INTERPLAN
INTEgrated opeRation PLAnning tool towards the Pan-European Network

Work Package 5

Operation planning and semi-dynamic simulation

Deliverable D5.3

Control system logics: cluster and interface controllers (first version)

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Abbreviations

AENS	*Average energy not supplied*
AMPL	*A Mathematical Programming Language*
AS	*Ancillary Service*
BESS	*Battery energy storage system*
BSC	*Base showcase*
BUC	*Base use case*
cdf	*Cumulative distribution function*
CF	*Control function*
DER	*Distributed energy resources*
DG	*Distributed generation*
DR	*Demand response*
DSM	*Demand Side Management*
RES	*Renewable energy sources*
DRES	*Distributed renewable energy resources*
DSL	*DIgSILENT Simulation Language*
DSO	*Distribution system operator*
EHV	*Extra high voltage*
ENS	*Energy not supplied*
ENTSO-E	*European Network of Transmission System Operators for Electricity*
EU	*European Union*
EV	*Electric vehicle*
fFRC	*Fast frequency restoration control*
HV	*High voltage*
FFR	*Fast Frequency Response*
IEAR	*Interrupted energy assessment rate*
IEX	*Information exchanged*
INTERPLAN	*Integrated operation planning tool for the pan-European network*
KPI	*Key performance indicator*
LV	*Low voltage*
LF	*Load Flow*
MV	*Medium voltage*
OPF	*Optimal Power Flow*
PF	*Power Flow*
RES	*Renewable energy sources*
RoCoF	*Rate of change of frequency*
SAIDI	*System average interruption duration index*
SAIFI	*System average interruption frequency index*
SI	*System inertia*
SC	*Showcase*
Sync. G	*Synchronous Generator*
TSO	*Transmission system operator*
UC	*Use case*
UFLS	*Under-frequency load shedding*
WP	*Work Package*
WTG	*Wind turbine generator*

Executive Summary

The deliverable provides the description of the logic controllers of the INTERPLAN tool as a set of algorithms able to cover a significant number of operational challenges. It also presents a summary of the issues and benefits of their application.

The Integrated Network Operation Planning tool developed in INTERPLAN is defined as *a methodology consisting of a set of tools (grid equivalents, control functions) for the operation planning of the Pan-European network by addressing a significant number of system operation planning challenges of the current and the future 2030+ EU power grid, from the perspective of the transmission system, the distribution system, and with a particular focus on the transmission-distribution interface*. In this sense, the main goal of the tool is to achieve the operation planning of an integrated grid from the perspective of a Transmission System Operator (TSO) or a Distribution System Operator (DSO) through handling efficiently and effectively intermittent Renewable Energy Sources (RES) as well as the emerging technologies such as storage, demand response and electric vehicles. In fact, the tool supports utilizing flexibility potential coming from RES, demand side management (DSM), storage and electric mobility for system services in all network control levels.

The INTERPLAN tool consists of three main stages: 1. Simulation functionalities, key performance indicators (KPIs) and scenario selection, 2. Grid model selection/preparation, 3. Simulation & Evaluation. First of all, the user identified as a TSO or a DSO selects the planning criteria he wants to consider for the network operation planning. This selection is based on a pre-defined list of planning criteria, such as minimizing losses, maximizing share of RES, mitigating grid congestion, assuring transient stability, optimizing TSO/DSO interaction, assuring voltage stability, and minimizing energy interruption.
Under the stage 1, the user selects the simulation functionality (e.g. Optimal Power Flow (OPF), Load Flow sensitivity, Stability Analysis Functions, and reliability assessment), the KPIs and the operating future scenario among the four INTERPLAN scenarios with the related target year. The stage 2 of the INTERPLAN tool is dedicated to the grid model selection and preparation. Under this stage, the user selects the grid model for the simulation phase in the next stage, and it is then adapted to the INTERPLAN scenario selected under the previous stage. If a grid equivalent model is required for the simulation phase, the user can select it from the grid equivalents library consisting of a list of pre-defined grid equivalents, or he/she can generate a grid equivalent model through the grid equivalent generation procedure made available by the INTERPLAN tool. When the grid model is decided, it is then adapted to the scenario selected under stage 1 through the scenario adaptation procedure.
Finally, the stage 3 of INTERPLAN tool is dedicated to the simulation and evaluation phase. Under this stage, the user performs the simulation by using one of the INTERPLAN control solutions (INTERPLAN control functions embedded within the use cases or the showcases) [1] according to the operation challenge that wants to investigate and the choices done in the previous stages. The evaluation phase follows the simulation one. In detail, here, the user makes the evaluation through the KPIs found in the simulation phase. If the user is satisfied with the KPI(s) found, the evaluation is complete and the process stops. Otherwise, the user can decide to investigate further INTERPLAN solutions addressing the same operation challenge under the same planning criteria. In this latter case, the process re-starts from stage 1.

This deliverable addresses the third step of the INTERPLAN tool that refers to the development of

the control functions related to the five INTERPLAN showcases (documented in deliverable D5.1 on INTERPLAN showcases [2]) including:

1. Low inertia systems
2. Effective distributed energy resources (DER) operation planning through active and reactive power control
3. TSO-DSO power flow optimization
4. TSO-DSO coordinated active and reactive power optimization for provision of tertiary reserve and improvement of voltage profiles
5. Optimal energy interruption management

A showcase is defined as the combination of sub use-case(s) [1] with planning criteria and control functions for emerging technologies, such as RES, distributed generation (DG), demand response or energy storage systems.

The detailed descriptions of control functions, which are developed in line with the objectives of the showcases are presented in this deliverable. This makes possible for the user of the INTERPLAN tool to analyse the operation challenges of the relevant use cases and evaluate the effectiveness, reliability and robustness of control functions by comparing the KPIs with the ones calculated for base showcases previously analysed by the INTERPLAN consortium and documented in D5.2 “operation planning tool development and semi-dynamic simulation of grid equivalents" [3].

1. Introduction

1.1 Purpose and scope of the document

This document falls in the scope of INTERPLAN Work Package 5 on Operation planning and semi-dynamic simulation.

As a result of the related work, the methodology to implement the control functions related to the 5 INTERPLAN showcases have been established. The list of the showcases is as follows:

1. Low inertia systems
2. Effective DER operation planning through active and reactive power control
3. TSO-DSO power flow optimization
4. TSO-DSO coordinated active and reactive power optimization for provision of tertiary reserve and improvement of voltage profiles
5. Optimal energy interruption management

The main goals of deliverable D5.3 are described as follows:

- Definition of the proper control functions for all seven use cases listed as follows:
    1. Coordinated voltage/reactive power control
    2. Grid congestion management
    3. Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations
    4. Fast Frequency Restoration Control
    5. Power balancing at DSO level
    6. Inertia management
    7. Optimal generation scheduling and sizing of DER for energy interruption management
- Establish the implementation method for applying control functions in use cases and then in showcases;
- Identify the final structure of each showcase based on the chosen control functions;
- Specify the interaction among control functions and cluster and interface controllers.
- Finalize the detailed method to implement control functions on the INTERPLAN showcases;
- Identify the properties of the test cases and grid equivalenting method needed to perform the simulations for showcases.

Deliverable D5.3 presents the preliminary version of the INTERPLAN control system logics, that will be simulated in the updated version of this deliverable to be released at the end of the project.

1.2 Structure of the document

The deliverable consists of six chapters. The purpose and scope of the deliverable are described in the first chapter. The second chapter consists of a short description of the INTERPLAN project. In the third chapter, the methodology used to develop control functions within the showcases are presented.

The fourth chapter presents the detailed description of the developed control function logics in the five INTERPLAN showcases. The fifth chapter is a summary of the report and an outlook for the future activities. In chapter 6, the references are presented, whereas in the Annex 1, the glossary of the terms and definitions used in the INTERPLAN project can be found.

2. INTERPLAN project

The European Union (EU) energy security policy faces significant challenges as we move towards a pan-European network based on the wide diversity of energy systems among EU members. In such a context, novel solutions are needed to support the future operation, resilience and reliability of the EU electricity system in order to increase the security of supply and also accounting for the increasing contribution of renewable energy sources (RES). The goal of the INTERPLAN project is to provide an INTEgrated opeRation PLAnning tool towards the pan-European Network, with a focus on the TSO-DSO interfaces to support the EU in reaching the expected low-carbon targets, while maintaining the network security and reliability.

INTERPLAN project looks at the potential operation challenges which TSOs and DSOs are called to address in the 2030+ power system. In fact, the ongoing deployment of the pan–European Network strongly depends on different potential scenarios related to the RES share in generation and installed capacity, as well as penetration of emerging technologies, such as storage and demand response (DR). Although these factors represent the preferential patterns to meet the EU decarbonized energy targets for 2030 and 2050, they bring new challenges for the energy system, which will outline the key operational needs of the European grid operators in the near future.
In such a context, TSOs will need to evolve progressively from a “business as usual approach” to a proactive approach in order to avoid a bottleneck effect in the future European grid, and this could be addressed through a proper system operation planning. As for the distribution networks, they have been traditionally designed and treated to transport electrical energy in one direction, i.e., from the generation units connected to the transmission system to the end-users. However, with the growing share of non-dispatchable distributed generation, customers are increasingly generating electricity themselves, and, by becoming “prosumers”, they are shifting from the end point to the center of the power system. As a result, DSOs will need to actively manage and operate a smarter grid through appropriate system control logics, by utilizing the flexibility potential in the grid, with the aim to optimize the distribution network performance. Furthermore, an additional critical issue is the interface between transmission and distribution systems, which is expected to evolve in the near future through a mutual cooperation between TSOs and DSOs, with the aim to address operational challenges as congestion of transmission and distribution lines and at the interface among them, voltage support between TSOs and DSOs, and power balancing concerns. The increasing complexity of the grids requires control and operation planning tools even more advanced and homogenous among European countries.

With these premises, the INTERPLAN idea was born. In such a framework, the projects aims to develop control system logics which suit the complexity of the integrated grid, while managing all relevant flexibility resources as “local active elements” in the best manner. Moreover, by looking at the 2030+ power system, the project also addresses policy and regulation aspects aiming to identify a set of possible amendments to the existing grid codes, reflecting the developments achieved in INTERPLAN through its tool, use cases and showcases. The aim of this analysis is to break down the current barriers to the integration of emerging technologies and to foster TSO-DSO cooperation in managing grid operation challenges.

In detail, a methodology for a proper representation of a “clustered” model of the pan-European network is provided, with the aim to generate grid equivalents as a growing library able to cover a number of relevant system connectivity possibilities occurring in the real grid, by addressing a number of operation planning issues at all network levels (transmission, distribution and TSO-DSO interfaces). In this perspective, the chosen top-down approach leads to an “integrated” tool, both in terms of voltage levels, moving from high voltage level down to low voltage level up to end user, as well as in terms of developing a bridge between static, long-term planning and operational issues considerations, by introducing proper control functions in the operation planning phase. Therefore, in the project, novel control strategies and operation planning approaches are investigated in order to ensure the security of supply and resilience of the interconnected EU electricity power networks, based on a close cooperation between TSOs and DSOs, thereby responding to the crucial needs of the ongoing pan-European network and its operators.

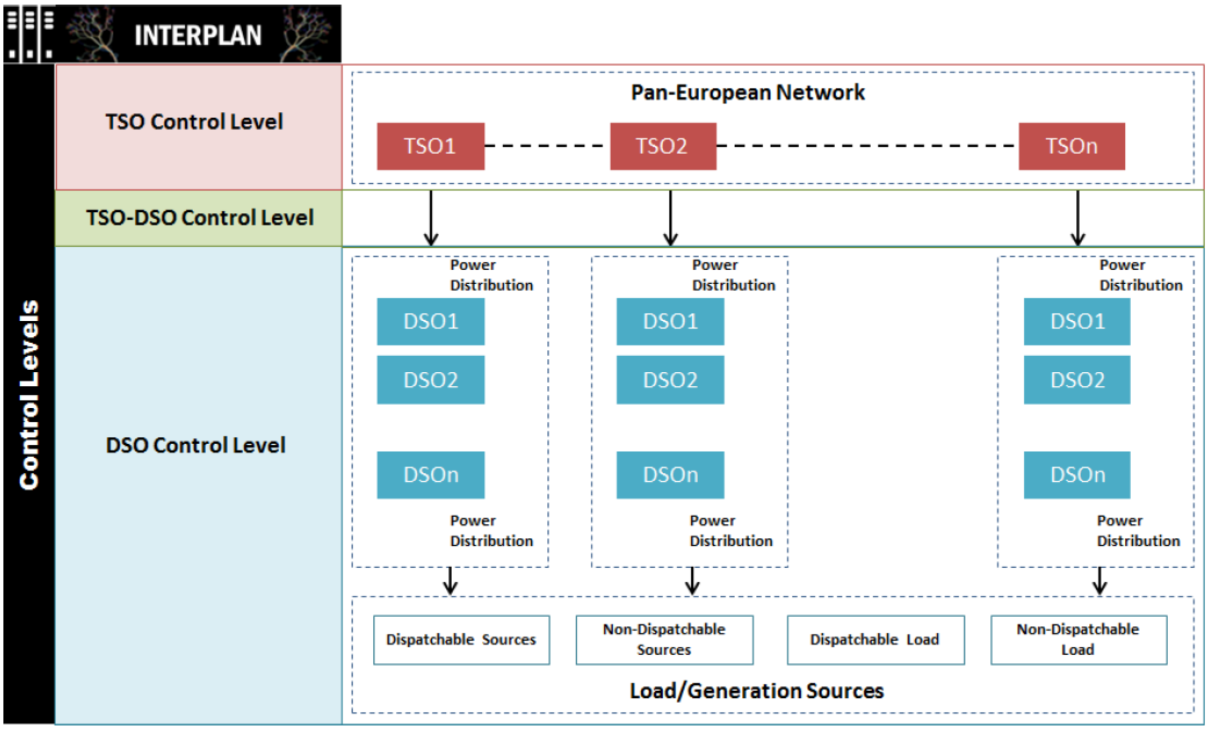


Figure 1: INTERPLAN concept

3. Methodology

3.1 Recall of the INTERPLAN Integrated Network Operation Planning tool

The integrated network operation planning tool developed in INTERPLAN consists of the following stages, which are presented in Figure 2 [3]:

- Stage 1: Simulation functionalities, KPIs and scenario selection;
- Stage 2: Grid model selection/preparation;
- Stage 3: Simulation & Evaluation.

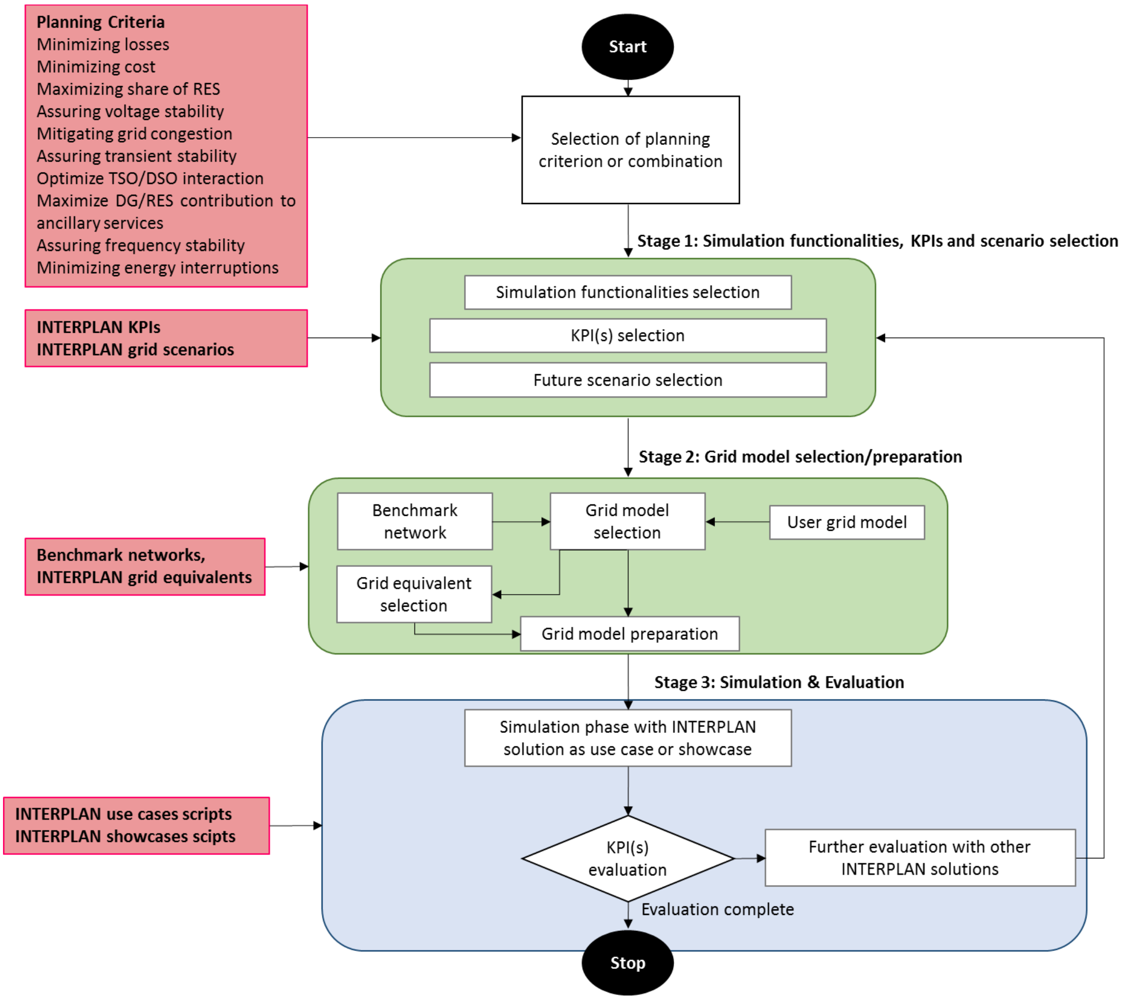


Figure 2: INTERPLAN tool overview *[3]*

Briefly, after the selection of planning criteria, what are carried out at each stage include:

- ✓ **<u>Stage 1</u>**: Simulation functionality can be selected from the list of simulation functionalities used for INTERPLAN use cases and showcases. The KPIs and scenario can also be selected from INTERPLAN KPIs and INTERPLAN scenarios.
- ✓ **<u>Stage 2</u>**: The user can select the grid model for simulation in this stage by using the own grid model or a benchmark. If a grid equivalent is required, the user can select one in the library or using the grid equivalent procedure available in the tool.
- ✓ **<u>Stage 3</u>**: The user performs the simulation either directly without selecting any of the

INTERPLAN solution or by using one of them according to the operation challenge he wants to investigate.

The current deliverable presents the INTERPLAN solution methods in stage 3 shown in Figure 3, which correspond to the control system logics embedded in INTERPLAN use cases and showcases.

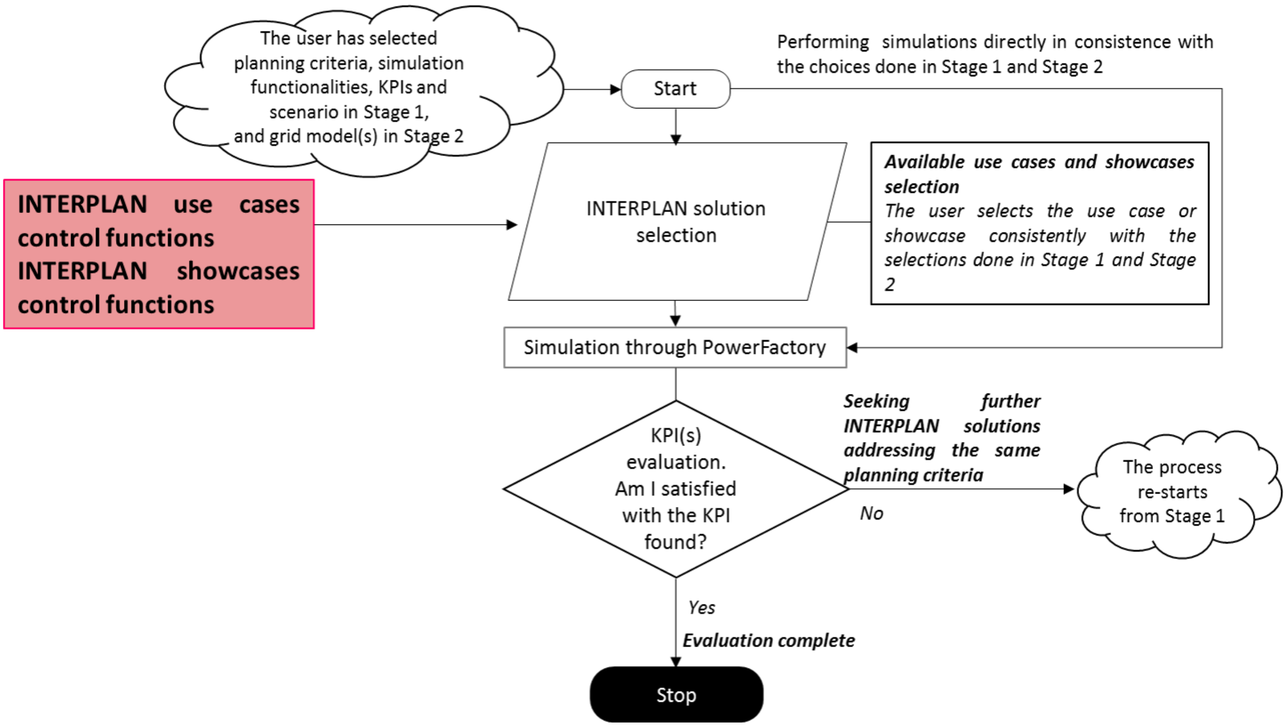


Figure 3: Stage 3 of INTERPLAN tool *[3]*

3.2 Development of control system logics

3.2.1 Cluster and interface controllers

Control functions are set of functions and set points defined for specific elements of the network such as RES and loads in order to reach the goal of a use case or showcase. According to Figure 4, a cluster controller, that can be a central controller in a substation, aggregates the signals of control functions in a part of the network. More cluster controllers in a larger part of the network can be interconnected with interface controller, which can facilitate the exchange command among cluster controllers. The interface controller can be, for example, a transmission operator acting as an interface between several cluster controllers.

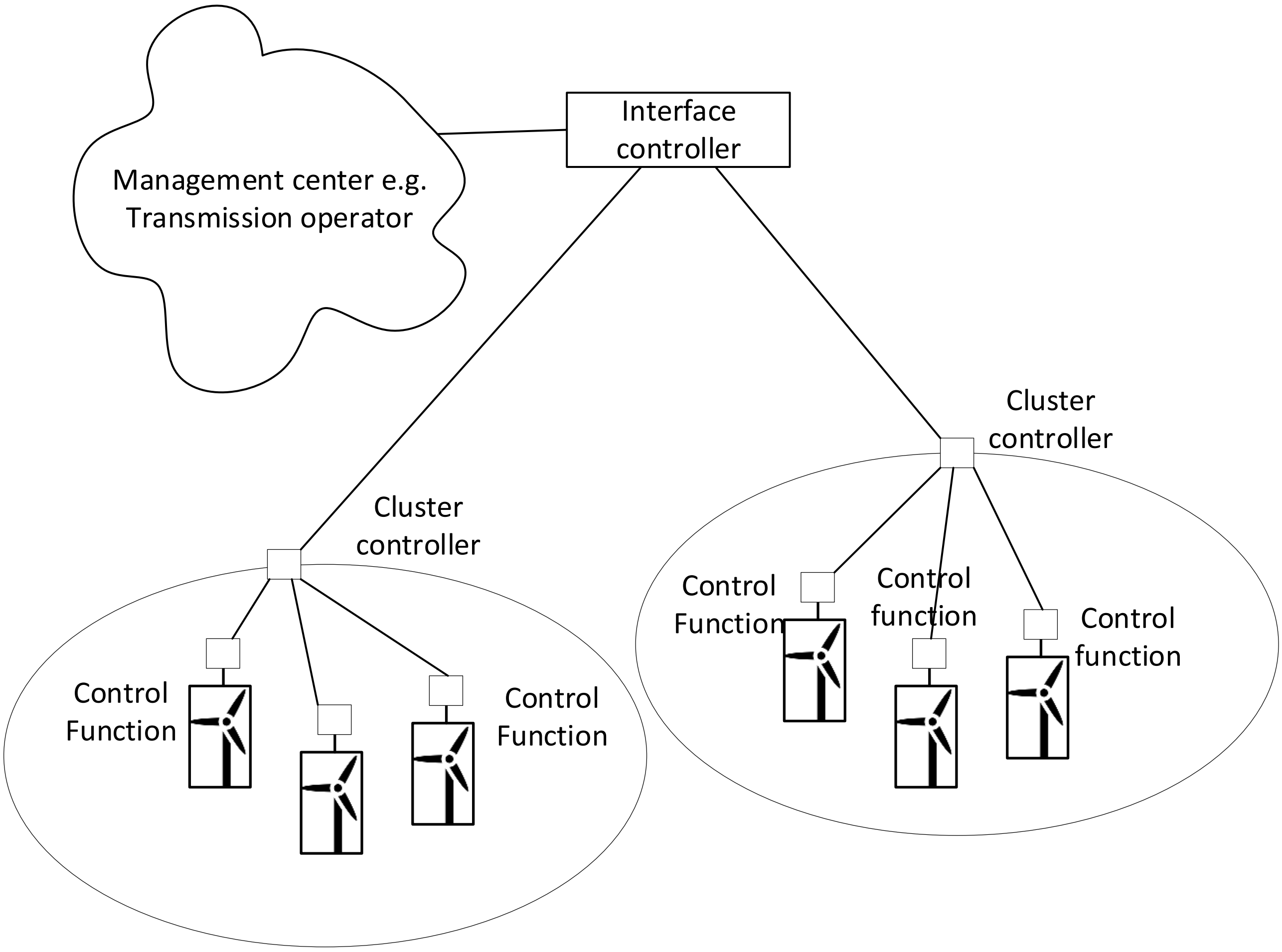


Figure 4: Cluster and Interface controllers

3.2.2 Control functions development

As documented in D5.2 [3], the base showcases have been implemented without employing control functions. It means that the grid status was analysed and the possible critical operational issues were discovered. The control functions here are designed to overcome those critical issues as well as to meet the requirements of the planning criteria. The list of planning criteria is as follows:

1. Minimize losses
2. Minimize costs
3. Maximize share of RES
4. Assure voltage stability
5. Mitigating grid congestion
6. Assure transient stability
7. Optimize TSO/DSO interaction
8. Maximize DG/RES contribution to ancillary services
9. Assure frequency stability
10. Minimize energy interruptions

The control functions for each showcase need to be developed in a way that those challenges can be covered. Since each showcase contains one or more use cases as depicted in Figure 5, the control functions need to be, first, designed and implemented in use cases. Afterwards, use cases with related control functions can be combined to form the relevant showcase. The assigned planning criteria for each showcase are also depicted in Figure 5.

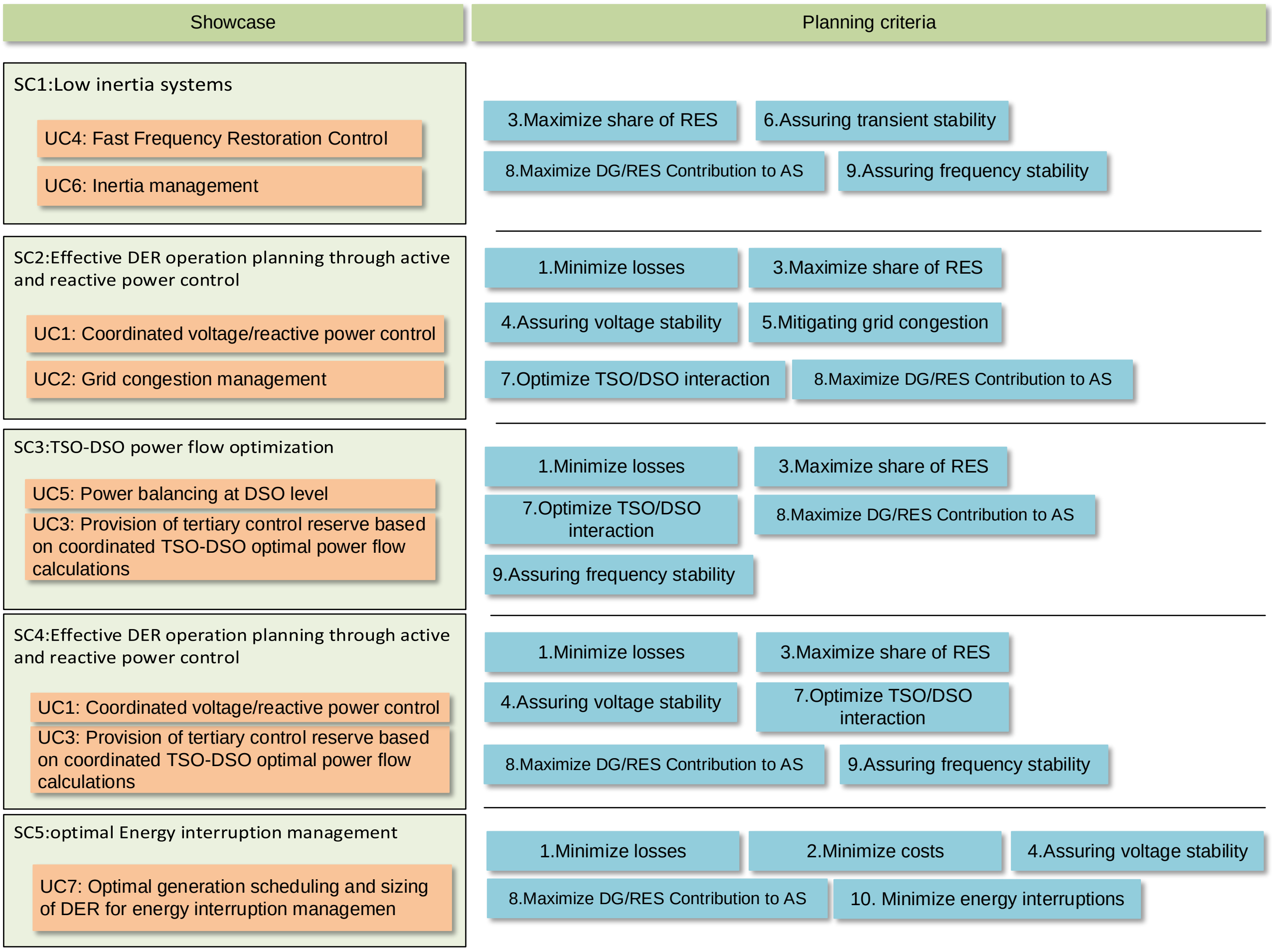


Figure 5: Relevant planning criteria and use cases for each showcase

Table 1 below presents the developed control functions for each use case and relevant showcase by indicating their benefits to meet the planning criteria and the programming language to implement. The development of control functions for each use case has been performed by entire consortium as follows:

- Use case 1: DG and renewable resource dispatch are used to manage reactive power while minimizing the total network losses.
- Use case 2: In order to overcome the grid congestion, active power management in DG is taken into consideration as proper control function.
- Use case 3: Optimization of power flow is applied in the network with high share of RES and DG to maximize the share of RES in providing tertiary reserve and minimize the power losses.
- Use case 4: To restore frequency stability, active power management in DG is performed.
- Use case 5: Storage systems and DG are used to maximize the local usage of energy within the DSO grid and minimize the energy exchange between TSO and DSO, while minimizing power losses and maximizing share of RES.
- Use case 6: Synthetic inertia (SI) is implemented in order to support frequency as local and central control function, to assure required RoCoF.
- Use case 7: Three control functions are applied: the first control function is load shedding to solve under voltage problems during a contingency. To solve the over-voltage problem during a contingency, two control functions including PV curtailment and DG redispatch are employed as the second and third control functions, respectively.

Table 1: Control functions and their benefits in each use case and showcase

Showcase	Use case	Proposed control function	Benefits of control function	Programming language
SC1	UC4	DG	Active Power management to restore frequency stability	Python, DSL model (PowerFactory)
	UC6	SI controllers	local controllers integrated into inverters for inertial support	DSL
		SI controller	central controller for managing RoCoF in a chosen time window	python
SC2	UC1	RES & DG	Reactive power management	PowerFactory/Ampl
	UC2	DG	Active Power management to solve/mitigate congestions problems	Python
SC3	UC5	DG & storage systems	minimizing power flow through 110 kV transformers and maximizing local usage of the energy in the DSO grid, as well as minimizing losses and maximizing share of RES	python
	UC3	RES & DG, Demand response	Optimization of power flow to maximize the share of renewable energy sources in providing tertiary reserve and minimize the power losses	Python + PowerFactory
SC4	UC1	RES & DG	Reactive power management	PowerFactory/Ampl
	UC3	RES & DG, Demand response	Optimization of power flow to maximize the share of renewable energy sources in providing tertiary reserve and minimize the power losses	Python + PowerFactory
SC5	UC7	Load shedding	Load shedding to solve under voltage problems during a contingency	Python+OPF (PowerFactory)
		PV curtailment	active Power curtailment to solve over voltage problems during a contingency	Python+QDSL model (PowerFactory)
		DG re-dispatch	active power re-dispatch to solve over and under voltage problems during a contingency	Python+OPF (PowerFactory)

4. Showcases control functions

As mentioned in the previous section, a showcase consists of one or several use cases with different control functions. Based on the characteristics and goals of the composing use cases, the relevant showcase may need to perform a grid equivalenting method. Eventually, the showcase needs to be implemented on a test case with specific features in order to evaluate the effectiveness of the developed control functions. Therefore, this section presents the control functions developed for the following showcases:

1. Low inertia systems;
2. Effective DER operation planning through active and reactive power control;
3. TSO-DSO power flow optimization;
4. TSO-DSO coordinated active and reactive power optimization for provision of tertiary reserve and improvement of voltage profiles;
5. Optimal energy interruption management;

To run the simulation of showcases, detailed features of the showcases including control functions properties within each use case and the implementation procedure of showcases need to be specified in line with goals of INTERPLAN tool. To this end, each showcase is presented in this section through five tables analysing: 1- properties, 2- control functions, 3- showcase structure, 4- test cases and 5- summary. The content of each table is summarized in below:

1. Showcase properties: In this part, the motivation and objective of the showcase is described and the solution to reach the objective of showcase is presented.
2. Control functions: As showcases include one or several use cases, the control functions for each use case are presented in this part. Control functions are developed to reach the objectives of use cases and showcases; therefore, all the data associated with their development such as the controllable variables, the tools/actors as well as the specific assumptions and requirements to implement them are introduced. Since all of control functions are mathematically formulated for the simulation of showcases, the input data, formulations as well as simulation environment and type are stated. If any use case needs to apply a grid equivalenting method to implement the control functions, the reason and the method of grid equivalenting is described in this part.
3. Showcase structure: The different steps of showcase implementation in the presence of developed control functions in use cases need to be organized to understand the applicability of showcase simulation. Therefore, the steps of showcase implementation are described in a way that input data, output data, grid area, and actions for each step are specified.
4. Test case: The selected grid model to simulate the showcase is presented in this part. The reason and suitability of the test case for showcases are stated together with the features of the grid model. The KPIs to be calculated in the next stage of the project are also presented.
5. Summary: This part presents the achievements, the learned lessons from the development of control functions for each showcase, and the way each showcase is included and considered in the INTERPLAN tool.

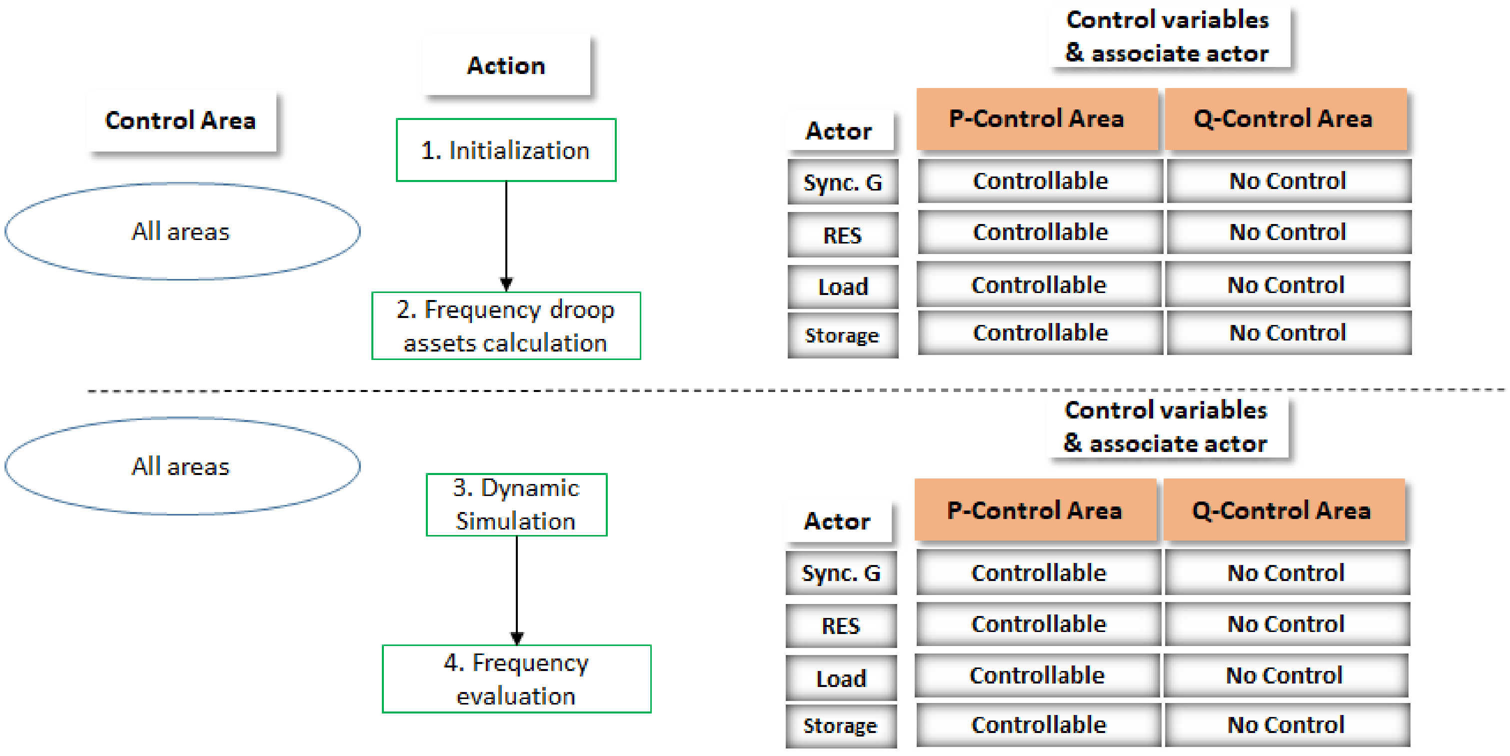
4.1 SC 1 - Low inertia systems

4.1.1 SC properties

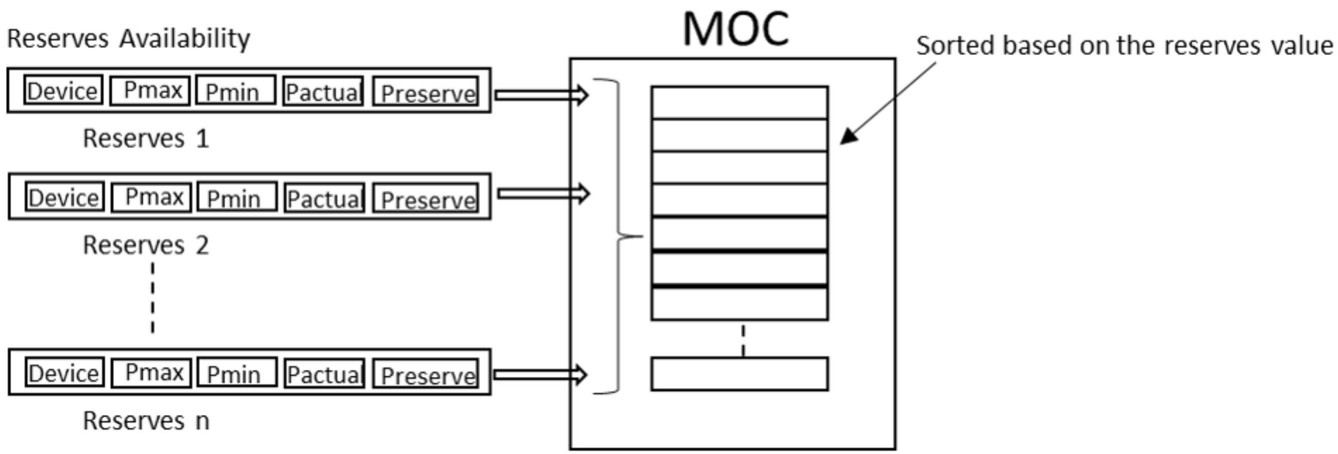
ID and Name	SC1: Low inertia systems	
Relevant use case/s	UC4: Fast Frequency Restoration Control UC6: Inertia management	
SC description	**Summary**	
	As the integration rate of RES is predicted to be high in the future power systems, inertia of the system diminishes so rate of change of frequency (RoCoF) and frequency stability can be jeopardized. Fast frequency restoration control and inertia management taking advantage of the capabilities of the distributed energy resources (DER) are employed in order to secure the system stability.	
	Motivation	
	Power systems with low share of synchronous generation, and consequently low total system inertia, are vulnerable to power imbalances. Such systems can experience frequency stability problems, such as high frequency excursions and higher rates of change of frequency. Therefore, the main focus of this showcase is to demonstrate how frequency stability in low inertia systems can be provided through capabilities of other power system objects present in the low inertia grids, such as RES, distributed generation (DG), controllable loads and storage systems. This showcase combines inertia management with fast frequency restoration control. Frequency stability of the first swing in the proposed solution is managed by estimating available and needed inertia for given system conditions, and then utilizing the needed inertia through synthetic inertia and fast frequency response controllers. For further reinforcements, optimal power flow-based frequency restoration is added, which, by using available energy sources, brings the frequency to its nominal value.	
	Objective	
	This SC's objective is to maintain frequency stability in low inertia systems through inertia management and fast frequency restoration.	
	Solution	
	In order to secure stability of the system, inertia management is employed together with the capabilities of emerging technologies to support the frequency through advanced control capabilities of fast frequency control.	

4.1.2 Control functions

4.1.2.1 Control function for Fast Frequency Restoration Control

UC ID 4: Fast Frequency Restoration Control	
Control variables & associate actor/tool & flowchart	
Assumptions	It is assumed that all assets are controllable.
Prerequisites	**Step 1:** • Load flow for initialization; • Frequency Droop calculation for each device.

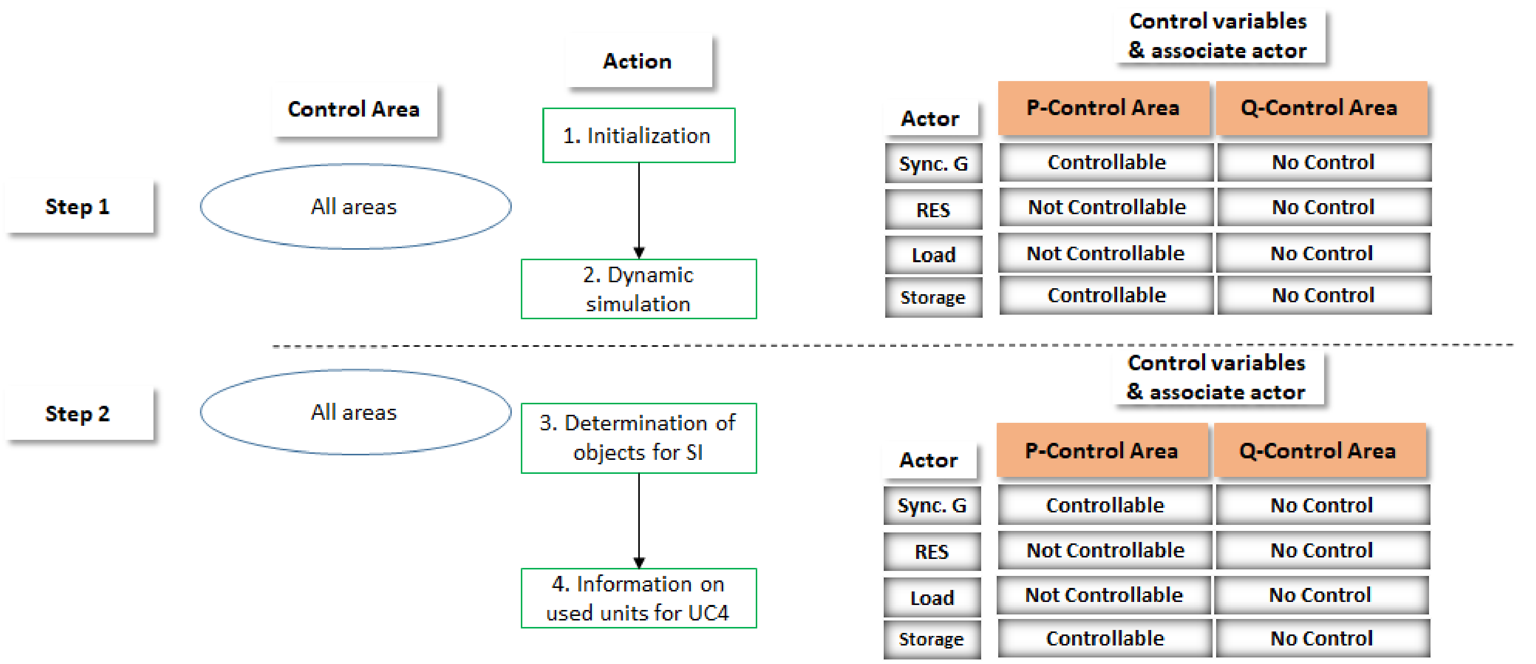
	<u>Step 2:</u> System Frequency evaluation.
Grid equivalenting	Grid equivalenting in use case 4 is used to represent detailed wind farms models, consisting of several wind turbines, transformers, lines and dynamic models, as a simplified models. The static equivalent consists of single wind turbine, two transformers and two lines, per each wind farm. Impedance of these lines and transformers is calculated in such a way that the wind farm is virtually shifted away from the point of common coupling (PCC), which is needed when it is located deep in the distribution grid. The dynamic equivalent uses models defined by the Western Electricity Coordinating Council (WECC) that mimic the behaviour of detailed models used in the full wind farm model.
Input	**<u>General grid data for all steps:</u>** Bus data Branch data Generator data
	<u>Step 1:</u> • Active power for load, RES and storage;
	<u>Step 2:</u> • Active power for load, RES and storage;
Formula	**<u>Step 1:</u>** For each control area, the total active power-frequency response is evaluated. For each resource in the control area, the active power flexibility is evaluated and stored within a merit order collection list:

	 P_{actual} is the active power provided by resource at time step *i.* $P_{reserve}$ is the active power resource reserve P_{max}-P_{min} at time step *i.* Starting from the total control-area's active power-frequency response and the frequency error threshold set, the device droop slope is calculated per each resource.
	Step 2: The dynamic simulation is performed to evaluate the grid frequency response.
Simulation environment	Powerfactory, Python
Simulation type	Semi-dynamic, dynamic

4.1.2.2 Control function for inertia management

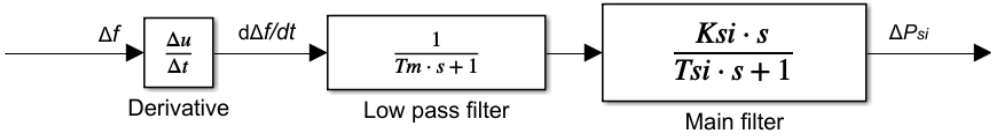
UC ID 6: Inertia management	
Control variables	Active power
Associate actor/tool	Storage units
Assumptions	It is assumed that all storage units are able to provide synthetic inertia.
Prerequisites	Network model should converge for both load flow and dynamic simulation for all time steps. Dynamic models for synchronous generators and storage units should be available and stable for no-event simulation.
Grid equivalenting	Grid equivalenting in use case 6 is used to represent detailed wind farms models, consisting of several wind turbines, transformers, lines and dynamic models, as a simplified models. The static equivalent consists, in this case, of single wind turbine, two transformers and two lines, per each wind farm. Impedance of these lines and transformers is calculated in such a way that the wind farm is virtually shifted away from the point of common coupling (PCC), which is needed when it is located deep in the distribution grid. The dynamic equivalent uses models defined by the Western Electricity Coordinating Council (WECC) that mimic the behaviour of detailed models used in the full wind farm model.
Input	• actual active power of system objects • synthetic inertia (SI) model parameters • apparent power of system objects • maximum active power of system objects • synchronous generators inertia

Flowchart



Formula

To provide appropriate response, first the parameters for SI has to be chosen. For each time step the gain (K_{si}) is scaled through weights, based on the dynamic simulation output and number of units chosen for SI support. There is no SI support if the RoCoF does not exceed the given maximum value.



$$\int_0^\tau y_{SI}(t)dt = \frac{K_{SI}T_{SI}}{T_m - T_{SI}}\left(e^{-\frac{\tau}{T_{SI}}}-1\right) - \frac{K_{SI}T_m}{T_m-T_{SI}}\left(e^{-\frac{\tau}{T_m}}-1\right) = \Delta E_\tau$$

In UC6 control, system inertia (H_{sys}) is calculated before and after the largest possible trip (of generation, load, etc.) for each time step according to the following formula:

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{S_{sys}}$$

Knowing this largest possible trip (ΔP) and post-disturbance system inertia, it is possible to estimate expected RoCoF (df/dt) in the grid:

$$\frac{df}{dt} = \frac{\Delta P f_n}{2H_{sys}S_{sys}}$$

The algorithm selects storage units for synthetic inertia provision taking into consideration two criteria:

1. the active power criterion:

Additional active power for synthetic inertia (P_{SI}) is equal to the sum of available active power from a chosen units (P_{avai}).

$$P_{SI} = \sum_{i=1}^{n} P_{ava_i}$$

The units are chosen in such a way that the difference between sum of their available active power (P_{avai}) and largest trip (ΔP) is minimum, while preferred solution is that the sum of P_{avai} is equal to or larger than ΔP.

$$\min \left| \sum_{i=1}^{n} P_{ava_i} - \Delta P \right|$$

$$\sum_{i=1}^{n} P_{ava_i} \geq \Delta P$$

where P_{avai} is maximum available active power from a storage unit *i*.

2. the energy criterion:

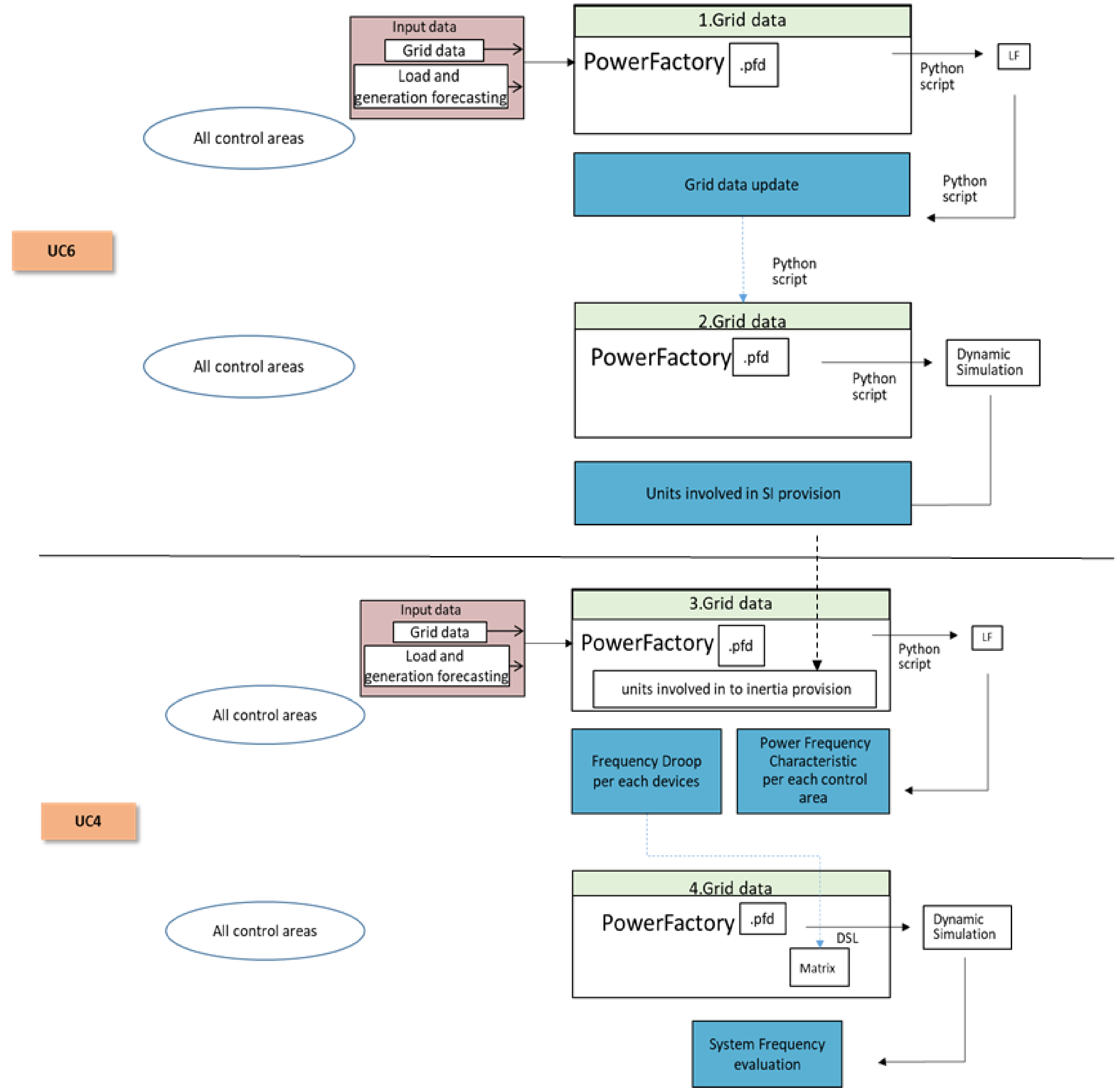
Additional energy for synthetic inertia (E_{SI}) is equal to the sum of available energy from chosen units (E_{avai}).

$$E_{SI} = \sum_{i=1}^{n} E_{ava_i}$$

The units are chosen in such a way that the difference between sum of their available energy (E_{avai}) and largest trip (ΔE) is minimum, while preferred solution is that the sum of E_{avai} is equal to or larger than ΔE_T.

	$$\min \lvert \sum_{i=1}^{n} E_{ava_i} - \Delta E_\tau \rvert$$ $$\sum_{i=1}^{n} E_{ava_i} \geq \Delta E_\tau$$ where $E_{ava\ i}$ is available energy from a storage unit *i*.
Simulation environment	Python, PowerFactory
Simulation type	Semi-dynamic, dynamic

4.1.3 Showcase structure

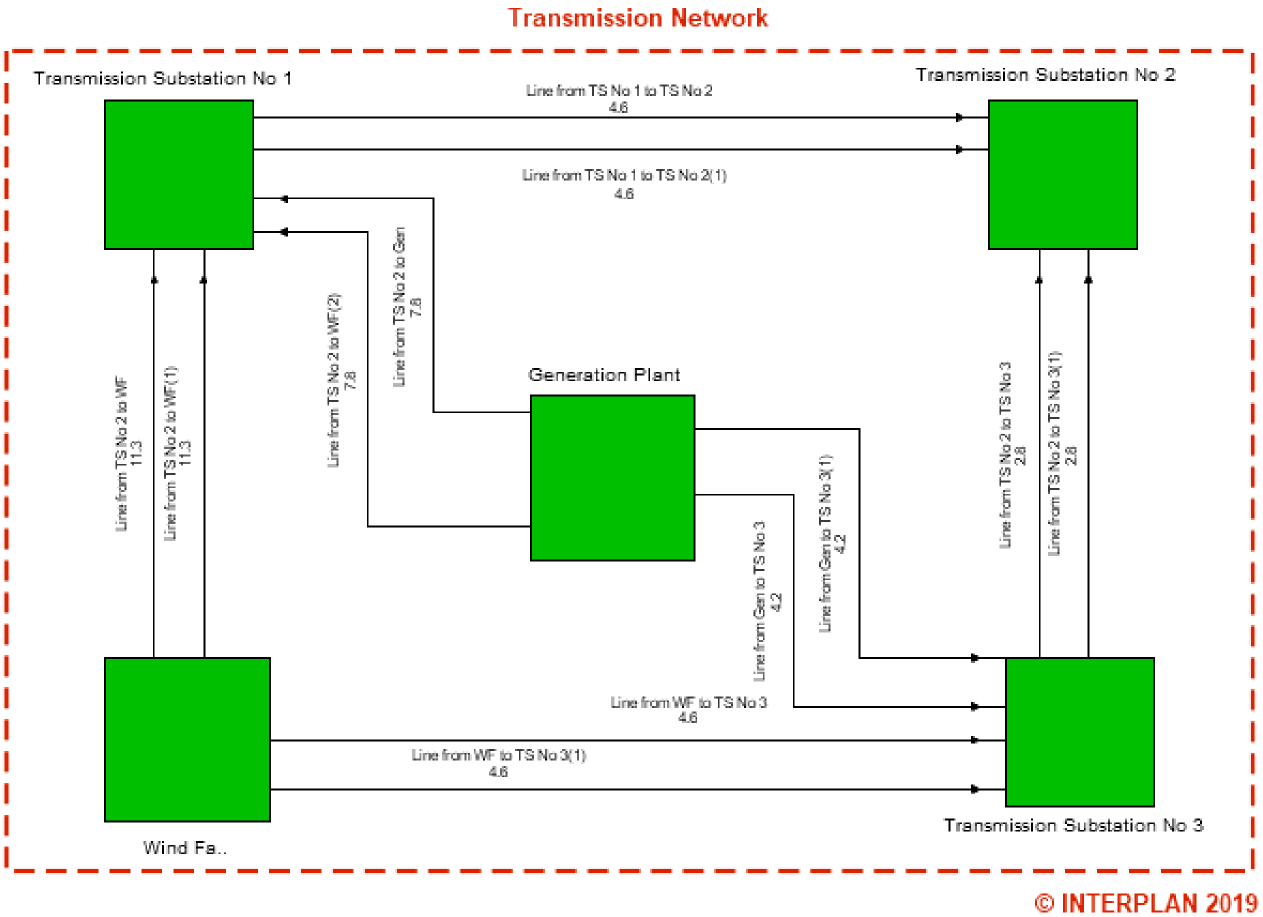
Sequence diagram	

<table>
<tr><td rowspan="5">Detailed description</td><td>Steps</td><td colspan="7">Description</td></tr>
<tr><td>1</td><td colspan="7">The UC6 control function reads internal information from the PowerFactory grid model such as inertia constants, active powers, nominal powers and systems’ kinetic energy. A load flow is performed and grid data are updated.</td></tr>
<tr><td>2</td><td colspan="7">System’s parameters such as kinetic energy or system inertia as well as system need for additional inertial support is calculated. A choice of power system assets for inertial support is made (active power flexibility/SI provision).</td></tr>
<tr><td>3</td><td colspan="7">Calculate the total power-frequency characteristic per each control area of the power grid under analysis. A static simulation is performed in order to calculate the total power-frequency characteristic per each control area of the power grid under analysis. The input is taken from step 2. Thus, based on the asset’s flexibility information, the frequency droop per each device is calculated. Calculation of frequency droop per each device is used as input setting for the asset’s dynamic models.</td></tr>
<tr><td>4</td><td colspan="7">Frequency Droop per each device is systematized under a matrix with DSL (DIgSILENT Simulation Language). A dynamic simulation of an instability event is performed. This is done in order to locate the instability event in the grid and verify the effectiveness of the devices frequency droop calculated at step one. System Frequency is evaluated whereas post-processing is performed offline. The post-processing result is a set of plots and KPIs metrics.</td></tr>
<tr><td rowspan="4">Sequence of actions</td><td>Steps</td><td>UC ID</td><td>Action</td><td>Content</td><td>Input</td><td>Operation</td><td>Output</td><td>Grid Area</td></tr>
<tr><td>1</td><td>6</td><td>Reading of system internal information and calculation of system internal information</td><td>Inherent grid information</td><td>Grid specifications under study</td><td>Python script and load flow</td><td>Inertia constraints, active powers and nominal capacities and systems’ kinetic energy</td><td>TSO&DSO</td></tr>
<tr><td>2</td><td>6</td><td>Flexibility assessment and potential of inertial support</td><td>Storage as flexibility assets are evaluated</td><td>Outputs of step 1</td><td>Static simulation</td><td>Power system assets list</td><td>TSO&DSO</td></tr>
<tr><td>3</td><td>4</td><td>Calculation of system internal information and results of the assets flexibility</td><td>Assets characteristics assessment</td><td>Grid specifications under study and outputs of step 2</td><td>Python script and load flow</td><td>PF calculation for the grid and each control area and droop</td><td>TSO&DSO</td></tr>
</table>

			assessment				calculation for the flexible assets	
	4	4, 6	Instability event, SC1 dynamic simulation and system Stability check	Dynamic simulations performed and Offline analysis	Outputs of step	Dynamic simulation, DSL used to systematize frequency-droops under matrix and KPI analysis	KPIs and plots	TSO&DSO

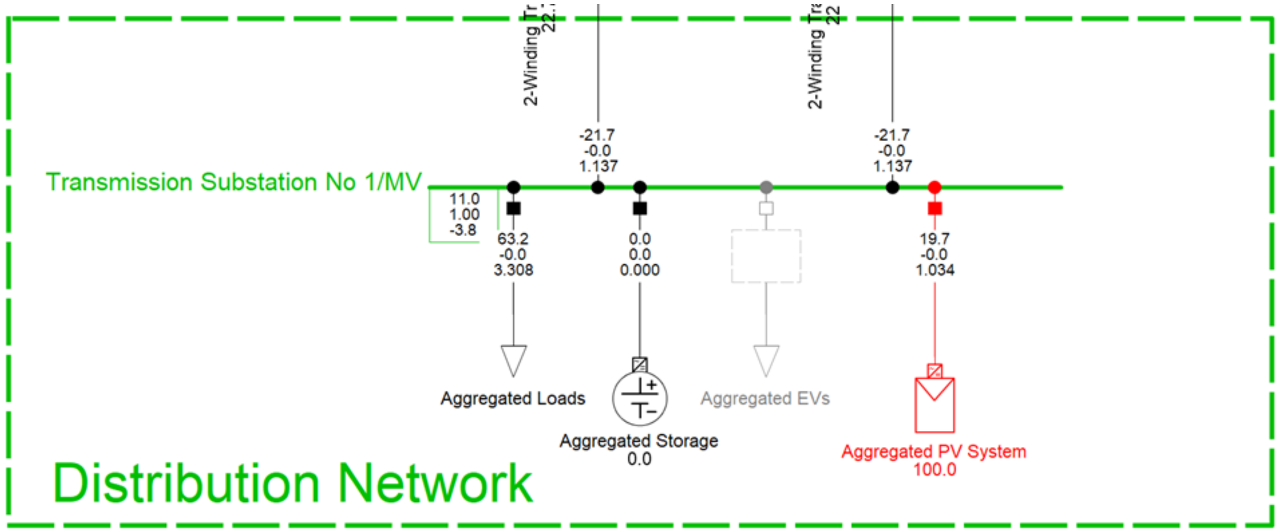
4.1.4 Test Case

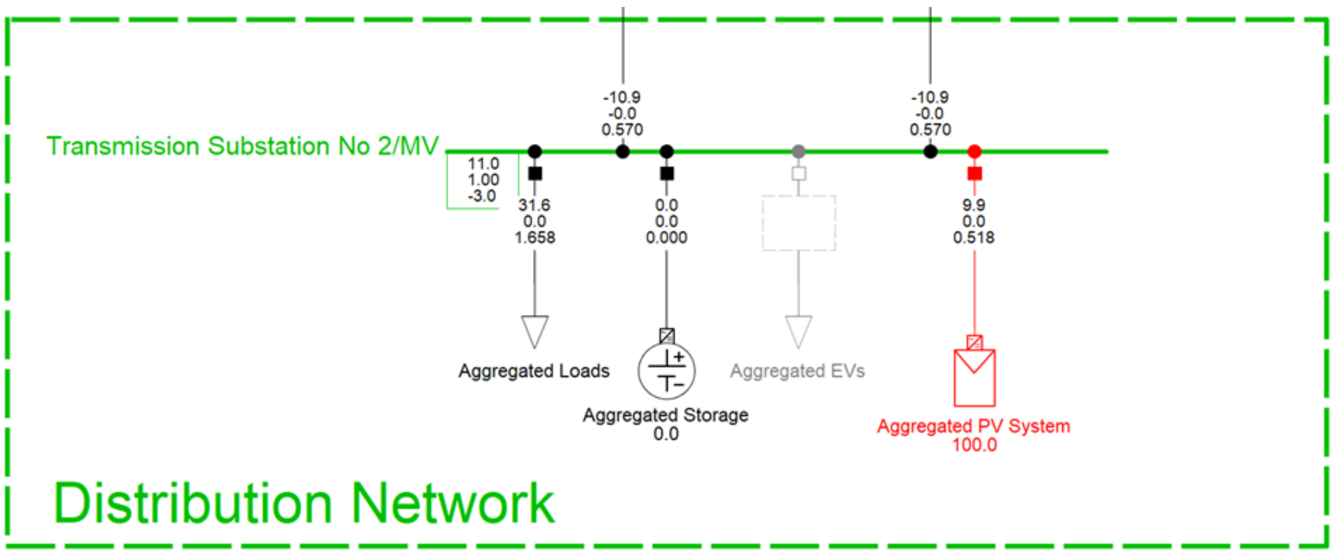
System under Test (SuT)	The power system model used to perform the dynamic simulations concerned in Showcase 1 is shown in the figures below. The particular system consists of five electrically connected areas and it represents a part of the real grid in Cyprus. This particular grid was selected to highlight the challenge of preserving the frequency stability in a grid with high RES penetration and zero interconnections with other bulk systems. Cyprus grid due to its specifities i.e. isolated and with no interconnections is the most challenging to test the operation of our controllers within this SC.

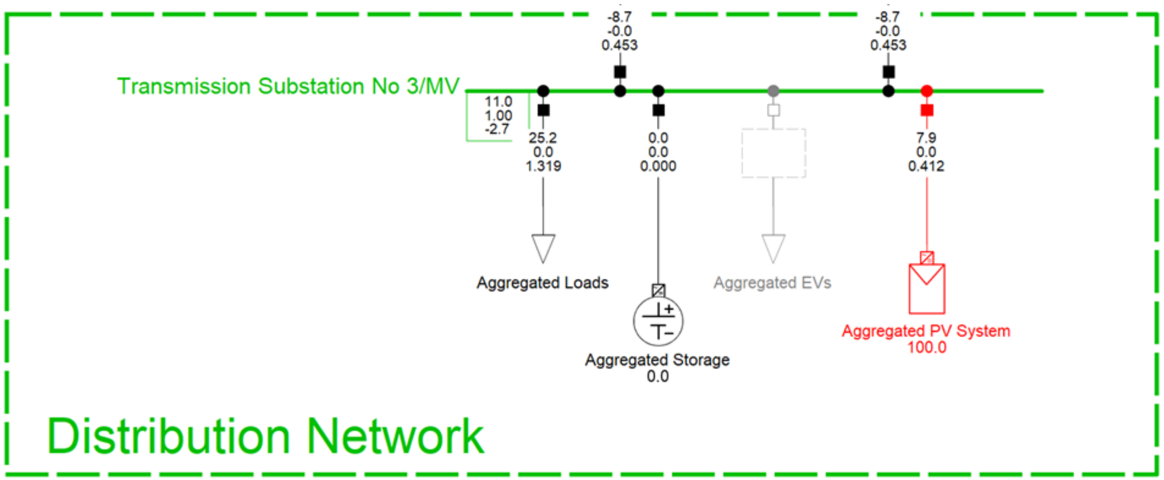


Three transmission substations with same electrical. specifications are included, which are:

- **Transmission Substation 1/Transmission Substation 2/ Transmission Substation 3**: with two feeders each where two HV to MV transformers of 100 MVA respectively serves the distribution side. Each of the substation serves at the MV side (11kV) load whereas PV and battery energy storage systems (BESS).


2-Winding Tr
22.
2-Winding Tr
22
-21.7
-0.0
1.137
-21.7
-0.0
1.137
Transmission Substation No 1/MV
11.0
1.00
-3.8
63.2
-0.0
3.308
0.0
0.0
0.000
19.7
-0.0
1.034
Aggregated Loads
Aggregated EVs
Aggregated Storage
0.0
Aggregated PV System
100.0
Distribution Network


-10.9
-0.0
0.570
-10.9
-0.0
0.570
Transmission Substation No 2/MV
11.0
1.00
-3.0
31.6
0.0
1.658
0.0
0.0
0.000
9.9
0.0
0.518
Aggregated Loads
Aggregated EVs
Aggregated Storage
0.0
Aggregated PV System
100.0
Distribution Network

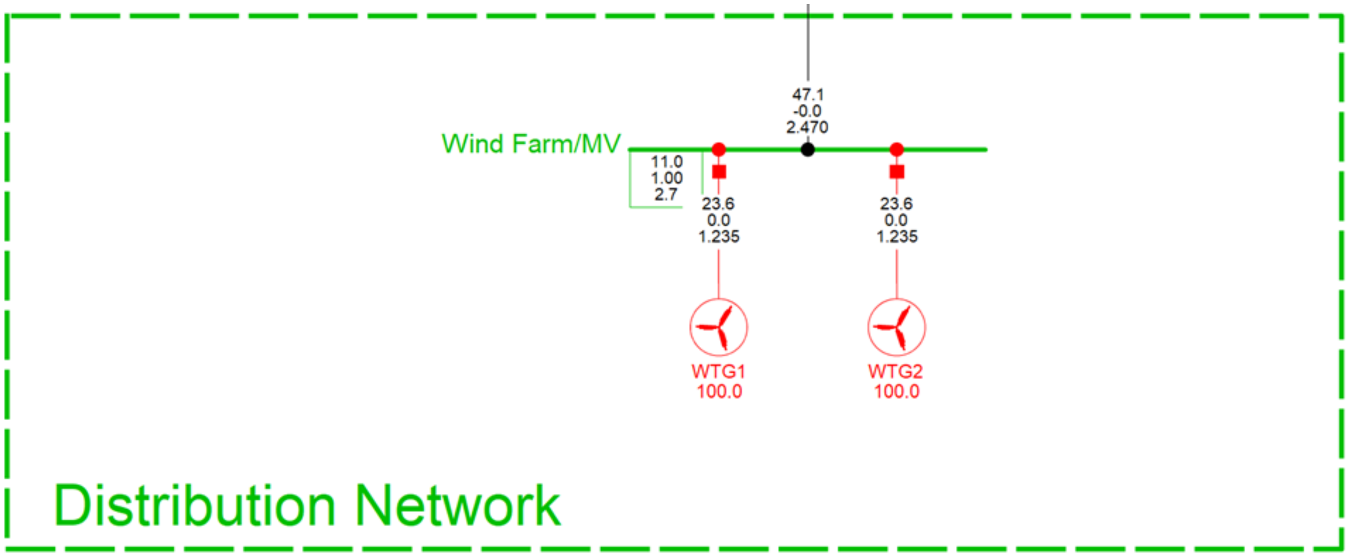


Generation Plant area:

- Two parallel synchronous machines operate for a total of 50 MVA each. The power provided by the generators is produced at the voltage level of 11 kV and delivered into the 132 kV transmission network, through two 100 MVA transformers.

Wind farm area:

- includes one 16 MVA transformer and two wind turbine generators (WTG).

<table>
<tr><td></td><td colspan="3">
</td></tr>
<tr><td>Objects under Test (OuT)</td><td colspan="3">

- Static Generators-2 wind turbine generators(23,57 MVA each)
- BESS - 3 aggregated storage systems-(user defined models-90 MVA each, pf=0.8)
- Load - 3 loads (user defined models-63,10 MW(area1)-31,65 MW(area2)-25,2 MW(area3))
- PV systems - 3 aggregated PV systems(user defined models)
- Synchronous Generators - 2 x 50 MVA each(Automatic Voltage Regulator Type: EXAC4, Speed Governor Type: TGOV1)

</td></tr>
<tr><td>Scenarios</td><td colspan="3">INTERPLAN-3: Large Scale RES</td></tr>
<tr><td>Input data</td><td colspan="3">

- Generation/demand profiles for all generators (synchronous generators, PVs, wind turbines) and loads are available for a 24 h period.
- Energy Storage systems battery energy storage systems (BESS) are assumed to support the system when needed. Time-series data: synthetic
- Generation and load forecasting

Time frame: 24 h
Time resolution: 15 min.</td></tr>
<tr><td rowspan="2">KPI under test</td><td>ID</td><td>Name</td><td>Formula</td></tr>
<tr><td>5</td><td>Frequency restoration</td><td>$F_{\text{restoerd}} - F_{\text{nom}} \leq \varepsilon, \varepsilon \to 0$</td></tr>
</table>

		control effectivity	
	14	Level of DG / DRES utilization for ancillary services	$UAS\% = \frac{E_{AS}}{E_{total}} * 100\ [\%]$ E_{AS} − the energy used for ancillary services $[MWh]$ E_{total} − the total energy produced $[MWh]$
	20	Frequency nadir/zenith	$max(\|f_n - f\|)\ [Hz]$ $f_n - nominal\ frequency\ [Hz]$ $f - system\ frequency\ [Hz]$
	21	Rate of Change of Frequency (RoCoF)	$\frac{df}{dt} = \frac{P_g - P_l}{2H_{sys}}$ $\frac{df}{dt}$ − rate of change of frequency $[Hz/s]$ P_g − generators′ active power [pu] P_l − demand active power $[pu]$ H_{sys} − system inertia $[s]$
	25	Indication of Stability	this KPI is a boolean value (YES/NO)
	26	Oscillation damping	$\sigma = \ln(\frac{p_1}{p_2})$ p_1, p_2 − max values of two consecutive swings of the signal
	27	Share of RES	$RES\% = \frac{P_{RES}}{P_{total}} * 100\ [\%]$ P_{RES} Active power provided by RES at a given time step $[MW]$ P_{total} Total active power provided by RES and non RES generators at a given time step $[MW]$
Output parameters	Output parameters would be: • System frequency		

	• List of units for SI provision • Droops characteristics for devices • P-f characteristic curves for devices Post processing of the outputs will result to the following figures: • Results of dynamic simulations performed for each time step during 24 hours: overfrequency activation, underfrequency protection activation. • Nadir/zenith of frequency (BSC and SC in the same diagram) • RoCoF calculated for each time window (BSC and SC in the same diagram).

4.1.5 Summary

Summary	The showcase addresses a combination of challenges, which are frequency stability and inertia management that may occur in the presence of high DER penetration level. The proposed integrated control functions (related to UC4 and UC6) allow system operators (DSOs) to solve these operation challenges through planning of unit dispatch under the frequency stability criterion and employing inertia management for assuring transient stability. A system operator (TSO and DSO) that wants to address these operation challenges by using the INTERPLAN tool will be guided by the user manual to select the following planning criteria: • 3.Maximizing share of RES • 6.Assuring transient stability • 8.Maximize DG/RES contribution to ancillary services • 9.Assuring frequency stability The simulation functionalities to be employed within the tool isBasic Load flow along with Stability Analysis Functions. The selected KPIs needed to measure the effectiveness of the control functions are: • 5. Frequency Restoration • 14. DG/RES utilization • 20. Frequency zenith/nadir • 21.RoCoF • 25. Indication of Stability • 26. Oscillation damping

	• 27. Share of RES The suggested INTERPLAN scenario is INTERPLAN-3: Large Scale RES Regarding the type of grid models to be used, the Cyprus grid has high RES penetration and zero interconnections with other bulk systems to model the frequency stability at the DSO side. The grid equivalenting is required to represent detailed wind farms models, consisting of several wind turbines, transformers, lines and dynamic models, as a simplified models. It has both static equivalent and dynamic equivalent. Once performed all these steps, the user is ready to select this showcase control function and perform the simulations through PowerFactory and with the Python scripts. The evaluation phase will follow with reference to the KPI(s) values found in the simulation.

4.2 SC2 - Effective DER operation planning through active and reactive power control

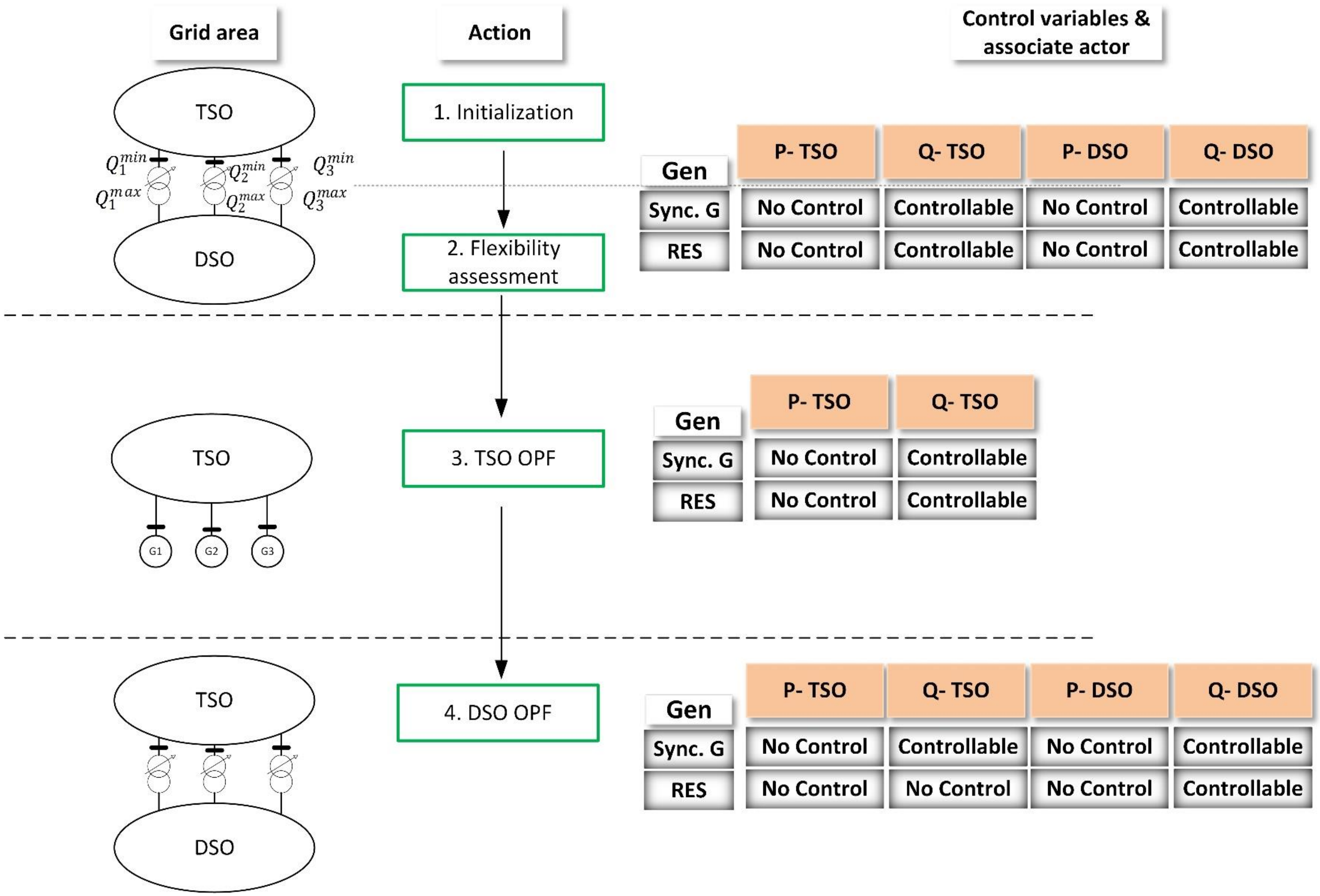
4.2.1 SC properties

ID and Name	SC2: Effective DER operation planning through active and reactive power control
Relevant UC/s	UC1: Coordinated voltage/reactive power control UC2: Grid congestion management
SC description	**Summary**
	Active and reactive power intelligent control for grid congestion management and coordinated TSO-DSO optimization.
	Motivation
	The presence of DER can significantly impact the power networks, exposing the system to much higher power fluctuations and compromising the system power quality. Ensuring voltage stability and solving power congestions become even more important issues to deal with the increasing penetration levels of DER. Therefore, innovative control schemes have to be considered in the future power systems.
	Objective
	The main focus of this showcase is to present a control scheme to improve TSO-DSO coordination both in managing the grid for voltage stability and solving the congestion issues occurring at all voltage levels. By applying a coordinated TSO-DSO optimization methodology, this showcase aims to regulate reactive and active power by using TSO and DSO power assets, including utilization of the DSO flexibilities, to respect TSO optimization objectives and restore the grid in the presence of congestion events.
	Solution
	In order to prevent congestion and voltages violations problems in the system, congestion management control with the Coordinated voltage/reactive power control are employed.

4.2.2 Control functions

4.2.2.1 Control function for coordinated voltage/reactive power control

UC ID 1: Coordinated voltage/reactive power control

Control variables & associate actor/tool & flowchart	
Prerequisites	**<u>Step 1:</u>** Load flow for initialization
	<u>Step 2:</u> -Reactive power flexibility assessment at the connection points, -DSO grid equivalent.
	<u>Step 3:</u> OPF in TSO and fix the reactive power set points in connection point
Grid	Grid equivalenting is employed in the third step of UC1 procedure to make a DSO equivalent, because DSO in this step is not under

<table>
<tr><td>equivalenting</td><td>control and just an equivalent generator representing the DSO is sufficient. The equivalent generators are connected to TSO-DSO connection point and their initial active and reactive power set points are extracted from LF in that node.</td></tr>
<tr><td rowspan="3">Input</td><td><u>General grid data for all steps:</u>
Bus data
<table>
<tr><td>Bus type</td><td>Active power load</td><td>Reactive power load</td><td>Bus area</td><td>Initial Bus voltage magnitude</td><td>Initial bus voltage angle</td><td>Maximum and minimum bus voltage</td><td>Nominal bus voltage</td></tr>
</table>
Branch data
<table>
<tr><td>Branch from which bus</td><td>Branch To which bus</td><td>Branch resistance</td><td>Branch reactance</td><td>Branch conductance</td><td>Branch susceptance</td><td>Branch capacity (max. current carrying capacity)</td><td>Branch type</td><td>Branch tap rate magnitude if it is a transformer</td><td>Branch phase shift angle if it is transformer</td></tr>
</table>
Generator data
<table>
<tr><td>Generator bus number</td><td>Generator type</td><td>Generator operation mode</td><td>Initial active power</td><td>Initial reactive power</td><td>Reactive power boundary</td><td>Voltage in case of operation mode slack or PV</td></tr>
</table>
</td></tr>
<tr><td><u>Step 1:</u> -Voltage magnitude and angle initialization for buses and generators,
-Initial active and reactive power for generators.</td></tr>
<tr><td><u>Step2:</u> -Voltage magnitude and angle initialization for buses and generators,
-Initial active and reactive power for generators,
-Active and reactive power for equivalent DSO generators,
-Minimum and maximum capable reactive power for DSO-TSO connection point (from step 1).</td></tr>
</table>

	Step 3: -Voltage magnitude and angle initialization for buses and generators, -Initial active and reactive power for generators, -Reactive power set point in DSO-TSO connection point (from step 2).
Formula	**Step 1:** **Objective function:** $$\boldsymbol{Q}_{\mathbf{CP}}^{\mathbf{Max}} = max \sum_t \sum_i \sum_j V_i(t)V_j(t)\left[G_{\mathrm{ij}} \sin\left(\theta_i(t)-\theta_j(t)\right) - B_{ij} \cos\left(\theta_i(t)-\theta_j(t)\right)\right]$$ $$\boldsymbol{Q}_{\mathbf{CP}}^{\mathbf{Min}} = min \sum_t \sum_i \sum_j V_i(t)V_j(t)\left[G_{\mathrm{ij}} \sin\left(\theta_i(t)-\theta_j(t)\right) - B_{\mathrm{ij}} \cos\left(\theta_i(t)-\theta_j(t)\right)\right]$$ **s.t.** $$-\sqrt{1-\left(\frac{P_g(t)}{S_g}\right)^2} \leq Q_g(t) \leq \sqrt{1-\left(\frac{P_g(t)}{S_g}\right)^2}$$ $$\frac{P_{\mathrm{ij}}(t)^2 + Q_{\mathrm{ij}}(t)^2}{V_{\mathrm{ij}}(t)^2} \leq I_{\mathrm{ij,max}}^2$$ Where: i, j: Index (set) of buses. t: Index (set) of time steps. g: Index (set) of generators. n: Index (set) of connection point. CP: Superscripts for connection point. SP: Superscripts for set point

G: Conductance of transmission line

B: Susceptance of transmission line

S: Apparent power

α: Weight/scale factor for objective function

β: Weight/scale factor for objective function

P: Active power.

Q: Reactive power.

V: Voltage magnitude

θ: Voltage angle

I: Electric current

This nomenclature can be applied for formulation of other steps.

Step 2:

Objective function:

$$\boldsymbol{P}_{\mathbf{losses}}: min \sum_{t}\sum_{i}\sum_{j} G_{\mathrm{ij}} \left[V_i(t)^2 + V_j(t)^2 - 2V_i(t)V_j(t)\cos\left(\theta_i(t) - \theta_j(t)\right)\right]$$

s.t.

$$-\sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2} \leq Q_g(t) \leq \sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2}$$

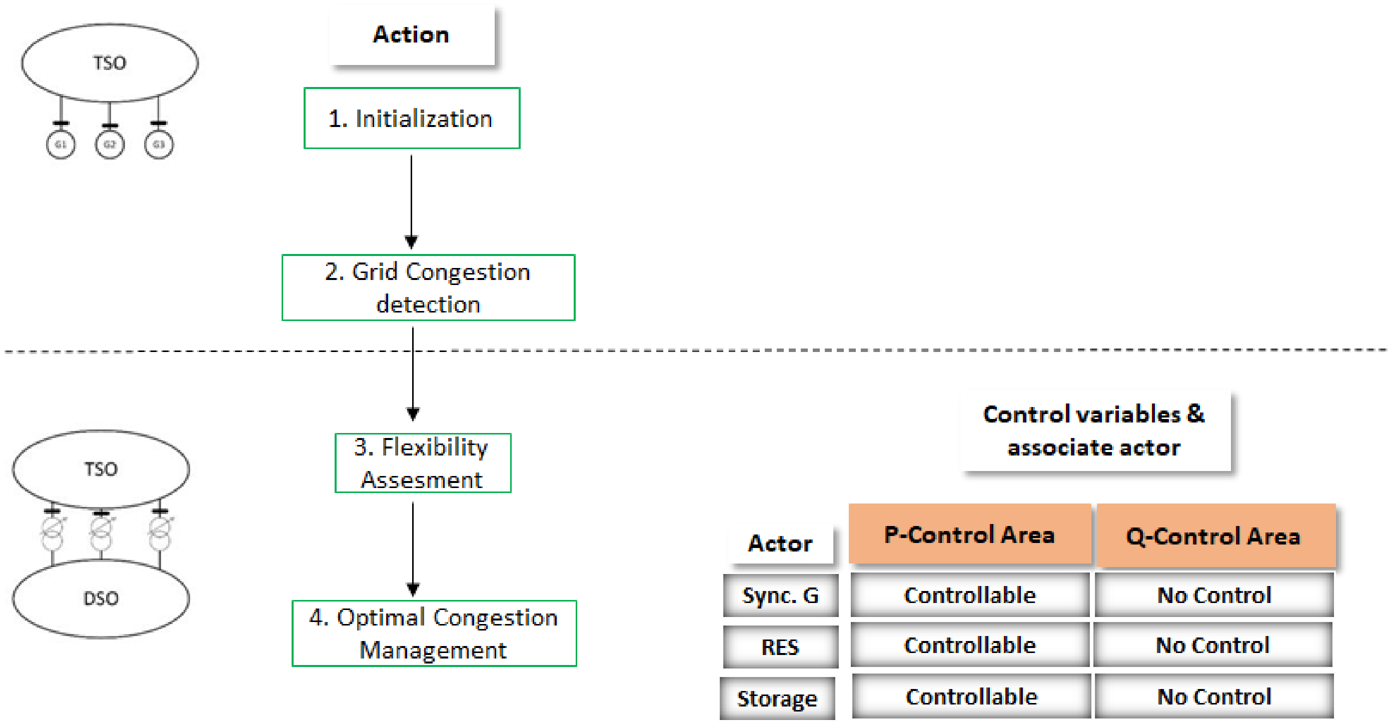
	$$\frac{P_{ij}(t)^2 + Q_{ij}(t)^2}{V_{ij}(t)^2} \leq I_{ij,max}^2$$
	<u>Step 3:</u> **Objective function:** $$\boldsymbol{P}_{\mathbf{losses}}: min \sum_t \left\{ \sum_i \sum_j G_{ij} \left[V_i(t)^2 + V_j(t)^2 - 2V_i(t)V_j(t)\cos\left(\theta_i(t) - \theta_j(t)\right)\right] + \sum_n \left(Q_{\mathrm{CP}_n}(t) - Q_{\mathrm{sp}_\mathrm{n}}(t)\right)^2 \right\}$$ **s.t.** $$-\sqrt{1-\left(\frac{P_g(t)}{S_g}\right)^2} \leq Q_g(t) \leq \sqrt{1-\left(\frac{P_g(t)}{S_g}\right)^2}$$ $$\frac{P_{ij}(t)^2 + Q_{ij}(t)^2}{V_{\mathrm{ij}}(t)^2} \leq I_{\mathrm{ij,max}}^2$$
Simulation environment	Powerfactory, AMPL
Simulation type	Semi-dynamic

4.2.2.2 Control function for grid congestion management

UC ID 2 : Grid Congestion Management	
Control variables	Active power

Associate actor/tool	DG
Assumptions	It is assumed that all assets are controllable and the n-1 criteria is satisfied
Prerequisites	• The grid model under test has to contain both TSO and DSO levels. • All assets in the grid are controllable
Grid equivalenting	No grid equivalenting is used in this UC. Due to it's need to preserve the lines information, and considering we assumed that all the assets in the grid are controllable, it is not possible provide a grid equivalent
Input	The input for the Control function are: • The information about the assets flexibility and lines characteristic • Sensitivities information about each bus bar • Congested lines information

Control variables & associate actor/tool & flowchart



Formula

Step 1:

Possible congestion problems at TSO level are detected. Per each line at TSO level, the following condition is checked:

$$P_{line_j} < 0.9 * P_{rating_{line_j}}$$

where:
P_{line_j} is the active power that flows through the line *j*;
$P_{rating_{line_j}}$ is the nominal active power of the line *j*;

In case of violation of the above condition, the congestion management process is triggered.

Step 2:

Objective function:

$$f = \min(\sum_{i=0}^{N_{busbar}} (\Delta P^{+}_{busbar_i} + \Delta P^{-}_{busbar_i}))$$

where:
$\Delta P^{+}_{busbar_i}$ is the positive active power variation at busbar *i*;
$\Delta P^{-}_{busbar_i}$ is the negative active power variation at busbar *i*;
N_{busbar} is the total number of bus.

s.t.

$$I_{rating_{line_j}} - \frac{\sqrt{\left(P_{lo_{linej}} + \frac{\partial P_{line_j}}{\partial P_i} * \Delta P_{busbar_i} + \frac{\partial P_{line_j}}{\partial Q_i} * \Delta Q_{busbar_i}\right)^2 + \left(Q_{lo_{linej}} + \frac{\partial Q_{line_j}}{\partial P_i} * \Delta P_{busbar_i} + \frac{\partial Q_{line_j}}{\partial Q_i} * \Delta Q_{busbar_i}\right)^2}}{\sqrt{3} * (U_{lo_{linej}} + U_{N_{line_j}} * (\frac{\partial u_{line_j}}{\partial P_i} * \Delta P_{busbar_i} + \frac{\partial u_{line_j}}{\partial Q_i} * \Delta Q_{busbar_i}))} \geq 0 \qquad \forall i, j$$

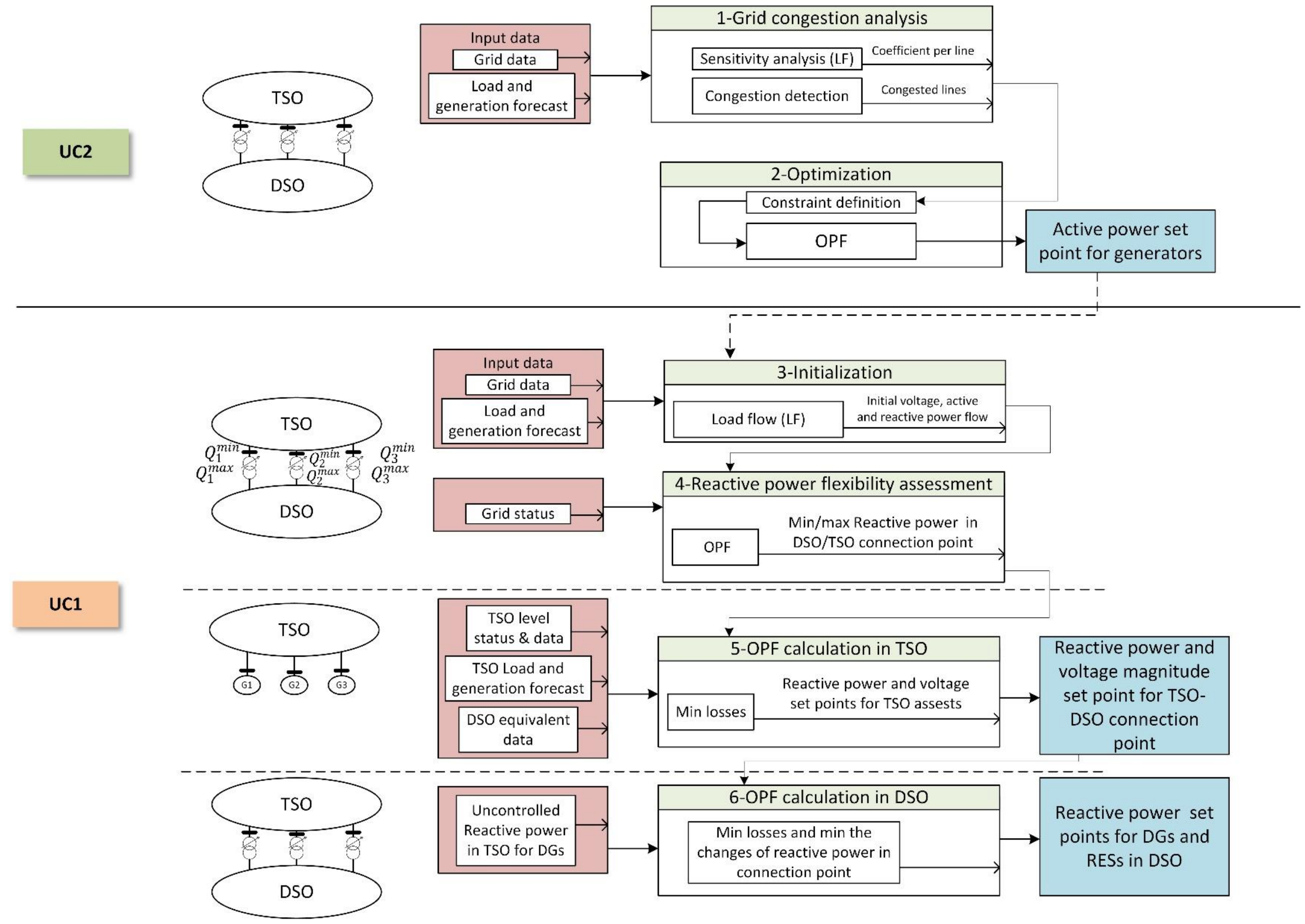
where:

$I_{rating_{line_j}}$ is the nominal current value of the line *j*;
$P_{lo_{linej}}$ is the active power initial condition that flows through the line *j*;
$Q_{lo_{linej}}$ is the reactive power initial condition that flows through the line *j*;
P_{line_j} is the active power that flows through the line *j*;
Q_{line_j} is the active power that flows through the line *j*;
$\frac{\partial P_{line_j}}{\partial P_i}$ is the effect on active power of the injection of Δ*P* at busbar i for the $line_j$.
$\frac{\partial P_{line_j}}{\partial Q_i}$ is the effect on active power of the injection of Δ*Q* at busbar i for the $line_j$.
$\frac{\partial Q_{line_j}}{\partial P_i}$ is the effect on reactive power of the injection of Δ*P* at busbar i for the $line_j$.
$\frac{\partial Q_{line_j}}{\partial Q_i}$ is the effect on reactive power of the injection of ΔQ at busbar i for the $line_j$.
$U_{lo_{linej}}$ is the voltage initial condition of the line *j*;

	$U_{N_{line_j}}$ is the nominal voltage $line_j$ $u_{line_j} = \frac{U_{line_j}}{U_{N_{line_j}}}$ where U_{line_j} is the voltage of the line j
Simulation environment	Python and Powerfactory
Simulation type	Semi-dynamic

4.2.3 Showcase structure

Sequence diagram	



Detailed description	Steps	Description
	1	Possible congestion problems are detected at TSO level. In case of problems detection, the congestion management process is triggered.
	2	The active power flexibility assessment per each resources at both TSO and DSO level is performed. This assessment is essential to know the possible active power variation at each busbar to solve the congestion problems detected at step 1. Then, a sensitivities analysis is performed to calculate the minimum active power variation at each busbar to solve the detected grid congestion problems at TSO level.

	3 4	The reactive power capability is evaluated at each TSO-DSO connection points with an optimization tool. Indeed, an OPF runs to find the maximum and minimum reactive power that DSO can exchange with TSO at each 15 minutes in a day. At step 3, first, an initialization is performed with running a power flow in order to calculate the initial values for different variables in the grid including voltage magnitude/angle as well as active and reactive power flow. The area of the network that needs to be analysed in this step is both DSO and TSO. Grid data including detailed information about buses, branches, and generators as well as time series for load and generation are required as input data for initialization. Then those data along with grid status information are transferred to the flexibility assessment step (step 4). To evaluate the reactive power capability from DSO to deliver to TSO, reactive power at DSO and TSO should be controlled for RESs and synchronous generators.						
	5	Finding the possible reactive power provision from DSO to TSO, those data are transferred to the step 5 that is TSO level re-dispatch via minimizing the grid losses. Indeed in this step, TSO level is scheduled for the next day based on the given reactive power capability from DSO. Therefore, in this step just the TSO level is analysed and the DSO equivalents are generated as generators in the connection points in a way that the maximum and minimum reactive power for the equivalent generators are set as calculated ones in the previous step. Initial operating active and reactive power for those equivalent generators are also obtained from power flow in the relevant bus. Hence, the reactive power set points for all generators are optimized at TSO in a way that TSO losses is minimized.						
	6	Given the reactive power set points from the last step, another OPF is performed in the overall grid in a way that the only under-controlled variables are all generators' reactive power at DSO level and just RESs' reactive power at TSO level. In other words, in the final step, reactive power at DSO is optimized while setting the TSO variables as calculated in the second step. The only exception is synchronous generators' reactive power at TSO level which is supposed to be controllable. Therefore, the optimum reactive power for RES are calculated by minimizing the total grid losses as well as the deviation of reactive power at connection points from what has been calculated in the second stage. It means that in addition to loss minimization, the problem aims to preserve the exchange reactive power in the optimum amount calculated in TSO OPF. This helps to obtain the DSO values independently from TSO level.						
Sequence of actions	Steps	Associate UC ID	Action	Content	Input	Operation	output	Grid area
	1	2	Grid congestion analysis	1-Sensitivity analysis, 2-Congestion detection	-Grid data -Load and generation forecast	Load flow	Coefficient per line Congested lines	TSO & DSO
	2	2	Optimization (removing congestion)	-Constraint definition, -Objective function minimization	Outputs from step 1	Optimal power flow	Active power set points for generators	TSO & DSO
	3	1	Initialization	Set the initial values of	-Grid data,	Load flow	Initial voltage,	TSO & DSO

				assets	-Load and generation forecast, -output from step 2		active and reactive power flow	
	4	1	Reactive power flexibility assessment	Definition of reactive power capability from DSO side for TSO grid	-Grid status -Output from step 3.	Optimal power flow	Reactive power capability in TSO-DSO connection point	TSO & DSO
	5	1	TSO optimization	Loss minimization in TSO grid.	-TSO level status and data -TSO load and generation forecast -DSO equivalent -Output from step 4.	Optimal power flow	Reactive power and voltage set points for TSO assets	TSO
	6	1	DSO optimization	Loss minimization and trying to keep the reactive power in the set points calculated in the step 5	-Output from step5 -Reactive power set points for TSO DGs and make them uncontrolled	Optimal power flow	Reactive power and voltage set point for RES and DGs in DSO	DSO

4.2.4 Test case

System under Test (SuT)	The power system under testing is the SimBench grid model. The SC2 aims to investigate congestions and voltages issue considering both TSO and DSO using the assets at all levels. The selected grid model presents both transmission and distribution levels as well as many distributed resources suitable for the proposed controllers

<table>
<tr><td colspan="1"></td><td colspan="3"></td></tr>
<tr><td>Objects under Test (OuT)</td><td colspan="3">Static Generators (Wind, PVs, Hydro)
Loads
Synchronous Generators (Gas, Coal)</td></tr>
<tr><td>Scenario</td><td colspan="3">INTERPLAN-2: Small and Local</td></tr>
<tr><td>Input data</td><td colspan="3">The grid model contains a total of 287 lines, 235 bus bars, 15 transformers, 225 loads, 257 static generators, 5 Synchronous Machine. The study is performed at TSO level which consists of 380kV and 220kV as well as DSO level which includes 110, 20 and 0.4 kV.

Time Frame: 24h
Time resolution: 15min</td></tr>
<tr><td rowspan="4">KPI under test</td><td>ID</td><td>Name</td><td>Formula</td></tr>
<tr><td>1</td><td>Level of losses in transmission and distribution networks</td><td>$$Percentage\ of\ losses = \frac{\text{Amount of injected energy } - \text{amount of energy delivered to the custo}}{\text{Amount of injected energy}} \times 100$$</td></tr>
<tr><td>2</td><td>Congestion detection</td><td>Congestion = If abs(P_{line_i}) > $P_{rating\_line\_i}$ the line-i is congested.
P_{line_i}[kW] is the active power that flows troughs the line i
$P_{rating\_line\_i}$[kW] is the nominal active power of the line i</td></tr>
<tr><td>10</td><td>Voltage Quality</td><td>According to the defined EN 50160 Standards and VDE-AR-N 4120 bus bar voltage magnitudes must comply with following allowed range of variation.
LV: (±10% of nominal voltage)
MV: (±5% of nominal voltage)
HV & EHV: (±4-7% of nominal voltage)
Voltage deviation indices can be defined to find the frequency or duration that the bus bar voltages violate the allowed voltage range.
Number of voltage excursions exceeded n minutes per year
Percentage of time that the transmission voltage exceeds the permissible limits</td></tr>
</table>

	13	Mean quadratic deviations from voltage and reactive power targets at each connection point between TSO and DSO grids	Let *C* be the set of connection points between TSOs and DSOs. Let $q_{c,target}(t)$ [kVar] be the target value for reactive power transmission from DSO to TSO at connection point c and time *t*, as e.g. calculated by grid operation planning. Let $q_c(t)$ be the reactive power actually provided from DSO to TSO at connection point *c* and time *t*. Then the KPI related to reactive power at time *t* is defined as: $\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(q_{c,target}(t)-q_c(t)\right)^2$ The KPI related to voltage is defined as follows. Let $u_{c,target}$ [V] be the nominal value for the line-to-line voltage at connection point *c*, calculated as mean over all phases. Let $u_c(t)$ be the actual line-to-line voltage mean over all phases. Then, the KPI at time *t* is: $\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(u_{c,target}-u_c(t)\right)^2$
	14	Level of DG / DRES utilization for ancillary services	$UAS\% = \frac{E_{AS}}{E_{total}} * 100\ [\%]$ E_{AS} − the energy used for ancillary services $[MWh]$ E_{total} − the total energy produced $[MWh]$
Simulation type	Semi-dynamic		
Output parameters	Active and reactive power set points for generators		

4.2.5 Summary

Summary	This showcase addresses a combination of network operation challenges, which are voltage stability and grid congestion that may occur in the presence of high DER penetration levels. The proposed integrated control functions (related to UC1 and UC2) allow system operators (TSOs and DSOs) to solve these operation challenges through an effective DER operation planning based on active and reactive power intelligent control for grid congestion management and coordinated TSO-DSO optimization.

	A system operator (TSO and DSO) that wants to address these operation challenges by using the INTERPLAN tool will be guided by the user manual to select the following planning criteria: • 1.Minimizing losses • 3. Maximizing share of RES • 4. Assuring voltage stability • 5. Mitigating grid congestion • 7. Optimize TSO/DSO interaction • 8. Maximize DG / DRES contribution to ancillary services. The simulation functionalities to be used are Load Flow+Load Flow sensitivities+ Optimal Power Flow, whereas the selected KPIs needed to measure the effectiveness of the control functions are: • 1. Level of losses in transmission and distribution networks • 2. Congestion detection • 10. Voltage Quality: Voltage magnitude variations • 13. Mean quadratic deviations from voltage and reactive power targets at each connection point between TSO and DSO grids • 14. Level of DG / DRES utilization for ancillary services The suggested INTERPLAN scenario is INTERPLAN-2 Small and Local. Regarding the type of grid models to be used, the grid investigated for control is a transmission-distribution grid. Grid equivalenting is required for two reasons: first of all, system operators may not share full details of their own network topology and data with the other operators, and second this will simplify the optimization process at each system operator network. In detail, the TSO network or the DSO network is replaced by proper grid equivalents which represents the active and reactive power values of the original network. Once performed all these steps, the user is ready to select this showcase control function and perform the simulations through PowerFactory. The evaluation phase will follow with reference to the KPI(s) values found in the simulation.

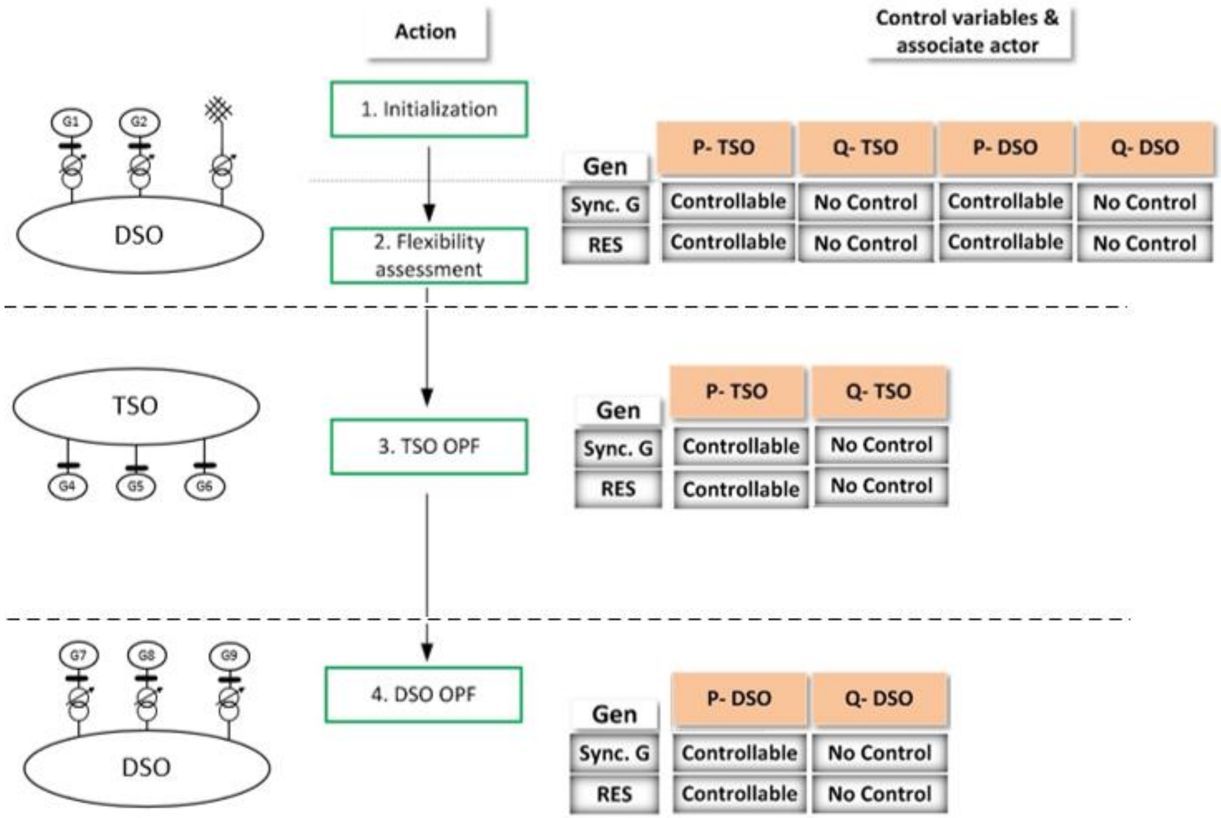
4.3 SC3 - TSO-DSO power flow optimization

4.3.1 SC properties

ID and Name	SC3: TSO-DSO power flow optimization	
Relevant UC/s	UC3: Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations UC5: Power balancing at DSO level	
SC description	**Summary**	
	Optimisation of tertiary reserve placement in both TSO and DSO levels and energy management in DSO level, with the aim of more efficient operation of the network and decrease of power losses.	
	Motivation	
	With the rising amount of distributed renewable energy sources, the grid operation planning has to be adapted to the new conditions. To ensure stable and optimal operation of the network, DSO power management as well as novel TSO-DSO tertiary control are being used in this showcase.	
	Objective	
	This showcase is to present an optimization strategy for energy flow management between transmission and distribution grid, ensuring the balance within a distribution network on one hand and on the other hand for participation of non-synchronous energy resources in the tertiary reserve market and supporting the TSO in keeping the whole network stable.	
	Solution	
	The solution is application of optimization strategies which are described in details in use case 3: Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations and use case 5: Power balancing at DSO level	

4.3.2 Control functions

4.3.2.1 Control function for provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations

<table>
<tr><th colspan="2">UC3: Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations</th></tr>
<tr><td>Control variables & associate actor/tool & flowchart</td><td>

<u>Note:</u> In this use cases some of the loads are also considered as controllable in order to represent demand response.</td></tr>
<tr><td rowspan="2">Prerequisites</td><td><u>Steps 1 and 2:</u> - Load flow for initialization,
- TSO grid equivalent.
- Active power flexibility assessment in the connection point.</td></tr>
<tr><td><u>Step 3:</u> - Optimisation function for TSO level,</td></tr>
</table>

	- DSO grid equivalent.
	Step 4: - Optimisation function for DSO level - TSO grid equivalent
Grid equivalenting	At each step of the use case process, either the TSO network or the DSO network is replaced by proper grid equivalents which represents the active and reactive power values of the original network. The reason for implementing this is fist system operators may not share full details of their own network topology and data with the other operators, second this will simplify the optimization process at each system operator network.
Input	**General grid data for all steps:** • Bus data • Branch data • Generator data
	Steps 1 and 2: - Initial active and reactive power for generators - Active and reactive power for equivalent TSO generators plus slack generator
	Step 3: - Initial active and reactive power for generators - Active and reactive power for equivalent DSO generators - Minimum and maximum available active power for DSO-TSO connection point (from step 1)
	Step 4: - Initial active and reactive power for generators - Active power set point in DSO-TSO connection point (from step 2)
Formula	**Step 2:** Objective function: $P_{\mathrm{PCC}}^{\max} = max \sum_{i}^{M} \sum_{k}^{N} V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$ $P_{\mathrm{PCC}}^{\min} = min \sum_{i}^{M} \sum_{k}^{N} V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$

	Constraints: $$P_{\text{gen}}^{\text{min}} <= P_{\text{gen}} <= P_{\text{gen}}^{\text{max}}$$ Obviously all power flow constraints for all units and parameters are considered. Where: P_{PCC}: Active power injected at point of common coupling P_{gen}: Active power generated by a generator V_i : Voltage magnitude at bus i G_{ik}: real part of admittance matrix B_{ik}: Imaginary part of admittance matrix *M*: total number of points of common coupling between TSO and DSO *N*: total number of buses in the network under analysis
	<u>Step 3:</u> Objective function: $$P_{\text{Losses}}^{\text{min}} = \min\left(\sum_{x}^{G} P_{\text{gen}} - \sum_{y}^{L} P_{\text{load}}\right)$$ Constraints: $$P_{\text{PCC}}^{min} <= P_{\text{PCC}} <= P_{\text{PCC}}^{\text{max}}$$ $$P_{\text{gen}}^{\text{min}} <= P_{\text{gen}} <= P_{\text{gen}}^{\text{max}}$$

Obviously all power flow constraints for all units and parameters are considered.

Where:

P_{PCC}: Active power injected at point of common coupling

P_{gen}: Active power generated by a generator

P_{load}: Active power consumed by a load

P_{Losses}: Active power losses in the network under analysis

G: total number of generators in the network under analysis

L: total number of aggregated loads in the network under analysis

Step 4:

Objective function:

$$P_{\mathrm{Losses}}^{\mathrm{min}} = \min\left(\sum_{x}^{G} P_{gen} - \sum_{y}^{L} P_{load}\right)$$

Constraints:

$P_{\mathrm{PCC}} = P_{\mathrm{PCC}}^{\mathrm{step\ 2}}$

$P_{\mathrm{gen}}^{\mathrm{min}} <= P_{\mathrm{gen}} <= P_{\mathrm{gen}}^{\mathrm{max}}$

Obviously all power flow constraints for all units and parameters are considered.

Where:

P_{PCC}: Active power injected at point of common coupling

$P_{\mathrm{PCC}}^{\mathrm{step\ 2}}$: The identified P_{PCC} in step 2 optimisation

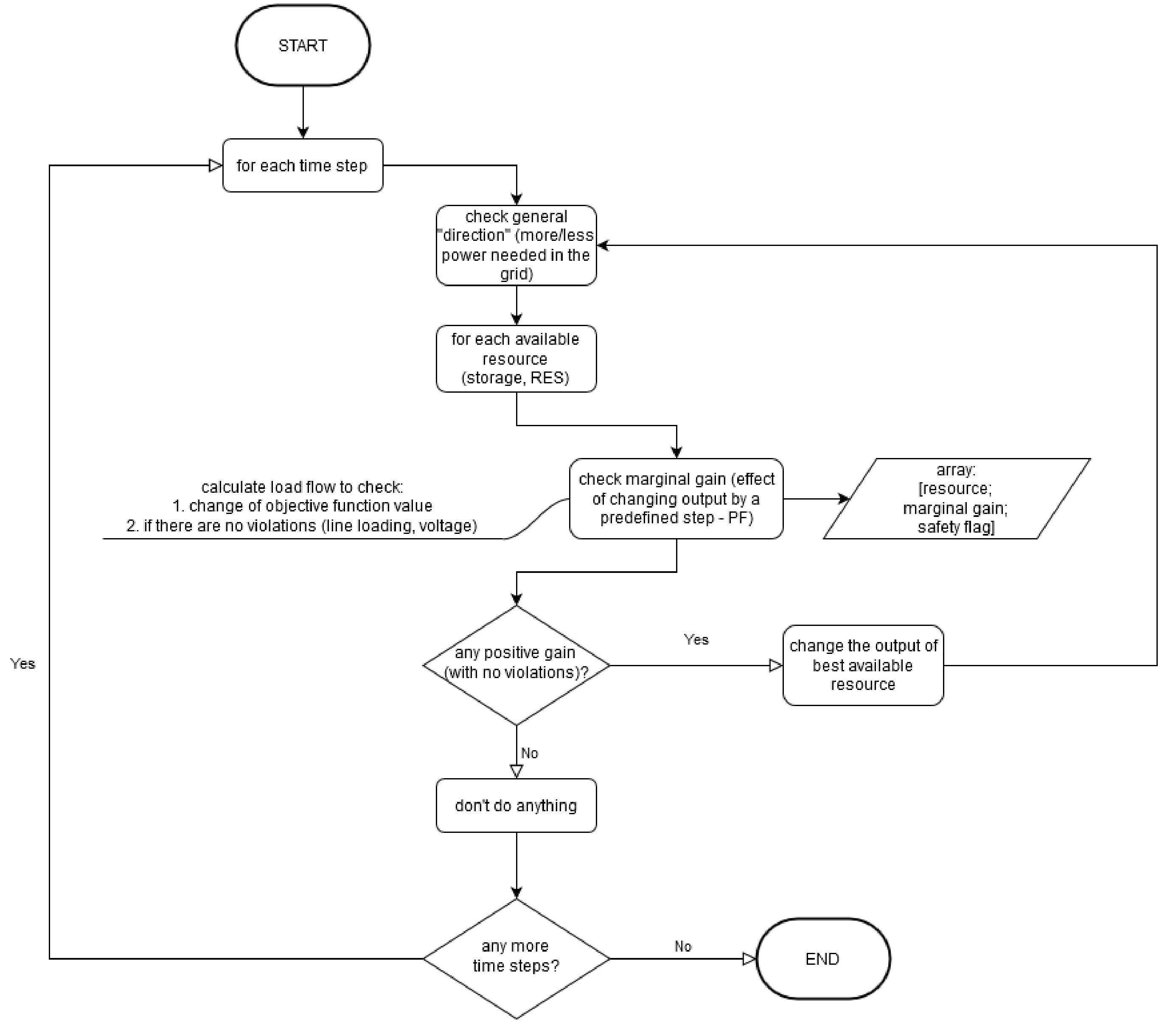
	P_{gen}: Active power generated by a generator P_{load}: Active power consumed by a load P_{Losses}: Active power losses in the network under analysis *G*: total number of generators in the network under analysis *L*: total number of aggregated loads in the network under analysis
Simulation environment	Python, PowerFactory
Simulation type	Semi-dynamic

4.3.2.2 Control function for power balancing at DSO level

UC ID 5 : Power balancing at DSO level	
Control variables	Active power
Associate actor/tool	DG and storage devices in DSO grid
Assumptions	• Flexible sources (DG including RES, storage) are available and controllable by the DSO • Forecast data for intermittent RES is available. • Load and generation profiles (including forecasted profiles) are available for each relevant network bus
Prerequisites	• Grid model includes both TSO and DSO grids. • The relevant DSO grid is radial. • There are no grid congestion or voltage profile issues (i.e. overloads, voltage limit violations) in the observable grid before the start of the UC.

Grid equivalenting	Grid equivalents are used for each TSO/DSO connection point and represent active and reactive power flow from/to TSO grid, as seen from the HV voltage side of the transformer. This simple representation of TSO grid is used since UC5 optimisation is performed only at the DSO level.
Input	• List of time steps for which the use case should be performed (as UC3 operates partly on the same resources and has higher priority in SC3, the time steps where UC3 performed any changes are excluded from UC5 operation). • Time series data for all relevant resources and other objects.

Flowchart


START
for each time step
check general "direction" (more/less power needed in the grid)
for each available resource (storage, RES)
calculate load flow to check:
1. change of objective function value
2. if there are no violations (line loading, voltage)
check marginal gain (effect of changing output by a predefined step - PF)
array: [resource; marginal gain; safety flag]
any positive gain (with no violations)?
Yes
change the output of best available resource
No
don't do anything
any more time steps?
Yes
No
END

<table>
<tr><td>Formula</td><td>
The objective function used for calculating marginal gain for each resource s in time step t is defined as following:

$$F(s,t) = \sum_{i=0}^{n} (W_i(s,t) * a_{W_i})$$

where:
$W_i(s,t)$ - single criterion used for objective function (see below);
a_{W_i} - weight factor for W_i criterion (see below).

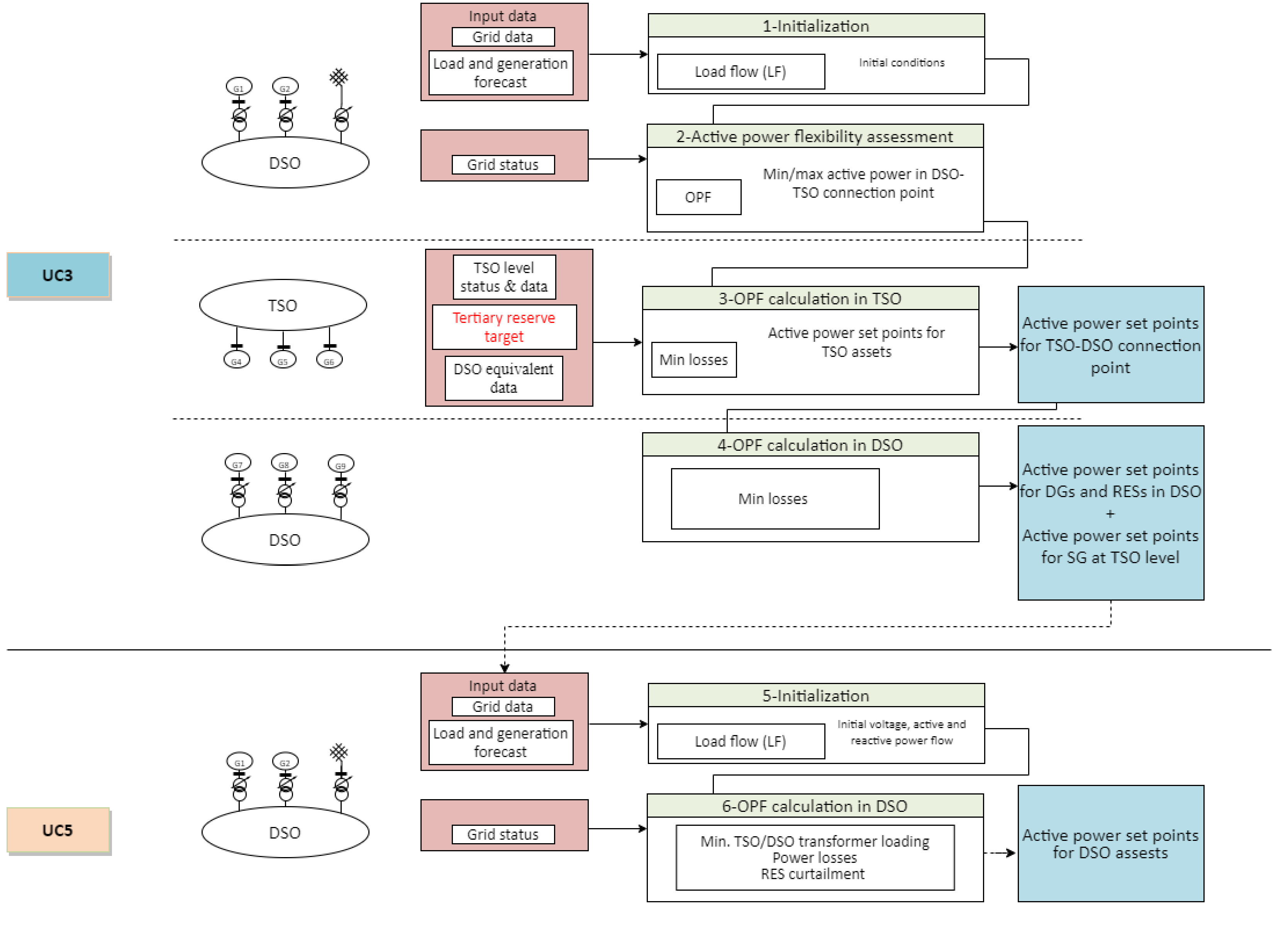
<table>
<tr><th>Criterion</th><th>Calculation method</th><th>Weight factor</th></tr>
<tr><td>TSO/DSO transformer loading</td><td>$1 - \text{loading } [pu]$</td><td>0,5 / 0,35*</td></tr>
<tr><td>Power losses in DSO grid</td><td>$1 - \frac{\text{losses after change of resource output}}{\text{losses before change of resource output}}$</td><td>0,15</td></tr>
<tr><td>RES curtailment</td><td>$\frac{\text{total RES power after change of resource output}}{\text{total RES power before change of resource output}}$</td><td>0,35 / 0,5*</td></tr>
</table>

* weight factor values for transformer loading and RES curtailments criteria are variable depending on transformer loading value: when it’s close to 1 pu, the weight for this criterion is higher.

The constraints checked after testing the effect of output change for each relevant resource are:

1. Loading of all lines in the relevant DSO grid (check for overloadings).
2. Voltage levels at all terminals in the relevant DSO grid (check for limit violations).
</td></tr>
<tr><td>Simulation environment</td><td>Python and PowerFactory</td></tr>
<tr><td>Simulation type</td><td>Semi-dynamic</td></tr>
</table>

Showcase structure

Sequence diagram	

Detailed description	Steps	Description
	1	In step1, a power flow is performed to collect the initial values of the network parameters.
	2	Then, the DSO, having a simple grid equivalent from transmission network, runs an optimisation, which is aimed to identify the active power flexibility it can provide to the transmission network in case of demand for provision of tertiary reserve for frequency control. In this step the maximum and minimum available active power for points of common coupling are identified.
	3	In this step, TSO gathers the information of flexibility from DSO level and with regards to the required tertiary reserve, runs an optimization in its own network while having the information of a DSO grid equivalent. The optimization is aimed to satisfy the tertiary reserve from the renewable sources available at DSO network as well as minimizing the losses a at TSO level. At the end of this step the active power values for the points of common coupling between TSO and DSO are defined as set points in addition to the active power set points for the generator units at TSO level.
	4	In this step, DSO will run another optimisation while the active power values for TSO-DSO points of common coupling are fixed and TSO grid is considered with a proper grid equivalent. The aim of optimization is to minimise the losses at DSO network with the defined constraints of active power exchange with TSO level. At the end of this step, the active power set points for the remaining controllable units in the networks meaning generators and controllable loads at DSO level are defined.
	5	After receiving data on Active power set points for generators and controllable loads at DSO level from UC3: Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations, the load flow is performed to evaluate the network operation point.
	6	In this step, the algorithm iteratively checks for all available resources how changing their output active power will effect chosen grid performance criteria (TSO/DSO transformer loading, grid losses in DSO grid, RES generation level). If the change is positive, the algorithm checks whether this caused any violations in the grid. At the end of the iterative process the active power set points for the controllable units at DSO level are defined.

Sequence of actions	Steps	Associate UC ID	Action	Content	Input	Operation	output	Grid area
	1	3	Initialization	Set the initial values of assets	-Grid data, -Load and generation forecast,	Load flow	Initial voltage, active and reactive power flow	Full network (TSO and DSO levels)
	2	3	Active power flexibility	Definition of active power flexibility from DSO side	-Grid initial condition.	Optimal power flow	Active power flexibility in the	Equivalent TSO, DSO

			assessment	for TSO grid			TSO-DSO point of common coupling	
	3	3	TSO optimization	Loss minimization in TSO grid.	-TSO network conditions -TSO load and generation forecast -DSO equivalent - Output from step 2.	Optimal power flow	-Active power set points for TSO-DSO points of common coupling -Active power set points for generators at TSO level	TSO, Equivalent DSO
	4	3	DSO optimization	Loss minimization considering the fixed values for active power exchange at TSO-DSO point of common coupling defined in step 3	-Output from step 5 -fixed values for active power exchange at TSO-DSO point of common coupling defined in step 3	Optimal power flow	Active power set points for generators and controllable loads at DSO level	Equivalent TSO, DSO
	5	5	Initialization	Determination of grid operation point	-Grid data, -Load and generation forecast, -output from step 4	Load flow	Initial voltage, active and reactive power flow	DSO, Equivalent TSO
	6	5	DSO optimization	DSO/TSO transformer loading minimization,	-Output from step 5	Optimal power flow	Active power set points for	DSO, Equivalent

				considering grid losses and RES curtailment, as well as constraints from UC5			DSO assets	TSO

4.3.3 Test Case

System under Test (SuT)	The power system under testing is the SimBench grid model (with radial DSO). The grid model contains a total of 287 lines, 235 busbars, 15 transformers, 225 loads, 262 static generators, 5 Synchronous Machine. The study is performed at TSO level, which consists of 380kV and 220kV as well as DSO level which includes 110, 20 and 0.4 kV. This grid was selected as it contains both TSO and DSO grids, which are needed, by UC3 and UC5. Moreover, UC5 has been designed for radial grid, which is provided by the selected grid model.		
Objects under Test (OuT)	• Static Generators (RES, storage) • Synchronous Generators • Controllable loads		
Scenario	INTERPLAN-2: Small and local		
Input data	The input data cosists of generation and consumption profiles of all units in the networks within a time frame of 24 hours and resolution of 15 minutes.		
KPI under test	**ID**	**Name**	**Formula**
	1	Level of losses in transmission and distribution networks	$P_{\text{losses}} = \frac{\text{amount of injected energy} - \text{amount of energydelivered to customers}}{\text{amount of injected energy}} * 100\ [\%]$
	7	Power losses	$P_{\text{losses}} = \sum_{i}^{Nline} \lvert I\rvert_i^2 r_i\ [kW]$ $I_i -$ magnitude of current flow in line i $[A]$ $r_i -$ resistance of line i $[\Omega]$
	14	Level of DG / DRES utilization	$UAS\% = \frac{E_{AS}}{E_{total}} * 100\ [\%]$

		for ancillary services	E_{AS} − the energy used for ancillary services $[MWh]$ E_{total} − the total energy produced $[MWh]$
	16	Transformer loading	$$Loading\% = \frac{\text{power at transformer primary winding}}{\text{transformer nominal power}} * 100\ [\%]$$
	17	RES curtailment	$$Curtailment\% = 100 - \frac{\text{energy supplied by RES to the grid}}{\text{RES available energy}} * 100\ [\%]$$
	22	Quadratic deviation from global active power exchange target	Let $p_{target}(t)$ be the global active power production target at time t. Let G be the set of generators producing active power, and $p_g(t)$ be the active power generated by generator g at a given time t. Then, the KPI at this time is: $$\left(p_{\text{target}}(t) - \sum_{g \in G} p_g(t)\right)^2$$
	23	Mean quadratic deviations from active power targets at TSO/DSO connection points	$$\frac{1}{\lvert C \rvert} \sum_{c \epsilon C} (P_{c,\text{target}}(t) - P_c(t))^2$$
	27	Share of RES	$$RES\% = \frac{P_{RES}}{P_{total}} * 100\ [\%]$$ P_{RES} = Active power provided by RES at a given time step [MW] P_{total} = Total active power provided by RES and non-RES generators at a given time step [MW]
Simulation type	Semi-dynamic		
Output parameters	Active power of generators, transformer losses and loading, line losses and loading, terminals voltage		

4.3.4 Summary

Summary	This showcase addresses a combination of network operation challenges, which are provision of appropriate tertiary reserve and energy management on DSO level in the presence of high DER penetration levels. The proposed integrated control functions (related to UC3 and UC5) allow system operators (TSOs and DSOs) to solve these operation challenges through an effective DER and storage operation planning based on active power control. A system operator (TSO and DSO) that wants to address these operation challenges by using the INTERPLAN tool will be guided by the User Manual to select the following planning criteria: • 1.Minimizing losses • 3. Maximizing share of RES • 7. Optimize TSO/DSO interaction • 8. Maximize DG / DRES contribution to ancillary services. • 9. Assuring frequency stability The simulation functionalities to be used are Load Flow and Optimal Power Flow, whereas the selected KPIs needed to measure the effectiveness of the control functions are: • 1. Level of losses in transmission and distribution networks, • 7. Power losses, • 14. Level of DG / DRES utilization for ancillary services, • 16. Transformer loading, • 17. RES curtailment, • 22. Quadratic deviation from global active power exchange target, • 23. Mean quadratic deviations from active power targets at TSO/DSO connection points, • 27. Share of RES. The suggested INTERPLAN scenario is INTERPLAN-2 Small and Local. Regarding the type of grid models to be used, the grid investigated for control is a transmission-distribution grid. Grid equivalenting is required for two reasons: first of all, system operators may not share full details of their own network topology and data with the other operators, and second this will simplify the optimization process at each system operator network. In detail, the TSO network or the DSO network is replaced by proper grid equivalents which represents the active and reactive power values of the original network. Once performed all these steps, the user is ready to select this showcase control function and perform the simulations through PowerFactory. The evaluation phase will follow with reference to the KPI(s) values found in the simulation.

4.4 SC4 - TSO-DSO coordinated active and reactive power optimization for provision of tertiary reserve and improvement of voltage profiles.

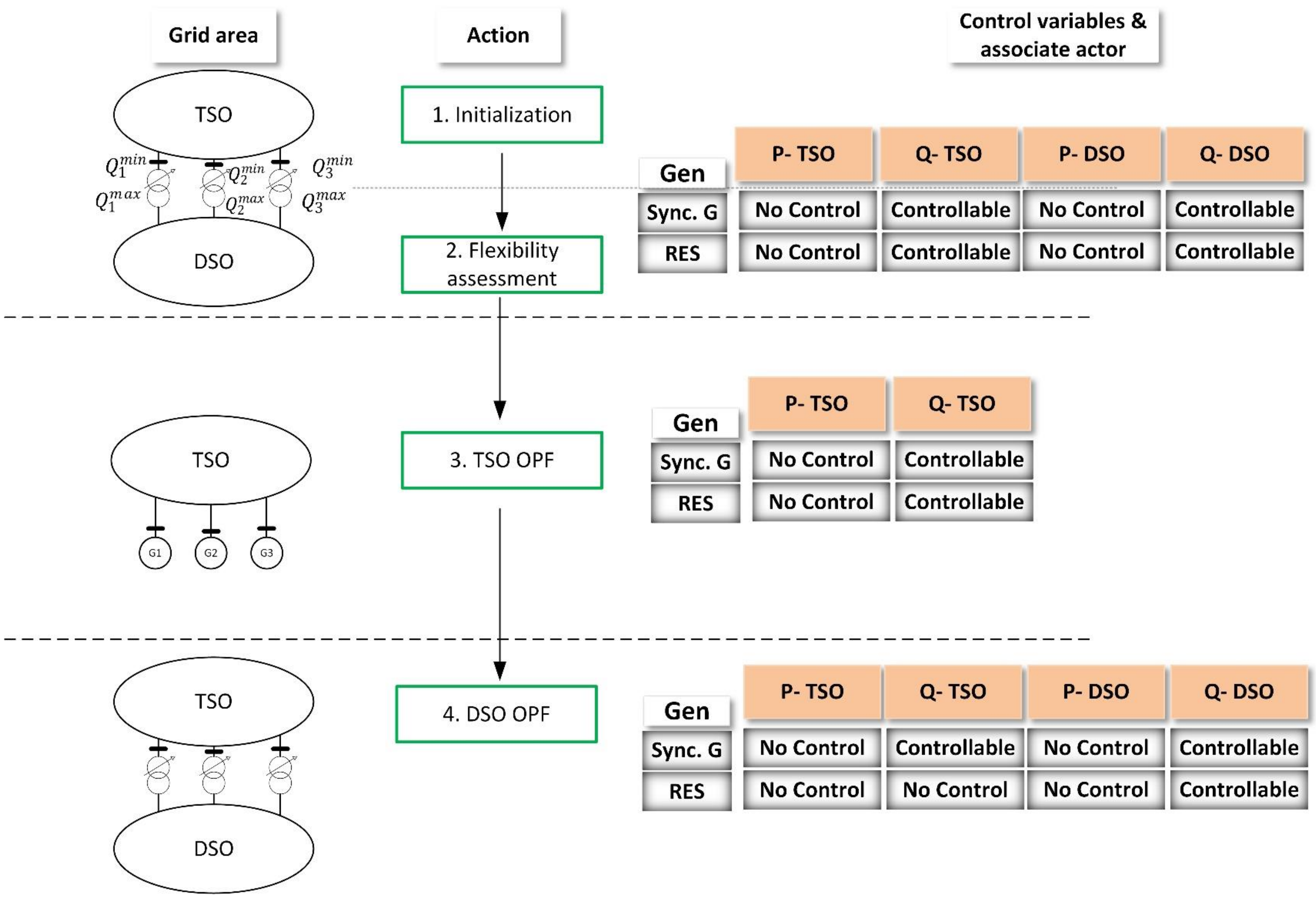
4.4.1 SC properties

ID and Name	SC4: TSO-DSO coordinated active and reactive power optimization for provision of tertiary reserve and improvement of voltage profiles.	
Relevant UC/s	UC1: Coordinated voltage/reactive power control UC3: Provision of tertiary control reserve based on coordinated TSO-DSO active power optimization	
SC description	**Summary**	
	Active and reactive optimisation of power flow in both TSO and DSO levels with the aim of efficient operation of the network ensuring high power quality and decrease of power losses	
	Motivation	
	The presence of renewable energy resources can significantly impact the power networks, exposing the system to much higher power fluctuations and compromising the system power quality. Ensuring high power quality through measures like voltage control and frequency control are even more challenging issues to deal with in presence of higher shares of such fluctuating sources. Therefore, innovative control schemes have to be considered in operation of the future power systems.	
	Objective	
	The objective of this showcase is to present an optimization strategy for parallel control of active and reactive power at transmission and distribution grids, for maintaining the voltage quality at both network levels on one hand and on the other hand for participation in the tertiary reserve market and supporting TSO in keeping the whole network stable. The control strategy must ensure an optimization of both active and reactive power of all available resources with no conflict in set points, considering the constraints.	
	Solution	
	The solution is application of optimisation strategies which are described in details in use case 1: Coordinated voltage/reactive power control and UC3: Provision of tertiary control reserve based on coordinated TSO-DSO active power optimization	

4.4.2 Control functions

4.4.2.1 Control function for coordinated voltage/reactive power control

UC 1: Coordinated voltage/reactive power control

<table>
<tr><td>Control variables & associate actor/tool & flowchart</td><td>
</td></tr>
<tr><td rowspan="3">Prerequisites</td><td><u>Step 1 and 2:</u> - load flow for initialization</td></tr>
<tr><td><u>Step 3:</u> - reactive power flexibility assessment at the connection points
- DSO grid equivalent</td></tr>
<tr><td><u>Step 4:</u> - OPF in TSO and fix the reactive power set points in connection point,</td></tr>
<tr><td>Grid</td><td>Grid equivalenting is employed in the third step of UC1 procedure to make a DSO equivalent, because DSO in this step is not under</td></tr>
</table>

<table>
<tr><td>equivalenting</td><td>control and just an equivalent generator representing the DSO is sufficient. The equivalent generators are connected to TSO-DSO connection point and their initial active and reactive power set points are extracted from LF in that node.</td></tr>
<tr><td>Input</td><td>
<u>General grid data for all steps:</u>
Bus data
<table>
<tr><td>Bus type</td><td>Active power load</td><td>Reactive power load</td><td>Bus area</td><td>Initial Bus voltage magnitude</td><td>Initial bus voltage angle</td><td>Maximum and minimum bus voltage</td><td>Nominal bus voltage</td></tr>
</table>
Branch data
<table>
<tr><td>Branch from which bus</td><td>Branch To which bus</td><td>Branch resistance</td><td>Branch reactance</td><td>Branch conductance</td><td>Branch susceptance</td><td>Branch capacity (max. current carrying capacity)</td><td>Branch type</td><td>Branch tap rate magnitude if it is a transformer</td><td>Branch phase shift angle if it is transformer</td></tr>
</table>
Generator data
<table>
<tr><td>Generator bus number</td><td>Generator type</td><td>Generator operation mode</td><td>Initial active power</td><td>Initial reactive power</td><td>Reactive power boundary</td><td>Voltage in case of operation mode slack or PV</td></tr>
</table>
</td></tr>
<tr><td></td><td><u>Step 1 and 2:</u> - Voltage magnitude and angle initialization for buses and considering voltage set points of generators
- Initial active and reactive power for generators</td></tr>
<tr><td></td><td><u>Step 3:</u> - Voltage magnitude and angle initialization for buses and considering voltage set points of generators,
- Initial active and reactive power for generators
- Active and reactive power for equivalent DSO generators
- Minimum and maximum capable reactive power for DSO-TSO connection point (from step 2)</td></tr>
<tr><td></td><td><u>Step 4:</u> - Voltage magnitude and angle initialization for buses and considering voltage set points of generators,
- Initial active and reactive power for generators,
- Reactive power set point in DSO-TSO connection point (from step 3).</td></tr>
</table>

Formula	Note: Within these optimisations, all decision variables including bus indexes and time are optimized in a way that this objective is going to reach. It means that all variables at buses and all time steps are involved to achieve this goal. And when those variables are being decided to minimize overall grid losses, they cause to reduce the grid losses at each time step. Briefly, the only way to minimize the grid losses over entire time steps is to reduce the grid losses at each time steps. Therefore, the overall grid losses is minimized and the results for each time step is extracted. **<u>Step 1 and 2:</u>** **Objective function:** $$\boldsymbol{Q}_{\mathbf{CP}}^{\mathbf{Max}} = \max \sum_t \sum_i \sum_j V_i(t) V_j(t) \left[G_{\mathrm{ij}} \sin\left(\theta_i(t) - \theta_j(t)\right) - B_{\mathrm{ij}} \cos\left(\theta_i(t) - \theta_j(t)\right) \right]$$ $$\boldsymbol{Q}_{\mathbf{CP}}^{\mathbf{Min}} = \min \sum_t \sum_i \sum_j V_i(t) V_j(t) \left[G_{\mathrm{ij}} \sin\left(\theta_i(t) - \theta_j(t)\right) - B_{\mathrm{ij}} \cos\left(\theta_i(t) - \theta_j(t)\right) \right]$$ **s.t.** $$-\sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2} \le Q_g(t) \le \sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2}$$ $$\frac{P_{\mathrm{ij}}(t)^2 + Q_{\mathrm{ij}}(t)^2}{V_{\mathrm{ij}}(t)^2} \le I_{\mathrm{ij,max}}^2$$ As mentioned active power is uncontrollable for all steps. Where: i, j: Index (set) of buses. (Buses in TSO-DSO connection points) t: Index (set) of time steps. The range of t is 96 time steps (each 15 minutes in 24 hours) g: Index (set) of generators. n: Index (set) of connection point.

CP: Superscripts for connection point.

SP: Superscripts for set point

G: Conductance of transmission line

B: Susceptance of transmission line

S: Apparent power

P: Active power.

Q: Reactive power.

V: Voltage magnitude

θ: Voltage angle

I: Electric current

This nomenclature can be applied for formulation of other steps.

Step 3:

Objective function:

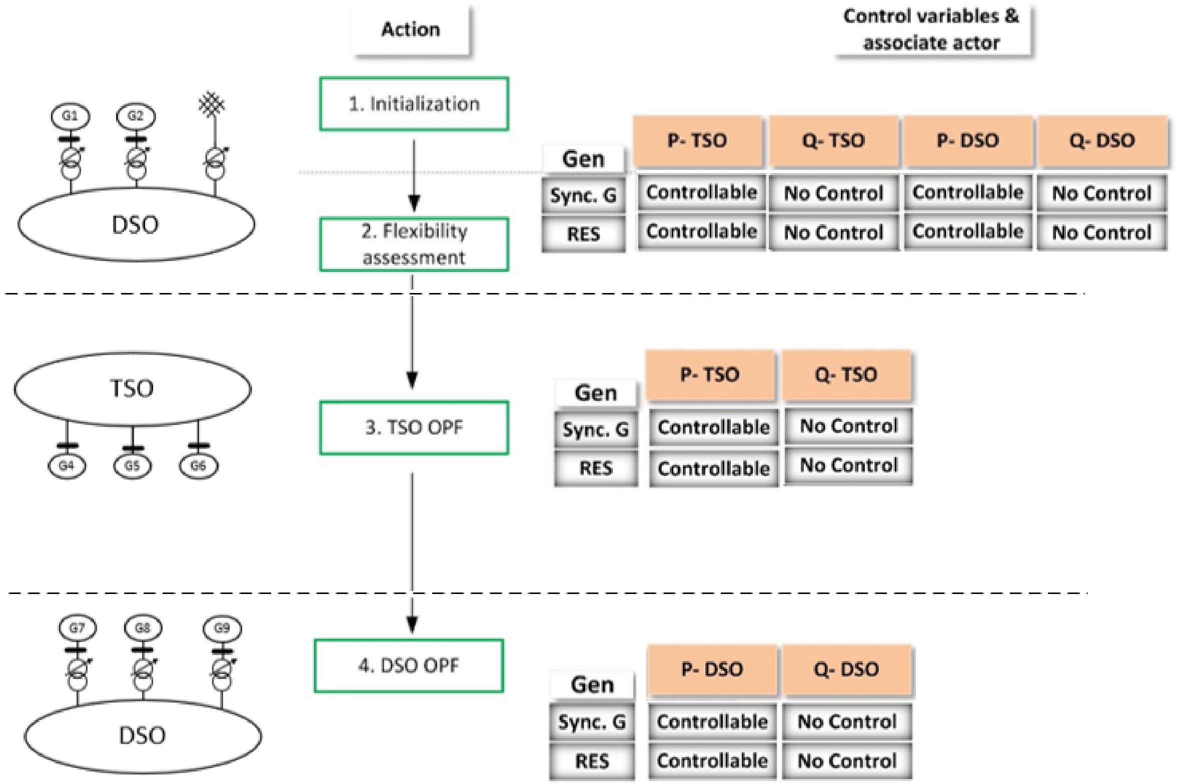
$$\boldsymbol{P}_{\mathbf{losses}}: \min \sum_{t} \sum_{i} \sum_{j} G_{\mathrm{ij}} \left[V_i(t)^2 + V_j(t)^2 - 2V_i(t)V_j(t) \cos\left(\theta_i(t) - \theta_j(t)\right) \right]$$

s.t.

$$-\sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2} \leq Q_g(t) \leq \sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2}$$

	$$\frac{P_{ij}(t)^2 + Q_{ij}(t)^2}{V_{ij}(t)^2} \leq I_{ij,max}^2$$ i, j: Index (set) of buses. (number of buses at TSO)
	Step 4: **Objective function:** $$\boldsymbol{P}_{\mathbf{losses}}\text{: min} \sum_t \left\{ \sum_i \sum_j G_{ij} \left[V_i(t)^2 + V_j(t)^2 - 2V_i(t)V_j(t)\cos\left(\theta_i(t) - \theta_j(t)\right) \right] + \sum_n (Q_{\mathrm{CP}_n}(t) - Q_{\mathrm{sp_n}}(t))^2 \right\}$$ **s.t.** $$-\sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2} \leq Q_g(t) \leq \sqrt{1 - \left(\frac{P_g(t)}{S_g}\right)^2}$$ $$\frac{P_{ij}(t)^2 + Q_{ij}(t)^2}{V_{ij}(t)^2} \leq I_{ij,max}^2$$ i, j: Index (set) of buses. (number of buses at entire network)
Simulation environment	Powerfactory, AMPL
Simulation type	Semi-dynamic

4.4.2.2 Control function for provision of tertiary control reserve based on coordinated TSO-DSO active power optimisation

<table>
<tr><td colspan="2">UC ID 3: Provision of tertiary control reserve based on coordinated TSO-DSO active power optimisation</td></tr>
<tr><td>Control variables</td><td>

Note: In this use cases some of the loads are also considered as controllable in order to represent demand response.</td></tr>
<tr><td rowspan="3">Prerequisites</td><td><u>Steps 1 and 2:</u> - Load flow for initialization
- TSO grid equivalent
- Active power flexibility assessment in the connection point</td></tr>
<tr><td><u>Step 3:</u> - Optimisation function for TSO level
- DSO grid equivalent.</td></tr>
<tr><td><u>Step 4:</u> - Optimisation function for DSO level
- TSO grid equivalent</td></tr>
</table>

Grid equivalenting	At each step of the use case process, either the TSO network or the DSO network is replaced by proper grid equivalents which represents the active and reactive power values of the original network. The reason for implementing this is fist system operators may not share full details of their own network topology and data with the other operators, second this will simplify the optimization process at each system operator network.
Input	**General grid data for all steps:** • Bus data • Branch data • Generator data
	Steps 1 and 2: - Initial active and reactive power for generators. - active and reactive power for equivalent TSO generators plus slack generator
	Step 3: - Initial active and reactive power for generators - active and reactive power for equivalent DSO generators - Minimum and maximum available active power for DSO-TSO connection point (from step 1).
	Step 4: - Initial active and reactive power for generators - Active power set points in DSO-TSO connection point (from step 2)
Formula	**Step 2:** Objective function: $P_{\mathrm{PCC}}^{\max}(t):\ max \sum_{i}^{M}\sum_{k}^{N} V_i(t)V_k(t)\left(G_{ik}\cos\theta_{ik}(t) + B_{ik}\sin\theta_{ik}(t)\right)$ $P_{\mathrm{PCC}}^{\min}(t):\ min \sum_{i}^{M}\sum_{k}^{N} V_i(t)V_k(t)\left(G_{ik}\cos\theta_{ik}(t) + B_{ik}\sin\theta_{ik}(t)\right)$ Note: The optimization is done for a fixed point of time (t). Constraints: $P_{\mathrm{gen}}^{\min}(t) <= P_{gen}(t) <= P_{\mathrm{gen}}^{\max}(t)$

	The reactive power set points for controllable units are considered as fixed values. Obviously all power flow constraints for all units and parameters are considered. Where: P_{PCC}: Active power injected at point of common coupling P_{gen}: Active power generated by a generator V_i : Voltage magnitude at bus i G_{ik}: real part of admittance matrix B_{ik}: Imaginary part of admittance matrix θ_{ik}: Voltage angle difference t: Index of time steps. The range of t is 96 time steps (each 15 minutes in 24 hours). *M*: total number of points of common coupling between TSO and DSO *N*: total number of buses in the network under analysis
	<u>Step 3:</u> Objective function: $$P_{\text{Losses}}^{\text{min}}(t) = min\,(\sum_{x}^{G} P_{\text{gen}}(t) - \sum_{y}^{L} P_{\text{load}}(t))$$ Note: The optimization is done for a fixed point of time (t). Constraints: $$P_{\text{PCC}}^{\text{min}}(t) <= P_{\text{PCC}}(t) <= P_{\text{PCC}}^{\text{max}}(t)$$

$$P_{\text{gen}}^{\min}(t) <= P_{\text{gen}}(t) <= P_{\text{gen}}^{\max}(\text{t})$$

The reactive power set points for controllable units are considered as fixed values.

Obviously all power flow constraints for all units and parameters are considered.

Where:

P_{PCC}: Active power injected at point of common coupling

P_{gen}: Active power generated by a generator

P_{load}: Active power consumed by a load

P_{Losses}: Active power losses in the network under analysis

t: Index of time steps. The range of t is 96 time steps (each 15 minutes in 24 hours).

G: total number of generators in the network under analysis

L: total number of aggregated loads in the network under analysis

Step 4:

Objective function:

$$P_{\text{Losses}}^{\min}(t) = min\,(\sum_{x}^{G} P_{\text{gen}}(t) - \sum_{y}^{L} P_{\text{load}}(t))$$

Note: The optimization is done for a fixed point of time (t).

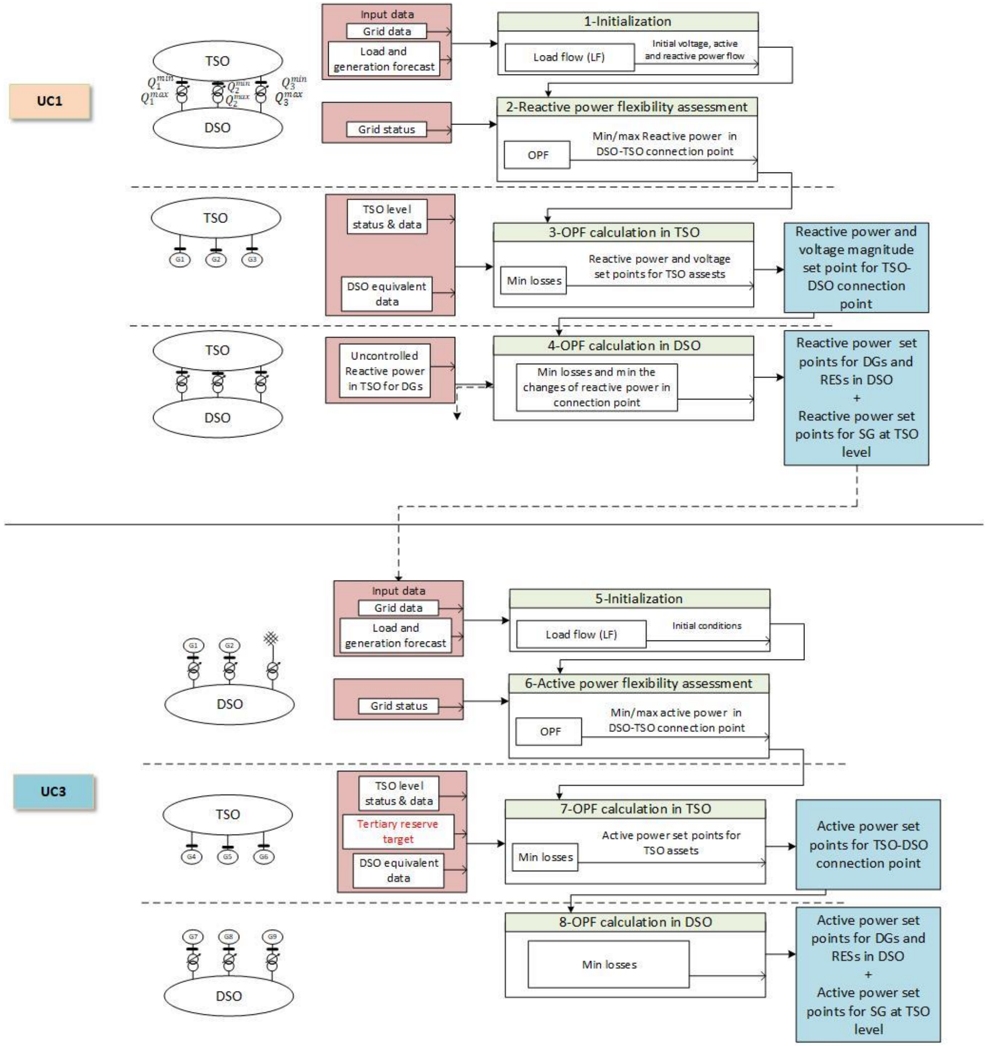
Constraints:

$$P_{\text{PCC}}(t) = P_{\text{PCC}}^{\text{step 2}}(\text{t})$$

$$P_{\text{gen}}^{\min}(t) <= P_{gen}(t) <= P_{\text{gen}}^{\max}(\text{t})$$

	The reactive power set points for controllable units are considered as fixed values. Obviously all power flow constraints for all units and parameters are considered. Where: P_{PCC}: Active power injected at point of common coupling $P_{\mathrm{PCC}}^{\mathrm{step\ 2}}$: The identified P_{PCC} in step 2 optimisation P_{gen}: Active power generated by a generator P_{load}: Active power consumed by a load P_{Losses}: Active power losses in the network under analysis t: Index of time steps. The range of t is 96 time steps (each 15 minutes in 24 hours). G: total number of generators in the network under analysis L: total number of aggregated loads in the network under analysis
Simulation environment	Python, PowerFactory
Simulation type	Semi-dynamic

4.4.3 Showcase structure

Sequence diagram		
Detailed description	Steps	Description
	1	The reactive power capability is evaluated at each TSO-DSO connection point with an optimization tool. Indeed, an OPF runs to find the maximum and minimum reactive power that DSO can exchange with TSO at each 15 minutes in a day. At
	2	

<table>
<tr><td rowspan="8"></td><td></td><td>step 1, first, an initialization is performed with running a power flow in order to calculate the initial values for different variables in the grid including voltage magnitude/angle as well as active and reactive power flow. The area of the network that needs to be analysed in this step is both DSO and TSO. Grid data including detailed information about buses, branches, and generators as well as time series for load and generation are required as input data for initialization. Then those data along with grid status information are transferred to the flexibility assessment step (step 2). To evaluate the reactive power capability from DSO to deliver to TSO, reactive power at DSO and TSO should be controlled for RESs and synchronous generators.</td></tr>
<tr><td>3</td><td>Finding the possible reactive power provision from DSO to TSO, those data are transferred to the step 3 that is TSO level re-dispatch via minimizing the grid losses. Indeed in this step, TSO level is scheduled for the next day based on the given reactive power capability from DSO. Therefore, in this step just the TSO level is analysed and the DSO equivalents are generated as generators in the connection points in a way that the maximum and minimum reactive power for the equivalent generators are set as calculated ones in the previous step. Initial operating active and reactive power for those equivalent generators are also obtained from power flow in the relevant bus. Hence, the reactive power set points for all generators are optimized at TSO in a way that TSO losses is minimized.</td></tr>
<tr><td>4</td><td>Given the reactive power set points from the last step, another OPF is performed in the overall grid in a way that the only under-controlled variables are all generators’ reactive power at DSO level and just RESs’ reactive power at TSO level. In other words, in the final step, reactive power at DSO is optimized while setting the TSO variables as calculated in the second step. The only exception is synchronous generators’ reactive power at TSO level which supposed to be controllable. Therefore, the optimum reactive power for RESs are calculated by minimizing the total grid losses as well as the deviation of reactive power at connection points from what has been calculated in the second stage. It means that in addition to loss minimization the problem aims to preserve the exchange reactive power in the optimum amount calculated in TSO OPF. This helps to obtain the DSO values independent from TSO level.</td></tr>
<tr><td>5</td><td rowspan="2">After UC1 is terminated, the assigned reactive power set points are transferred to use case 3. Considering these values a power flow is performed to collect the initial values of the network parameters. Then, the DSO, having a simple grid equivalent from transmission network, runs an optimisation which is aimed to identify the active power flexibility it can provide to the transmission network in case of demand for provision of tertiary reserve for frequency control. In this step the maximum and minimum available active power for points of common coupling are identified.</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td><td>In this step, TSO gathers the information of flexibility from DSO level and with regards to the required tertiary reserve, runs and optimization in its own network while having the information of a DSO grid equivalent. The optimization is aimed to satisfy the tertiary reserve from the renewable sources available at DSO network as well as minimising the losses at TSO level. At the end of this step the active power values for the points of common coupling between TSO and DSO are defined as set points in addition to the active power set points for the generator units at TSO level.</td></tr>
<tr><td>8</td><td>In this step, DSO will run another optimisation while the active power values for TSO-DSO points of common coupling are fixed and TSO grid is considered with a proper grid equivalent. The aim of optimization is to minimise the losses at DSO network with the defined constraints of active power exchange with TSO level. At the end of this step, the active power set</td></tr>
</table>

		points for the remaining controllable units in the networks meaning generators and controllable loads at DSO level are defined.						
Sequence of actions	Steps	Associate UC ID	Action	Content	Input	Operation	output	Grid area
	1	1	Initialization	Set the initial values of assets	-Grid data, -Load and generation forecast,	Load flow	Initial voltage, active and reactive power flow	TSO & DSO
	2	1	Reactive power flexibility assessment	Definition of reactive power capability from DSO side for TSO grid	-Grid status -output from step 1.	Optimal power flow	Reactive power capability in TSO-DSO connection point	TSO & DSO
	3	1	TSO optimization	Provision of required tertiary reserve as much as possible from DSO level with the aim of loss minimization in TSO grid	-TSO level status and data -Required tertiary reserve -TSO load and generation forecast -DSO equivalent -output from step 2.	Optimal power flow	Reactive power and voltage set points for TSO assets	TSO, Equivalent DSO
	4	1	DSO optimization	Loss minimization and trying to keep the reactive power in the set points calculated in the step 5	-Output from step 3 -reactive power set points for TSO DG and make them uncontrolled	Optimal power flow	Reactive power and voltage set point for RES and DGs in DSO	Full network (TSO, DSO)

	5	3	Initialization	Set the initial values of assets	-Grid data, -Load and generation forecast,	Load flow	Initial voltage, active and reactive power flow	Full network (TSO and DSO levels)
	6	3	Active power flexibility assessment	Definition of active power flexibility from DSO side for TSO grid	-Grid initial condition.	Optimal power flow	active power flexibility in the TSO-DSO point of common coupling	Equivalent TSO, DSO
	7	3	TSO optimization	Loss minimization in TSO grid.	-TSO network conditions -TSO load and generation forecast -DSO equivalent - Output from steps 2 to 6.	Optimal power flow	-Active power set points for TSO-DSO points of common coupling -Active power set points for generators at TSO level	TSO, Equivalent DSO
	8	3	DSO optimization	Loss minimization considering the fixed values for active power exchange at TSO-DSO point of common coupling defined in step 5	-Output from step 5 -Fixed values for active power exchange at TSO-DSO point of common coupling defined in step 5	Optimal power flow	Active power set points for generators and controllable loads at DSO elevl	Equivalent TSO, DSO

4.4.4 Test case

<table>
<tr><td>System under Test (SuT)</td><td colspan="3">The power system under test is the SimBench grid model.
The grid model contains a total of 287 lines, 235 busbars, 15 transformers, 225 loads, 257 static generators, 5 Synchronous Machine. The study is performed at TSO level which consists of 380kV and 220kV as well as DSO level which includes 110, 20 and 0.4 kV.
This grid was selected as it contains both TSO and DSO grids which are needed by UC3 and UC5. Additionally, the share of static generators is considered high enough to address the selected scenario and prove the functionality of control algorithms in dealing with high share of RES.</td></tr>
<tr><td>Objects under Test (OuT)</td><td colspan="3">• Static Generators (Renewable based)
• Synchronous Generators (Fossil based)
• Aggregated loads</td></tr>
<tr><td>Scenario</td><td colspan="3">INTERPLAN-2 “small and local”</td></tr>
<tr><td>Input data</td><td colspan="3">The input data consists of generation and consumption profiles of all units in the networks within a time frame of 24 hours and resolution of 15 minutes.</td></tr>
<tr><td rowspan="4">KPIs under test</td><td>ID</td><td>Name</td><td>Formula</td></tr>
<tr><td>1</td><td>Level of losses in transmission and distribution networks</td><td>$\text{Percentage of losses} = \frac{\text{Amount of injected energy } - \text{amount of energy delivered to the customers}}{\text{Amount of injected energy}} \times 100$</td></tr>
<tr><td>10</td><td>Voltage Quality</td><td>According to the defined EN 50160 Standards and VDE-AR-N 4120 bus bar voltage magnitudes must comply with following allowed range of variation.
• LV: (±10% of nominal voltage)
• MV: (±5% of nominal voltage)
• HV & EHV: (±4-7% of nominal voltage)
Voltage deviation indices can be defined to find the frequency or duration that the bus bar voltages violate the allowed voltage range.
• Number of voltage excursions exceeded n minutes per year
• Percentage of time that the transmission voltage exceeds the permissible limits</td></tr>
<tr><td>13</td><td>Mean quadratic deviations from voltage and reactive power targets at each connection point</td><td>Let C be the set of connection points between TSOs and DSOs. Let $q_{c,target}$ (t) [kVar] be the target value for reactive power transmission from DSO to TSO at connection point c and time t, as e.g. calculated by grid operation planning. Let $q_c(t)$ be the</td></tr>
</table>

		between TSO and DSO grids	reactive power actually provided from DSO to TSO at connection point *c* and time *t*. Then the KPI related to reactive power at time *t* is defined as: $$\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(q_{\mathrm{c,target}}(t)-q_c(t)\right)^2$$ The KPI related to voltage is defined as follows. Let $u_{c,target}$ [V] be the nominal value for the line-to-line voltage at connection point *c*, calculated as mean over all phases. Let $u_c(t)$ be the actual line-to-line voltage mean over all phases. Then, the KPI at time *t* is: $$\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(u_{\mathrm{c,target}}-u_c(t)\right)^2$$
	14	Level of DG / DRES utilization for ancillary services	$$\mathrm{UAS\%}=\frac{\mathrm{E_{AS}}}{\mathrm{E_{total}}}*100\ [\%]$$ E_{AS} – the energy used for ancillary services $[MWh]$ E_{total} – the total energy produced $[MWh]$
	22	Quadratic deviation from global active power exchange target	Let p_{target} (t) be the global active power production target at time t. Let G be the set of generators producing active power, and $p_g(t)$ be the active power generated by generator g at a given time t. Then, the KPI at this time is: $$\left(p_{\mathrm{target}}(t)-\sum_{g\in G}p_g(t)\right)^2$$
	23	Mean quadratic deviations from active power targets at TSO/DSO connection points	Let C be the set of connection points between TSOs and DSOs. Let $p_{c,target}$ (t) [kW] be the target value for active power transmission from DSO to TSO at connection point c and time t, as e.g. calculated by grid operation planning. Let $p_c(t)$ be the active power actually provided from DSO to TSO at connection point c and time t. Then the KPI related to active power at time t is defined as: $$\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(p_{\mathrm{c,target}}(t)-p_c(t)\right)^2$$
	24	Reactive energy provided by RES and DG	Let G be the set of RES and DG generators producing reactive power, and $q_g(t)$ be the reactive power generated by generator g at a given time t. Then, the KPI during

			the time interval t1..t2 is: $$\sum_{g\in G}\sum_{t=t1}^{t2}\lvert q_g(t)\rvert$$ [Kvarh]
	27	Share of RES	$$RES\% = \frac{P_{\text{RES}}}{P_{\text{total}}} * 100\ [\%]$$ P_{RES} = Active power provided by RES at a given time step [MW] P_{total} = Total active power provided by RES and non-RES generators at a given time step [MW]
Simulation type	Semi-dynamic		
Output parameters	Active and reactive power set points for generators, Active power set points for controllable loads.		

4.4.5 Summary

Summary	This showcase addresses a combination of network operation challenges, which are voltage stability and provision of tertiary reserve to ensure frequency stability in an optimum way. The proposed integrated control functions (related to UC1 and UC3) allow system operators (TSOs and DSOs) to solve these operation challenges through an effective DER operation planning based on active and reactive power intelligent control and coordinated TSO-DSO optimization. A system operator (TSO and DSO) that wants to address these operation challenges by using the INTERPLAN tool will be guided by the user manual to select the following planning criteria: • 1.Minimizing losses • 3. Maximizing share of RES • 4. Assuring voltage stability • 7. Optimize TSO/DSO interaction • 8. Maximize DG / DRES contribution to ancillary services • 9. Assuring frequency stability The simulation functionalities to be used are Load Flow+ Optimal Power Flow, whereas the selected KPIs needed to measure the effectiveness of the control functions are:

	• 1. Level of losses in transmission and distribution networks, • 10. Voltage quality • 13. Mean quadratic deviations from voltage and reactive power targets at each connection point between TSO and DSO grids • 14. Level of DG / DRES utilization for ancillary services, • 22. Quadratic deviation from global active power exchange target, • 23. Mean quadratic deviations from active power targets at TSO/DSO connection points, • 24. Reactive energy provided by RES and DG • 27. Share of RES. The suggested INTERPLAN scenario is INTERPLAN-2 Small and Local. Regarding the type of grid models to be used, the grid investigated for control is a transmission-distribution grid. Grid equivalenting is required for two reasons: first of all, system operators may not share full details of their own network topology and data with the other operators, and second this will simplify the optimization process at each system operator network. In detail, the TSO network or the DSO network is replaced by proper grid equivalents which represents the active and reactive power values of the original network. Once performed all these steps, the user is ready to select this showcase control function and perform the simulations through Python and PowerFactory. The evaluation phase will follow with reference to the KPI(s) values found in the simulation.

4.5 SC5 - Optimal energy interruption management

4.5.1 SC properties

ID and Name	SC5: Optimal energy interruption management	
Relevant use case/s	UC7: Optimal generation and load scheduling for energy interruption management Sub UC7.1: Load flow for the identification of credible contingency list and sensitivity analysis for prioritizing resources Sub UC7.4: Optimal energy interruption management in the presence of a contingency event	
SC description	**Summary**	
	Minimizing the energy interruption in the presence of a contingency event by re-scheduling the generators and controlling interruptible loads	
	Motivation	
	The climate change impacts and the unforeseen events have revitalized the importance of energy interruption planning. The grid of the future should be able to make smart choices by re-dispatching of available generation capacity and control of interruptible loads to ensure reliable supply to critical loads and minimize the total energy interrupted .	
	Objective	
	The showcase demonstrates a tool that performs optimal energy interruption scheduling and generator dispatch while minimizing the total energy interrupted in the network. Grid congestion resulting from a contingency is an important consideration. The critical lines and buses are identified, and the sensitivity analysis is performed to prioritize resources that reduce the likelihood of grid congestion and voltage constraint violation.	
	Solution	
	Applying UC7 ‘optimal generation and load scheduling for energy interruption management’ with two sub use cases including UC 7.1 ‘Load flow for the identification of credible contingency list and sensitivity analysis for prioritizing resources’ and UC 7.4 ‘optimal energy interruption management in the presence of a contingency event ‘. The UC 7.1 acts as base showcase that identifies a set of credible contingencies and use sensitivity analysis to prioritize load flexibility that leads to congestion minimization. It configures inputs for the showcase control function. The energy interruption is minimized in the presence of a contingency event by re-scheduling the generators and controlling interruptible loads in UC 7.4. For a given time step, a load flow is performed and contingencies that can occur in transmission or distribution system are enlisted. They are either specified by a TSO/DSO or can be listed based on peak loaded lines/transformers or the terminals having peak voltage levels. One of the contingencies is activated and load flow is performed. Afterwards, sensitivity analysis	

	is performed towards the heavily loaded line/transformer or bus that could result in a network operational constraint violation. This information is used to prioritize resources that can effectively meet the demand and to prevent the network constraint violation.

4.5.2 Control functions

4.5.2.1 Control function for optimal generation and load scheduling for energy interruption management

To develop the control functions for this part, two sub use cases including UC7.1 'Load flow for the identification of credible contingency list and sensitivity analysis for prioritizing resources' and UC 7.4 'optimal energy interruption management in the presence of a contingency event' are used in which the former has no control action and the later implements the control functions.

4.5.2.1.1 Information for the identification of credible contingency list and sensitivity analysis for prioritizing resources

UC 7.1: Load flow for the identification of credible contingency list and sensitivity analysis for prioritizing resources	
Control variables	No control action is performed in this UC. The contingency identification process and sensitivity analysis prepares the network for UC 7.4.
Associate actor/tool	• The load flow of HV and MV levels is used to prepare the pre-contingency state of the network. • Load flow analysis is used to identify critical contingencies • Sensitivity analysis is used to prioritize load flexibility for each contingency
Assumptions	• It is assumed that all flexible loads can be communicated to reduce their active power. • The synthetic cost variable can have different scaling factors, that may influence the impact on generator dispatch that has also associated costs. An elaborate mechanism of prioritizing load flexibility is not explored in this study.
Prerequisites	• The network size should at least have 10 terminals (buses). • The grid model must contain a transmission system and distribution system. • Reliability data from lines, loads and transformers will be required. • Load flow for initialization. • The model should have controllable generators and interruptible loads at MV and HV levels. • The detailed feeder models of some of the LV feeders are not be required unless there is significant flexibility in those feeders and can be remotely activated. Therefore, the equivalent of the such low voltage networks has been obtained and respective profiles for the equivalent load been identified and associated. • The time tariffs of load flexibility in terms of nature of loads (residential, commercial or industrial) are identified. • Generator costs related to dispatch are specified.

Grid equivalenting	The grid model under test has detailed urban and rural feeder models and number of equivalent feeder models representing typical urban and rural distribution networks. In this use case the detailed grid models for some low-voltage feeders is not needed for the cases in which contingency in MV or neighbouring LV feeder is considered. Therefore, for such feeders network equivalence is required. It is used to reduce the simulation calculation effort and also when detailed data or information about the grid are not available.
Input	<u>**General grid data for all steps:**</u> Bus data <table><tr><td>Bus type</td><td>Active power load</td><td>Reactive power load</td><td>Initial Bus voltage magnitude</td><td>Initial bus voltage angle</td><td>Maximum and minimum bus voltage</td><td>Nominal bus voltage</td></tr></table> Branch data <table><tr><td>Branch from which bus</td><td>Branch To which bus</td><td>Branch resistance</td><td>Branch impedance</td><td>Branch capacity</td><td>Branch type</td><td>Branch rate of power if it includes transformer</td><td>Branch tap changer number if it includes transformer</td></tr></table> Generator data <table><tr><td>Generator bus number</td><td>Generator type</td><td>Generator operation mode</td><td>Initial active power</td><td>Initial reactive power</td><td>Reactive power boundary</td><td>Active power boundary</td><td>Initial voltage magnitude and angle</td></tr></table> In addition, Penalty costs EUR/MWh Fixed costs EUR/h

Reliability parameters

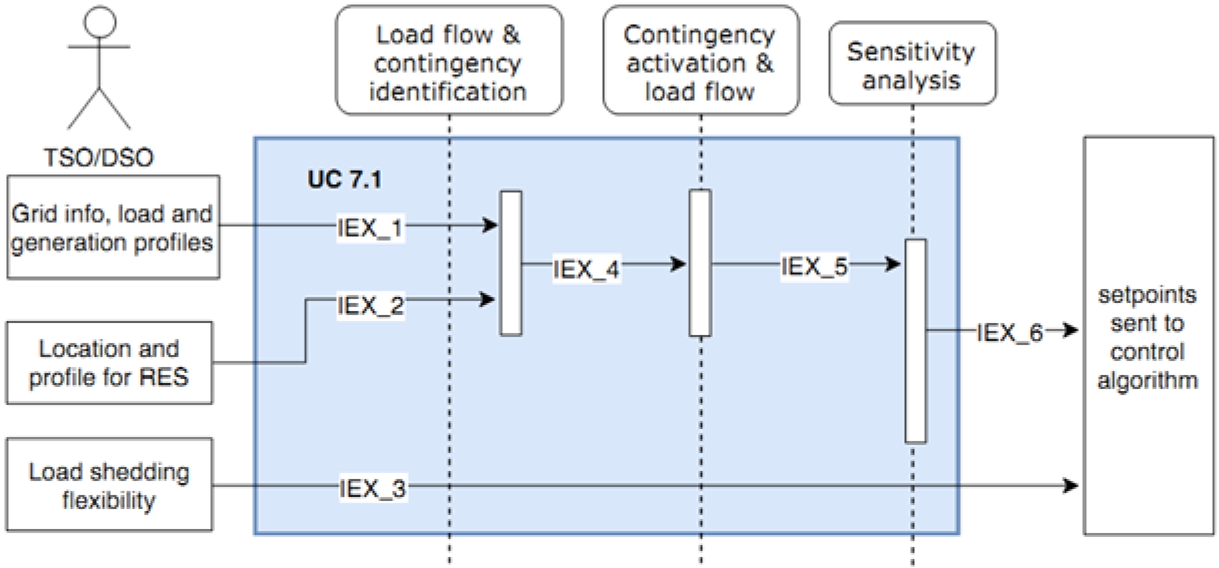
Reliability model parameters		Failure rate	Additional failure rate per connection	Repair time
		$\lambda[1/a]$	$\lambda[1/a]$	$d[h]$
Busbar failure	11 kV	0.001	0.001	2
	33 kV	0.001	0.001	2
	230 kV	0.22	0.22	10
		$\lambda[1/a * km]$	$\lambda[1/a]$	$d[h]$
Line failure	11 kV	0.065	-	5
	33 kV	0.046	-	8
	230 kV	0.02	-	10
		$\lambda[1/a]$	$\lambda[1/a]$	$d[h]$
Transformer failure	11kV/0.4kV	0.015	-	200
	138kV/33kV	0.01	-	15
	230kV/138kV	0.02	-	768

Time tariffs for loads flexibility whether loads are industrial, residential or commercial.

Load flexibility is identified as one of the candidate schemes

scenario	House Hold	Commercial	Industrial
base scenario	0 - 40 %	0 - 30 %	0 - 40 %
Scenario 1	0 - 50%	0 - 50%	0 - 50%
Scenario 2	0 - 70%	0 - 60%	0 - 60%
Scenario 3	0 - 100%	0 - 70%	0 - 70%

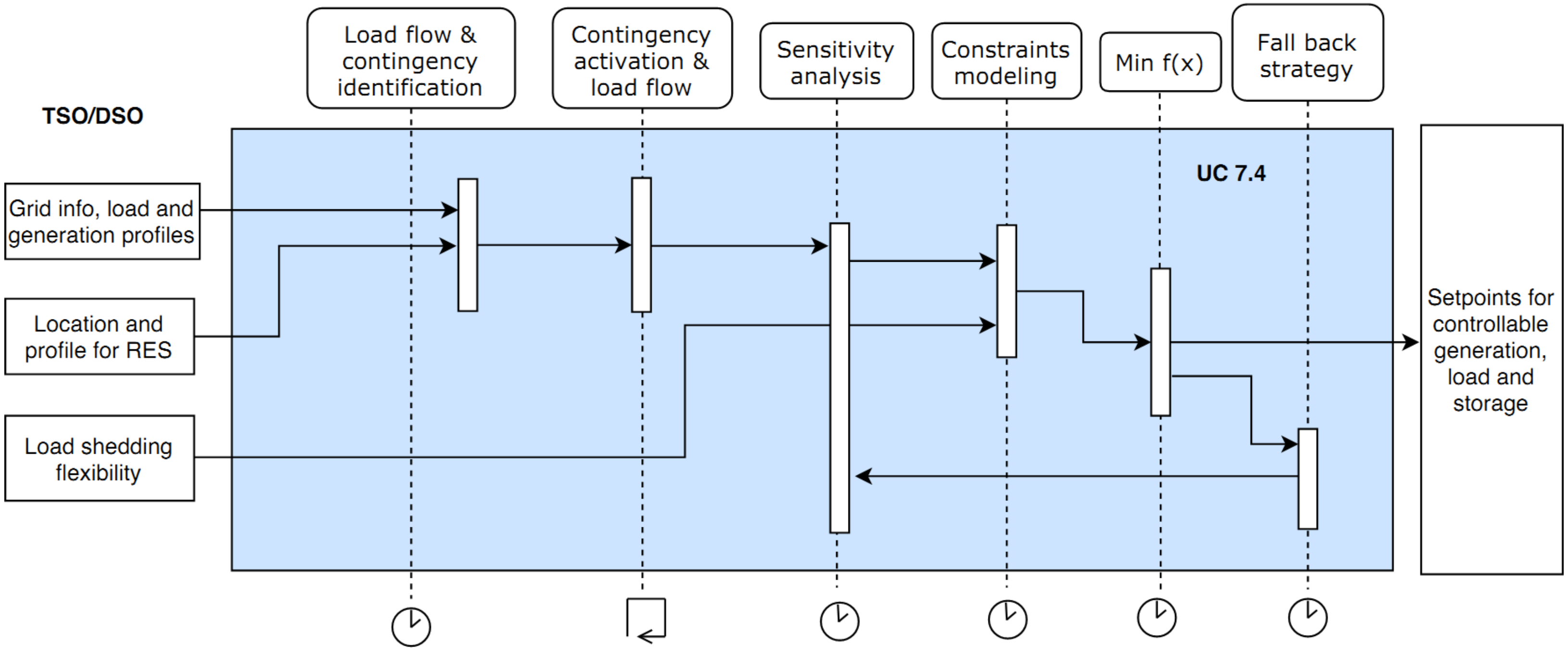
load shedding flexibility scenarios

Flowchart	
Formula	No control action is performed
Simulation environment	Powerfactory, Python
Simulation type	Semi-dynamic simulation

4.5.2.1.2 Control function for optimal energy interruption management in the presence of a contingency event

UC7.4: Optimal energy interruption management in the presence of a contingency event	
Control variables	The control variables are new set-points for loads that can be reduced as well as new active/reactive set-points for dispatchable generators.

Associate actor/tool	Optimal power flow for load interruption and generator re-dispatch.
Assumptions	It is assumed that if a contingency creates an island in the network and if there is local generation sufficient for meeting the load in the island then the generator possess sufficient grid forming capability and capacity to supply energy to loads. The contingency activation does not result in the load-flow failure.
Prerequisites	The contingency list has been created as output of UC 7.1. Secondly, the additional costs related to the objective of grid congestion minimization have been associated with the load flexibility.
Grid equivalenting	The grid model under test has detailed urban and rural feeder models and number of equivalent feeder models representing typical urban and rural distribution networks. In this use case the detailed grid models for some low-voltage feeders is not needed for the cases in which contingency in MV or neighbouring LV feeder is considered. Therefore, for such feeders network equivalence is required. It is used to reduce the simulation calculation effort and also when detailed data or information about the grid are not available.
Input	The inputs to the UC 7.4 are the outputs of UC 7.1

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


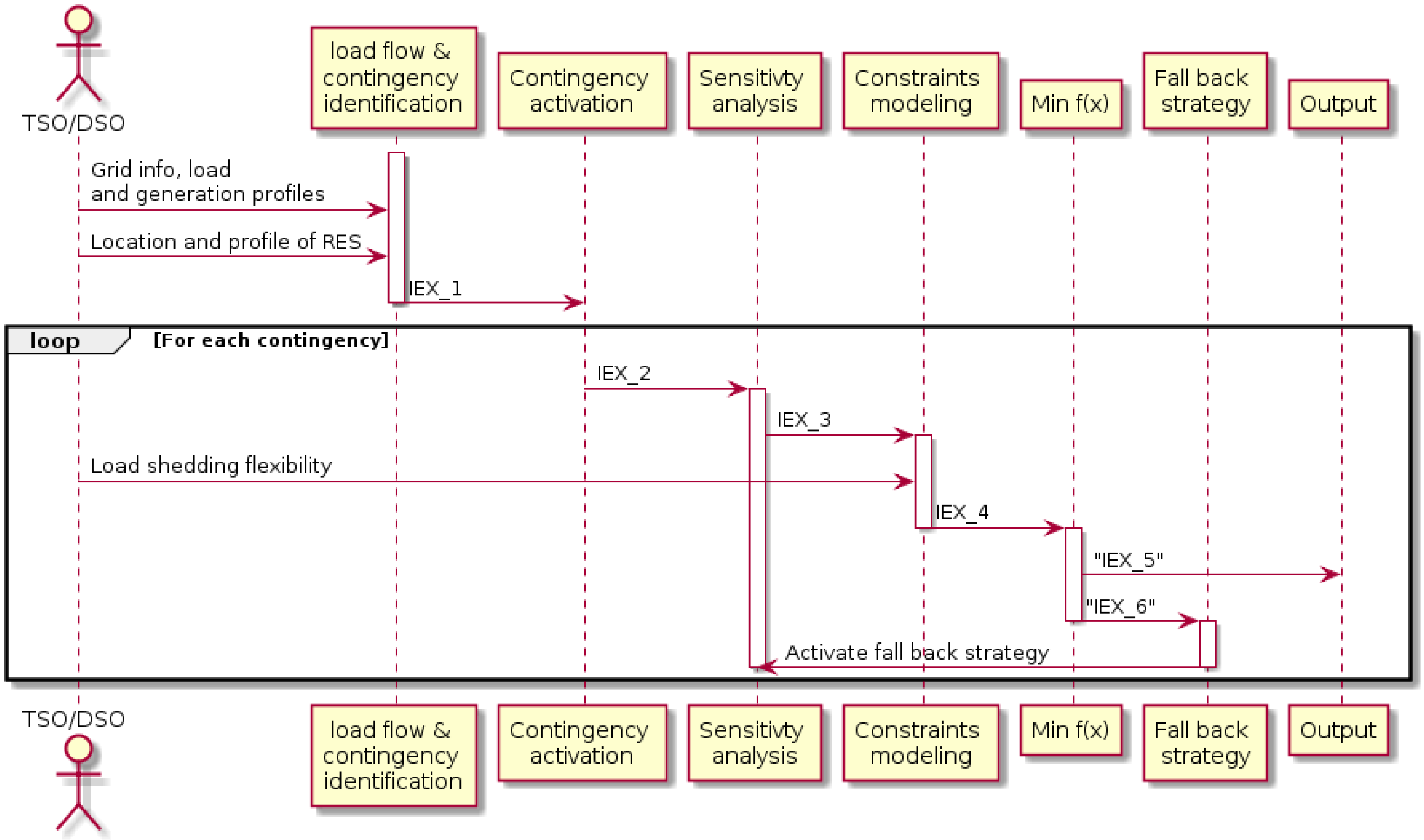
For each contingency following steps are performed.

1. Reliability analysis is performed using reliability assessment tool with two cases after a contingency from the contingency list is activated. One case is without any control action and in the second case the selected control functions is specified.
2. The contingency is manually activated and OPF is performed in PowerFactory with objective of “minimization of load shedding” with generator actor power dispatch activated.
3. The impacted loads and generators set-points are changed to reflect the post-optimization scenario.
4. In case the contingency activation creates an island, and if there is local generation then the terminal connected to the largest generator becomes the slack node. In case there are more than one generator then the terminal connected to largest generator becomes the slack node.
5. Reliability analysis is performed for the new scenario and reliability-related KPIs are saved for the contingency case.
</td>
</tr>
<tr>
<td>Formula</td>
<td>
The optimal energy interruption problem is formulated using Newton-Lagrange method which corresponds to the minimization of the Lagrange function given as:

$$L(\vec{x}, \vec{s}, \vec{\lambda}) = f(\vec{x}) - \mu \sum_i log(s_i) + \lambda^{\vec{T}} [g(\vec{x}) + h(\vec{x}) + \vec{s}] \quad (1)$$
</td>
</tr>
</table>

	where, $\vec{x}$ is the state vector at the i^{th} bus, (P^i, Q^i, V^i, $\boldsymbol{\theta}^i$). $g(\vec{x}) = 0$. load flow equations $h(\vec{x}) \leq 0$. Inequality constraints, e.g., $v^i \leq 1.1$ p.u. (2) Rest of the variables includes: $\vec{s}$ is the slack variable for each inequality constraint, where, $\vec{s} \geq 0$ such that $h(\vec{x}) + \vec{s} = 0$, $\vec{\lambda}$ as Lagrangian multiplier and μ is the multiplier for logarithmic function of $\vec{s}$ as a penalty factor. The objective function, $f(\vec{x})$ is given as: $$f(\vec{x}) = W_L \sum_{j=1}^{N_L} C_{LS}^j \left\|P_{LS}^j\right\| + W_G \sum_{k=1}^{N_G} C_{GD}^k \left\|P_{GD}^k\right\| \quad (3)$$ here, C_{LS}^j and C_{GD}^k are the cost factor of load curtailed and generator re-dispatch, W_L and W_G are the weighing factors of loads and generators and N_L and N_G are number of loads that can shed and number of generators that can be re-dispatched. The P_{LS} and P_{GD} represents the load shedding and generator re-dispatch flexibility.
Simulation environment	Powerfactory, Python
Simulation type	Semi dynamic simulation

4.5.3 Showcase structure

<table>
<tr><td>Sequence diagram</td><td colspan="2">
</td></tr>
<tr><td>Detailed description</td><td>Steps</td><td>Description
[Note: the showcase has two conceptual levels: contingency identification (load flow analysis, identification of critical lines, generators and loads) and energy interruption planning (activating the contingency in the grid, performing sensitivity analysis, modelling the constraints, optimization). In case if the optimization fails, then the fall-back strategy is activated, and the process is repeated until the dispatch signals for the generators and interrupt able loads are identified. Following is the description of the individual actions]:</td></tr>
</table>

	1	**Load flow and contingency identification** The user can be a TSO or a DSO who provides the grid information (network model) and load & generation forecasts. This action performs the load flow to calculate the status of the grid. This information is used to identify the critical contingencies in the grid; the user (TSO/DSO) can also specify them. List of credible contingencies is sent to next stage.
	2	**Sensitivity analysis** Here, the sensitivity of the critical lines and buses is calculated with respect to the buses having dispatchable generators and interrupt-able loads for the selected contingency. The sensitivity information is used to define the penalty cost terms that assigns less penalty costs to the terminals whose control action can influence more the grid constraint violation. This information is communicated to the next stage of constraint modelling.
	3	**Constraints modelling** This action prepares the matrices for the constraints for the optimization process. The mathematical model of the problem is sent to the optimizer.
	4	**Min f(x): objective function minimization** At this stage, the optimization problem is solved with constraints enabled in the network. The optimization results are load and generator set-points.
	5	**Fall back strategy** If the optimization process is either unable to meet the demand due to lack of generation or there is a grid constraint violation, then the fall back or pre-defined backup strategy is selected. That could include allowing more load to be interrupted.
	6	**Output signal** In this step, the control signals from the optimizer are received and send them to the respective generators and loads.

Sequence of actions	Steps	Associate UC ID	Action	Content	Input	Operation	output	Grid area
	1	7.1	Grid information, load and generation profile information	PowerFactory grid model is created with reliability and load flexibility data configured.	TSO/DSO	Network configuration	Network model	Complete grid
	2	7.1	Load flow analysis	PF balanced quasi-dynamic simulation performing load flow at each 15-minute step for the yearly data.	Network model, criteria for contingency identification	Load flow	Set of nodes and lines that are candidate contingencies	Complete grid

	3	7.4	Contingency activation	The node, line or transformer contingency is activated by making corresponding object out of service	Contingency list	Object parameter change	Network model with contingency activated	Complete grid
	4	7.4	Sensitivity analysis	It performs the sensitivity analysis from the node connected to generator or flexible load to the most vulnerable line or node after the contingency event	Contingency is activated	Sensitivity analysis	A list of sensitivity parameters that are used to adjust the auxiliary costs for prioritizing resources	Complete grid
	5	7.4	Reliability indices calculations	PF reliability assessment tool is used with contingency object specified to calculate reliability indices	Configured grid from step 3	Reliability calculation	Reliability parameters calculate that are noted as without controls	Complete grid
	6	7.4	Optimization activation	The OPF is run with the objective of minimizing load shedding and with the active power dispatch of generators enabled	Contingency is activated	OPF	New set-points for controllable loads and generators	Complete grid
	7	7.4	Fall-back strategy	In case OPF fails, then load flexibility is re-defined. Afterwards step 5 is repeated	OPF failure	Load flexibility changed	New load shedding flexibility	Complete grid
	8	7.4	Reliability indices calculations	PF reliability assessment tool is used to calculate reliability indices	The new set-points for loads and generators are updated in the network	Reliability calculation	Reliability parameters calculate that are noted as with controls	Complete grid

4.5.4 Test case

<table>
<tr><td>System under Test (SuT)</td><td>The test case under test is a synthetic grid having the HV, MV and LV sections. The network represents typical urban and rural networks at MV and LV levels and is based on the statistics of a large set of real distribution grid models from four European countries. The AIT synthetic grid consists two MV feeders one for urban and rural network and 34 LV feeders. Among them, 10 LV feeders are modeled in details while rest of LV networks are represented by the equivalent models.

The SC5 aims to investigate how to optimally dispatch generators and interruptible loads after the contingency situation. The grid model allows to define contingency events at both MV and LV levels. It provides a suitable platform to evaluate the impact of contingency events on the grid and how optimal activation of flexibility can bring the system with-in operational constraints. The impact is evaluated on the reliability metrics that require a comprehensive data about reliability in LV and MV grids. Moreover, the impact of network equivalence on the results is also studied.</td></tr>
<tr><td>Objects under Test (OuT)</td><td>Terminals, generators set-points, load that have flexibility, lines</td></tr>
<tr><td>Scenario</td><td>INTERPLAN _2 Small and Local</td></tr>
<tr><td>Input data</td><td>The synthetic network used in this showcase consists of 34 LV feeders connected to two MV feeders (rural and urban).

<table>
<tr><th>Feeder name</th><th>No. of PVs</th><th>No. of generators</th><th>No. of lines</th><th>No. of loads</th><th>No. of terminals</th><th>No. of transformers</th></tr>
<tr><td>MV Rural</td><td>0</td><td>4</td><td>39</td><td>6</td><td>61</td><td>22</td></tr>
<tr><td>MV Urban</td><td>0</td><td>4</td><td>15</td><td>0</td><td>25</td><td>10</td></tr>
<tr><td>LV urban 5</td><td>14</td><td>0</td><td>21</td><td>19</td><td>21</td><td>0</td></tr>
<tr><td>LV urban 1</td><td>20</td><td>0</td><td>28</td><td>25</td><td>28</td><td>0</td></tr>
<tr><td>LV urban 2</td><td>14</td><td>0</td><td>22</td><td>19</td><td>22</td><td>0</td></tr>
<tr><td>LV urban 3</td><td>20</td><td>0</td><td>30</td><td>26</td><td>30</td><td>0</td></tr>
<tr><td>LV urban 4</td><td>24</td><td>0</td><td>34</td><td>31</td><td>34</td><td>0</td></tr>
<tr><td>LV rural 1</td><td>12</td><td>0</td><td>26</td><td>16</td><td>26</td><td>0</td></tr>
<tr><td>LV rural 2</td><td>10</td><td>0</td><td>22</td><td>14</td><td>22</td><td>0</td></tr>
<tr><td>LV rural 3</td><td>12</td><td>0</td><td>30</td><td>17.0</td><td>30</td><td>0</td></tr>
<tr><td>LV rural 4</td><td>16</td><td>0</td><td>34</td><td>22</td><td>34</td><td>0</td></tr>
<tr><td>LV rural 5</td><td>0</td><td>0</td><td>2</td><td>1</td><td>2</td><td>0</td></tr>
</table>

Some of the LV grids are equivalented, following is the information about them</td></tr>
</table>

	No. of PVs	No. of generators	No. of lines	No. of loads	No. of terminals	No. of transformers
Rural LV 14	1	0	105	103	105	0
Rural LV 15	2	0	108	110	108	0
Rural LV 4	2	0	137	139	137	0
Rural LV 20	1	0	114	114	113	0
Rural LV 21	2	0	110	116	108	0
Rural LV 10	1	0	77	104	77	0
Rural LV 11	0	0	96	103	95	0
Rural LV 12	0	0	88	103	86	0
Rural LV 3	1	0	152	144	151	0
Rural LV 5	1	0	137	123	135	0
Rural LV 6	1	0	114	111	112	0
Rural LV 8	0	0	109	103	109	0
Rural LV 9	6	0	79	100	79	0
Rural LV 1	1	0	169	144	164	0
Rural LV 16	4	0	83	109	83	0
Rural LV 17	3	0	118	113	118	0
Rural LV 18	2	0	121	117	121	0
Urban LV 3	4	0	683	213	676	0
Urban LV 5	2	0	390	193	388	0
Urban LV 7	4	0	457	200	451	0
Urban LV 9	0	0	438	173	437	0
Urban LV 1	1	0	98	113	96	0

No. of static generators connected to MV grid

Name	Nominal power (MW)
Biomass 1	1.2
Biomass 2	0.2
DG1_Coal-fired combustion turbine	0.25
DG2_Natural gas combustion turbine	0.4
DG3_Coal gasification combined-cycle (IG	1.2
DG4_Natural gas combined-cycle	0.2
DG5_Hydroelectric	0.5

	DG6_Hydroelectric Wind Farm 1 Wind Farm 2	0.65 3.2 1.4	
	No. of Busbars 346 No. of Lines 311 No. of Loads 273 No. of 2-w Trfs. 34 No. of 3-w Trfs. 2 During execution of UC 7.4, each contingency is activated and corresponding date and time is set.		
KPI under test	**ID**	**Name**	**Formula**
	3	SAIDI (System Average Interruption Duration Index)	$SAIDI = \frac{sum\ of\ all\ customer\ interruption\ duratios}{total\ number\ of\ customers\ served}$
	7	Power losses	$P_{\text{losses}} = \sum_{i}^{Nline} \lvert I \rvert_i^2 * r_i\ [kW]$ I_i $-$ magnitude of current flow in line i $[A]$ r_i $-$ resistance of line i $[\Omega]$
	8	AENS & ENS (Average Energy not Supplied & Energy not Supplied)	$AENS = ENS/\sum C_i$ $ENS = \sum LPENS_i$ $LPENS_i$: Load Point i Energy Not Supplied $C_{i:}$: Customer *i* $ACIT$: Average Customer Interruption Time

	9	IEAR(Interrupted Energy Assessment Rate)	$EAR = \frac{EIC}{ENS}$ in $ / kWh EIC: Expected Interruption Cost, in units of [M$/y], is the total expected interruption cost ENS: Energy Not Supplied, in units of [MWh/a], is the total amount of energy on average not delivered to the system loads
	18	SAIFI(System Average Interruption Frequency Index)	$SAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers served}}$
	24	Reactive energy provided by RES and DG	During this showcase the reactive power provided by DGs connected to MV grid are recorded.
	27	Share of RES	Maximum share of RES as hosting y capacity is calculated for the feeder in which contingency occurs and is calculated for UC 7.3 only. This KPI is not calculated for the showcase.
Output parameters	Active power set-points for the generators and for flexible loads		

4.5.5 Summary

Summary	This showcase addresses the operational challenges arising due to contingency events in the grid that are related to voltage limits, line and transformer loading constraints. Although contingency studies are routinely performed in the power grid, post-contingency situations are diverse and will require frequent re-assessment in terms of network reliability due to high penetration of DER in the system. In addition, weather-dependent events also increase volatility of the grid and require advance network planning. In such situations, the flexibility offered by DER and interruptible loads can be used to recover the system to operational condition after the contingency. Therefore, SC5 provides a suitable platform for the grid operator to plan the flexibility in the grid. If the dispatchable DERs are available in MV grid, they can be dispatched by the algorithm. Following planning criteria can be selected by the operator using INTERPLAN tool. • 1. Minimizing losses • 2. Minimizing the cost • 4. Assuring voltage stability • 8. Maximize DG / DRES contribution to ancillary services • 10. Minimizing energy interruptions

	The simulation functionalities used are load flow, sensitivity analysis, reliability calculation and optimal power flow. The KPIs used to measure the effectiveness of the control are: • 3.System average interruption duration index • 7. Power losses • 8. Average energy not supplied • 9. Interrupted energy assessment rate • 18. System average interruption frequency index • 24. Reactive power provided by DGs • 27. Share of RES The suggested INTERPLAN scenario is INTERPLAN-2 Small and Local. The grid model used is a synthetic grid with number of LV grids modeled as equivalents. This is necessary, as the contingency analysis requires the consideration of large number of credible contingencies against whom flexibility resources are needed to be planned. In such situations, grid simplifications reduces the problem complexity. This is particularly important, as the SC5 will be needed frequently by the grid operator within the tool. The equivalent LV feeders should provide the equivalent impedance, active and reactive power, and equivalent reliability parameters. Once network equivalence is performed, the user is ready to select the showcase function and performs simulations through PowerFactory. The evaluation phase will follow with reference to KPI results from the simulation studies.

5. Summary and outlook

In this deliverable D5.3, the preliminary actions related to control system logics and development of cluster and interface controllers have been accomplished. Detailed descriptions of the developed control functions for all five INTERPLAN showcases have been presented. These showcases include:

- Low inertia systems
- Effective DER operation planning through active and reactive power control
- TSO-DSO power flow optimization
- TSO-DSO coordinated active and reactive power optimization for provision of tertiary reserve and improvement of voltage profiles
- Optimal energy interruption management

The control functions have been developed under the concepts of cluster controllers and interface controllers. All the control functions are aggregated in a part of the network by cluster controllers, which are located in different parts of the network and connected to each other with an interface controller in a bigger part of the network. The proposed control functions allow the user of the INTERPLAN tool to solve specific network operation challenges. To this end, the user who can be a system operator (TSO or DSO) selects one of the following planning criteria:

- Minimize losses
- Minimize costs
- Maximize share of RES
- Assure voltage stability
- Mitigating grid congestion
- Assure transient stability
- Optimize TSO/DSO interaction
- Maximize DG/RES contribution to ancillary services
- Assure frequency stability
- Minimize energy interruptions

The suitable simulation functionalities to achieve the planning criteria are selected from the following list:

- Optimal Power Flow (OPF);
- Basic Load Flow (LF);
- LF sensitivities;
- Stability Analysis Functions (RMS simulation);
- Optimization tool;
- Reliability assessment.

Some control functions may also need to use a grid equivalent which is selected from pre-defined library in INTERPLAN tool.

The main features of each showcase control function developed in this deliverable are summarized as follow:

- SC1 addresses two network operation challenges including frequency stability and inertia management. The proposed integrated control functions (related to UC4 and UC6) solve these operation challenges through planning of unit dispatch under the frequency stability criterion and employing inertia management for assuring transient stability. A system operator (TSO and DSO) that wants to address these operation challenges selects the following planning criteria: 3.Maximizing share of RES, 6.Assuring transient stability, 7.Assuring frequency stability, 8.Maximize DG/DRES contribution to ancillary services. The Simulation functionalities to be employed within the tool are: Basic Load flow and Stability Analysis Functions. The Cyprus grid is used for showcase simulation with selected INTERPLAN scenario: ‘INTERPLAN-3: Large Scale RES’ in Python and PowerFactory environment.

- SC2 addresses two network operation challenges including voltage stability and grid congestion. The proposed integrated control functions (related to UC1 and UC2) can solve these operation challenges through active and reactive power control of DER for grid congestion management and coordinated TSO-DSO optimization. A system operator (TSO and DSO) that wants to address these operation challenges selects the following planning criteria: 1.Minimizing losses, 3.Maximizing share of RES 4. Assuring voltage stability, 5. Mitigating grid congestion, 7.Optimize TSO/DSO interaction, 8.Maximize DG/DRES contribution to ancillary services. The simulation functionalities to be used are Load Flow+Load Flow sensitivities+Optimal Power Flow. Simbench grid model is applied with selected INTERPLAN scenario: 'INTERPLAN-2: small and local' to evaluate the effectiveness of the developed control functions in PowerFactoy environment.
- SC3 addresses two network operation challenges including provision of appropriate tertiary reserve and energy management on DSO level in the presence of high DER penetration levels. The proposed integrated control functions (related to UC3 and UC5) can solve these operation challenges through an effective DER and storage operation planning based on active power control. To address these operation challenges by an operator using the INTERPLAN tool, the following planning criteria are selected: 1.Minimizing losses, 3. Maximizing share of RES, 7.Optimize TSO/DSO interaction, 8.Maximize DG/DRES contribution to ancillary services, and 9. Assuring frequency stability. The simulation functionalities to be used are Load Flow and Optimal Power Flow. Simbench grid model is applied to implement the showcase and evaluate the effectiveness of the control function in PowerFactoy and Python environment.
- SC4 addresses two network operation challenges including voltage stability and provision of tertiary reserve to ensure frequency stability in optimum way. The proposed integrated control functions (related to UC1 and UC3) can solve these operation challenges through an effective DER operation planning based on active and reactive power control and coordinated TSO-DSO optimization. A system operator addresses these operation challenges by using the INTERPLAN tool with selection of the following planning criteria: 1.Minimizing losses, 3. Maximizing share of RES, 4. Assuring voltage stability, 7.Optimize TSO/DSO interaction, 8. Maximize DG/DRES contribution to ancillary services, 9.Assuring frequency stability. The simulation functionalities to be used are Load Flow+ Optimal Power Flow. Simbench grid with selected INTERPLAN scenario 'INTERPLAN-2 Small and Local' is used for this showcase control function to perform the simulations through Python and PowerFactory.
- SC5 addresses several operational challenges arising due to contingency events in the grid that are related to voltage limits, line and transformer loading constraints. The proposed integrated control functions (related to UC7) can solve these operation challenges through flexibility offered by DER and interruptible loads to recover the system to operational condition after the contingency. A system operator addresses these operation challenges by using the INTERPLAN tool with selection of the following planning criteria: 1.Minimizing losses, 2.Minimizing costs, 4.Assuring voltage stability, 8.Maximize DG/DRES contribution to ancillary services, and 10. Minimizing energy interruptions. The simulation functionalities for this showcase are load flow, sensitivity analysis, reliability calculation and optimal power flow. A synthetic grid with selected INTERPLAN scenario 'INTERPLAN-2 Small and Local' is used to implement the showcase simulation and evaluate the effectiveness of the developed control functions in PowerFactory environment

The simulations of showcases are being prepared to be performed and the calculation of KPIs will be presented in deliverable D5.4 'Control system logics: cluster and interface controllers (final version)'. The relevant KPIs will be compared with the ones calculated for the associated base showcases extracted in deliverable D5.2 in order to verify the effectiveness of the embedded control functions. Moreover, the "proof-of-concept" of INTERPLAN tool will be also verified through one of the INTERPLAN showcases selected by the consortium.

6. References

[1] "INTERPLAN, 'Deliverable D3.2 INTERPLAN scenarios and use cases', (Public report), October 2018."
[2] "INTERPLAN, 'Deliverable D5.1 INTERPLAN showcases', (Public report), December 2018."
[3] "INTERPLAN, 'Deliverable D5.2 Operation planning and semi-dynamic simulation of grid equivalents', (Public report), November 2019."

7. Annex

7.1 List of Figures

7.2 List of Tables

7.3 Glossary of terms and definitions

7.3.1 Definition of project general terms

Term	Definition
Use Case	The specification of a set of actions performed by a system, which yields an observable result that is, typically, of value for one or more actors or other stakeholders of the system.
Sub Use Case	Description of a specific situation a use case is applied to. A Sub Use Case is always attributed to one (main) use case, but one use-case may have multiple sub use cases which detail the main use case in at least one aspect.
Base showcase	Presentation of base use case(s) with no planning criteria and no controllers for emerging technologies, such as RES, DG, demand response or storages in the frame of chosen scenario, simulation type, test model, and time-series data. The base showcase allows to analyze the operation challenges of the related use case(s) and improvements achieved through the application of planning criteria with related implementation of controllers in the associated showcase.
Showcase	Presentation of use case(s) in the frame of chosen scenario, simulation type, test model, time-series data and planning criteria
Scenario	Definition of a future situation applying to a well-defined time (most often year). A scenario can be fictional or predicted from the present situation. In INTERPLAN, scenarios describe the future situation of the European electric network, typically including grid topology, generation mix, loads and diffusion of EV, RES and storages.
Dynamic Simulation	A simulation experiment which considers the time dependent behaviour of a physical system, looking at events occurring in real-time operation, with a frequency of occurrence of less than one second of real time. The simulation may run faster or slower than real time, and may, despite the fast event frequency, span a total time interval of several hours real-time.
Semi-Dynamic Simulation (also: Quasi-Dynamic Simulation)	A medium- to long-term simulation experiment based on steady-state analysis, considering the state of a physical system at discrete steps of real time through user-defined time step sizes. The real time between the steps is at least one minute.
Grid Cluster	A group of grids and parts of grids with similar characteristics
Grid Equivalent	A simplified network model, which approximately behaves like an associated complex physical network or a group of physical networks. The grid equivalent thus is a representation of the physical network(s), which is typically used for a simulation experiment.
Control function	A set point definition, which is determined based on the goals of each use case. A control function defines the set points of specific elements (e.g. OLTC, DGs, RESs) or some programs (e.g. demand response)

	calculated by an operation objective in the network.
Interface	A means of transmitting information between two or more controllers or actors. It usually includes a specification about which information is to be transmitted, how this information is represented by data elements, and defines a physical means for transmission of those data elements.
Cluster Controller	A controller to aggregate all control functions signals in a part of the network such as a central controller in a substation.
Interface Controller	A controller, which is intended to be the interface among different cluster controllers in big part of the network and receives information from other cluster controllers. This can facilitate the exchange of commands among the cluster controllers. For instance, the transmission operator can be seen as an interface controller for different clusters residing in several substations.
Local Controller	A controller which is associated with a single specific generator, load or grid asset and which operation does not rely on remotely received information originating from any remote source. i.e. the operation only relies on information available within the local area network of the local controller's installation site.
Co-simulation	A simulation which consists of different parts that form a coupled problem and are modelled and simulated in a distributed manner (cp. Wikipedia). The parts are called "Co-simulation subsystems" and are exchanging data during the simulation. Different models and simulation means can be used in different subsystems. The Co-simulation (in the ideal case) is carried out by running the subsystems, which were individually tested and validated beforehand, in a black-box manner. In INTERPLAN, the data exchange between subsystems is done by the OpSim platform.
Co-simulation subsystem / Co-simulation subcomponents	A part of a Co-simulation which is developed, modelled and validated individually, while at the same time able to be integrated into the Co-simulation platform. In INTERPLAN, a subsystem might represent e.g. a DSO or TSO operation centre, a controller, or even the real physical network model.
Data model	An abstract model that represents a real-world entity, and defines, organizes and standardizes the description of the data elements related with that entity. Since real-world entities are typically consisting of other entities (e.g. an electric grid consists of lines, transformers etc.), a data model typically is hierarchically structured and also allows to define interrelations between entities.
V2G and G2V	Vehicle-to-grid (V2G) describes a system in which *plug-in electric vehicles* communicate with the *power grid* to sell *demand response* services by either returning electricity to the grid or by throttling their charging rate. When an EV is being charged, it's called G2V (Grid to Vehicle).
Allocation	With reference to the grid operation planning phase, it is the process deciding, which are the most suitable resources to commit and

	dispatch among *n* operating resources for a specific objective and under specific constraints.
Placement and sizing	With reference to the grid planning, it is the process deciding the most proper location (bus) and the size of a resource (active power) for a specific objective and under specific constraints.
Energy Not Supplied	Energy Not Supplied is defined as the amount of energy that would have been supplied to the customer if there had been no interruption.
Energy spillage	Energy spillage is the production (from Solar and Wind) that is unable to be accommodated due to demand being lower than production.

7.3.2 Definition of actors

Term	**Definition**
TSO - Transmission System Operator	Natural or legal person responsible for operating, ensuring the maintenance of the transmission system and, if necessary, developing the transmission system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the transmission of electricity. The term ‘transmission’ means the transport of electricity on the extra high-voltage and high-voltage interconnected system with a view to its delivery to final customers or to distributors, but does not include supply.
DSO - Distribution System Operator	A natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity. The term ‘distribution’ means the transport of electricity on high-voltage, medium-voltage and low-voltage distribution systems with a view to its delivery to customers, but does not include supply.
ESCO	Electricity supply company (sometimes also: Electricity service company). General term for a company which supplies end users with electric energy. An ESCO may offer additional services, e.g. electricity generation, metering or supply with non-electric energy.
Prosumer	Active energy consumer who consumes and produces electricity. Various types of prosumers exist: residential prosumers who produce electricity at home - mainly through rooftop PV, citizen-led energy cooperatives, commercial prosumers whose main business activity is not electricity production, and public institutions.
Generator	A device which produces electricity.
Load	A device which consumes electricity.
Producer	A natural or legal person generating electricity.
Consumer	A natural or legal person consuming electricity.
Distributed	A source or sink of electric power that is located on the distribution system,

Energy Resource (DER)	any subsystem thereof, or behind a customer meter. DER may include distributed generation, electric storage, electric vehicles and demand response.
Aggregator	Company who grouping distinct agents in a power system (i.e. consumers, producers, prosumers, or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the system operator(s).
Distributed generation (DG) unit	Any source of electric power of limited capacity, directly connected to the power system distribution network. DG can be powered by photovoltaic system, micro-turbines, combustion engines, fuel cells, wind turbines, geothermal, etc.
Flexible Loads	A load which consumption can be influenced in terms of power, time, or total energy consumed while still serving its intended purpose. The influence may be exerted by manual means (e.g. switching the load on or off at arbitrary times) or automatic means (e.g. external control signal).