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List of Abbreviations

AC	Alternating Current
CPPS	Cyber-Physical Power System
CVC	Coordinated Voltage Control
DER	Distributed Energy Resource
EMC	Electromagnetic Compatibility
EMT	Electromagnetic Transients
FMI	Functional Mock-Up Interface
FMU	Functional Mock-up Unit
FS	Functional Scenario
HV	High Voltage
ICT	Information and Communication Technology
IED	Intelligent Electronic Device
IP	Internet Protocol
LEC	Local Energy Community
LV	Low Voltage
MV	Medium Voltage
OA	Open Access
OLTC	On-Load Tap Changer
OPC UA	OPC Unified Architecture
OS	Open Source
PCC	Point of Common Coupling
PreCISE	Preparing Concise Information for Simulation Experiments
PV	Photovoltaic
R&D	Research and Development
RI	Research Infrastructure
RL	Resistive Load
RoCoF	Rate of Change of Frequency
RT	Real-Time
RTT	Round Trip Time
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SoC	State of Charge
TC	Test Case
UC	Use Case
WAMPAC	Wide Area Monitoring, Protection, and Control

Executive Summary

This document presents results from the “Benchmark Scenarios” activity conducted in the ERIGrid 2.0 project. The main objective of this activity is to establish reference benchmarks for validating concepts and implementations of smart grid technologies to be further used in the ERIGrid 2.0 project and by interested external users.

Benchmark configurations are very valuable instruments for providing a comparative assessment of new technological approaches and implementations. Based on the Functional Scenarios (FSs) previously defined as the high-level scenarios in ERIGrid 2.0 to provide system descriptions, corresponding Use Case (UC) and Test Case (TC) descriptions, and experimental setup descriptions, this document presents the three benchmark configurations that have been defined and the ready-to-use numerical models that have been developed. The benchmarks are independent and each benchmark targets one or more FSs. The first benchmark consists of a microgrid configuration with relatively high penetration of power electronics conversion and includes several renewable energy sources. The second benchmark represents a multi-carrier energy system linking thermal and electrical distribution networks through a power-to-heat facility. Finally, the third benchmark models a smart grid with an explicit representation of the Information and Communication Technology (ICT) layer. An overview of the three benchmarks developed within ERIGrid 2.0 is provided below.

Name	Domain	Simulation Environment
Electrical Network	Electrical	MathWorks MATLAB/Simulink
Multi-Energy Networks	Electrical, Thermal	pandapower, Modelica, Python
ICT-Enhanced Power Systems	Electrical, ICT	DIgSILENT PowerFactory, Mininet

The present document provides a brief summary of these three benchmarks organised in separate sections. Each of these sections includes the main motivation for the benchmark configuration, the general structure of the considered system, and examples of use. Finally, recommendations for better use and known limitations are reported.

The intention of this work is to provide an overview to the interested reader without duplicating the information contained in the Preparing Concise Information for Simulation Experiments (PreCISE) templates that should be considered as the main source of documentation of these benchmarks. In this perspective, this document contains the reference directing to the PreCISE documents for a more comprehensive and exhaustive description template of the experiment regardless of the tools and models. The corresponding models and documentation are available at an Open Access (OA)/Open Source (OS) repository.

1 Introduction

1.1 Purpose and Scope of the Document

This document presents results from the "Benchmark Scenarios" activity conducted in the ERIGrid 2.0 project. The main objective of this activity is to establish reference benchmarks for validating concepts and implementations of smart grid technologies to be further used in the project and by interested external readers.

Present power systems have been rapidly evolving in the last two decades to address the societal requirements for more environmentally sustainable development and to incorporate the advancements in communication, monitoring, and data processing. Smart grids will most likely incorporate Information and Communication Technology (ICT), power electronics converters, and renewable energy sources. Moreover, sustainability and energy efficiency tend to favour holistic approaches where multiple energy sources and carriers are considered, including, for example, thermal energy or conversion from hydrogen. This may also correspond to a less centralised structure for energy management and a more complicated power flow compared to a conventional grid architecture with a few large generators and loads only in the distribution system. A more recent trend is the digitalisation of the power system and the progressive integration of ICT components, especially in the control and monitoring of smart grids.

These developments have been reflected in the definition of six FSs in a previous activity of ERIGrid 2.0 (Raussi et al., 2020) resulting in:

1. Ancillary services provided by Distributed Energy Resources (DERs) and active grid assets,
2. Microgrids & energy communities,
3. Sector coupling,
4. Frequency and voltage stability in inverter dominated power systems,
5. Aggregation and flexibility management, and
6. Digitalisation.

Benchmark configurations are very valuable instruments for providing a comparative assessment of new technological approaches and implementations. Based on the FSs defined as mentioned earlier, the task defined three benchmark configurations and developed ready-to-use numerical models. The benchmarks are independent, and each benchmark targets one or more FSs. The first benchmark consists of a microgrid configuration with a relatively high penetration of power electronics conversion and includes several renewable energy sources. The second benchmark represents a multi-carrier energy system linking electrical and thermal distribution networks through a power-to-heat facility. Finally, the third benchmark models a smart grid with an explicit representation of the ICT layer.

At the end, three benchmarks have been developed and documented according to the Preparing Concise Information for Simulation Experiments (PreCISE) (Widl et al., 2020) approach. The PreCISE approach provides templates for describing the simulation experiments regardless of specific models, tools, and methods, which allows users to collaborate among them.

This document aims to provide an overview for interested readers without duplicating the information contained in the PreCISE templates which is the main documentation of these three benchmarks. In this perspective, this document contains references directing to the PreCISE documents for a more comprehensive and exhaustive description. References are also provided to the online repositories containing the benchmark implementations developed. Each of these sections includes the main motivation for the benchmark configuration, the general structure of the system considered, and some examples of use. Finally, recommendations for better use and known limitations are provided.

1.2 Structure of the Document

This document is organised as follows: Section 2 provides an overview about the general approach and the used methodology. Sections 3 to 5 are dedicated to the three benchmark configurations. The conclusions are presented in Section 6.

2 General Approach and Methodology

This section provides a summary of the common approach and methodology for developing the models that are applicable to the three benchmarks. The process for developing those benchmark models and for further validation and documentation of them is highlighted by describing each step of the task execution.

2.1 Benchmark Description

A number of TCs are developed in the previous Deliverable D5.2 (Raussi et al., 2021) which covered key technological areas and six FSs defined in Deliverable D5.1 (Raussi et al., 2020). Thus, this activity aimed at developing the benchmark models that cover several TCs to enhance smart grid and energy systems development, validation, and roll-out. Since the number of TCs that could be covered by benchmarks is relatively large, due to the many research directions covered by the field of smart grid and energy systems, it was considered not feasible to develop individual benchmarks for each possible relevant TC because of the limited resources available for the work and for the consequent risk that the quality of each of these benchmarks could be lower than required. As a result, three benchmarks were initiated to represent a wider topic area that can be adapted to several UCs. These benchmarks are summarised in Table 1 in context of the tackled domain(s) as well as the used simulation environment(s).

Table 1: Overview of the three ERIGrid 2.0 benchmarks.

Name	Domain	Simulation Environment
Electrical Network	Electrical	MathWorks MATLAB/Simulink
Multi-Energy Networks	Electrical, Thermal	pandapower, Modelica, Python
ICT-Enhanced Power Systems	Electrical, ICT	DIgSILENT PowerFactory, Mininet

In the following sections, the identified benchmark scenarios are briefly outlined. The detailed descriptions of them are provided in the following Sections 3 to 5.

2.1.1 Benchmark 1: Electrical Network

The first benchmark has been defined to represent a modern electrical system with a high penetration of power electronics converters and distributed energy generation from renewable sources. This benchmark can serve to test, for example, distributed or centralised controllers for energy management, grid forming, and grid following control schemes for power converters or synchronisation algorithms for connection to an external grid. The benchmark is intended to focus only on the electrical domain by assuming an ideal communication between the components. The benchmark has been developed entirely in the MATLAB/Simulink environment with the additional use of the Simscape Power System toolbox and libraries.

2.1.2 Benchmark 2: Multi-Energy Networks

The second benchmark focuses on energy systems where multiple energy carriers are present. The benchmark is intended to highlight aspects related to energy management and coordination between multiple energy carriers but also addresses the issues associated with the handling of a multi-domain environment for simulation and co-simulation. Indeed, the benchmark has been defined to include both an electrical power system and a thermal distribution system. The mosaik co-simulation framework has been used to develop two different implementations of this benchmark, showcasing different options for modelling the thermal domain of such a multi-energy network application.

2.1.3 Benchmark 3: ICT-Enhanced Power Systems

The development of digitalisation of energy systems has increased the interactions between ICT and energy systems, and this mutual interdependence can affect the power system like by causing cascading failures, wide-area blackouts, and others. The third benchmark addresses the impact of ICT on electrical power systems. Similarly to the first benchmark, the third benchmark focuses on the communication delays and interruptions that would cause the delay of controlling algorithms but also the issues related to the simulation or co-simulation of the electrical and ICT domains.

2.2 Test Case Description

After the completion of the simulation models and the testing of the functionalities at both component and system levels, relevant TCs have been identified to illustrate the capabilities of the benchmark models and their possible use. Twenty-five TC profiles are defined in Deliverable D5.2 (Raussi et al., 2021) which are categorised into three key technological areas aligned with the three benchmarks. Based on the developed three benchmarks, interested users can select the TC profiles depending on investigation purposes like test phenomenon, type of assessment, and test system or test component. The details of the selected TCs are provided in the following Sections 3 to 5 for each benchmark.

2.3 Benchmark Documentation

The benchmarks have been developed with the intention of being an open access resource. As such, the developed models are stored in an online OA/OS repository. To facilitate the usability of the benchmarks, the last activities are devoted to documenting the numerical models and providing examples of use. A brief information of each benchmark is presented in the following Sections 3 to 5 of this document including a system description, examples of use, limitations, and recommendations. The intention of this document is to provide high-level information of each benchmark for interested readers. A more complete form of documentation has been prepared according to the PreCISE (Widl et al., 2020) approach for each benchmark and is available at ERIGrid 2.0 GitHub environment[1].

[1] https://github.com/ERIGrid2/

3 Benchmark 1 – Electrical Network

This section covers the description of the "Electrical Network" benchmark of ERIGrid 2.0. In the following, a brief overview, the used system description, an example of use, the limitations and recommendations, and an outlook about the future work of the benchmark is provided.

3.1 Overview

The reference setup to be used as a benchmark for the scenarios involving an electrical system with high penetration of power electronics and renewable energy sources are tackled. The main objective is to be used for the simulation of several TCs regarding only the electrical network (i.e., no other energy form or additional ICT layer). Within this context, the most relevant FSs (as defined in Deliverable 5.1 (Raussi et al., 2020)) include "Microgrids & energy communities" and "Frequency and voltage stability in inverter dominated power systems".

This benchmark refers to a Low Voltage (LV) distribution network, which has various DERs connected to it via converters. At the DER nodes, local loads are also connected so that anti-islanding techniques for DERs can be investigated during grid faults. Parts of the power distribution network can operate as an autonomous microgrid (i.e., it can be islanded from the rest of the network). In addition to a resistive load, the microgrid is equipped with a grid-forming inverter that maintains the reference frequency and ensures the stability of the microgrid when it operates in islanded mode. The LV network is fed by the Medium Voltage (MV) network via an MV/LV distribution transformer, which has an On-Load Tap Changer (OLTC) for voltage control. To simulate the relevant TCs, different loads are connected to the benchmark network, including resistive and resistive-inductive loads and a variable-speed asynchronous motor.

Finally, a synchronous generator is also connected to the LV network, allowing to consider in simulation the interactions between power electronics and mechanical components during grid faults. The synchronous machine has a different behaviour compared to power converters which show intrinsic inertia but a slower response time. This interaction can affect the performance of the protection scheme or Energy Management System controller. The purpose of the benchmark is to be used for the TCs of the ERIGrid 2.0 project, including system-level energetic simulations, assessment of flexibility and energy services, dynamic simulations, response to grid faults, assessment of autonomous microgrid operation, simulation of grid controls, etc. The benchmark does not cover the explicit modelling of all possible components of a distribution network, nor is it intended for all kinds of studies (switching transients, small-signal stability, Electromagnetic Transients (EMT), Electromagnetic Compatibility (EMC), etc.).

The used background material and TCs developed in ERIGrid 2.0 project (see Deliverable 5.2 (Raussi et al., 2021) and corresponding OA/OS repository[2]) include among others:

- TC01: Control of Voltage with an On-Load Tap Change Controller,
- TC10: Evaluation of Secure Transition from Grid-connected to Islanded Operation for Uninterruptible Power Supply,
- CIGRE Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources (Strunz et al., 2014), and
- "The Evolution of Research in Microgrids Control" (Vasilakis, Zafeiratou, Lagos, & Hatziargyriou, 2020).

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

3.2 System Description

The development of the benchmark model was initiated to define the key elements and features that should be included in the model. The key aspects considered in the modelling development are:

- Sufficient number of buses and lines to ensure an adequate complexity of the network.
- Inclusion of circuit breakers at relevant points of the network, to test different kinds of disconnections but also to consider, through proper switching, different network topologies (both radial and meshed).
- Representation of inverters as controllable voltage sources and inclusion of the associated control schemes, to better evaluate their behaviour in a wide range of different scenarios.
- Inclusion of a microgrid, in order to assess its role and impact within the larger LV network and its ability to operate in islanded mode.
- Modelling of at least two different DERs (generation units, Photovoltaics (PVs), batteries) to test their behaviour and interactions with synchronous generation.
- Inclusion of a distribution MV/LV transformer equipped with OLTC transformer, to test its behaviour under different system conditions.

To accommodate all these points and to enable simulations over different time horizons, two distinct versions of the benchmark model have been developed. The first version, named "Basic Version", includes all network components that are relevant for dynamic simulations over short time intervals; a synchronous generator, a synchronous motor, a grid-following inverter, Resistive Load (RL) loads, an MV/LV transformer with OLTC, LV lines, a microgrid with a grid-forming inverter and a simple resistive load, and the MV grid equivalent voltage source. This is shown in Figure 1 and is meant to be used for dynamic simulations with a time horizon of a few seconds.

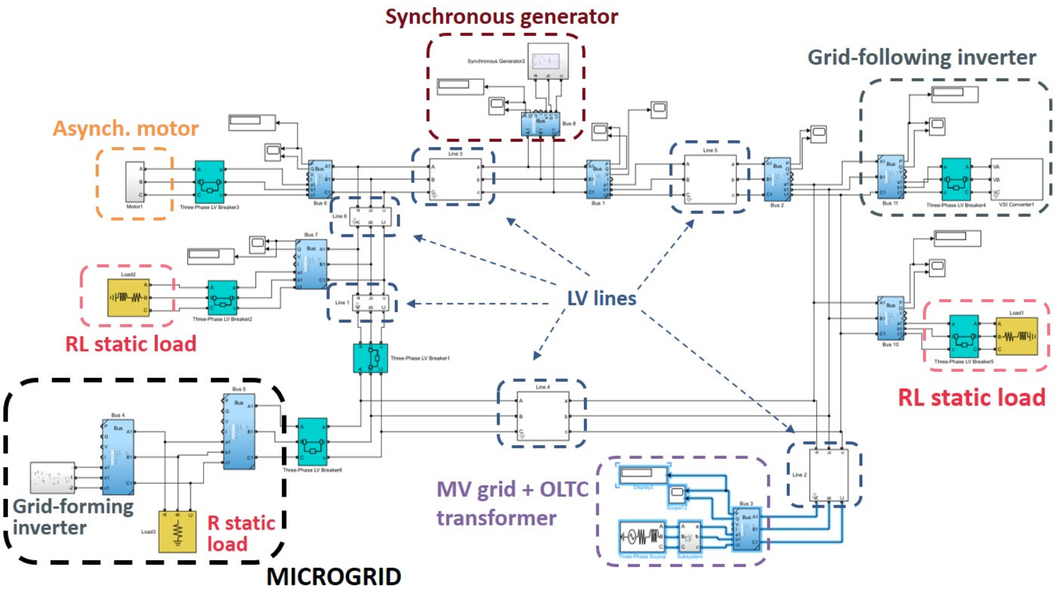

Figure 1: Simulink diagram of the "Electric Network" benchmark model (basic version).

The second version is the “Phasor Version” by removing the inverter models and adding an energy storage unit, a PV farm and a model of residential loads. This model is shown in Figure 2 for simulating with a phasor method and running “energetic” scenarios on longer time scales, e.g., one day, accounting for the time-varying generation/load profiles of the DERs and of the residential loads.

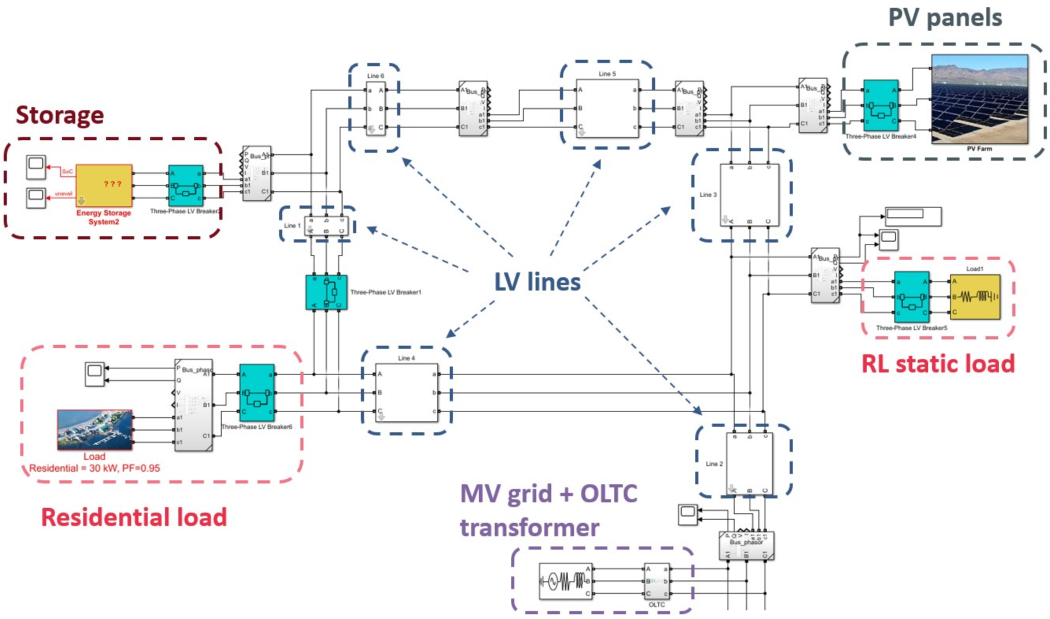

Figure 2: Simulink diagram of the “Electric Network” benchmark model (phasor version).

3.3 Example of Use

3.3.1 Variant 1

The TC10 “Evaluation of Secure Transition from Grid-connected to Islanded Operation for Uninterruptible Power Supply” (Raussi et al., 2021) is selected for one of the examples of use for this benchmark.

Original Test Case Description

The considered TC10 analyses the transition of a microgrid from grid-connected to islanded operation state when critical frequency conditions arise in the connected LV grid. TC10 originally envisages three different steps, focusing respectively on the capability of the protective equipment to detect disturbances in the upstream distribution grid, the ability of the protection subsystem to detect voltage disturbances, and the response of the microgrid inverters after the disconnection of the microgrid. These elements are considered under five distinct scenarios which consist of three cases of critical frequency conditions (frequency reaching the 50.5 Hz and 49.5 Hz thresholds or Rate of Change of Frequency (RoCoF) of 1 Hz/s) and two cases of critical voltage conditions (voltage of the LV grid reaching the upper and lower limits of +15% and -20%, respectively). In all the envisaged scenarios, the frequency at the Point of Common Coupling (PCC) and the voltage at different points of the microgrid are the key quantities that are monitored to assess and evaluate the transition of the microgrid to islanded operation.

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Test and Model Adaptation

Some adjustments and modifications have been introduced to conduct a meaningful and accurate simulation of the TC over the developed benchmark network. In particular, the testing focused on the behaviour of the grid-forming inverter in the microgrid during the transition to islanded mode, neglecting the analyses on the protection equipment (not modelled in the benchmark grid). The study has been performed for two critical frequency conditions, with the MV grid frequency reaching the upper value of 50.5 Hz (Scenario A) and the lower value of 49.5 Hz (Scenario B).

To achieve in simulation the critical frequency conditions envisioned for the test, the MV source and the OLTC transformer of the original benchmark model have been replaced by a programmable LV source that allows to flexibly adjust the voltage frequency. Since the protection equipment is not included in the network model, the disconnection of the microgrid has been obtained by opening the three-phase breaker connecting the microgrid with the rest of the system at the specific time instant in which the network frequency violates the threshold admissible value. This time is known a priori since it is determined by the frequency profile of the voltage source in the LV network, which is set in advance of the simulation.

Finally, given the absence of an ad-hoc frequency measurement block in the Simulink environment chosen for the simulation, the frequency of the microgrid and the MV network in the simulation have been estimated ex-post. The frequency values have been determined as the inverse of the time interval between two negative-to-positive zero crossings of the voltage signal. A moving average low-pass filter has been applied to smooth out oscillations.

Simulation Results

For compactness, only the results of Scenario A are reported, since the outcomes of the Scenario B simulation are qualitatively similar. For Scenario A, the relevant simulation events to consider are the following:

- $Time = 0.2\ s$: connection of the synchronous generator in the LV grid.
- $Time = 1.0\ s$: the LV grid frequency starts ramping up at a rate of 0.5 Hz/s.
- $Time = 2.0\ s$: as the frequency reaches the maximum threshold of 50.5 Hz, the microgrid is disconnected and begins to operate in islanded mode.
- $Time = 5.0\ s$: end of simulation.

The frequency estimation for the LV network (measured at the transformer bus) and for the microgrid (measured at the grid-forming inverter) are shown in Figure 3.

After the initial oscillations between 0.2 and 0.8 s (due to the connection of the synchronous generator), the frequency values at the two measurement points remain equal until the microgrid disconnection occurs at 2.0 s. The grid-forming inverter of the microgrid is able to restore the frequency in less than one second (after some oscillations and an undershoot at about 2.4 s), the microgrid frequency quickly reaches its nominal value and does not exhibit further variations.

The power exchanged by the grid-former inverter in the microgrid during the simulation has also been analysed and is shown in Figure 4.

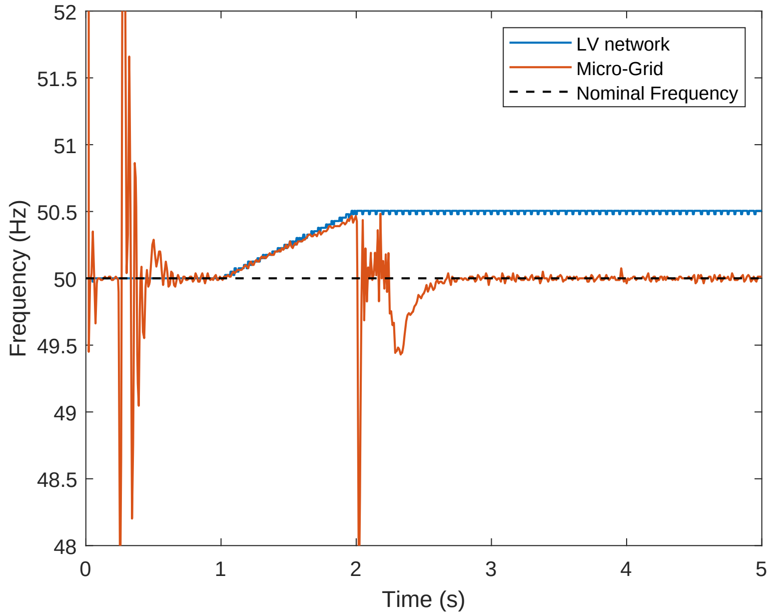

Figure 3: Frequency profile in the LV network (blue) and estimated frequency in the microgrid (red).

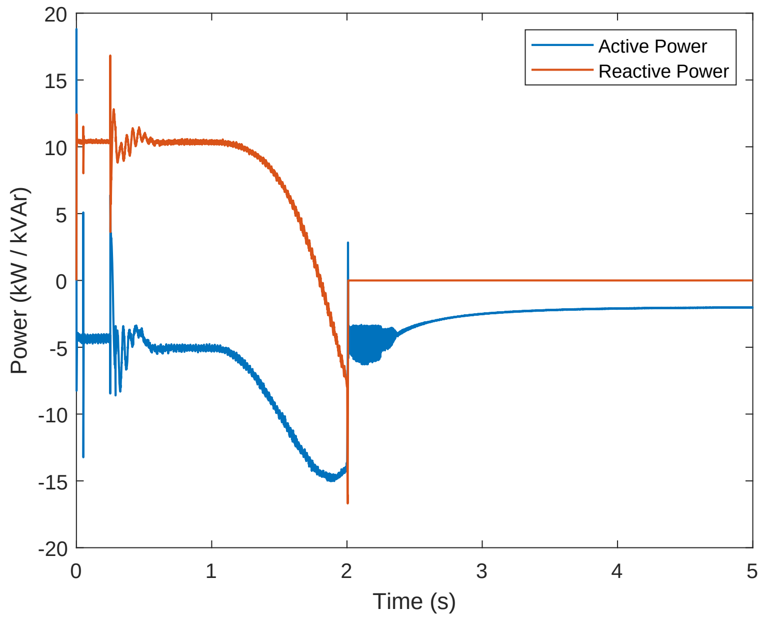

Figure 4: Active and reactive power exchanged by the microgrid inverter.

When connected to the grid, the microgrid inverter injects about 5 kW of active power (indicated by convention with a negative sign) and absorbs around 10 kVAr of reactive power. As the frequency increases (starting from 1.0 s), the direction of the reactive power exchange is gradually reverted and more active power is injected into the grid (up to 15 kW). At the time of disconnection (2.0 s), no reactive power is exchanged. As the microgrid begins to operate in islanded mode, the controller of the grid-forming inverter ensures that the injected active power (after some brief oscillations between 2.0 and 2.3 s) corresponds to the quantity requested by the resistive load of the microgrid.

3.3.2 Variant 2

The TC01 "Control of Voltage with an On-Load Tap Change Controller" (Raussi et al., 2021) is also illustrated as an example of use for this benchmark.

Original Test Case Description

The considered TC assesses the capability by an OLTC transformer to regulate the voltage of a distribution network within an acceptable working interval. The test accounts for the impact of the components connected on the LV side of the grid and of external parameters such as weather disturbances. Based on the considered control strategy, it is envisaged that the voltage measurements could be performed locally or remotely, accounting also for the possibility of utilising end-user (i.e., smart meter) measurements. In addition to the voltage regulation activity of the OLTC transformer, the TC can also evaluate the ICT communications with the Remote Terminal Units (RTUs) and the associated automated switch gear. This benchmark does not, however, investigate the impact of the ICT.

Test and Model Adaptation

To conduct the TC over the developed phasor model of the benchmark network, some adjustments and modifications have been implemented. In particular, the simulations have focused on the performance of the OLTC controller, neglecting the communication layer and the automated switchgear elements, which are not represented in the benchmark model. The disconnection of lines or network components, introduced in the simulation to assess the resulting behaviour of the OLTC, is not triggered by critical system/component conditions but is instead performed deterministically at specific simulation times that are defined as ex-ante.

Simulation Results

The operation of the OLTC and its voltage regulation performance have been evaluated in the simulation over a 24 h interval. The relevant simulation events to consider are the following:

- $Time \in [0, 2]$ h: the battery energy storage device performs a constant 15 kW charge, bringing its State of Charge (SoC) from 0.5 to 0.9.
- $Time = 10$ h: fault on the line connecting the residential load and the storage device (see Figure 2 for reference), which is cleared after 15 minutes.
- $Time = 20$ h: disconnection of the RL static load from the grid, with no reconnection within the considered simulation time interval.
- $Time = 24$ h: end of simulation.

Within the described simulation setup, the operation of the OLTC transformer (represented by the tap position over time) and the resulting voltage values (measured at the primary and secondary side of the transformer) are represented in Figure 5.

To emphasise the activity of the transformer, a low value has been set for the voltage-step-per-tap and for the deadband considered in the voltage regulation (both equal to 0.00375 p.u.). In general, it can be seen that the transformer is able to maintain the LV voltage within the specified deadband (centred around the 1 p.u. nominal value) throughout the whole considered time interval. For example, the gradual voltage reduction on the LV side between $t = 5$ h and

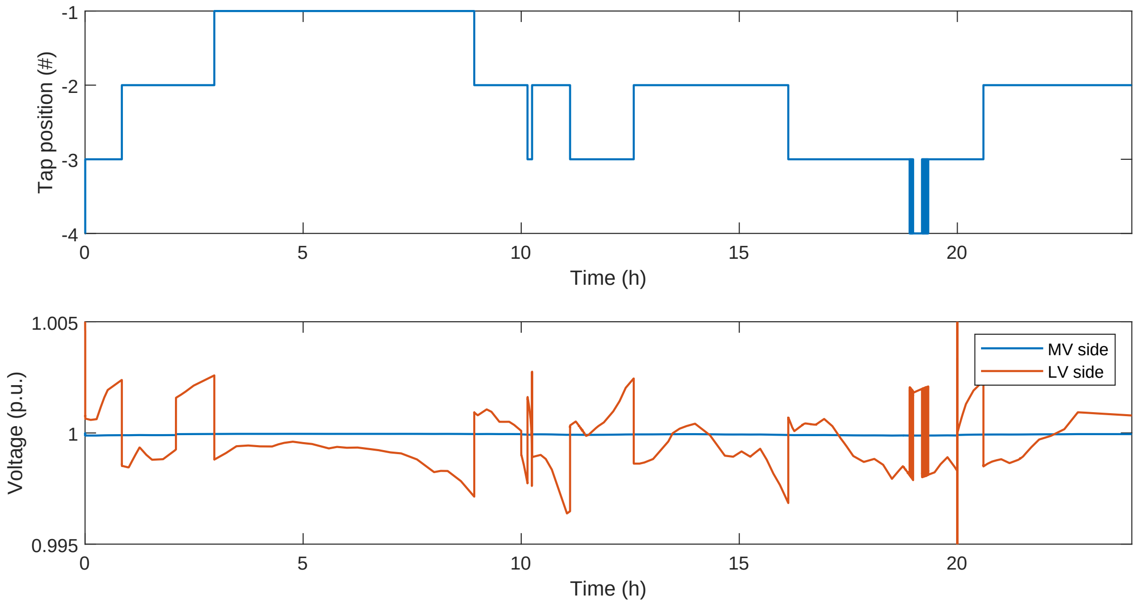

Figure 5: Tap position (top) and voltage on primary/secondary side (bottom) of the OLTC transformer.

$t = 8\ h$ is interrupted by the transformer tap switching from position -1 to position -2, thus avoiding a violation by the LV voltage of the imposed regulation boundaries. A similar action is performed in the opposite sense at around $t = 21\ h$, when the tap position switches from -3 to -2 following the voltage increase in the previous hour. It can also be seen how the OLTC is able to react to network events such as the line tripping at $t = 10\ h$; the tap position switches from -2 to -3 right after the event and then returns to its original value once the fault is cleared, after 15 minutes.

In terms of transformer currents, displayed for a single phase on the LV side in Figure 6, it can be seen that the impact of the tap switching is negligible (given the chosen low value of voltage-step-per-tap) and the current evolution over time is mostly dictated by the network dynamics and events. In this regard, the significant current drop at $t = 2$h, in correspondence of the storage terminating its charging process.

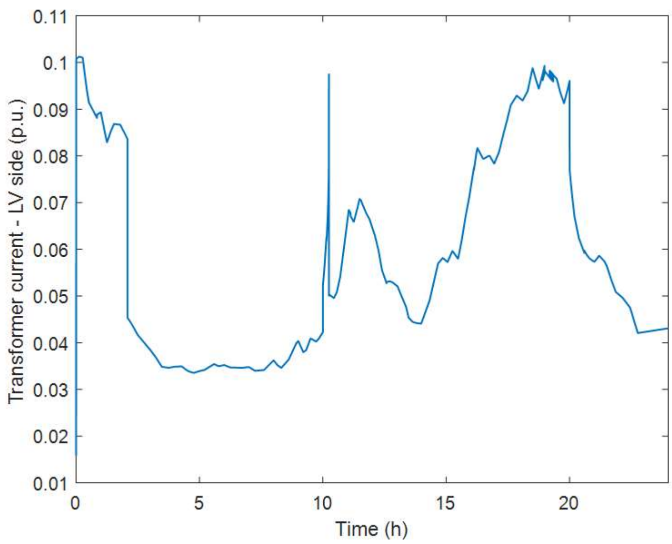

Figure 6: Current profile on the secondary side of the OLTC transformer.

3.4 Limitations and Recommendations

The developed benchmark model can perform a wide range of dynamic simulations over different time scales, with straightforward and simple modifications via Simulink. However, it should be noted that there are some limitations that should be taken into account for the experiment.

In terms of the individual components of the basic model, the current implementation considers the dynamics of the asynchronous motor to be decoupled from the grid and only the relevant energy exchanges are considered. Moreover, the modelling of the lines envisages conductors of limited length and therefore only includes resistive and reactive terms (assuming a negligible capacitance). It should also be mentioned that, in its current implementation, a power/speed regulator has not been included for the synchronous generator, which operates with a constant mechanical power reference. In general, the overall model appears to be stable over a wide range of parameter values and operating conditions. The only instability cases have been experienced when the length of the lines has been increased substantially and when additional inverters have been included in the islanded operation of the microgrid, suggesting the necessity to include ad-hoc control mechanisms to properly simulate this kind of scenario. Finally, it should also be emphasised that the relevant complexity of some blocks in the basic version of the model (in particular for the inverter and the associated control schemes) leads to significant simulation time which accounts for approximately 40 minutes of runtime simulation for 5 seconds using a standard personal computer.

For the phasor model, given its scope and the objective of fast simulations over long time horizons, simplified representations have been adopted for most of the considered network components. In particular, the PV farm, the storage device, and the residential load are all modelled by combining a power regulation logic that accounts for the different characteristics of the components and the use of controlled Alternating Current (AC) current sources which inject currents based on the prescribed load/generation profile. This implies that, differently from the basic model, the power electronics dynamics of some components (e.g., inverters) are not considered. In general terms, it should be emphasised that the phasor model has appeared quite robust and stability has been obtained in simulation over a wide range of parameters and operating conditions. Only in some cases, right after steep operational variations of the components (e.g. the ending of the charging process by the storage device or line faults), the calculated electrical quantities might not be extremely accurate, but this is believed to be consistent with the chosen phasor simulation model.

3.5 Summary and Future Work

The benchmark with two developed models for LV electrical networks and microgrids allow interested users to simulate in a quick and efficient manner a wide range of different scenarios and system conditions. To facilitate the usages, adaptation and expansion of the developed simulation framework, a thorough description of the models has been provided according to the PreCISE. The system configurations for the basic and phasor models are available online (DePaola, 2021), providing a hierarchical representation of the different model components and high-level information on their functionality, characteristics and mutual interconnections. To facilitate tuning and refinements of the benchmark model, a more detailed description of each network element has been provided separately, with additional information on the adopted mathematical models and on the procedures to validate and test the components.

The current version of the benchmark models can be further expanded and enhanced. For example, to facilitate a high-level user experience that avoids unnecessary complexity, the use of Simulink masks could be strengthened and extended to all components, allowing to modify their relevant parameters and operative flags with a few clicks. Moreover, greater modularity could be introduced in the model, including additional elements (e.g., heat pumps, detailed models of the renewable generators powering the network inverters) and providing the possibility of selecting different modelling blocks of varying complexity for the same component, so that the user can achieve the desired trade-off between accuracy and simulation time.

4 Benchmark 2 – Multi-Energy Networks

This section covers the description of the “Multi-Energy Networks” benchmark of ERIGrid 2.0. In the following, a brief overview, the used system description, an example of use, the limitations and recommendations, and an outlook about the future work of the benchmark is provided.

4.1 Overview

This benchmark describes a reference setup for a multi-energy sector coupling application, where a power-to-heat facility provides a coupling point between a low-voltage distribution network and a local branch of a heating network. By consuming local excess PV generation, the power-to-heat facility can be used at the same time to improve the stability of the electrical network and support the supply of the thermal network.

The primary purpose of this benchmark is the promotion of Research and Development (R&D) of sector coupling applications for thermal-electrical systems, by providing a simple as possible yet interesting reference setup. It also intends to inspire the use of co-simulation for simulating these types of technical systems, comprising several domains (power, heat, control) that are typically covered by different domain-specific simulation tools. Therefore, the benchmark has been modelled with the help of two different approaches, illustrating potential implementation alternatives for adopters. However, this benchmark is not intended to serve as a classical simulation benchmark (compared, for instance with IEEE test feeders), which typically aim at providing a numerical reference for comparing and validating simulation tools.

This multi-energy networks benchmark follows in the track of the third FS focusing on sector coupling (Raussi et al., 2020), which is motivated by the anticipated massive roll-out of power-to-X components in the near future. Within this context, this benchmark primarily addresses the UC “Regulating power provisions by power-to-X units”, which aims at the characterisation of power-to-X service availability and its impact on the electrical domain on the system level. As such, this benchmark is also associated to the following TCs[2] (see also Deliverable D5.2 (Raussi et al., 2021)):

- TC11: Characterisation of power-to-heat service availability and its impact on the networks, and
- TC12: Verification of improved self-consumption of RES in a coupled heat and power network using power-to-heat.

4.2 System Description

The system used for this benchmark resembles a sub-urban area with a relatively large amount of PV installations. The chosen scenario implements a Local Energy Community (LEC), with the goal to use excess PV generation locally for operating a power-to-heat facility. The system configuration comprises the following sub-systems and components:

- *Electrical LV distribution network:* Two consecutive lines (0.3 km each), connected to an external power grid,
- *Thermal network:* Three consecutive main pipes (0.5 km each), connected to an external district heating grid,

- *Consumption:* Two consumers, each representing the aggregated loads (electrical and thermal) of a residential neighbourhood and connected to both networks, and
- *Generation:* Two PV systems (one of 150 $kW_{el,peak}$ and one of 50 $kW_{el,peak}$)
- *Power-to-heat facility:* heat pump (max. 100 kW_{el}) connected to a thermal tank (100 m^3) feeding into the thermal network.

Figure 7 gives an overview of the overall system configuration. Figures 8 and 9 give a more detailed view of the components of the electrical and the thermal sub-systems, respectively.

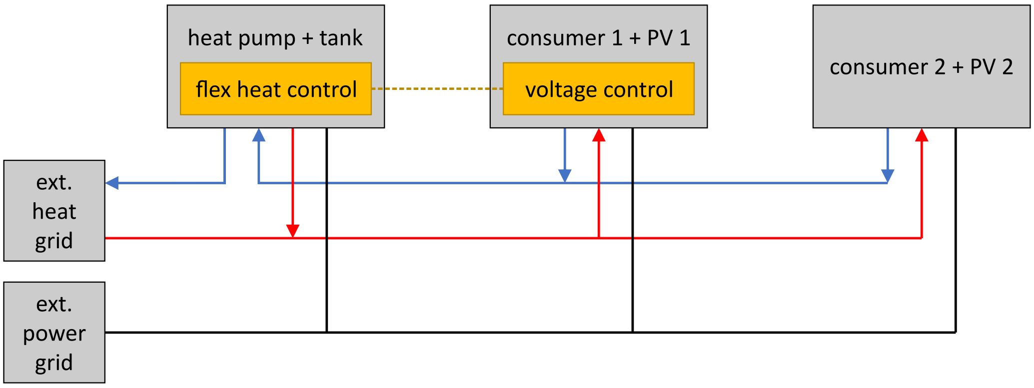

Figure 7: Overview of the overall system configuration used in the "Multi-Energy Networks" benchmark model.

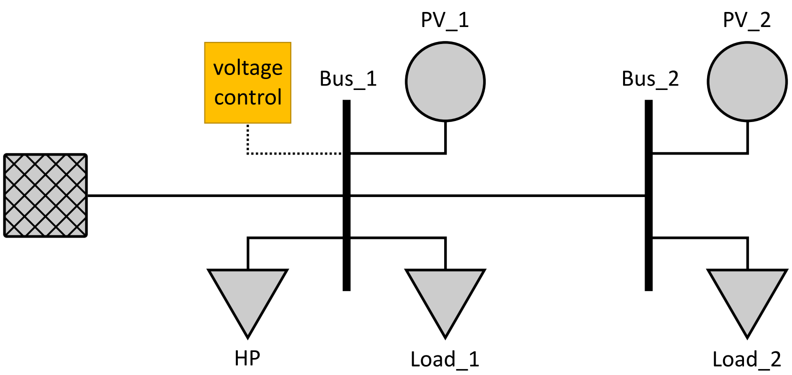

Figure 8: Detailed view of the components of the electrical sub-system used in the "Multi-Energy Networks" benchmark model.

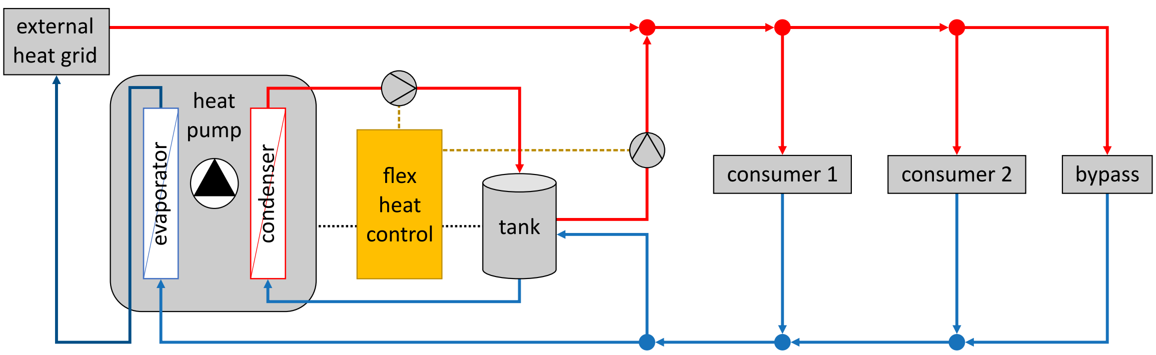

Figure 9: Detailed view of the components of the thermal sub-system used in the "Multi-Energy Networks" benchmark model.

The TC for this benchmark addresses issues related to self-consumption in a LEC. In order for a LEC to be autonomous, the PV system has to be sized accordingly. However, a mismatch between energy demand and energy supply from the PV systems can lead to a significant voltage rise in parts of the power grid. Therefore, synchronisation of consumption with generation is necessary in order to ensure power quality and avoid disruptions due to overvoltage limit violations.

To this end, a simple voltage control scheme is applied. The voltage at *Bus_1* is monitored and the power consumption setpoint of the heat pump is adjusted (i.e., controllable/flexible load) to keep the voltage within acceptable limits. The corresponding voltage control algorithm is shown in Figure 10.

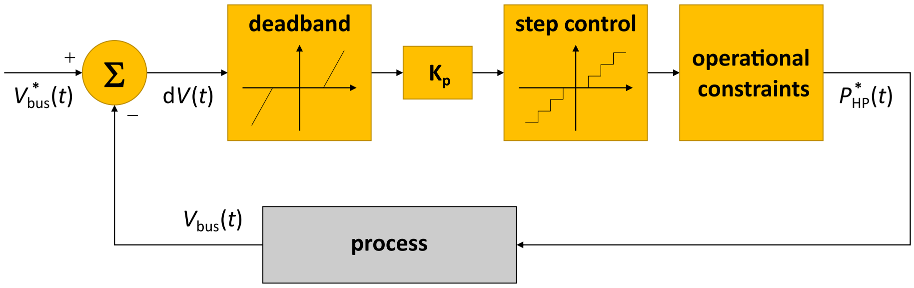

Figure 10: Schematic view of the voltage control algorithm applied in the "Multi-Energy Networks" benchmark model.

The thermal sub-system uses a dedicated controller scheme – referred to as flex heat control – to operate the heating network and the power-to-heat facility. This controller decides whether the heat supply is covered entirely through the external grid or whether the power-to-heat facility supports by discharging the tank. If required, the heat pump is used to charge the tank, always respecting the power consumption threshold of the voltage controller (i.e., the power consumption never exceeds the setpoint, but may be less). Based on the measurement of the storage tank temperature and the power consumption threshold for the heat pump, the flex heat controller can switch between several modes of operation. The switching between these modes follows a simple set of rules, represented by a state machine, where each state corresponds to a specific operational mode. Figure 11 shows a graphical representation of the flex heat controller's state machine.

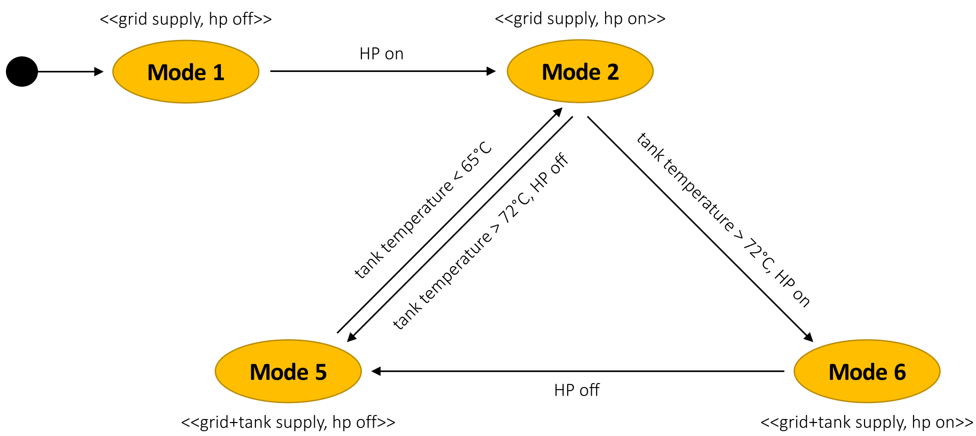

Figure 11: Schematic view of the flex heat control algorithm applied in the "Multi-Energy Networks" benchmark model.

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The system configuration and control schemes have been kept as simple as possible, in order to provide a benchmark that focuses on the application without unnecessarily increasing the complexity. Nevertheless, the thermal and electrical sub-systems show a strong coupling, where the effects of one sub-system influence the other and vice versa:

- The voltage control scheme determines the power consumption setpoint of the heat pump,
- The power consumption setpoint of the heat pump influences the charging rate of the tank,
- The thermal demand together with the charging/discharging rate of the tank determines the temperature of the tank,
- Discharging the tank affects the temperature of the return line and subsequently the efficiency of the heat pump (as the return line serves as the source for the heat pump),
- The temperature of the tank and the efficiency of the heat pump determine the actuation of the heat pump by the flex heat controller, and
- The actual power consumption of the heat pump (which can be less than the setpoint) directly affects the decisions of the voltage controller.

This circular dependency causes a feedback between both sub-systems whose dynamics can only be fully captured by assessing both sub-systems simultaneously. Hence, this seemingly simple setup serves as an excellent benchmark for multi-energy applications.

4.3 Example of Use

Due to the complex feedback between the thermal and the electrical sub-system, the voltage controller affects the operation of both systems. Hence, the example of use for this benchmark provides a joint assessment of the full multi-energy system for a complete characterisation of the effects of the voltage controller. The following quantities are assessed simultaneously:

- Reduction of voltage band violations,
- Reduction of line overloading, and
- Change in heat generation of heat pump.

Figure 12 and Figure 13 show histograms of voltage measurements at *Bus_1* and line loadings of *Line_1*, respectively. These histograms show both the results for the case with (blue) and without (orange) voltage control enabled. In the case without voltage control, the heat pump is operated with its maximum power consumption (100 kW_{el}) when turned on by the flex heat controller. As can be clearly seen, the simple voltage control algorithm is mostly successful in restricting the observed voltages at *Bus_1* to the desired voltage band (1 ± 0.1 p.u.). At the same time, also the overloadings of *Line_1* can be avoided.

Figure 14 shows the corresponding power consumption setpoint for the heat pump as determined by the voltage controller. The resulting effect on the thermal subsystem is shown in Figure 15, which depicts the evolution of the average tank temperature with (blue) and without (orange) voltage control enabled. Without voltage control, whenever the tank temperature reaches the lower threshold, the flex heat controller stops discharging the tank to the supply

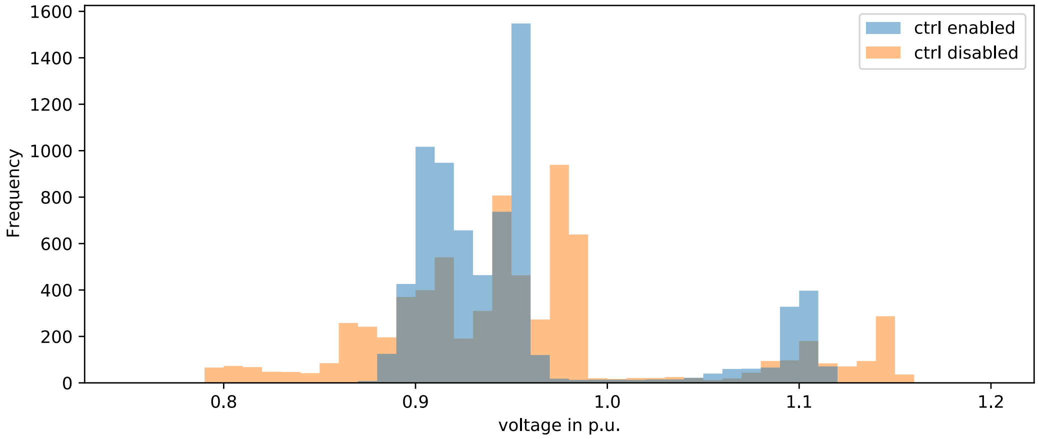

Figure 12: Histogram of observed voltages at "Bus_1" with (blue) and without (orange) voltage control enabled.

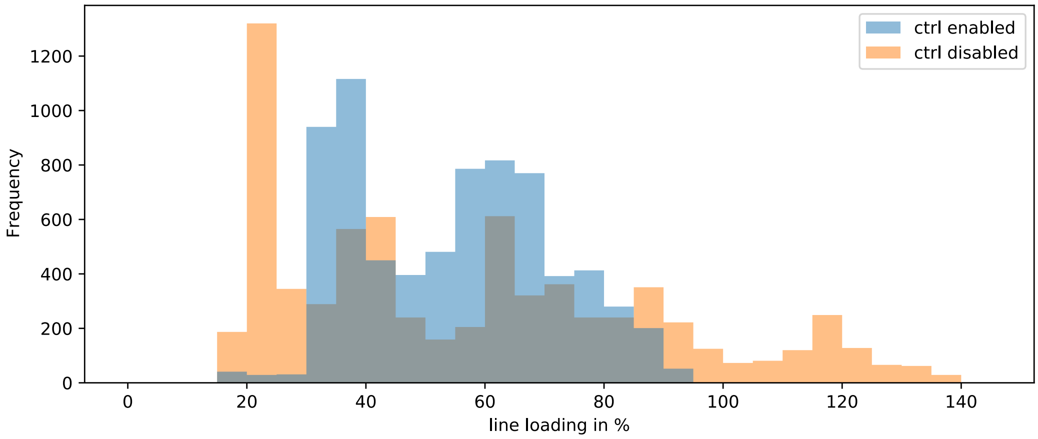

Figure 13: Histogram of line loadings at "Line_1" with (blue) and without (orange) voltage control enabled.

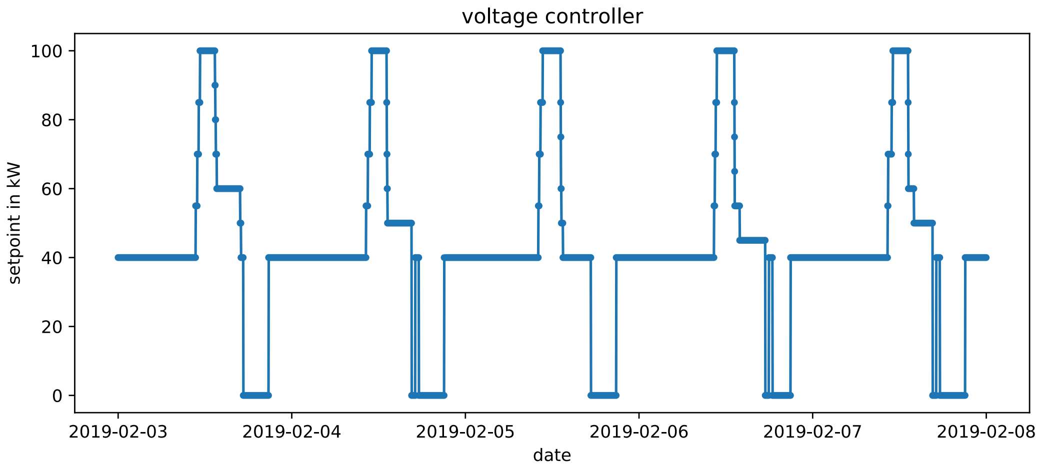

Figure 14: Power consumption setpoint for the heat pump as determined by the voltage controller.

line and turns on the heat pump (corresponding to Mode 2 in Figure 11). Once the tank temperature reaches the upper threshold, the flex heat controller resumes discharging the tank to the supply line and turns off the heat pump (corresponding to Mode 5 in Figure 11). However,

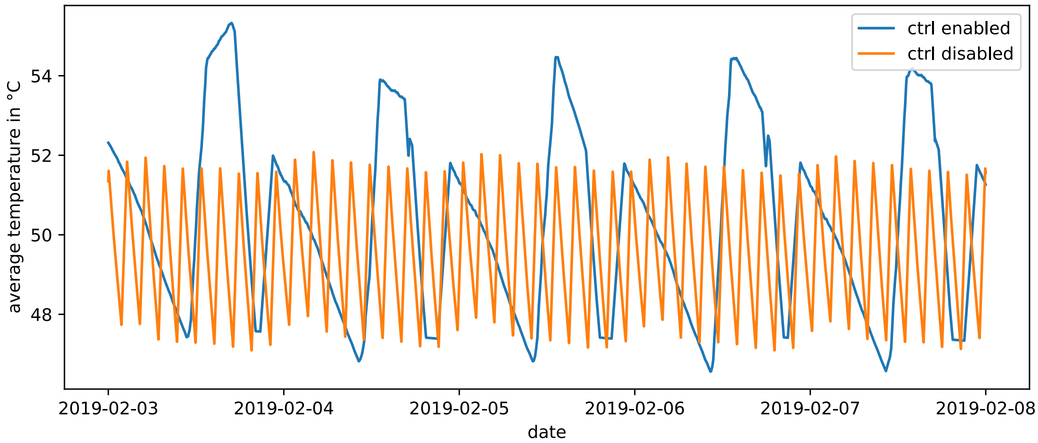

Figure 15: Evolution of the average tank temperature with (blue) and without (orange) voltage control enabled.

with voltage control enabled, the actuation pattern of the tank and the heat pump gets more complex (corresponding to the additional Mode 6 in Figure 11). This results in an operational mode where the tank is discharged to the supply line and heated up by the heat pump at the same time, with the heat pump operating in part load.

4.4 Limitations and Recommendations

The need for assessing the thermal and electrical sub-systems jointly is a challenge for modelling tools. However, energy-related simulation tools traditionally focus on just one specific engineering domain, such as power grids, heating networks, or buildings. From a historical perspective, this approach is quite natural, given that these tools are typically either the result of long-term academic research efforts of specific fields of engineering or have been developed by industry with a specific aim and audience in mind. Unfortunately, even though these tools have been very successful in delivering valuable insights in the past, they are as such not suited for analysing multi-energy systems.

To overcome the challenges of modelling and simulating multi-energy systems, a lot of research and development has been carried out in recent years. In the context of technical assessments, which target primarily issues related to the operation and closed-loop control of such systems, multi-domain modelling languages (Modelica, MATLAB/Simulink, etc.) and co-simulation approaches (mosaik, etc.) have gained a lot of popularity.

In fact, both approaches have been successful in showing their potential regarding the assessment of multi-energy systems. However, most simulation experts have no or very little experience with these approaches. For this reason, two different implementations of this benchmark have been publicly published alongside the benchmark specification, which aim at promoting these approaches and encourage researchers and engineers to adopt them.

Both implementations use pandapower (Thurner et al., 2018) for simulating the electrical domain and Python for implementing the controllers. However, they apply different tools for the thermal domain, to showcase alternative approaches:

- One implementation uses the Modelica DisHeatLib library[3] for simulating the thermal domain. Figure 16 shows the graphical representation of the thermal system model,

[3] https://github.com/AIT-IES/DisHeatLib/

depicting how the district heating network and the power-to-heat facility are built up from individual component models (pipes, junctions, pumps, tanks, etc.). This demonstrates how Modelica's multi-physics modelling approach can be applied in a very intuitive way to represent the thermal system. The resulting model also allows to capture the thermo-hydraulic dynamics of all the components in high detail. Unfortunately, the model currently requires the proprietary Dymola tool[4] to compile. Even though the compiled model can be shared (as a Functional Mock-up Unit (FMU)) and executed without a Dymola license, this represents a potential obstacle for users to adopt this approach.

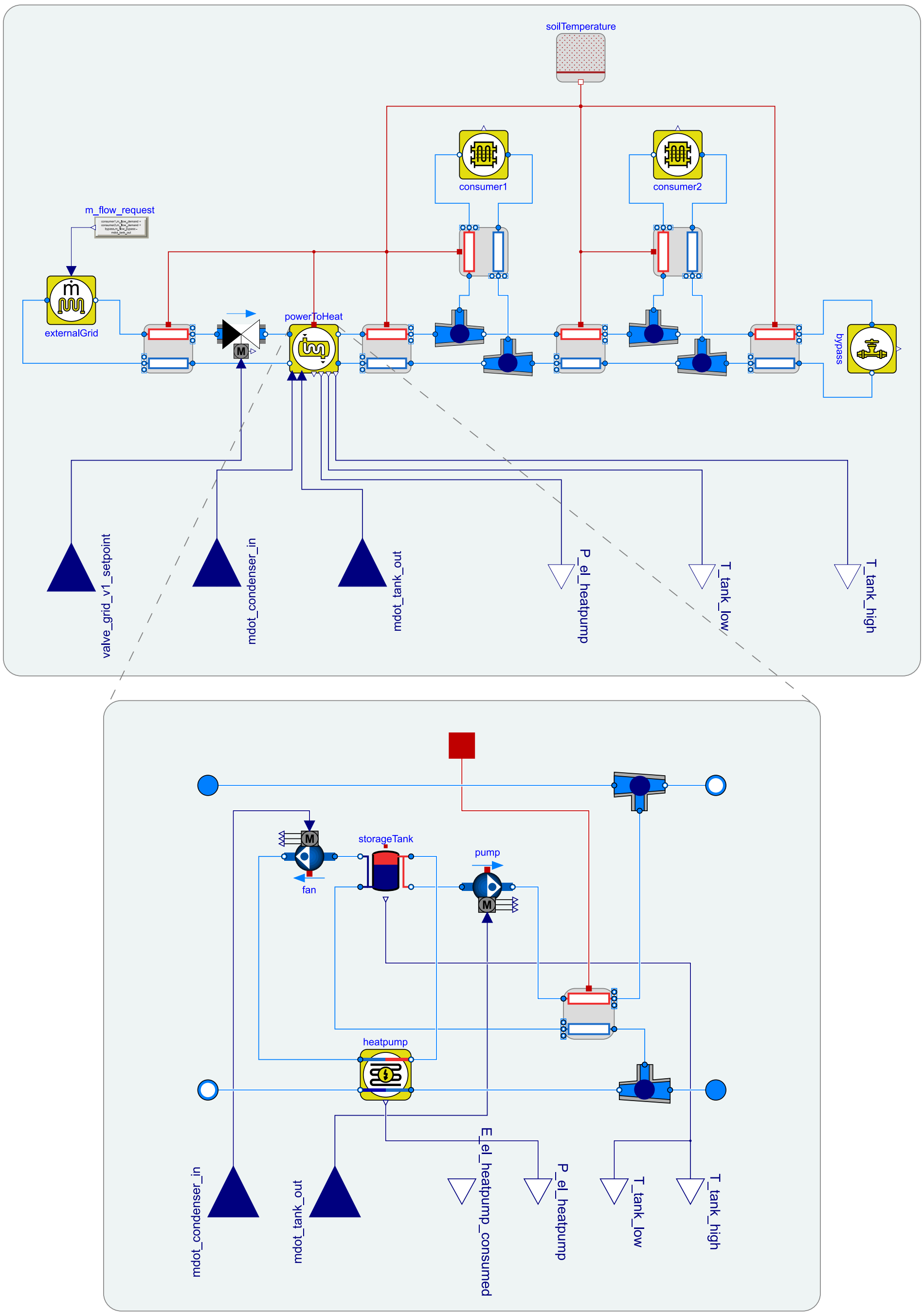

Figure 16: View of the thermal system implemented with the help of the Modelica library DisHeatLib.

[4] https://www.3ds.com/products-services/catia/products/dymola/

- Another implementation uses the Python package pandapipes (Lohmeier, Cronbach, Drauz, Braun, & Kneiske, 2020) for simulating the thermal domain. It depends solely on open source tools and libraries, making it easy for users with little background in modelling thermal systems to adopt this approach. However, rigorous testing of the implementation has revealed that the current release of pandapipes (version 2.6.0) has problems with solving some of the thermo-hydraulic equations for this system configuration. Even though the tool succeeds in computing the heat flow in the system, the computation of the pressure distribution fails in the case of more than one source (i.e., when both the external thermal grid and the storage tank feed into the network's supply line).

4.5 Summary and Future Work

This multi-energy networks' benchmark has been implemented in two different co-simulation setups based on the mosaik co-simulation framework[5].

The limiting factors of both implementations are expected to be solved by future developments of the corresponding software packages.

The reference implementations of this benchmark are available online (Widl, 2021). In addition, it is planned to make them available as executable simulation setups via the ERIGrid 2.0 project virtual access facilities[6]. Furthermore, this benchmark is also intended for further use for education and training activities within ERIGrid 2.0 and interested external users.

[5] http://mosaik.offis.de/
[6] https://smartest-sim-lab.erigrid2.eu/

5 Benchmark 3 – ICT-Enhanced Power System

This section covers the description of the "ICT-Enhanced Power System" benchmark of ERIGrid 2.0. In the following, a brief overview, the used system description, an example of use, the limitations and recommendations, and an outlook about the future work of the benchmark is provided.

5.1 Overview

The development of digitalised power systems has driven mutual interdependency between ICT and electrical power infrastructures. For example, the Wide Area Monitoring, Protection, and Control (WAMPAC) system located at substations provides state estimation, fault location, novel autonomous control functions, and protection algorithms including self-healing services to maintain a reliable and secure power system operations. As the smart grid requires bidirectional communications for real-time monitoring and control, this benchmark serves as a reference for a Cyber-Physical Power System (CPPS) setup consisting of the power system with ICT based communication.

This section presents high-level information of this benchmark focusing on ICT-enhanced power systems. This benchmark is aligned with the FS on digitalisation aspect presented in Deliverable 5.1 (Raussi et al., 2020) and accounts also for other FSs when ICT infrastructure or communications are an integral part of the system description. According to FS of digitalisation, three different aspects on defining a combination of power system and ICT infrastructure are considered which are

1. Automated grid operation and distributed coordination,
2. Substation automation, and protection, and
3. Cybersecurity.

This benchmark model can be applied to a wide range of TCs involving the three mentioned aspects of the digitalised power system. Examples of TCs[2] developed in ERIGrid 2.0 (see also Deliverable 5.2 (Raussi et al., 2021)) that can be strongly associated with this benchmark model are:

- TC21: Performance characterization of new equipment and communication technologies
- TC22: Resilience assessment of ICT infrastructure
- TC24: Interoperability testing
- TC25: Impact analysis in terms of cybersecurity

The focus of this benchmark targets on assessing the performance of communication systems like the delay of information transmission or the package loss that would affect the control commands and measurements of a power system. It should be noted that the algorithm for verification and validation is not covered within this benchmark. Two models are applied in this benchmark and these are described below. To demonstrate the wider applicability, electrical transmission and distribution networks are considered and explained in the following section.

5.2 System Description

Two models have been applied for this benchmark: 1) IEEE 39-Bus New England test system representing the electrical transmission network, and 2) CIGRE MV Benchmark model consisting of 14 feeders representing the electrical distribution network. The IEEE 39-Bus model consists of 10 synchronous generators, 19 loads, 34 lines, and 12 transformers. Both reference models incorporate measurement and control variables that can be implemented in DIgSILENT PowerFactory[7] software. As a specific example of distribution networks, the CIGRE MV benchmark model (feeder 1) is used, as shown in Figure 17.

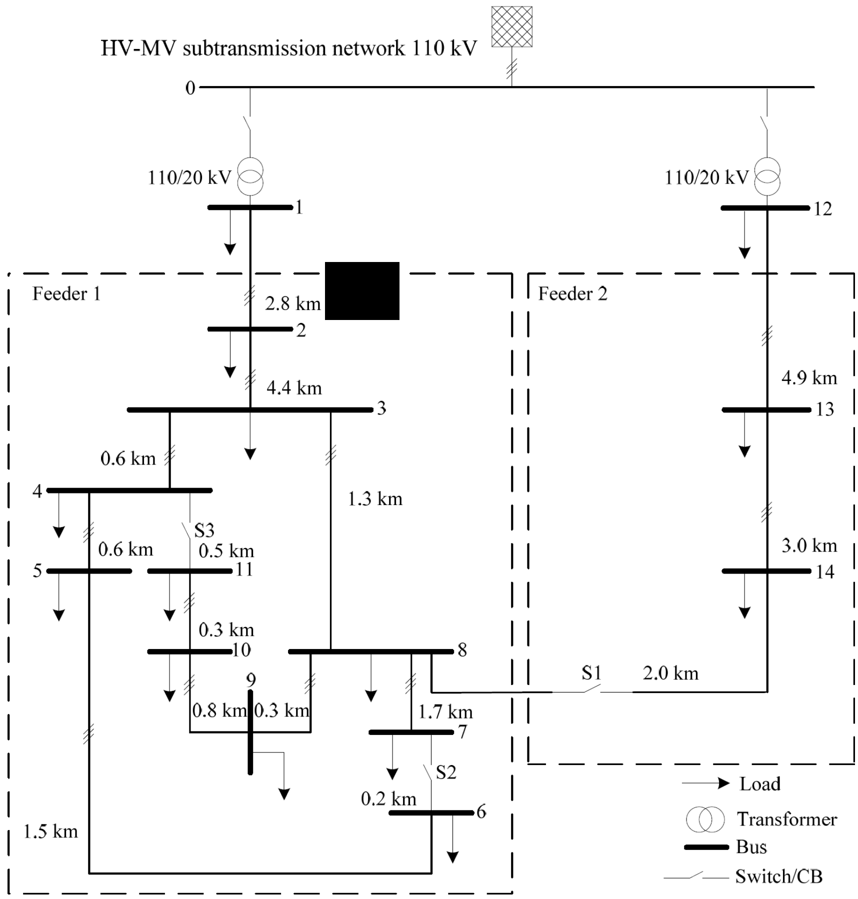

Figure 17: CIGRE medium voltage network used in the “ICT-Enchanced Power System” benchmark model.

For the co-simulation interface and data exchange between DIgSILENT PowerFactory software and the communication emulator, Mininet, the OPC Unified Architecture (OPC UA) interface is used which is a machine-to-machine communication protocol for industrial automation. The OPC UA method follows a client-server architecture wherein all the state and control variables are communicated to a central OPC UA server. Any OPC UA client connecting to the server can access and modify the variables, which is then reflected in all clients. For this benchmark, DIgSILENT PowerFactory represents one client and Mininet being the other. As previously mentioned, the focus of this benchmark is only to highlight and utilise such interfacing techniques between AC power systems and ICT which can then be further developed and refined in other activities within ERIGrid 2.0.

[7] https://www.digsilent.de/de/powerfactory.html

The communication infrastructure of this benchmark reference setup aims to enable information flow from several remote locations in the power system to a centralised location like for a Supervisory Control and Data Acquisition (SCADA) control room. Hence, the communication infrastructure mainly consists of simulated ICT components and the simulated flow of packets using Internet Protocol (IP) based on communication protocols. The emulated communication network model is shown in Figure 18. This topology architecture is based on a digital substation system, consisting of multiple hosts that represent field devices such as RTUs, data concentrators, Intelligent Electronic Device (IED), Ethernet switches, routers, etc. This network example consists of six nodes/hosts representing measurement devices, three switches, one gateway to the control centre, and one router. The power system measurement data is sent from Host 1 via network communication to the control centre which performs the voltage control algorithm. The calculated set-point is then communicated back to IED1 within the substation that controls the tap position of a transformer with an OLTC.

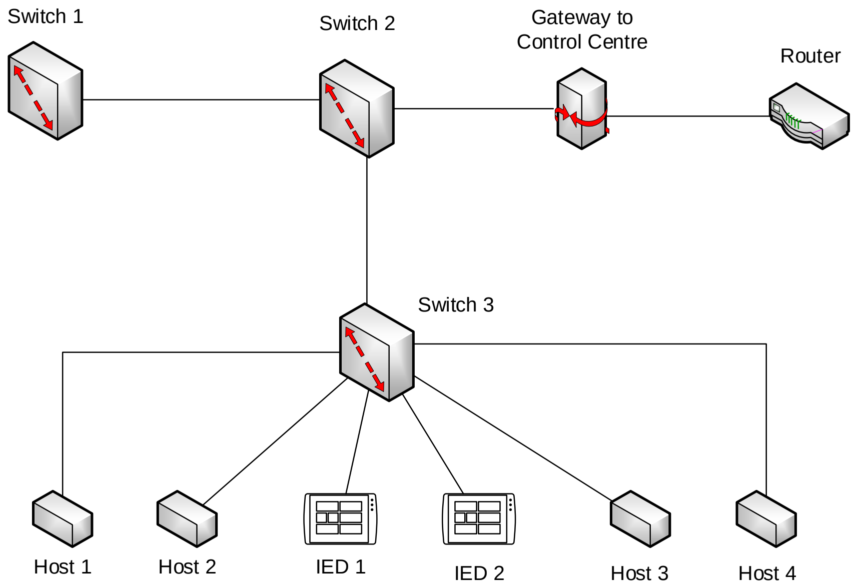

Figure 18: Modelled communication network in the "ICT-Enchanced Power System" benchmark model.

In this particular benchmark model, a Coordinated Voltage Control (CVC) service of a distribution network is deployed. This service allows a control centre to define the optimal operating point of the controllable elements in a distribution grid, (OLTC transformers, DERs, shunt capacitors, etc). It operates in a centralised manner like receiving voltage measurement information from the bus bars. Based on the input measurements, the voltage control algorithm performs multiple load flow calculations using different operational states for controlling elements and then storing the results. These results are compared to predefined value criteria and then define the outputs which result in the most optimal operating point for the electrical network. Example criteria could be compliance with reactive power limits of High Voltage (HV)/MV transformers or grid code regulations. The calculated outputs (i.e., control setpoints) are sent to the controllable elements in the power system through the communication infrastructure. The entire system architecture can be visualised in Figure 19.

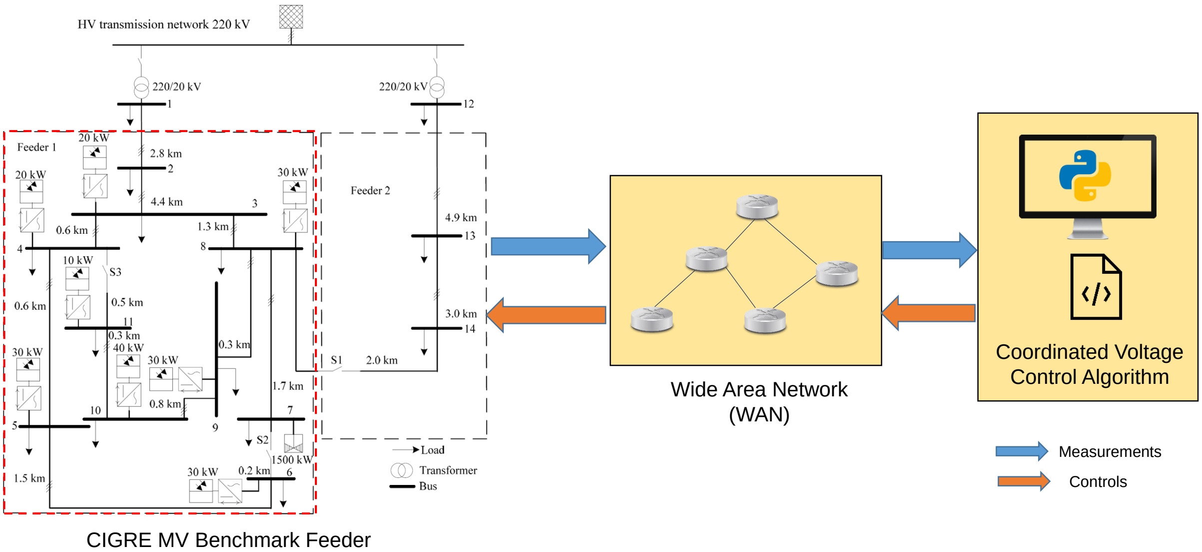

Figure 19: System architecture for the AC and ICT benchmark test system.

5.3 Example of Use

This section presents the results of an example scenario using the previously discussed benchmark model. Quasi-dynamic simulations were carried out to investigate the behaviour of the distribution grid and voltage control algorithm over a period. In this case, a time interval of an entire year with daily resolution (i.e., 365 days in total), is considered. A benchmark load profile, as presented by Sarajlić & Rehtanz (Sarajlić & Rehtanz, 2020) is applied for the loads in Feeder 1 (see also Figure 17). As a result, the variations of the voltage of Bus 01 range between 1.02 and 1.04 p.u as shown in Figure 20. It can be seen that there is a change of voltage level at the day 200^{th} due to the transformer tap position being reduced by one to maintain the voltage level within the limits, as previously described in Section 5.2.

As the communication network is emulated, it is possible to alter some of the network characteristics. Figure 21 depicts the cumulative density function plots for two latency cases of 0 ms and 100 ms between Host 1 and Switch 3 in the emulated network (see also Figure 18). As a result, even when the latency is set to a theoretical limit of zero, there is a 90% chance of the latency being 0.2 ms or higher. On the other hand, when the link latency is set to 100 ms affected by the Round Trip Time (RTT), the values are greater than 220 ms by average 90%. This network performance is undesirable to manage network congestion and equipment malfunctions which can greatly impact the communication between the substation and the control centre, leading to major consequences on the power system (e.g., blackout).

Figure 22 shows the impact of communication network latency that causes the voltage control performance. Assuming the ideal condition, the tap position of the transformer would change at 93 s simulation time. However, even with a small latency of 10 ms of the communication network between Host 1 and Switch 3, it affects the set point which is offset by nearly 30 s due to the added latencies of communication and algorithm calculation.

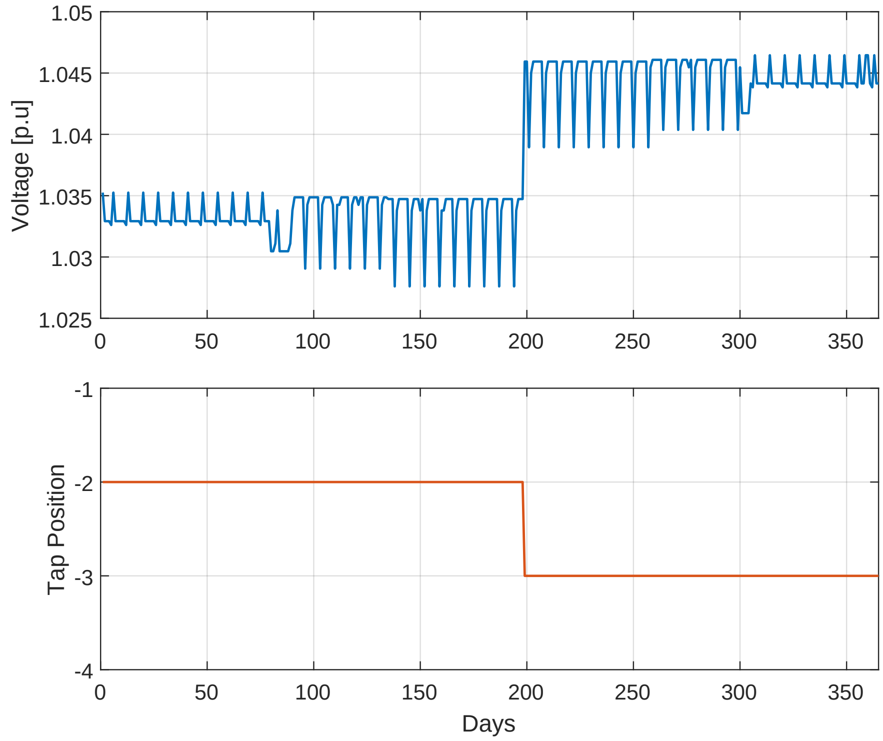

Figure 20: Operation of voltage control algorithm in the "ICT-Enchanced Power System" benchmark model.

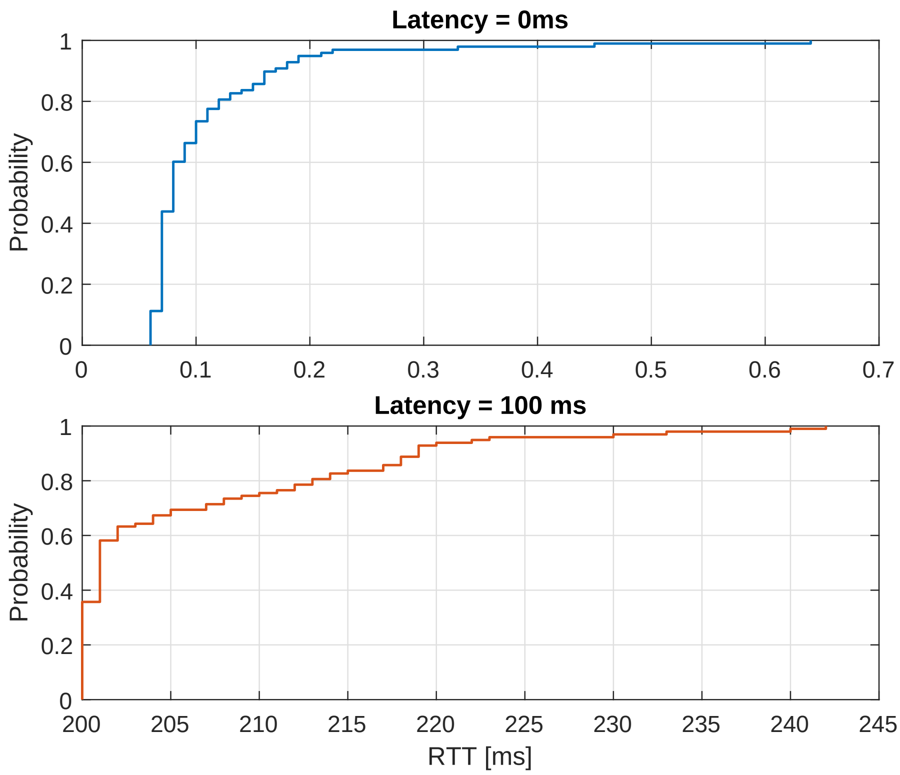

Figure 21: Effect of latency in emulated communication network in the "ICT-Enchanced Power System" benchmark model.

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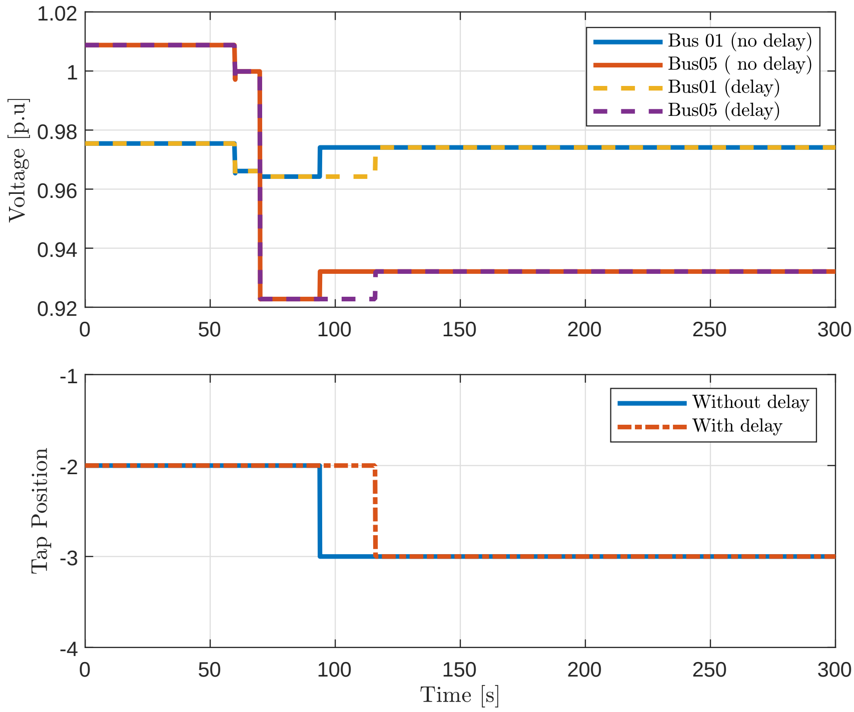

Figure 22: Impact of communication delays on performance of voltage control in Ithe "ICT-Enchanced Power System" benchmark model.

5.4 Limitations and Recommendations

This benchmark serves as an example for the implementation of a co-simulation between electrical power and ICT systems. However, it is not based on the real-world scenarios. The OPC UA interface is chosen for the convenient use of the available power system simulation software in this work. Another interfacing option is also possible like the Functional Mock-Up Interface (FMI). Furthermore, this benchmark can be further developed to cover non-Real-Time (RT) or RT coupling where appropriate TCs can be applied.

5.5 Summary and Future Work

This benchmark represents an ICT-enhanced power system towards smart grid development. Reliable and secure bidirectional communications are essential for automated operation and control to maintain power system stability and security of supply. This benchmark serves as reference model for interested users to investigate the impact of ICT components to the control algorithm for both distribution and transmission power systems. Two power system models can be used which are the IEEE 39-Bus for transmission networks and the CIGRE MV model for distribution networks.

Several TCs developed in (Raussi et al., 2021), e.g., resilience and performance assessment of ICT components, interoperability testing, and vulnerability analysis can be applied to this benchmark model. The OPC UA is chosen for a co-simulation interface and data exchange between the power system modelling software and the communication emulator (e.g., Mininet), but not limited to other interfaces such as FMI. Interested users can apply this benchmark to mimic the information flow from several substations to the control room (i.e., SCADA) in order to operate the control algorithm of electrical infrastructure (e.g., OLTC). Furthermore, it can be also applied for grid stability caused by cyber-attacks.

This benchmark model is published online (Rajkumar, 2021) where the detailed description is provided using the PreCISE method.

6 Conclusions

This document presents the “Benchmark Scenarios” to serve as the reference models within ERIGrid 2.0 and also facilitates their applications for interested external partners. Three benchmarks are developed which are 1) “Electrical Network”, 2) “Multi-Energy Networks”, and 3) “ICT-Enhanced Power System”. The “Electrical Network” benchmark represents a LV electrical network with controllable high penetration of DERs. The “Multi-Energy Networks” benchmark focuses on the handling of multiple energy carriers (i.e., electrical and thermal power) by using a co-simulation framework. The “ICT-Enhanced Power System” benchmark represents the digitalisation of the power system and illustrates the interdependency between the power and ICT systems. These benchmarks cover the key technological areas and FSs of smart grid and energy systems developments.

The benchmarks allow interested users to experiment with a wide range of the TCs in a simple and efficient manner. Together with the TC developed in the ERIGrid 2.0 project, these three benchmarks can facilitate experiments for validating concepts and implementations of smart grid and energy system technologies at various Research Infrastructures (RIs). Some simulation software and interfaces are presented for easy usage of the benchmarks, but they are not limited to other tools.

These three benchmarks are documented in detail following the PreCISE method. The OA/OS repository for the models and the detailed documentations are available via ERIGrid 2.0’s GitHub environment[8].

[8] https://github.com/ERIGrid2

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