European Research Infrastructure supporting Smart Grid and Smart Energy Systems Research, Technology Development, Validation and Roll Out – Second Edition

Work Package WP5

NA4 - Iterative Creation of Scenarios and Test Case Profiles

Deliverable D5.2

D-NA4.2 Common Reference Test Case Profiles

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List of Abbreviations

CEC	Citizen Energy Community
CHIL	Controller Hardware-in-the-Loop
DER	Distributed Energy Resource
DFIG	Double-Fed Induction Generator
DMS	Distribution Management System
DRTS	Digital Real-Time Simulator
DuI	Domain under Investigation
EC	European Commission
EMS	Energy Management System
ERIGrid	European Research Infrastructure supporting Smart Grid and Smart Energy Systems Research, Technology Development, Validation and Roll Out
ES	Experiment Specification
EU	European Union
FACTS	Flexible Alternating Current Transmission System
FRT	Fault-Ride-Through
FS	Functional Scenario
FuI	Function under Investigation
FuT	Function under Test
HIL	Hardware-in-the-Loop
HTD	Holistic Test Description
ICT	Information and Communications Technology
IED	Intelligent Electronic Device
IP	Internet Protocol
JRA	Joint Research Activity
LEC	Local Energy Community
OuI	Object under Investigation
PHIL	Power Hardware-in-the-loop
PoI	Purpose of Investigation
PV	Photovoltaic
P2P	Peer-to-Peer
QS	Qualification Strategy
REC	Renewable Energy Community
RES	Renewable Energy Resource
RI	Research Infrastructure
R&D	Research and Development
SCADA	Supervisory Control And Data Acquisition
SuT	System under Test
TC	Test Case
TCP	Test Case Profile
TES	Thermal Energy Storage
TS	Test Specification
UC	Use Case

Executive Summary

Transforming an existing energy system to an intelligent system, a so-called smart grid, requires a multidisciplinary approach because of its complexity involving Information and Communications Technology (ICT) integration, amongst others. The technical challenges arise on how to integrate the new technology into the existing system considering the interoperability and performance. This requires new solutions involving testing scenarios, technology development, validation processes, and roll-out procedures. The ERIGrid 2.0 project aims to enhance the research infrastructures' capabilities and supports the research and technology development towards smart energy systems in Europe. This necessitates system-level testing before further deployment and roll-out. New innovative testing scenarios, Use Case (UC) and Test Case (TC) need to be developed, extended, updated, and shared with researchers and practitioners.

This report presents the "Common Reference Test Case Profiles" to serve as the reference TCs in the ERIGrid 2.0 project and also facilitates their application for interested external partners. Functional Scenario (FS) are used to define a high-level description of the TC. There are twenty-five TCs developed in the project which are mapped using the six FSs: 1) ancillary services provided by Distributed Energy Resources (DERs) and active grid assets, 2) microgrids and energy community, 3) sector coupling, 4) frequency and voltage stability, 5) aggregation and flexibility management, and 6) digitalisation. These six FSs can cover a significant proportion of relevant aspects of a multi-domain cyber-physical energy system.

To facilitate the implementation at Research Infrastructures (RIs), The Holistic Test Description (HTD) approach from the predecessor project ERIGrid is used to formulate the TC, for instance the system description, System under Test (System under Test (SuT)), Object under Investigation (OuI), Domain under Investigation (DuI), Use Case (UC) and Purpose of Investigation (PoI). In addition, each TC is defined with keywords to define the characteristics of the technological area, which is useful for the users to select the specific TC. The keywords are defined corresponding to four relevant dimensions: 1) domain under investigation, 2) the phenomenon under test, 3) type of assessment, and 4) test system/component. Each TC is individually presented as a document with the HTD template.

The TCs serves as the reference pool within and beyond ERIGrid 2.0 by providing, for example, identifying key uncertainties for developing various validation approaches, demonstration of the method for the coupling of real-time/co-simulation and Hardware-in-the-Loop (HIL) as well as approaches for setting up the experiment and collaborate with other RIs, projects, and initiatives.

1 Introduction

1.1 Purpose and Scope of the Document

This document presents Test Cases (TCs) that will serve as a reference for the activities in the ERIGrid 2.0 project. They are used to formulate a Test Case Profile (TCP) that will serve for the harmonisation of holistic test procedures, for example traditional laboratory experiments, cross Research Infrastructure (RI) configurations, or simulation case extensions.

The outcomes of these activities are reflected in TCs, which are each individually presented as a document with the format of the TC description created during the *European Research Infrastructure supporting Smart Grid and Smart Energy Systems Research, Technology Development, Validation and Roll Out (ERIGrid)*[1] project, thereby linking each TC to their respective Use Cases (UCs) and system configuration descriptions.

Additionally, this document presents a methodology that defines an iterative process for the interaction between the potential specific requirements of the TCs and the partners of the ERIGrid 2.0 project. Finally, this document shows a methodology to customise TCPs that address particular technology areas by selecting the FSs and keywords.

1.2 Structure of the Document

This document is organised as follows: Section 2 provides general information about the TC description template. Section 3 introduces the TC development process together with how the TCs can be linked with other activities in the ERIGrid 2.0 project. Section 4 presents the definitive list of developed TCs, describing the final outcome of a TC description by illustrating two exemplary TCs. Section 5 presents the description of the TCPs which are covering major technological areas. Finally, the conclusions of this work are presented in Section 6 followed by two example TCs in Appendix A: Test Case TC04 and Appendix B: Test Case TC09.

[1] https://erigrid.eu/

2 General Test Case Description

2.1 Holistic Test Case Description

A smart grid is a complex system that encompasses multiple disciplines (ICT, automation, physical infrastructure) and affects several physical domains (electricity, heating, energy storage, etc.), with causal interactions and feedback loops spanning across disciplines and domains (Heussen et al., 2019). Appropriate tests for multi-domain systems are harder to plan than tests within established disciplinary boundaries. Moreover, experimental platforms are being enhanced and interconnected to address the testing needs in smart energy. The growing complexity of multi-domain systems and their required experimental platforms were tackled by ERIGrid, i.e., the predecessor of ERIGrid 2.0. One of the outcomes of the project was a methodological tool, named Holistic Test Description (HTD), a useful methodology for guiding and supporting researchers in planning tests (*ERIGrid/Holistic-Test-Description: v0.5*, 2019; Heussen et al., 2019).

The HTD is composed of three templates – *1) Test Case (TC)*, *2) Test Specification (TS)*, and *3) Experiment Specification (ES)* – that are used as concrete steps in the methodology. In addition, the HTD provides two intermediate steps that have been incorporated facilitating the transition from each step to the next. These are the *Qualification Strategy (QS)* (a free form document) and the *RI Mapping* of the *ES*.

2.1.1 Test Case

The *Test Case (TC)* structures the motivation for a test. By combining narrative with graphical, qualitative, structured, and quantitative/formal elements, domain specifics are providing a shared testing context. There are three main parts of the TC:

- *Test Objectives* and *Purpose of Investigation (PoI)*: Main goals of the test, respectively in narrative form and analytical form;
- *System under Test (SuT)* and its function: Description of system functions and components aiming to isolate the focal points of the investigation; and
- *Test Criteria*: Further information of the test objectives in terms of measures of performance and behaviour, usually quantitative.

2.1.2 Qualification Strategy

The *Qualification Strategy (QS)* describes how the qualification goals (as defined in the TC) are to be met by a combination of tests. This step is recommended for more complex test designs, where multiple experiments and/or multiple RIs can be included.

2.1.3 Test Specification

The *Test Specification (TS)* defines a specific test design, including metrics, the domain configuration (test system), its parameterisation, inputs, measurements, metrics, and test sequences. The TS defines the description of the experiment whereas the experiment specification describes the experimental platform, i.e, the required equipment for testing.

2.1.4 Experiment Specification

The *Experiment Specification (ES)* defines how the experimental platform (testbed) is configured and used to realise an experiment. Formally, it is a mapping of a single TS to the components, structure, procedures, or simulation platform of a given RI.

2.1.5 Research Infrastructure Mapping

The *RI Mapping* is an optional step between TS and ES and helps the user to define the distribution (mapping) and execution of the specified test system in a given research infrastructure. This step is supported by a guideline document that includes three distinct methods (table method, tree method, and relaxation method). The scope of these methods is two-fold:

- Guide users in identifying the most suitable RI (one or many) to realise a given TS, and
- Aid users in the actual realisation of a TS through the mapping of an abstract test setup description onto actual RI components.

2.2 Structure of Test Cases in Context of Functional Scenarios

In Deliverable D5.1 (Raussi et al., 2020), a so-called *Functional Scenario (FS)* has been introduced as high-level description of UCs and TCs of potential interest for ERIGrid 2.0. A FS provides a qualitative description with the aim to collect and harmonise similar topics and UCs under the same umbrella scenario. Each FS comprises a short, informal description of the following contents:

- The *system description* states the physical system addressed in the FS,
- The *motivation* describes the overall purpose of the entire FS by explaining the problem that is to be solved and who is impacted by this problem,
- The *use case* addresses the functionality that the solution provides in normal operation and the intended function or behaviour of the system subject to testing,
- The *test case* describes how the solution can be tested,
- The *experimental setup* describes the equipment required to conduct the testing, and
- The *relevance* explains why and how the FS is relevant for ERIGrid 2.0.

Compiling the FS collection provided in Deliverable D5.1 (Raussi et al., 2020) served as a way to focus on specific application areas for further ERIGrid 2.0 activities. To continue this process and translate the qualitative FS content into a more formal framework for facilitating concrete laboratory implementations, this work relied on the concept of the HTD. The high-level content provided by each FS has been refined and broken down into specific HTD descriptions, defining concrete target criteria, variability attributes, and quality attributes via the following formal categories:

- The *System under Test (SuT)* identifies the system boundaries of the test system encompassing all relevant subsystems and interactions (domains) required for the investigation,
- The *Object under Investigation (OuI)* identifies the subsystem(s) or component(s) in scope of the test objective, and with respect to which the test criteria need to be formalised,

- The *Domain under Investigation (DuI)* identifies the relevant physical or cyber-domains of test parameters and connectivity,
- With reference to UCs, the full set of *Function under Test (FuT)* and the specific *Function under Investigation (FuI)* are identified, and
- The *Purpose of Investigation (PoI)* formulates the test objective, also stating whether it relates to characterisation, validation, or verification objectives.

3 Test Case Selection Process

The main objective of this work is to select and describe a set of TCs that are aligned to the FSs. These TCs will offer different reference profiles, focusing in major technology areas, such as microgrids, multi-energy systems, inverter-dominated grids, and cyber-physical systems, among others. These TCPs will serve references within the ERIGrid 2.0 project.

In the following, the methodology and selection criteria of the TCs are presented, in which an iteration process is defined for the continuous update of the alignments defined by the stakeholders of ERIGrid 2.0.

3.1 Test Case Selection Criteria

An important aspect to consider for the selection and description of TCs is requirements and expected outputs of ERIGrid 2.0. It is essential to define a methodology for exchanging the information and inputs between stakeholders to meet the expected ERIGrid 2.0 output. Figure 1 shows the methodology on how TCs are identified, redefined, and harmonised by using an iteration process with the partners of ERIGrid 2.0.

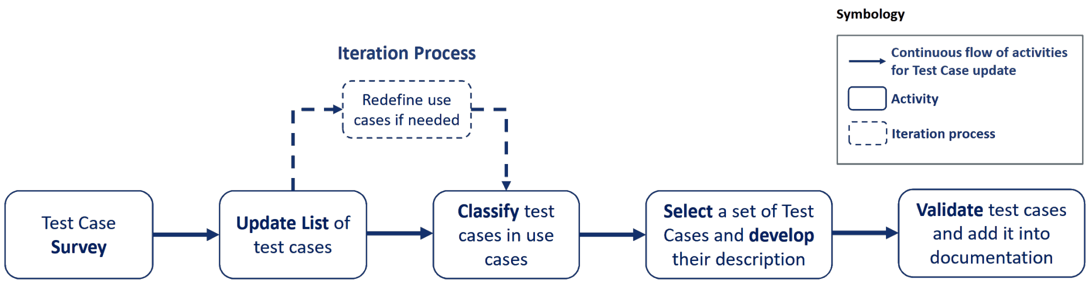

Figure 1: A process for TCs identification with iterative interaction.

This iteration process contains the following actions:

- *TC Survey*: A first set of TCs is collected by means of an initial survey[2] that was created at the beginning of this work, and answered by the partners in ERIGrid 2.0. The survey results provided a first list of TCs.
- *Continuous input from ERIGrid 2.0 partners*: The survey described in the previous point is kept open and available for all partners who wish to add TCs along the duration of ERIGrid 2.0.
- *Update of the list of TCs*: This action consists in adding the TCs that are proposed during the duration of the project to the list of TCs. New TCs might be proposed by either the working partners via the TC survey, or by ERIGrid 2.0 partners working on other activities.
- *Redefine UCs if needed*: This action consists in readapting the UCs to allow their assignment to the new TCs added in the TC list. This action is done only if needed, depending on the new TCs added to the test case list.
- *Classify TCs in TCs*: The TCs that are added to the list of TCs must be assigned to the respective UCs.

[2]https://umfrage.offis.de/index.php/669925?lang=en

- *Select a set of TCs and develop their description*: During this work, the involved partners select a set of TCs and develop their TC description according to the guidelines presented in Section 2. These TCs are selected by each partner according to their interests and maintaining a balance with regard to the amount of TCs per FS. While developing the TCs, partners working on the Joint Research Activitys (JRAs) are given the details of the TCs, and they can provide, if needed, requirements or comments for the TCs.
- *Validate TCs and add them into documentation*: Once a set of TCs are developed, their overall quality is checked (quality criteria are presented in Section 4.2), the TC is uploaded to a common repository (more information given in Section 4.3) and a set of keywords is assigned to them (more information presented in Section 5).

3.2 Mapping to Use Cases and System Configuration

The TCs developed within this work are part of a general structure denoted *"Functional Scenario (FS)"*. The main function of a FS is to collect and harmonise a set of similar topics. As described in (Raussi et al., 2020), a FS corresponds to an umbrella term which includes one or several system descriptions.

The system descriptions state the physical systems that are addressed in a FS, and may be linked to different UCs. A UC corresponds to the functionality that a certain solution provides in normal operation, reflecting the expected behaviour of a SuT. And finally, a TC description that indicates how a certain solution may be tested.

In Deliverable D5.1 (Raussi et al., 2020), a total of six FSs are identified:

- *FS1: Ancillary Services provided by DERs and Active Grid Assets*
- *FS2: Microgrids & Energy Community*
- *FS3: Sector Coupling*
- *FS4: Frequency and Voltage Stability in Inverter Dominated Power Systems*
- *FS5: Aggregation and Flexibility Management*
- *FS6: Digitalisation*

Additionally, Deliverable D5.1 (Raussi et al., 2020) defines a preliminary set of system descriptions, UCs, and TCs of each of these FSs. During the activities of this work, these elements are reassessed and updated to fit with the overall list of TCs identified by the stakeholder discussion.

As an overall result, the TCs that are identified following the methodology described in Section 3.1 are assigned to their respective FSs, system descriptions, and UCs.

In Table 1, the list of TCs identified for FS1 is shown, indicating the system configuration(s) and UCs to which each of them is assigned. Analogously, Table 2, Table 3, Table 4, Table 5, and Table 6 show the list of TCs identified for FS2, FS3, FS4, FS5, and FS6, respectively.

Table 1: List of TCs for the FS1.

System Descriptions →	Decentralised Networks				Inverter Functionalities				
Use Cases →	Voltage Regulation	Energy Losses Reduction	Power & Freq. Control	Active Network Mgmt	Power Quality Improv.	Specific System Service	Interaction between inverters & components	Ancillary Services/Functionalities	Dynamic behavior
Test Cases									
Evaluation of energy loss and cost reduction on distribution grid.	✓	✓							
Control of voltage with an on-load tap changer controller.	✓								
Assessment of ancillary services provision in island grids, weak grids or microgrids.	✓								
Characterization of communication latencies and synchronization of various measurements.			✓						
Characterization of power/energy response to DR signals.				✓					
Characterization and verification of aggregator portfolio, including management methodology.				✓					
Assessment of parallel operation between DERs and conventional power plants in interconnected grids.			✓	✓					
A simulated distribution network coupled to the hardware converter and DC source through a power amplifier.							✓		
Precise control of PV system operational settings (smart inverter) for reactive power and active power.						✓	✓		
Estimating possible THD caused by EV chargers on a specific network layout.			✓		✓				
Configuration of control systems of power electronics.							✓		
Configuration of hardware (multi-level converters, passive and active filters, etc.).							✓		
Secondary frequency control (distributed, decentralized, etc)			✓			✓			
Compliance with Fault Ride Through requirements in grid-connected inverter-based microgrids						✓		✓	
Black Start								✓	
Voltage control (Q-V, cosϕ-V, etc)			✓					✓	
Primary frequency control (P-f, virtual inertia, etc)			✓					✓	
Configuration of hardware (multi-level converters, passive and active filters etc).									✓
Configuration of control systems of power electronics									✓
Power efficiency characterization of a power inverter									
Interaction between inverters & components							✓		✓

Table 2: List of TCs for the FS2.

System Descriptions →	Synchronously connected microgrid		
		Local multi energy system	
		Islanded Microgrid	
Use Cases →	Distributed power quality support	Flexibility invocation by aggregator entities – implementation aspects	Self-consumption, P2P trading, and flexibility in multi-energy systems
Test Cases			
Interoperability characterization of a P2P Multi-Agent System			✓
Evaluation of cost-effective operation of P2P-based local energy system			✓
Characterization of flexibility response provided by small-scale DER/Prosumers		✓	✓
Evaluation of voltage control in distribution grid	✓		
Evaluation of frequency response in islanded power system	✓		
Evaluation of congestion management in distribution grid		✓	✓
Characterization of self-consumption capability			✓
Evaluation of secure transition from grid connected to islanded operation-Uninterruptible Power Supply	✓		
Characterization of Black-Start service provision	✓		

Table 3: List of TCs for the FS3.

System Descriptions →	electrical system + independent power-to-X units	electrical system + heat network + power-to-heat units		electrical system + heat network + gas network + X-to-Y units	
Use Cases →	Regulating power provision using independent power-to-X units	Regulating power provision in a coupled heat and power network	Thermal network optimization	Regulating power provision using X-to-Y units	Multi-energy system
Test Cases					
Characterization of power-to-X service availability and its impact on the electrical domain	✓				
Characterization of power-to-heat service availability and its impact on the networks		✓			
Verification of improved self-consumption of RES in a coupled heat and power network using power-to-heat			✓		
Characterization of X-to-Y service availability and its impact on the networks				✓	
Verification of real-time X-to-Y service provision in multi-energy systems					✓

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Table 4: List of TCs for the FS4.

System Descriptions →	Voltage Stability		Frequency Stability	Black-start
Use Cases →	Multi-level voltage control	Harmonic distortion	Frequency control using converter-interfaced resources	Black- start using distributed converter interfaced resources
Test Cases				
Coordinated DER+OLTC services at MV and LV level support mitigation of voltage violations	✓			
Harmonic distortion in the case of DER/EV high penetration	✓	✓		
Synthetic inertia and fast frequency response/control provided by converter-based resources			✓	
Coordinated Voltage Control	✓			
Testing Black- start capabilities using distributed converter interfaced resources				✓

Table 5: List of TCs for the FS5.

System Descriptions →	A single LV distribution feeder				
	MV/LV distribution networks				
Use Cases →	Aggregators offer congestion management services to DSO	Peer-to-peer trading platform for energy community management	Continuous service provision under disruptions	Frequency-based ancillary services provided from DER in the LV grid	Joining of local resource management system in Peer-to-peer trading platform
Test Cases					
Multiple aggregators offer grid services, congestion management request as an added feature	✓				
Evaluation of various service definitions and activation patterns		✓	✓		
Pre-qualification of service provision including software, communication, and flexibility characterisation aspects, and addition/removal of resources.	✓		✓	✓	
Extrinsic TSO signal triggers flexibility reserves at distribution network level focusing on local control, DER capability and communication aspects.				✓	
Test methods for integration/interoperability assessment for building and resource-level management systems in participation with peer-to-peer platform.		✓			✓
Evaluation of unintended impacts of activation of flexibility resources on the quality of supply.			✓	✓	
Impact evaluation of vulnerabilities for new security issues such as load altering attacks on the quality of supply.		✓	✓		

Table 6: List of TCs for the FS6.

System Descriptions →	Digital Substations							
	Distribution feeder							
						Full power system		
Use Cases →	Automated grid operation and distributed coordination - Network monitoring	Automated grid operation and distributed coordination - Resilient aggregation	Automated grid operation and distributed coordination - Novel service restoration	Substation automation and protection - Novel fault location	Substation automation and protection - System integration	Cybersecurity - Cyber resilience	Cybersecurity - Intrusion detection	Cybersecurity - Impact analysis
Test Cases								
Performance characterisation of novel monitoring concepts (e.g. multi-source state estimation)	✓							
Verification of the reliability of a redundant system or algorithm (e.g. failover)		✓						
Proof-of-concept validation of novel concepts+ algorithms (e.g. autonomous service restoration, fault location)			✓	✓				
Performance characterisation (of new equiments, comm. technologies)					✓			
Interoperability testing					✓			
Verification of resilience of ICT infrastructure						✓		
Performance characterisation of intrusion detection mechanism							✓	
Validation of impact analysis model								✓

3.3 Testing Approaches

As previously mentioned, the TCs developed in this work serve as a reference for other activities in ERIGrid 2.0. In this section, a more thorough description of the synergies between this work and other activities in ERIGrid 2.0 is given. Additionally, a general description of the different testing approaches that may be employed in the developed TCs is given.

The TCs will serve as a reference especially for the following activities:

- *JRA1 – Enhanced Validation Methods, Concepts, Procedures, and Benchmark Criteria*
  The objective of this activity is to develop a systematic framework for TC validation that can be applied to the developed TCs of this work. This necessitates the use of statistical methodologies to consider relevant variances to enhance the design of the experiment. A set of TCs from this work serve as the TC pool in JRA1 to perform the different test setups. The goal of JRA1 is to develop methods and guidelines for holistic testing considering comparability, reproducibility, and scalability.
  - *JRA1.1 – Reference Setups and Benchmarking:* The main aim of JRA1.1 is to develop benchmarks for analysis of multi-domain energy system configurations spanning across power systems, ICT, and energy vectors. The reference benchmark systems are set up based on the inputs from the TC development in this work.
  - *JRA1.2 – Uncertainty Representation and Validation Methods:* JRA1.2 aims to develop suitable validation methods to represent the qualification of uncertainties parameters and quantifying uncertainties within the benchmark systems. This can be done by using the statistical methods to address the key uncertainties for holistic

testing. A set of TCs developed in this work can be used to identify key uncertainties to develop different validation approaches.

- *JRA2 – Improved and Extended Real-Time/Co-simulation and HIL Tools*
  This activity aims to develop the interconnecting capabilities of multiple instances of non-real-time simulators, real-time simulators, HIL components, and physical laboratory equipment. The TCs from the basis for the testing and validation of the JRA2 developments.
  - *JRA2.1 – Multi-domain Co-simulation & JRA2.2 – Real-time Coupling and Hardware-in-the-Loop Approaches:* The key focus of JRA2.1 is on multi-domain co-simulation and of JRA2.2 is real-time coupling and HIL. This covers aspects such as coupling of simulators with different time scale dynamics, co-simulation between multiple domains, and distributed control systems. The TCs developed within this work serve as baseline for testing and validation of the JRA2.1 developments.
  - JRA2.3 – Configuration Management: Configuring and managing TCs that interconnect different simulators and/or RIs spanning multiple organisations is considered challenging (complexity) and error prone(manual operation). Hence, JRA2.3 aims to develop an approach using multi-domain and multi-RI system descriptions for automatically configuring the simulation/experimental setup, and (centrally) managing the configurations. This activity will focus on the TCs developed in this work that incorporate more than one domain and simulator across different RIs.
- *JRA3 – Improved and Extended Services (RI integration, coupling, and automation)*
  The broad objective of JRA3 is to augment and extend the development of standardised laboratory interfacing and data exchange services. Hence, TCs developed within this work with an experimental focus spread across multiple laboratories will directly be applied in JRA3.1 and JRA3.2.
  - *JRA3.1 – Distributed Laboratory Middleware:* This activity will focus on the development of a distributed laboratory middleware solution to enable seamless integration between multiple RIs. Relevant TCs from this work that can be distributed across multiple laboratories will be used to test the developed middleware solution.
  - *JRA3.2 – Data-as-a-service Prototype:* JRA3.2 will serve as a proof of concept for multi-RI integration. The main objective of this activity is to demonstrate how the developed middleware from JRA3.1 satisfies requirements to combine multiple distributed simulators as part of a larger joint simulation experiment. This activity will follow JRA3.1 in using the TCs to demonstrate the middleware features.
  - *JRA3.3 – Extended Services for Integrated Real-Time and non-Real-Time environments:* JRA3.3 is intended to close several automation gaps, some of which were identified as major efficiency drains during the experimental work conducted in the ERIGrid project. JRA3.3 is expected to interact with this work in two ways. Near the start of the JRA3.3 activities, the TC collection will be used to set an appropriate level of ambition within the available resources. Secondly, JRA3.3 can be expected to define reference tests for the functionality developed within the activity. These reference tests will likely take the form of additional ESs (and possibly extensions to existing TSs) and will be provided to this work for consideration as amendments to existing TCs.
  - *JRA3.4 – Simulation Setup Automation:* The main activities of this task are to develop tools for RI connection management, automation of test configuration and ex-

ecution, data logging, and scenario handling. Therefore, the experiences resulting from the implementation of TCs selected from this work will benefit the development activities of the task. In the reverse direction, the final outcome of the task can be applied for reducing the effort of running these TCs.

- *JRA4 – Integration and Demonstration of Services in the Extended Research Infrastructure*
  JRA4 will demonstrate the services made available by the extended RIs, composed by a combination of simulators, HIL and physical laboratories. The integration of the RIs allows to take into account additional domains that are not locally available, and which can be provided by another facility in terms of simulation or physical components. In this activity several testing methodologies will be applied; from simulation to co-simulation, from HIL to distributed physical laboratories. In particular, the following tasks will use the TCs and FSs defined in this work for outlining the TCs to be implemented in JRA4.3.
  - *JRA4.1 – Test Cases Definition:* This task will define the TCs to be demonstrated in JRA4.3 using the HTD. JRA4.1 will take as input the list of TCs and FSs defined in this work and will select a narrow list of representative TCs and services that require RIs integration.
  - *JRA4.3 – Demonstration of the Services in the Extended Research Infrastructure:* This task will perform the experiments defined in the TCs formulated in JRA4.1. The TCs will include single and multiple RIs experiments and several testing methods (i.e., co-simulation, pure hardware, Power Hardware-in-the-loop (PHIL) and a combination of them).

4 Test Cases and Corresponding Descriptions

4.1 Example of a Test Case

To describe how TCs are formed and how their contents are defined, two exemplary TCs will be presented in this section. In particular, the Test Case TC04 "Investigation of different voltage control techniques for inverter-interfaced DERs in microgrids" and the Test Case TC09 entitled "Evaluation of congestion management in distribution grid" will be described.

TC04 aims to investigate the voltage control schemes for inverter-based microgrids, i.e., microgrids that are formed from inverter-interfaced DERs. In addition, TC09 intends to evaluate different congestion management methods in distribution grids under the circumstance of high penetration of DERs and other active loads such as electric vehicles, heat pumps, and so on. The general idea of TC09 is provided in Figure 2. All the details of those two exemplary TCs are provided in Appendix A: Test Case TC04 and Appendix B: Test Case TC09

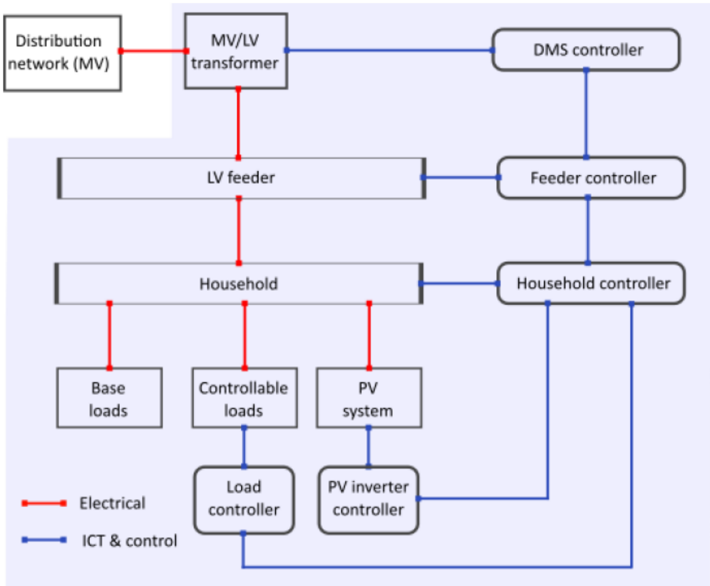

Figure 2: An example SuT of TC09.

As it can be observed from the detailed descriptions of TC04 and TC09, the initial parts of the TC are focussing on the wider concept and more specifically on highlighting the narrative of the TCs. Further, the focus is set on defining the function, object, and DuI as well as the SuT and the FuT. As an example, the DuI of both TC04 "Voltage Control" and TC09 "Congestion Management", is electrical power and control systems. In the sequel, the test criteria and target metrics of the TCs are given in Section 5.

Then, the QS for each TC is provided, followed by the TS which starts with its rationale and the specific test system, given in graphical form. As an example, in TC04, for the TC under discussion, a Controller Hardware-in-the-Loop (CHIL) simulation setup is shown, comprised by an Digital Real-Time Simulator (DRTS) and a real-time PC. Similarly, in TC09 a single-line diagram of a realistic DER-dominated distribution network with detailed load, solar, and wind profiles is provided. This part of the TC also defines the input and output parameters, the test design and the initial system state. Finally, any source of uncertainty or any suspension/stopping criteria are given at this point.

At the final part of the TC, the ES is shown. In particular, the experiments associated with each TS are given. As an example, for the Test “Performance of Different Voltage Control Techniques for Inverter-Interfaced DERs in Microgrids” of TC04, three experiments are defined to meet the PoI. Other instance can be seen in the two experiments in TC09. The first experiment is a co-simulation setup between DIgSILENT PowerFactory and Mathworks MATLAB, with mosaik being the master algorithm. The second experiment is a simulation in Mathworks MATLAB with a local service model developed in Mathworks Simulink. Under each ES, the RI, the experiment setup, the precision of the equipment, and the storage of the experiment data are discussed among others.

4.2 Quality Guidelines for the Test Cases

Once the TCs had been submitted, to guarantee a consistency in quality, each case has gone through a quality check process.

As this process was carried out by different people, a set of guidelines was designed to provide a standard quality check output in order to give consistent feedback to the corresponding authors. The process was designed not to be as in-depth as a full peer review process (this should already have been carried out before the submission stage), but to focus on the following factors:

- *Completeness and correctness:* Each TC is submitted in a standard template. The objective of this check is to verify that each of the necessary corresponding template sections is complete and that they are completed with the correct information.
- *Logical story line:* Considering completeness and correctness, the objective of this check is to verify that the main content of the TC is understandable and follows a logical structure, identifying any conceptual gaps.
- *Language:* This check is a standard English spelling, grammar, and sentence formatting verification.

Upon completion of the quality check process, feedback is given to the corresponding authors to make final amendments before submitting the final version of their TC.

4.3 Developed Test Cases

The TCs identified and developed throughout the activities of this work are listed in Table 7. They are also made available in a corresponding public repository[3].

[3] https://github.com/ERIGrid2/Test-Cases

Table 7: List of identified and developed ERIGrid 2.0 TCs.

#	Name of the TC	FS Ref.
TC01	Control of voltage with an on-load tap changer controller	FS1
TC02	Complying with the Fault-Ride-Through (FRT) requirements in inverter-based droop-controlled microgrids	FS1
TC03	Real-time supervision of a Photovoltaic (PV) system and control of operational settings for centralised active power limitation and localised voltage regulation	FS1
TC04	Investigation of different voltage control techniques for inverter-interfaced DERs in microgrids	FS1
TC 05	Power efficiency characterisation of PV inverters	FS1
TC06	Evaluation of frequency restoration response in islanded power system	FS2
TC 07	Evaluation of cost-effective operation of Peer-to-Peer (P2P)-based local energy system	FS2
TC08	Evaluation of voltage control in distribution grids	FS2
TC09	Evaluation of congestion management in distribution grid	FS2
TC10	Evaluation of secure transition from grid-connected to islanded operation: uninterruptible power supply	FS2
TC11	Characterisation of power-to-heat service availability and its impact on the networks	FS3
TC12	Verification of improved self-consumption of Renewable Energy Resources (RESs) in a coupled heat and power network using power-to-heat	FS3
TC13	Characterisation of hydrogen storage scale for power systems support and services	FS3
TC14	Synthetic inertia and fast frequency response/control provided by converter-based resources	FS4
TC15	Smart grid control algorithm – optimal centralised coordinated voltage control	FS4
TC16	Testing black-start capability using distributed converted interfaced resources	FS4
TC17	Fault tolerance/ recovery of a multi-aggregator dispatch mechanism	FS5
TC18	Evaluation of various service definitions and activation patterns	FS5
TC19	Evaluation of unintended impacts of activation of flexibility resources on the quality of supply	FS5
TC20	Test methods for integration/interoperability assessment for building and resource-level management systems in participation with aggregation platform	FS5
TC21	Performance characterisation of new equipment and communication technologies	FS6
TC22	Resilience assessment of ICT infrastructure	FS6
TC23	Verification of the reliability of a redundant system or algorithm (e.g., failover)	FS6
TC24	Interoperability testing and validation in the activation chain of flexibility-related events in a local distribution network	FS6
TC25	Cyber-security of digital substations and impact analysis	FS6

5 Definition of a Test Case Profile

5.1 Profile Approach

The output of this work is not only to define a set of exemplary TCs aligned to the FSs, but also to define a small number of generalised Test Case Profiles (TCPs) for major technological areas.

To create those profiles for the major technological areas, multiple clusters of TCs are defined according to a particular set of keywords. The set of keywords defines the characteristics of the technological area and the TCs within the corresponding cluster compose the Test Case Profile (TCP). The keywords are simple but sufficiently clear for untrained users to identify and create TCPs, simply by selecting keywords based on their particular interests. The corresponding information for the creation of customised TCPs is given in Section 5.2.

To provide a methodical approach to the TC profiling challenge, a multidimensional approach was considered during this work. The benefits of the multidimensional methodology is to provide a convenience for users to be able to identify relevant examples with different aspects, and to classify new TC contributions. Each TC can be viewed from three different dimensions namely objective, method, and system. This method can help the users to generalise the TC with two abstract levels. First, it focuses on a generalised specification (*Objective + Method*) and then identifies a possible implementation (*Objective + Method + System*).

The three dimensions can address the high-level requirement of the TC:

- **Objective**: Address *"Why is a TC being investigated'?"* to define the phenomenon under the test.
- **Method**: Address *"How can a TC be investigated?"* to tackle the problems.
- **System**: Address *"What is a system of a TC to be conducted?"* to apply in a given system.

Defining an appropriate TC under the multidimensional method mentioned above is not limited to only one keyword under each dimension. As a result, a set of keywords are defined under each dimension to help the users to select the profile that meets the objectives and requirements for the experiment.

This work activity applies three dimensions including a new dimension extension of the DuI and also proposes minor name changes from the original ones for the convenience of intended users. The four relevant dimensions for profiling the developed TCs are as follows:

- Domain under Investigation (DuI),
- Phenomenon under Test,
- Type of Assessment, and
- Test System/Components.

For each one of these dimensions, different keywords (cf. Table 8-11) are identified and described with simple explanations especially for external users who are not familiar with the technical terminology.

Table 8: Keywords for TCP Dimension 1: Domain under Investigation.

Dimension 1: Domain under Investigation (DuI)	
Keyword	**Description**
Control	This domain comprises the logic, algorithms, and signal definitions for controllers. The communication network is not included.
Electrical Power	The domain of electrical power generation, transmission, management, and/or consumption.
Heating/Cooling	Energy consumption for heating and cooling purposes (buildings, industrial processes, etc).
ICT	This domain consists of the communication medium and systems used to transfer and access data.
Market	This domain deals with purchases, through bids to buy; sales, through offers to sell; and short-term trading, generally in the form of financial or obligation swaps, of energy.
Mechanical	This domain includes all mechanical systems that concern forces and movements.
Thermal	Physics associated with thermal effects like the thermal stress of a component.

Table 9: Keywords for TCP Dimension 2: Phenomenon under Test.

Dimension 2: Phenomenon under Test	
Keyword	**Description**
Transient Response	The (electro-magnetic) system response to a stepwise perturbation of a steady state.
Frequency Stability	The ability of a power system to maintain steady frequency following a severe system upset resulting in significant imbalance between generation and load.
Short Circuit Behaviour	Response of a power system or electrical component to short circuits.
Rotor Angle Stability	Stability of conventional synchronous generators due to lack of synchronising torque or small-disturbance stability due to lack of damping.
Congestion	Restriction of transmission of electrical power throughout two or more voltage levels because the transmission capacity of the elements (e.g., power lines, cables) connecting those voltage levels are reached.
Power Balance	Phenomena that concern the constraint that power produced and the power consumed must be equal on average for a given reference time frame.
Energy Balance	Accounting of the total amount of energy extracted from the environment, traded, transformed, and used/consumed by end-users.
Ancillary Services	Services to support the power system operation, acquired by system operators. Service typically measured on the point of common coupling.
Fault Event Sequence	Response following a sequence of abnormal events (e.g., short-circuits, sudden disconnection of components, N-2 contingency).
Cascading Failure	Situation in which the sudden failure of a component has the consequence of producing the sudden disconnection of one or more components.
Voltage Stability	The ability of a power system to sustain a fixed tolerable voltage at every single bus of the network under standard operating conditions as well as after being subjected to a disruption.

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Voltage Quality	Variation of voltage like voltage flicker, violation of voltage bounds, etc.
Harmonic Distortion	Distortion caused by nonlinear characteristics of electronic components, that generate unwanted harmonics of the fundamental frequency.
Harmonic Stability	Phenomena that relate to waveform distortions in frequencies below and above the fundamental frequency caused by small-signal stability problems (e.g., subsynchronous resonance interaction between Flexible Alternating Current Transmission System (FACTS) and Double-Fed Induction Generator (DFIG) wind turbines).
Small-signal Stability	Power system small signal-stability investigation (e.g., tuning of power system stabiliser of a synchronous generator).
Communication Phenomena	Any occurrence, event or observed situation happening in the communication medium or in the domain of ICT.
Package Loss	Communication phenomenon – response to discarded packages (basic Internet Protocol (IP) mechanism).
Cyber-security Events	Any occurrence in an information system or network that has, or may potentially result in, unauthorised access, processing, corruption, modification, transfer, or disclosure of data.
Communication Delays	Time elapsed between the emission of a communication package from a particular component and its reception at a particular component.
Communication Congestion	Reduced quality of service due to the communication link overloading caused by the incoming data being sent faster than the link is able to manage.
Sector Coupling	Phenomena resulting from the exchange of energy between two or more energy sectors, affecting energy carriers such as electricity, heat, and gas.
Economic Performance	Economic outcome of a service (e.g., provision of an ancillary service) or a market mechanism (cost/benefit, profit analysis, etc).

Table 10: Keywords for TCP Dimension 3: Type of Assessment.

Dimension 3: Type of Assessment	
Keyword	**Description**
Characterisation	Process in which the behaviour of a function or component is quantified through one or more experiments.
Verification	Process to prove or establish accuracy according to the requirements and specifications.
Validation	The process of assuring that a product, service, device, or system meets the needs of the customer and other identified stakeholders.
Device Compliance Verification	Checking the conformity of a device with a legislative or regulatory requirement, or a recognised standard.
Functional Performance	Testing according to functional specifications, resulting in quantified performance.
Technical Feasibility	Assessment of the functionalities of components.
Controller Conflicts	Situation in which the action of one or more controllers in one or more particular variables opposes the action of other controller(s) on at least one or more of these variables, resulting in a quantifiable performance deterioration.
Interoperability Testing	Testing to check whether two or more software or hardware entities are compatible and capable of interacting.
Cyber-security Performance/Resilience	Evaluation of the capacity to withstand to/recover from abnormal situations.

Control System Functional Verification	Process in which a control system is subjected to one or more tests to verify that it functions according to what is expected.
Communication Performance	Communication performance aspects like bandwidth, delay, etc.
Protection Equipment Response	Assessment of protection behaviour (e.g., selectivity, sensitivity, response time).
Device Testing	Evaluation of a physical device.
Software Testing	Method to check whether a software matches expected requirements.
Algorithm Testing	Process in which an algorithm is subjected to one or more situations (test) with the aim of determining if it complies with its objectives.
Normal Condition	Testing under standard operating conditions.
Fault Condition	Induction of abnormal state like short circuit or ground fault.
ICT Failure Impacts	The study of the consequences of an ICT failure (for testing fall-back mechanisms, reliability/resilience, etc.).
Configuration Failure Impact	Response of a solution to accidental or intentional ICT misconfigurations.

Table 11: Keywords for TCP Dimension 4: Test System/Components.

Dimension 4: Test System/Components	
Keyword	**Description**
DER aggregate	Collection of distributed energy resources.
Microgrid	A decentralised group of electricity sources, loads, and storage that normally operates connected to and synchronous with the traditional wide area synchronous grid (macrogrid), but can also disconnect to “island mode” and function autonomously as physical or economic conditions dictate.
Local Energy Community (LEC)	Organised community internally managing energy supply, consumption and storage; defines a (virtual) system boundary toward the energy system like Citizen Energy Community (CEC) or Renewable Energy Community (REC) defined by the European Commission (EC); being not a microgrid, the community is defined in economic, legal, and social terms, not technically.
Low Voltage Grid	Part of the electric power distribution system which carries electric energy from distribution transformers to end customers at voltages lower than 1 kV.
Medium Voltage Grid	Part of the electric power system which connects the high voltage electrical system to a geographical area of consumers in lower voltage levels.
High Voltage Grid	Electric power transmission system, including set of upper voltage levels used in power systems for bulk transmission of electricity.
Heat Network	Infrastructure that transports heat between producers and consumers within a district or city, by circulating water through pipes.
Gas Network	Infrastructure that transfers gas from the gas producers to the consumers.
Energy Market	System, components, subsystems and/or processes that deal specifically with the energy trading.
Communication Infrastructure	The communication systems and devices.
ICT Aggregation Platform	Infrastructure for managing, acquiring data and distributing setpoints to a large number of distributed resources.

Control Devices/ Intelligent Electronic Devices (IEDs)	IEDs that receive data from sensors in the power equipment and can give/receive commands and information (e.g., remote inputs/setpoints) based on a programmable logic.
DMS/EMS/SCADA	DMS/EMS/SCADA are collections of applications for monitoring and controlling of infrastructures and systems, e.g., distribution grid.
DER Controller	A controller attached/associated with a DER device to control and/or monitor the various controllable aspects and the generation.
Energy Market Agents	Entities directly interacting with an energy market, e.g., through submitting bids.
DER Device	Decentralised and modular generators, flexible loads, and storages, typically with rated capacity lower than 10 MW.
Heat Consumer	Entity that consumes energy in the form of heat.
Sector Coupling Component	A part or device which integrates at least two sectors such as electricity, heat, or gas.
Heat Storage	A subtype of Thermal Energy Storage (TES) technology that stocks thermal energy by means of a heating storage medium so that the stored energy can be used at a later time for heating applications and power generation.

Exemplary TCPs are presented in the following section, presenting the keywords to obtain the corresponding cluster of TCs and the major technological areas addressed by the set of keywords.

5.2 Test Case Profiles

This section presents a set of exemplary TCPs according to the definition given in Section 5.1.

Since the purpose of this work is to define TC profiles applicable in ERIGrid 2.0 projects, it is essential to identify the technological areas for future demonstrations and experiments. Multiple instances of non DRTS, DRTS, HIL components, and physical laboratory equipment are essential to be integrated in order to accommodate tests which span multiple test infrastructures and multiple domains.

These considerations brought us to the definition of the following three major technological areas:

- *Active electrical distribution grid:* Pure electrical network where several types of DERs and loads are connected.
- *Multi-domain energy systems:* Coupling of multiple energy vectors related to the smart grid environment.
- *ICT-enhanced energy systems:* Combination of multiple domains integrated in a power system, including ICT. In contrast to the first major technological area, here the ICT impacts on the energy system behaviour.

These major technological areas cover most of the requirements of the ERIGrid 2.0 project and allow to have a broad range of TCs to choose from for testing activities. Many other technology areas can be identified but this is out of this work scope.

Every major technological area corresponds to a set of keywords for each dimension defined in Section 5.1. Indeed, a major technological area involves multiple TCPs, which, in turn, can be identified as a restricted set of keywords that clusters it. The following subsections provide the keywords corresponding to each major technological area and some examples of TCP.

5.2.1 Test Case Profile for Active Electrical Distribution Grid

The “Active Electrical Distribution Grid” major technological area includes only the electrical power domain, avoiding the interaction with other domains and focusing on the behaviour of the electrical distribution grid. Under this area, several phenomena related to the electrical domain can be investigated, from transient to steady-state analysis. Since the ICT domain is not included, assessment related to the communication are not considered. This area is designed for power system testing, particularly for validation of algorithms and controls; device testing is not included. Lastly, “Active Electrical Distribution Grid” covers TCs related to validation processes, more attractive for Research and Development (R&D) activities. All characterisation and verification methods are not part of this area. Table 12 shows the keywords assigned to the “Active Electrical Distribution Grid” major technological area and spreads over six functional scenarios.

Table 12: Keywords and their associated TCs for the major technological area “Active Electrical Distribution Grid".

		Domain Under Investigation	Tested phenomenon										Type of Assessment													Test System/Components					
Functional Scenario	Test case	Electrical Power	Transient Response	Frequency Stability	Short Circuit Behaviour	Congestion	Power Balance	Energy Balance	Ancillary Services	Fault Event Sequence	Cascading Failure	Voltage Stability	Functional Performance	Technical Feasibility	Controller Conflicts	ICT Failure Impacts	Configuration Failure Impact	Control System Functional Verification	Fault Condition	Normal Condition	Communication Performance	Protection Equipment Response	Validation	Device Testing	Algorithm Testing	DER aggregate	Microgrid	Local Energy Community	Low Voltage Grid	Medium Voltage Grid	DER Controller
FS1	TC1	✓										✓	✓							✓			✓	✓					✓	✓	
	TC2	✓	✓		✓				✓	✓		✓	✓	✓	✓			✓	✓				✓		✓		✓		✓	✓	✓
	TC3	✓							✓			✓						✓						✓	✓				✓		✓
	TC4	✓	✓						✓			✓						✓		✓			✓	✓			✓		✓	✓	✓
	TC5	✓											✓	✓						✓				✓							✓
FS2	TC6	✓		✓			✓		✓				✓					✓		✓			✓		✓		✓		✓		✓
	TC7	✓					✓	✓												✓	✓		✓		✓			✓	✓		✓
	TC8	✓																		✓			✓			✓	✓	✓	✓	✓	✓
	TC9	✓				✓			✓									✓			✓				✓	✓		✓	✓	✓	✓
	TC10	✓	✓	✓								✓	✓					✓				✓	✓				✓		✓		✓
FS3	TC11	✓						✓				✓	✓															✓	✓		
	TC12	✓						✓				✓	✓															✓	✓		
	TC13	✓					✓	✓	✓				✓																		
FS4	TC14	✓	✓	✓					✓				✓										✓								✓
	TC15	✓	✓				✓		✓			✓	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓		✓	✓	✓
	TC16	✓	✓	✓						✓	✓	✓		✓					✓	✓			✓	✓	✓					✓	
FS5	TC17	✓											✓			✓			✓						✓	✓			✓	✓	✓
	TC18	✓				✓			✓			✓	✓					✓		✓					✓	✓		✓	✓	✓	✓
	TC19	✓				✓			✓			✓	✓	✓		✓			✓	✓						✓			✓	✓	✓
	TC20	✓											✓							✓	✓		✓		✓	✓		✓			
FS6	TC22	✓									✓					✓	✓						✓								
	TC24	✓					✓	✓	✓			✓									✓		✓						✓	✓	✓
	TC25	✓								✓						✓	✓		✓		✓	✓									

Each TCP is created by selecting one keyword per domain, and results in a group of TCs for which those keywords are assigned. Many TCPs can be defined in the context of this area, ideally equal to the number of possible keyword combinations. For this reason, only two examples are reported here. Figure 3[4] shows two exemplary TCPs.

[4] The figure refers to the ID of the TCs, which can be consulted in Table 7 in Section 4.3.

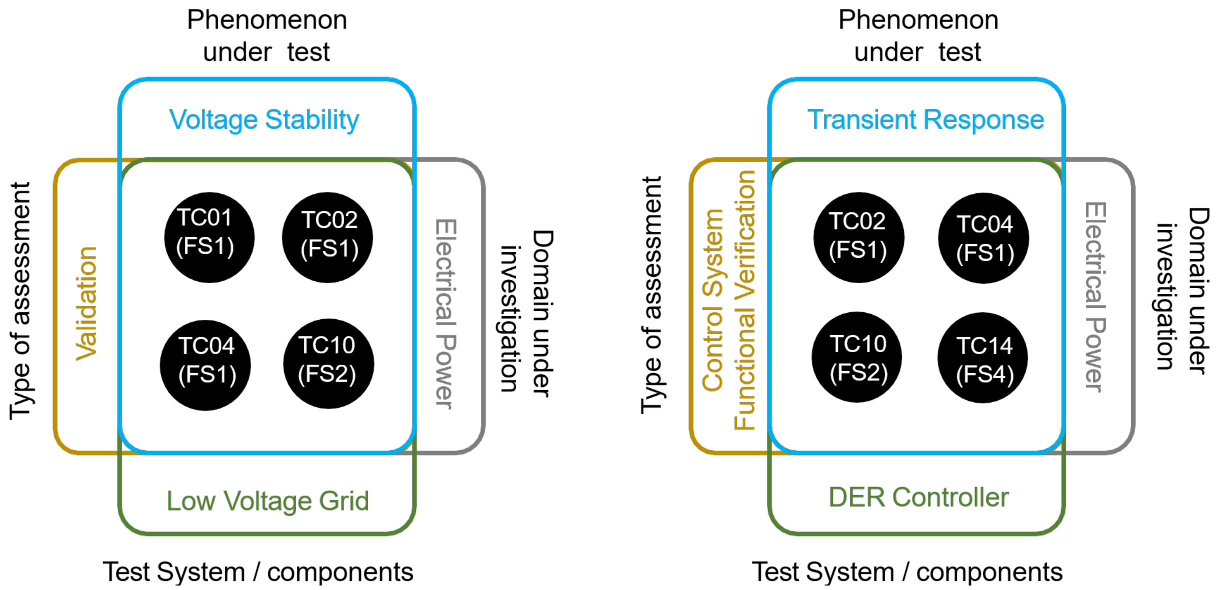

Figure 3: Two examples of TCPs corresponding to the major technological area "Active Electrical Distribution Grid".

5.2.2 Test Case Profile for Multi-Domain Energy Systems

"Multi-domain Energy Systems", predominantly resulting from sector coupling involve the exchange of energy flexibility across sectors, for example by utilising the flexibility of a heat storage and associated heat pumps to offer energy services to the stakeholders in the electricity network. TCs in this profile typically aim to quantify or validate the mutual benefits achieved through cooperation across domains.

Figure 4 shows the two keyword profiles for four specified TCs related to multi-domain energy systems. Two of the TCs concern sector coupling phenomena, where in both cases a district heating network is included in the test system configuration, where the investigated functional performance of sector coupling controls is investigated. In the second identified keyword profile, both TCs quantify the economic performance of flexibility solutions involving heating and cooling from the perspective of the heat consumer. Beyond the common keywords, assessments such as controller conflicts and control algorithm testing can be highlighted.

Table 13: Keywords and their associated TCs for the major technological area "Multi-domain Energy System".

Functional Scenario	Test case	Domain Under Investigation: Heating and Cooling	Tested phenomenon: Congestion	Power Balance	Energy Balance	Ancilliary Services	Communication Phenomena	Voltage Stability	Voltage Quality	Sector Coupling	Economic Performance	Type of Assessment: Functional Performance	Controller Conflicts	Normal Condition	Characterisation	Verification	Validation	Algorithm Testing
FS2	TC7	✓		✓	✓		✓				✓			✓	✓		✓	✓
FS3	TC11	✓	✓	✓		✓				✓		✓	✓		✓			
	TC12	✓			✓			✓	✓	✓		✓				✓		
	TC13	✓			✓	✓				✓	✓	✓			✓	✓		

Functional Scenario	Test case	Test System/Components: DER aggregate	Microgrid	Local Energy Community	Low Voltage Grid	Medium Voltage Grid	Heat Network	Gas Network	Energy Market	Communication Infrastructure	ICT Aggregation Platform	Control Devices / IED	DER Controller	Energy Market Agents	DER	Heat Consumer	Sector Coupling Component	Heat Storage
FS2	TC7			✓	✓				✓	✓	✓		✓	✓	✓	✓		
FS3	TC11			✓		✓	✓						✓		✓	✓	✓	✓
	TC12			✓	✓		✓					✓				✓	✓	✓
	TC13					✓		✓				✓				✓	✓	

Figure 4 shows two examples of TCs with the different phenomena, test system and type of assessment. One example is related to the function performance with a heat network that focuses on the local energy community like TC11 and TC12. Another example derives for the heat consumer to characterise the behaviour of function or component like in TC07 and TC12. These four TCs under the multi-domain energy are strongly related to the FS in Table 3.

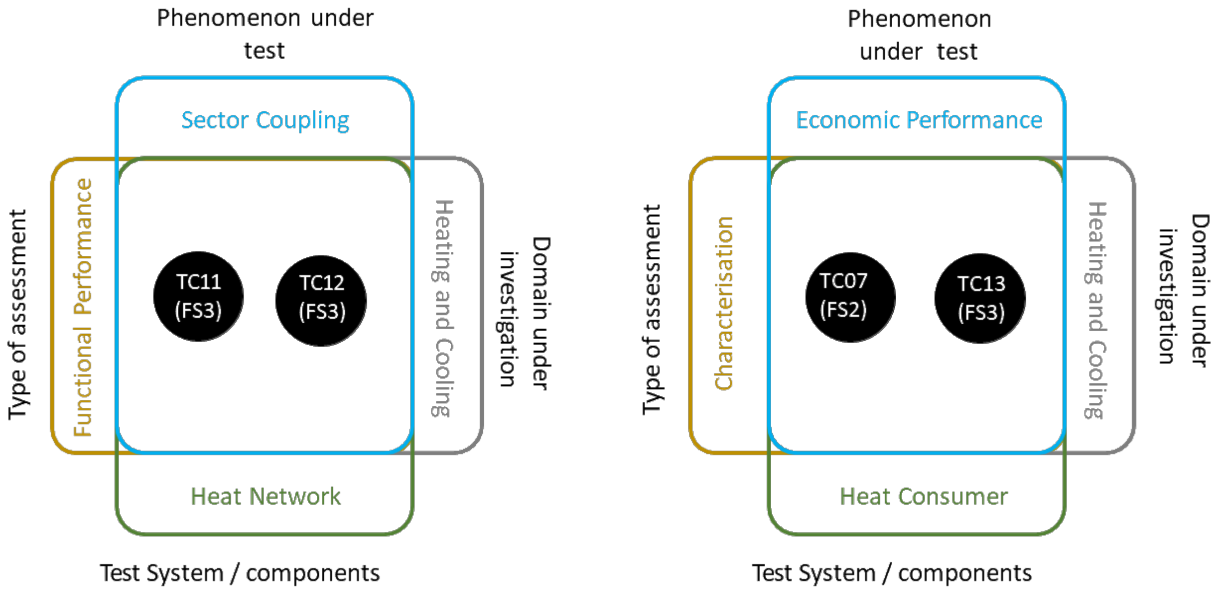

Figure 4: Two examples of TCPs corresponding to the major technological area “Multi-domain Energy System”.

5.2.3 Test Case Profile for ICT-enhanced Energy Systems

The TC profiles for “ICT-enhanced Energy Systems” combine the domains of electrical systems and associated ICT infrastructure as a major technological area and focus on the interaction between the electrical system and ICT network. Therefore, all the topics under the domain of ICT are highlighted in this TCP including testing the impact of different phenomena in the ICT sphere, such as latency, package loss, congestion, and cyber-security events, on the operation of the electrical system under both normal and fault conditions.

This TCP assesses the impact of ICT failures and functional performance of the ICT network including device and algorithm testing within characterisation, verification and validation. Apart from communication infrastructure, also ICT aggregation platforms, control devices, IEDs, and management systems are relevant which closely interlink the two domains. There are thirteen TCs relevant for this major technological area, which are portrayed in Table 14 along with the relevant keywords.

Figure 5 shows two exemplary TCPs. Each of them is created by selecting one keyword per domain, and, result in a group of TCs for which those keywords are assigned.

Table 14: Keywords and their associated TCs for the major technological area "ICT-enhanced Energy Systems".

Functional Scenario	Test case	Domain Under Investigation	Tested phenomenon						Type of Assessment														Test System/Components				
		ICT	Cascading Failure	Communication Phenomena	Package Loss	Cyber-security Events	Communication Delays	Communication Congestion	Functional Performance	Interoperability Testing	ICT Failure Impacts	Cyber-security Perfromance / Resilience	Fault Condition	Normal Condition	Communication Performance	Protection Equipment Response	Characterisation	Verification	Validation	Device Testing	Software Testing	Algorithm Testing	Communication Infrastructure	ICT Aggregation Platform	Control Devices / IED	DMS / EMS / SCADA	DER Controller
FS1	TC1	✓							✓					✓				✓	✓	✓					✓		
FS2	TC6	✓					✓		✓					✓					✓			✓	✓				✓
	TC7	✓		✓										✓	✓		✓	✓	✓			✓	✓	✓			✓
	TC8	✓												✓			✓	✓	✓					✓	✓	✓	✓
	TC9	✓													✓		✓	✓				✓				✓	✓
FS4	TC15	✓		✓			✓		✓					✓	✓			✓	✓	✓		✓	✓		✓		✓
	TC16	✓	✓							✓			✓	✓			✓	✓	✓	✓		✓				✓	
FS5	TC17	✓		✓	✓		✓	✓	✓		✓		✓				✓	✓			✓	✓	✓	✓	✓		✓
	TC18	✓		✓					✓					✓				✓				✓	✓	✓			✓
	TC19	✓		✓		✓	✓		✓		✓		✓	✓									✓	✓			✓
	TC20	✓							✓					✓	✓				✓			✓					
FS6	TC21	✓					✓		✓					✓	✓		✓			✓			✓		✓		
	TC22	✓	✓			✓					✓	✓							✓								
	TC23	✓	✓	✓	✓	✓	✓		✓			✓		✓		✓				✓	✓		✓		✓		
	TC24	✓		✓	✓		✓			✓					✓				✓				✓		✓	✓	✓
	TC25	✓		✓	✓	✓	✓				✓	✓	✓		✓	✓							✓		✓		

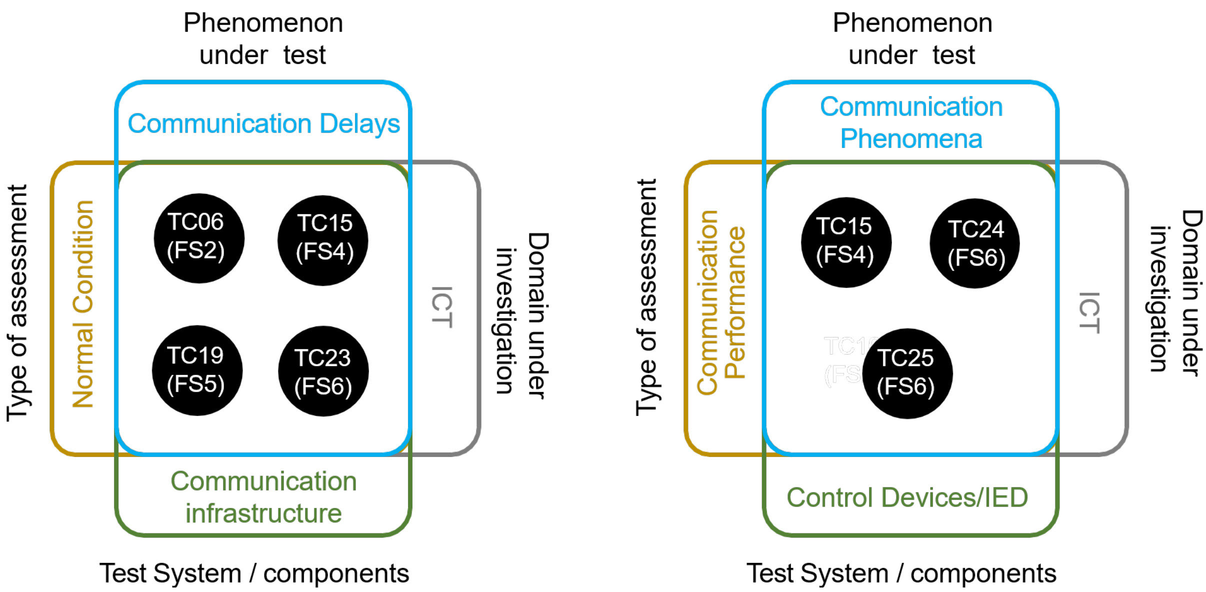

Figure 5: Two examples of TCPs corresponding to the major technological area "ICT-enhanced energy systems".

6 Conclusions

This work aims to develop a set of TCs that can be used throughout the ERIGrid 2.0 project. The common TCs are derived from the high-level FS descriptions. The FS provides the qualitative description to harmonise the similar UCs. There are six FSs representing an umbrella for dominant aspects of multi-domain cyber-physical energy systems: 1) ancillary services provided by DER, 2) microgrid and energy community, 3) sector coupling, 4) frequency and voltage stability in the inverter, 5) aggregation and flexibility management, and 6) digitalisation.

The iteration process for developing the TCs started with the TC survey followed by iterative interaction to refine TCs. The proposed UC were analysed, selected, and categorised according to the FS, resulting in twenty-five TCs. Finally, the TCs are formulated using the HTD for experimental design. In addition, each TC is assigned a set of keywords to define the characteristics of the technological area. This is useful for external users or project partners to, if possible automatically, screen and select the specific TC use of the keywords. The TCs are mapped into three major technological areas: 1) active electrical distribution grids, 2) multi-domain energy systems and 3) ICT-enhanced energy systems.

The set of TCs developed in this work can serve as the reference TC inventory covering major technological areas in the ERIGrid 2.0 project, which the external users or project partners can adapt and apply to meet the specific requirement for the experimental implementation. Each TC description is available online[5]. The TCs can support interested users for demonstrating the experiment within and across RIs within and beyond the European Union (EU).

[5] https://github.com/ERIGrid2/Test-Cases

 doi:10.5281/zenodo.5522373

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Raussi, P., Mäki, K., Evens, C., Grönroos, E., Pröstl Andrén, F., Widl, E., ... Theocharides, S. (2020). *D-NA4.1 Functional Scenarios.* Deliverable D5.1, ERIGrid 2.0 Consortium. doi:10.5281/zenodo.3991723

Appendix A: Test Case TC04

ERIGrid 2.0 GA No: 654113654113 17/08/2021

Test Case 4

Author: A. Paspatis, A. Kontou, A. F. Cortés Borray, Julia Merino Version: 3
Project: ERIGRID 2.0 Date: 13/04/2021

Name of the Test Case	Investigation of different voltage control techniques for inverter-interfaced DERs in microgrids
Narrative	A microgrid with inverter-interfaced distributed energy resources (DERs) is considered. In order to respect the system regulations and successfully feed the microgrid load, the voltage across the microgrid needs to be regulated close to its nominal value. Through the control design of the inverter-interfaced distributed energy resources, different control schemes are investigated. In particular i) master-slave voltage control, ii) conventional droop grid-forming control and iii) inverse droop grid-forming control.
Function(s) under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	Voltage regulation in a microgrid with inverter-interfaced DERs
Object under Investigation (*OuI*) "the component(s) (1...n) that are to be qualified by the test"	Inverter-interfaced distributed energy resources controllers
Domain under Investigation (*DuI*): "the relevant domains or sub-domains of test parameters and connectivity."	Electrical Power Control systems
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	Comparison of different voltage control schemes
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	A microgrid that hosts multiple inverter-interfaced distributed energy resources, lines, loads, etc.
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT.	Different voltage control schemes to achieve microgrid load voltage regulation
Test criteria *(TCR)* Formulation of criteria for each PoI based on properties of SuT; encompasses properties of test signals and output	Microgrid operation according to the designed control algorithm

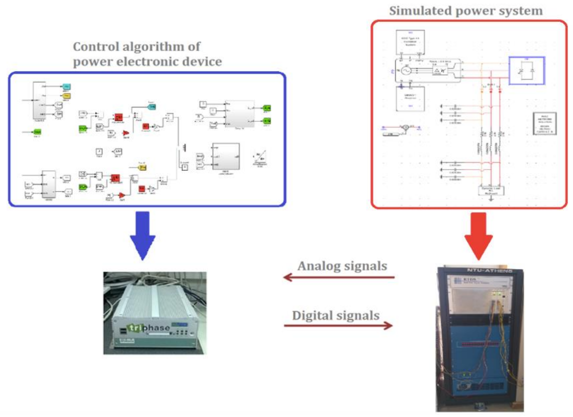
1 of 4

measures.	
Target Metrics *(TM)* Measures required to quantify each identified test criteria	1. Voltage measured at the output of the inverter (Is proper voltage regulation achieved?) 2. Number of interruptions (Is continuity of service achieved after a sudden change in the demand and/or output of RES, or a generator outage?) 3. Overall performance (What are the advantages and disadvantages of each technique?)
Variability Attributes *(VA)* controllable or uncontrollable factors and the required variability; ref. to PoI.	1. Different microgrid loading 2. Different line impedance nature (i.e., resistive or inductive or complex)
Quality Attributes *(QA)* threshold levels for test result quality as well as pass/fail criteria.	Microgird voltages inside the ±5% of the nominal voltage / Successful

Qualification Strategy

The most common voltage control algorithms for inverter-based microgrids will be validated through three tests, one for each control technique, where the inverters forming the inverter-based microgrid will be equipped with the appropriate voltage control algorithm. Then, the results will be collected to perform the comparison between the different voltage control techniques.

Test Specification 4.01

Reference to Test Case	TC4
Title of Test	Performance of different voltage control techniques for inverter-interfaced DERs in microgrids
Test Rationale	This test will perform a comparison between different voltage control schemes that are widely used in inverter-based microgrids, i.e., master-slave control, conventional droop control and inverse droop control. Aiming to quantify the effectiveness of the aforementioned techniques, their pros & cons will be ultimately identified.
Specific Test System (graphical)	Laboratory setup 
Target measures	Microgrid voltages

Input and output parameters	*Input:* • *Level of unbalance of the load* • *Inverter power injection set-points and limits* • *DERs control parameters* • *Microgrid characteristics* *Output:* • *Microgrid voltages*
Test Design	*1. Operate multiple inverters in parallel* *2. Perform load changes and observe voltage regulation (continuity of service)* *3. Save the experimental results*
Initial system state	• *Inverter controllers enabled* • *Load disconnected* • *Grid voltages based on the nominal output values of the inverters* • *Hardware or simulated network and devices up and running* • *Power analyzer and computers displaying and saving data*
Evolution of system state and test signals	*The microgrid system is subjected to load variations (step changes)*
Other parameters	*N/A*
Temporal resolution	*At least 0.1 ms.*
Source of uncertainty	*Impedance of load and lines, inverter sensors operation*
Suspension criteria / Stopping criteria	*Abnormal current/ power injections from inverters or tripping of inverters*

Mapping to Research Infrastructure

Experiment Specification 4.01.01

Reference to Test Specification	*4.01*
Title of Experiment	Master-slave voltage control
Research Infrastructure	Electric Energy Systems Laboratory (ICCS-NTUA)
Experiment Realisation	Multiple inverters forming a microgrid, both through hardware setup and through simulated components in the RTDS
Experiment Setup (concrete lab equipment)	1. Hardware controller (e.g., Three-phase real-time computer) 2. Simulated microgrid network and inverters in the RTDS 3. Optional: Hardware inverter (e.g., Three-phase inverter)
Experimental Design and Justification	Microgrid that hosts multiple inverter-interfaced DERs. At least one DER should operate in grid-forming mode and be the master unit, while the rest of the units can operate in grid-following mode as slaves.
Precision of equipment and measurement uncertainty	Software and power analyzer are of high precision, inverter sensing system may be of lower precision
Storage of experiment data	Power analyzer and computer memory

Experiment Specification 4.01.02

Reference to Test Specification	*4.01*
Title of Experiment	Conventional droop grid-forming control
Research Infrastructure	Electric Energy Systems Laboratory (ICCS-NTUA)
Experiment Realisation	Multiple inverters forming a microgrid, both through hardware setup and through simulated components in the RTDS
Experiment Setup (concrete lab equipment)	1. Hardware controller (e.g., Three-phase real-time computer) 2. Simulated microgrid network and inverters in the RTDS 3. Optional: Hardware inverter (e.g., Three-phase inverter)
Experimental Design and Justification	Microgrid that hosts multiple inverter-interfaced DERs. All inverter-interfaced DERs are equipped with the conventional droop grid-forming control in order to regulate the microgrid voltage.
Precision of equipment and measurement uncertainty	Software and power analyzer are of high precision, inverter sensing system may be of lower precision
Storage of experiment data	Power analyzer and computer memory

Experiment Specification 4.01.03

Reference to Test Specification	*4.01*
Title of Experiment	Inverse droop grid-forming control
Research Infrastructure	Electric Energy Systems Laboratory (ICCS-NTUA)
Experiment Realisation	Multiple inverters forming a microgrid, both through hardware setup and through simulated components in the RTDS
Experiment Setup (concrete lab equipment)	1. Hardware controller (e.g., Three-phase real-time computer) 2. Simulated microgrid network and inverters in the RTDS 3. Optional: Hardware inverter (e.g., Three-phase inverter)
Experimental Design and Justification	Microgrid that hosts multiple inverter-interfaced DERs. All inverter-interfaced DERs are equipped with the inverse droop grid-forming control in order to regulate the microgrid voltage.
Precision of equipment and measurement uncertainty	Software and power analyzer are of high precision, inverter sensing system may be of lower precision
Storage of experiment data	Power analyzer and computer memory

Appendix B: Test Case TC09

Test Case 9

Author: Tran The Hoang, Luigi Pellegrino, Quoc Tuan Tran
Project: Erigrid 2.0
Version 1
Date: 02/03/2021

Name of the Test Case	Evaluation of congestion management in distribution grid
Narrative	The distribution network has been becoming congested because of the introduction of bi-directional power flow (due to the increasing penetration of DERs), unpredictable and increased power demands for consumption by the residential consumers (due to the introduction of new forms of loads such as Heat Pumps, EVs, etc.). As a result, the distribution network operators (DSOs) need to focus on the challenge of balancing power supply and demand. Congestion in the distribution network refers to an overvoltage at the connection points as well as overloading of the network components. On the one hand, to mitigate the network strains, conventionally DSOs focus mainly on network development by installing new cables and transformers to meet the increasing power flows. Nonetheless, the distribution loads are spread over large geographically areas and in a distributed manner, making the upgrade of the network more financially infeasible in a short term. Another alternative solution is to develop grid congestion management approaches so that the network infrastructure can be utilized in a better way. There are two types of congestion management methods namely direct as well as indirect. The former technique is realized by performing load curtailment, local generation reduction, network reconfiguration, new installation of Battery Energy Storage System (BESS). In contrast, the latter approach focuses on solving the optimization of electricity cost with the constraints ensuring the transformers/feeders not to be overloaded. The direct congestion management method in this test includes two stages. The first stage consists of using a machine learning method, such as support vector machine, multi-class classification, decision tree, ANN..., in order to build congestion classification models. Once congestion is detected, it has to be labeled to one of the following statuses: normal, alert, emergency, and critical depending on the output of the trained models. In the second step, DSOs will use the congestion labeling to calculate the expected flexibility portfolio. With the expected procurement cost, the flexibility available in the feeders/households can be used to solve the congestion problem. After comparing the results with different conditions, the best setting for the congestion management can be chosen. On the other hand, an indirect congestion management needs to be based on an online learning technique to emulate the demand flexibility of a network. As for emulating the demand flexibility, the concept of price elasticity of demand can be

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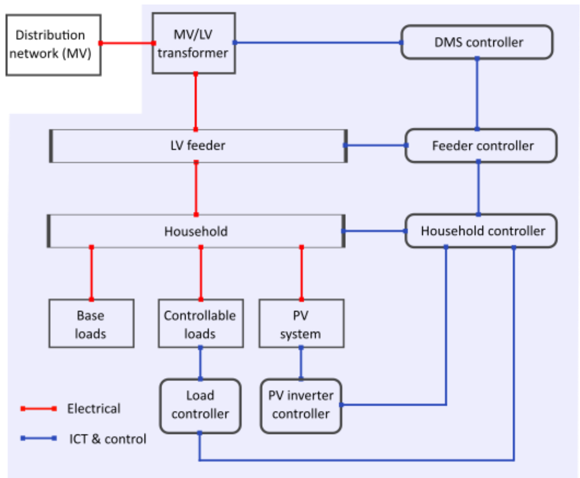
	considered. Accordingly, demand flexibility during all time-periods of a day shall be treated as a commodity that can be substituted or complemented to each other. The objective of this Test Case is to evaluate different congestion management methods in distribution grid under the circumstance of high penetration of DERs and other active loads such as EVs, HPs ...
Function(s) under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	Congestion management of the DMS controller ▪ Direct approach: mitigating congestions by curtailment of load and local generation and by influencing the voltage level at the secondary side of a MV/LV transformer ▪ Indirect approach: motivating individual prosumers with dynamic prices through intermediate market entities such as aggregators and retailers. DSOs also incentivize customers by providing compensations for their load reduction when needed to solve network congestions.
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test"	• DMS controller
Domain under Investigation (*DuI*): "the relevant domains or sub-domains of test parameters and connectivity."	• Electrical domains • Control and ICT domain
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	• Characterization and comparison of different congestion management methods.
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	In electric power domain: • DMS controller • DER (PV system) • Household appliances • Distribution transformer • Aggregator/consumer/prosumer controllers • Household controllers • Household appliance controllers • DER controllers In ICT domain: • Communication network

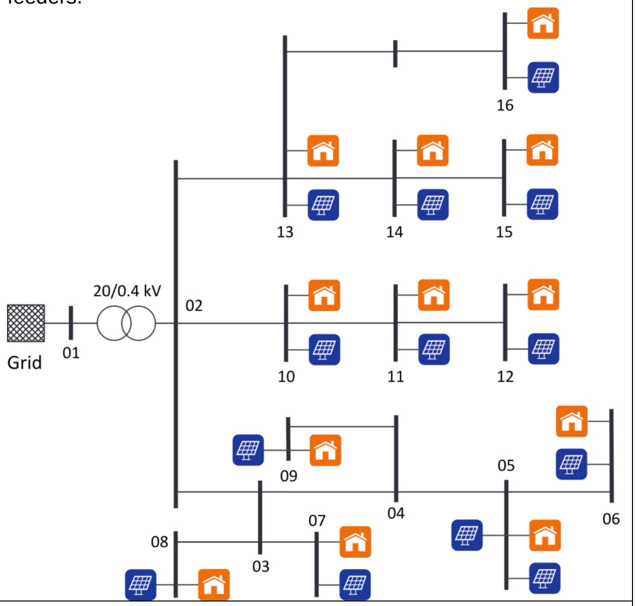
	
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT.	• DMS congestion management functionality • DER power output control • Household appliances control of the aggregator/consumer/prosumer controller • Communication via ICT
<u>Test criteria</u> *(TCR)* Formulation of criteria for each PoI based on properties of SuT; encompasses properties of test signals and output measures.	• Performance of the congestion management algorithm under realistic conditions • The transformer and feeders should not be overloaded • Reduction in the cost of flexibility procurement
Target Metrics *(TM)* Measures required to quantify each identified test criteria	• Accuracy of congestion prediction • Transformer overloading/loss of transformer life/Hot spot temperature of the transformer/transformer loss • Feeder overloading • Cost of congestion management • DER power curtailment • Household voltage profiles • Flexibility procured by DSO • Reduction in peak demand
Variability Attributes *(VA)* controllable or uncontrollable factors and the required variability; ref. to PoI.	• Household consumption profiles • DER generation (weather condition) • Packet loss • Communication delay
Quality Attributes *(QA)* threshold levels for test result quality as well as pass/fail criteria.	• Transformers/feeders are not overloaded • Voltage deviation within ±10% (typically for LV networks)

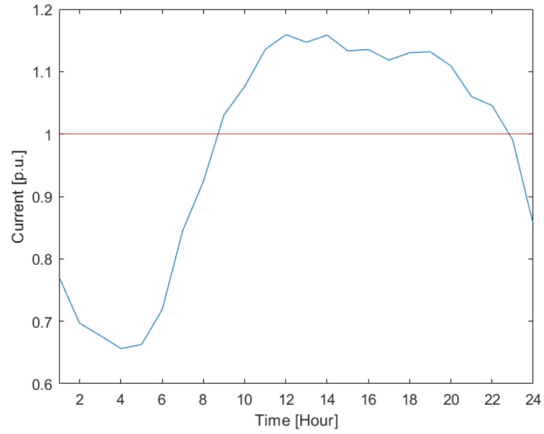
		• Reduction in DER power curtailment

Qualification Strategy

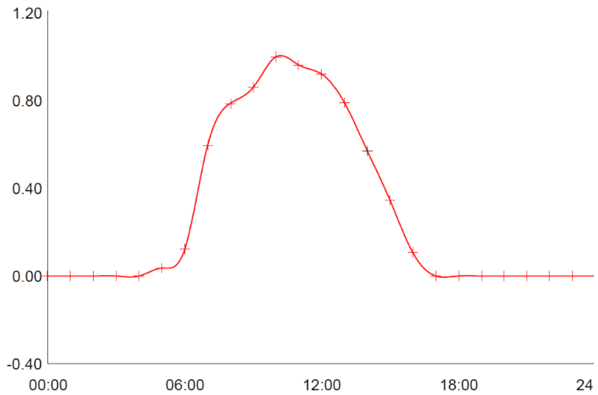
The test case is split in two TSs: one to characterize the direct method, one to characterize the indirect method. Then, the results will be analysed to compare the performances of the two methods. For the TSs, either a pure simulation or a co-simulation will be performed.

Test Specification TC9.TS01

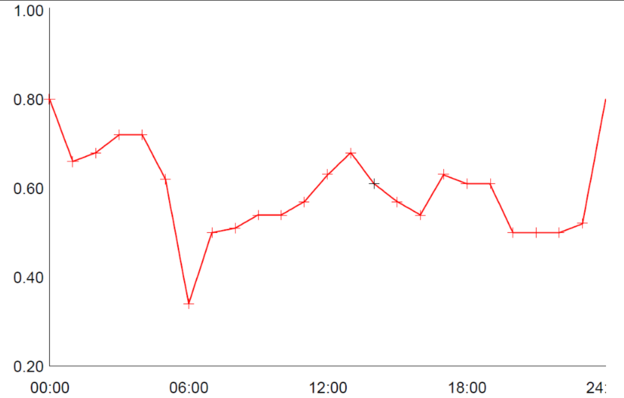
Reference to Test Case	TC9
Title of Test	Characterisation of direct method
Test Rationale	The goal of this Test is to evaluate the performance of a direct congestion management method. The results of the developed congestion forecasting model will be compared to the actual values to assess its accuracy. Afterwards, the efficiency of the method will be evaluated in terms of target metrics specified in the Test Case description.
Specific Test System (graphical)	The Test System includes a LV (0.4 kV) network with realistic data provided by a local utility company. This network consists of three feeders with various loads and PV systems connected along the feeders. 
Target measures	Voltages, currents of all grid components.
Input and output parameters	Weather conditions (hence DER production), grid topology, household load profiles, controllable generation production
Test Design	• Initialize the simulation, achieving a steady state condition; • Keep the simulation running with the feeding load and generation profiles in order to create several congestion conditions (peak of load or peak of generation) over the whole simulation run • Evaluate the results of the test in terms of transformer

<table>
<tr><td></td><td>loading power, flexibility procured by the DSO, and procurement cost in two cases with and without the congestion management functionality in the DMS controller
• Reinitialize the simulation and repeat the test with different congestion condition.</td></tr>
<tr><td>Initial system state</td><td>Transformer and feeders loading in permissible ranges.</td></tr>
<tr><td>Evolution of system state and test signals</td><td>The evolution of the congestion at the MV/LV transformer is illustrated in the figure below:


The evolution of the system state is shown in the figures below:

Solar profile:


Wind profile:</td></tr>
</table>

	
Other parameters	n/a.
Temporal resolution	15 minutes
Source of uncertainty	Measurement uncertainty
Suspension criteria / Stopping criteria	Low accuracy of the congestion classification model during the training process, i.e., less than 80%

Test Specification TC9.TS02

Reference to Test Case	TC9
Title of Test	Characterisation of indirect method
Test Rationale	The goal of this Test is to evaluate the performance of the indirect method considering the impact of the communication latency and packet losses on a LV grid congestion management.
Specific Test System (graphical)	The Test System includes a LV (0.4 kV) network with realistic data provided by a local utility company. This network consists of three feeders with various loads and PV systems connected along the feeders.

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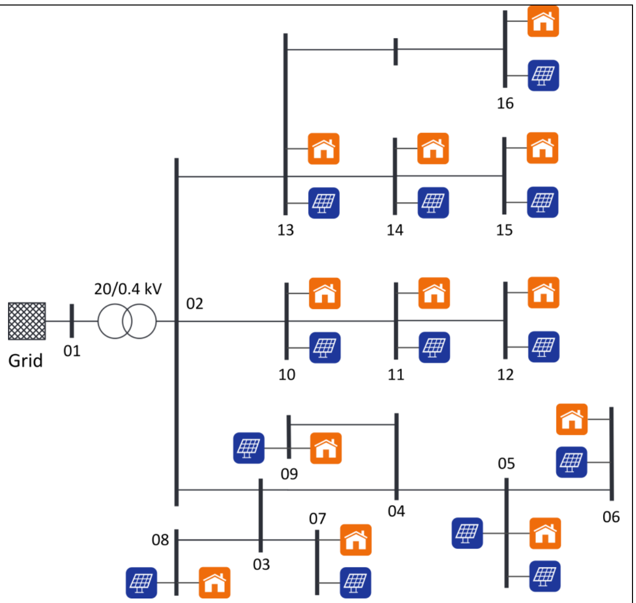
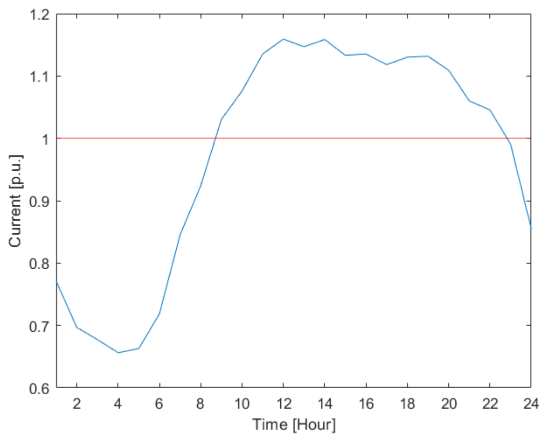
<table>
<tr><td></td><td>

In addition to the above network, a market model is also developed.</td></tr>
<tr><td>Target measures</td><td>Voltages, currents of all grid components and grid services cost.</td></tr>
<tr><td>Input and output parameters</td><td>Weather condition (hence DER production), grid topology, household load profiles, controllable generation production</td></tr>
<tr><td>Test Design</td><td>Initialize the simulation; achieve a steady state condition; trigger a congestion condition (peak of load or peak of generation); evaluate the response of the DMS controller; reinitialize the simulation and repeat the test with different congestion condition and the baseline.</td></tr>
<tr><td>Initial system state</td><td>Transformer and feeders loading in permissible ranges.</td></tr>
<tr><td>Evolution of system state and test signals</td><td>The evolution of the congestion at the MV/LV transformer is illustrated in the figure below:


The evolution of the system state is shown in the figures below:</td></tr>
</table>

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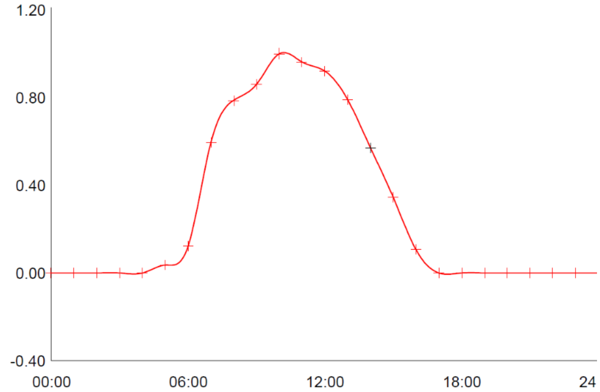
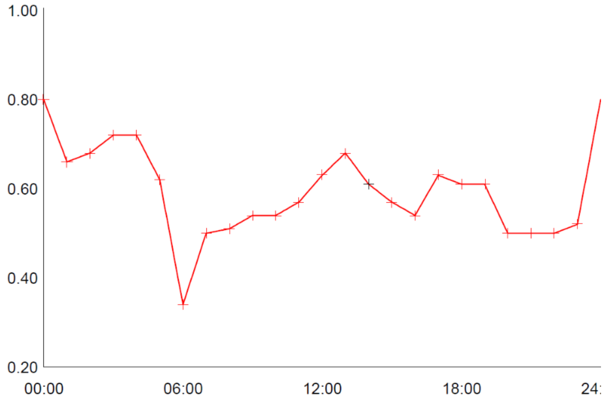
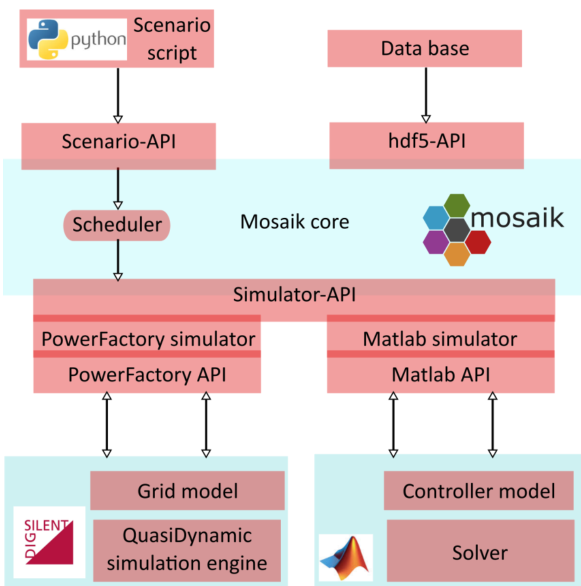
	Solar profile:  Wind profile: 
Other parameters	n/a.
Temporal resolution	15 minutes
Source of uncertainty	Measurement uncertainty
Suspension criteria / Stopping criteria	Not converging of the optimization method.

Mapping to Research Infrastructure

Experiment Specification TC9.TS01.ES01

Reference to Test Specification	TC9.TS01
Title of Experiment	*Co-simulation for performance evaluation of direct congestion management method*
Research Infrastructure	CEA
Experiment Realisation	The experiment is realized by performing a co-simulation setup between PowerFactory and Matlab using Mosaik as a master algorithm. The congestion management functionality and all the neces-

<table>
<tr><td></td><td>sary control functions are modeled in Matlab. A realistic LV network with high penetration of PV systems is implemented in PowerFactory and is run in QuasiDynamic mode.</td></tr>
<tr><td>Experiment Setup
(concrete lab equipment)</td><td>


</td></tr>
<tr><td>Experimental Design and Justification</td><td>All the load consumption and PV generations will be varied following different pre-defined profiles to create congestion issues in order to evaluate the performance of the designed congestion management function.</td></tr>
<tr><td>Precision of equipment and measurement uncertainty</td><td>N/a</td></tr>
<tr><td>Storage of experiment data</td><td>hdf5 or csv files</td></tr>
</table>

Experiment Specification TC9.TS02.ES02

Reference to Test Specification	TC9.TS02
Title of Experiment	*Simulation for performance evaluation of indirect congestion management method*
Research Infrastructure	RSE
Experiment Realisation	The experiment is realized by performing a simulation in Matlab. All the necessary control functions are modeled with a script in Matlab. The local services market model is developed in Simulink and a realistic LV network with high penetration of PV systems is implemented in SimPowerSystem using phasor models. All the simulation components are managed by a master algorithm which setup all the experiment configurations (input, models parameters, etc.).
Experiment Setup (concrete lab equipment)	The whole experiment is performed in Matlab environment. In particular, the local services market model is developed in Simulink, the LV network model in SimPowerSystem while the

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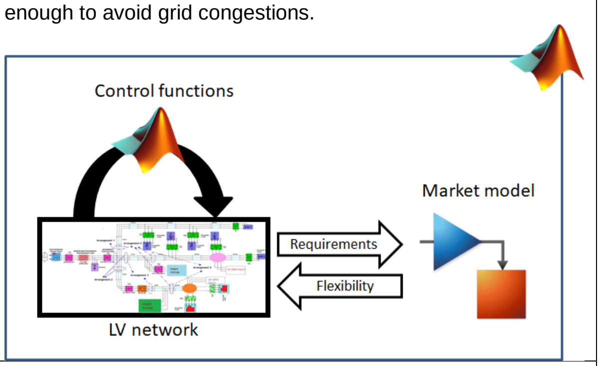
	control functions of the components are .m file integrated with SimPowerSystem. In order to validate the indirect congestion management, the flexibility provided by the local services market should be enough to avoid grid congestions. 
Experimental Design and Justification	All the load consumption and PV generations will be varied following different pre-defined profiles (see TC24.TS02) to create congestion issues in order to evaluate the flexibility provided by the local services market.
Precision of equipment and measurement uncertainty	Since the experiment is a simulation, this is not available.
Storage of experiment data	All variable states are saved in a .mat file with a time-step of 15 minutes.

Consortium

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