 Objectives of Simulation and Field Trials

For Sv_A, the major objectives of the simulations and field trials are as follows:

- Validating the control concept,
- Investigating the implications of these concepts to the network codes that are listed in D5.2.

The validation of the control concept in Sv_A involves the following steps:

- Verification of the WSI concept, i.e. to see if the grid impedances are identified correctly
- Implementing the VOI algorithm and observing simulation in real time
- Implementing the dynamic stability monitoring algorithm

These steps involve offline simulations under WP3, as well as real-time simulations and field trials under WP5. Furthermore, similar to cases of Sf_A and Sf_B, the real-time simulations for Sv_A will use a 5G flight rack to test the Sv_A's communication requirements.

Two (2) laboratory real-time simulation related experiments were done leading to the field trial. The procedure is briefly summarized as follows:

1. The first setup tests the performance of the WSI concept in a real-time environment. This setup uses a Hardware-in-the-Loop (HiL) Simulation with LabVIEW and OPAL-RT.
2. The second step tests the control concept developed using a new converter which is envisioned as a low cost and mobile impedance measurement device. The built converter will be used to measure the impedance of a passive load and then measure the impedance of the grid.
3. The converter is the same converter planned for the field trial.

Table 3-2 summarises all the offline and real-time simulations for Sv_A.

Table 3-2. Tests for validating the concepts in Sv_A

Title	Type	Objective	Deliverable containing the details
Hardware-in-the-Loop (HiL) Simulation with	Real-time simulation	Test the performance of the WSI concept on a real-time simulation	D3.4
Trial with the new converter in RWTH, Aachen Lab	Lab Trial with Inverter hardware	Implement and test the complete voltage/current control concept using an actual converter. Perform WSI noise injection to extract a load/grid impedance.	D3.9 and D5.3
Irish Trials	Field trial	To show that the impedance can be determined with a real grid and to determine the magnitude of PRBS noise required to accurately determine the grid impedance. To demonstrate an ancillary service that inverters can provide for DSOs – Inverters can relay impedance information to DSOs so that the DSOs can monitor and ensure stable operation of inverters.	D3.9 and D5.3

The details about the objectives, components, schematic diagrams, and planned timelines for each of the setups are given in the following sections.

3.1.3.2 Lab-Setup 1: Hardware-in-the-Loop (HiL) Simulation with LabVIEW and OPAL-RT

Objective: Test the performance of the WSI concept on a real-time simulation

Description: This setup uses the schematic diagram in Figure 3-2. The PRBS generator, voltage/current data acquisition, and impedance calculation routines are implemented in LabVIEW. The RT-Lab environment of OPAL-RT system provides the link to MATLAB Simulink. This allows detailed switched models of power converters[1] and grid-connected converters built in MATLAB Simulink to be transferred to the RT-LAB environment, where the complex system can be simulated in a real-time manner with the feasibility of real-time multiple inputs and outputs. This allows the distribution grid model with converters and active rectifiers from MATLAB Simulink to be loaded into RT-LAB for real-time simulations. The input to this simulation from the external world is the PRBS signal and the output is the voltage and current values.

Main Finding: The WSI concept was validated and the inverter was able to measure grid impedance accurately under the presence of both passive loads and active loads.

Reference to Deliverable: The results are included in D3.4.

[1] In other deliverables of RESERVE, the term “inverter” may be used in place of “power converter”. Please note that inverter is one type of power converter. In D1.2 and this deliverable, the term power converter is used to cover the different types of power converters that may be present in future power systems (e.g. rectifiers, inverters, DC-DC converters)

Objectives:

- Test the performance of the WSI concept in a real-time simulation

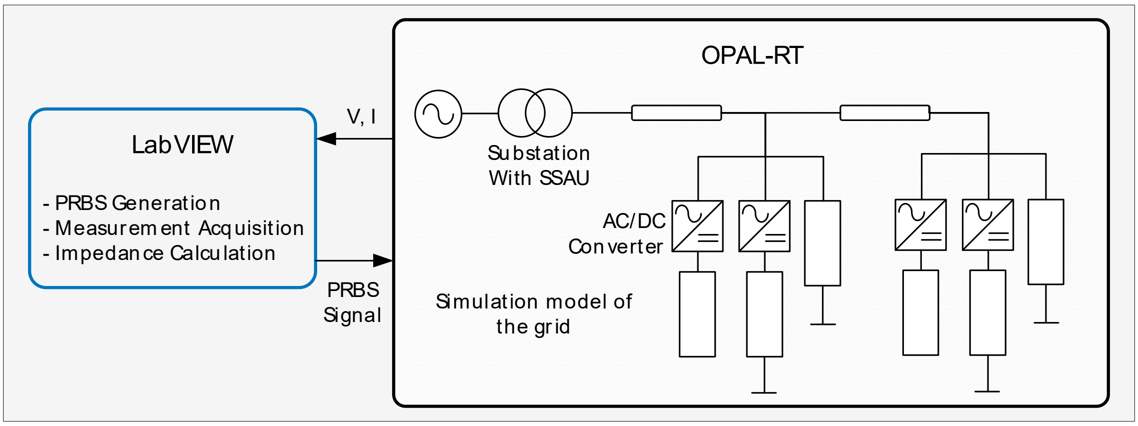

Figure 3-2. Schematic Diagram of HiL Simulation with LabVIEW and OPAL-RT for Sv_A

3.1.3.3 Lab-Setup 2: Trial with the new converter in RWTH, Aachen Lab

Objective: Implement and test the complete voltage/current control concept using an actual converter. Perform WSI noise injection to extract a load/grid impedance.

Description: The field trials will use the schematic diagram in Figure 3-3. The inverter synchronizes to the trial grid following which the WSI tool present in the controller of the inverter injects PRBS noise for a short time. In parallel, the output voltage and current at the inverter's terminal are recorded. Post processing is done to calculate the grid impedance.

Main Finding: The converter works as expected and was able to accurately measure the impedance of a passive load.

Reference to Deliverable: The results will be included in D3.9 and D5.3.

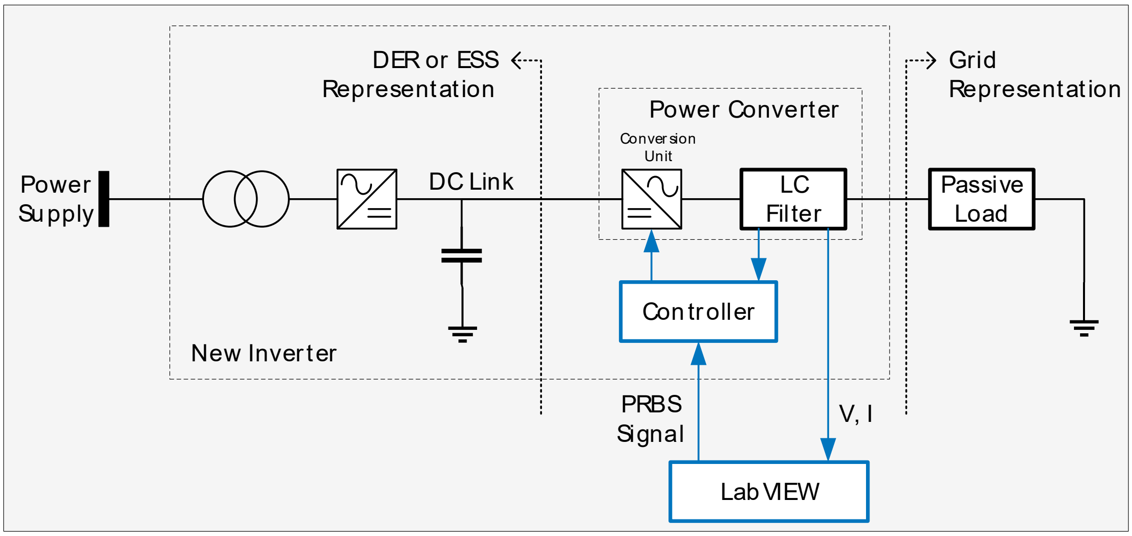

Figure 3-3. Schematic Diagram of Aachen Lab trial for Sv_A

3.1.3.4 Irish Trials

After the laboratory trials, the power converter capable of performing WSI and VOI Control functions is brought to the field. They will be installed in the ESB trial grid, where its performance in the field will be validated and assessed. The trial grid is a part of the Irish low-voltage distribution network managed by ESB.

Objective: To show that the impedance can be determined with a real grid and to determine the magnitude of PRBS noise required to accurately determine the grid impedance. To demonstrate an ancillary service that inverters can provide for DSOs – Inverters can relay impedance information to DSOs so that the DSOs can monitor and ensure stable operation of inverters.

Description: The inverter synchronizes to the trial grid following which the WSI tool present in the controller of the inverter injects PRBS noise for a short time. In parallel, the output voltage and current at the inverter's terminal are recorded. Post processing is done to calculate the grid impedance.

Reference to Deliverable: The results will be included in D3.9 and D5.3.

Remark: In parallel to the tests in Table 3-2 which are described in this section, ICT tests have also been done to validate the behavior (e.g. in terms of latency, reliability) of communication components that are required to implement the concepts. The details of these tests can be found in deliverables D5.8 and D5.9.

3.1.4 Overview of Findings and Milestones

Below are the findings so far from the completed tests in Sv_A:

- Month 12 to Month 17
  - The impedance identification works, i.e., WSI tool is verified and developed
  - Currently the VOI controller is under development.
  - WSI and VOI algorithms are developed but will be tested in the coming months (Before March)
- Month 18 to Month 24
  - The WSI concept was verified on a stand-in laboratory converter.
  - The amount of PRBS required to determine the grid impedance was determined.
- Month 24 to Month 30
  - VOI design was completed and validated via real-time simulation
  - Low power inverter hardware was designed and commissioned. The proposed concept can be integrated into existing inverters or can be used as an impedance measurement device
- Month 30 to Month 36
  - The highly programmable low power inverter prototype is envisioned as a mobile and non-invasive wideband grid impedance measurement device
    - low cost and weight
    - plug-play capable
    - wideband measurement
  - The device is capable of measuring upto 25 kHz when used with a sampling frequency of 50 kHz and measure highly accurately until 10 kHz.
  - Frequency resolution of the device is around 24 Hz
  - Time required to D-axis impedance is 40.9 ms and the time required to measure Q-axis impedance is also 40.9 ms. A time gap of 20 ms between the D and Q axis

impedance measurement is allowed so that the transients arising from D-axis perturbations can settle down. Thus, the device can complete the grid impedance measurement process in 100.8 ms, which is roughly 5 cycles of the fundamental period.

3.1.5 Major changes in system-level requirements and test procedure

Below are the major changes in the system-level requirements and test procedures for Sv_A from Month 12 to the present. It does not include small refinements in word selection and phrasing.

- Month 12 to Month 17
    - The control sequence is updated to reflect the developments in the theoretical formulation of the impedance monitoring.
- Month 18 to Month 24
    - The planned monitoring cycle for the field trial is reduced from 1 hour to 5 minutes. The change was due to the reduction of the number of households that are planned to be monitored from 10,000 to 400 or 500 households.
- Month 24 to Month 30
    - Proposed two implementation ideas for the placement of WSI tool. The WSI tool can be placed within the inverter or it can be placed at the SSAU.
    - ICT requirements for the case with WSI tool placed within the SSAU was derived
- Month 30 to Month 36
    - No major changes

3.2 Sv_B

3.2.1 Control Concept in Summary

3.2.1.1 Objective of the control concept

The concept used in Sv_B is called Active Voltage Management (AVM). The objectives of AVM are as follows:

- Maintain the RMS values of distribution voltages within their allowable limits despite the penetration of DERs and ESSs in future distribution systems.
- Minimize the power losses and voltage unbalance in the system.

In order to achieve these objectives, AVM will use the numerous power converters expected in future grids. With AVM, the system will be able to accommodate an RES connection on the most electrically distant point on LV feeders while also facilitating connections on MV that exhibit altogether closer electrical proximity.

3.2.1.2 Updated Control Sequence

In Section 4.1.3 of D1.2, the steps for implementing the control sequence in Sv_A were discussed. Since the submission of D1.2, there are no updates on these steps. However, we provide below the summary of these steps in the numbered list. This list is not present in D1.2.

Steps for implementing AVM:

1. The *SSAU* selects a power converter in the system.
2. The *SSAU* performs *Optimized Curve Selection* for the power converter.
3. The *SSAU* performs *Curve Implementation* for the power converter.

4. Steps 1 to 3 are repeated for all power converter in the system.

Optimized Curve Selection and Curve Implementation are both functional requirements in Sv_B. Both requirements are defined in Section 4.2.2 of D1.2. Moreover, the next section contains the updates for both requirements, along with the updates for the other requirements in Sv_B.

3.2.2 Updated System-Level Requirements

Figure 3-4 shows the schematic diagram of the system level and functional requirements to perform AVM control in Sv_B. The updated definitions of the system-level requirements for Sv_B are shown in Table 3-3. Moreover, Table 3-3 shows the final definitions of these requirements for AVM. The definitions in Table 3-3 were updated from their earlier versions in deliverables D1.2 and D1.5 based on the validation procedure followed in the project. The validation procedure for studying the voltage control concepts in Sv_B are discussed in Section 3.2.3of this report.

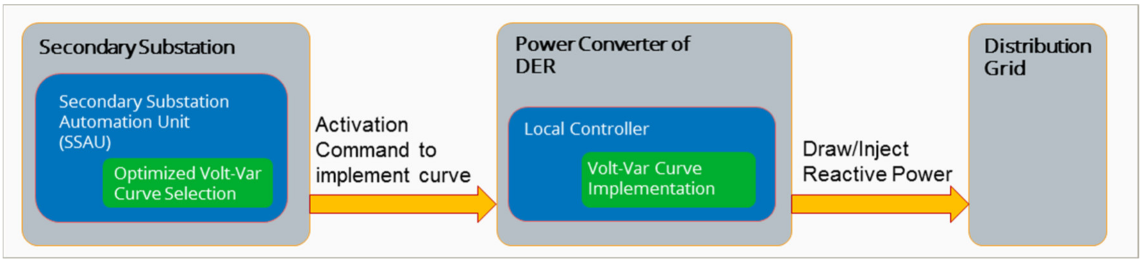

Figure 3-4. Overview of the system level and functional requirements for Active Voltage Management in Sv_B

Table 3-3 shows the updates in the component and functional requirements in Sv_B since the submission of D1.2.

Table 3-3. Changes in the definitions of component and functional requirements for voltage control in Sv_B

Requirement	Updated Definitions	Changes with respect to the definitions in D1.2
Component Requirements		
Power Converters	The power converters provide the interface between the grid and DER and other flexible resources. The power converters will provide AC to DC, DC to DC, or DC to AC conversion.	Minor changes in wording (M24)
Local Meters	These meters measure the RMS value of the voltage and current at the connection point of the converter and the distribution system. These meters also provide the real and reactive power consumption or generation flowing through the converter.	No changes
Local controllers	These are the same controllers used in Sv_A, but without the need for WSI Tools or VOI controllers.	No changes
SSAU	The SSAU stays at the secondary substation and house different control and automation functions for the DSO.	No changes

Functional Requirements		
Optimized Curve Selection	For each converter, the SSAU will select an appropriate Volt-var curve to use. The selection will be based on the objective set by the DSO, which can be to minimize losses or cost.	The optimization objective was updated from *minimizing losses or cost* to *minimizing losses or voltage unbalance (M18)*. Minor changes in wording (M24)
Coordination with the present voltage control devices	During the transition from the present scenario to the converter-based feeder in Sv_B, the control actions of converters, OLTC, shunt devices are incorporated into the offline modeling phase of Sv_B, for more information refer to D 3.2. This coordination ensures they will not reduce the effectiveness of each other and voltage hunting problems are mitigated.	It is clarified that the present control devices will be incorporated in the offline-modeling phase of Sv_B.
Reactive power injection or consumption of RES or ESSs	Future network codes must contain provisions on the required reactive power generation or consumption of converter-based RES or ESSs. This means that the power factor of RES should be allowed to be leading or lagging. In the section DCC6.9.1 of ESB Networks Distribution code, customers can operate from 0.9 to 1 when drawing power, and between 0.95 to 1 when injecting power. The same section specifies that wind generators must have a power factor between 0.92 and 0.95 lagging. These present requirements assume that the loads and their RES or ESSs only consume reactive power. However, RES or ESSs should be able to provide reactive power in the future to provide voltage control. This means that present limitations must be relaxed to allow RES, ESSs, and converter interfaced loads to operate at a leading power factor.	Minor modifications in wording (M18),
Optimized Volt-Var curves	The DSO must derive and provide optimized Volt-var curves for each participating power converter. These curves will not only ensure that voltages in the power system are within acceptable values, but it could also improve the power system efficiency by optimizing power losses, improve the voltage unbalance among the different phases of the AC system, and minimize operation cost. Different Volt-var curves will be required for different optimization objectives. The optimization must	Minor modifications in wording (M18, M24).

	not lead to violation of thermal constraints of lines and transformers in the power system	
Curve Implementation	Each power converter receives its own curve. Each local controller follows this curve for regulating the voltage and reactive power injection or consumption of the converter.	No changes

3.2.3 Validation Procedure

The concept of AVM will be validated through the offline simulations in WP3, and real-time simulations and field trials in WP5. The validation procedure follows the following steps:

1. Perform *Optimized Curve Selection* on a simulated network.
2. Perform the whole concept of AVM on a simulated network.
3. Simulate in a real-time environment (OPAL-RT) the performance of AVM for each planned field trial.
4. Perform field trials.

Four separate field trials are planned on the Irish LV distribution system using converter-based RES:

1. Battery storage
2. Vehicle-to-grid charger
3. Photovoltaics and
4. Air-sourced heat pumps.

In WP3, the simulations for each field trial are to be undertaken in the second half of the project. The objective is to determine, from the offline studies, the selection of volt-var curves native to each RES field-trial network. Further simulations will be reported and in WP3 to inform the efficacy of the volt-var technique.

Validation of these simulations by way of the field trial results will be reported in WP5. In addition, the actual distribution networks for each field trial are discussed in detail in Section 2.2 of Deliverable D5.1.

In addition to the simulations and field trials, the concept of AVM will also be demonstrated live during the project review meeting. This demonstration will use the VILLAS Node connection at TSSG Waterford Ireland and the real-time simulator in RWTH Aachen Germany. In this demonstration, live measurements from a vehicle-to-grid charger will be communicated to a network simulated in real-time to showcase the volt-var control of AVM in Sv_B. More details about the VILLAS platform can be found in deliverable D4.1.

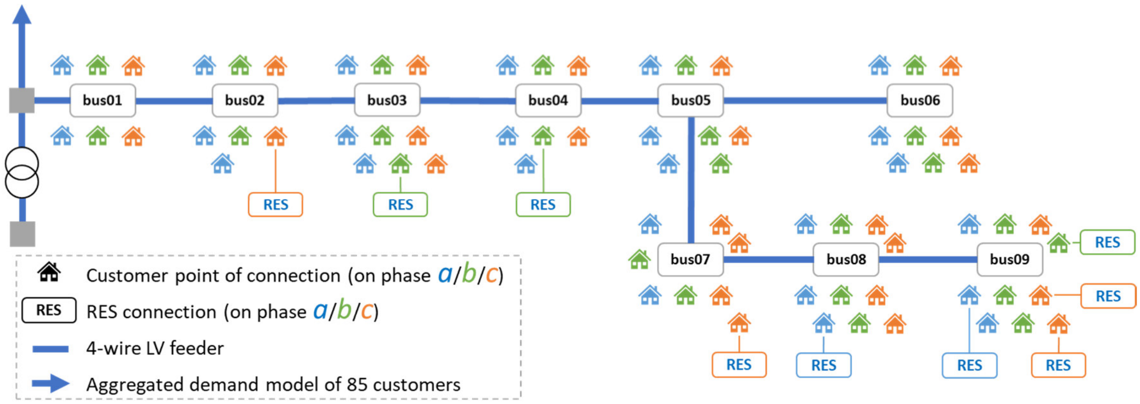

Figure 3-5. The chosen network to showcase the AVM technique, and determine the volt-var curves for a series of RES, is a radial LV feeder with 85 nodes

Table 3-4 summarises all the offline and real-time simulations for Sv_B.

Table 3-4. Tests done for validating the concepts in Sv_B

Title (Timeline)	Type	Objective
Testing the AVM concept for solar PV in Portlaoise	Offline simulation and field trial	Test performance to minimize voltage unbalance and/or energy losses. AVM
Testing AVM concept for battery in Ballyvolane Fire Station	Offline simulation and field trial	Test performance to minimize voltage unbalance and/or energy losses.
Testing AVM concept for V2G charger in Leopardstown	Offline simulation and field trial	Test performance to minimize energy losses.
Testing AVM concept for battery in Nenagh Library	Offline simulation and field trial	Test performance to minimize voltage unbalance and/or energy losses.
Testing the AVM concept for battery in Newtown	Offline simulation and field trial	Test performance to minimize voltage unbalance.

Testing the AVM concept for battery in Kilumney	Offline simulation and field trial	Test performance to minimize energy losses.

In parallel to the tests in Table 3-4, ICT tests have also been done to validate the behavior (e.g. in terms of latency, reliability) of communication components that are required to implement the concepts. The details of these tests can be found in deliverables D5.8 and D5.9.

3.2.4 Overview of Findings and Milestones

Below are the findings so far from the completed tests in Sv_B:

- Month 12 to Month 18
  - The "Optimized Curve Selection" is complete on a simulated network (see Figure 3-5) with notional RES connection, as reported in D3.2. Expanding this technique to a real network with actual RES characteristics is the subject of the simulations in WP3 and the real-time simulations and field trials in WP5.
- Month 18 to Month 24
  - Offline simulations for each field trial were already done. In the simulations, the selection of Volt-var curves native to each RES field-trial network was accomplished. The details of these field trials are available in D5.2.
  - The AVM concept has been validated on one field trial site for battery storage systems is already complete.
  - The AVM concept is being validated on other field trials sites for vehicle-to-grid charger, solar photovoltaics, and another battery storage system.
  - The field trial site for Air-sourced heat pumps is under preparation.
- Month 24 to Month 30
  - Offline simulations for two additional field trials were already done. In the simulations, the selection of Volt-var curves native to each RES field-trial network was accomplished. The details of these field trials will be available in D5.3.
  - Some technical improvements on online implementation of AVM in one of the field trials (battery storage systems) have been completed.
  - The AVM concept is being validated on a field trial site for a battery storage system in a heavily loaded LV case study
  - Another battery storage system is being investigated in which some other RES technologies are present (with their own control strategies)
- Month 30 to Month 36
  - Tweaking the Volt-var curves for each RES field-trial network based on the online measurements in collaboration with TSSG and ESB.
  - Defining the performance index to measure the technical and economic capability of the AVM algorithm.
  - Validation of the simulation results (based on the data supplied by ESB) and actual measured data (provided by ITC infrastructure designed by TSSG).
  - The updated details of the Irish field trials for SV_B are available in D5.3.
  - Developing the second version of network codes and ancillary services related to SV_B. The details and recommendations are available in D3.9.

3.2.5 Major changes in system-level requirements and test procedure

Below are the major changes in the system-level requirements and test procedures for Sv_B from Month 12 to the present. It does not include small refinements in word selection and phrasing.

- Month 12 to Month 17
    - Definition of “Optimized Curve Selection”: The optimization objective was updated from *minimizing losses or cost* to *minimizing losses or voltage unbalance*.
    - Definition of “Coordination with the present voltage control devices”: It is clarified that the present control devices will be incorporated in the offline-modeling phase of Sv_B. This coordination ensures they will not reduce the effectiveness of each other and voltage hunting problems are mitigated
- Month 18 to Month 24
    - No major changes.
- Month 24 to Month 30
    - Incorporation of the current operating condition of RES in the implementation of AVM strategy
    - Considering the technical limitations of RES technologies in finding the optimal AVM strategy while the DNO’s requirements at the system level are taken into account.
- Month 30 to Month 36
    - No major changes

4. Conclusions

This deliverable contains the updated system-level requirements of the frequency and voltage control concepts studied in RESERVE. It also documents the changes the happened since these requirements were initially defined in D1.2 in M12 of the project. These updates are the result of using a simulation or field environment to validate the control concepts.

The validation procedures followed in the project are also discussed in this deliverable. However, this deliverable only gives an overview of the related tests done in from WP2, WP3, and WP5. Nevertheless, it cites the respective deliverable which contains the technical details of each test. Furthermore, the planned validation procedures reported in D1.2 were also updated during the course of the project. These updates are also reported in this deliverable.

For the different frequency control concepts in Sf_A, the validation procedures include the use of the All-island Irish Transmission Grid (AIITS), New England 39-bus system, and the Romanian power system database. For Sf_B, the procedures include the use of the WSCC 9-bus system to validate the concept of LSD.

For Sv_A, the WSI concept and VOI algorithm were validated through real-time simulations and laboratory trials using a low-power converter that was built and developed in the project. For Sv_B, the AVM concept was validated using simulations and field trials in the Irish low-voltage network with different technologies and different optimization objectives.

The validation procedures followed in the project did not only validate the functionality of the studied concepts for frequency and voltage control. As shown in this deliverable, it also refined the definitions of the system-level requirements of these concepts. Furthermore, the validation procedures should also increase the stakeholders' confidence in 1) the concepts developed in the project and 2) the network code proposals that resulted from the investigations of these concepts.

5. List of Figures

6. List of Tables

7. References

[1] Texas A&M University, "Electric Grid Test Cases Repository - Engineering, Texam A&M University," [Online]. Available: https://electricgrids.engr.tamu.edu/electric-grid-test-cases/wscc-9-bus-system/. [Accessed 24 February 2018].

[2] R. V. Meshram, M. Bhagwat, S. Khade, S. R. Wagh, A. M. Stanković and N. M. Singh, "Port-controlled phasor hamiltonian modeling and IDA-PBC control of solid-state transformer," *IEEE Transactions on Control Systems Technology,* vol. 27, no. 1, pp. 161-174, 2017.

8. List of Abbreviations

AGC	Automatic Generation Control
AIITS	All-island Irish Transmission Grid
AVM	Active Voltage Management
DER	Distributed Energy Resources
DMS	Distribution Management System
DSO	Distribution System Operator
ESS	Energy Storage Systems
HiL	Hardware-in-the-Loop
LSD	Linear Swing Dynamics
PFC	Primary Frequency Control
PV	Photovoltaic
RES	Renewable Energy System
RoCoF	Rate-of-Change-of-Frequency
RTDS	Real-Time Digital Simulator
RTS	Real-Time Simulator
RTU	Remote Terminal Units
SFC	Secondary Frequency Control
SMIB	Single-Machine Infinite-Bus
SSAU	Secondary Substation Automation Unit
SV	Synchronverter
VOI	Virtual Output Impedance
VPP	Virtual Power Plant
VSC	voltage-sourced power controllers
VSG	Virtual Synchronous Generator
WSCC	Western System Coordinating Council
WSI	Wideband System Identification

Annex

A.1 Solid-State Transformer Use-Case

This annex gives an overview of the potential requirements for using solid-state transformers (SST) in power systems with up to 100% renewable energy penetration. SSTs were not listed as a requirement in the scenarios since the idea was introduced in the middle of the project when the experiments are already planned and ongoing.

The idea of using SSTs came up during the project discussions as a result of discussions among the partners. However, there was not enough time to perform simulations and live trials for SSTs. Therefore, SSTs were not listed as requirements in the scenarios. Nevertheless, the results of the discussions about SSTs are provided in this annex.

SSTs or smart transformers are key technological enablers for several types of applications, such as traction systems, distribution electricity networks, including microgrids, storage deployment, etc.). SSTs are devices that use power electronics to ensure power flow from a voltage level (focus on MV) to another voltage level (focus on low voltage) by using high-frequency transformer (HFT) coupling (e.g., 5 kHz to 50 kHz) instead of standard industrial frequency (50 or 60 Hz).

A possible schematic for SST is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** .

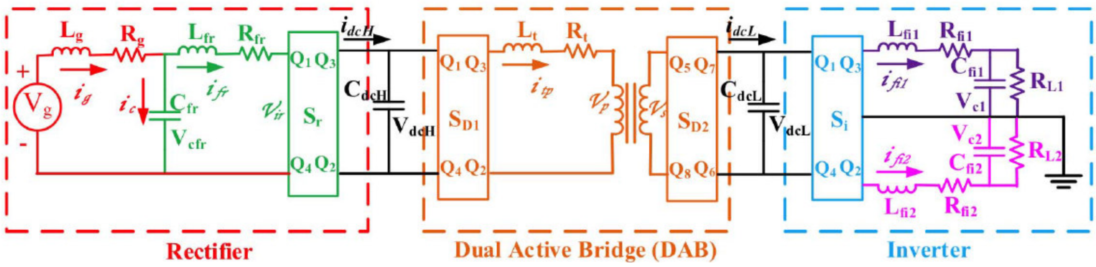

Figure A- 1 Solid-State Transformer Schematic [2]

Different topologies are available for SST. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a topology where the DC/DC converter is based on the Dual Active Bridge (DAB) topology.

The potential use of SST in the Virtual Output Impedance (VOI) approach of the voltage control technique has been reported in D3.9.

The dynamic requirements necessary for using the SST in the VOI approach can be summarized as follows:

- Bidirectional power transfer capability from medium-voltage to low-voltage segments of the grid.
- Reactive power can be either be absorbed or injected by the rectifier or inverter to maintain the desired AC-side line voltages on both LV and MV sides.
- DC/DC Converter topology needs to be bidirectional (e.g. Dual Active Bridge is bidirectional) for enabling bidirectional power transfer. Advantages such as galvanic isolation and high efficiency of the DC/DC converter is highly desirable.
- Impedance measurement needs to be integrated on both Rectifier/Inverter to monitor both the LV side and MV side grid impedances.
- The Adaptive VOI control concept for both Rectifier and Inverter is needed to adapt the grid impedance change and actively mitigate harmonic resonance.