European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project

Interoperability/Interchangeability via Simulation and Laboratory Testing, IISLT

Grant Agreement No:	**654113**
Funding Instrument:	**Research and Innovation Actions (RIA) – Integrating Activity (IA)**
Funded under:	**INFRAIA-1-2014/2015: Integrating and opening existing national and regional research infrastructures of European interest**
Starting date of project:	**01.11.2015**
Project Duration:	**54 month**

Contractual delivery date:	**XX**
Actual delivery date:	**13.12.2019**
Name of lead beneficiary for this deliverable:	Prof. Dr. Antonello Monti, RWTH Aachen University
Deliverable Type:	**Report (R)**
Security Class:	**Public**
Revision / Status:	**draft**

Project co-funded by the European Commission within the H2020 Programme (2014-2020)

Document Information

Document Version: 1

Revision / Status: draft

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Distribution List [AIT]

Document History

Revision	Content / Changes	Resp. Partner	Date
1.0	First version of the document completed – ready for review	RWTH	13.12.19

Document Approval

Final Approval	Name	Resp. Partner	Date
[Review Task Level]	[Given Name + Name]	[Partner Short Name]	DD.MM.YY
[Review WP Level]	[Given Name + Name]	[Partner Short Name]	DD.MM.YY
[Review Steering Com. Level]	[Given Name + Name]	[Partner Short Name]	DD.MM.YY

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Abbreviations

AVD	Admitted Voltage Deviation
BAP	Basic Application Profile
BAIOP	Basic Application Interoperability Profile
CHIL	Combined Hardware in the Loop
CP	Common Pattern
DER	Distributed Energy Resource
DoE	Design of Experiments
DSL	Digital Subscriber Line
DSO	Distribution System Operator
EV	Electric Vehicle
FLEX	Flexibility source
GIES	Grid Integrated Energy Storage Systems
HIL	Hardware in the Loop
ICT	Information and Communication Technology
JRC	Joint Research Centre
LV	Low Voltage
NIST	National Institute of Standards and Technology
PHIL	Power Hardware in the Loop
PLC	Power Line Communication
RES	Renewable Energy Source
RF	Radio Frequency
RTC	Real Time Communication
RTU	Remote Terminal Unit
SC	Super Category
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
SGAM	Smart Grid Architecture Model
SGIRM	Smart Grid Interoperability Reference Model
TA	Trans-national Access
UC	Use Case
VGI	Vehicle Grid Integration

Executive Summary

The Smart Grid (SG) vision has led to new demands on electric distribution systems. For example, the distribution networks should be able to integrate Distributed Energy Resources (DERs), Electric Vehicles (EV), or Demand Response systems, while guaranteeing the quality of supply to customers at a cost-effective price. Information and Communication Technology (ICT) will play a significant role in the implementation and control of Renewable Energy Sources (RESs), EV and Grid Integrated Energy Storage Systems (GIES) as elements of SGs. Developing interoperability across different application domains and actors such as smart appliances, energy management, GIES, and aggregator systems seems to be an inevitable part of the SG role in integrating the needs of electrical providers, power-delivery systems and prosumers while allowing a two-way communication between the utility and its customers.

In this regard and as a step forward towards a methodological interoperability testing in SGs, this work focuses on an interoperability test suite. First, different objectives for a flexibility activation mechanism within a European context are identified out of which a specific scenario with a specific ICT architecture is selected for the interoperability testing. For this purpose, validation experiments for different scenarios are conducted at AIT SmartEST laboratory for the evaluation of interoperability between the different components for the direct flexibility activation mechanism, namely the flexibility itself, the flexibility requester and potential intermediates such as Remote Terminal Unit (RTUs).
In the proposed testing platform, based on the results obtained from the in-depth Smart Grid Architecture Model (SGAM)-based interoperability/interchangeability study of the European H2020 InterFlex Project (under grant number 731289), exemplary scenarios for the voltage support service will be demonstrated in laboratory tests. These tests required specific tools to be further developed, adapted or integrated by the User Group (UG). For the interoperability analysis, focus has been put on the profiling phase, the experimental design and the interpretation of the results based on the defined inputs and outputs of the system under test mainly according to a European Smart Grid interoperability testing methodology.

1 General Information of the User Project

USER PROJECT	
Acronym	IISLT
Title	Interoperability/Interchangeability via Simulation and Laboratory Testing
ERIGrid Reference	04.021-2018
TA Call No.	654113

HOST RESEARCH INFRASTRUCTURE			
Name	AIT SmartEST		
Country	Austria		
Start date	03.02.2019 & 05.05.2019	Nº of Access days	5 & 10
End date	08.02.2019 & 17.05.2019	Nº of Stay days	6 & 13

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2 Research Motivation

Nowadays, RESs are increasing their penetration in power systems. Consequently, the infrastructures are growing in terms of complexity and interdependency, and the communication system used for information flow is also being extensively developed along with the operational methods. Interoperability is one of the greatest challenges facing the power grids as a multitude of technologies, systems, and devices need to securely and effectively talk to each other. Interoperability and interchangeability are two essential enablers for technologies to scale up as they move systems away from today's state of highly customized integration

2.1 Objectives

IISLT aims at investigating the interoperability/interchangeability issues addressed in the European demonstration Project InterFlex [1] where six different demonstration sites are realized with a focus on flexibility services from energy generation and demand. InterFlex is a multi-player environment with Distribution System Operators (DSOs), aggregators, EV charging operators and other actors, providing a representative overview of contemporary flexibility use and implementation options. Within this context, IISLT can work out technical solutions and recommendations to tackle the existing difficulties to ensure interoperability among different components/actors of SGs. It is noteworthy that although IISLT is based on the results obtained from interoperability study of InterFlex project, however the same procedure can be applied to any set of demonstrations.

2.2 Scope

To achieve the above-mentioned research objectives, a combination of hardware infrastructure together with well-designed software simulation tools are required. In this context, AIT Smart Electricity Systems and Technologies (SmartEST) laboratory and LabLink framework were used to facilitate the development process for the interoperability tests. In particular, AIT LabLink [2] as a communication middleware is utilized for rapid and simple laboratory testbed creation by linking simulator software, laboratory hardware, and the real-time simulators. The scope of the research work based on the tentative proposed milestones reported in the TA proposal could be categorized as below:

1. Identification of common patterns as the core requirement for any flexibility usage in an EU power system context.
2. Identification of flexibility activation architectures for the interoperability testing.
3. Exhaustive analysis of the Lablink tool.
4. Setting up the selected set of actors and components in SmartEST Lab.
5. Adoption/development of the simulated DSO SCADA system and the power grid.
6. Implementation of the test suite including the flexibility activation mechanism.
7. Experimental analysis of the whole test set-up under different exemplary scenarios.

The first two steps are the preliminary analyses which led to the definition of the test suite. In other words, the first two steps were carried out remotely and in conjunction with the H2020 European Project of InterFlex (under grant agreement number 73128 [1]) while for the other steps the host infrastructure was exploited to conduct the tests. For more detailed information about the preliminary analysis, the reader can refer to the deliverable reports of InterFlex (specifically deliverables D3.1-3) and the respective publications [3], [4], [5]. For the sake of avoiding redundancy, this TA report focuses mainly on the parts related to the test scenario conducted at SmartEST.

3 State-of-the-Art

Meeting the EU climate change and energy policy objectives for 2020 and beyond requires a major transformation of electricity infrastructure. The European power grid, one of the largest and most complex systems in the world, is undergoing challenging technological, social and regulatory modifications [6]. Therefore, upgrading and reshaping the existing electricity network and making it smarter is of paramount importance to foster sustainability, increase energy efficiency, enhance grid security and attain the internal energy market objectives.

SGs are systems-of-systems with a broad scope integrating electricity, information, communications, business process, and diverse appliances, in addition to interconnecting with other systems and enabling markets and transactions. As we move towards a new era of intelligent energy management, it is increasingly important to continue learning about the ways SGs are able to transform energy production, distribution and use, how the different SG components work together, and how the proposed standards ensure interoperability among these components. Due to the revolution that will take place in the next decades, large fleets of EVs will demand huge energy flows from the SG and distributed production of electric energy will in turn supply considerable energy to the SG. As a result, the pattern of production and consumption of electric energy will be completely changed. Society must cope with this revolution in the use and production of electricity. Therefore, the current energy infrastructure will have to become more flexible, requiring the establishment of data communications among all actors (industrial and end users). In other words, the challenge will be to guarantee that all components work together without problems, i.e. are ‘interoperable’.

Interoperability was identified from the very beginning as the main challenge for the deployment of the SGs, where technologies and companies from very diverse domains converge: electricity technologies at large, grid measurement, protection and control, DER management, industrial automation and power electronics, ICTs at large, building and home automation, smart metering. However, this diversity of domains gives place to the overlapping of many standards and different standardization approaches. Interoperability means the ability of two or more intelligent electronic devices from different vendors to exchange information and use that information for correct execution of specified functions. Interoperability is more than a simple data transfer; it realizes information exchange between two or more devices of similar intelligence. It is required that the receiver understands the syntax (structure) of the data as well as its meaning which corresponds to the semantics in the context of the process and of its tasks. In some cases, it may be possible to replace a device supplied by one manufacturer with a device supplied by another manufacturer without the need to make any changes to the rest of the system. This is called interchangeability.

Different research works have tried to address the interoperability issues within the SG concept. Paper [7] highlights the motivation for standardization to increase interoperability as well as extend this concept with a new metric based on the current state of the art in the context of SG. In this regard, domain specific examples on the soundness of the approach as well as an outlook on the real world application in the SGAM toolbox are presented. The current model of the Interoperability Score (i-Score) from [8] is used in this paper while the normalized i-Score is improved and more domain-fitting interoperability levels are proposed. In paper [9], the standardization of Vehicle Grid Integration (VGI) is studied. The requirements of interoperable VGI are examined at multiple interoperability layers defined by reference architecture models, including European Commission's Mandate 490 (EC-M490), National Institute of Standards and Technology (NIST) SGAM, and IEEE 2030 Smart Grid Interoperability Reference Model (SGIRM). The current status of standards and technology development is reviewed and VGI demonstrations are discussed. The paper identifies barriers for the implementation of an interoperable VGI and provides recommendations to address these challenges.

4 Executed Tests and Experiments

In this chapter, there will be first a preliminary analysis which narrows down the focus of the research work towards a specific test conducted within IISLT project. After this analysis, the remaining subsections describe the test plan, the methodology proposed for conducting the experiments, the test setup and the scenarios considered for the experiments.

4.1 Preliminary analysis

In the IISLT project, an interoperability testing suite is worked out based on the results of the SGAM-based interoperability/interchangeability study carried out in the EU H2020 InterFlex project [1].
In general terms, the work performed in the IISLT project is based on two main findings from InterFlex project:

- The set of Super Categories (SCs) created from the Common Patterns (CPs) which have been identified as the required services used by the DSOs for activating the flexibility chain across the InterFlex demonstrators ([5] and Table 1).
  Out of these SCs, the focus of IISLT is on the Voltage Support service.
- The two identified architectures (InterFlex Deliverable D2.1 [3] and Figure 1 Lower-bound (left) and upper-bound (right) validation architectures (extracted from InterFlex Deliverable D2.1)Figure 1) which are at DSO's disposal for activating the flexibility source via a direct (lower-bound) or indirect (upper-bound) interface, respectively. More specifically, the DSO could either employ its own field gateway (Remote Terminal Unit, RTU) to access the sources of flexibility (lower bound architecture) or, alternatively, the DSO's SCADA system can be first interfaced with an intermediate actor (an aggregator or an energy management system) and then access the flexibility via an RTU (upper bound architecture).
  The lower-bound architecture is chosen within IISLT project and employed for the laboratory testing.

Name	***Description***
Congestion	Congestion management pattern
Frequency	Dynamic frequency support pattern
Voltage	Voltage support pattern
Support	Support services pattern
Non-validatable	Patterns which are difficult to test in a lab validation

Table 1 Super Categories identified for laboratory validation analysis (extracted from [5])

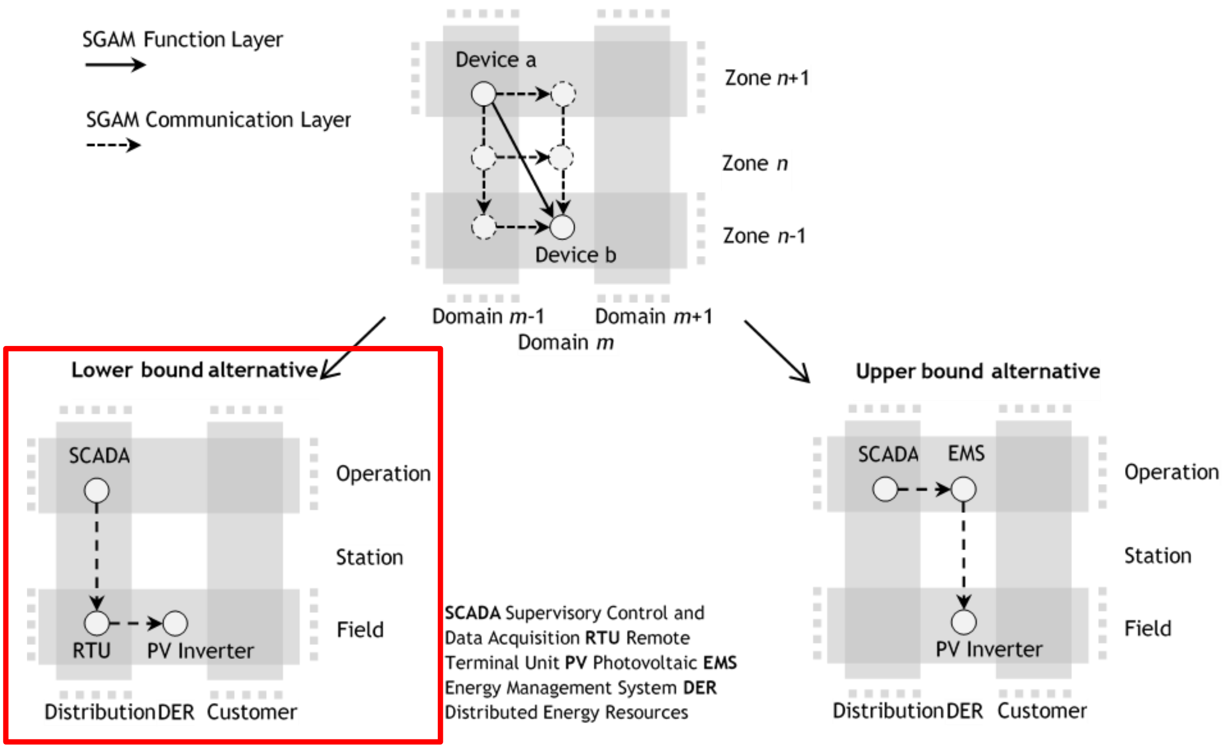

Figure 1 Lower-bound (left) and upper-bound (right) validation architectures (extracted from InterFlex Deliverable D2.1 [3])

In the following sections, the lower-bound architecture employed by the DSO in order to activate the flexibility source for providing a voltage support service is analyzed from an interoperability perspective.
For performing a structured interoperability testing, IISLT project follows some of the methodological directions reported in [10]. A brief overview of this methodology and details on how it is specifically applied in IISLT project are given in § 4.3.

4.2 Test Plan

As shown in Figure 1, in the lower bound validation architecture the DSO is directly interfaced with the flexibility device through a Remote Terminal Unit (RTU).
In general terms, the testing plan can be depicted as follows. The DSO-SCADA constantly monitors the voltage level of the power grid. As soon as the voltage falls outside a predefined threshold, SCADA system detects it. Consequently, the DSO requires support from the flexibility source located at the customer premises, by sending a flexibility request signal (via an RTU) towards the flexibility source itself. The translation of the flexibility request is in the form of a voltage support mechanism. After the flexibility is activated, in the meantime SCADA keeps on monitoring the power grid and reading the node voltages from the grid, reporting back the final voltage value when the whole available flexibility amount is injected into the system. The ability of the flexibility source in restoring the node voltage within the predefined threshold can be analyzed under an interoperability point of view, as better detailed in § 4.5.
In this setup, some assumptions are made (additional information is provided § 4.4):

- whenever a flexibility is requested, there is already some amount of flexibility which could potentially provide the DSO system with a voltage support service.
- the disturbance at a certain time occurs at a specific node of the power grid, leading to a voltage drop. As soon as this situation is detected by the SCADA system, the intermediate

device (RTU) sends the activation signal to the flexibility source which is always ready to deliver a certain amount of flexibility to the same node.
- the distribution system is operating in normal conditions and the voltage values at the different nodes are compliant with reference values of the reference power grid model used in this setup (§ 4.4).

For the sake of completeness, the schematics of the case study can be observed in the message sequence chart of Figure 2.

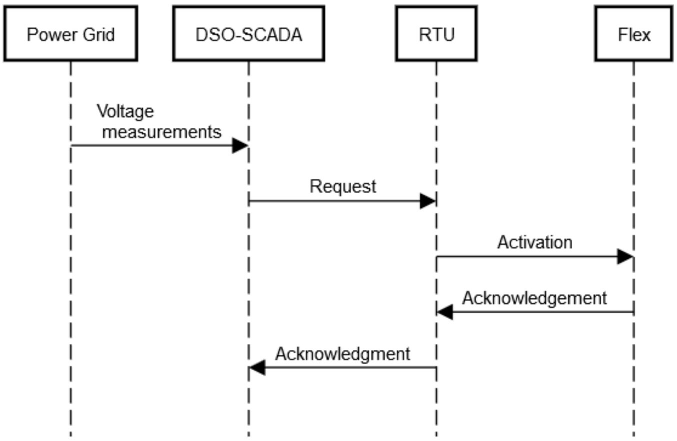

Figure 2 Sequence chart of the voltage support lower-bound validation setup

After selecting the service ("voltage support") and the way this service is implemented by the DSO (through a lower-bound architecture), the telecommunication infrastructure needs to be selected.
In the IISLT laboratory testing, three different telecommunication architectures are investigated which could be mapped to the InterFlex demo implementations as well as emerging trends for the telecom infrastructure (§ 4.4).
In parallel to the telecommunication infrastructure, a Hardware-in-the-loop (HIL) mode needs to be chosen for conducting the tests. Combined-HIL (CHIL) refers typically to a HIL system with a modelling environment, such as Simulink, which is used to create the plant model and includes a model of the controller strategies for components not available for the test system. Power-HIL (PHIL) is instead related to the connection of real power hardware components (e.g., the storage unit, PV inverter, etc.) to the simulated network in a closed loop. In particular, for building the IISLT testing environment CHIL is chosen and the control boards represent the hardware components that are directly connected to the power electronic periphery, which is entirely simulated in a real-time simulation environment.
Once the HIL mode is selected, the following step is the designing of the laboratory experiments (DoE). The DoE procedure followed in the IISLT project is depicted in § 4.5.
After the laboratory experiments are carried out, data processing and interpretation of the results under an interoperability perspective are performed (§ 5).

4.3 Standards, Procedures, and Methodology

As already mentioned, the interoperability testing work performed in the IISLT project mostly follows the methodological guidelines proposed in the technical report of the European Commission (EC) Joint Research Center (JRC) [10] and [11].
The JRC methodology schematics is depicted in Figure 3.

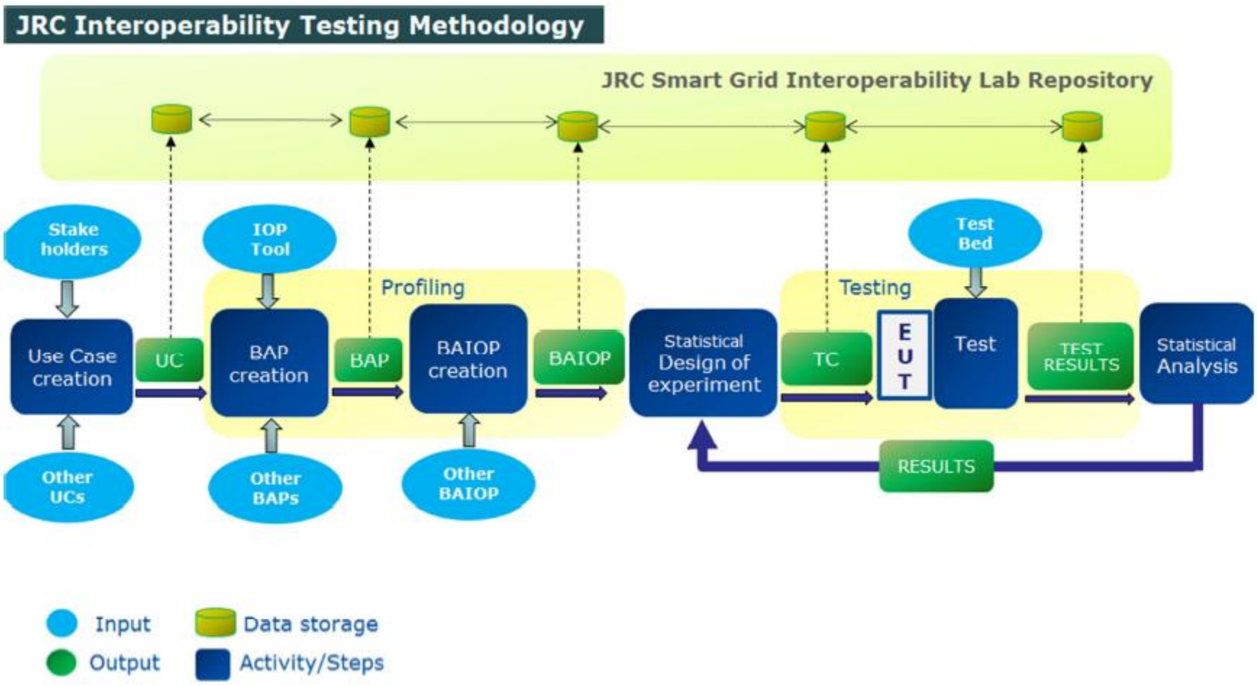

Figure 3 JRC Interoperability testing methodology (extracted from [10])

In the following, the specification of how this methodology is applied within the interoperability testing performed in IISLT project is presented.

<u>Use Case Creation</u>

The voltage support service (extensively described in § 4.2) constitutes the Use Case (UC) studied in the IISLT project.

After selecting a specific UC, the JRC interoperability methodology includes the definition of the Basic Application Profile (BAP) and Basic Application Interoperability Profile (BAIOP).

<u>BAP creation</u>

In IISLT project, the BAPs are defined by looking at the different communication technologies implemented in the InterFlex demonstrators as well as potential candidates for future implementations. As already mentioned, the three actors taking part to the UC are DSO-SCADA, RTU and the Flexibility source (FLEX). The list of the considered BAPs related to the interfaces between these three UC actors is shown in Table 2. The communication parameters specifying each of the communication technologies generating the BAPs are reported in Table 3.

Interaction link between actors		*Technology*	*BAP ID*
From	*To*		
DSO	RTU	xDSL/cable	BAP 1.1
DSO	RTU	Mobile network	BAP 1.2
DSO	RTU	RTC	BAP 1.3
DSO	RTU	Narrow-band PLC / RF Mesh	BAP 1.4
RTU	Device	Fiber(home) / Local Ethernet	BAP 2.1
RTU	Device	Narrow-band PLC / RF Mesh	BAP 2.2

Table 2 List of the BAPs defined according the considered communication technologies

Technology	*Techno*	*Bandwidth (Mbps)*	*Back-ground traffic (Mbps)*	*Delay (µs)*	*Jitter (µs)*	*Packet loss (%)*	*Dupli-cate (%)*
Fiber (home) / Local Ethernet	Ethernet	100	Link dependent	3000	1000	0	0
xDSL / cable	Ethernet	20	Link dependent	30000	10000	0	0
Mobile network	Radio	10	Link dependent	60000	20000	1	0
Narrow-band PLC / RF Mesh	PLC	0.1	Link dependent	300000	100000	3	0
RTC	Twisted pair	0.056	Link dependent	150000	50000	0	0

Table 3 Communication parameters specifying the different considered technology options

<u>BAIOP creation</u>
After defining the BAPs for all the interfaces, the BAIOPs have to be defined.
In IISLT project, out of all the potential BAPs combinations only some of them have been considered. The resulting BAIOPs are reported in Table 4, each one of them being characterized by a unique combination of the communication technologies reported in Table 3.

Validation architecture	*BAIOP ID*	*BAPs ID*
Lower Bound	BAIOP 1	BAP 1.1 and BAP 2.1
	BAIOP 2	BAP 1.2 and BAP 2.2
	BAIOP 3	BAP 1.1 and BAP 2.2

Table 4 List of the BAIOPs considered for the lower bound validation architecture

Design of Experiment

After the preliminary stages of Use Case creation and profiling phase, JRC interoperability testing methodology focuses on the DoE.

The DoE procedure entails experiments scope definition, specification of input and output factors, statistical characterization of the inputs and sampling of N points within the input space for carrying out the laboratory experiments.

A detailed discussion of the DoE procedure applied in the IISLT testing suite together with the considered scenarios is reported in § 4.5.

4.4 Test Set-up

The test setup utilized for the HIL testing within IISLT project is depicted in Figure 4.

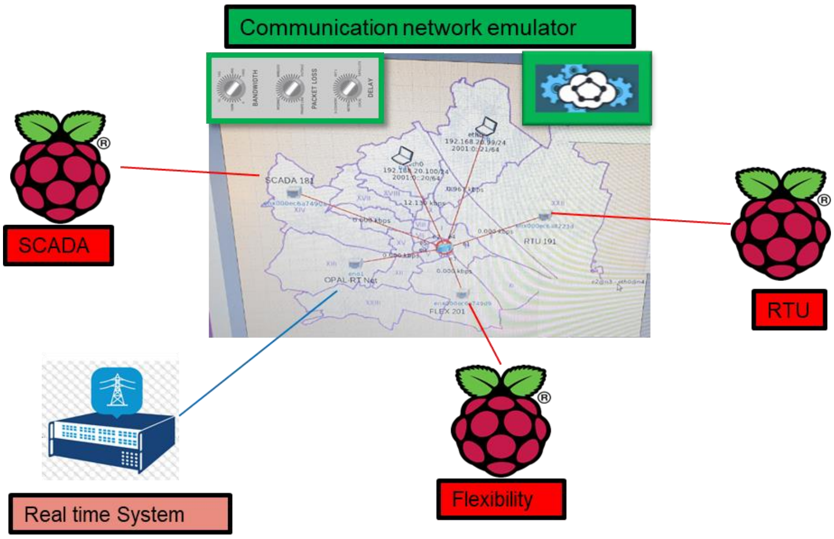

Figure 4 Test-bed built for the interoperability testing

Power grid and model components

The LV distribution network benchmark proposed by the European Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources Task Force C6.04 [12] is used for the IISLT testbed.

It is clear that the usage of a reference grid model makes the results totally independent from any specific demonstrator and removes any negative impact on the interoperability testing results which could originate from grid parameters.

Generally speaking, the low-voltage (LV) distribution benchmark network consists of three feeders of residential, industrial, and commercial character, respectively. In Figure 5, the topology of the European LV distribution network benchmark could be observed which was modelled in MATLAB

Simulink. For the interoperability testing, the residential feeder was specifically chosen as the power grid under test and simulated using the OPAL-RT real-time simulator.

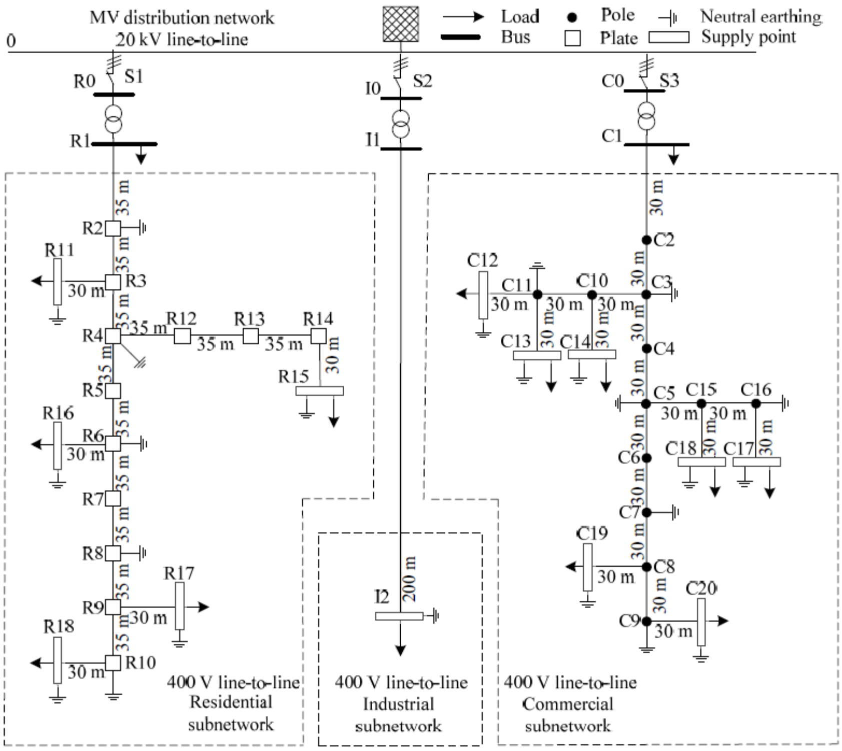

Figure 5 Topology of the CIGRE LV distribution network [12]

<u>Communication and software infrastructure</u>

For emulating the communication network, the NRL CORE network emulator running on a laptop with UBS-to-RJ45 connectors is employed [13].

LabLink simulation and middle-ware framework of the host infrastructure [2] have been utilized.

The three components of DSO-SCADA, RTU and FLEX are made running on three Raspberry Pi single board computers. The logic behind these components is showed in a code-like form in Figure 6, Figure 7 and Figure 8, respectively. It is noteworthy that as the CIGRE LV grid is chosen as a reference grid and the focus is towards the flexibility activation mechanism in this context, a dominant resistive behaviour for the lines is observed. Therefore, the flexibility source is considered in terms of injection of active power. In fact, based on simulation results, reactive power-based flexibility did not lead to significant voltage support for the grid under test. However, reactive power-based flexibility for the test bench could be quite easily integrated. As a result, keeping in mind the assumptions for the location of the disturbance and the source of flexibility, active power-based flexibility is considered in this report.

```
% set initial conditions
        Vmeas_IN = [ ];
        Vref = 399.99;
        Threshold = 0.05;

% start collecting the voltage measurements
        for n = 1:10
                Vmeas_IN(n) = [Vmeas_IN; Vmeas_IN(n)];
        end

% Compute the mean of the latest 10 voltage measurements
        Vmeas_mean10 = mean(Vmeas_IN(1:10));

% Compare the mean voltage with the reference voltage and implement the logic for deciding
whether to send the flex request or not
        if abs(Vmeas_mean10 - Vref) < threshold;
        send_request_to_RTU = 1;
                else send_request_to_RTU = 0;

        end
```

Figure 6 Implementation of the DSO-SCADA model

```
% set initial conditions
        RTU_Proc_T = 0;

% check whether there is a request from SCADA. If yes, send the activation signal to FLEX
        if send_request_to_RTU == 1
                send_request_to_FLEX = 1;
                elseif send_request_to_FLEX = 0;
        end

% Wait "RTU_delay" time before sending the activation signal to FLEX
        if send_request_to_FLEX == 1
        RTU_Proc_T = RTU_Proc_T + 75 ms;
        end
```

Figure 7 Implementation of the RTU model

```
% set initial conditions
        Power_at_node_16 = 0;
        FLEX_Proc_T = 0;
        FLEX_Cap = 156750;

% check whether there is a request from RTU. If yes, inject the amount of Flexibility specified by
Flex_Cap, after waiting for "Flex_Resp_T" time;
        if send_request_to_FLEX == 1

                FLEX_Proc_T = FLEX_Proc_T + 70 s;

                Power_at_node_16 = Power_at_node_16 + FLEX_Cap;

        end
```

Figure 8 Implementation of the FLEX model

4.5 Data Management and Processing

In this section, first different parameters of the experiments are described. Afterwards, the scenarios for conducting the experiments are categorized in accordance to the proposed testing methodology.

4.5.1 Design of Experiments

As explained in § 4.3, the set of inputs and outputs needs to be identified before conducting the tests.

Input factors
Two categories of input factors are taken into account for the DoE of the laboratory testing.

- Input factors related to the telecommunication architecture: these fixed parameters are those characterizing the three considered BAIOPs (§ 4.3, Table 3 and Table 4). They are reported in Table 5.
- Input factors related to the three actors involved in the flexibility activation chain: these parameters are characterized by a certain range of variation, as reported in Table 6. In particular, four service-related parameters are defined:

  $\mathrm{IF}_1 =$ *RTUProcT*, which refers to the internal RTU time delay

  $\mathrm{IF}_2 =$ *AVD*, which is the “Admitted Voltage Deviation”

  $\mathrm{IF}_3 =$ *FlexRespT*, which is the time required for the flexibility to activate

  $\mathrm{IF}_4 =$ *FlexCap*, which is the available flexibility capacity

  It should be pointed out that the variation intervals of each of these four parameters have been specified according to demo-specific implementations and literature review.

Bandwidth (Mbps)	***Background traffic (Mbps)***	***Delay (µs)***	***Jitter (µs)***	***Packet Loss (%)***	***Duplicate (%)***
Characterizing the analysed communication architectures (BAIOPs)					

Table 5 Telecom-related input factors

IF₁ **RTUProcT (ms)**	***IF₂*** **AVD (%)**	***IF₃*** **FlexRespT (s)**	***IF₄*** **FlexCap (KW)**
Mean = 90	Min = 2.5	Min = 60	Min = 41.8
Standard deviation = 10	Max = 7.5	Max = 80	Max = 156.75

Table 6 Service-related input factors

Output factors
DSO measures two system responses:
- Restored voltage (V_{res}^{i}), i.e. the value of the voltage measured at node i after the flexibility is activated for restoring the voltage within the allowed DSO-specific voltage range (*AVD*).
- Restoration time (t_{res}^{i}), i.e. the time the system took in order to restore the voltage at node i

4.5.2 Scenarios under analysis

Within the IISLT testing suite, two types of analysis have been carried out, specifically “inter-telecom” and “intra-telecom”, which are briefly described in the following.

Inter-telecom analysis
In order to realise which is the impact of the telecommunication architecture on the system response towards a flexibility activation request, an analysis across the three communication technology options (considered for the testing) is performed. In the following, we refer to it as “inter-telecom” analysis.
For this set of experiments, the service-related input factors (Table 6) are fixed at a predefined value, specifically their mean value taking into account the respective ranges of variation.
By running the lab experiments with this specific input configuration, the DSO voltage support service across each telecommunication architecture is assessed by measuring the system response in terms of V_{res} and t_{res}. The inter-telecom results are shown in § 5.1.

Intra-telecom analysis
For a thorough analysis of the interactions between the different actors providing the voltage support service, there is a need to conduct an interoperability analysis within a specified telecommunication architecture. In the following, we refer to it as “intra-telecom” analysis.
In other words, the purpose of these tests is to analyse how the variation of the different service-related parameters (Table 6) related to the different actors involved in the flexibility chain (IF_{1-4}) will impact the system response (V_{res} and t_{res}) within each telecommunication architecture.
Even if an intra-telecom analysis may be carried out for each of the three considered technology options, only one of them is chosen by evaluating the inter-telecom analysis results. More specifically, the telecommunication infrastructure which delivers the “best” system response (in terms of optimal combination of V_{res} and t_{res} from a DSO’s perspective) is chosen and investigated under an intra-telecom perspective.
The results and the respective discussions for these intra-telecom experiments are shown in § 5.2.

5 Results and Conclusions

In this chapter, an analysis is provided for the experimental scenarios described in § 4 and there are some conclusion drawn based on the obtained results.

5.1 Inter-telecom analysis

By running the experiments for the inter-telecom analysis, the system response towards the different possible communication links between the lower bound actors is analysed (Figure 9).
As observed in Figure 9, the different communication technology options can equally support the voltage deviation and restore the voltage to 0.96 per unit. On the other hand, the system response in terms of t_{res} shows more dependency on the communication technology.
From this type of analysis, it may be derived that the attention of the DSO, in order to “score” the quality of the voltage support service, can be oriented towards the telecom architecture capable of delivering the least t_{res}.

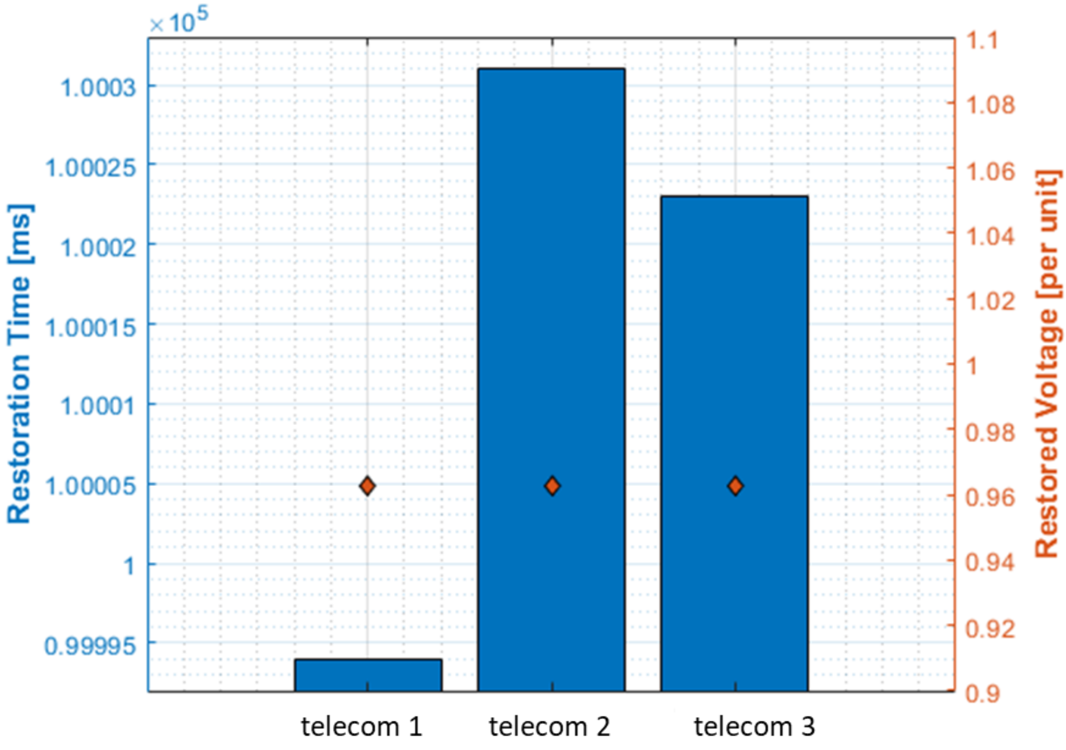

Figure 9 Inter-telecom analysis

5.2 Intra-telecom analysis

As discussed in § 4.5.2, intra-telecom analysis is carried out within the telecom architecture which has provided the best results after the inter-telecom analysis (§ 5.1).
In this particular case, it is assumed that the DSO (in order to be able to deliver the "best" quality of service according to its own preference) chooses telecom 1, where an optimal combination of restored voltage and restoration time is achieved.
For this particular communication technology option the intra-telecom analysis provides an insight about the interoperability between different actors involved in the flexibility activation chain.
In this type of analysis each input factor, in turn, is left free to vary within its interval of variation, the others being fixed at their mean value. Therefore, an analysis for each of the service-related parameters is carried out.

DSO-related analysis

To analyse the impact of the regulatory bandwidth (*AVD*) that the DSO considers for the voltage support service, $\mathrm{IF}_{1,3,4}$ are set to their mean values while *AVD* varies in its range. A random sampling is performed within the range of variation of *AVD*.
The results can be observed in Figure 10, where the red bars stand for "fail" and the green ones for "pass".

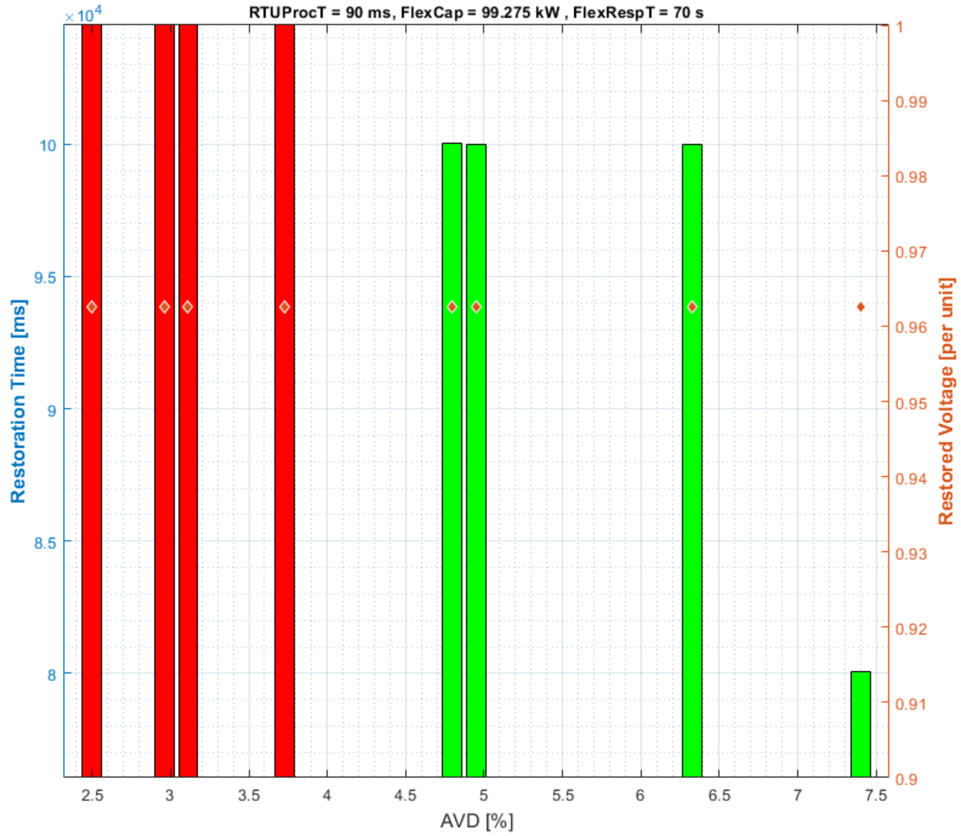

Figure 10 Intra-telecom analysis – impact of Admitted Voltage Deviation

As depicted, the quality of service that the DSO wants to provide after a disturbance is able to affect the restoration time while the amount of restored voltage is not affected at all.
It can be noticed that, when the flexibility and RTU-related parameters are fixed at their mean value, there is a minimum amount of *AVD* required for the system to restore otherwise the interoperability test fails.

Flexibility-related analysis

Then, the impact on the system response of FLEX-related input factors (*FlexRespT* and *FlexCap*) is investigated. For this purpose, the values of IF_1 and IF_2 are set to the mean value in their variation range.
To analyse *FlexCap*, *FlexRespT* is also set at its mean value. As shown in Figure 11, it can be observed that *FlexCap* has an influence on both DSO service criteria measures, i.e., V_{res} and t_{res}.
It can be observed that there should be a minimum amount of flexibility to restore the voltage: if the amount of *FlexCap* is below a certain amount, the interoperability test will fail (red bars of the bar plot).

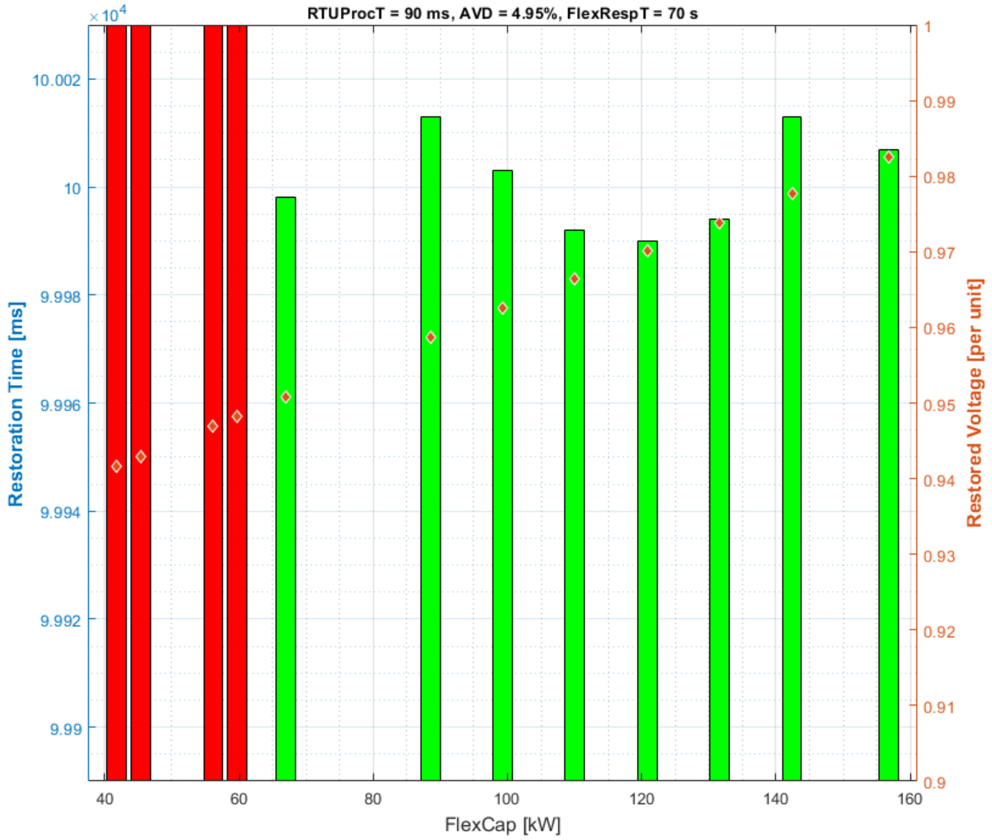

Figure 11: Intra-telecom analysis – impact of Flexibility capacity

Similarly, in order to analyse *FlexRespT*, *FlexCap* is set at its mean value and the response of the system is observed in Figure 12.

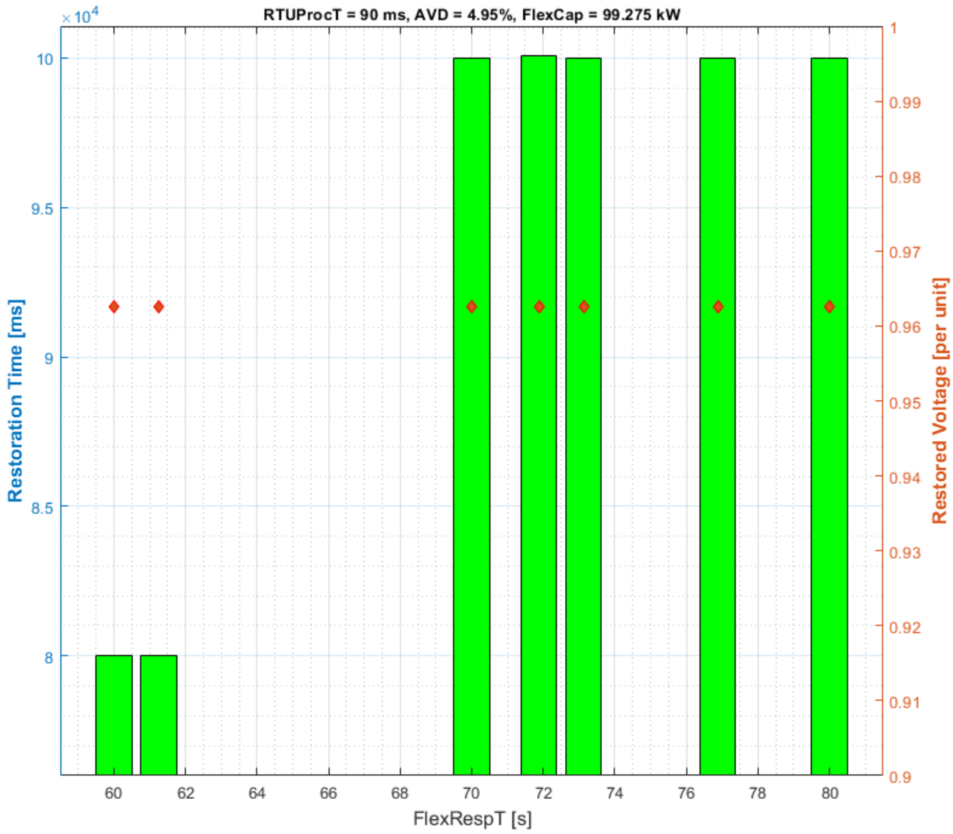

Figure 12 Intra-telecom analysis – impact of Flexibility Response Time

As observed, the flexibility response time influences the system response only in terms of the restoration time, the restored voltage value not being affected at all.

<u>RTU-related analysis:</u>

Finally, the parameters related to DSO and FLEX are set to their mean values, while *RTUProcT* varies within its predefined range. The result can be observed in Figure 13.

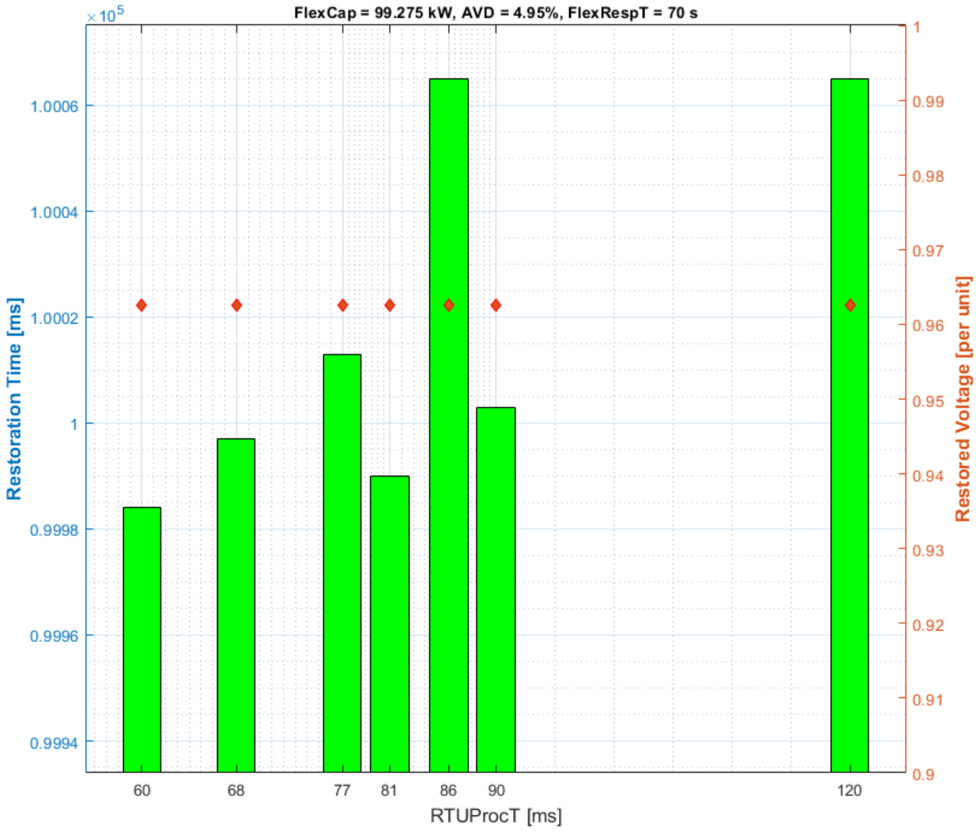

Figure 13 Intra-telecom analysis – impact of RTU Processing Time

As observed, the response time of RTU influences the behaviour of the system only in terms of the restoration time. Also, by comparing the results of Figure 12 and Figure 13, it can be concluded that *FlexRespT* has a higher impact on affecting the restoration time compared to *RTUProcT*.

5.3 Conclusions

In the previous two paragraphs, the results of inter-telecom and intra-telecom tests are reported, which have been performed for analysing the lower bound validation architecture supporting the "voltage support" service. With these results, for the interoperability tests conducted within the context of IISLT and considering the assumptions made, the following conclusions can be reported.

First, the DSO can decide about which telecommunication infrastructure to use based on the optimal restoration time irrespective of the restored voltage. However, the decision for the telecom architecture is dependent on the available technologies and economic considerations.

Second, after the selection of a telecom infrastructure, in order to deliver a certain voltage support service, the DSO should define the quality of service by setting the allowed voltage deviation (*AVD*) threshold according to its preference. Since *AVD* mainly impacts the restoration time in comparison to the restored voltage, the DSO should put a certain attention towards the amount of flexibility which can potentially impact both restoration time and restored voltage.

Moreover, an interaction between *AVD* and *FlexCap* and its impact on the quality of voltage support service could be observed. The DSO keeping this in mind can take the necessary contractual agreements with flexibility owners.

The two other input factors, namely *RTUProcT* and *FlexRespT*, do have impact on the amount of time that it takes the system to restore, though not influencing the restored voltage at all. However, based on the obtained range of interval for t_{res}, it can be concluded that the impact of the flexibility source response time on t_{res} is higher compared to that of the intermediate actor of RTU.

6 Open Issues and Suggestions for Improvements

As future work, a similar set of experiments could be conducted for other services such as congestion management and/or other flexibility activation architectures. Obviously, for such experiments the methodology remains the same. However, different actors and scenarios might need to be modelled and proposed, respectively. The test setup is also capable to be expanded to include power equipment such as PV inverters, storage units, etc. which are available at the host SmartEST infrastructure. Different vendors and manufacturers can also make use of the test setup to test their equipment in terms of interoperability and by identifying the scope of the service that the source of flexibility is providing for the power grid.

As improvements, the UG suggests the development of more advanced controllers and models for the different actors involved in the flexibility activation chain. Furthermore, more comprehensive scenarios could be covered which consider the simultaneous presence of different sources of flexibility at different grid nodes as well as the decision making algorithms for the activation of these sources based on the quality of service (as the objective function of the DSO, flexibility owner, intermediate aggregators, etc.).

7 Dissemination Planning

Accepted publication:

- J. Kazmi, A. Ahmadifar, M. Ginocchi, F. Kupzog, M. Cupelli, O. Genest, M. Calin, M. Savic and A. Monti. “Identification of common services in European flexibility demonstrators for laboratory-based interoperability validation’’, 8th International Conference on Renewable Energy Research and Applications (ICRERA), Brasov, 2019

Potential opportunities for further dissemination

- Open Access Journal by MDPI: Simulation-Based Validation and Design of Smart Grids
- Open Access Journal by MDPI: Smart Grid and Future Electrical Networks
- Open Access Journal by Energies: Monitoring and Control of Active Electrical Distribution rids and Urban Energy Grids
- 8th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, April 2020, Australia

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8 Annex

8.1 List of Figures

8.2 List of Tables