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PoSyCo

Power System Cognification

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ProjektnehmerIn (Institution)	AIT – Austrian Institute of Technology GmbH
AnsprechpartnerIn	DI Helfried Brunner, MSc
Postadresse	Giefinggasse 2
Telefon	+4350550-6382
Fax	+4350550-6390
E-mail	helfried.brunner@ait.ac.at
Website	https://www.ascr.at/power-system-cognification-posyco/

PoSyCo

Power System Cognification

Authors:

Helfried Brunner, Christian Messner, AIT Austrian Institute of Technology GmbH
Alfred Einfalt, Andreas Fernbach, Siemens Österreich AG
Wolfgang und Natalie Prüggler, MOOSMOAR Energies OG
Daniel Herbst, Technische Universität Graz, Institut für Elektrische Anlagen und Netze
Gertrud Rossa-Weber, TU Wien, Institut für Energiesysteme und Elektrische Antriebe
Thomas Frühwirth, TU Wien, Institute of Computer Engineering, Automation System Group
Roland Zoll, Wiener Netze GmbH
Andreas Schuster, Melisa Kis-Juhasz, Aspern Smart City Research

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2 Introduction

2.1 Scope of Work

Today's distribution grid operation is facing big challenges, especially through the penetration of decentralized, mostly renewable energy generation units. Additionally, the increasing number of electric vehicles and therefore necessary charging infrastructure as well as the substitution of other energy demands (e.g. heating) trough electricity will strengthen usage of existing infrastructure especially in urban distribution grids. The classical solution would be an extension of the impacted grid section.

Smart grid technologies can fundamentally contribute to a solution facing the new technical and organizational challenges which are arising trough this development. Although a lot of promising solutions are already available at medium and high voltage levels, there is still a barrier using smart grid solutions at lower distribution grid voltage levels in a cost-effective way. One of the reasons for this is that there is not 'the one' solution providing a positive business case with one functionality. Therefore, research in combined Use Cases provided by very flexible and easy adaptable systems is needed. Thus, the integration of smart grid applications must be achieved on different system levels. Within the flagship project PoSyCo these levels are categorized as three 'dimensions': physical dimension, ICT dimension and process dimension. For better understanding, two Showcases are illustrated in Figure 1 and Figure 2 showing the scope, impact and challenge.

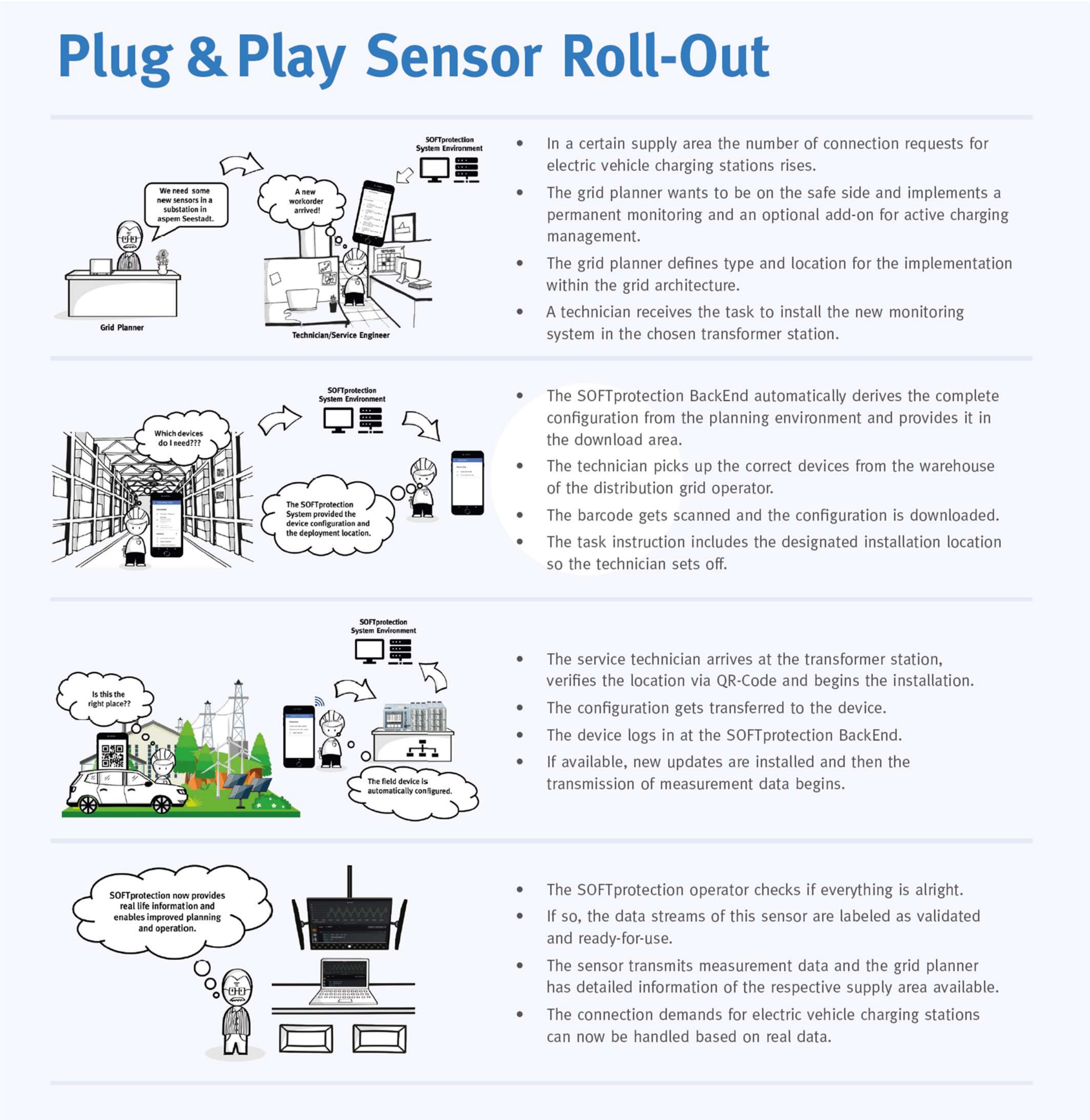
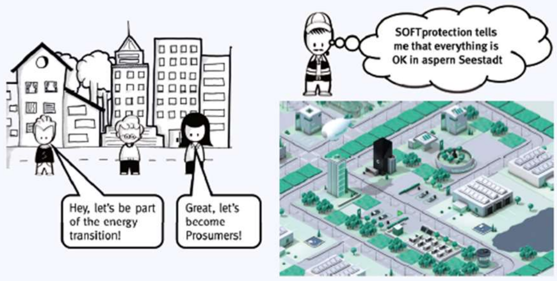
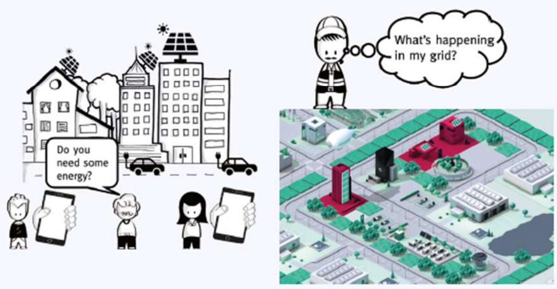


Figure 1: Showcase 1 – Plug&Play Sensor Rollout.

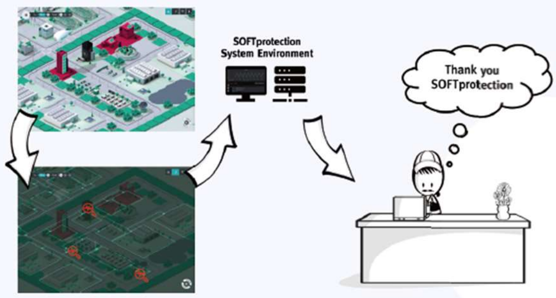
Grid Supervision



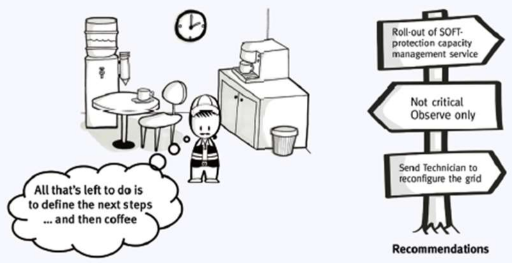
- Until now, the energy demand of the inhabitants was passive and easy to predict.
- The low voltage grids are equipped with capacity reserves and no detailed supervision is needed.
- As explained in the showcase before, a SOFTprotection measurement system has been installed in aspern Seestadt due to a recent increase of requests for electric vehicle charging stations.
- Now the residents themselves want to become part of the energy transition.



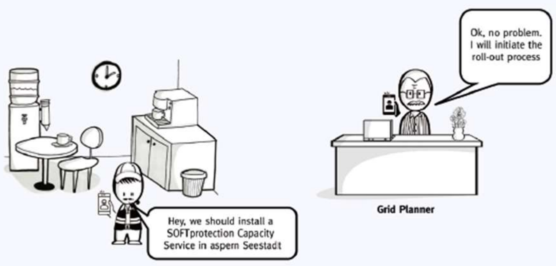
- The aspern Seestadt residents have switched to electric vehicles, have installed photovoltaic systems and participate in energy communities.
- The grid sensors provide continuous monitoring and send alerts when thresholds are exceeded.
- These alerts are sent to the SOFTprotection BackEnd where they get processed.
- The SOFTprotection operator gets notified and quickly has to find the source of the problem.



- SOFTprotection receives an alert and requests error logs (= high resolution measurements).
- To support the trouble shooting process SOFTprotection requests data of topologically related sensors as well. This can include sensors at the supplying transformer, neighboring grid branches and neighboring transformers.
- The SOFTprotection operator starts his day and logs in to SOFTprotection.
- With all the additional information gathered it is very easy to identify the underlying problems of all reported alerts.



- Now the SOFTprotection operator has to decide how urgent and critical the issue is.
- SOFTprotection supports all further steps. Options range from closely monitoring the grid section to sending a technician.
- Additional functionalities can be added to make smart solutions like grid capacity management possible.



- In this case the SOFTprotection operator opts for the smart solution of an active capacity management.
- The request is sent to the grid planer who now uses a planning tool like in Showcase 1, to define the optimal configuration for this functionality.
- The new functionality can be installed and activated via SOFTprotection BackEnd without the need for on-site work.

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Figure 2: Showcase 2 – Grid Supervision.

Accordingly, the functional goal of the PoSyCo project is a concept and proof of concept for a ‘SOFTprotection’ as an add-on for protection and control in low and medium voltage grids. The project result is a widely autonomous support system to optimize the whole smart grid / power system. One major aspect of the solution is, that existing automation, and especially protection systems retain their independence of SOFTprotection in critical situations. This goal is investigated within several PoSyCo Use Cases along the dimensions mentioned before.

The overarching goal based on the investigation of the functional goal mentioned above is to enable a complete analysis of how a distribution system operator (DSO) can implement an advanced smart grid protection and control functionality in his technical and organizational framework. Thus, PoSyCo delivers a blueprint of smart grid implementation based on examples of practical importance. Beside the technical solution of this ICT system for automated operation also the roll out process, how to deal with malfunctions as well as how to integrate in working processes is of high importance. Finally, one additional focus within this goal is the human-to-machine interaction to ensure that DSOs employees are supported by trustful and necessary information at the right time and in an intuitive way.

2.2 Alignment to the Program

The Use Cases and developments within the PoSyCo project addressed the call topic “Energy Systems and Grids” of the related energy research program. More specifically, sub-topic “Smart Grids” (TF2.1). The sub-goals of TF2.1 targeted by PoSyCo are:

- Smart grid technology, system components and concepts:
    - overall architectures for re-structuring and convergence of grid infrastructures, automation and control solutions incl. integration of ICT, new protection technology (safety, security, privacy, resilience, convergence of systems);
    - processes, tools and basic technology for safety critical power system components, integration of communication technology in Smart Grid components etc.;
- information models for system, application, control and communication aspects;
- diagnosis, automation and control concepts for intelligent power systems and its components validation and test approaches for Smart Grids / power systems;
- further development of power systems with special regard to decentralized and cellular approaches.

The major program goals followed by the PoSyCo flagship project are:

1. Grand challenges: Research on energy technologies in the center of large societal challenges;
2. Austrian technological leadership opens access to international markets;
3. Research on energy technologies and innovation as driver for employment in Austria).

The goals of the call reached by PoSyCo are:

- R&D on technologies, components and system integration;

- innovations for societal benefit by focusing on the human factor as user, client and active part of the energy system, and companies as well as research organizations using innovation for societal benefit;
- to secure and enlarge the industrial location in Austria by reducing energy and CO_2 use;
- to bridge the long time of development in energy technologies up to commercial take-up;
- to reduce high technological and economical risks of research and technological development that are not covered by the market;
- to reduce costs of innovative and highly efficient technologies to pave the way for market penetration;
- to avoid ‘stranded assets’ of future investments in infrastructures.

2.3 Methodological Approach

PoSyCo addresses its objectives along three dimensions: the physical world of power system engineering, the ICT (information and communication technology) aspects of smart grids, and the process dimension. The **three dimensions ‘Physical’, ‘ICT’ and ‘Process’** form a structure for the systematic investigation of challenges in the real commissioning of smart grid technologies. Moreover, this structure builds a guideline for the research activities.
The smart grid architecture model (SGAM) approach [1], [2] and project-standardized forms based on the IEEE Standard on Requirements Engineering [3] are used for the Use Case definition and description to ensure the applicability of the derived solutions in the three considered dimensions. The detailed explanation of the defined **Use Cases (UCs)** and the related requirements set up the base for work in the project. The following Use Cases, considering seamless cooperation of **aggregation, action and adaption** in the SOFTprotection, are identified and described:

- **Aggregation (Stage 1)**
  - **Sensor onboarding and sensor network integration (UC0)**: Concept for the integration of existing sensor networks and individual sensors into PoSyCo’s SOFTprotection concept. The requirements and standardized onboarding procedures enable the initial system setup and ongoing modifications.
  - **Acquisition of field data streams and fault records (UC1)**: Builds on top of the integrated sensor network and ensures sufficient data acquisition allowing for more accurate fault analysis.
- **Aggregation & Action (Stage 2)**
  - **Distributed fault analysis for service restoration acceleration (UC2)**: This includes subsequent analysis tools to find the root cause of a breakdown. Service restoration acceleration builds upon this root cause analysis by adding functionalities supporting system operators in quickly returning to normal operation.
  - **Overload prevention by customer activation (UC3)**: This Use Case provides efficient ways to detect local overload situations (e.g. triggered by fast charging stations) and develops negotiation methods for automated fault prevention.
  - **Overload prevention by temporary meshing (UC4)**: Introduces a selected number of

'intelligent' and remotely operable switches enabling overload prevention through temporary meshing.

- **Aggregation & Action & Adaption (Stage 3)**
  - **Stakeholder-overarching system interaction and process adaptation (UC5)**: A great example for stakeholder-overarching systems and their operation comes up with the topic of local energy communities and their impact on grid operation. In this scenario remaining flexibility provided by the energy community is managed and distributed by a dedicated flexibility utilisation module. Through cooperative bundling with the SOFTprotection module complex overload situations can be prevented and compensated.

Figure 3 presents **the six selected PoSyCo Use Cases** embedded in three stages as well as three dimensions, showing an increasing complexity from left to right.

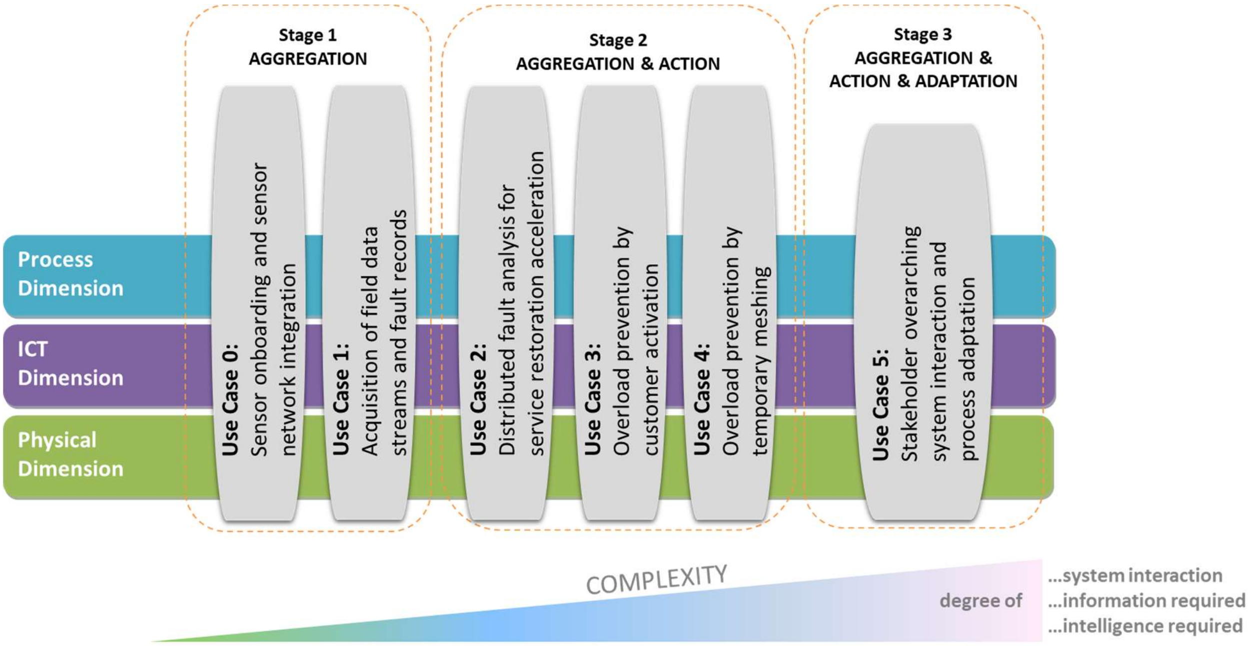


Figure 3: Overview of PoSyCo Use Cases.

The aim of PoSyCo is to extend the state-of-the-art protection system with intelligent add-ons. The envisioned 'SOFTprotection system' provides intelligent overload prevention functionalities and allows the power system operators to actively integrate information on faults into their operation as well as their planning processes. Intelligent fault analysis and prevention can only be realized on top of a resilient and dependable aggregation network, which collects, preprocesses, and efficiently stores the needed measurement values in system-wide services. UC 0 to UC 5 describe this seamless cooperation of aggregation, action and adaption in the SOFTprotection system by facing the upcoming challenges in the physical dimension, the ICT dimension and the process dimension. The six Use Cases are embedded in three stages and show increasing complexity. Stage 1 (UC 0, UC 1) provides a decision base for improved analysis, stage 2 (UC 2, UC 3, UC 4) optimizes the grid operation and stage 3 (UC 5) realizes an overarching system interaction and enables process adaptations for efficient grid operation.

UC 0 "Sensor onboarding and sensor network integration" provides the aggregation base by defining an integration concept of how existing sensor networks and individual sensors can be integrated into PoSyCo. Requirements and standardized onboarding procedures enable the initial system setup and on-going modifications.

UC 1 "Acquisition of field data streams and fault record" builds on top of the integrated sensor network and ensures sufficient data acquisition. While continuous data streams enable longtime analysis (e.g. to prevent failures) fault records are event-triggered high-resolution measurements during the event of failure allowing for more accurate fault analysis. Both, continuous data streams and fault records, are collected and combined to a system-wide service.

In the next stage these data services are used to determine the cause of a breakdown (after the event of failure) and to prevent overload faults (before the event of failure). **UC 2 on "Distributed fault analysis for service restoration"**, includes a subsequent analysis tool to find the root cause of a breakdown. Furthermore, service restoration acceleration builds upon this root cause analysis by adding functionality supporting system operators in quickly recovering from failures and returning to normal operation.

While UC 2 ensures the root cause analysis and accelerates the restoration, **UC 3 on "Overload prevention by costumer intervention"** and **UC 4 on "Overload prevention by temporary meshing"** use the acquired data for overload prevention. As overload prevention of line segments is a major step towards fault prevention, UC 3 provides efficient ways to recognize local overload situations (e.g. triggered by fast charging stations) and develops negotiation methods for an automated fault prevention. This allows for an optimal network loading close to the operational limits.

UC 4 introduces a selected number of 'intelligent' and remotely operable switches to additionally enable overload prevention through temporary meshing resp. grid reconfiguration. Thereby, the radial structure of the distribution grid is temporarily and locally replaced by a meshed structure to prevent overload of line segments to reduce outage times and losses as well as to enable an uninfluenced local market for energy exchange using a community battery storage system.

In conclusion, stage 3 studies the efficient integration of PoSyCo in existing protection and operation systems to ensure an improved system behavior. Therefore, **UC5** special focus is on the difficulties in "**stakeholder overarching system interaction and process adaptation"**. As one of many examples, the currently heavily debated topic of local energy communities was chosen, because SOFTprotection will be the ideal prerequisite to face these challenges. To handle the impact on grid operation, in this scenario remaining flexibility provided by the energy community is managed and distributed by a dedicated flexibility utilization module. Through interaction with the SOFTprotection module potential overload situations can be prevented and compensated.

These three dimensions and stages are overlapping. The integration is ensured by the **PoSyCo concept validation activities and related approaches** (for more details see chapter 3.2). The approach to describe the lab-scale and field tests within PoSyCo is formalized by methods for the specification of tests in the H2020 ERIGrid project [4], [5]. As a result, templates for the formal description of test cases, test specifications and experiment specifications are developed.

The first step is the specification of holistic test cases. **Test cases** are derived from the individual **PoSyCo Use Cases, representing different SoftProtection stages**. A test case identifies possible functions and system configurations to be tested. It describes the test objective and gives insights into why the tests are needed and what is expected to find out. Within the PoSyCo project **the test cases are mapped to the domain of investigation (physical, ICT, process dimension)**.

For complex validation problems it might be necessary to split the test case up into multiple sub-tests. A subtest may focus on a certain function or component, but the result should reflect the overall test objective(s) of the holistic-test case. Several cross-dependencies between the sub-tests may exist and must be identified within this step.

In addition, the **test cases are mapped to a certain testing and validation environment**. The PoSyCo testing environments are (for more details see chapter 3.2):

- **Laboratory tests** by AIT, using a software and hardware in-the-loop test framework for the PoSyCo UC3 – "Overload prevention by customer activation". The Technical University of Graz (TUG) conducts "circuit breaker laboratory demonstrator tests" for U4 - "Overload prevention through temporary meshing";
- **Simulation tests** are performed by Siemens for demonstration and validation of selected SOFTprotection functionalities. They are demonstrated with the simulation environment Bifrost as an accelerated-time simulation and visualization platform. Additional simulations to validate UC4 have been performed by AIT using automated power flow simulations.
- **Field trials** focusing on the process dimension are done in the Living-lab at the Aspern Smart City Research testbeds. Tests for UC3 are performed at the new Siemens testbed for electromobility.

In course of the project a continuous testing and validation prioritization was indicated, depending on resources and testbed availability.

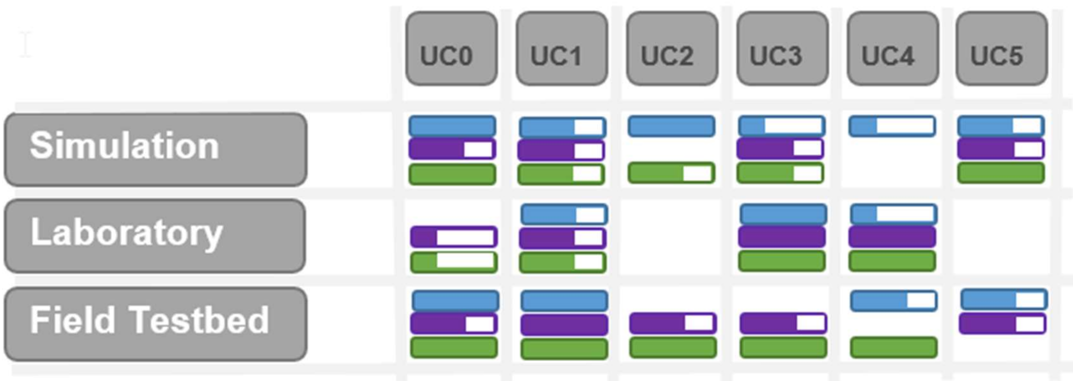


Figure 4: Planned testing in the individual Use Cases with priority - Process dimension in blue, ICT dimension in purple, physical dimension in green; bars with high priority (fully colored bars), medium priority (bars colored at approx. 60%) or lower priority ((bars colored at approx. 25%).

From an economic perspective, Use Case related DSO process adaptations result in new staff roles as well as workflows. Accordingly, case study specific cost benefit evaluations (especially addressing capital expenditures – CAPEX as well as operational expenditures – OPEX) are of interest for DSOs on one hand. On the other hand, long term investment strategies for DSO decision makers are important as well. Thus, a bivalent economic evaluation approach was chosen within the PoSyCo project. Based on detailed economic case study results, a SWOT analysis was performed to identify strategies and measures for future grid digitalization.

The case study addressed a test grid including future scenarios of photovoltaic (PV) and electric vehicle (EV) development (see chapter 4.1). Based on this setting, crucial economic parameters were identified performing sensitivity analyses (compare chapter 4.4.1). Finally, these crucial parameters were used for a SWOT analysis workshop to identify “Strengths, Weaknesses, Opportunities as well as possible Threats” of grid digitalization in low voltage grids (for details see chapter 4.4.2).

2.4 Structure of Work

Following the aforementioned methodology, this report presents the project concept as well as the project results along the three project dimensions (Physical’, ‘ICT’ and ‘Process’) as well as the related PoSyCo Use Cases. Chapter 3 presents the overall project concept including a detailed description of the project dimension and the Use Cases, as well as a description of the validation approach with the testing environments. Chapter 4 presents the results and conclusion on the physical dimension (functional algorithms in chapter 4.1), the ICT and communication framework (ICT dimension in chapter 4.2), the process dimension (chapter 4.3), economic and SWOT analysis (chapter 4.4) and finally the overall analysis along the validation activities (chapter 4.5). Chapter 5 provides a summary followed by an outlook and recommendations in chapter 5.

3 Project Concept

3.1 Project Dimensions and Use Cases

3.1.1 The “north star”

The two examples presented in chapter 2.1 corroborate that it is insufficient to focus only on the technical development of new algorithms, e.g. to avoid overloading situations, in order to mitigate prosumer and renewable energy driven power system challenges. These challenges require the design of an integrative smart grid ecosystem, which facilitates a wide range of novel smart grid services such as voltage and reactive power control, distributed generation optimization, decentralized market interaction, electric vehicle charging and storage control algorithms. Such services are based on intelligent and interconnected smart grid entities, e.g., smart meters, smart breakers, electric vehicles, smart storage systems, and smart buildings. To ensure that the existing infrastructure is not overburdened, an intelligent ‘supervising and protection’ system is necessary.

To simplify the following explanations, the term SOFTprotection is introduced as a synonym for the system investigated and established in the context of PoSyCo. For clarification, the synonym ‘HARDprotection’ is used in the following for the existing, conventional protection technology.

The focus on power system protection and protection-supporting automation within PoSyCo is adressing the most critical part in any power system. While methods and solutions developed in previous and current research projects and related pilots indirectly impact the HARDprotection system (by preventing faults that could lead to triggering the protection system on an operational level), a majority of the underlying HARDprotection (e.g. fuses, breakers) do not yet exhibit any form of intelligence. The area of protection systems in the context of interaction with intelligent network participants have not gained much attention in recent years. Figure 5 describes the intended application area for HARDprotection and SOFTprotection as well as the overlapping area, where SOFTprotection operates in a supporting role.

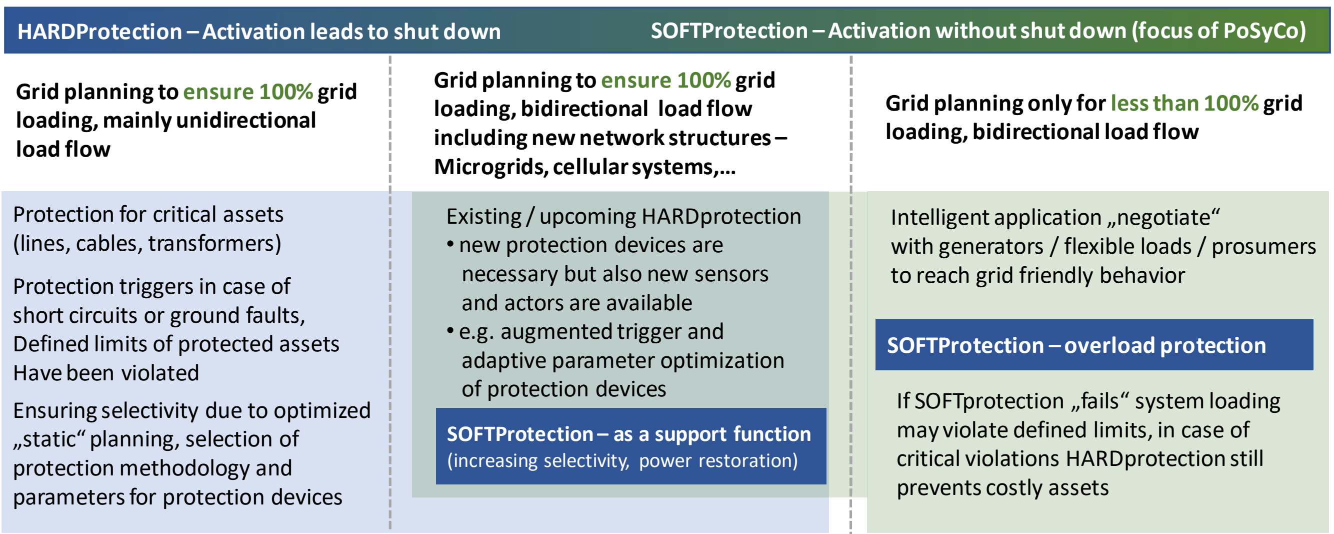


Figure 5: Core functionalities of HARD- and SOFTprotection and R&D within PoSyCo.

Of course, the drivers mentioned above also trigger an increased need for research in the field of HARDprotection. These trends and research results will be observed by the project team, however, HARDprotection is not in the direct focus of PoSyCo.

The functional goal of this flagship project is a **concept and proof of concept for a 'SOFTprotection' as add-on for protection and control in low and medium voltage grids.** The project result shows the first steps towards a widely autonomous support system to optimize the whole smart grid / power system. One major aspect of the solution is that existing automation and especially protection systems should retain their independence of SOFTprotection in critical situations. This goal was elaborated considering the six PoSyCo Use Cases (as introduced in chapter 2.3 and shown in Figure 3) and along the physical, ICT and process dimension.

3.1.2 The three project dimensions

Based on the investigation of the functional goal mentioned above, the overarching goal is to enable a complete analysis how a DSO can implement an advanced smart grid protection and control functionality in his technical and organizational framework. Thus, PoSyCo aims for a **blueprint of smart grid implementation** based on an example of practical importance. SOFTprotection includes a set of smart grid functionalities which are crucial to ensure the operation of a reliable distribution grid infrastructure in case of bidirectional load flows and if it is economically not possible to extend distribution network to 100% loading for any point in time. A number of precessor projects have shown that only active network management on distribution level is hardly enough to present a business case. Introducing flexible automation systems, e.g. based on IoT technology that enables the combination of different applications allows for econmical feasible solutions.
The core messages of Figure 3 can be summarized as follows:

*The **three dimensions 'Physical', 'ICT' and 'Process'** form a structure for the systematic investigation of challenges in the real commissioning of smart grid technologies. Moreover, this structure builds a guideline for the research activities and is embedded into the structure of PoSyCo.*

- The **physical dimension** deals with the basic algorithms and technical function blocks as a base for the functional goal of SOFTprotection as an add-on for protection and control in low and medium voltage grids**.** The project result as described in chapter 4.1 shows the first steps towards a widely autonomous support system to optimize the whole smart grid / power system. One major aspect of the solution is that existing automation, and especially protection systems, retain their independence of SOFTprotection in critical situations. Finally, intelligent algorithms executed on the physical dimension must ensure energy resilience within the complete smart grid.
- The **ICT dimension** has considered research questions arising predominantly in the area of the design of the ICT framework considering two characteristics - dependability and resilience – which are of utmost importance for systems used in critical infrastructure, such as the power system. Devices or parts of SOFTprotection need to be particularly resistant against environmental influences and physical damage, which is already ensured by requiring conformance to the corresponding standards and therefore less relevant from a pure scientific perspective. The term dependability has its root in communication technology and is still very dominant in this area. Today's dependable communication

systems are, however, tailored to a very specific application and take advantage of meticulous planning, redundant computational hardware and wiring, predefined assumptions on faults and other aspects that limit their applicability in more flexible environments. In contrast, the smart grid itself is constantly changing, including but not limited to its devices, network topology and applications, and requires a dependable communication system with substantially increased flexibility.

- **Process dimension**: Beside the technical solution of the ICT system for automated operation, the roll out process and how to deal with malfunctions as well as how to integrate in working processes is of similarly high importance. Finally, one additional focus within this goal is the human-to-machine interaction to ensure that DSOs employees are supported by trustful and necessary information at the right time in an intuitive way. Due to the fact, that different functionalities and applications must be associated to different departments and people within DSOs organisational structure the efficient and encompassing process integration is crucial. This means that the topic of process integration as a field of research also raised several research questions for PoSyCo.

3.1.3 The six PoSyCo Use Cases

The **six selected use cases** presented in Figure 3 are embedded in three stages and show an increasing complexity from left to right.

- **Stage 1 'AGGREGATION'** includes two PoSyCo Use Cases of SOFTprotection functionalities providing data and information for higher-tier systems. SOFTprotection is operating as a data and information provisioning system for improvement of planning tasks, active network management as well as workforce management systems and/or protection planning.

  "Stage 1 provides a decision base for improved analysis"

- **Stage 2 'AGGREGATION & ACTION'** enhances the data and information provisioning of Stage 1 with selected ways of system interaction. Use Case 2 sketches new ways how to operate a system of increasing complexity by the application of AI technologies for root cause analysis. Use Case 3 and 4 are the typical examples to describe the core functionality of SOFTprotection – the overload prevention. State of the art for overload prevention in the distribution level is a consideration in planning rules. It is assumed that initially, nothing is connected to the grid which may lead to an overload of grid components. The use cases illustrate what happens if this situation changes and point out the need of active grid management down to the low voltage grids.

  "Stage 2 optimizes the grid operation"

- **Stage 3 'AGGREGATION & ACTION & ADAPTION'** includes a Use Case representing the third main functionality of SOFTprotection. It considers an efficient interaction with upcoming challenges like energy communities and flexibility utilization in the lower end of the grid. On the one hand, there will be an impact on grid operation and thus also on SOFTprotection and on the other hand, e.g. energy communities can also be integrated as additional "actor" for SOFTprotection's overload prevention capabilities.

  "Stage 3 offers system interaction functionalities"

3.1.4 Limitation of expectations

It was not a goal of PoSyCo to research protection systems themselves (i.e. HARDprotection) or to implement a prototypical SOFTprotection (i.e. TRL 5 or higher). The challenges for existing and also future HARDprotection systems were taken into consideration but only as possible application where SOFTprotection is able to support the HARDprotection. So PoSyCo was not investigating new protection schemes, e.g. considering unintended islanding or blinding issues. The concepts for SOFTprotection were investigated and implemented as far as it was necessary for the laboratory proof-of-concept. The primary goal was the research on the overall system integration aspects whereas the example SOFTprotection was used. A prototypical implementation and field tests on system level was not foreseen.

The flagship character of PoSyCo allowed pursuing goals on the functional as well as the system level and addressed the need for Power System Cognification to face future challenges. The approach to reach the PoSyCo goal was well thought out and is shown in the following figure. Two important aspects (to be achieved at once) were considered for the choice of the described Use Cases:

1. Through the summary of the targeted functionalities of the six PoSyCo Use Cases (as introduced in Chapter 2.1) the SOFTprotection as an add-on support system is enabled. This is not just any smart grid functionality, but also one of the most important functionalities for DSOs in the next few years, by solving the challenges described in the previous chapters.
2. The approach offers an increasing degree of complexity. Looking at the PoSyCo Use Cases from left to right, the degree of intelligence and information required as well as interaction increases. This allows for a systematic mapping of Use Cases to system dimensions and a step-by-step investigation of the associated challenges. Facing the upcoming challenges in the physical dimension, the ICT dimension and the process dimension will lead to a deep understanding of dependencies and necessary system improvements.

3.2 Validation Approach

This section presents a description of the validation and testing approach applied within the PoSyCo project, as well as a detailed description of the testing and validation environments (simulation, laboratories, and field test areas).

3.2.1 Overview

The first step was to elaborate possible **test cases** for each PoSyCo Use Case and to perform a mapping to the "*physical, ICT, and process domain*" as well as to the testing environment "*laboratory, simulation, field*". The test cases provide a generic description, which comprises a set of conditions under which a test can determine whether or how well a system, component or one of its aspects is working.

The next step was to derive more specific test- and experiment specifications with focus on the functional proof of concept of the SOFTprotection system(s).

For the Use Case specific “lab validation”, simulation and laboratory tests with focus on the ICT and physical domain are from interest.
A subset of SoftProtection proof-of concept validations was implemented in the BIFROST design and simulation environment for realistic replication of e.g. smart cities or energy communities. Demonstrations in BIFROST are related to the PoSyCo Use Case 3 “overload prevention by customer activation” and Use Case 5 “Stakeholder overarching system interaction and process adaption”.
A different type of simulation test was implemented for Use Case 3 at an innovative Controller Software-in-the-loop setup at AIT. It allows to deploy multiple controllers in a software environment and to test the functionality and behavior under realistic conditions, which can be close to the final implementation in the field. To validate the concept a comparison with the presented simulation results in deliverable D3.3 (offline simulations in Matlab) is done.
Software-based tests are also performed to verify the Switching Management System (SMM) algorithm for temporary meshing at unfavorable and changing environmental conditions during the algorithm runtime. The basic functionality of the SMM algorithm was demonstrated at the laboratory demonstrator at TUGraz.
For the Use Case specific “living lab proof of concept validation” field tests and partially simulation tests with measurement data from the field are done. At the Aspern living lab, test cases in the process dimension e.g. for automated sensor rollout are from interest. At the Siemens testbed for electromobility (described in chapter 3.2.2.4) for tests with EV charging stations are done. Tests and developments for Use Case 2 were done, to better understand occurring events in the grid, and to apply a root cause analysis on real data.

3.2.2 Test environments

3.2.2.1 Bifrost

Within PoSyCo, possible processes and interfaces considering the SOFTprotection functionalities were identified within DSO environments. For each Use Case of the PoSyCo project, corresponding roles (as well as new roles) and workflows (incl. new workflows) were identified. These roles and workflows were further merged into special Show Cases. A selection of these Show Cases was implemented in BIFROST, extended and used to demonstrate and validate selected SOFTprotection functionalities.
BIFROST is a design tool and simulation environment for the realistic replication of e.g. smart cities or even energy communities with a strong focus on power grid and communication infrastructure. Supported by a powerful simulation engine, a browser-based, 2,5D user interface (see Figure 6) allows researchers, grid operators and planning experts to emulate a wide range of possible scenarios with corresponding dependencies. The internal "state" representing the simulation world, including all physical dynamics and structures, is fully exposed to external applications, such as control algorithms or time series analysis tools. Considering the feedback during process-related investigations, BIFROST has been enhanced and improved along with the PoSyCo related activities around information and communication technologies. Thus, BIFROST can also be used as a virtual testbed for PoSyCo-related testing and validation.

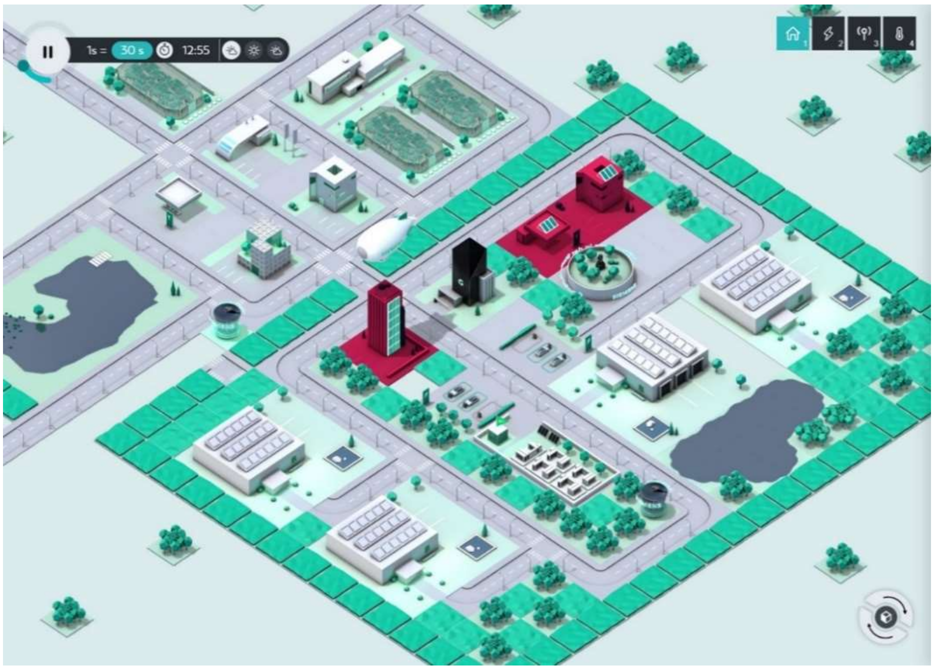


Figure 6: Overview of current Graphical User Interface within BIFROST.

Owing to the diverse nature and widely disparate time constants of the processes involved in Smart Grid operation, most simulation tools focus on narrow aspects of the whole: projecting equipment failure, sub-second voltage spikes, package loss in communication networks, et cetera. Integrating all those processes into a coupled simulation is exceedingly difficult or even impossible given limitations of computer hardware, and in most cases unnecessary. For example, inspecting frequency fluctuations, which occur in the millisecond range or lower, across an entire year of weather changes is unlikely to yield significant information gains as compared to a more tightly designed experiment.

However, there are many processes in the Smart Grid which do not need detailed physical simulation to be understood in terms of their influence on the larger picture. To gauge the effect of electric vehicle (EV) charging on the overall voltage level of the low-voltage grid, it is not necessary to model the charging current on the connection point between car and charger: a statistical measure of the overall charging current would suffice.

Existing simulation tools can be divided into two different kinds:

1. Tools which focus on one narrow aspect such as load flow solvers (e.g., “Pandapower”). While those tools are optimized for the specific use case, they lack the possibility of including new aspects or adapting the underlying time constraints.
2. Multi-modal tools, which are equipped to deal with different domains (e.g., electrical grid, thermal grid) like “SINCAL” or which provide a standardized interface for new components (e.g. community controller) like “Mosaik”.

While tools associated to point 1 obviously lack the possibility to adapt to multi-modal use cases with different time constraints, existing multi-modal tools either do not have a simple and standardized interface or do not provide an interactive graphical interface allowing for:

- Graphical grid design and visualization;
- Interactive result visualization;
- Dynamic adaptation of existing and integration of new domain data and time constraints;
- Simple standardized interface for new components.

The BIFROST simulation platform provides a way to gauge the performance of an existing or planned Smart Grid installation by offering an accelerated-time simulation and visualization of dynamic components across an arbitrary variety of physical and social domains, including, but not limited to:

- energy flow;
- (wireless or wired) communications;
- weather/climate;
- thermal grids (remote heating/cold) and
- social aspects (e.g., energy pricing, traffic density).

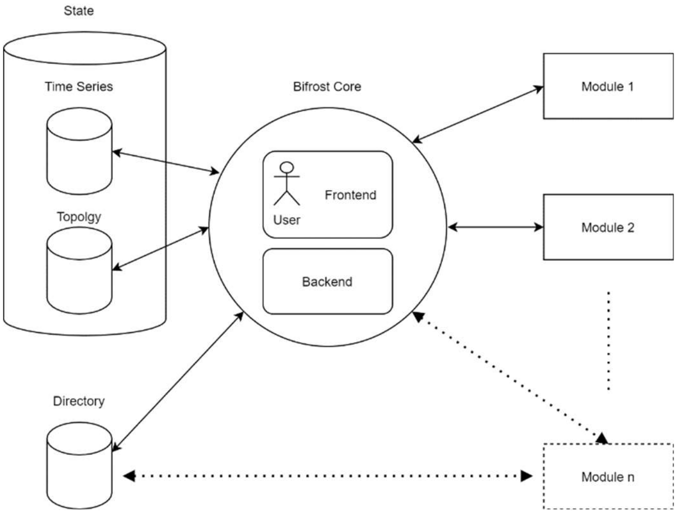


Figure 7: BIFROST Simulation Concept.

Figure 7 describes the main idea behind the proposed simulation concept. The user can access the simulation environment through the Bifrost frontend. It can be used to build a new or import an existing smart grid segment (buildings, electrical grid, communication grid, etc.), which is then stored as topology information in the Bifrost "state". The frontend provides an interactive 3D view of the current grid segment, where the user can switch through multiple different layers (e.g., landscape, grid, or communication layer) helping to focus on the related structures. All placed structures are automatically enriched with related structures and their parameters ("dynamics"). For example, a residential building must have a smart meter and this smart meter has physical parameters such as voltage, current, power, etc. In addition, the house could also have an indoor temperature or several residents. The complete state comprises the entirety of data pertinent to the simulated installation, including the position and exact nature of architectural components, such as roads and buildings; active components, such as power transformers, switches, routers and cabling; and the highly time-variant physical quantities ("dynamics") of these built or natural components as time series, such as: voltage levels, packet switching speeds, ambient temperature, traffic density or building occupancy.

The available set of structures and dynamics, as well as their mapping is stored in a database called "Directory". The Bifrost core itself does not make any assumptions about the content of the directory. Both structures, as well as dynamics can be adjusted to the user's needs (Bifrost provides a standardized scheme for existing and new structures/dynamics). New elements can be added, existing ones can be modified or deleted. The core automatically updates the state according to changes in the directory. This allows for a maximum of flexibility.

While the Bifrost frontend handles the grid visualization in an 2,5D interactive way (construction, visualization, manipulation, import/export, etc.), the Bifrost backend manages the directory modifications and simulation process. The Bifrost core itself does not calculate any new dynamic values; it only provides the unified state including both information about the structures (topology) and the current value of all dynamics (can be stored in a time series database). Any kind of calculation is handled by software components that describe isolated processes (called "modules"). These modules are coupled into the main simulation software ("Bifrost Core") with a remote access interface and can introduce any kind of behavior necessary for the current simulation run (e.g., load flow solver, weather generator, energy community controller, etc.)

BIFROST is also used in other research projects and the PoSyCo specific enhancements are continuously merged with contributions from other projects. The actual state of development is also part of the non-scientific dissemination (https://bifrost.siemens.com/en)

3.2.2.2 TUG circuit breaker laboratory demonstrator

To enable the practical suitability and a realistic analysis of the Switching Management Module (SMM) algorithm developed for implementing UC 4, the project team has initiated the development as well as the construction of a corresponding laboratory demonstrator. Using this, the method of automated reconfiguration at low-voltage level is to be evaluated under laboratory conditions with real, industrially available components. The underlying concept, shown in Figure 8, consists of four low-voltage compact circuit breakers with associated secondary devices (control voltage supply, motor drives, communication).

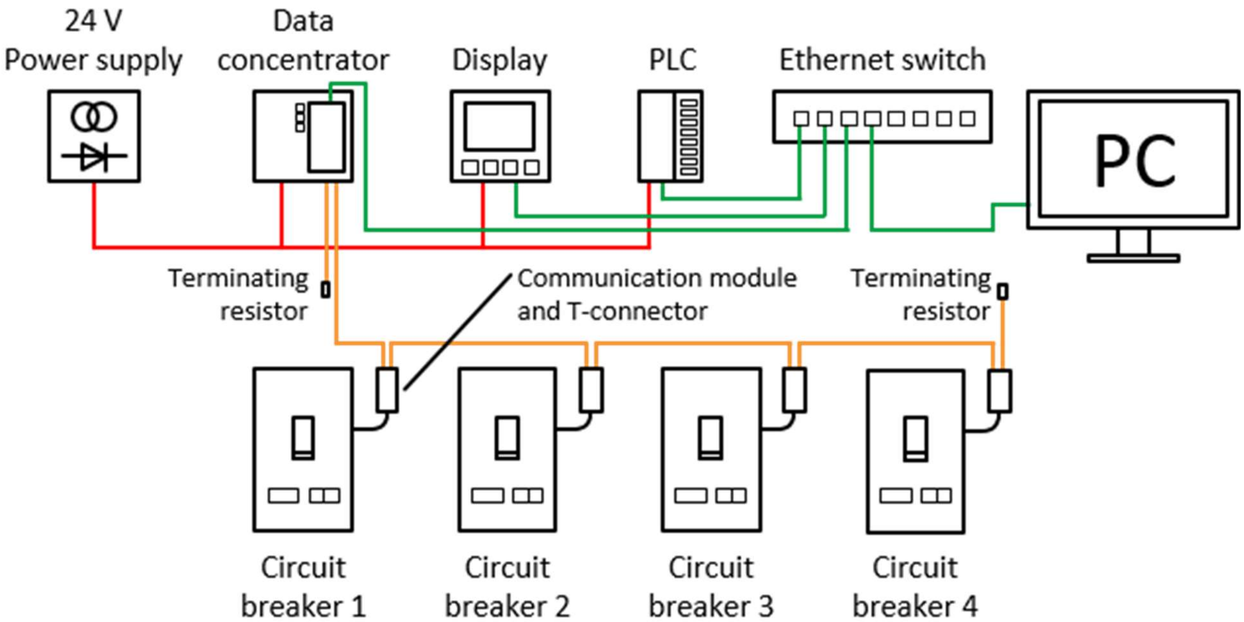


Figure 8: Schematic diagram of the laboratory demonstrator with four LV compact circuit-breakers, control voltage supply and communication equipment (data concentrator, display, PLC, Ethernet switch).

In the final configuration of the laboratory demonstrator, the four compact circuit breakers are connected in the form of an open ring structure as shown in Figure 9, with outlets for sources/feeders and loads/consumers located at different points. Depending on the application, these can be connected to the demonstrator using conventional CEE (Commission on the Rules for the Approval of the Electrical Equipment) or type F connectors, 4 mm safety laboratory connectors or 6 mm power laboratory connectors. In addition, the setup has the option of using industrial power connectors (Phoenix/Harting) in the upper and lower stubs to integrate line models for simulating corresponding line lengths.

The communication equipment of the demonstrator and the corresponding motor drives enable remote control of the circuit breakers using the corresponding manufacturer software. For the application of the developed SMM algorithm on the laboratory demonstrator, the developed code is used together with the additional hardware (PLC), which is required as an interface solution.

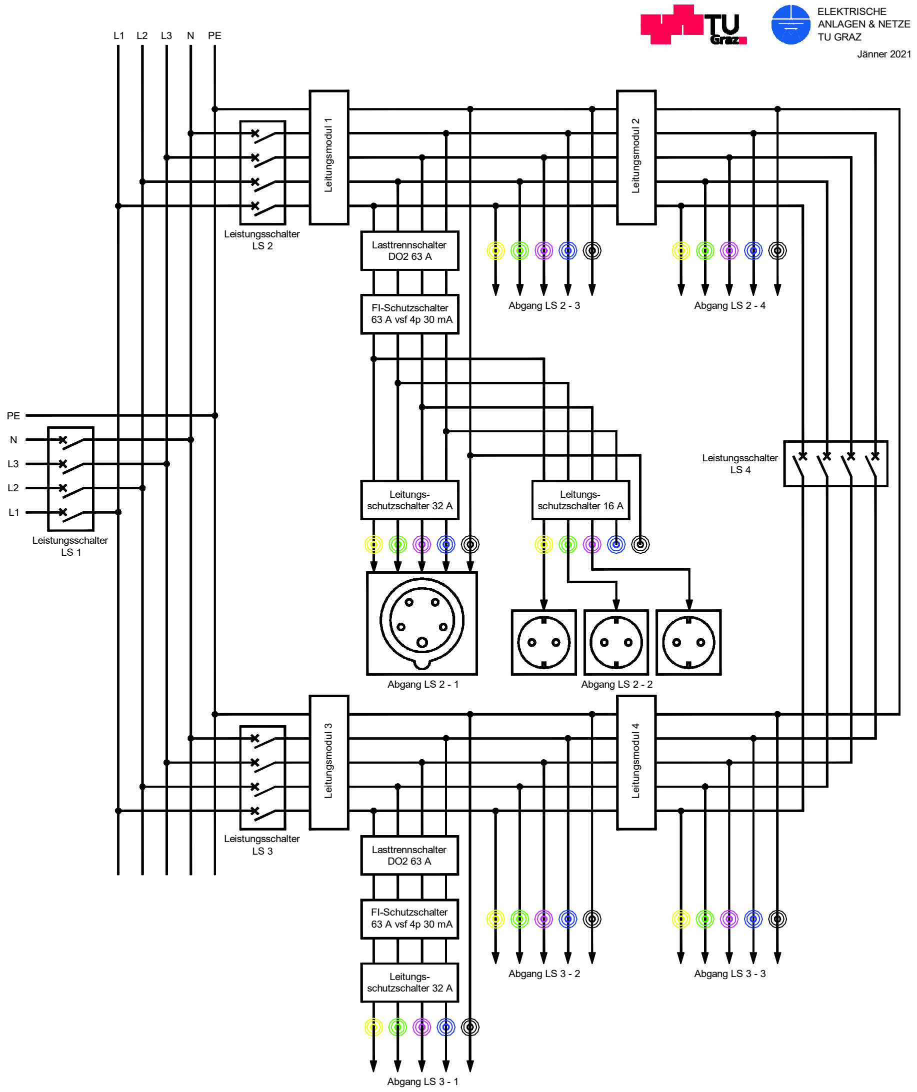


Figure 9: Basic wiring of the four compact circuit-breakers in the demonstrator with schematic representation of the available outlets for sources and loads.

Figure 10 shows the final developed and assembled laboratory demonstrator. The left picture shows the closed distribution board with the operating elements (push-buttons and display) in the upper area and the schematic view of the demonstrator below, including 4 mm safety laboratory sockets for measuring purposes. The open distributor is shown on the right, with various terminals as well as fuses, residual current devices (RCDs) and miniature circuit breakers (MCBs) visible in the upper part. In the lower part, in addition to further terminals, are the four low voltage (LV) compact circuit breakers together with the associated communication equipment (data concentrator, bus adapter, PLC, Ethernet switch).

This demonstrator is used to investigate the SMM algorithm, the necessary interface solutions and practical tasks or applications in the laboratory before being used in practice. In particular, the demonstrator will be used to prove the general functionality as well as the practicability of the developed SMM algorithm by means of industrially available hardware. Detailed information regarding the developed algorithm is summarized in the deliverables D3.1 and D3.2.

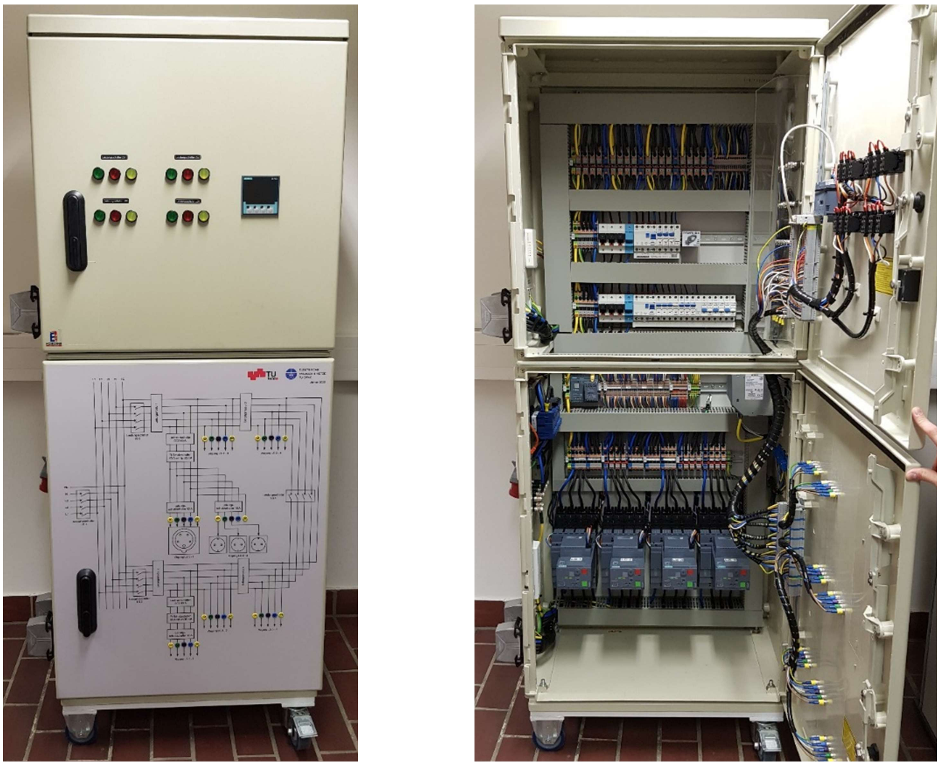


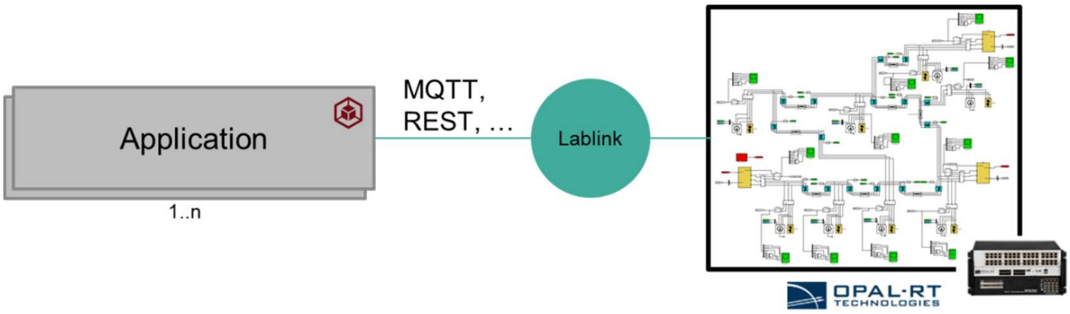
Figure 10: Real structure of the laboratory demonstrator, closed view with operating elements and sockets for measuring purposes (left), open view with fuse installations (top right) and circuit breakers including communication (bottom right).

Figure 11: Test setup for the SMM algorithm with transformer, laboratory demonstrator, PHIL power amplifier, electrical fan heaters as well as control PC.

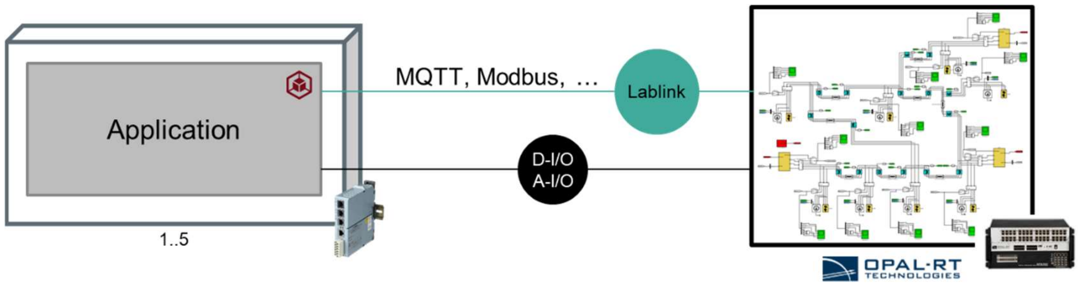
3.2.2.3 AIT Software – Hardware in the Loop Platform

To analyze the developed cyber-physical energy system, one needs three main components: 1) the physical system, 2) the control system, and 3) the communication network between the controllers. AIT's implementation is based on OPAL-RT (real time simulation), which emulates the physical system, Lablink and Redis for creating a communication between controllers and simulation. This allows for a flexible setup that can be used for validation of multiple types of controllers.

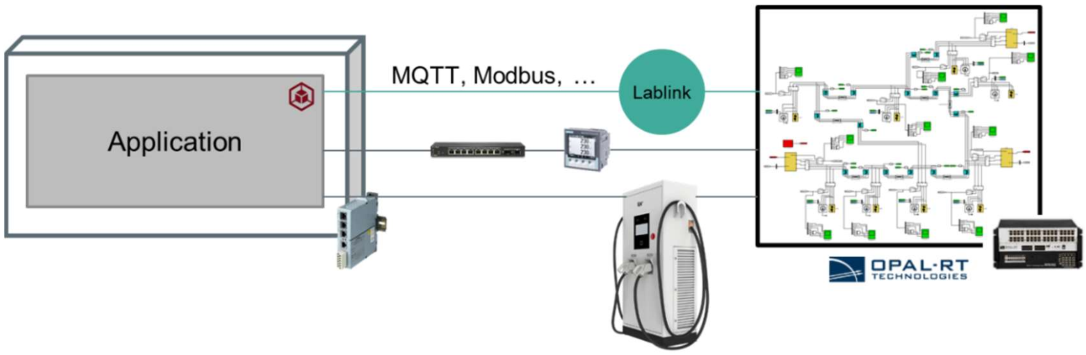
Basically, three kind of testing solutions are available using this setup as seen in Figure 12. A Controller Software-In-the-Loop (C-SIL) setup (see Figure 12-a) is useful during development of a controller and for testing situations where multiple controllers (e.g., 100 controllers) are deployed. After the controller has been validated in a C-SIL setup, the next step is a validation using a Controller Hardware-In-the-Loop (C-HIL) setup (see Figure 12-b). Here, the controller is tested on its target platform, as opposed to the C-SIL case where the controller application is running on a standard PC hardware. The last step is the Controller Power Hardware-In-the-Loop (C-PHIL) setup (see Figure 12-c), where the controller is combined with other real power and measurement equipment.



(a)



(b)



(c)

Figure 12: Controller real-time testing solution at AIT: (a) Controller Software-In-the-Loop (C-SIL), (b) Controller Hardware-In-the-Loop (C-HIL), (c) Controller Power Hardware-In-the-Loop (C-PHIL).

3.2.2.4 Siemens Testbed for Electromobility

The smart charging application as elaborated within UC3 is being implemented and tested in the newly built charging testbed at the Siemens site in Vienna as illustrated by Figure 13 and Figure 14.

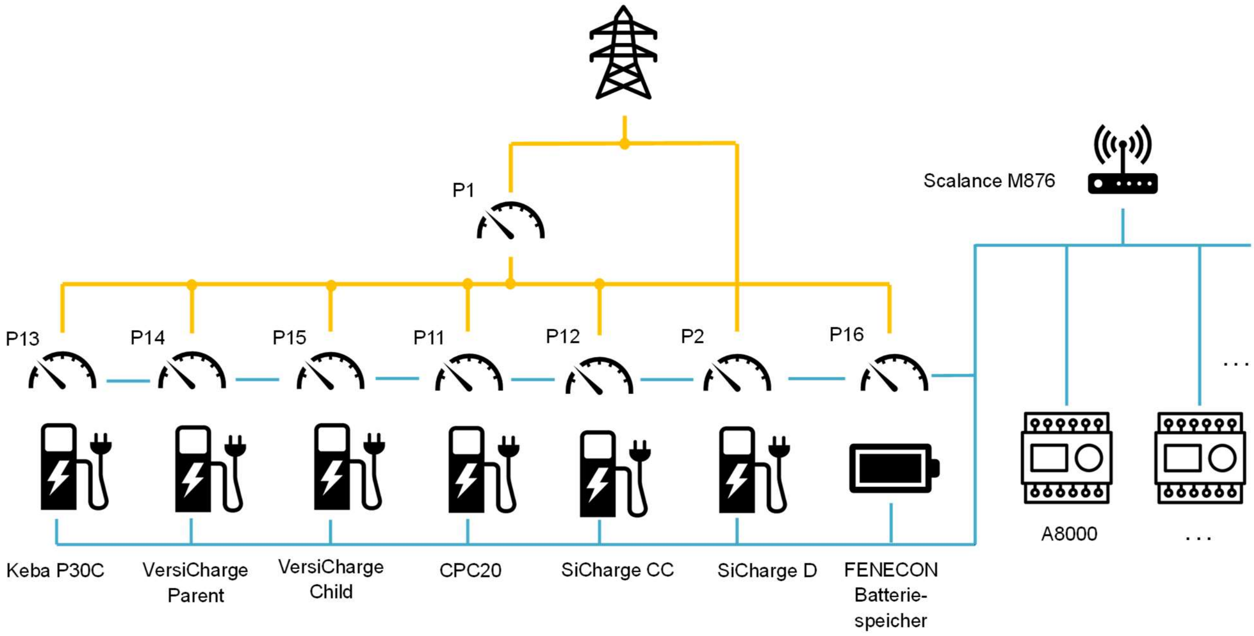


Figure 13: Overview and architecture of field test environment provided by Siemens.

This testbed encompasses six different types of charging stations, a battery energy storage system and meters measuring the energy flow of each asset. Connectivity among these components is enabled by a local IP network. For the deployment of applications there are various controllers (among others two SICAM A8000) available.

Figure 14: Outdoor E-Mobility Charging Testbed – Siemens Vienna.

3.2.2.5 ASCR Testbed Aspern

ASCR's (Aspern Smart City Research) multi-layered infrastructure is exhaustive for performing research and validating current questions. The model region, which is investigated within the PoSyCo project provides the perfect environment for SOFTprotection: It contains intelligent buildings with decentralized production of electrical power and heat. Furthermore, the entire necessary communication infrastructure is already in place there. The power grid can be monitored and all necessary data is collected. The smart charging use case considering interaction with public charging infrastructure was investigated in a parking garage testbed "SeeHub" as shown in Figure 15.

Figure 15: Multifunctional parking garage SeeHub – a part of ASCR testbed in Vienna.

The ASCR testbed consists of 3 different parts: Smart Building – Smart Grid – Smart ICT. Beside the SeeHub, the Smart Grid Part is the most important for PoSyCo and therefore described in detail. More information is available at https://www.ascr.at.

Smart grids connect every player in the energy system via a communication network, thereby enabling prompt bidirectional and cost-efficient communication between grid components, producers, storage facilities and consumers.

The low-voltage network testbed consists of

- 12 secondary substations;
- 24 transformers of different types;
- ~100 sensors in the substations and supply lines with different measurement accuracy;
- >500 smart meters.

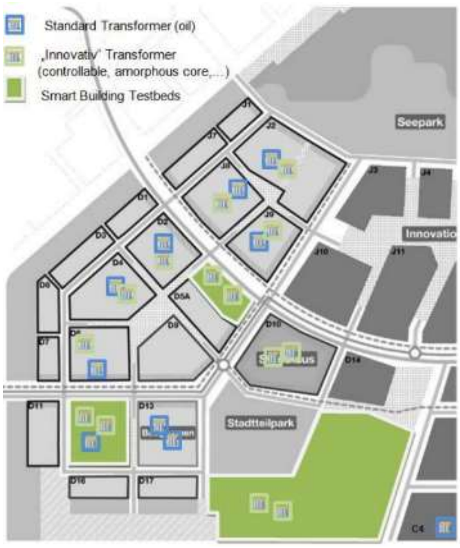


Figure 16: Smart Grid Testbed Aspern.

Figure 17: Smart Secondary Substation.

Furthermore, there are five grid storage systems in the substation with important functions both for the grid and the energy market. ASCR is investigating how to turn passive distribution network operations into actively managed smart grid operations.

Using load forecast models for transformer stations instead of installing sensors is a beneficial opportunity to replace actual sensor technology by calculated values. Thereby, investment and operating costs can be reduced. Using numerous of these smart transformer stations within the WN service area, a significant cost reduction is expected.

The approach that has been adopted is based on the optimal use of existing copper reserves and the integration of smart ancillary technologies – not overnight, but continuously, along the smart grid migration path:

- Phase 1 of the migration path is monitoring what sensors and data are needed in which resolution. The challenge is to find the right balance between costs of sensor roll-out and their benefits.
- Phase 2 makes use of the sensors and pushes the equipment to its limits.
- Phase 3 is characterized by the efficiency gains from automation and active management.

Two types of sensors were installed by Wiener Netze at different locations and the provided data was analyzed and compared. An example of a test setup is shown in Figure 18. On the left side, the grid monitoring device (GMD), which is in principle a reduced version of an AMIS Smart Meter is installed. Split-core current transformers are used for the current measurement. The communication interface is power line communication (PLC). At the right side, an EGS (enhanced grid sensor) meter is installed. It uses Rogowski coils for the current measurement. The EGS has an additional GPRS communication interface implemented. For locations in which PLC can't be used the EGS can be used instead. It provides also higher transmission rates as the GMD meter and might be necessary for certain use-cases e.g. load management.

Figure 18: GMD (left side) and EGS (right side) measurement device.

4 Results

4.1 Functional

Based on the concepts for tackling the future challenges for the operation of low-voltage grids, which were designed and discussed by PoSyCo in the initial phase of the project, different approaches and associated algorithms have been developed. In relation to the PoSyCo Use Cases, the following three algorithms have been identified:

- Distributed fault analysis for service restoration acceleration (UC 2);
- Overload prevention by customer activation (UC 3);
- Overload prevention by temporary meshing (UC 4).

These functionalities and related algorithms for the three Use Cases are briefly described in the following subsections 4.1.1, **Fehler! Verweisquelle konnte nicht gefunden werden.** and 4.1.3.

4.1.1 Distributed fault analysis for service restoration acceleration (UC 2)

4.1.1.1 Realization Concept

The monitoring and control of electrical grids represents a central aspect of a smart grid, as it enables proactive operational management of electrical grids. At medium and high voltage level, the monitoring and control of the grids is done by using SCADA (supervisory control and data acquisition) systems. At low voltage level, however, SCADA systems are not widely used.

There are several reasons for this: A grid operator has many low-voltage grids in its grid area, so the rollout of SCADA systems in all low-voltage grids would represent significant investment costs. In addition, low-voltage grids are not normally equipped with the necessary ICT infrastructure that a SCADA system requires, which would further increase the investment costs. To provide the grid operator with SCADA-like functionality in low-voltage grids, PoSyCo was working on a simple first implementation of UC 2 functionality for monitoring low-voltage grids, based on the theoretical preliminary investigations around the CAM (Context Aware Monitoring) approach (see also deliverable D3.1).

Following the proposed SOFTprotection system architecture (see deliverable D4.1), a hybrid approach is chosen named “Supervision and Event Detection” (SED). This initially consists of a function centrally located in the BackEnd of the distribution system operator with the working title "distributed SCADA" (dSCADA). This function is supplemented by the “Edge Grid Watch Dog” module, which is operated in a decentralised manner in a corresponding Smart Grid Tool Kit in an intelligent grid station (iSSN intelligent secondary substation node). The aim of the application is to enable experts to provision simple monitoring and control rules in a low voltage grid. As the example in Figure 19 shows, an expert wants to be informed when the phase angles in the grid are out of the regular range.

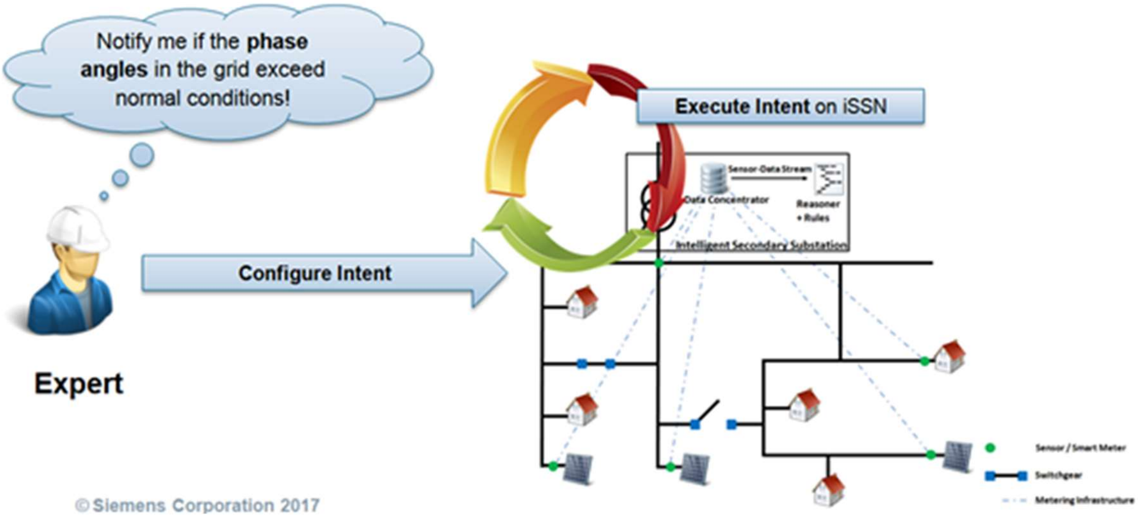


Figure 19: Overview of how a need for information is handled.

According to Figure 19 an expert formulates a rule in the form of an intent. As soon as the rule occurs, the expert and/or applications installed on the iSSN are informed about the occurrence of the rule. In this way, monitoring and control mechanisms can be provided in a low-voltage grid also in a distributed way even without a centralised SCADA system.

4.1.1.2 Sub-system architecture

Without going deep into the deployment architecture (for details see deliverables D4.1, D4.2 and D4.3) the main components are:

- the Rule Generator, running as a Spring Boot Java application on the D-SCADA node;
- the Rule Engine, running as a Go application either on the D-SCADA node or directly on the EDGE (a Smart Grid Tool Kit with SICAM A8000 CP-8050 device).

The communication between these two components is either possible by using NATS (Connective technology for adaptive edge and distributed systems) or Message Queuing Telemetry Transport (MQTT), depending on the profile in use. The setup described in this document uses NATS as shown in Figure 20.

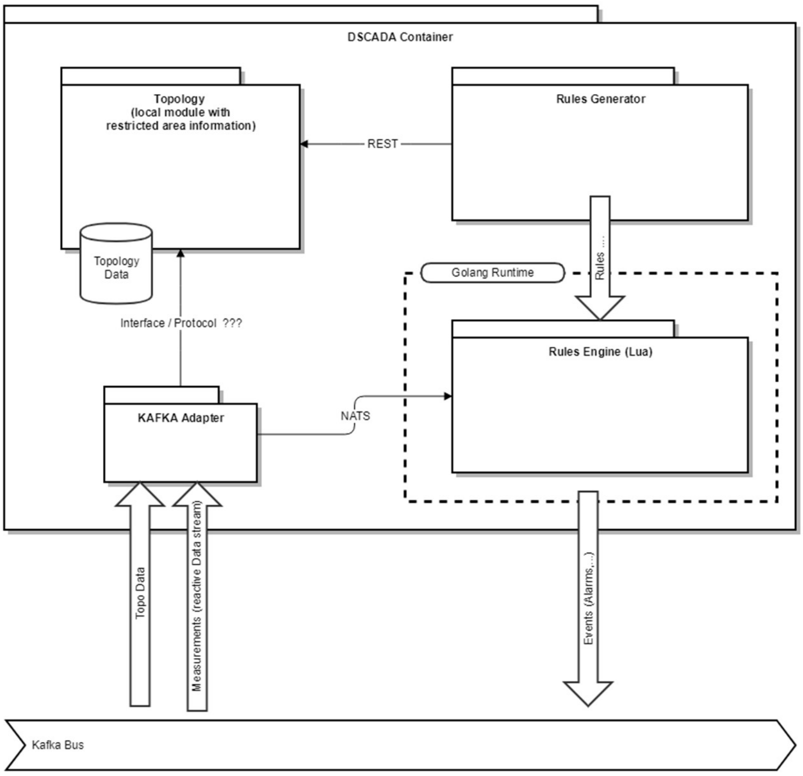
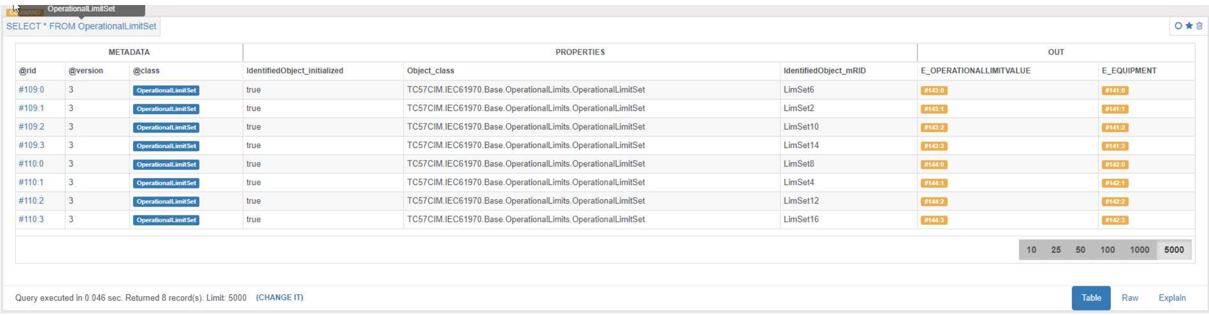


Figure 20: Sub-System architecture of Supervision and Event Detection (SED).

The rules are generated within the function block “rule generator” by using the defined limit sets in the D-SCADA OrientDB instance. So, if a consistent digital twin of the network and their assets is in place, it is not necessary to define rules manually. To show the steps of the generation, Figure 20 refers to the OrientDB Studio, which can show the contents of the database in the browser.



OperationalLimitSet

SELECT * FROM OperationalLimitSet

METADATA			PROPERTIES			OUT	
@rid	@version	@class	IdentifiedObject_initialized	Object_class	IdentifiedObject_mRID	E_OPERATIONALLIMITVALUE	E_EQUIPMENT
#109:0	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet6	#143:0	#141:0
#109:1	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet2	#143:1	#141:1
#109:2	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet10	#143:2	#141:2
#109:3	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet14	#143:3	#141:3
#110:0	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet8	#144:0	#142:0
#110:1	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet4	#144:1	#142:1
#110:2	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet12	#144:2	#142:2
#110:3	3	OperationalLimitSet	true	TC57CIM.IEC61970.Base.OperationalLimits.OperationalLimitSet	LimSet16	#144:3	#142:3

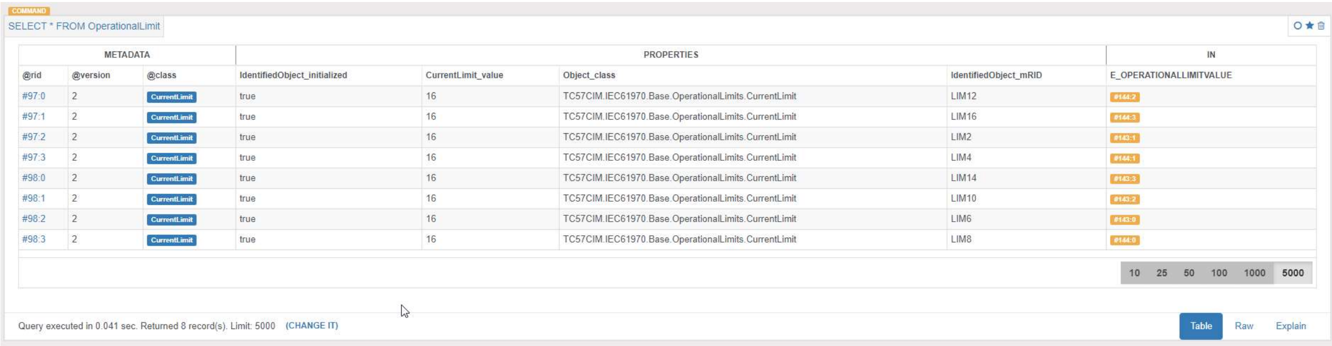
10 25 50 100 1000 5000

Query executed in 0.046 sec. Returned 8 record(s). Limit: 5000 (CHANGE IT)

Table Raw Explain

Figure 21: Query selection for automatic limit retrieving.

Nevertheless, it is possible to define individual limits. Such OperationalLimitSets are assigned to a specific equipment and can contain one or more OperationalLimits that represent the real limits to be used. The query as shown in Figure 22, also showing the assignment of limits to their sets by referring to the edge is shown as OUT from the limit sets in the figure above and as IN to the limits in the figure below.



METADATA			PROPERTIES				IN
@rid	@version	@class	IdentifiedObject_initialized	CurrentLimit_value	Object_class	IdentifiedObject_mRID	E_OPERATIONALLIMITVALUE
#97:0	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM12	#144:2
#97:1	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM16	#144:3
#97:2	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM2	#143:1
#97:3	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM4	#144:1
#98:0	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM14	#143:3
#98:1	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM10	#143:2
#98:2	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM6	#143:0
#98:3	2	CurrentLimit	true	16	TC57CIM.IEC61970.Base.OperationalLimits.CurrentLimit	LIM8	#144:0

Figure 22: Query selection for operational limits of selected IDs.

The limits are imported into the Rule Generator from the D-SCADA OrientDB instance after receiving a start signal. This signal will eventually be originating from D-SCADA by use of one of the provided communication mechanisms. To test the components independently from the D-SCADA components, this signal can be issued by using a REST interface if using the `debug` profile in the Spring Boot application:

The Rule Engine uses the Lua script provided by the Rule Generator to detect violations of the incoming measurement data. Upon detecting such violation an alarm is raised to inform an operator of this incident. Incoming Lua scripts are tested for syntactical and logical validity before accepting it, thus overriding the current active Lua script. Furthermore, the new Lua script is kept as a file which is used during startup to load the last valid Lua script into the engine.

4.1.2 Overload prevention by customer activation (UC 3)

For UC3, two algorithms were developed for the coordinated charging of electric vehicles. The first algorithm is based on the input of actual or estimated load profiles, load flow calculations and the evaluation of the results. The second algorithm is based on sparse measurements in the low-voltage grid and the evaluation of the measurement results.

4.1.2.1 Approach 1 – Load flow-based coordination of Electric Vehicle Charging Stations [6]

4.1.2.1.1 Methodology

The developed coordination algorithms are analysed using load flow simulations in a combined LV grid and costumer plant (CP) model. The model is implemented and the load flow (LF) calculations are conducted in PSS SINCAL, while the algorithms are implemented in MATLAB. Both tools are connected through the COM-interface.

Model Description / Test setup

The scope of this study is set on LV and CP level. Therefore, both levels are included in the power system model used.

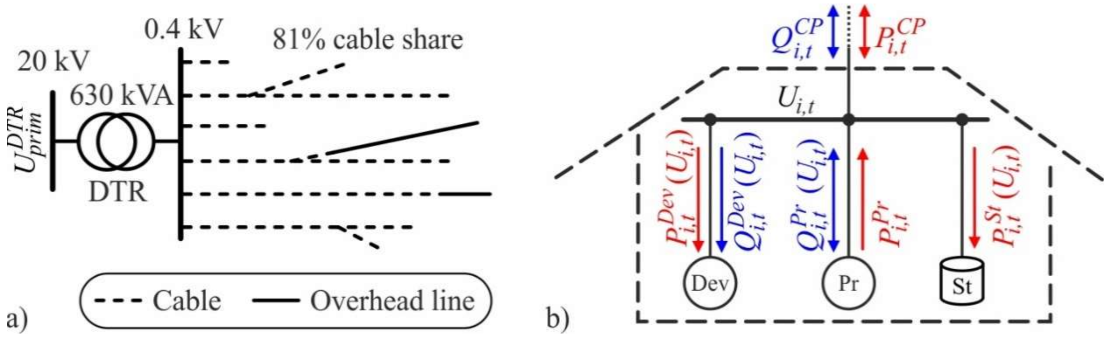


Figure 23: Power system model: (a) Simplified one-line diagram of the low voltage grid, (b) Structure of the customer plant.

<u>Low voltage grid</u>

Figure 23 (a) shows the simplified one-line diagram of the LV grid model. It represents a real urban grid with a cable share of 81 % that connects 91 residential CPs. The 20 kV / 0.4 kV distribution transformer is rated with 630 kVA and has its tap changer fixed in mid-position. The slack node is located at the distribution transformer (DTR) primary bus bar.

<u>Customer plant</u>

Figure 23 (b) shows the structure of the CP model. It includes three components: the device (Dev.), producer (Pr.), and storage (St.) model, representing the household appliances, the photovoltaic (PV) system, and the electric vehicle (EV) battery, respectively. Asymmetry is not considered. The Dev.-model power contributions depend on the CP supply voltage, (1) and (2). Therein, ZIP-coefficients from [7] are used; and power contributions at nominal voltage are defined by load profiles.

$$P_{i,t}^{Dev} = P_{nom,i,t}^{Dev} \cdot \left(1.31 \cdot U_{i,t}^2 - 1.94 \cdot U_{i,t} + 1.63\right) \quad (1)$$

$$Q_{i,t}^{Dev} = Q_{nom,i,t}^{Dev} \cdot \left(9.2 \cdot U_{i,t}^2 - 15.27 \cdot U_{i,t} + 7.07\right) \quad (2)$$

The voltage-independent active power injections of the Pr.-models are defined by one common load profile. Meanwhile, their reactive power contributions are determined by the common Q(U)-characteristic suggested as default in [8]. The maximum reactive power value is set according to (3) and (4).

$$Q_{max}^{Pr} = 0.4843 \cdot P_{max}^{Pr} \quad (3)$$

$$P_{max}^{Pr} = 5\ kW \quad (4)$$

The voltage-dependent St.-model active power consumption is determined by (5); ZIP-coefficients from [9] are used. The corresponding reactive power contributions are set to zero. (6) is used to calculate the actual state-of-charge.

$$P_{i,t}^{St} = P_{nom,i,t}^{St} \cdot \left(-0.02 \cdot U_{i,t}^2 + 0.03 \cdot U_{i,t} + 0.99\right) \quad (5)$$

$$SoC_{i,t}^{St} = SoC_{t,i-1}^{St} + \Delta t \cdot {P_{i,t-1}^{St}}/{E_{max}^{St}} \quad (6)$$

When charging, (7) and (8) determine the corresponding active power consumption at nominal voltage, and otherwise, they are set to zero.

$$P_{nom,i,t}^{St} = P_{max}^{St} \quad \ldots when\ permission\ granted \quad (7)$$

$$P_{nom,i,t}^{St} = P_{min}^{St} \quad \ldots when\ permission\ refused \quad (8)$$

The batteries are charged whenever the conditions according to (9) and (10) are satisfied.

$$SoC_{i,t}^{St} < 99\% \quad (9)$$

$$t \geq t_{start,i}^{St} \quad (10)$$

Scenario definition

Figure 24 shows the load profiles of the device- and producer-models created with the tool described in [10].

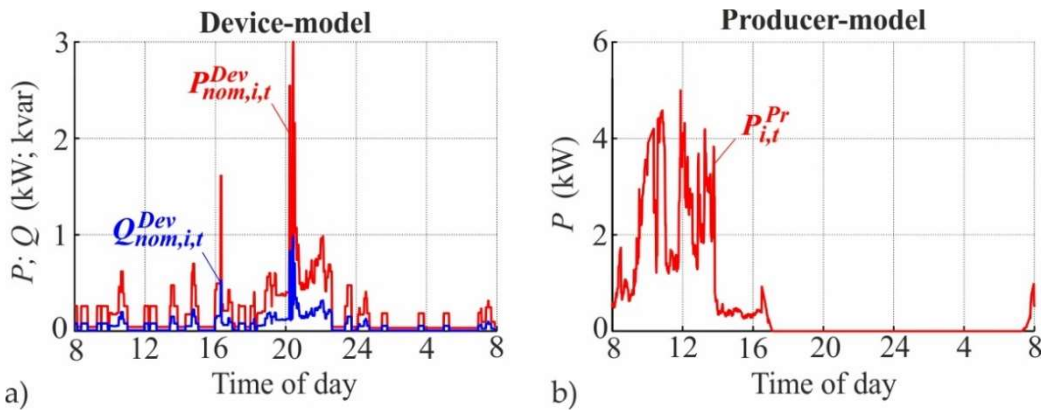


Figure 24: Actual load profiles of different CP components: (a) Dev.-model, (b) Pr.-model.

For the device-model of each CP individual profiles are used. The reactive power profile is derived from the active power one using an inductive power factor of 0.95. Meanwhile, due to the spatial proximity of all CPs connected to one LV grid, the same active power profile is used for all producer-models. This profile is characterized by spikes that are provoked by clouds. In each CP, the charging process is initiated at an individual instant of time, defined according to a normal distribution with mean value μ = 18:00 and standard deviation σ = 1 h. The selected mean value corresponds to the daytime at which most working residents arrive at their homes [11]. Initially, the SoCs (state of charge) of all EV batteries are set to 25 %. The corresponding storage capacity and the maximal and minimal charging power are set to 40 kWh, 11 kW and 5 kW, respectively. The DTR primary voltage of 1 p.u. is used.

Charge requests

Whenever the conditions according to (9) and (10) are satisfied, the algorithm executing device receives charge requests from the corresponding wall boxes (WBs). As long as no permissions are granted, they charge with the minimal power.

State estimation

The decisions of the coordination algorithms rely on estimations of the LV grid state. State estimation (SE) in LV level is a complex topic, which is beyond the scope of this study. Instead of implementing a real SE algorithm that copes with measurement errors, bad data, etc., the grid state is estimated by calculating the LF in the deposited power system model for assumed DTR primary voltage and CP power contributions. To analyse the coordination algorithms and the impact of state estimation accuracy separately, two cases are considered: ideal and non-ideal state estimation.

Ideal

The LF is calculated using the ideal power system model including the actual ZIP-coefficients and Q(U)-characteristic of the CP model components; and the actual load profiles and DTR primary voltage, (11) to (14).

$$\tilde{U}^{DTR}_{prim} = U^{DTR}_{prim} \quad \textbf{(11)}$$

$$\tilde{P}^{Dev}_{nom,i,t} = P^{Dev}_{nom,i,t} \quad \textbf{(12)}$$

$$\tilde{Q}^{Dev}_{nom,i,t} = Q^{Dev}_{nom,i,t} \quad \textbf{(13)}$$

$$\tilde{P}_{i,t}^{Pr} = P_{i,t}^{Pr} \quad (14)$$

<u>Non-ideal</u>

The ideal grid model, but with incomplete CP model parameters, is available for the LF calculations. While the exact Q(U)-characteristic is known, the ZIP-coefficients are unknown; constant power models are employed instead of using (1), (2) and (5). The exact DTR primary voltage and estimated load profiles are used. For all device-models the standard load profile [12] shown in Figure 25 (a) is used. The profile is scaled to reach the same maximum value as the mean of the actual device-model active power consumptions. The appearance of clouds and thus the spikes on the load profile of PV-systems can hardly be forecasted. Therefore, the profile resulting from the clear sky radiation is used to estimate the producer-model active power injections, Figure 25 (b).

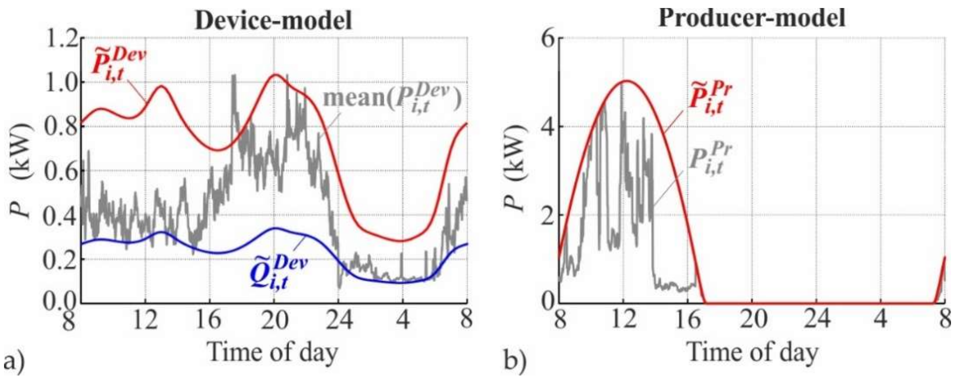


Figure 25: Estimated load profiles of different CP components: (a) Dev.-model, (b) Pr.-model.

4.1.2.1.2 Coordination algorithms

The analysed coordination algorithms rely on the generalised flow chart shown in Figure 26. As the algorithms reduce the power consumption of WBs when potential congestions are detected, they can mitigate loading limit violations provoked by downstream active power flows, i.e., from DTR to LV feeder end, in fact regardless of the reactive power flow directions. When starting the algorithms, all charge requests are initially permitted. To prepare the LF calculations, the active power contributions of the St.-models are specified according to (15), (16), (17) and the present permissions; and the reactive ones are set to zero.

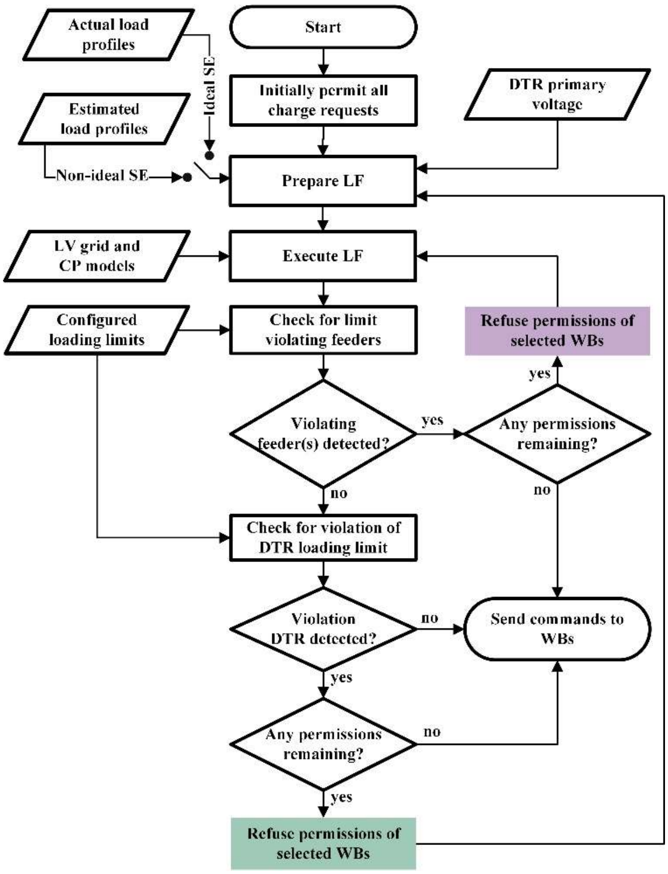


Figure 26: Generalised flow chart of coordination algorithms.

$$\tilde{P}_{i,t}^{St} = P_{max}^{St} \quad \ldots when\ request\ is\ presently\ permitted \qquad \textbf{(15)}$$

$$\tilde{P}_{i,t}^{St} = P_{min}^{St} \quad \ldots when\ request\ is\ presently\ refused \qquad \textbf{(16)}$$

$$\tilde{P}_{i,t}^{St} = 0 \quad \ldots without\ request\ from\ CP_i\ at\ t \qquad \textbf{(17)}$$

Meanwhile, the power contributions of the device and producer models are set for ideal and non-ideal SE according to the actual and estimated load profiles and DTR primary voltage, respectively. Subsequently, the LF engine uses the LV and CP models to calculate the grid state that would result with the present permissions. If violations of the configured line segment loading limits are detected, the permissions of selected EV charges are refused, and the preparation and execution of LF is repeated. This cycle is repeated until no violations of the line segment loading limits remain, or all permissions are refused. In the latter case, the algorithms are not sufficient to eliminate all limit violations, and total charging prohibition should be considered. When no limit violations occur in the feeders, the actual LF results are examined for violations of the configured DTR loading limit. If limit violations are detected and permissions are still remaining, the permissions of selected WBs are refused and the LF preparation and execution is repeated. Otherwise, the commands are sent to the WBs. Different options may be used for the selection processes of WBs for permission refusal, i.e. for the process-steps represented by the two coloured boxes Figure 26. Three options are investigated: one command per LV grid, one per LV feeder, and one per WB.

One command per LV grid

The same command is sent to all WBs connected to the LV grid. When limit violations in line segments or the DTR are detected, the permissions of all WBs are refused (both coloured boxes).

One command per LV feeder

The same command is sent to all WBs connected to one LV feeder. When a violating feeder is detected, the permissions of all thereto WBs are refused (violet box). When no feeder but the DTR violates its limit, all WBs connected to one random feeder are selected for permission refusal (green box).

One command per WB

To each WB is sent an individual command. When a violating feeder is detected, the permission of one random WB connected behind the most distant (from DTR) violating line segment is refused (violet box). When no feeder but the DTR violates its limit, one random WB is selected for permission refusal (green box).

4.1.2.1.3 Results

The execution period of the algorithms is set to five minutes, i.e. the algorithms are executed each 5th minute. It is assumed that the resulting commands are available at the WBs in the next simulated instant of time, i.e. by no later than one minute. The configured loading limits of the DTR and line segments are set to 90 %. Table 1 summarizes the energy loss in DTR and all line segments and the average charge time per EV for all simulated coordination setups.

Table 1: Energy loss and average charge time per EV for all simulated coordination setups

SE	Commands	Energy loss (kWh)	Average charge time per EV (min)
-	-	181.39	162.07
Ideal	One per LV grid	119.17	311.73
	One per LV feeder	135.30	246.49
	One per WB	144.32	222.22
Non-ideal	One per LV grid	118.88	312.78
	One per LV feeder	132.99	254.85
	One per WB	139.80	233.98

Figure 27 shows the simulation results without coordination. As Figure 27 (a) illustrates, violations of the configured and nominal loading limits appear between 18:05 and 21:14, and between 18:12 and 20:55, respectively. The EV batteries are charged between 14:58 and 23:45, Figure 27 (b). The charging with maximal power provokes linear increases of the battery SoCs, an average charge time of 162.07 min, and energy losses of 181.39 kWh. The grid state at 19:42, where the maximal loading value appears, is shown in Figure 27 (c). The loading limits are violated in the foremost line segments, and the lower voltage limit is violated at one feeder end.

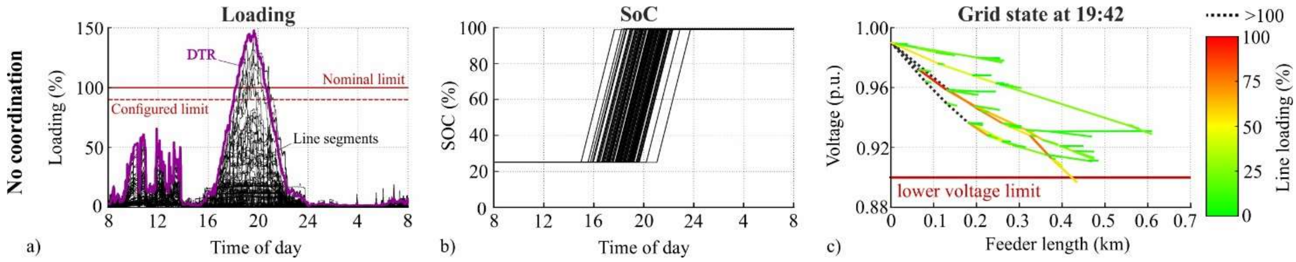


Figure 27: Simulation results without coordination: (a) Loading of DTR and all line segments; (b) SoC of all EV batteries; (c) Grid state at 19:42.

Figure 28 shows the simulation results for the coordination setups with ideal SE. No limit violations appear when one command per LV grid is used, Figure 28 (a). All permissions are refused between 18:04 and 24:14, increasing the average charging time to 311.73 min, and decreasing the energy loss to 119.17 kWh. In Figure 28 (b), temporary violations of the configured and nominal loading limits appear. The feeder-wise permission refusal provokes an average charging time of 246.49 min, and an energy loss of 135.30 kWh. When individual commands are used for each WB, the maximum loading sticks close to the configured limit, Figure 28 (c). The result is an average charging time of 222.22 min and an energy loss of 144.32 kWh.

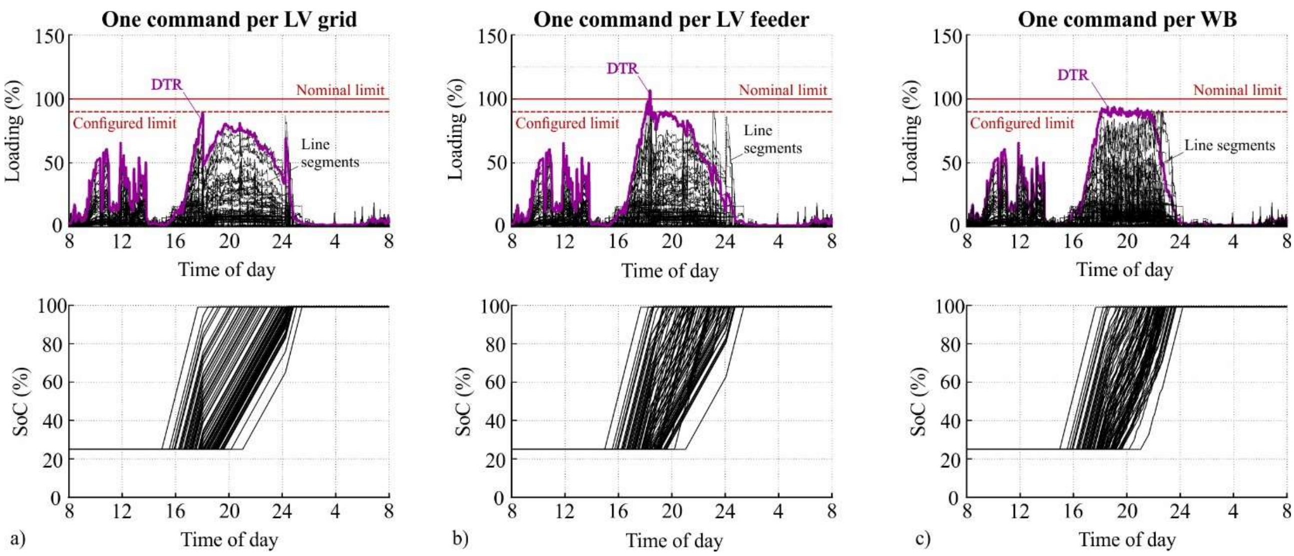


Figure 28: Loading of DTR and all line segments and SoCs of all EV batteries with ideal SE and different coordination algorithms: (a) One command per LV grid; (b) One command per feeder; (c) One command per wallbox.

The results of the coordination setups with non-ideal SE are shown in Figure 29. The use of one command per LV grid yields similar result for the ideal and non-ideal SE, except that permissions are refused slightly longer in the latter case, Figure 29 (a). This provokes an average charge time of 312.78 min and an energy loss of 118.88 kWh. When one command per feeder is used, the configured but not the nominal loading limit is temporarily violated, Figure 29 (b). With this coordination setup, the charge time averages to 254.85

min, and the losses add up to 132.99 kWh. Regarding the use of individual commands, Figure 29 (c) shows that the maximum loading does not stick to the configured limit as close as in the case of ideal SE. The average charging time of 233.98 min is reached, provoking an energy loss of 139.80 kWh.

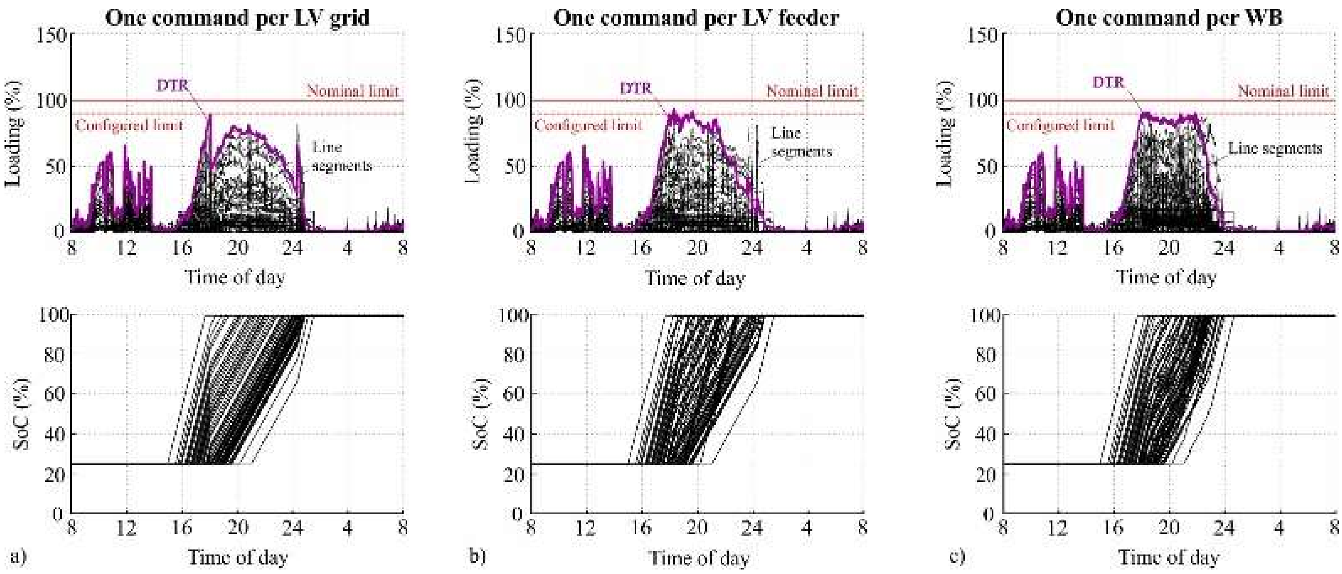


Figure 29: Loading of DTR and all line segments and SoC of all EV batteries with non-ideal SE and different coordination algorithms: (a) One command per LV grid; (b) One command per LV feeder; (c) One command per WB

4.1.2.2 Approach 2 – Sparse Measurement-Based Coordination of Electric Vehicle Charging Stations [13]

4.1.2.2.1 Methodology

The detection of feeder congestions is essentially aggravated by the presence of distributed generation. In the past, when the power flows were of unidirectional character, the maximal line segment loading appeared always in the foremost segments, i.e. the line segments connected directly at distribution substations. Nowadays, the distributed power feed in may provoke the maximum loading somewhere along the feeders, making the detection of congestions exclusively based on distribution substation measurements impracticable.

Mathematical Formulation

European LV grids are typically of a radial structure, and the costumer plants (CPs) are connected somewhere along the feeders [14]. The detailed structure of a LV grid with F feeders is schematised in Figure 30 (a). To each feeder f are connected N_f customer plants that may inject and absorb active and reactive power. Currents with different magnitudes flow through each line segment, provoking the maximum line loading somewhere along the feeders. The calculation of each line segment's loading in close-to-real-time is possible only when state estimation is applied.

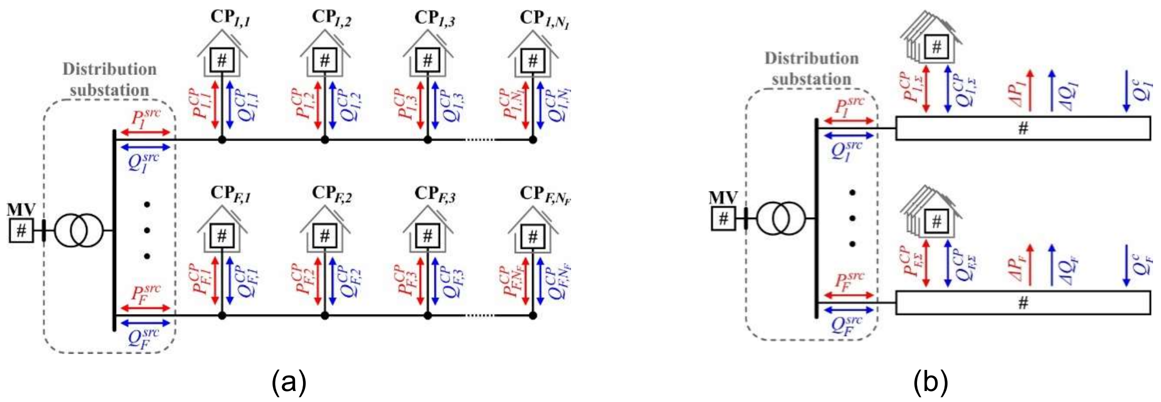


Figure 30: Structure of low voltage grids: (a) detailed, (b) simplified.

Another option to detect congestions is to estimate the maximum line loading by neglecting the detailed structure of the low voltage feeders. This concept is illustrated in Figure 30 (b), wherein each feeder is represented by the #-symbol, indicating that their detailed structure is not relevant for the calculation procedure.

Based on this concept, which is described and documented in detail in [13], (18) and (19) allow for estimating the maximum line segment loading ($Loading_f^{max}$) of the feeder *f*.

$$S_f^{src,in} = \sqrt{\left(P_f^{src,in}\right)^2 + \left(Q_f^{src,in}\right)^2} \quad (18)$$

$$Loading_f^{max} = S_f^{src,in} / \left(\sqrt{3} \cdot U_f^{min} \cdot I_f^{th,min}\right) \quad (19)$$

The estimated maximum line segment loading and the measurement of the active power at feeder beginning are used to specify the feeder related congestion flag (CF_f), which indicates whether a potential congestion is detected (true) or not (false). It is set to true, when (20) and (21) are satisfied, and otherwise to false.

$$Loading_f^{max} \geq Loading_f^{limit} \quad (20)$$

$$P_f^{src} > 0 \quad (21)$$

where $Loading_f^{limit}$ is the limit of the line segment loading, specified by the grid operator. (21) roots on the assumption that the feeder is sufficiently dimensioned to cope with the installed PV rating, so that upstream (from feeder end to distribution substation) active power flows do not cause an exceedance of the specified loading limit. This assumption is justified by the following considerations: Due to the spatial proximity of CPs connected to one LV grid, their PV systems always inject simultaneously. The resulting upstream active power flows cannot be reliably reduced by demand response, as the availability of the necessary resources (e.g., EVs connected to EVCSs (Electric Vehicle Charging Stations), whose battery is not fully charged) is not guaranteed. The reduction of the PV infeed itself means a waste of renewable energy that should be avoided in any case. Therefore, the only way to allow the full PV injection while avoiding violations of the defined loading limit is to sufficiently dimension the feeder.

Application to real LV grid

When applying the algorithm to coordinate the EVCSs connected to a real low voltage grid, several data must be acquired to enable the estimation of the maximum line segment loading. As shown below, this data is derived from the grid data, measurements, and estimations.

$I_f^{th,min}$	derived from grid data
$P_f^{src,in}$, $Q_f^{src,in}$ and U_f^{min}	derived from measurements
$P_{f,i}^{CP,in}$, $Q_{f,i}^{CP,in}$ and Q_f^c	estimated

Grid Data

Low voltage feeders typically consist of main and side strands. The side strands usually connect one CP to the main strand, which establishes the connection of all side strands to the distribution substation. The side strands are typically of smaller cross-section (e.g., 50 mm²) than the main ones (e.g., 150 mm²), and thus possess lower thermal limit current. While the side strands transmit only the power contributions of the directly connected CP, the main strand is loaded by the power contributions of many CPs, see Figure 31.

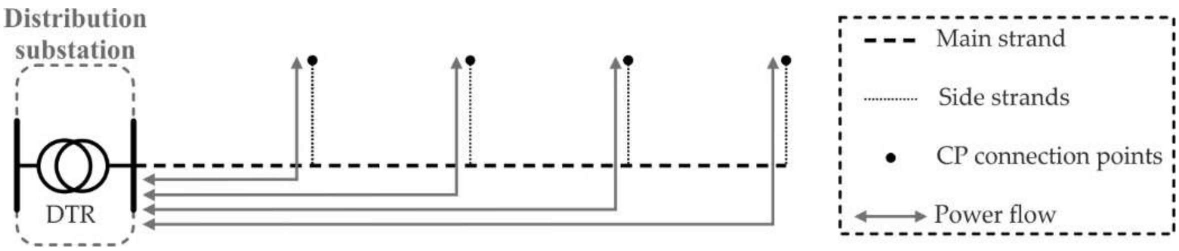


Figure 31: Current flows through a low voltage feeder with main and side strands.

Consequently, reducing the simultaneity of the CP power contributions by using coordinated electric vehicle charging cannot unload the side strands but only the main ones. Therefore, as specified in (22), the minimal thermal limit current is determined by considering only the line segments of the main strands

$$I_f^{th,min} = \min_{l_m}\left(I_{f,l_m}^{th,main}\right) \qquad \textbf{(22)}$$

where $I_{f,l_m}^{th,main}$ is the thermal limit current of line segment l_m, which is part of the main strands of feeder *f*.

Measurements

The number of measurement devices should be kept as low as possible to reduce the associated capital expenditures. Figure 32 illustrates the suggested placement of the measurement devices on one representative real low voltage feeder. The active and reactive power flowing into the feeder and the voltage at the secondary bus of the DTR are measured within the distribution substation. In addition, the voltages are measured close to the feeder end. When the feeder is branched and has several ends, more voltage measurements may be necessary.

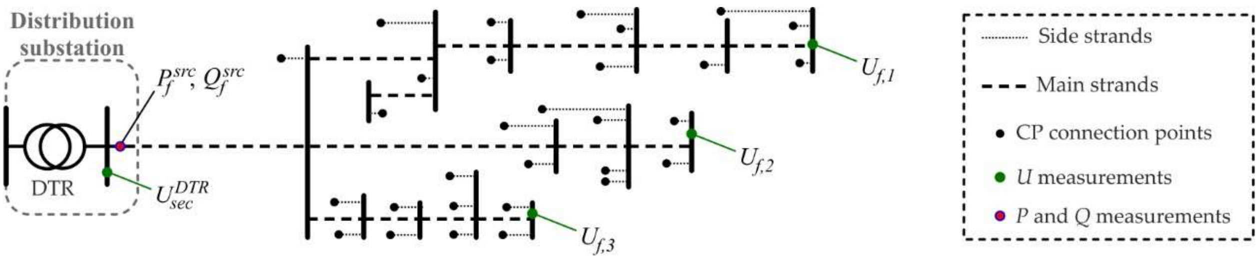


Figure 32: Suggested placement of measurement devices on one representative real LV feeder.

The active and reactive power injected by the distribution substation is directly derived from the corresponding power measurements using formulation see [13]. At low voltage level, the CPs are typically distributed homogeneously along the feeders, and their power contributions lie within the same order of magnitude. All PV systems inject active power simultaneously. If no bulk producers (e.g., excessively rated PV system) or consumers (e.g., garage with many EVCSs) are connected in the central portion of the feeder, the voltage usually increases or decreases monotonically along each feeder. In this case, measuring the voltages at the feeder beginning and end is sufficient to capture the minimal voltage value. When bulk producers or consumers are involved, the voltage at their connection points should be measured additionally. As in (23), the minimal feeder voltage is derived by selecting the minimal value of the corresponding measurements.

$$U_f^{min} = \min\left(\min_j\left(U_{f,j}\right), U_{sec}^{DTR}\right) \quad \textbf{(23)}$$

<u>Customer Profiles (Estimation)</u>
The CP Profiles were estimated according to [13].

Detection of DTR Congestions

The loading of the DTR (*Loading*^{DTR}) is calculated based on the measurements in the distribution substation using (24).

$$Loading^{DTR} = \sqrt{\left(\sum\nolimits_{\forall f} P_f^{src}\right)^2 + \left(\sum\nolimits_{\forall f} Q_f^{src}\right)^2} \Big/ S_{rated}^{DTR} \quad \textbf{(24)}$$

where S_{rated}^{DTR} is the rated apparent power of the DTR. When (25) and (26) are satisfied, the DTR-related congestion flag (CF_{DTR}) is set to true, and otherwise to false.

$$Loading^{DTR} \geq Loading_{DTR}^{limit} \quad \textbf{(25)}$$

$$\sum\nolimits_{\forall f} P_f^{src} > 0 \quad \textbf{(26)}$$

4.1.2.2.2 Coordination Algorithms

The developed coordination strategy involves two components: the central controller and the distributed EVCSs. It is designed to prevent enduring overload of LV grid equipment based on sparse measurements and a simple communication infrastructure, which allows transmitting one Boolean value from the central controller to all EVCSs connected at the same feeder (unidirectional). State estimation is not required. Both the central controller and the distributed EVCSs are intended to execute algorithms.

Figure 33 (a) shows the algorithm 'specify permissions' that is executed by the central controller. It specifies one Boolean control signal per feeder - denoted as feeder permission - that indicates whether the EVCSs connected to the corresponding feeder shall charge with reduced (false) or full power (true). The DSO configures the algorithm, i.e. sets the loading limits of the DTR and the line segments, which shall not be exceeded during grid operation. The algorithm is executed periodically, e.g., each 5th minute, to impose low requirements on the associated communication infrastructure. As the first step, the DTR is checked for congestion as described in section 0. When the DTR-related congestion flag is true, all feeder per-missions are set to false and are sent out to the EVCSs. Otherwise, each feeder is consecutively checked for congestions according to the procedure described in 4.1.2.1. If the feeder-related congestion flag is true, the corresponding feeder permission is set to false, and vice versa. When all feeders are checked for congestions, all feeder permissions are sent out to the EVCSs.

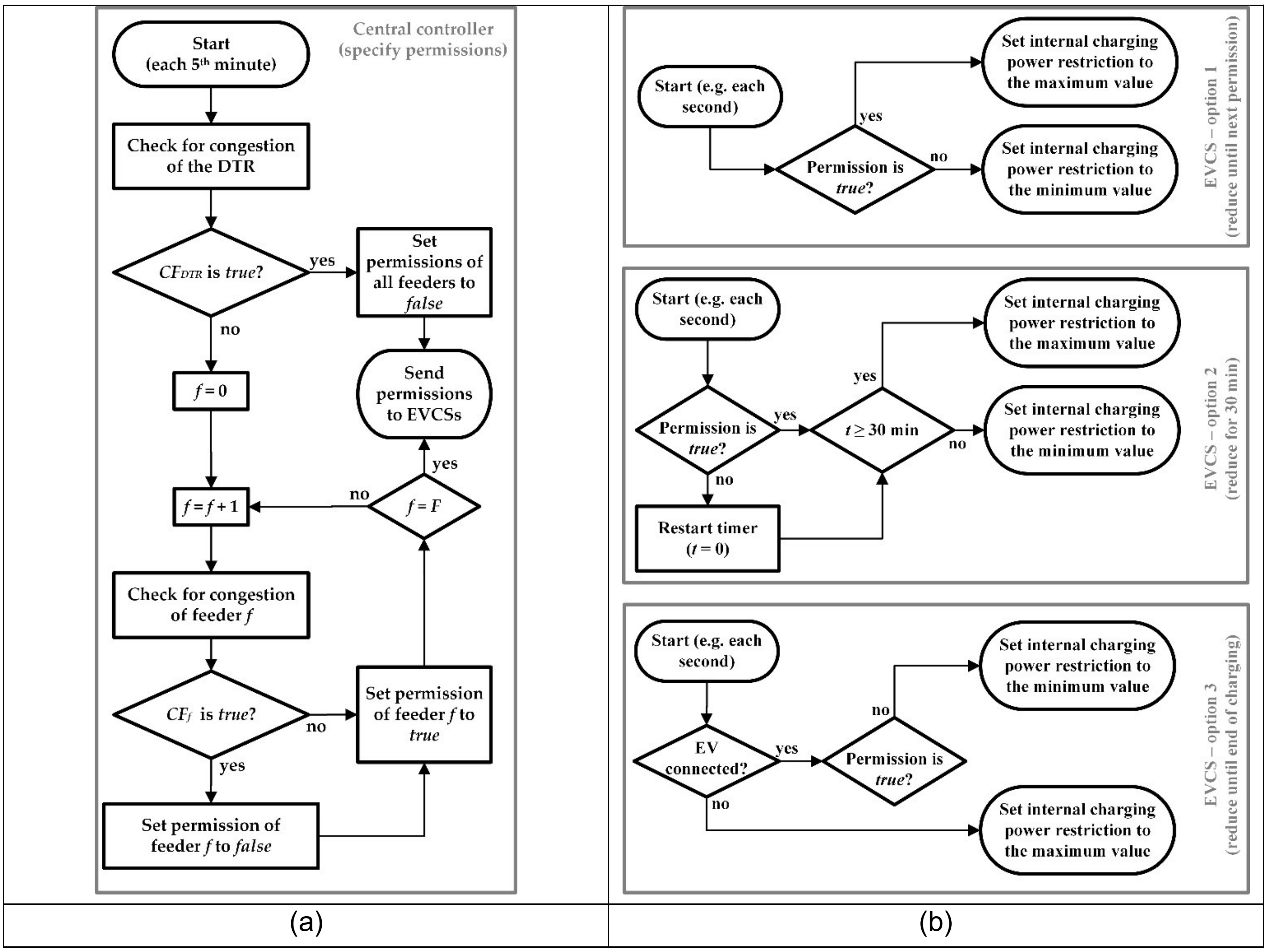


Figure 33: Overview of the coordination algorithms executed by different devices: (a) central controller, (b) different options for the distributed electrical vehicle charging stations (EVCS).

Each EVCS periodically (e.g., each second) executes an algorithm to finally set the internal charging power restriction depending on the actual value of the corresponding feeder permission. The execution period must be shorter than that of the central controller and may be set very short as no further communication is required. Three different options for this algorithm are shown in Figure 33 (b): reduce until next permission, reduce for 30 min, and reduce until the end of charging. The impact of each option on the behavior of the LV grid is analysed separately in this study.

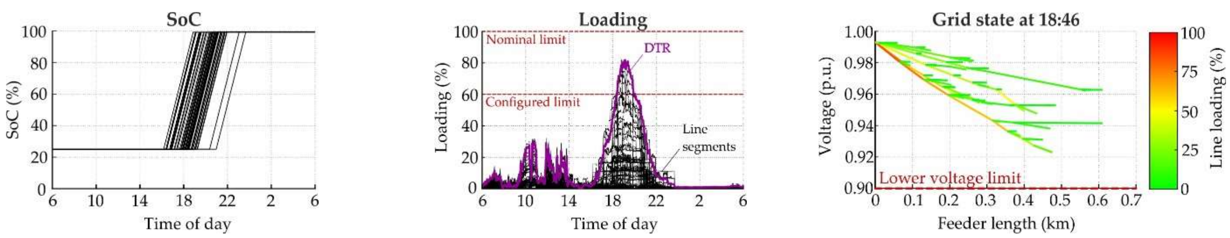
- Reduce until next permission
  The EVCSs update their internal charging power restrictions each time new per-missions are received.
- Reduce for 30 minutes
  Option 2 allows charging with maximal power only when the permission is true for at least 30 minutes.
- Reduce until end of charging
  This algorithm firstly checks if an EV is currently connected to the EVCS. If this is the case, and a false permission is received, the charging power restriction is reduced to the minimal value until the EV is disconnected.

4.1.2.2.3 Results

The test setup used is the same as for approach 1 (4.1.2.1.1), however, different ZIP coefficients were used for the two approaches. Details are described in [15] and [13].
Different evaluations were made analyzing charging in the morning, during the day or in the evening hours [13]. Exemplary the results for charging in the evening are shown.

Simultaneous charging in the evening without any coordination

Figure 34 shows the simulation results for the scenario ‘Simultaneous charging in the evening’ without any coordination. The uncoordinated charging with 11 kW per EVCS leads to linear increasing SoCs (state of charge) of the EV batteries between 16:10 and 23:40, Figure 34 (a). The intensive consumption provokes high loadings of the DTR and all line segments, Figure 34: Simulation results for the scenario ‘Simultaneous charging in the evening’ without any coordination: (a) SoCs of all EV batteries; (b) equipment loading; (c) grid state at 18:46.
(b). They exceed the specified limit between 18:16 and 20:02, while the maximum value appears at 18:46. The resulting grid state at the moment of maximal loading is illustrated in Figure 34 (c). The voltage profiles of all feeders are plotted on the y-axis, while the line segment loading is presented by color shades from green for 0% loading to red for 100% loading. The diagram shows that no violations of the lower voltage limit and the nominal loading limit appear. The energy losses and the average charging time amount to 56.65 kWh and 161 min, respectively.



(a) (b) (c)

Figure 34: Simulation results for the scenario 'Simultaneous charging in the evening' without any coordination: (a) SoCs of all EV batteries; (b) equipment loading; (c) grid state at 18:46.

To examine the behavior of the sparse measurement-based approach to detect feeder congestions, the line segment loadings are shown separately for each feeder in Figure 35. Furthermore, the corresponding congestion flag is shown in orange solid lines for estimated values of $P_{(f,i)}^{Pr}(t)$, and in dashed grey lines for the exact ones. In both cases, congestions are detected only for feeders 1, 3, and 4. The inaccurate estimation of the PV injection impacts the congestion flag of feeder 4, while no differences occur for the other feeders.

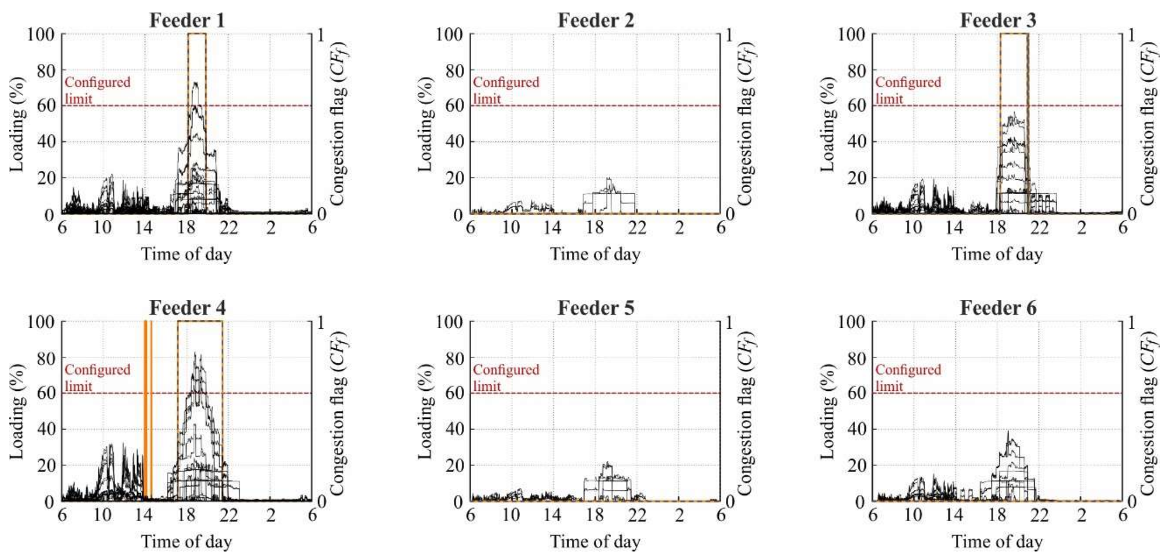


Figure 35: Line segment loadings and congestion flag of different feeders for the scenario 'Simultaneous charging in the evening' without any coordination.

For feeder 1, the congestion flag is true between 18:09 and 19:50, while the configured loading limit is exceeded from 18:26 to 19:20. This corresponds to a detection accuracy of 92.92%. Regarding feeder 3, congestions are detected between 18:18 and 20:53, and at 20:59, although no limit violations appear at all. However, an accuracy of 89.11% is achieved in this case. Feeder 4 exceeds the configured loading limit between 18:16 and 19:55, while congestions are detected from 13:59 to 14:08, at 14:36, and from 17:09 to 21:27, yielding an accuracy of 81.26% when the PV injection is estimated. The exact knowledge of the PV production eliminates the incorrect detections in the early afternoon, improving the detection accuracy to 82.03%. The limit compliance of feeders 2, 5, and 6 is correctly detected with an accuracy of 100%.

Simultaneous Charging in the Evening with coordination

Figure 36 shows the loadings of the DTR and all line segments as well as the SoCs of all EV batteries for the scenario 'Simultaneous charging in the evening' with coordination and different algorithms at the EVCS level. Updating the internal charging power restrictions of EVCS each time new permissions are received provokes fluctuating power consumptions, which increase the SoCs of the corresponding EV batteries with an alternating gradient (Figure 36 (a), at the bottom). As the consequence, the LV equipment loading oscillates in the evening hours, causing numerous short-term violations of the configured DTR and feeder loading limits between 18:26 and 20:09 (Figure 36 (a), at the top). The corresponding energy losses and the average charging time per EV amount to 44.54 kWh and 233.43 min, respectively.

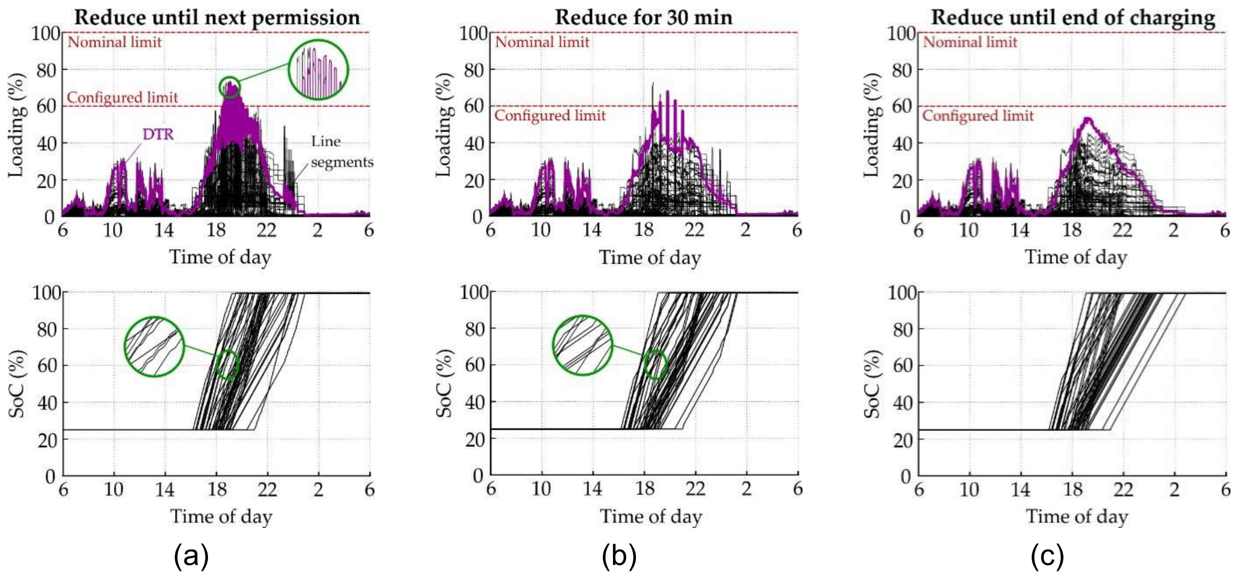


Figure 36: LV equipment loading and SoCs of all EV batteries for the scenario 'Simultaneous charging in the evening' with coordination and different algorithms in EVCS level: (a) reduce until next permission; (b) reduce for 30 minutes; (c) reduce until end of charging.

If charging with maximal power is allowed only when the permission is true for at least 30 minutes, the related power consumptions fluctuate slowly, leading to low-frequency oscillations of the LV equipment loading, Figure 36 (b). Four loading peaks occur that violate the configured loading limits. In this case, the energy losses and average charging time reach 39.38 kWh and 273.89 min, respectively. In (c), where the reception of a false permission reduces the power until the EV battery is fully charged, the loading limits are satisfied throughout the whole day. Energy losses are reduced to 37.80 kWh by prolonging the average charging time to 285.50 min.

Impact on Charging Times and Energy Losses

The presented algorithms for the coordination of EVCSs modify the loading of the LV equipment by manipulating the SoC-curves of the EV batteries. In further consequence, this affects the energy losses of the grid and the average charging time per battery. As the permissions are specified without conducting any load flow simulations, their impact on the resulting system state is unknown in advance, giving the concept a "try-out-and-observe" character. In principle, this strategy is applicable, as lines and transformers endure short-term violations of their thermal limits without sustaining significant deterioration. The overall system behavior greatly differs between the investigated EVCS-internal algorithms and the simulated scenarios. The energy losses and the average charging time in all simulated setups are overviewed in Table 2. Each coordination algorithm prolongs the EV battery charging on average, which reduces the associated grid losses in further consequence.

Table 2: Energy losses in the LV grid and average charging time per EV battery

Scenario	Coordination Algorithm		Energy Loss in kWh	Average Charging Time in min
	Central Controller	Distributed EVCSs		
Simultaneous charging in the evening	None	None	56.65	161.00
	Specify permissions	Reduce until next permission	44.54	233.43
		Reduce for 30 min	39.38	273.89
		Reduce until end of charging	37.80	285.50

Updating the EVCS-internal charging power restrictions each time new permissions are received provokes severe oscillations of the charging power and the LV equipment loading in all simulated scenarios. This behavior is to be interpreted as many trials, which are observed to be inappropriate by the central controller in its next algorithm execution. Due to numerous intervals in which the EVCSs charge with maximal power, the resulting average charging time is - compared to the other algorithm options - relatively low, while the energy losses are relatively high. The number of trials is significantly decreased when a delay of 30 minutes is implemented in the algorithm, reducing the frequency of the oscillations. This prolongs the periods of charging with minimal power, thus increasing the average charging time and reducing the associated losses. When the charging power is reduced until the end of the charging process as soon as dictated by the central controller, the oscillations are completely avoided. The maximal average charging time and the lowest energy loss is calculated for this case.

The algorithms ‘reduce until next permission’ and ‘reduce for 30 min’ are not sufficient to eliminate the violations of the configured loading limits when the customers simultaneously charge their EV batteries in the evening hours. If the simultaneity is relatively low and no limit violations appear at all, all algorithms reduce the charging power of at least some EVCSs unnecessarily. Reducing the power consumption until the corresponding battery is fully charged is the only option that establishes compliance to the configured loading limits in all simulated cases.

4.1.2.3 Discussion and Outlook for UC3 Approach 1 and Approach 2

The results show that all proposed methods and all tested algorithms reliably detect congestions and effectively mitigate transformer and line segment overloading. However, in the case of sparse measurement-based congestion detection in some cases false positive overload detection occurs when none are present.

The results within approach 1, where customer activation is performed with different structural granularity, show, that the average charging time is lower when specifying more individual commands (higher granularity). This comes with a higher energy loss. The accuracy of the state estimation has no influence on the average charging time, at least in the investigated scenarios, where each customer owns a 11 kW wall box.

Within approach 2, a minimal detection accuracy of 73.07 % is found across all simulations. The coordination algorithms react to detected congestions by reducing the power consumption of the corresponding charging stations. When properly designed, this strategy avoids congestions reliably but conservatively. Therefore, unnecessary reduction of the charging power may occur. In total, the solution offers an acceptable performance while requiring low implementation effort; no complex adaptions are required after grid reinforcement and expansion.

4.1.3 Overload prevention by temporary meshing (UC4)

A possible challenge for future low-voltage grids can be a local line overload situation. One solution to counteract this can be temporary meshing. To implement such a temporary meshing approach, an algorithm called Switching Management Module (SMM) was developed. The following sections describe this algorithm in more detail.

4.1.3.1 Switching Management Module (SMM)

To implement a temporary meshing functionality, an individual method was developed allowing an automated grid reconfiguration execution. The core of the concept is the SMM which is basically shown in Figure 37 as an overall system overview.

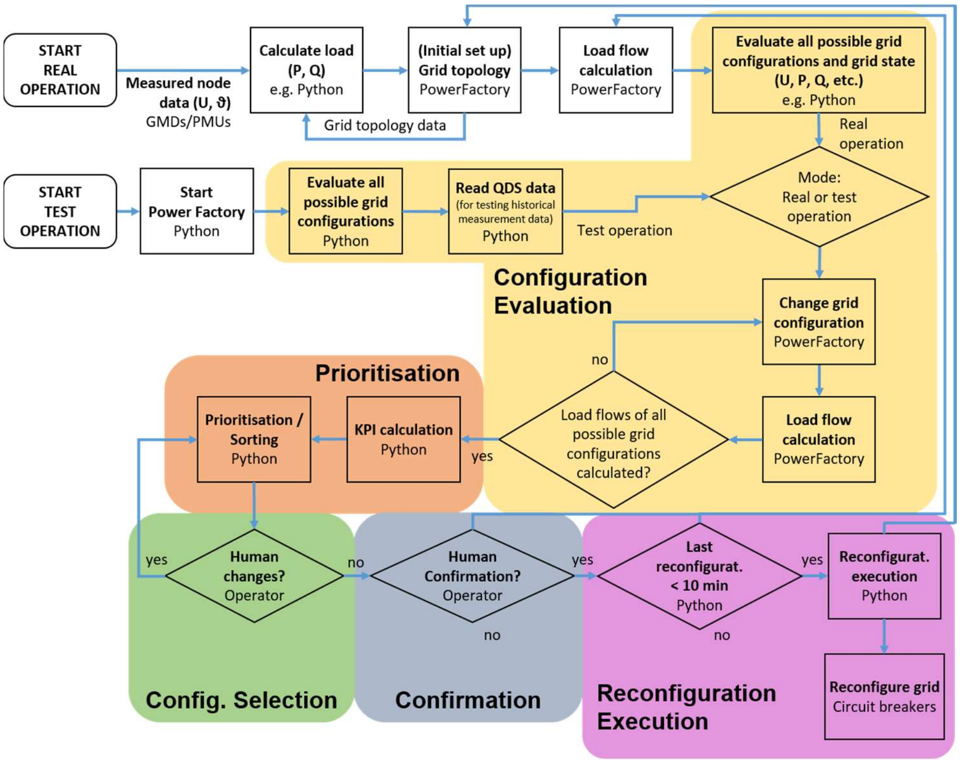


Figure 37: System Overview of Switching Management Module (SMM) and its relationships [16], [17].

On one hand, the colored main components of the SMM can be seen in the figure, and on the other hand, the different external components for real operation as well as for test operation are visible.

The Switching Management System consists of the following five sub-modules: Configuration Evaluation, Prioritization, Configuration Selection, Confirmation and Reconfiguration Execution.
The following subsections describe the basic initialization (pre-settings, parameter) of the system and the five mentioned sub-modules of the SMM regarding their sequence and their functionality.

- ***Initialize automatic reconfiguration:***
  After the first SMM system start by the operator the whole parameter and pre-settings, essential to run the system, are initialized.

- ***Configuration Evaluation:***
  SMM starts with evaluating all possible grid configurations out of the existing grid topology together with all its corresponding load flow results. Thereby the following sequence is considered:
    - Availability check of installed devices to execute a grid reconfiguration (e.g., available lines, circuit breaker);
    - Evaluate possible grid configurations (binary variation of all existing switches);
    - Load flow calculation of evaluated grid configurations.

- ***Prioritisation:***
  After the evaluation of all possible grid configurations they are sorted based on the initially defined pre-settings and can be, e.g., based on
    - the various grid configurations associated load flow results (e.g., to reduce overload situation, to minimise losses) or
    - other parameter data (e.g., to relieve a device).

- ***Configuration Selection:***
  Based on the derived prioritisation, the operator chooses a specific grid configuration based on two principal options:
    - Automatic selection of a grid configuration based on the highest priority determined by the SOFTprotection system;
    - Manual selection of a grid configuration determined by the operator with expert knowledge of working processes and workflows, e.g., based on planned maintenance work or other reasons.

- ***Confirmation:***
  To designate a responsible person for the system’s automatic switching execution, the operator must confirm the reconfiguration procedure.

- ***Reconfiguration Execution:***
  After the operator’s confirmation, the SOFTprotection system automatically reconfigures the LV grid by sending specific switching commands to the affected circuit breaker(s) – assuming that such will exist in the future. To avoid unsupplied customers, a ‘make-before-break’ routine must be implemented.

It is a prerequisite that a corresponding digital representation of the real grid in form of a grid model is available.

4.1.3.2 Simulation scenarios

As shown in Figure 37 for test operation of SMM the grid’s state is evaluated by using historical measurement data. These are real measurement data or generated ones, depending on the used test grid (for details see deliverable D3.3). This data set is enriched by specific defined scenarios to transform historical load situation to possible future ones. Mainly two scenarios are defined for simulations and testing the developed algorithm:

Scenario I, which is the basic grid scenario:

- 70 % of load nodes have PV (nominal power is 56 % of respective load);
- 40 % of load nodes have EVCS (40 % of respective load);
- 40 % of load nodes have heat pumps (HP) (25 % of respective load);
- 60 % of PV are PV-storage (40 % of respective load).

Scenario II, which is the same as scenario I but without any PVs (distributed generation):
A list of the elements (lines) under the highest load and with the highest occurrence is defined by running quasi-dynamic simulation (QDS) in the corresponding LV grid over one year with a 15 minutes time interval. The nominal values of the respective load are obtained using a feeder load scaling approach which distributes the aggregated measurements to all loads according to their nominal power values and time characteristics. The time series used here for loads, PV, EVCS, HP and PV-storage are generated based on the 'SimBench' dataset [18] to derive normalised profiles. These QDS-based preliminary analyses form the input for the SMM algorithm described in the following.

4.1.3.3 SMM Algorithm

Basically, the algorithm consists of the mentioned SMM initialisation as well as the five SMM sub-modules, see also 4.1.3.1 and Figure 37. The most important of these five sub-modules are (a) Configuration Evaluation and (b) Prioritisation, so they will be discussed in detail further below, see also [16] and [17].

(a) Configuration Evaluation

After initialisation, the developed algorithm analyzes the grid by its available circuit breakers to evaluate all possible configurations. During PoSyCo a distinction was made between grid topology and grid configuration: The *grid topology* is understood to be the totality of all equipment available in the grid (transformers, lines, circuit breakers) with which the various *grid configurations* (switching states) can be achieved.
This evaluation is made by means of a binary variation of all available circuit breakers (CBs, power switches) where the overall number of variations is calculated by

$$v_{\mathrm{n}} = 2^{CB_n} \qquad (27)$$

where $\mathrm{CB_n}$ is the number of available circuit breakers. As shown in Table 3 for example, it follows that with 3 circuit breakers available in a grid topology, there are a total of 8 different grid configurations A to H.

Table 3: Example of all possible grid configurations for 4 circuit breakers

Grid Configuration	Decimal number	CB 3	CB 2	CB 1
A / 1	0	0	0	0
B / 2	1	0	0	1
C / 3	2	0	1	0
D / 4	3	0	1	1

E / 5	4	1	0	0
F / 6	5	1	0	1
G / 7	6	1	1	0
H / 8	7	1	1	1

After this first step of the evaluation the algorithm checks in a loop, if one circuit breaker in the digital grid model is open or closed and sets all CBs to the actual needed grid configuration. Afterwards the algorithm runs a load flow calculation for the actual configuration with setting the study time to the result of the QDS pre-analysis[1]. This is repeated according to the number of possible grid configurations, i.e. $2^3 = 8$ times using the previous example with 3 switches.

(b) Prioritization

The results of the load flow calculations then are analyzed in more detail to achieve a prioritization of all available grid configurations. For this purpose, the following key performance indicators (KPIs) are defined:

- *KPI_1 – voltage limit violations:* number of voltage limit violations, normalized to the highest occurring number of violations related to all grid configurations;
- *KPI_2 – line loading violations:* number of overloaded lines, normalized to the highest occurring number of violations related to all grid configurations;
- *KPI_3 – total grid losses:* value of total grid losses, normalized to the maximum occurring overall grid losses related to all grid configurations;
- *KPI_4 – line overload reduction:* relief of the originally most loaded line (according to the initial grid configuration QDS result), normalized to the maximum occurring line loading related to all grid configurations;
- *KPI_5 – distance of circuit breaker:* distance between the originally most loaded line and the affected switch(es) / circuit breaker(s);
- *KPI_6 – meshing:* 0 if sub grid is in radial structure, 1 if sub grid is meshed.

The following equations describe the calculation of the previously mentioned KPIs for each grid configuration.

KPI_1 – voltage limit violations:

$$KPI_{1,j} = k_1 \cdot \frac{\mathrm{card}(A_{i,j})}{\max\limits_{j=1,\dots,v_\mathrm{n}} \left(\mathrm{card}(A_{i,j})\right)} \quad , \quad \begin{matrix} i = 1, \dots, T_\mathrm{n} \\ j = 1, \dots, v_\mathrm{n} \end{matrix} \tag{28}$$

with

$$\mathrm{card}(\mathrm{A_{i,j}}) \text{ ...cardinality/number of set } \mathrm{A_{i,j}} \tag{29}$$

and

$$A_{i,j} = \{T_i | V_{T_i} < V_\mathrm{min} \lor V_{T_i} > V_\mathrm{max}\} \tag{30}$$

[1] The algorithm first analyses the QDS results (historical measurement data) due to which line of the grid is most often the most heavily loaded one. Then it takes that time step of the year where this line is most heavily loaded.

KPI₂ – line loading violations:

$$KPI_{2,j} = k_1 \cdot \frac{\text{card}(B_{l,j})}{\max\limits_{j=1,\dots,v_\text{n}} \left(\text{card}(B_{l,j})\right)} \quad , \quad \begin{matrix} l = 1, \dots, L_\text{n} \\ j = 1, \dots, v_\text{n} \end{matrix} \tag{31}$$

with

$$\text{card}(\text{B}_{\text{l,j}}) \text{ ...cardinality/number of set } \text{B}_{\text{l,j}} \tag{32}$$

and

$$B_{l,j} = \{L_l | LineLoading_{L_l} > LineLoading_{\max}\} \tag{33}$$

KPI₃ – overall grid losses:

$$KPI_{3,j} = k_3 \cdot \frac{S_{\text{LossGrid},j}}{\max\limits_{j=1,\dots,v_\text{n}} \left(S_{\text{LossGrid},j}\right)} \tag{34}$$

KPI₄ – line overload reduction:

$$KPI_{4,j} = k_4 \cdot \frac{\dfrac{LineLoading\left(L_{\text{LineLoading}_{\text{QDS,max}}}, j\right)}{LineLoading_{\text{QDS,max}}}}{\max\limits_{j=1,\dots,v_\text{n}} \left(\dfrac{LineLoading\left(L_{\text{LineLoading}_{\text{QDS,max}}}, j\right)}{LineLoading_{\text{QDS,max}}}\right)} \tag{35}$$

KPI₅ – distance of circuit breaker:

$$KPI_{5,j} = k_5 \cdot \frac{\min\left(\text{distance}\left(CB, L_{\text{LineLoading}_{\text{QDS,max}}}\right)_j\right)}{\max\limits_{j=1,\dots,v_\text{n}} \left(\min\left(\text{distance}\left(CB, L_{\text{LineLoading}_{\text{QDS,max}}}\right)_j\right)\right)} \tag{36}$$

KPI₆ – meshing:

$$KPI_{6,j} = k_6 \cdot \begin{cases} 1 & \text{if} \quad V_j \text{ is meshed} \\ 0 & \text{if} \quad V_j \text{ is radial} \end{cases} \tag{37}$$

<u>Legend:</u>

$\text{k}_1 \dots \text{k}_6$…weighting factor for each KPI
T_i…terminal with $\text{i} = 1, \dots, \text{T}_\text{n}$
T_n…number of terminals
$\text{V}_{\text{T}_\text{i}}$…3ph RMS voltage at terminal T_i
V_min…lower voltage limit value for $\text{V}_{\text{T}_\text{i}}$
V_max…upper voltage limit value for $\text{V}_{\text{T}_\text{i}}$
v_j…variation, grid configuration with $\text{j} = 1, \dots, \text{v}_\text{n}$
v_n…number of variations, grid configurations
L_l…line with $\text{l} = 1, \dots, \text{L}_\text{n}$
L_n…number of lines
CB…circuit breaker, switch

$k_1 \dots k_6 T_i i = 1, \dots, \text{T}_\text{n} \text{T}_\text{n} V_{T_i} T_i V_\text{min} V_{T_i} V_\text{max} V_{T_i} v_j j = 1, \dots, v_\text{n} v_\text{n} L_l l = 1, \dots, L_\text{n} L_\text{n} CB$Basically, all KPIs one to six are scaled resp. normalised to the value 1. According to its relevance for the user of the algorithm, each KPI is additionally multiplied by an appropriate weighting factor to scale its value.

As mentioned before, the calculation of all six KPIs has to be carried out for each grid configuration. Afterwards, the six KPIs are summed up to get an overall sum of all six KPIs of each grid configuration.

$$KPI_{\text{sum},j} = KPI_{1,j} + KPI_{2,j} + KPI_{3,j} + KPI_{4,j} + KPI_{5,j} + KPI_{6,j} \tag{38}$$

To perform a prioritisation of the various possible grid configurations, the resulting sum of all KPIs are sorted by its values. Therefore, the j values of $\text{KPI}_{\text{sum,j}}$ are sorted in descending order.

4.1.3.4 Simulation-based tests

The SMM algorithm presented was tested simulatively using different digital grid models. The selected example grid is part of the Aspern Seestadt grid, especially DTR / transformer substation TS10 of rating 630 kVA. It connects the grid area to the 20 kV voltage level (20 kV / 0.4 kV). The grid has a total cable length of 1.58 km and supplies 17 residential customers. Figure 38 represents the single line diagram of the grid with a total number of 22 nodes and 21 lines with two main feeders including the four circuit breakers CB 2 to CB 5 which are used for first tests of the UC 4 algorithm.

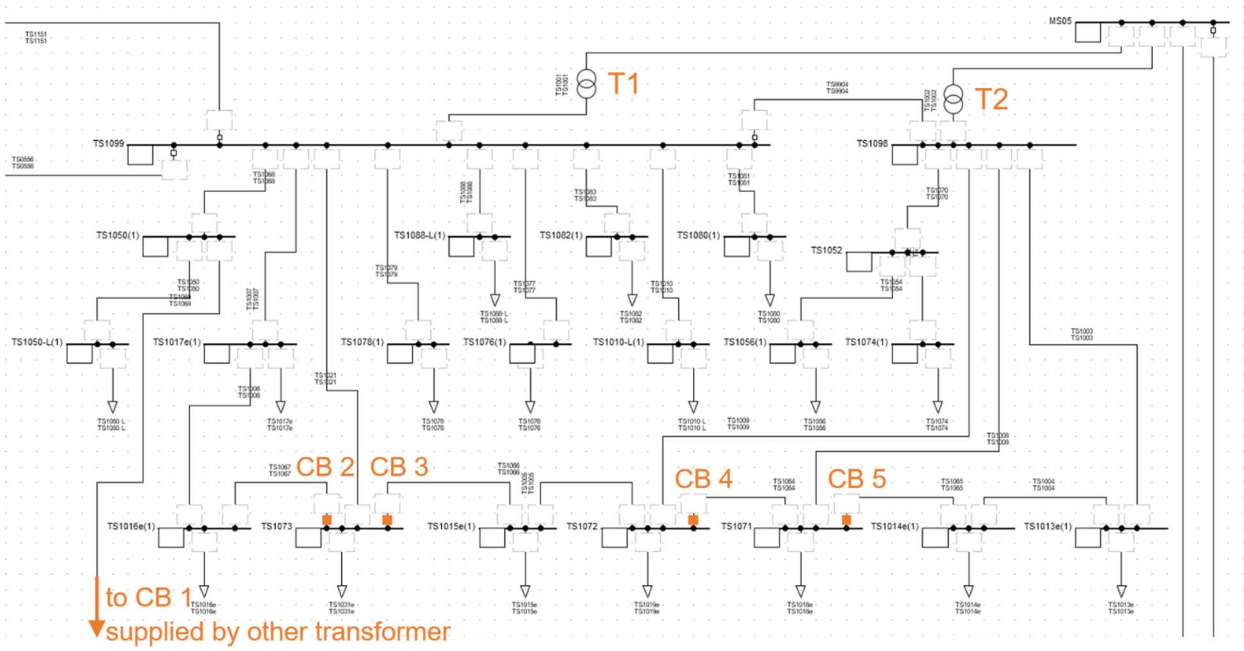


Figure 38: Urban LV grid Aspern Seestadt TS10 sub grid with available circuit breakers (CBs) for automatic reconfiguration from AIT [1].

The Aspern grid itself consists of 11 transformer substations of rating 630 kVA for each. These sub-stations connect different grid areas to 20 kV voltage level (20 kV / 0.4 kV). The grid consists of a total cable length of 15.14 km and supplies 114 residential customers.

The Aspern Seestadt LV grid model was used as the first test grid to investigate the SMM algorithm in a simulative way. Thereby, the possible switching states of four available circuit breakers as well as its resulting grid configurations are evaluated by means of calculating six different KPIs. Each KPI value can be weighted by a specific weighting factor which – for testing purpose – is set to one (“1”). The following two figures shows in each case the different six KPIs on the left-hand side and the calculated sum of KPIs on the right-hand side. Figure 39 shows the results of the scenario with EVCS and **with** PV, Figure 40 shows the results of the scenario with EVCS and **without** PV.

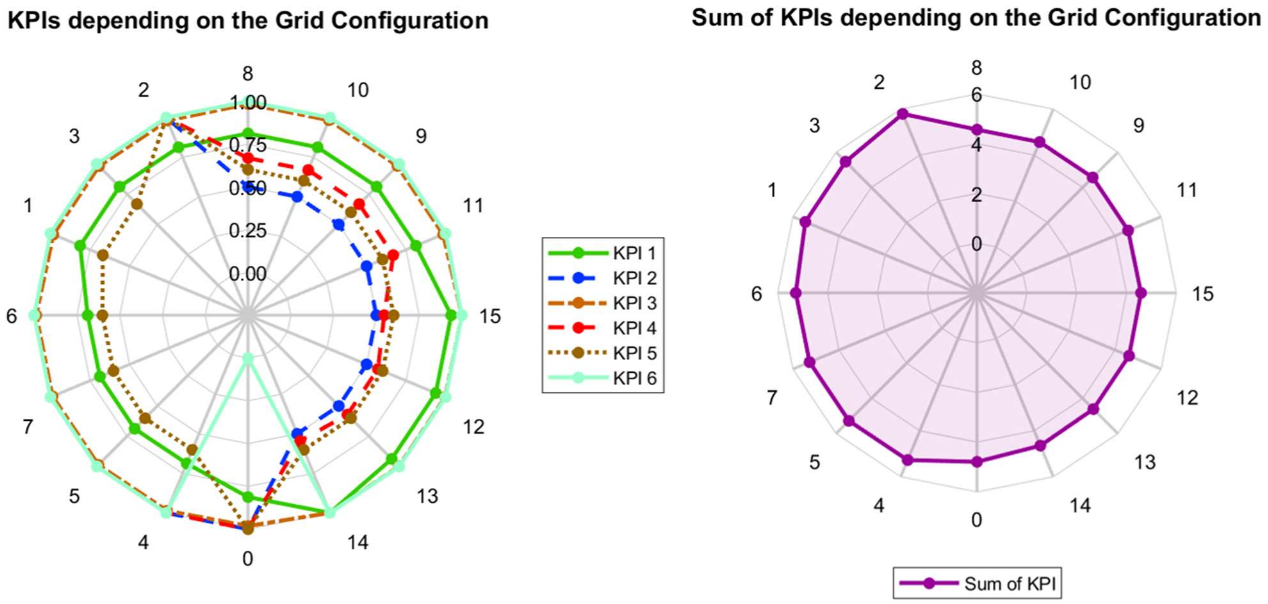


Figure 39: SMM simulation results of Aspern Seestadt TS10 sub grid using CB 2 to 5 sorted by priority, scenario with EVCS and with PV
(KPI1: voltage limit violations, KPI2: line loading violations, KPI3: total grid losses, KPI4: line overload reduction, KPI5: distance of circuit breaker, KPI6: meshing).

Due to the fact, that the weighting factors of the KPIs are set to one, the maximum value of the sum of all six KPIs (right hand side in Figure 39 and Figure 40) can reach a maximum value of six ("6"). As explained in detail in deliverable D3.2, the best case is a low value of a KPI (in the range of zero, little negative impact) and the worst case is a high value of a KPI (in the range of one, great negative impact).
As an example, in Figure 39 (left), KPI6 (meshing) shows that only configuration 0 leads to a value of KPI6 = 0. Further, for just the half of the variations (8, 10, 9, 11, 15, 12, 13, 14) KPI2 is in the range of 0.5 which means that there are less line loading violations expected than with the other variations.
Figure 39 (right) shows the overall sum of KPIs sorted in descending order, corresponding to the different grid configurations' prioritisation. As there have not been any further discussions with DSOs regarding individual weighting factors (WF), the WF of each KPI is set to 1.0. Therefore, the sum of all KPIs can only reach a maximum value of 6.0. The variations 0 (all circuit breakers are open) and 15 (all circuit breakers are closed) are not preferable regarding the KPI calculation procedure, which suggests that the reconfiguration approach leads to an improvement of the initial situation. Variation 8 (only circuit breaker CB 2 from Figure 38 is ON) is determined as the best case or optimal grid configuration.

In comparison, Figure 40 (right) shows a changed prioritisation due to the used scenario **without** PV, therefore with a changed load situation), whereby grid configuration 13 instead of 8 is determined as the best. [16], [17]

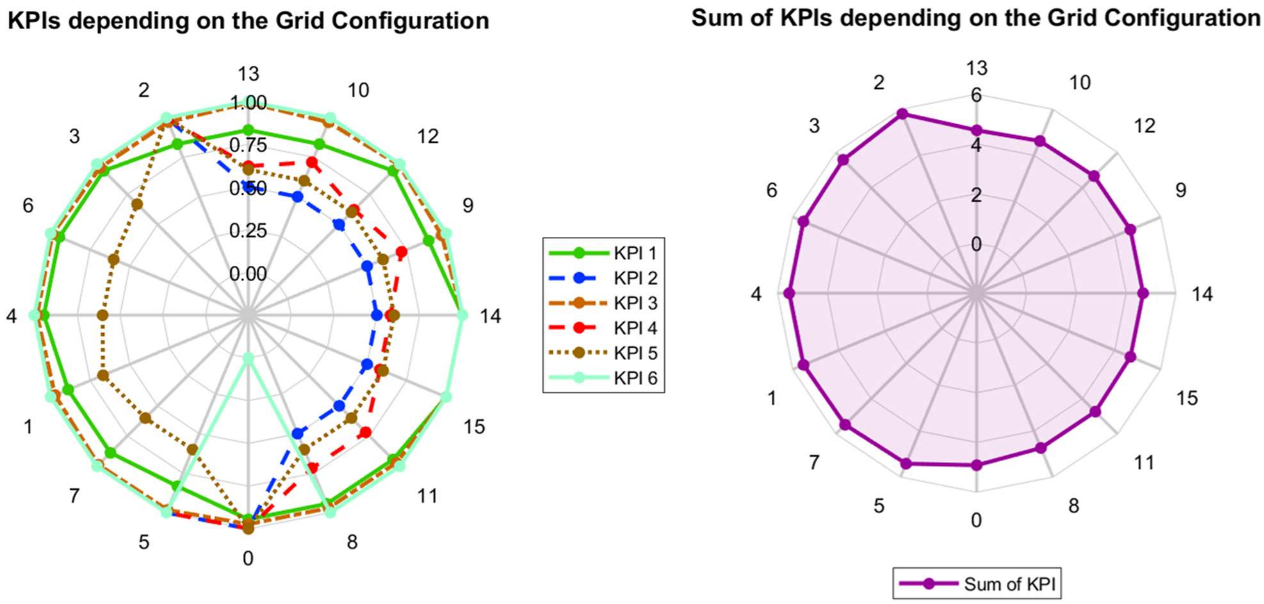


Figure 40: SMM simulation results of Aspern Seestadt TS10 sub grid using CB 2 to 5 sorted by priority, scenario with EVCS and without PV
(KPI1: voltage limit violations, KPI2: line loading violations, KPI3: total grid losses, KPI4: line overload reduction, KPI5: distance of circuit breaker, KPI6: meshing).

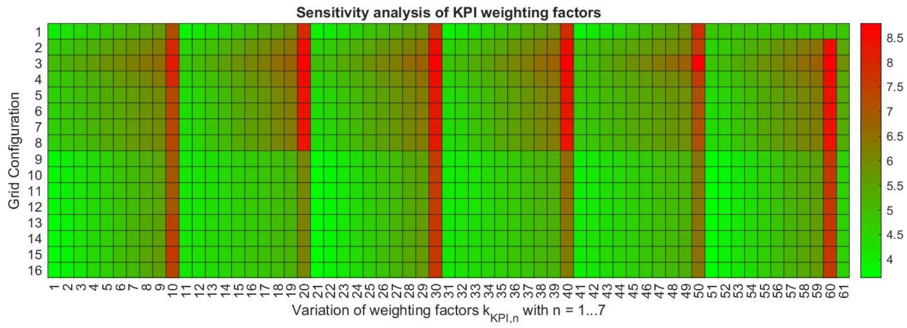
As a next step, a kind of sensitivity analysis is performed to identify the impact of each KPI to the prioritisation of the different grid configurations. Therefore, the weighting factors $k_{KPI,n}$ of each KPIs are going to be varied in overall 10 steps (chosen range: 0.05, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 4). For the sake of simplicity and to significantly reduce the number of variations, only one KPI weighting factor at a time is varied within the stated range and the others are left at the value 1.0.

The following Figure 41 shows the results of such a sensitivity analysis by using carpet plots on the scenario of no installed PV (**without** PV). Thereby, one can see the different variations of the weighting factors $k_{KPI,n}$ with Figure 41 (d). All in all, there are 61 columns resp. steps for different combinations of the values of the weighting factors (10 steps · 6 KPIs + 1 = 61, "+ 1" for a further seventh KPI which is not yet integrated). Figure 41 (a) to (c) shows three types of illustrations of the addressed sensitivity analysis:

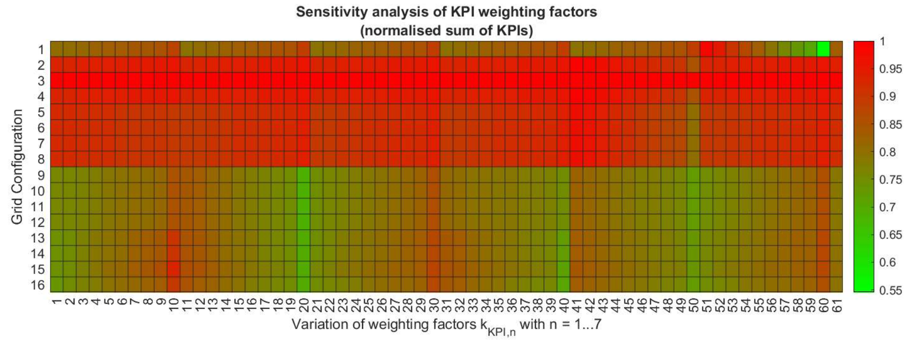
(a) direct illustration of values of sum of KPIs – the calculated sum of KPIs where the value depends on the selected KPI weighting factors;
(b) normalised sum of KPIs – the calculated sum of KPIs normalized to the highest occurring sum which can assume a value range from zero to one;
(c) sorted order of sum of KPIs – the sorted order of the calculated sum of KPIs which can assume a value range from one to n = number of possible grid configurations, the highest priority is signified by the value 1.

Figure 41 (a) is the first attempt at visualization and shows that due to the corresponding variations in the weighting factors of the KPIs, a respective variation can either be good overall (green according to the colour scale) or bad (red area of the colour scale).

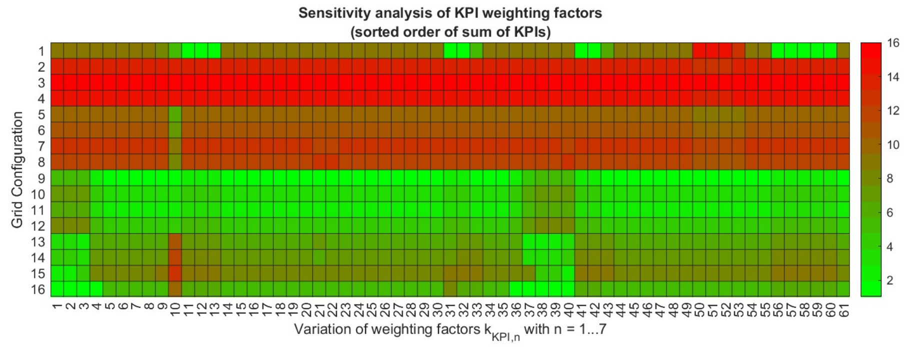
Another approach to visualization, in contrast, is the normalized sum of the individual KPIs per variation (Figure 41 (b)) in relation to the totality of the calculated KPI sum values. This shows that there are basically two hemispheres: On one hand, grid configurations 1 to 8, indicating a rather negative evaluation, and on the other hand, grid configurations 9 to 16, indicating a rather positive one.



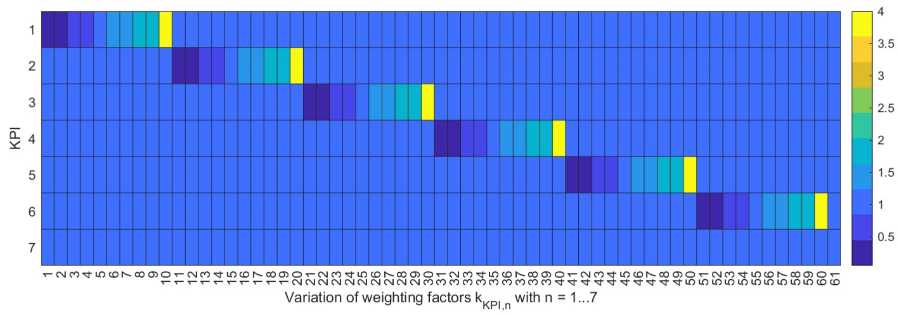
(a)



(b)



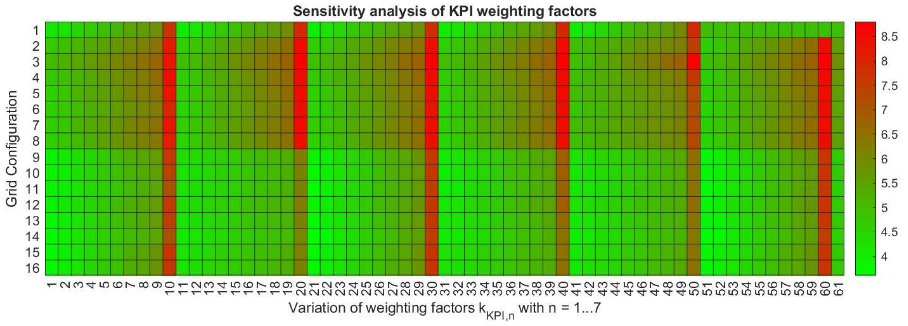
(c)



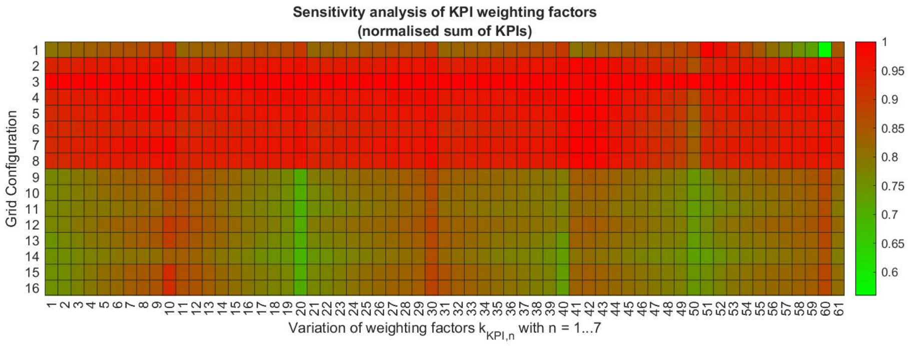
(d)

Figure 41: Sensitivity analysis of KPI weighting factors $k_{KPI,n}$ for Aspern Seestadt test grid, scenario with PV.

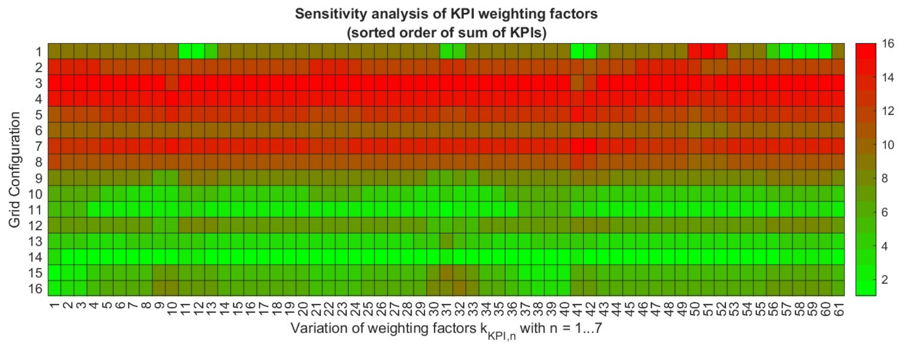
The third type of visualization, however, deals with the prioritization resp. the sorted order of the individual grid configurations sum of KPIs (Figure 41 ©), which results in a discrete value distribution with a total of 16 values (= number of possible grid configurations per variation of the weighting factors). It can be seen that, similar to Figure 41 (b), once more two hemispheres are formed, butless clearly this time due to the significant influence of all weighting factors resp. KPIs, for example, on grid configuration 1.
As a comparison, the scenario **without** PV should be used again, for which the results of the sensitivity analysis are shown in Figure 42.



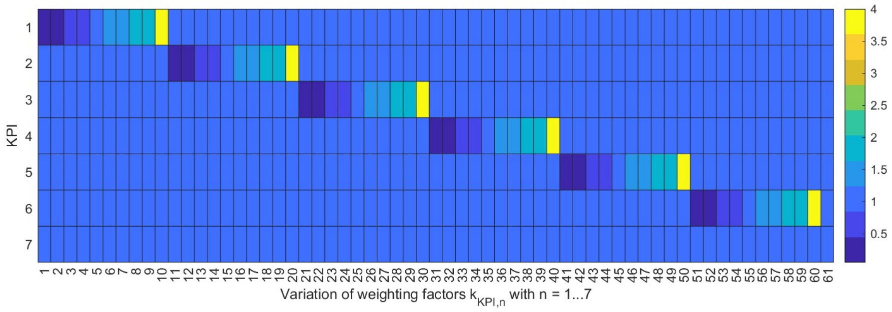
(a)



(b)



(c)



(d)

Figure 42: Sensitivity analysis of KPI weighting factors $k_{KPI,n}$ for Aspern Seestadt test grid, scenario without PV

There are hardly any differences between Figure 41 (scenario **with** PV) and Figure 42 (scenario **without** PV). The carpet plots (a) and (b) are approximately the same for both scenarios. In contrast, there is a somewhat more noticeable difference in the sub-figure Figure 42 (c) compared with sub-figure Figure 41 (c): Here, especially the southern hemisphere (grid configuration 9 to 16) suggests a greater influence of the KPI weighting factors. Also, some differences with respect to the sorted order of the grid configurations in the weighting factor variation 10 are recognizable.

All in all, it can be stated that there are only noticeable influences of the weighting factors outside the range of small signal stability (e.g., the weighting factors 0.05, or 4). In addition, the prioritisation of some grid configurations is almost completely independent of different weighting factors as well as different scenarios. For example, configuration 3 almost always represents the worst variation or the one with the lowest prioritisation.

For further details on simulations and their associated results and interpretation, reference is made to deliverable D3.3.

4.1.4 Summary

In accordance with the Use Cases established in the project planning, the three methods resp. algorithms for supporting the automated operation of electrical grids described in the previous chapters were developed and tested during the PoSyCo project.
Thereby the algorithm considering "**Distributed fault analysis for service restoration acceleration** (implementation of **UC 2**)", should enable proactive operational management of an electrical grid. To deal with the special challenges when thinking on hundreds or thousands of low-voltage grids in its grid area, PoSyco has started to investigate a hybrid approach to provide SCADA-like functionality for supervision of them. This hybrid approach named "Supervision and Event Detection" (SED) consists of a function centrally located in the BackEnd of the distribution system operator with the working title "distributed SCADA" (dSCADA). This function is supplemented by the "Edge Grid Watch Dog" module, which is operated in a decentralized manner in a corresponding Smart Grid Tool Kit in an intelligent grid station (iSSN intelligent secondary substation node).

For “**Overload prevention by customer activation** (implementation of **UC 3**)”. the results show that all proposed and tested algorithms reliably detect congestions and effectively mitigate transformer and line segment overloading. In the case of sparse measurement-based congestion detection in some cases false positive overload detection occurs when none are present. In total, the solution offers an acceptable performance while requiring low implementation effort. No complex adaptions are required after grid reinforcement and expansion.
For "**Overload prevention by temporary meshing** (implementation of **UC 4**)", the so-called Switching Management Algorithm (SMM) was developed. Based on a digital grid model of the affected low-voltage grid section, SMM evaluates the “best” grid configuration. This is performed by load flow calculations of all possible grid configurations with respect to a historic worst-case scenario. The different results of the load flow calculations are prioritized by means of calculating six different KPIs. Software-based tests of the algorithms were carried out for at least four different digital grid models and have shown stable results.

However, all three algorithms are dependent on the knowledge of the state of the affected grid section. This requires the measurement of corresponding electrical values (e.g. voltages and currents) at neuralgic points in the grid and the further processing as well as forwarding to the corresponding units. Thus, the development of a suitable ICT system for this purpose is described in the following chapter.

4.2 Information and Communication Framework

The information and communication aspects of PoSyCo are closely interlinked, but each has a different focus. The **information framework** focuses on information modelling, while the **communication framework** focuses on data exchange between SOFTprotection modules. Both aspects combined enable exchanging, processing, and storing semantically enriched data and are integrated in the PoSyCo information and communication framework.

4.2.1 Information framework requirements engineering

To ensure a manageable scope for the requirements elicitation process, we started this process by focusing on one PoSyCo Use Case, with the intention to then extend these requirements so that the needs of the other Use Cases are also covered. To that end, UC3B has been chosen because it heavily relies on information about the power grid topology.

UC3B (described in detail in deliverable D2.1 and deliverable D5.1) is concerned with providing an explanation service to various grid stakeholders including:

- Power grid end customers such as owners of electric vehicle charging stations who might want an explanation as to why the charging power of their device is under the expected limit; and
- DSO employees who also require an explanation of certain grid states that cannot be easily explained.

In more detail, the aim is to provide explanations for faults or exceptional states in the smart grid (e.g., reduction of loading capacity at electric vehicle charging stations because the corresponding transformer reached unsafe loading levels). As such, network topology information is needed to:

- Identify anomalies/faults/events arising at the level of each network equipment based on the measurement data available for elements (i.e., the time series data);
- Identify events arising from changes in the network topology (e.g., power line disconnected; switch closed);
- Localize faults/anomalies of the network equipment – as a side effect of points 1 and 2 above;
- Consider galvanic connections between network equipment, as these connections play a role in tracing back root-causes, i.e., deriving explanations (an anomaly at equipment A is probably induced by anomalies of connected equipment on arbitrarily long connection paths).

From the above, several information representation requirements for this Use Case are distilled and represented in table below.

Table 4: Overview of Use Case specific requirements

Req. Type	Req. Nr.	Requirement name
Equipment and Topology	R1	Network equipment and typology
	R2	Network equipment internal composition or division in logical units
	R3	Network topology (“galvanic connections”)
	R4	(Link to) Measurement data

Measurement Data	R5	Anomalies
Time and change management	R6	Topology change events
	R7	Time-based network status (historization)

In the following, we describe each requirement in more detail:

- *R1: Network equipment and typology:* This requirement refers to the need of describing the various equipment/devices that form part of the power network such as transformers, loads, and power lines. It is also important to be able to assign a type to each network equipment, considering also more complex type hierarchies. For example, it is important to specify not just that a device is a *Transformer*, but also in more detail that it is a *TwoWindingTransformer* or a *ThreeWindingTransformer*. Finally, it is needed to describe those device features which are relevant (e.g., the *phases* of a transformer, the resistance or the conductance of a transformer winding).
- *R2: Network equipment internal composition or division in logical units*: Compositional information also plays an important role in power grids. On the one hand, the network is often divided in logical units such as *Regions*, which then can contain *Stations* etc. Such division in logical units should be represented. On the other hand, containment relations also exist between various equipment types, for example, *Transformers* contain *TransformerWindings* and *TapChangers*. This also needs to be represented.
- *R3: Network topology ("galvanic connections"):* Galvanic/physical connections between network equipment (e.g., through power lines) need to be represented.
- *R4: (Link to) Measurement data*: Measurement data of power-grid-specific indicators (e.g., voltage levels) obtained by sensors and various grid monitoring devices are important sources of information for monitoring the functionality of the entire power grid and identifying potential faults/failures. While measurement data by itself is not strictly part of the network topology, it is important to be able to establish a connection between power grid equipment and relevant measurements taken at or in the (physical) vicinity of the equipment (e.g., for fault localization).
- *R5: Anomalies:* This requirement refers to the representation of anomalies of different types. Firstly, anomalies that refer to or are induced by changes in the network topology need to be represented, ideally with a clear description of the cause of the anomaly. Secondly, anomalies can be deduced based on power grid measurement data – this should be represented at the corresponding/involved network equipment level.
- *R6: Topology change events:* Although traditional power grids are to a large extent static in terms of their composition and layout, future power grids will be subject to much more frequent change events due to, for example, addition/removal of elements such as photovoltaic (PV) stations or electric vehicle charging stations. To account for that, topology representations should offer means to capture changes to network equipment and topology. For example, it should be possible to record network equipment status and its updates (e.g., a Switch being set on/off) as well as temporary additions to the power grid in terms of new network equipment (e.g., a PV station). Besides the affected equipment, change events should also capture the time of change and the

agent performing this change (e.g., an operator or a software agent). Furthermore, for changes performed manually, it is important to capture the different timings of when the change was executed manually and the time when it was registered into a grid management system, to detect intervals of inconsistency between real and represented grid structure that might have led to erroneous calculations/assumptions.

- *R7: Time-based network status (historization):* Related to R6, it is not only important to represent when a change took place, but also to keep a historic track of such changes. This is essential to be able to reproduce the actual network topology (including equipment and connections) at a given moment in time.

4.2.2 Communication framework requirements engineering

The functional and non-functional requirements discussed in deliverable D4.1 motivated the development of the PoSyCo system architecture, including the PoSyCo communication framework and the PoSyCo Runtime as its core component. However, to select suitable technologies to implement the PoSyCo communication framework, these requirements are further refined in the following. Thereby, each requirement is briefly described, and an example motivated by the PoSyCo use cases is provided.

Request-Reply-based communication

- Description: A SOFTprotection Module issues an asynchronous request that needs to be processed and replied to by another SOFTprotection Module.
- Example: The Switching Management Module requests historical data from the Data Management Module.

Publish-Subscribe-based communication

- Description: Process data is continuously sensed and published. All interested SOFTprotection Modules can subscribe to the data, process the data, and publish their results. This requirement enables flexible data streams.
- Example: A sensor publishes voltage measurement data, which are processed by the Data Preprocessing Module. The preprocessed result is provided to the Visualization Backend.

Transport of documents

- Description: A SOFTprotection Module issues an asynchronous request for a document such as a configuration file or a report, and the responsible SOFTprotection Module returns the document.
- Example: Transfer configuration file in YAML, JSON, or XML file format

Transport of streams

- Description: A SOFTprotection Module provides a stream of data measurements to the entire system. Other SOFTprotection Modules subscribe to the stream if they are interested.
- Example: Voltage measurements are sampled continuously and streamed to other SOFTprotection Modules.

End-to-end acknowledgment

- Description: A SOFTprotection Module should be able to detect whether the receiving SOFTprotection Module has processed a message sent to it.
- Example: The Switching Management Module needs confirmation that a switch has performed the requested action before the switching management algorithm can continue.

Reliable multicast

- Description: A SOFTprotection Module should be able to send a message to a set of devices reliably. An error shall be reported if the delivery of the message is unsuccessful.
- Example: A set of devices needs to confirm that they received a message, e.g., a firmware update.

Abstract data and service API

- Description: A SOFTprotection Module requests data and services via an abstract API (Application Programming Interface) that is not specific to the SOFTprotection Modules providing the data or services.
- Example: An external system that provides data to the SOFTprotection system is exchanged for an internal one. The API to these data stays the same as it is abstract.

Data access rights (Role-based access control)

- Description: Only specific SOFTprotection Modules shall be able to read from or write to topics according to their assigned role within the system.
- Example: A circuit breaker is allowed to read commands from a specific topic to execute its functionality but is blocked from sending switching commands to other circuit breakers.

Adding external data sources and devices

- Description: External data sources and devices can be integrated into the system in a generalized way.
- Example: A sensor only offers its data via OPC UA, LoRaWAN, or a cloud interface and is integrated via these interfaces.

Adding additional SOFTprotection Modules

- Description: The addition of SOFTprotection Modules is supported as a dynamic feature.
- Example: A new SOFTprotection Module needs to be added to support a new use case.

Adding additional datapoints

- Description: New datapoints can be added to the SOFTprotection system. Existing SOFTprotection Modules should adopt these datapoints if relevant for their purpose.
- Example: A new voltage sensor is added at a specific position in the grid. The state estimation SOFTprotection Module should pick up the new values and produce better results without having to change the SOFTprotection Module.

Changing the grid topology

- Description: The grid topology can be changed at any point without changing the SOFTprotection Modules.

- Example: A new line, power source, or load is added to the topology. The state estimation SOFTprotection Module should pick up the changes and produce results for the updated topology without having to change the SOFTprotection Module.

Modeling data quality

- Description: The quality of data, e.g., its precision, shall be transmitted and stored such that it can be used by the SOFTprotection Modules.
- Example: SOFTprotection Modules can change to other sources for a datapoint if the data quality is not good enough for the provided services.

Support for semantic data

- Description: A measurement value shall be transported, stored, and processed with its semantics and metadata.
- Example: Voltage measurements are stored together with their location in the grid, their units, timestamps, and other relevant metadata.

Integration of time-series, document, and topology databases

- Description: Database implementations for Timeseries, Document, and Topology need to be made accessible via the communication framework for various SOFTprotection Modules.
- Example: The time-series data for a voltage measurement datapoint is available via the communication framework.

4.2.3 PoSyCo system architecture - SOFTprotection Modules in the context of SGAM

The SGAM framework allows for the definition of new Smart Grid applications on five layers (Component, Communication, Information, Function, and Business) across different zones (Process, Field, Station, Operation, Enterprise, Market) and domains (Generation, Transformation, Distribution, Distributed Energy Resources (DER), Customer Premises). Every application is distributed over several of the layers, zones, and domains. The same holds for the PoSyCo Use Cases. Based on the elements of UC1, Figure 43 exemplifies where the individual SOFTprotection Modules and devices of the SOFTprotection system are in SGAM. This is done to simplify the graphic but can be done for all Use Cases individually or even together. However, the other Use Cases were left out for clarity in Figure 43.

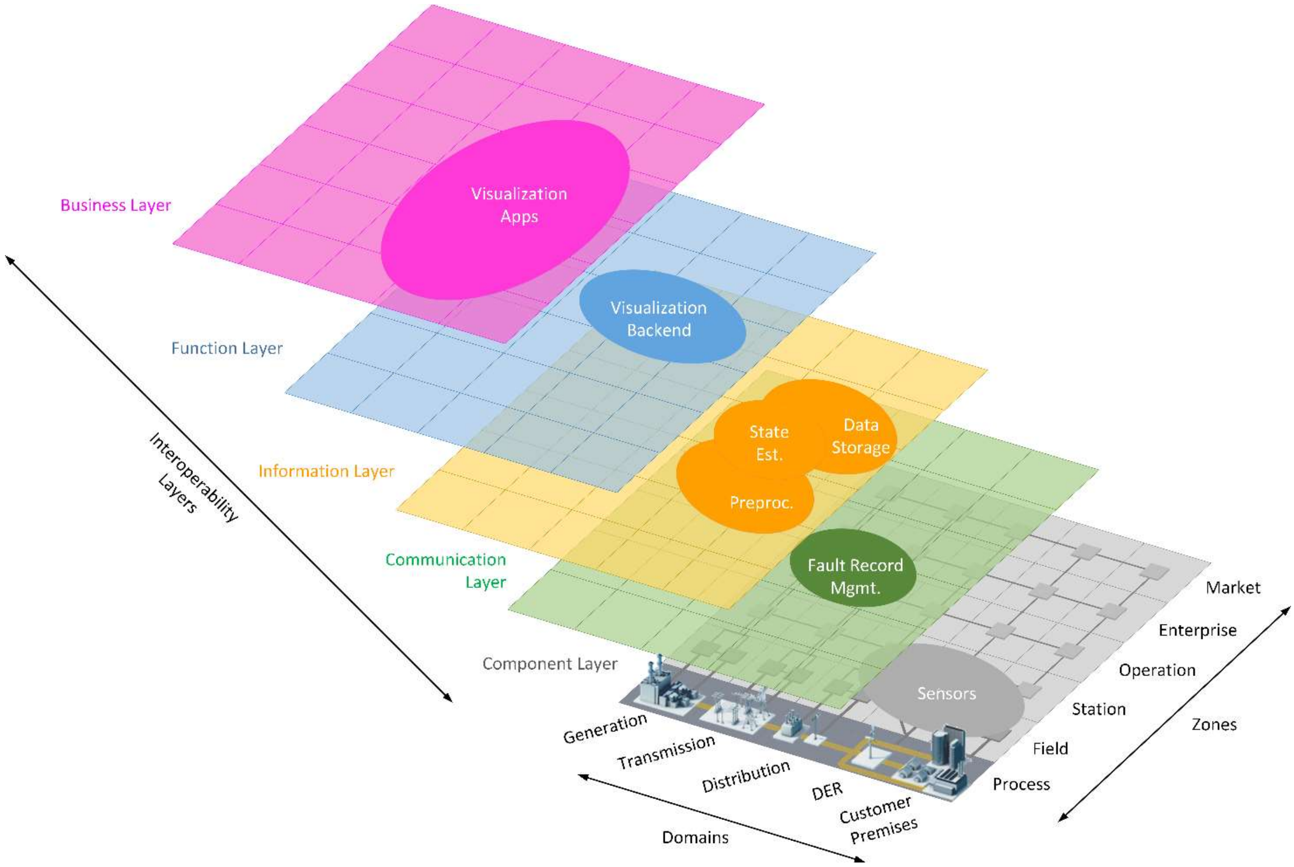


Figure 43: Smart Grid Architecture Model (SGAM)

The individual elements cover the three domains Distribution, DER, and Customer Premise and the zones Process, Field, Station, Operation, and Enterprise. For the combination of the Use Cases, this holds for almost every layer. Therefore, it is more important to discuss the individual layers that are relevant for the individual features than the domain or the zone. As mentioned in the previous section, the SOFTprotection Modules represent the individual features that were deduced from the use cases. Figure 44 shows how these modules, as well as external parts such as the visualization applications and external sensors, are positioned in the individual SGAM layers.

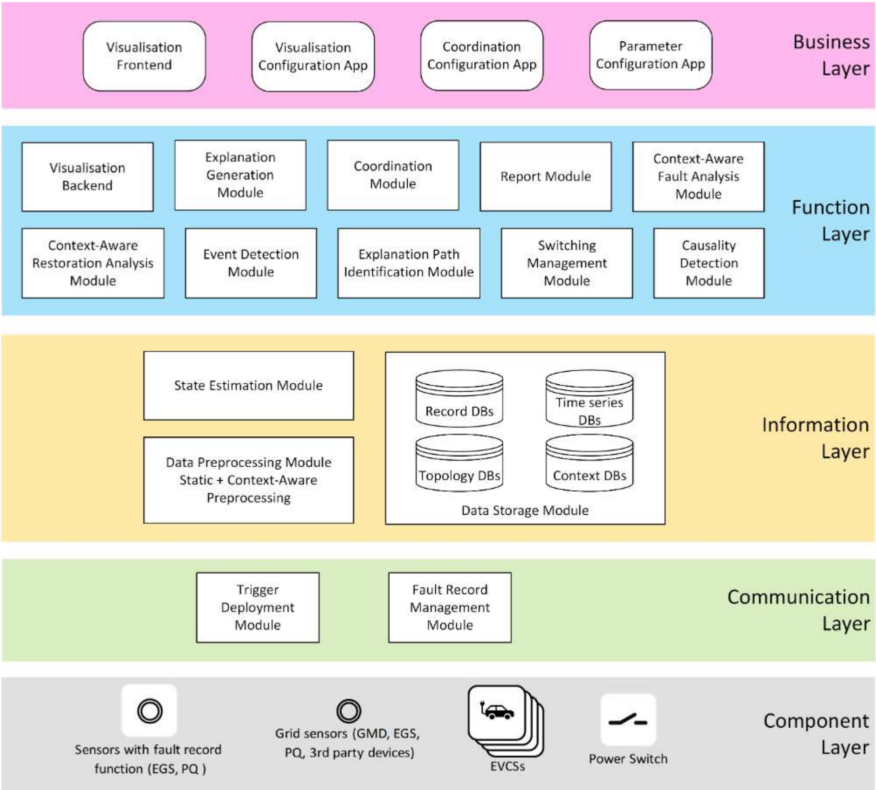


Figure 44: SOFTprotection Modules and their location in the SGAM model

Because the SOFTprotection system is designed to integrate with the already available infrastructure, no modules are present in the component layer. There are rather external devices such as already present sensors with fault record functionality and grid sensors as well as power switches and EVCSs that form this layer. However, they are not under the influence of the system and may only provide data or consume data in predetermined ways. The same holds for the business layer for which user-facing applications are already present and are used to access data and present data from the SOFTprotection system. The actual modules of the system are distributed over the three middle layers according to their intended purpose. Each layer depends on the layer below in terms of function and data. The modules in the communication layer are concerned with communication with external data sources and services. The acquired data is stored and managed in the information layer, which additionally provides storage services to the function layer.

4.2.4 PoSyCo information framework

From the requirements above an abstract (i.e., technology-agnostic) data model is derived that fulfills the described requirements. The model is depicted in Figure 45 and contains the following main elements in terms of concepts and their relations:

Core to the model is the *Equipment* concept, which represents a network equipment as required by R1. Subsequently, a number of more specialized concepts can be declared that represent types of equipment, such as *Lines*, *Feeders*, *Loads*, or *Transformers*. The typology of *Equipment* can be further extended either in breadth (e.g., adding new *Equipment* types) or in depth (e.g., further specializing the concepts, such as shown in the case of the *Transformer* concept, which was further specialized in *3WindingTransformer* and *2WindingTransformer*).

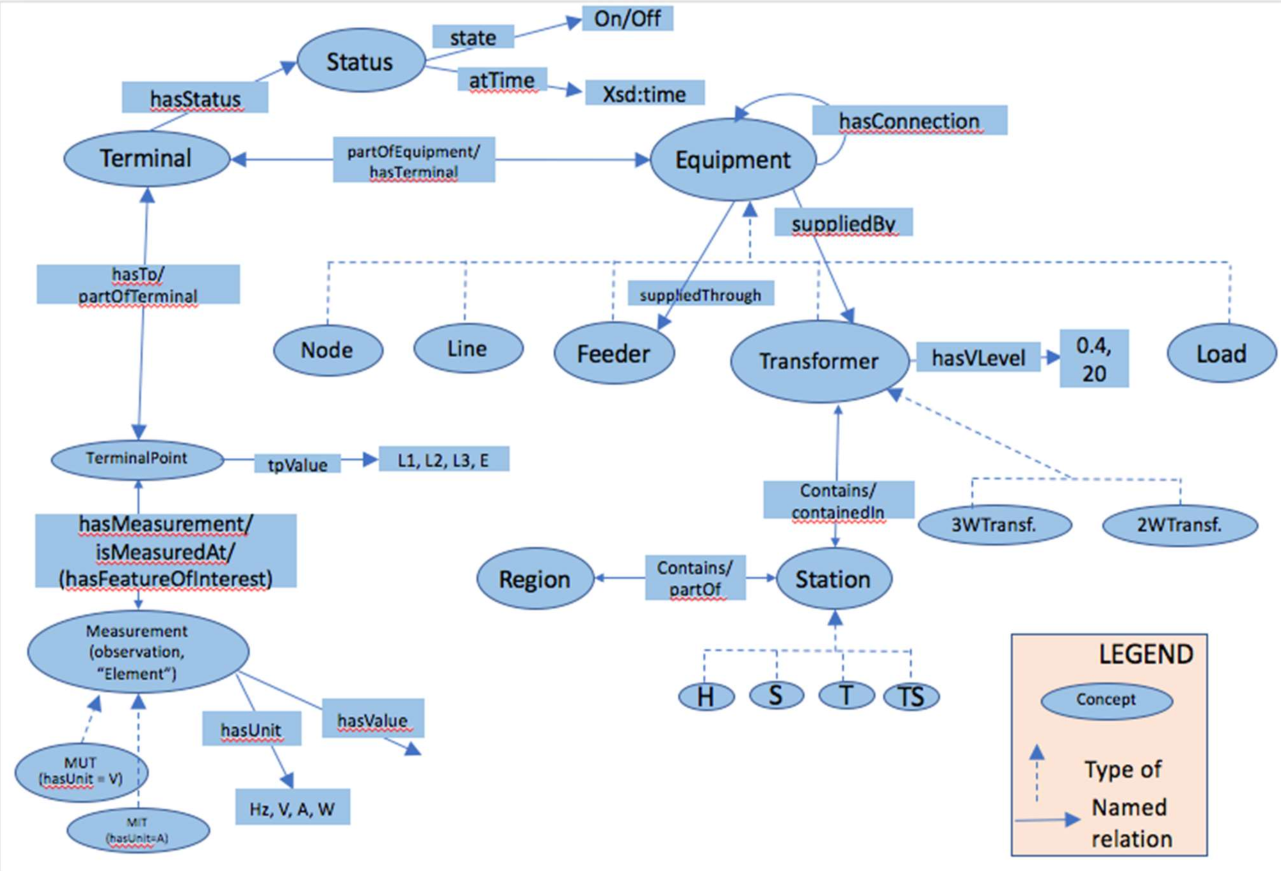


Figure 45: PoSyCo information model

Important relations to be specified by each *Equipment* are:

- *hasTerminal:* An equipment can have one or more *Terminals,* which play a crucial role in establishing connections between *Equipment* (as for R3). Indeed, we model connection between equipment always through a Node-type equipment, to which equipment terminals connect.
- *hasConnection:* If two equipments' terminals connect to the same Node, then a galvanic connection is established between them, which can be directly represented by the *hasConnection* relation (in line with R3). Note that the *hasConnection* relation can be derived from *Terminal*/*Node* information (according to the rule stated above) and, therefore, does not need to be declared explicitly. In fact, it can be seen as "syntactic sugar" to quickly find connected equipment without the need to look into the underlying detailed connections at *Terminal*/*Node* level.
- *suppliedBy:* Equipment is supplied by a *Transformer*. It is important to record this information to maintain compatibility with state-of-the-art grid equipment addressing schemes.
- *suppliedThrough:* Equipment is supplied through a *Feeder*. It is important to record this information to maintain compatibility with state-of-the-art grid equipment addressing schemes.

*Transformer*s are core elements of power grids and, therefore, have additional relations, such as those that specify their voltage level as well as the (Sub)Stations they are contained in. Such containment relations into *Stations (*and then through transitivity to the *Regions* where stations are located*)* relate to requirement R2 in terms of specifying logical composition of power grid equipment.

Terminals belong to *Equipment* (*partOfEquipment* relation models such composition in lieu of R2) and play an important role in:

- Connecting equipment to *Nodes* (as discussed above at *Equipment*);
- Being the element where measurements are made, concretely at *TerminalPoints* situated on different Phases; *hasTP* captures the containment relation of the terminal's *TerminalPoints* (R2);
- Being the element where equipment status changes are recoded (as for requirement R6/R7). A connection to a *Status* type object is made with the *hasStatus* relation.

An example of this model showing a few equipment elements with associated measurement values to their terminals is shown in Figure 46 .

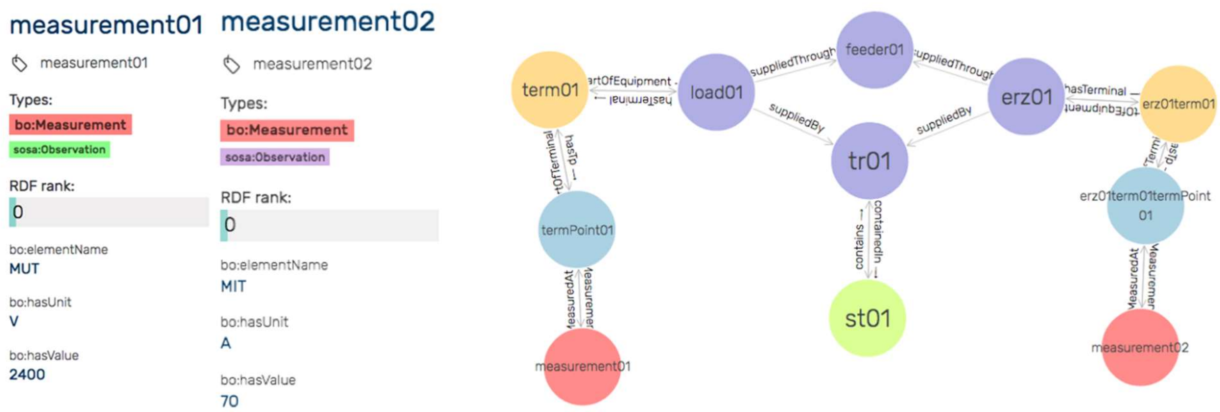


Figure 46: Instance example of the PoSyCo information framework

4.2.5 PoSyCo runtime and communication systems

Due to the size of the described system and the inherent complexity that follows from it, an appropriate system architecture is necessary to ease the difficulties during the application design phase. The PoSyCo System Architecture aims to solve these difficulties via modularization, standardized communication, and a service-oriented approach. The SOFTprotection modules have already been determined during the Use Case development and are further used as elements in the system architecture. These modules should be able to communicate with each other and with external systems to bring sensor data into the application and provide data and commands to consumers or field devices. Hence, a standardized communication concept is needed and shall be implemented via the PoSyCo System Bus. Because every interaction between modules passes this bus, it must support all necessary interaction patterns, e.g., publish-subscribe style message passing, synchronous requests, and remote procedure calls. The interfaces of each module are defined in the early development phase and can be used by other modules to access services and data. However, to make the interfaces more accessible, they are abstracted into a datacentric view of the whole system. A module does not use the interface of another module directly but instead describes the kind of data or service it wants to interact with. The PoSyCo Framework translates this description into the appropriate requests. This framework consists of two parts, as can be seen in Figure 47.

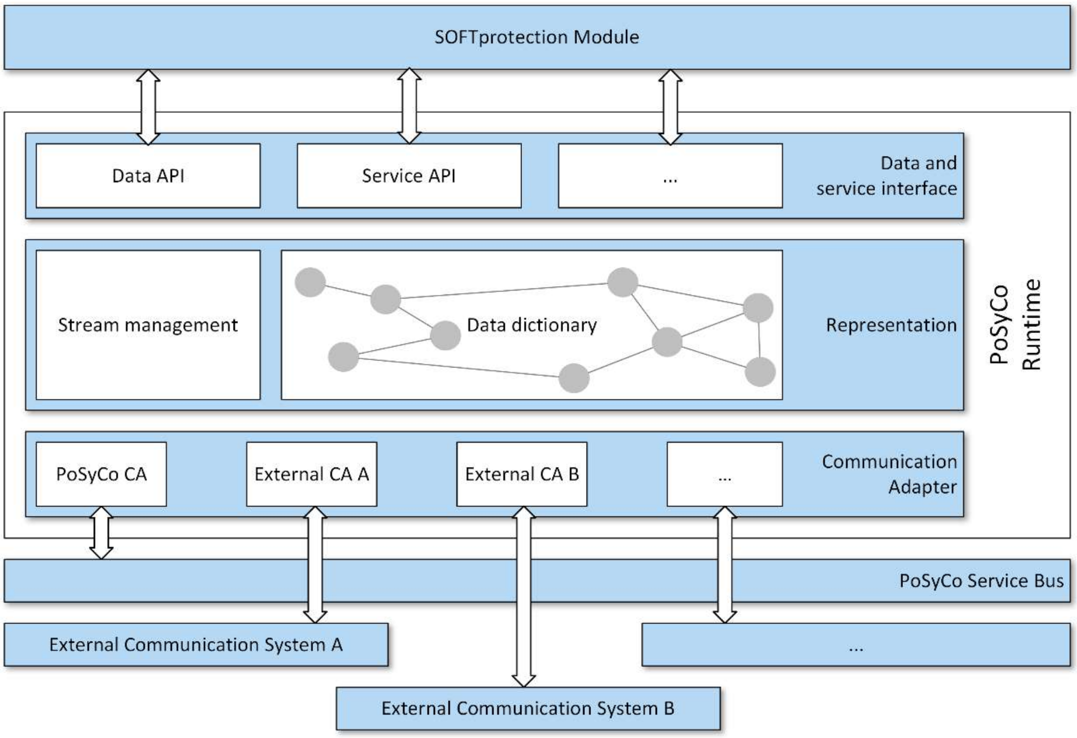


Figure 47: PoSyCo communication framework

The PoSyCo Runtime is deployed with every module and implements the interface to the framework and, therefore, to the rest of the application. The PoSyCo Runtime is comprised of several components that can be sorted into three aspects represented as layers in Figure 47. Several components serve as data and service interfaces to the SOFTprotection Module. These interfaces abstract away the decentralized nature of the application. Each interface endpoint is inherently data focused and is not depending on the distribution of data and services onto different modules. The next aspect of the PoSyCo Runtime is tasked with the representation of the data and data management. Its components are responsible for translating the description of the data and services provided to the interface components to the physical location of data and services and the associated transport or communication mechanisms. The information that connects the data and service description to services, data streams or data bases is stored in the data dictionary component. The desired endpoints and channels can be deduced from this data using data queries. The stream management is responsible for keeping track of the open subscriptions on data streams. The third aspect of the PoSyCo Runtime is responsible for the interface to specific communication systems. The components in this aspect are communication adapters that translate the generic communication description from the data dictionary into the technology-specific messages and requests. The PoSyCo Communication Adapter (CA) is responsible for interacting with the PoSyCo Service Bus, which is the only internal communication channel (i.e., between SOFTprotection Modules). Similarly, external communication adapters interface with external systems.

The PoSyCo Service bus is the standard communication channel between all SOFTprotection Modules. It provides request-response, data streaming and remote-procedure-call capabilities. Data is encoded together with its metadata to enable introspection at any point in the application.

In Figure 48, a possible implementation consisting of three modules of UC1 is shown. The Preprocessing module uses the PoSyCo Runtime to access sensor readings via an OPC UA (Open Platform Communications Unified Architecture) adapter and sends the acquired data to the other modules via the PoSyCo Service Bus. The other modules use the PoSyCo Runtime to read new data from the PoSyCo Service Bus and process them according to their intended purpose.

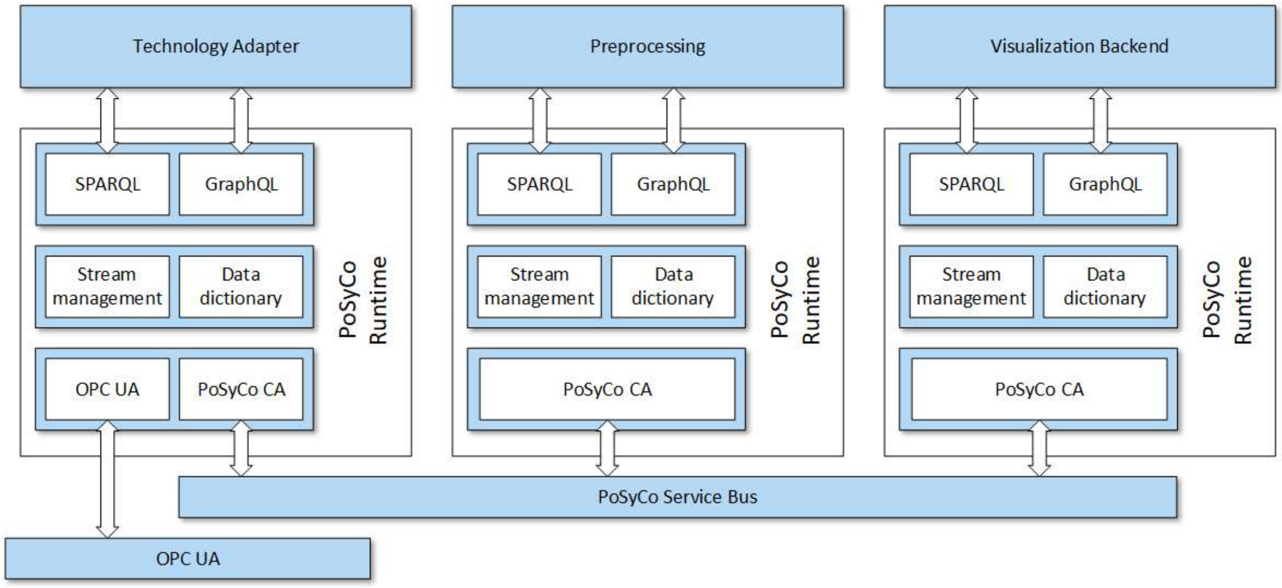


Figure 48: PoSyCo communication framework exemplified on UC1

4.2.6 Data and service interface

A SOFTprotection Module interacts with the PoSyCo Runtime via the data and service interfaces, which need to support request-reply-based and public-subscribe-based communication schemes to receive/send data via the data dictionary. SPARQL Protocol and RDF Query Language (SPARQL)[2] is a suitable interface to query and manipulate data provided via the data dictionary in RDF format. However, SPARQL only implements the request-reply communication scheme. For this reason, the SPARQL Event Processing Architecture (SEPA)[3] was identified as a suitable open-source technology to add publish-subscribe capabilities alongside SPARQL.

[2] https://www.w3.org/TR/sparql11-query/
[3] https://github.com/arces-wot/SEPA

The SPARQL 1.1 Query Language only specifies the language to formulate queries but not the communication protocol to exchange these queries and their corresponding results. The SPARQL 1.1 Protocol[4] is the suggested communication protocol for this purpose. It specifies a REST HTTP interface to exchange semantic data. The SPARQL 1.1 Protocol is available in many different programming languages, which is ideal for its use in PoSyCo as it does not limit the implementation of SOFTprotection Modules in this regard. Furthermore, having a well-defined REST interface allows separating the SOFTprotection Module from its corresponding PoSyCo Runtime and executing them on different devices. Therefore, very resource-constrained devices, not capable of executing their functionality and the PoSyCo Runtime in parallel, can be integrated into the PoSyCo communication framework.

As mentioned, the SPARQL 1.1 Query Language and the SPARQL 1.1 Protocol do not currently support publish-subscribe-based communication. This capability is added by the SEPA[5] open-source project, which is currently designed as a self-contained service that can be executed on top of existing SPARQL endpoints. SEPA specifies the SPARQL 1.1 Subscribe Language, which offers the *subscribe*, *unsubscribe*, and *notify* services. Thereby, the client formulates a SPARQL query and immediately gets the result to this query based on the information available in the RDF store. Furthermore, as long as the client remains subscribed, it is continuously informed about changes to relevant parts of RDF store. As this functionality cannot be implemented via REST, an additional WebService interface is defined by SEPA.

4.2.7 Configuration and data representation

Meta-information about the data that each SOFTprotection Module can access is provided via the corresponding data dictionary. The core component of the data dictionary is an RDF store, which stores ontologies in the form of triples. Thereby, triples are of the form *Subject Predicate Object*, as in *“Paper” hasColor “White”*. RDF stores are available in a variety of programming languages. The most predominant implementation regarding supported features, popularity, and community support is Apache Jena[6]. Therefore, the PoSyCo data dictionary includes an Apache Jena triple store.

Maintaining only meta-information but no process data in the data dictionary is a key concept of the PoSyCo Runtime. Nevertheless, process data needs to be provided by the PoSyCo Runtime to the SOFTprotection Module upon request via one of the Data and service interfaces. The fact that some of the data (meta-data) are not actually stored in the data dictionary, while other data (process data) are, should be transparent to the SOFTprotection Module. This behavior can be achieved with the help of custom property functions. Thereby, the SPARQL query engine identifies if an *Object* (or its value) shall be read from the internal triple store or retrieved via an external connection. The concept was implemented and presented to the scientific community using an OPC UA communication adapter in [19].

[4] https://www.w3.org/TR/sparql11-protocol/
[5] https://github.com/arces-wot/SEPA
[6] https://jena.apache.org/

Figure 49 depicts the main software components required for ontology-based data access via custom property functions. If the SPARQL engine invokes a custom property function, the data value is retrieved from the OPC UA server via an OPC UA client. All information necessary to connect to the OPC UA server is provided as meta-information in the data dictionary. The resulting data value is then passed to the SPARQL Endpoint as a result of the SPARQL Query request. In addition to the concept of custom property functions, the publication also showed that the Data Dictionary can partially be generated from an existing OPC UA server by a process called OPC UA Ontology Extraction.

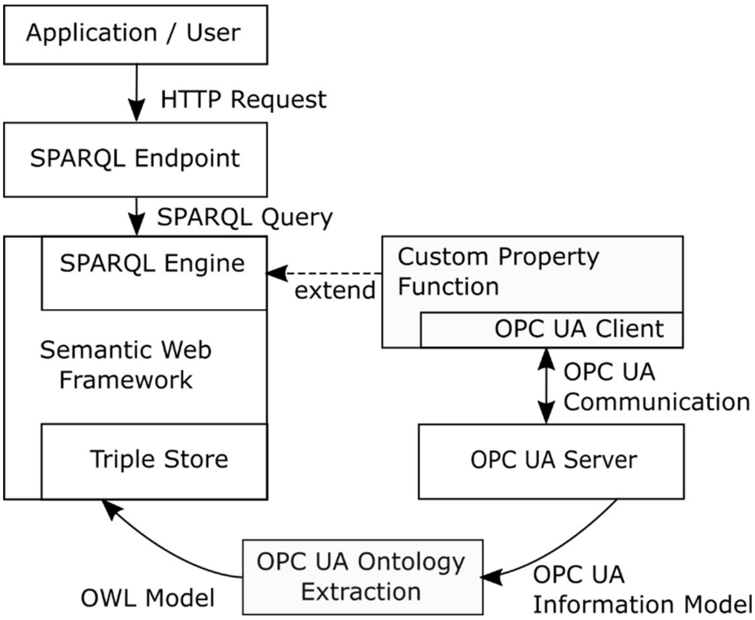


Figure 49: Concept of Ontology-Based Data Access [3]

4.2.8 Communication Adapter

The final layer of the PoSyCo Runtime handles data exchange with other PoSyCo Modules and Field Devices. Thereby, the PoSyCo Runtime can use a variety of Communication Adapters (CAs), depending on the devices it must communicate with. Most importantly, data exchange with other PoSyCo Modules is handled by the PoSyCo Service Bus and its corresponding PoSyCo CA. In contrast to external CAs (e.g., the OPC UA CA), the PoSyCo CA is not necessarily technology-specific and can even be implemented using a combination of multiple communication technologies. As a starting point, Apache Kafka was identified as a suitable technology to implement the PoSyCo CA, as it already supports all the above communication requirements directly or via appropriate extensions.

4.2.9 Deployment

For deployment, the PoSyCo Communication framework heavily builds upon the concept of containerization. The deployment concept is illustrated in Figure 50. As mentioned, each SOFTprotection Module consists of the module's functionality, which is encapsulated in the SOFTprotection Module container, and it's corresponding PoSyCo Runtime, which is encapsulated in the PoSyCo Runtime container. For easier deployment, these two containers can be combined into one *pod*.

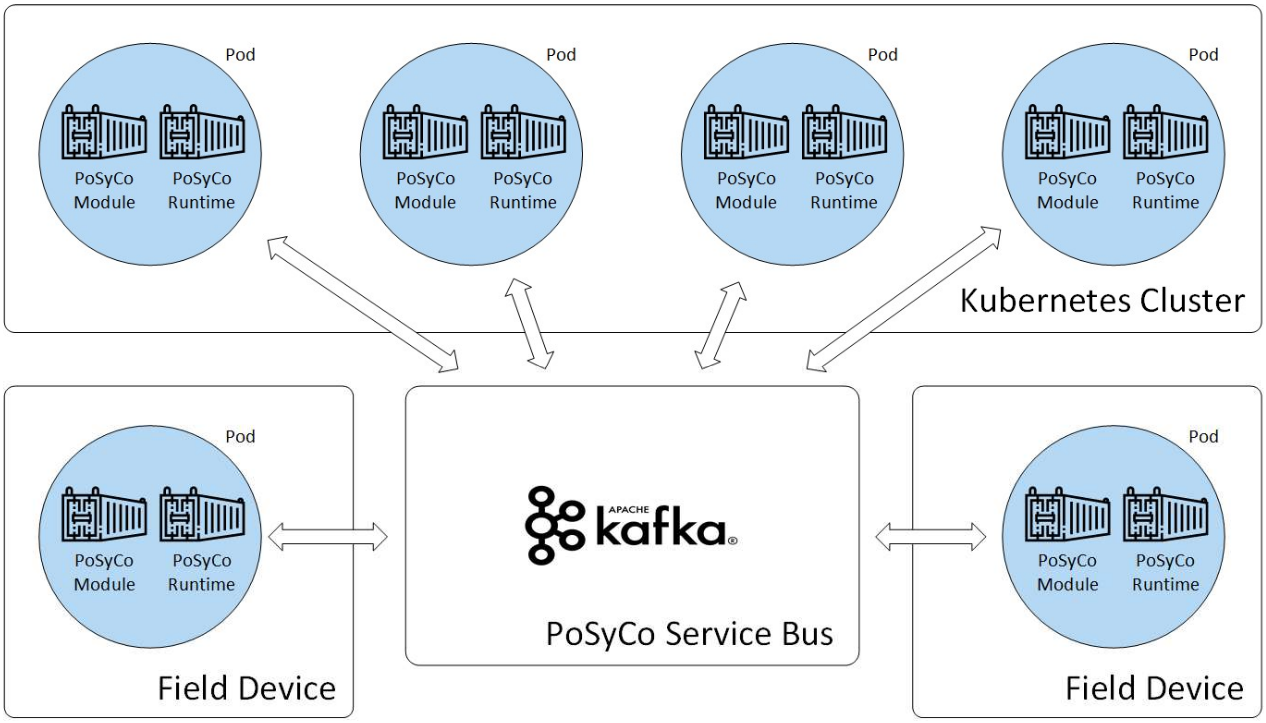


Figure 50: PoSyCo Deployment

A pod is simply a bundle of one or more containers that are guaranteed to be executed on the same node. By using this concept, communication latency between the SOFTprotection Module and its corresponding PoSyCo Runtime can be kept to a minimum while still preserving the benefits of separating the functionalities in different, well-encapsulated containers.

Pods can either be deployed on a dedicated machine using the Podman Manager tool (podman[7]) or on a cluster of compute nodes using Kubernetes[8]. The former method is more suitable for PoSyCo Modules which need to be executed on a specific node (such as a field device controlling a switch), while the latter is intended for resource intensive SOFTprotection Modules (such as the Data Preprocessing Module) that operate independently of their specific location, e.g., in a data center. A cluster of 24 Raspberry PIs was set up to test the automatic deployment of SOFTprotection Modules. It is depicted in Figure 51.

[7] https://podman.io/
[8] https://kubernetes.io/

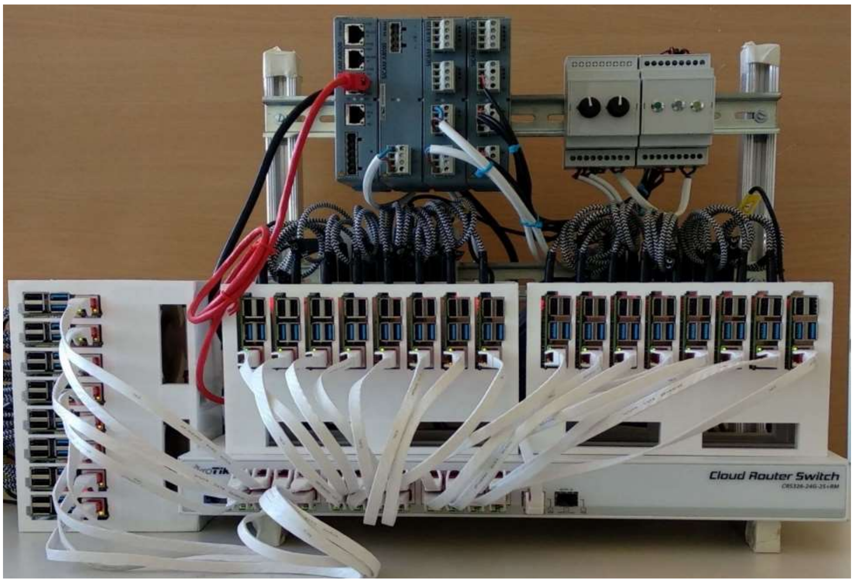


Figure 51: PoSyCo Kubernetes cluster

Furthermore, using containers and pods for the deployment of SOFTprotection Modules allows to flexibly deploy the necessary software for each module without cumbersome, time-consuming, and error-prone software setups on individual devices. For example, the PoSyCo runtime and the library it uses (such as Apache Jena and SEPA) are implemented in Java. Therefore, without containerization, each device participating in the PoSyCo system would require the Java Runtime Environment (JRE) in the correct version, aside from additional software required for module functionality and other tasks.

Another advantage of containerization in the context of PoSyCo is scalability: Containers can easily be replicated to cope with increased processing requirements. For example, the Data Preprocessing Module can easily be duplicated if additional sensors are added to the system. Likewise, redundancy to improve availability is also enabled by this concept.

Lastly, while combining the SOFTprotection Module container and the PoSyCo Runtime container into one pod is recommended for performance reasons, this is not strictly necessary. For resource-constraint devices, it may be beneficial to execute the PoSyCo runtime container on a different node, which is also supported. In this case, the memory and computational overhead introduced by containerization can even be completely bypassed by execution in the SOFTprotection Module functionality directly on the device without encapsulating it in a container. Therefore, the deployment concept also permits extremely resource-constraint devices, as they only need to implement a simple HTTP REST interface to communicate with their corresponding runtime.

4.2.10 Prototype and Validation

The PoSyCo Runtime implementation was evaluated with a large number of automated software tests. Furthermore, to show its applicability in a demo/prototypical scenario, the setup illustrated in Figure 52 was used. It consists of two SOFTprotection Modules: The A8000 Demo Application Module and the Visualization Backend Module.

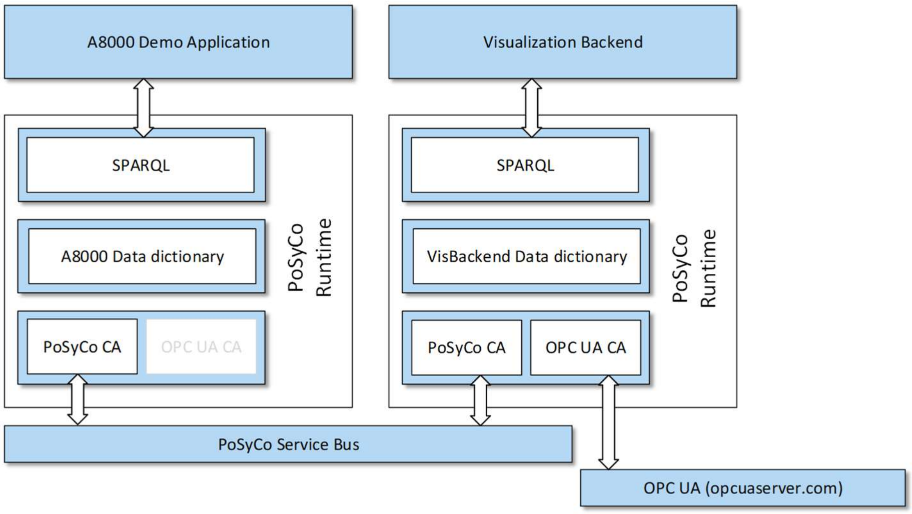


Figure 52: Prototypical setup consisting of two SOFTprotection Modules

The A8000 Demo Application Module was executed as a container application on a CP-8050 module of the SICAM A8000 series, which is specifically designed for SG (smart grid) applications. It controls two LEDs, each representing a power switch/circuit breaker (see Figure 53, left). As a second module in the prototypical setup, an instance of the Visualization Backend Module was used. Thereby, the Visualization Backend Module hosts a website (see Figure 53, right) displaying information about the grid topology, measurement values gathered from an external OPC UA Server, and buttons to control the LEDs of connected to the CP-8050 module. The data dictionaries of the two modules follow the structure defined by the PoSyCo information framework (see Section 4.2.4), thus combining information and communication aspects into a powerful framework for SG applications.

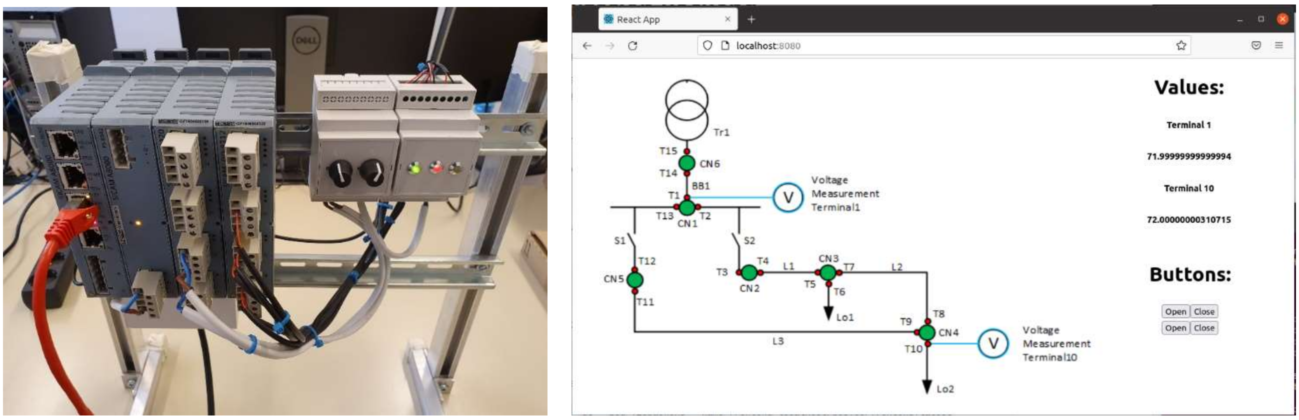


Figure 53: Information and Communication framework prototype: CP-8050 field device + Visualization

4.3 Process

In general, all PoSyCo's use cases demand optimized operation processes within the organisational structure of DSOs. Thus, this chapter discusses and introduces the following new roles and workflows for the process implementation of a SOFTprotection system:

Roles

- Asset Manager / Smart Grid Toolbox Responsible
- Asset Manager / Smart Grid Toolbox Test Expert
- SOFTprotection Operator / System Architect
- SOFTprotection Operator / System Manager
- SOFTprotection Operator / Data Manager

Workflows

- Workflow 1: Information required on a critical node
- Workflow 2: Sensor "mass" rollout
- Workflow 3: Event processing and visualisation
- Workflow 4: Grid supervision
- Workflow 5: Detect a pattern behind a reoccurring fault
- Workflow 6: Detect and prevent a looming fault
- Workflow 7: Restore an opened fuse
- Workflow 8: Coordination of EV charging power
- Workflow 9: Coordination of EV parking/charging hub
- Workflow 10: Customer request handling - EVCS
- Workflow 11: Automatic reconfiguration

These roles and workflows will furthermore be merged in specific Show Cases and analysed in depth (process optimisation and cost-benefit analysis) within deliverable D5.2 as well as PoSyCo system validation activities (see chapter 5). As a summary, Figure 53 provides an overview of newly identified roles together with already existing ones.

4.3.1 Roles

In general, a role represents the position or purpose that someone or something has in a situation, organization, society, or relationship. In the context of PoSyCo, a role represents a person who is in charge of carrying out specific duties within the organizational structure of a distribution grid operator. One person can be in charge of several roles. Accordingly, general roles within a DSO environment, which can be in charge of existing but also new duties, are presented as shown in the following figure. Thereafter, the specific duties of each role are described in detail.

The grey box in Figure 54 indicates the system limits of SOFTprotection. Roles at the boundaries of this box already exist in the company. However, in course of digitization in general and the introduction of

SOFTprotection, their areas of responsibility will be adapted or expanded to enable process integration. The roles within the grey box must be newly established and currently do not exist in this form at a DSO. However, it is not excluded that existing roles within the company also have to take over these tasks. For example, specialists from the IT department could take on the role of "SOFTprotection Operator / Data Manager". However, PoSyCo should not anticipate this as it may vary from DSO to DSO.

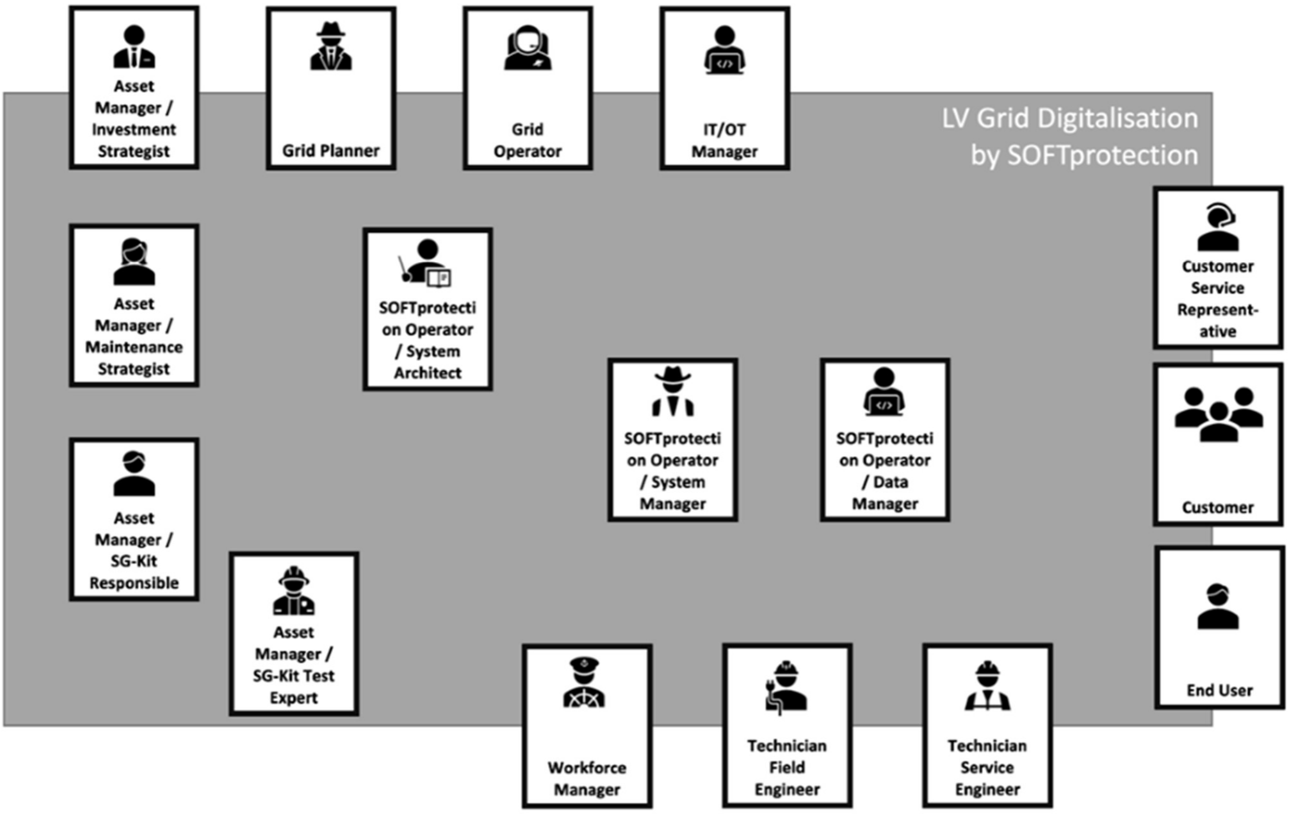


Figure 54: ***Existing and newly identified roles within DSO environments implementing SOFTprotection***

4.3.2 Exemplary Workflow “Sensor onboarding and sensor-network integration”

A workflow represents the sequence of industrial, administrative, or other processes through which a piece of work passes from initiation to completion. Thereby, the different Use Cases of the project define further duties for each role or person as described in the following chapters. Table 5 provides an overview of defined workflows. The first one can be found in this chapter whereas the others are described within deliverable D5.1.

Table 5: Overview of Use Cases and related Workflows

Use Case 0	Workflow: Information required on a critical node
	Workflow: Sensor "mass" roll-out
Use Case 1	Workflow: Event processing and visualization
	Workflow: Grid supervision
Use Case 2	Workflow: Detect a pattern behind a reoccurring fault

	Workflow: Detect and prevent a looming fault
	Workflow: Restore an opened fuse
	Workflow: Coordination of charging power
Use Case 3A	Workflow extension: Coordination of EV parking/charging hub
Use Case 3B	Workflow: Customer request handling - EVCS
Use Case 4	Workflow: Automatic reconfiguration

The higher-level PoSyCo Use Cases (e.g. UC 1 to 4) require sufficient and reliable measurement data from a distributed sensor network that is, at least partially, already present in conventional LV grids. Based on experience from Grid Measurement Devices (GMD) installation within Aspern Testbed during the project "Smart City Demo Aspern" (SCDA), such as time-consuming and challenging onboarding, problems with the direction of current transformer, etc., a user-oriented approach for the efficient integration of sensors into existing as well as new DSO processes is chosen as a mission statement for UC 0. It is therefore necessary that all roles are defined in such a way that a field technician without any additional IT training should be able to install sensors and also more complex toolboxes in an intuitive way. A lightweight digital twin in the SOFTprotection back-end enables the complete chain from planning, automatic pre-configuration, guided installation, and Plug&Play onboarding.

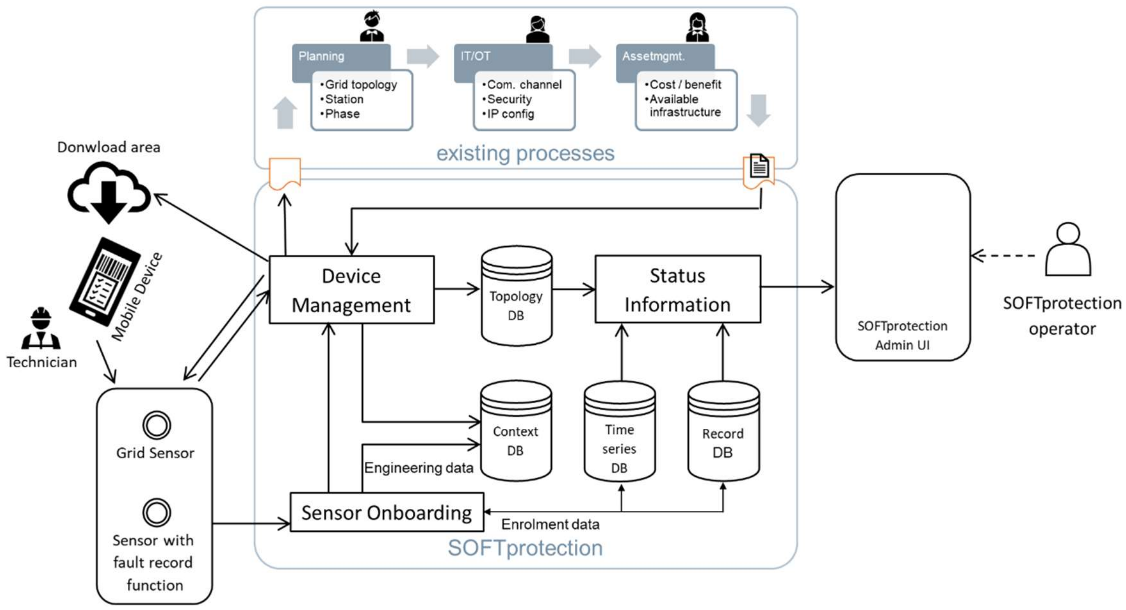


Figure 55: Functional Diagram of Use Case 0

Based on the functional diagram of UC 0, significant roles and workflows are defined as follows:

4.3.2.1 Role description for UC0

In UC0 the following **Roles** according Figure 55:

- Grid Planer
- IT/OT Manager
- Asset Manager / Investment Strategist
- Workforce Manager
- Technician / Service Engineer
- SOFTprotection Operator / System Manager

4.3.2.2 Workflow description for UC 0 „Workflow "information required on a critical node"

1. After an increasing number of connection requests, e.g. 11 kWp EVCS' on a specific LV feeder in Vienna's 19th district, the Grid Planner wants to be safe and decides to implement permanent monitoring and potentially an enhancement for congestion management later on.
2. The Grid Planner defines the location for implementation within the grid topology. Measurements at the transformer, the affected feeder and the two neighbour feeders will be necessary.
3. The IT/OT Manager takes the existing communication environment at the defined station into account, decides the preferred connectivity realisation and defines security affordances.
4. The Investment Strategist performs a cost-benefit analysis (CBA) and checks the availability of the needed smart grid toolbox (SGTB). The SGTB is available, and one is reserved for this project. The device identifiers and stickers for QR code are generated for the inventory system.
5. After the process chain 1-3, the configuration template is filled, and the Device Manager (a software module of the SOFTprotection system management) takes over the further onboarding process. The full configuration is ready for implementation and will be provided in a download area.
6. The Workforce Manager checks the output of the Device Manager and schedules the installation process for the available workforce.
7. A Technician gets the work order to implement the new SGTB at the selected transformer station.
8. The Technician takes the right hardware (HW) from the DSO's device stock and drives to the transformer station.
9. The bar code at the HW is scanned, and the configuration is downloaded.
10. The configuration is transferred to the sensor.
11. The SGTBs are logging in at the Device Manager.
12. If available, an update from the Device Manager is installed.
13. The sensor connects to the onboarding area. The SOFTprotection Operator checks if everything is ok. If yes, the data streams of this SGTB are set as validated and ready to use.
14. The sensor starts transmitting measurements and den Grid Planer has detailed information about this LV feeder. The connection requests can be investigated based on real data.

4.3.3 Process simulation

To optimise the implementation of processes, interfaces and roles within distribution system operators' environments, BIFROST has been chosen by the project team. BIFROST is a design tool and simulation environment for the realistic replication of e.g. smart cities or even energy communities with a strong focus on power grid and communication infrastructure. Supported by a powerful simulation engine, a browser-based 2.5D user interface allows researchers, grid operators and planning experts to emulate a wide range of possible scenarios with corresponding dependencies. The internal "state" representing the simulation world, including all physical dynamics and structures, is fully exposed to external applications, such as control algorithms or time series analysis tools (for further details see chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**). Thus, BIFROST will be used as a virtual testbed for PoSyCo related solutions at a later stage also for the testing described in chapter 5.

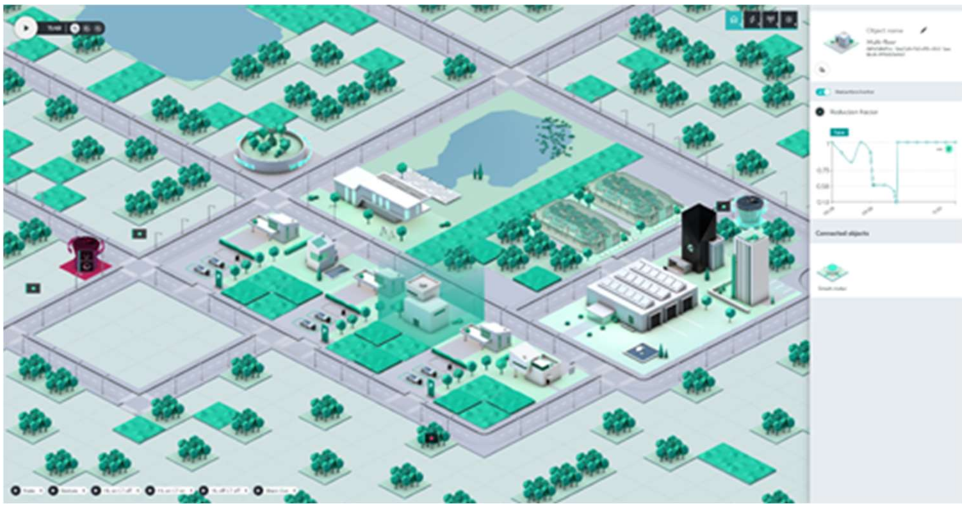


Figure 56: Architecture view of a BIFROST scenario

4.3.4 Explanations for complex processes

With simulation-based development of the algorithms as described in chapter 4.1 and the implementation using the PoSyCo runtime environment according to chapter 4.2, the main challenges for a future proof system platform have been elaborated.

But SOFTprotection is not only considering the physical challenges of avoiding the violation of infrastructural limits. The customers, operators and service engineers need information concerning power consumption restrictions, electricity prices, energy management and load management. Moreover, different scenarios such as public charging considering the interaction of DSOs Grid Operation and E-Car Operation Center of E-Mobility provider as well as the single charging pole of LV grid connected customers are considered within the approaches and available testbeds. Overall, a complex Cyber-Physical Systems (CPS) must be operated.

PoSyCo make use of the BIFROST smart-city simulator to model test scenarios and develop explainability algorithms accordingly.

This simulation-based approach enables (1) quick development of algorithms as extensive time needed to collect and clean data from the real grid is circumvented; (2) the simulation of events that cannot be enacted in vivo due to safety reasons; (3) the investigation of settings that are interesting for future business cases but not yet implemented in current grids, e.g., flexibility operators; (4) scalability testing of algorithms by increasing the size of the simulated scenario.

4.3.4.1 Explainability System

We provide a technical solution based on sematic technologies which enjoy an increased uptake in CPS research across domains [20] while also experiencing a strong industrial uptake through knowledge graphs (KG) [21]. Thanks to their capabilities of explicit knowledge representation, semantic technologies are ideal for integrating heterogeneous (CPS) data, as a basis for complex analytics to provide explanations and as enablers of meaningful interactions with users (as they already capture user vocabularies). Accordingly, core to the proposed solution is creating a large knowledge graph which aggregates and integrates different data about the smart grid (topology, events detected from sensor readings, weather) in terms of a semantic structure defined based on domain standards such as CIM (Common Information Model). Furthermore, rules capturing causalities in the smart grid (e.g., that higher solar intensity leads to increased PV production) are applied to the KG to derive causal links between individual events and provide a basis for algorithms that, given an event, extract a causality-based explanation for this event. The results are ranked and shown to various stakeholder groups by personalizing the presentation to the vocabulary and domain knowledge of the stakeholders.

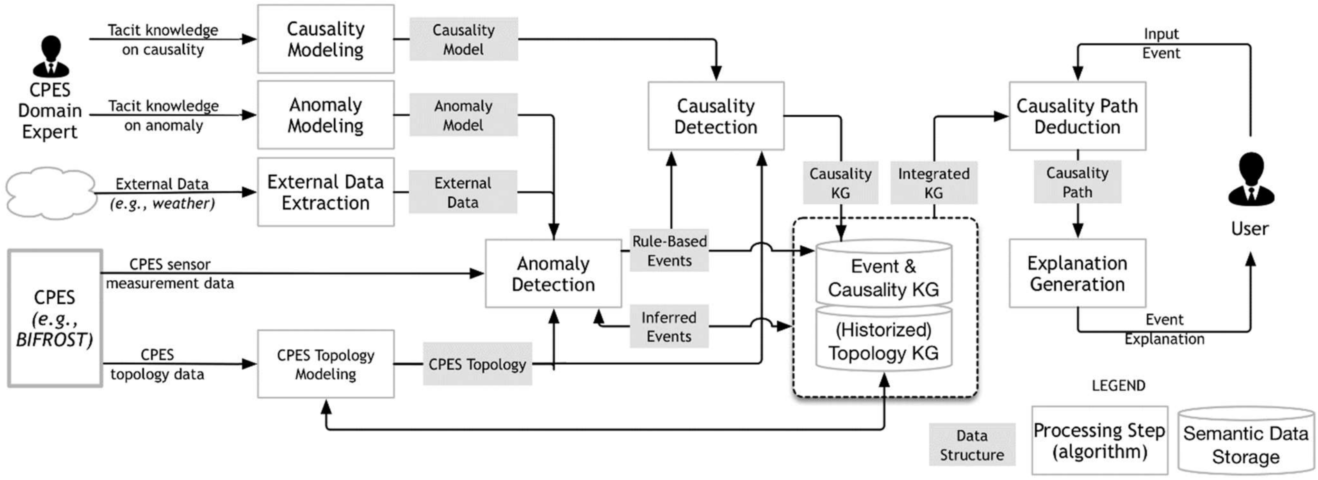


Figure 57: Explainability System Architecture

Figure 57 shows the architecture of the explainability system. On the left side of the figure are the data sources including: (I) data coming from the CPS, both static (e.g., the network topology) and dynamic (real-time sensor readings/simulated data); (ii) contextual data (weather) and (iii) tacit knowledge from domain experts about what and how events are happening, and the causal relationship that govern the CPS. Preprocessing steps are required to transform the raw data source into the knowledge graph. Measurement data are lifted using an ontology, while expert knowledge is represented formally. Events are detected and annotated from measurements data and causal rules are used to infer causalities between the events.

The right side of the figure illustrated the user-facing subsystems. They are responsible for taking the input event that needs to be explained, extracting the causality path of that event, and presenting the explanation to the user. In summary, the explainability system abstracts fine-grained measurement data into finite sets of events, augments topological structure with causal relationships, and combines them in the knowledge graph as a basis for an explainability algorithm to extract explanations of an event.

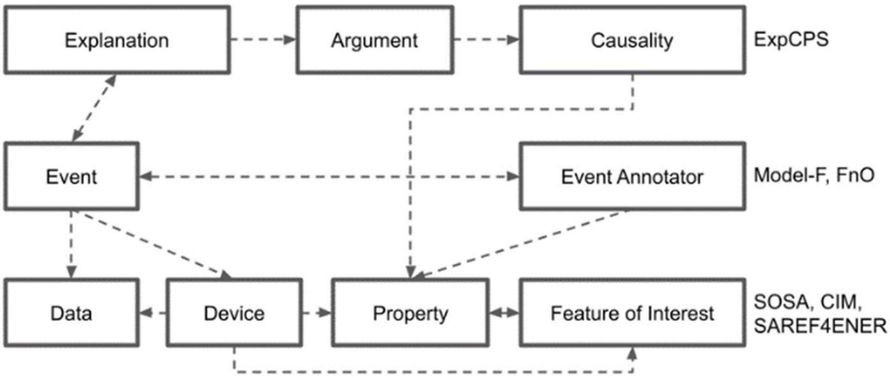


Figure 58: Ontology used in the knowledge graph of explainability systems

Figure 58 depicts the ontology we use in the knowledge graph. On the bottom is the vocabulary used to describe the system based on existing ontology CIM, Sensor- Observation-Sample-Actuator (SOSA) ontology, and SAREF4ENER ontology. Classes in the middle are used to describe events and how they can be detected. It reuses function ontology to describe event detector and represent event detection process as function application with pre-defined parameters. On top of the figure are classes used to describe explanation by using causality relationship on the system topology.

4.3.4.2 Results

After the integration of the BIFROST grid simulator with the explainability system, it is possible to make use of an illustrating scenario related to the explanation of an overload event occurring at the transformer in a grid. The simulator models not only the consumption pattern of electricity but also a demand response program participation. However, due to an unexpected situation – for example, a normally self-sustaining house suddenly taking in power from the grid due to their solar panel not producing enough power, or some resident coming home early before weekend and charging their electric vehicle – the load on the transformer increases, and an alarm is raised. The goal of the Use Case is to explain why the overload alarm in the transformer occurs.

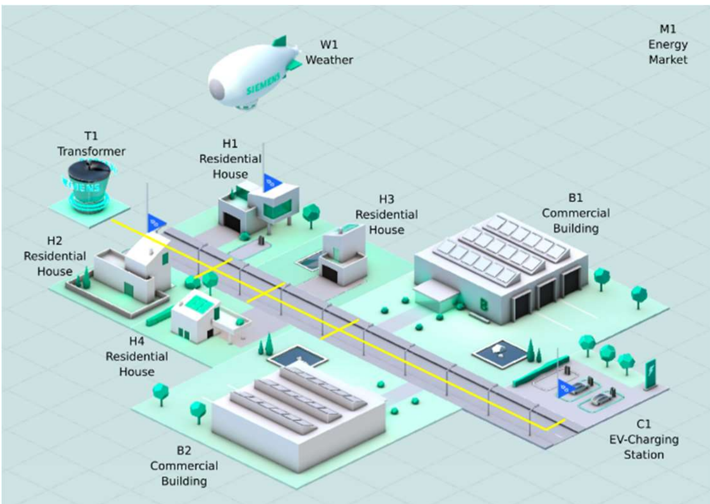


Figure 59: Use Case visualized in 2,5D UI of BIFROST simulation environment

Figure 59 illustrates the described use case scenario. The transformer T1 provides power to other buildings in the settlement. Contextual data (i.e., weather) are also simulated, which is symbolized by the airship. Not shown in this picture is an application server for managing the demand response participant regarding the allowance or request to change its consumption behavior.
Figure 54 shows an exemplary explanation result when the explainability system is asked to give a reason for the transformer overload. The output is a serialized version of an explanation tree by listing each branch as pairs of events that are related by a causal relationship. In this example, the explanation of a transformer overload is due to the increase in consumption (PeakConsumption) because residential houses' (1) higher energy demand and the reduced energy production of solar panels due to low solar intensity (i.e., bad weather); and (2) the respond to a flexibility market event of increasing consumption due to low energy costs.

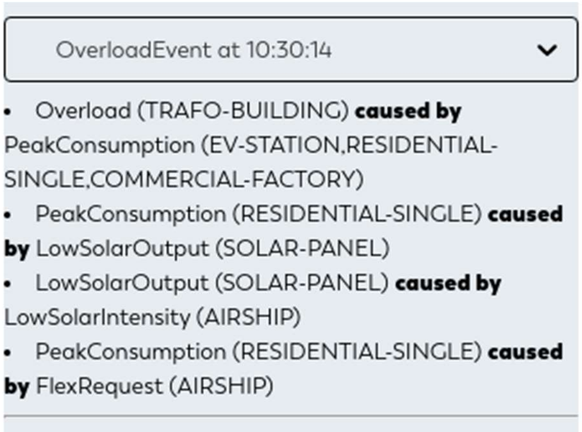


Figure 60: Textual explanation output of a given event (Transformer Overload)

4.4 Results of economic and SWOT analysis

4.4.1 Economic analysis

During the project, several test grids were analysed from technical perspective. Accordingly, one of these test grids was also chosen for a detailed economic analysis considering defined Use Cases. However, as case study specific analysed are mostly not generalisable the main goal of the performed analysis was to identify crucial parameters in the context of the PoSyCo project as well as future grid digitalization strategies. The following figure outlines the chosen test grid[9] including foreseen measurement points (P,Q and U) by the PoSyCo project team.

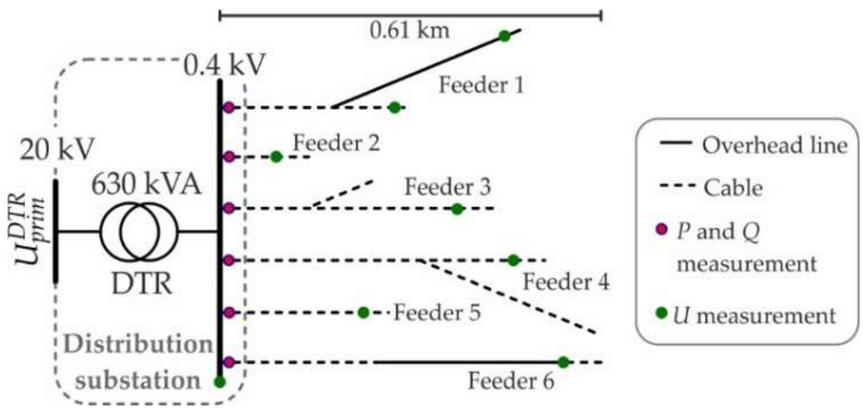


Figure 61: Simplified one-line diagram of the analyzed low voltage grid (incl. foreseen measurement points)

According to the new roles and workflows defined within chapter 4.3, the economic analysis intents to rate their corresponding costs. Thus, the following table summarises chosen economic parameters. These parameters were also varied to rate their impact on economic performance.

Table 6. Summary of chosen economic parameters for the analyzed low voltage grid

Number of additional PoSyCo roles	5
Yearly staff cost per role in [€]	70000
Number of transformers of Wiener Netze	10841
Digitalization rate	15%
Weighted Average Cost of Capital (WACC)	4,88%
Inflation rate	2%
Number of measurement points in test grid	14
Integration cost per measurement point in [€]	1150
Operation cost per measurement point in [€/yr]	50
PoSyCo controller hardware cost per transformer in [€]	3000

[9] Several PV installations (5kW) as well as EV charging stations (11 kW) are considered in this LV grid; for details it is referred to the deliverables D3.1, D3.2 and D3.3).

Cable laying cost (average) in [€/m]	450
Asset lifetime – cables in [yr]	40
Asset lifetime – IT equipment in [yr]	10

Furthermore, several grid reinforcement timelines were defined by the PoSyCo team considering the length and age of each feeder as shown in Table 7. The reference year was set at 2020. Thus, in the reinforcement timeline "original planning" the reinforcement years were calculated according to the expected asset lifetimes (e.g. Feeder 1's age in 2020 is 10 years resulting in 2050 as reinforcement year, as the asset lifetime of 40 years is reached). However, due to increasing power demand (e.g. for fast EV charging) the alternate "fit&forget" reinforcement timeline overcomes upcoming grid capacity bottlenecks by preponed cable upgrades (e.g. Feeder 2 is upgraded 5 years prior to original planning).

As an alternative, the reinforcement timeline "early digitalization" assumes that the developed PoSyCo Softprotection becomes operational in the year 2023 which prevents, for example, the necessity for a preponed upgrade of Feeder 2. In a similar way, the reinforcement timeline "late digitalization" assumes a deployment-ready SOFTprotection system at the beginning of 2030. For the timeline "late digitalization", extra costs for customer complaints management were considered between 2028 and 2030 (assumed cost of 40 k€/yr).

Table 7. Summary of derived grid reinforcement timelines for the analyzed low voltage grid

	Feeder length in [m]	Feeder age in [yr]	Feeder reinforcement expected in year (original planning)	Feeder upgrade due to EV develop-ment in year (fit&forget)	Feeder upgrade due to EV develop-ment in year (early digitalisation)	Feeder upgrade due to EV develop-ment in year (late digitalisation)
Feeder 1	1.040	10	2050	2040	2050	2050
Feeder 2	205	30	2030	2025	2030	2025
Feeder 3	810	35	2025	2023	2023	2023
Feeder 4	1.550	10	2050	2040	2050	2050
Feeder 5	490	35	2025	2022	2022	2022
Feeder 6	880	10	2050	2035	2050	2050

Based on this, the economic evaluation compares the net present values of each reinforcement timeline setting and its corresponding operational as well as capital expenditures.

Accordingly, the following figure illustrates the calculated investment paths (as net present values referred to year 2020). The blue line represents the reinforcement timeline "original planning" for the analysed low voltage grid. Reinforcement timeline "fit&forget" is indicated in red, "early digitalization" in green as well es "late digitalization" in violet.

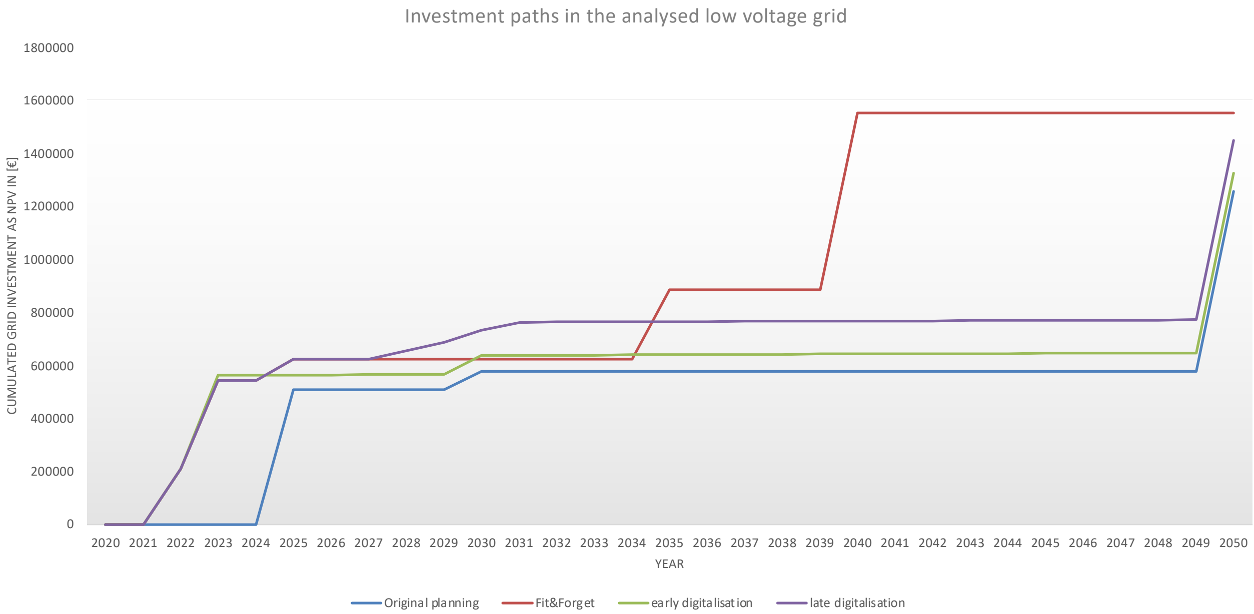


Figure 62. Calculated investment paths of the analyzed low voltage grid

The net present value difference of each timeline is illustrated in Figure 63. Depending on the investment timing the additional grid investment cost (compared to the reinforcement timeline “original planning”) change. For instance, the additional cost of the “fit&forget” timeline in year 2040 is quite high (974 k€) as several feeders must be upgraded earlier than originally planned. However, those additional cost reduce at the end of the evaluation period (year 2050) as also the net present values (NPV) of feeder upgrades in the “original planning” timeline are eligible within the calculation. What remains as additional cost is the lower discounting effect of preponed feeder upgrades.

When the timelines “early digitalization” and “late digitalization” are compared to the timeline “fit&forget”, Figure 64 shows the calculated additional cost or savings for the analysed low voltage grid. Additional costs are mainly given at the implementation phase of the digitalization (years 2025 and 2030) due to investment cost of sensor rollouts. Savings increase depending on the investment timing in the “fit&forget” timeline (e.g. high savings due to feeder upgrades in year 2040 within the “fit&forget” timeline). At the end of the evaluation period in 2050, the calculated savings remain mainly due to discounting effects of postponed feeder upgrades reduced by OPEX (Operational Expenditures) of SOFTProtection. It must be mentioned that these results rely on the parameter setting of Table 6. The impact of parameter changes will be shown in the following chapters.

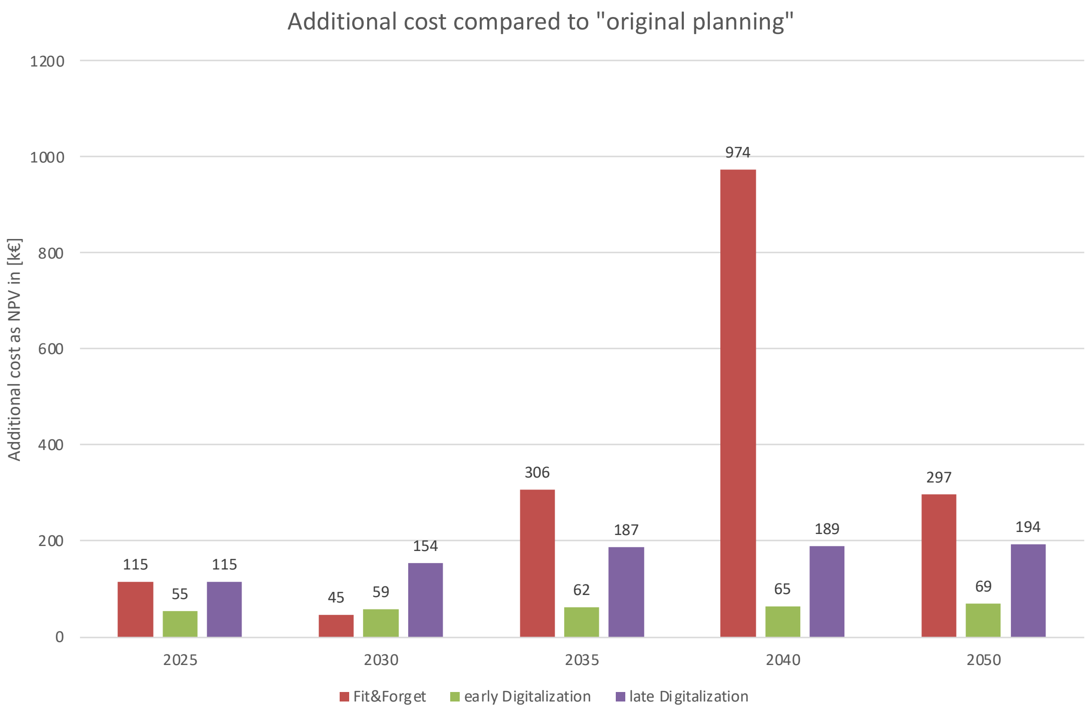


Figure 63. Additional cost compared to “original planning” in the analyzed low voltage grid

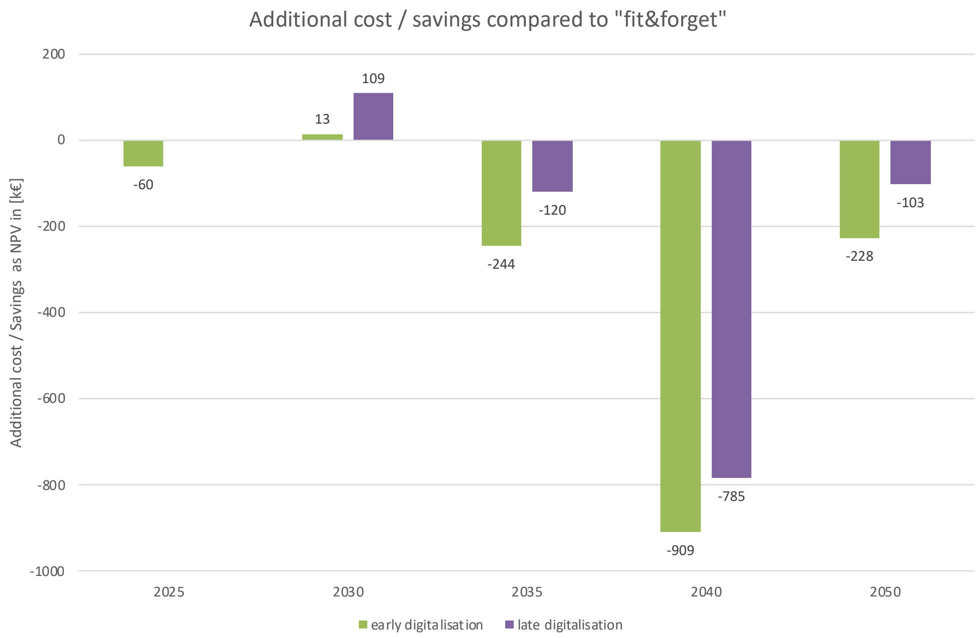


Figure 64. Additional cost compared to “fit&forget” in the analyzed low voltage grid

Even more, a sensitivity analysis (variation of one economic parameter besides unchanged other parameters) war performed within the case study.

Figure 65 e.g. shows that there is a strong impact of inflation rate (increasing CAPEX (capital expenditures) and OPEX in the future) variations. Inflation rate increases influence both fit&forget as well as digitalization strategies. However, due to increasing OPEX shares of digitalization strategies and resulting discounting effects (if WACC (weighted average cost of capital) keeps constant) the potential digitalization savings could reduce significantly, or even result in extra cost.

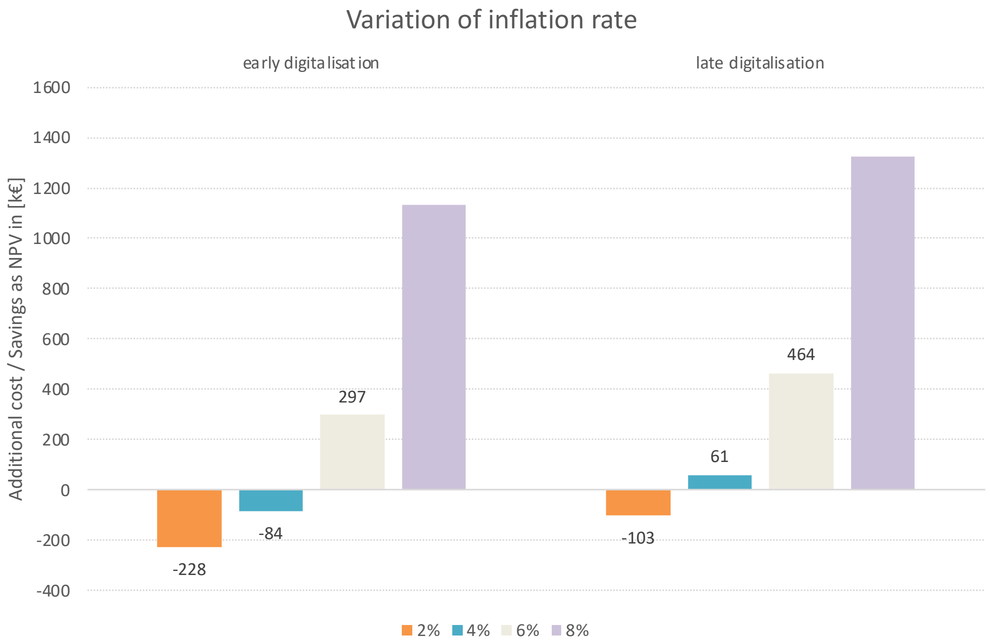


Figure 65. Net present value impact (year 2050) of inflation rate in the analyzed low voltage grid

In general, the performed sensitivity analysis showed that:

- Due to the long evaluation period sensor integration cost impacts are lower than expected.
- At high digitalization rates, impacts of role numbers are low.
- Medium impacts can be seen for variation of sensor numbers, sensor OPEX and feeder length.
- High impacts are given for variation of cable prices, digitalization rate as well as inflation (if WACC keeps unchanged see
- Figure **65**).

4.4.2 SWOT analysis

Based on the case study results as well as therein identified critical economic parameters, the PoSyCo project team decided to perform a SWOT (Strengths, Weaknesses, Opportunities as well as Threats) analysis in the context of future grid digitalization.

In several discussions, the following SWOT analysis tables were derived building a basis for strategic decisions for a transition to grid digitalization. Table 8 summarises internal, Table 9 relevant external factors.

Table 8: Summary of internal SWOT Analysis factors towards grid digitalization

Internal factors	
Strengths	**Weaknesses**
Where are DSOs strong? - Strong engineering: well-functioning approach to network planning to date - Reliable fulfillment of supply mandate - Appropriate investments are recognized - Internal planning certainty exists - Assets are (still) sufficient, which means that a decision regarding digitalization can still be delayed short-term. What competencies already exist that can contribute to digitalization? - Accounting already digital - Legal background knowledge available - ICT competence already built up through smart metering - New competencies already partially established through generation change In which areas does the DSO already have positive experience with digitalization? - Additional knowledge already possible through evaluation of smart metering data - Focus mainly on quality management and interaction of components - Quality of Supply could be strengthened	Where do DSOs have weaknesses? - Rigid structures (relative) - Concerns are present – grid reinforcement limits reached? - Previous planning approach no longer works so well (most diverse and simultaneous requirements) - Automation in network planning is missing - Little information in the low-voltage sector - Strength of long-term planning lost (already lagging behind, especially in terms of personnel) Where are resources missing? - ICT and digitization components need to be expanded - Personnel overload - Less focus on internal personnel development / competence building - Need for know-how transfer due to staff reductions - New roles (e.g. SOFTProtection) not yet established Where do DSOs lose money or know-how without digitalization? - Without additional information from the network, it is difficult to improve services. - Customers may receive fewer services

Table 9: Summary of external SWOT Analysis factors towards grid digitalization

External factors	
Opportunities	**Threats**
What can DSOs improve through digitalization? - Adapt processes (no longer wait and see) - Increase efficiency (personnel and assets) also for future development - Increase transparency and create argumentation basis (e.g. for necessary interventions) - Better services (e.g. flexible network services/capacities increased "value for money" for customers) - Avoidance of digging as marketing / increased customer satisfaction - Facilitation of energetic space planning more efficient customer expansion How to respond to political/social trends? - Political mandate to maintain high supply security and quality as well as secure grid operation can be secured - Existing experience in planning can be improved - Early system change can result in an enabler image - Timely implementation will support the requirements of energy communities and the fulfillment of (future) legal requirements. What new (customer)needs can be expected? - New information systems for planning and network operation - New information services for customers (e.g. data insight on voltage quality, contribution of consumers to stable grid operation, warning messages if connected load reaches e.g. 80%; status of energy community consumption, flexible tariffs, etc.). - Demand for affordable basic supply - Predictive maintenance of components - Automated documentation of faults or switching operations	What negative effects can be expected with/without digitalization? - Misallocation in the socialization of costs - Wrong decisions in society could lead to energy poverty - Reduction of perceived security of supply - Difficulty in countering customer complaints - Increasing OPEX (missing profit components) - Slowing down of the energy transition - Rapid change of e.g. inflation rates or component costs (chip shortages) resulting in significant economic impacts What happens if digitalization is "slept through"? - Media bashing - DSO appears as a preventer - Triggered regulatory requirements - Complaints from customers (if power quality or outage times do not fit) - Parallel systems (e.g., own sensors in energy communities) - Unrecognized overload situations - Accidents / personal injuries - Difficult data management / data economy Where are DSOs becoming more vulnerable due to digitalization? - Security gaps in the system (security must be a high priority) - Communication / component failures (external dependencies) - Analog (load-side) attacks must not be forgotten

Based on these internal and external factors, the following strategies and measures towards future grid digitalization were derived:

- Use the internal momentum, triggered by the ongoing generation change, as well as already existing competences and additional knowledge (through new available data) to increase DSOs efficiency (e.g. improvement of grid planning, operation and maintenance);
- Don't hide behind the political mandate to maintain security of supply and grip operation, but act as an enabler to support upcoming customer needs (e.g. for Energy Communities, Prosumers, flexible load allocation). Use this "Enabler Image" for development and marketing towards new customers services (data insight on voltage quality, contribution of consumers to stable grid operation, warning messages if connected load reaches e.g. 80%; status of energy community consumption, flexible tariffs, etc.);
- Use additional revenues of new services of "Premium" customers to secure an affordable basic supply;
- The long-term grid planning as well as operation expertise using grid digitalization technologies must be adopted in time. Accordingly, DSO wide measures must be implemented in order to rate still existing grid reserves as well as to establish a timeline towards know-how development and transfer between affected departments;
- Adequate communication strategies must be developed which state, that the transformation processes in large scale infrastructures need adequate time and planning for correct implementation. This must be performed both DSO internally as well as with external actors. Medial bashing should be prevented by that;
- Additionally, a pro-active external discussion process with need-owners (e.g. Energy Communities, Prosumers, EV charging station operators, aggregators etc.), Regulatory Authorities as well as Politics should be established in order to identify and develop the right digital and grid related services;
- The system architecture must be "Safe and Secure by Design" whereas the dependence on external actors shall be limited;
- Adequate measures must be implemented in order to limit economic impacts of critical factors such as e.g. rapid change of inflation rate, component costs / availability (chip shortages) or higher OPEX during digital grid operation;
- As the previous planning approach no longer works so well (diverse and simultaneous requirements, little information in the low-voltage sector) the necessity for a change of processes and data availability becomes more and more evident to DSOs;
- This rising awareness must be used to expand ICT and digitization components in the system to reduced personnel overload and improve system operation;
- New roles (e.g. SOFTProtection Operator) as well as know-how transfer have to be established.
- Increased information at low voltage could even more enable a more efficient facilitation of energetic space planning for both urban (Smart Cities) as well as rural areas;
- The relatively rigid structures at DSO level must be overcome to avoid increased customer complaints as well as regulatory penalties in the long run;
- Accordingly, the DSO internal awareness for the PROs and CONs of an evolving grid towards

digitalization must be established. The needs of staff members as well as the staff council should be considered in long term investment decision;

- In the long run, a sufficient recruiting of well-trained employees must be secured e.g. by establishing tailor-made digitalization trainee programs including fair pay.

4.5 Lab Evaluation and System Validation

For validation and demonstration of the PoSyCO SOFTprotection functionalities, Use Case specific Lab and System evaluation as well as Living Lab evaluation in the field was realized. The testing and validation activities have been performed along the six PoSyCo Use Cases. The following is an overview of the individual test cases, as they were performed and implemented in the individual testing environments (see chapter 3.2.2). Then, the results and lessons learned from the individual testing and validation activities are presented.

UC0 – Sensor onboarding and sensor network integration: The test cases focus mainly on the integration in existing DSO processes and the technical realization of plug&play sensor and smart grid tool-box roll-out. This process, linked with the DSO system landscape, was tested by Wiener Netze technicians.

Table 10: Test Cases for Use Case 0

Test Case	Dimension	Test Environment
Experience the interaction with next generation sensor prototype	Physical / ICT	BIFROST
Validation of low-cost current sensor networks for efficient integration in secondary substation feeders	Physical	EGS test setup at Siemens
Sensor Rollout	Process	ASCR Testbed Aspern

UC1 – Acquisition of field data streams and fault records: The test cases verify if the data from the integrated sensor network is delivered in the required quality and can be used for fault detection and fault determination. Wiener Netze installed two types of meters at several locations: a grid monitoring device (GMD) with power line communication and Enhanced Grid Sensors (EGS) with GPRS communication interface. Both meters deliver measurement data which is subsequently analyzed for plausibility and to facilitate comparisons between both devices.

Table 11: Test Cases for Use Case 1

Test Case	Dimension	Test Environment
Integration and testing of sensors in BIFROST	Physical, ICT, Process	BIFROST
Smart Grid Tool Kit functionality	Physical, ICT, Process	Information and Communication framework prototype: CP-8050 field device + Visualization tested at Siemens
Data acquisition of real sensor prototypes in testbed.		ASCR Testbed Aspern / offline Analysis

UC2 – Distributed fault analysis for service restoration acceleration: Test cases for UC2 evaluate the applicability of the fault prevention and fault analysis, as well as proper filtering and preprocessing of events to support grid operations. The GMD/EGS measurements are implemented in an application for customer service center of Wiener Netze and realized as Proof-of-Concept.

Table 12: Test Cases for Use Case 2

Test Case	Dimension	Test Environment
Understanding Events	Process	BIFROST / ExpCPS framework prototype
Application of Root Cause Analysis on real data	Process	Camunda

UC3 – Overload prevention by customer activation: The test cases focus on the activation of customers to prevent overload of low voltage (LV) line segments with focus on (fast) charging stations for electric vehicles (EV). Tests are performed with the AIT Software-Hardware-in-the-Loop platform (simulation and laboratory) and at the Siemens testbed for electromobility (Living Lab validation).

Table 13: Test Cases for Use Case 3

Test Case	Dimension	Test Environment
Dynamic utilization of available grid capacity of an EVCS hub – BIFROST simulation	Physical, ICT	BIFROST
Parameter optimization using a BIFROST based digital twin	Process	BIFROST
Implementation of grid friendly charging management in a SIL environment	Physical, ICT	AIT Software-Hardware-in-the-Loop Platform
Distributed LV control by SOFTprotection and DSO Interface	Physical, ICT	Siemens Testbed for Electromobility
OCPP infrastructure and local interaction	Physical, ICT	Siemens Testbed for Electromobility

UC4 – Overload prevention through temporary meshing: Test cases for UC4 evaluate the practical suitability of the temporary meshing algorithm using a laboratory demonstrator with four industrially available low-voltage compact circuit breakers. The switching management module (SMM) algorithm is analyzed by scaling and varying the weighting factors on digital grid models, going beyond the software-based tests carried out in WP3. Scenarios with incomplete and/or corrupt input data from the integrated sensor network are considered. Situations are emulated in which the grid status and characteristics changed during algorithm execution. Extended software-based test cases evaluate how the SMM algorithm is performing in case of missing and/or corrupt measurement data as well as the in case of changing grid status and characteristics during algorithm execution.

Table 14: Test Cases for Use Case 4

Test Case	Dimension	Test Environment
Functionality of the Switching Management System algorithm, executed at a laboratory demonstrator	Physical, ICT	TUG circuit breaker laboratory demonstrator
Robustness of the SMM algorithm at unfavorable environment conditions	Physical, ICT	Python / Power Factory simulation analysis (AIT, TUGraz)
Robustness of the SMM algorithm at changing environment conditions during the algorithm runtime	Physical, ICT	Python / Power Factory simulation analysis (AIT, TUGraz)

UC5 – Stakeholder overarching system interaction and process adaption: Test cases for UC5 aim to validate the flexibility utilization module and to verify if flexibility requests do not cause local overloads. It is analyzed whether the provision of flexibility from different actors can avoid overloading caused by external events. Therefore, the BIFROST / Explainability CPS (Cyber Physical System) environment has been enhanced.

Table 15: Test Cases for Use Case 5

Test Case	Dimension	Test Environment
SoftProtection for ensuring grid friendly flexibility requests	Physical	BIFROST
Overload prevention support due to community flexibility activation	ICT, Process	BIFROST

4.5.1 Use Case 0: Sensor onboarding and sensor network integration

4.5.1.1 Experience the interaction with next generation sensor prototype

The aim of this test case was to "experience" the workflow for the simple and intuitive installation of future IoT sensors during a technical proof-of-concept. The focus was on the use of simple tools such as BIFROST as a kind of planning environment for sensor placement, a smart phone app for process support and prototypically realized smart grid modules that interact with BIFROST via different communication channels (e.g. LTE, NB-IOT) in a hardware-in-the-loop set-up. For a better understanding of an efficient plug-and-play rollout of sensors a solution was developed and tested, which consists of a backend, a Field

Device a ConfigBox and a device which contains the configuration (e.g., a smartphone). The concept and the field box are shown in Figure 66 and Figure 67.

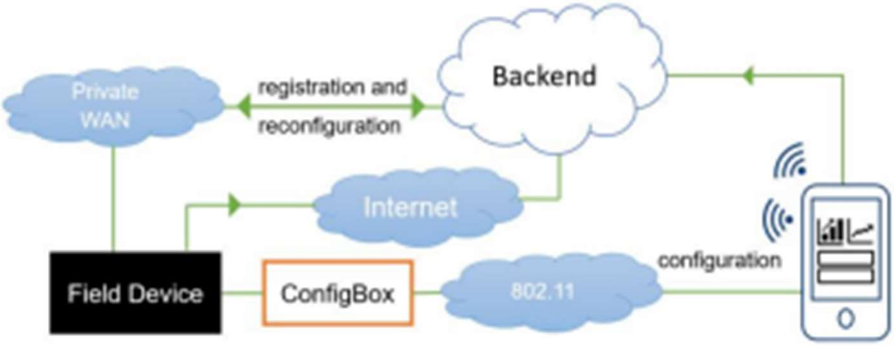


Figure 66: System architecture diagram

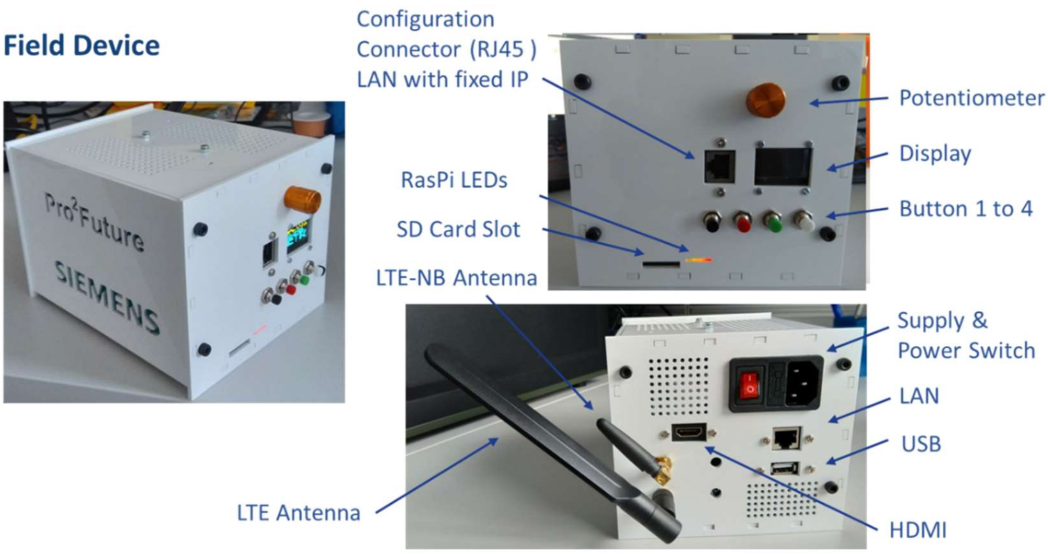


Figure 67: Field device prototype

The virtual testbed BIFROST was used for demonstrating the starting point of the sensor placement as well as the provision of measurement data collected by the sensor's prototypes. A live presentation of the show case was produced at a virtual test bed and can be requested from the technical coordinator.

The test case covered the range of the problem very well and the transfer to the real sensor system EGS could take place step by step. Of course, some compromises had to be made here due to the functional scope of the very early EGS prototype and, above all, the lack of back-end software.

The test case was valuable in that it provides a certain target vision of how an efficient and, above all, user-friendly roll-out of sensor technology and, later, more complex Smart Grid modules can be carried out. For a successful go-to-market, not only the technical requirements but also the handling and acceptance are a decisive factor. This is therefore a very valuable input for sensor system vendors and for users like DSOs regarding their requirements.

4.5.1.2 Validation of low-cost current sensor networks for efficient integration in secondary substation feeders

In addition to the sensors for distribution cabinets, the topic of sensors for the secondary panels of the transformer stations was an issue. In order to save costs, the idea is not to provide a separate enhanced grid sensor (EGS) for each feeder, but to implement separate, cheaper current measurements. They are designed to form a sensor network and, in conjunction with a voltage measurement on the busbar, enable correct active and reactive power measurements. For validation, a wired (incl. power-over-LAN) variant was analyzed in course of the project.

The communication between an advanced current sensor (ACS) and EGS on a local Ethernet-based bus is tested, jitter and propagation delays are measured. The achieved results of values reaching < 1 µs are promising for an efficient integration of ACS together with EGS for a low-cost measurement in secondary substations. The test setup is shown in Figure 68 and one result of a jitter measurement is shown in Figure 69.

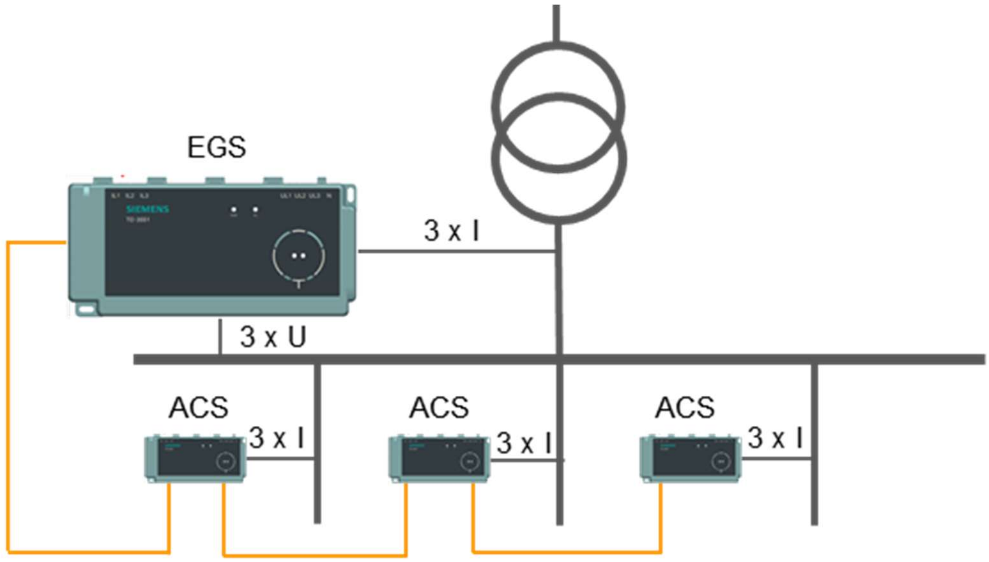


Figure 68: EGS test setup

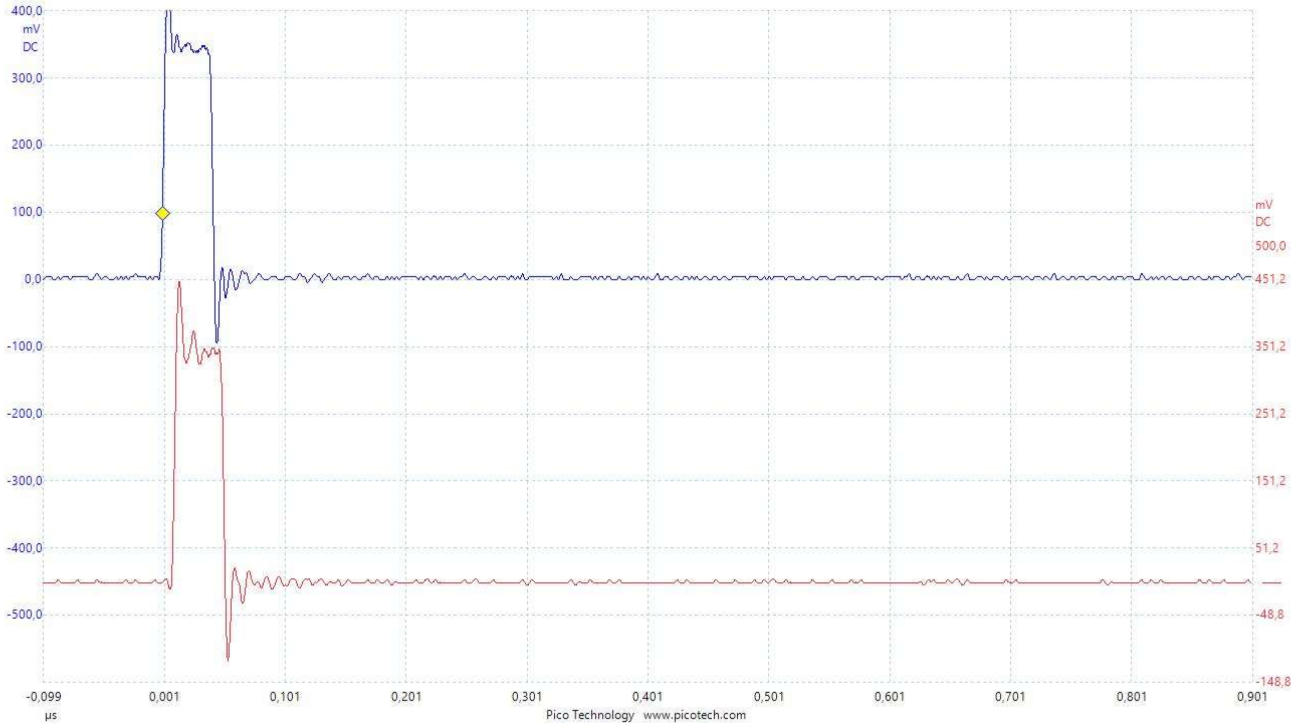


Figure 69: Example of a jitter measurement

As an extension of the EGS, prototypes of this sensor network are now intended for use in the field as well. Depending on internal as well as external feedback, a decision will then be made whether a corresponding pre-series development will take place. As an alternative, the extent to which sensor networks based on radio technologies can be used will also be evaluated.

4.5.1.3 Sensor Rollout

As depicted in Figure 70 a sensor rollout process starts with the definition of requirements, selection and pretesting of a device. By use of templates an allocation of the required grid functions to the grid plan is done (e.g. by selecting the area for a sensor placement at the geographic information system (GIS).

For increasing the effectiveness of a rollout process, device-specific engineering shall be automated as well as possible. By using a group of component templates in one workflow, the process shall be optimized. As an example, a voltage controller would include templates for field devices and applications as well as a backend application for system integration. The generation and editing of the templates shall be done in one workflow.

A “How To” user manual of a rollout process is presented and is included in Deliverable D6.2 and a screenshot of the sensor placement step given. It shows how to start and login to the SCADI App and how to deploy and place a device at the grid plan to the desired location and feeder connection point. The process is shown in Figure 71 and Figure 72.

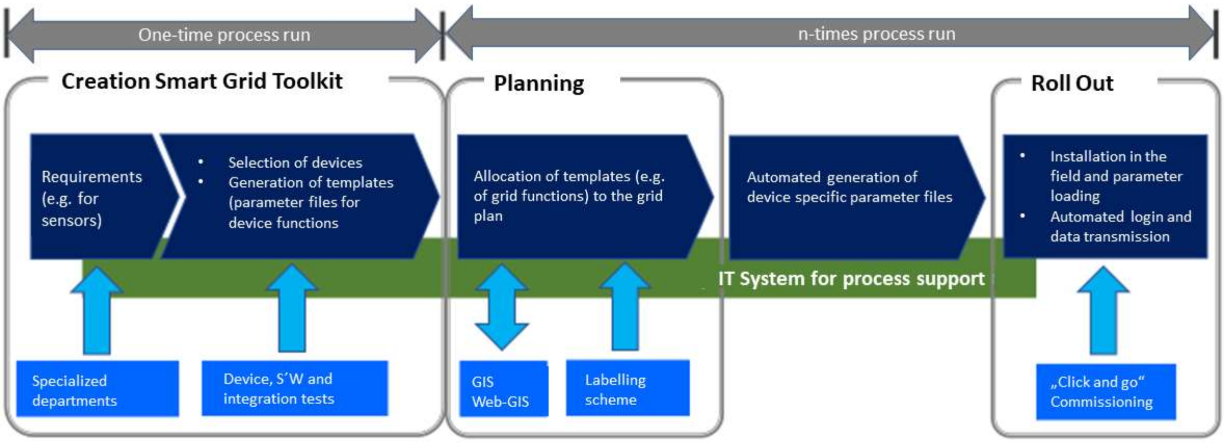


Figure 70: Rollout process – defining and deployment of grid functions

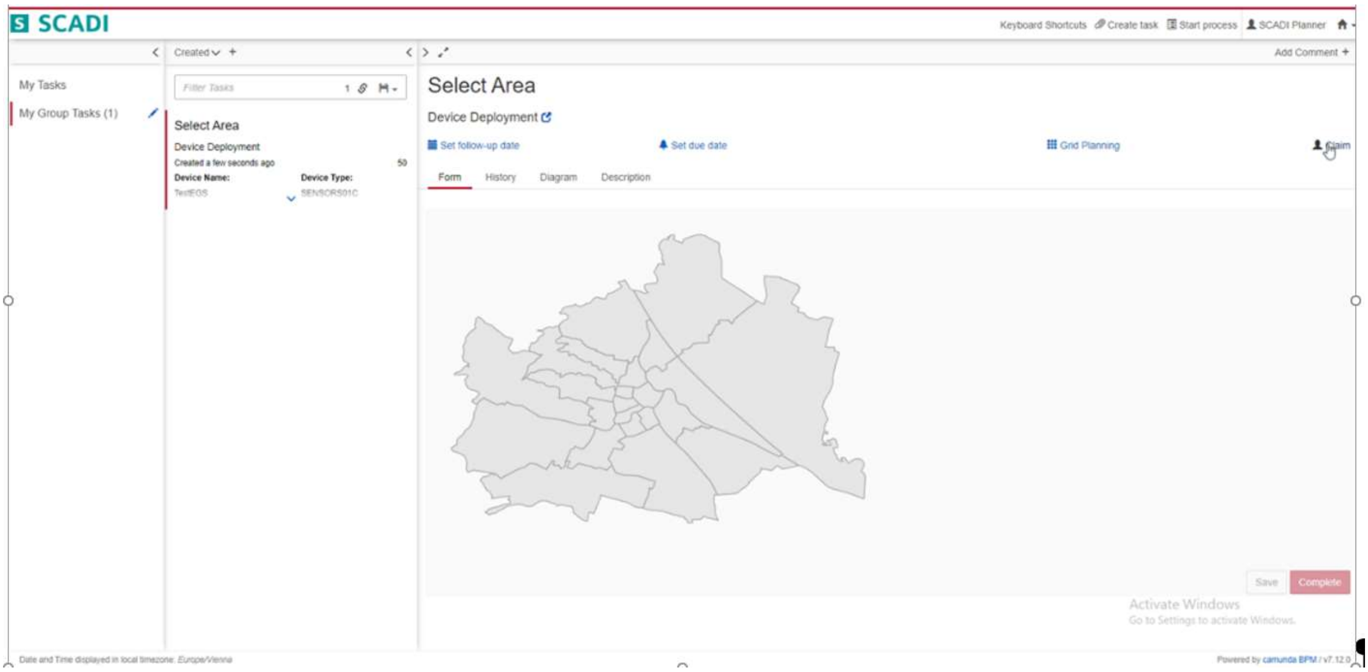


Figure 71: Example of Area Selection in the SCADI App

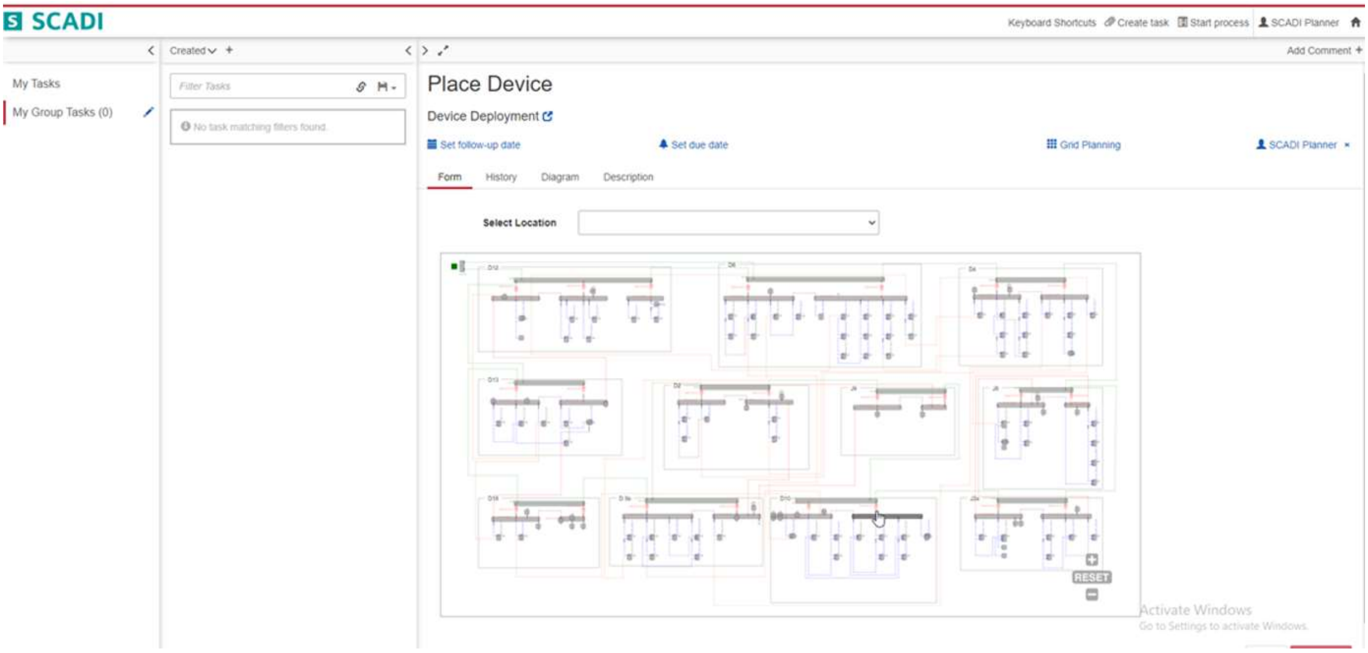


Figure 72: Example of Device Placement in the SCADI App

Different challenges for the practical use of automated rollouts must be considered. In case of network switchovers, the assignability of the measurement points to the network topology must be kept. For the selection of system components, regular exchange to other departments, respective also to component suppliers, is necessary and requires an effective communication structure. Component responsibilities for maintenance etc. must be clearly defined.

Automatic parameterization by setting a pin in the GIS system and the integration into the backend systems is seen as a main feature, which is required in the future for saving personal resources.

4.5.2 Use Case 1: Acquisition of field data and streams and fault records

4.5.2.1 Integration and testing of sensors in BIFROST

Measurement sensors are deployed in the BIFROST virtual testbed. It is possible to emulate realistic sensor behavior, including noise or transmission losses. The values are stored in an influx database and can be viewed in Grafana (Figure 73). A fault record function is implemented, which allows to store data in a higher time resolution than usual after a trigger event, e.g. critical events such as overloads.

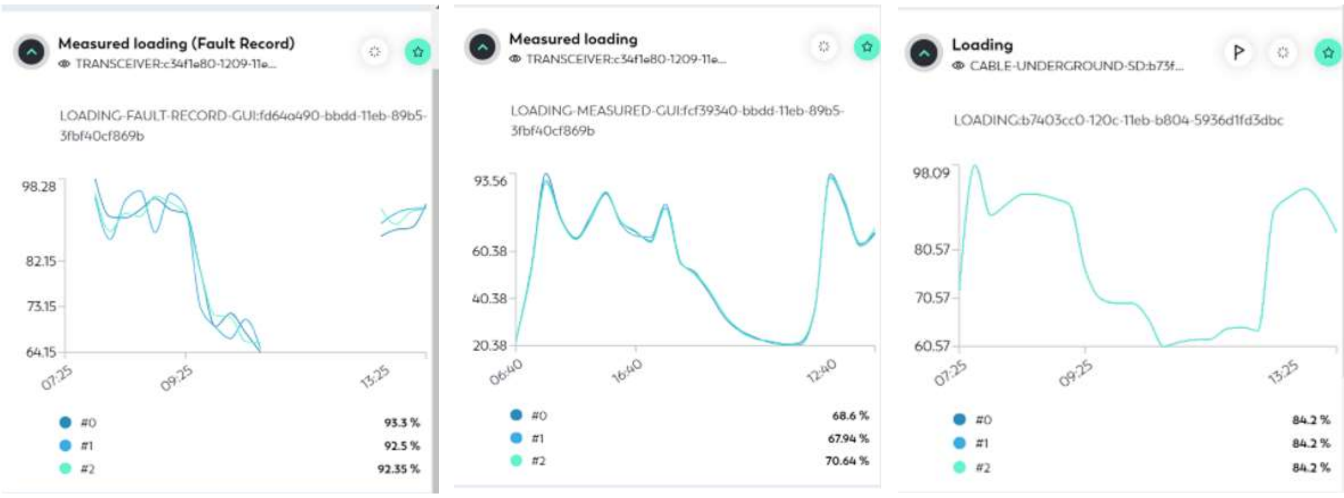


Figure 73: Bifrost visualization

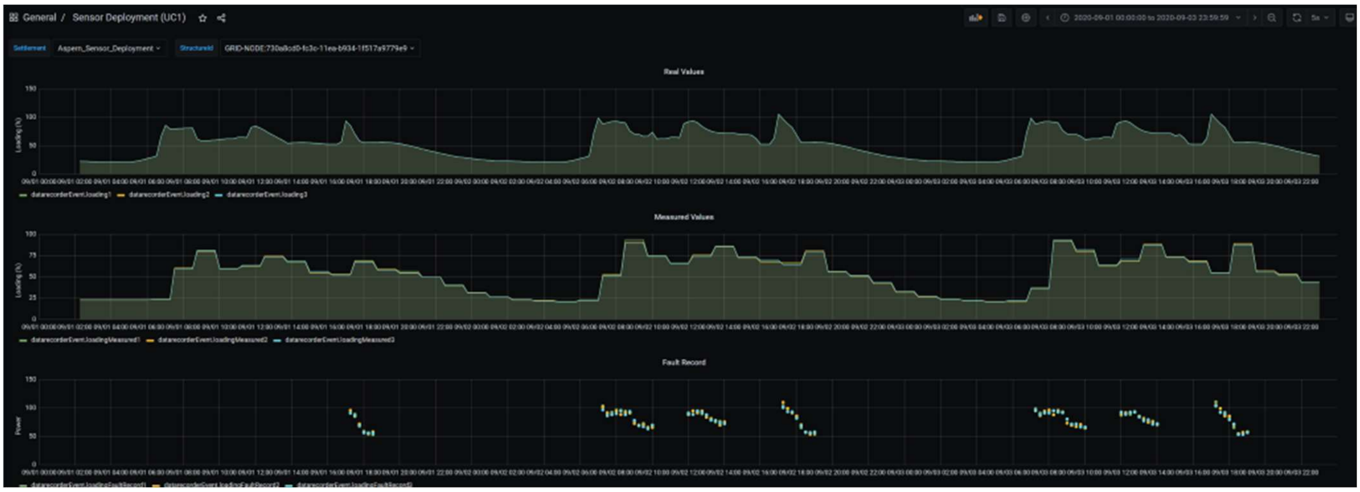


Figure 74: UC1 visualization in Grafana

The functionality of placing sensors itself worked quite well. Due to the way BIFROST displays diagrams, the real load and the sensor measurement differ in time. BIFROST shows the last 24 values, which corresponds to 5 times the time period of the sensor. Depending on the increment rate, this can be confusing. The "averaging effect" and the resolution of the fault record depend on the Bifrost time step. The mean value in this example corresponds to the last 5 measurements, no matter which time steps were used to simulate them. Therefore, it is recommended not to simulate too fast.

The application of BIFROST as virtual testbed to validate process-oriented show cases like the placement and activation of sensors was valuable itself. The learnings were collected and provided as feedback for later BIFROST versions. The goal of demonstrating the value but also the difficulties in using real world IoT measurements in future grid operation and decision support systems was achieved and can now be transferred to Siemens business units.

4.5.2.2 Smart Grid Tool Kit functionality

The development of test scenarios for the Smart Grid Tool Kit validation setup, including a prototype demonstrator, was done within WP4 and WP6 and first test results are already presented in D4.3. The Setup architecture and visualization frontend for the demo is shown Figure 53. Detailed Test results were already presented in in in D4.3. The tests applied to use case 1 (sensor integration) and use case 4 (temporary meshing). First results are promising to go from a prototype demonstrator to real life smart grid applications by using the WP4 developed algorithm and Information and Communication network.

The separation of communication aspects (PoSyCo runtime) from operational aspects (PoSyCo modules functionalities) enabled extremely fast implementation of module-specific functionalities. Other benefits of this approach were easy testing, as individual modules can be simulated/implemented as Mock-ups, and efficient, parallel development of multiple modules. On the negative side, integrating the SICAM A8000 controller revealed that the Docker-based container environment is too heavy-weight for industrial devices. As a countermeasure, the PoSyCo runtime was moved to an external Raspberry Pi. However, a more lightweight solution that can be executed directly on the SICAM A8000 and similar devices would increase performance and simplify the integration of field devices. In addition, while the data dictionary is very well-structured, tool support is inevitable for real-world applications beyond laboratory setups.

Tool support for generating the data dictionary is the logical next step and will be addressed via the SG application framework developed in WP5. Furthermore, the PoSyCo runtime will be evaluated in applications beyond the SG, e.g., in the industrial automation domain. It will be continuously improved and extended with domain-specific information models and the required communication adapters.

4.5.2.3 Data acquisition of real sensor prototypes in testbed.

Measurement data of EGS and GMD sensor pairs is analyzed and compared. The measurement span is between the 25.10.2021 to 25.01.2022. The analysis showed a good agreement for the voltage measurements (see Figure 75) and slight deviations of about 1.5% of active power. It revealed that the phase assignment for active and reactive power was wrong for one measurement device pair, while for another one the reactive power sign was wrong. Figure 76 shows an example. This shows that the installation procedure is error-prone. Checklists and an automated measurement data validation check would be beneficial for the future.

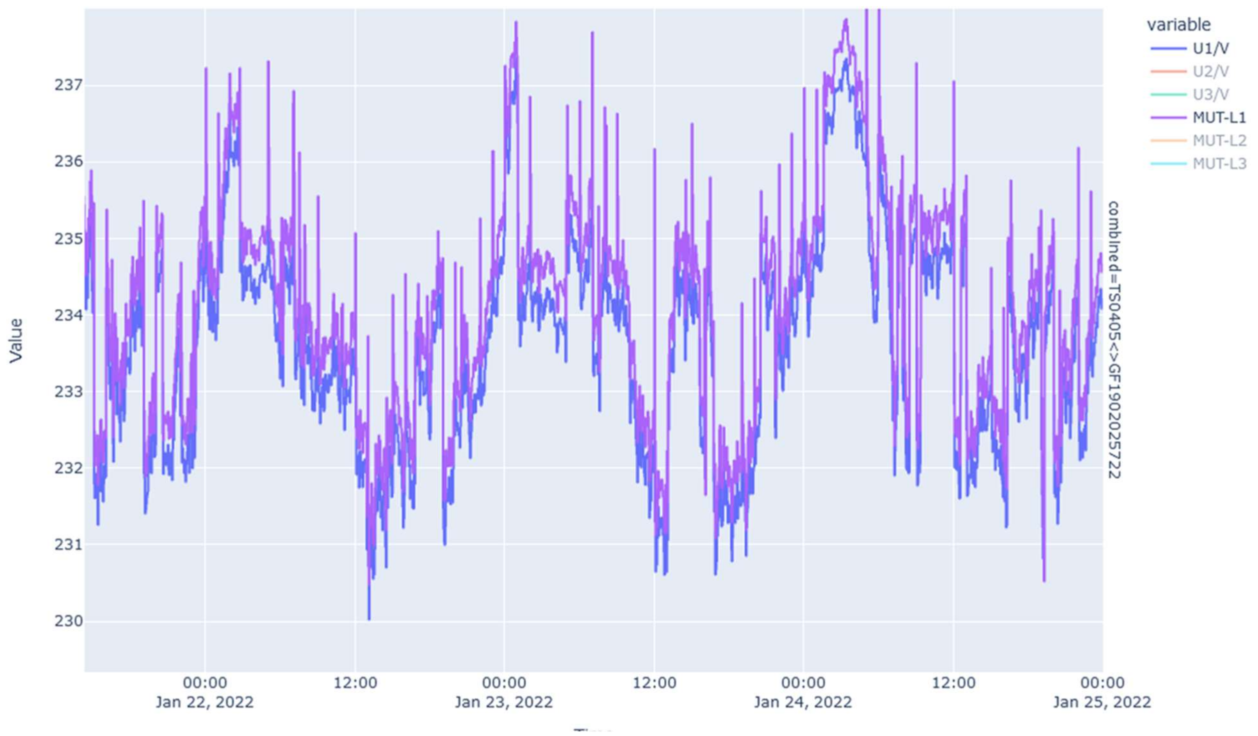


Figure 75: Voltage congruence of first phase-pair of EGS & GMD after time alignment; good visual matching

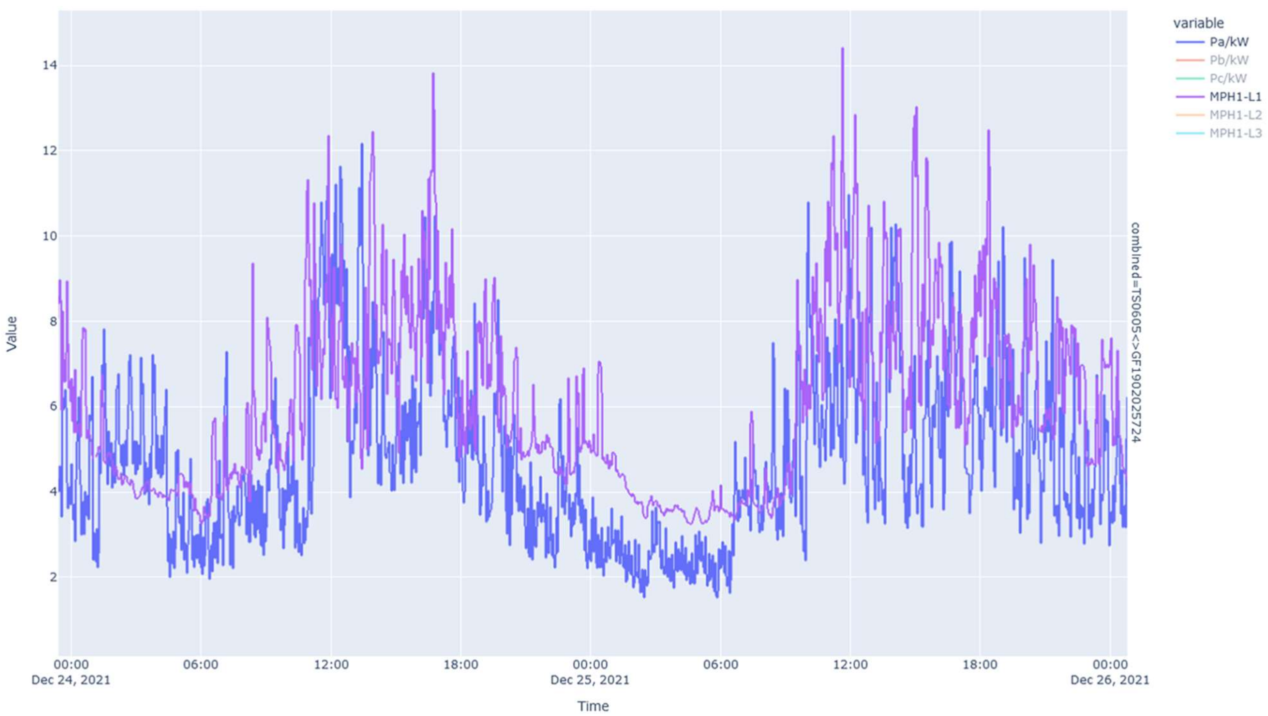


Figure 76: Power congruence of first phase-pair of EGS & GMD after time alignment; bad visual matching

4.5.3 Use Case 2: Distributed fault analysis for service restoration acceleration

4.5.3.1 Understanding Events

Faults, malfunctions and customer complaints, especially in low-voltage grids, are currently mostly solved reactively. This means that when one or more customers call and complain about an outage, for example, a team is sent out to check on the situation. The actual creative task is done by an experienced technician who finds out what the problem is and then also develops the solution for it - e.g. a switchover and resupply after an excavator has damaged a cable. The technical SOFTprotection answer to this challenge is Root cause analyses (RCA). Therefore, the goal of RCA is twofold. First, it aims to provide system operators and field engineers with information about the causal factors of a failure in order for them to react to those failures on the short term (e.g., by fixing the issue in the field). Second, operators and decision makers can use RCA to determine proactive measures that are meant to prevent the identified failure to occur in future. A generic 4 step approach was introduced and is shown in Figure 77.

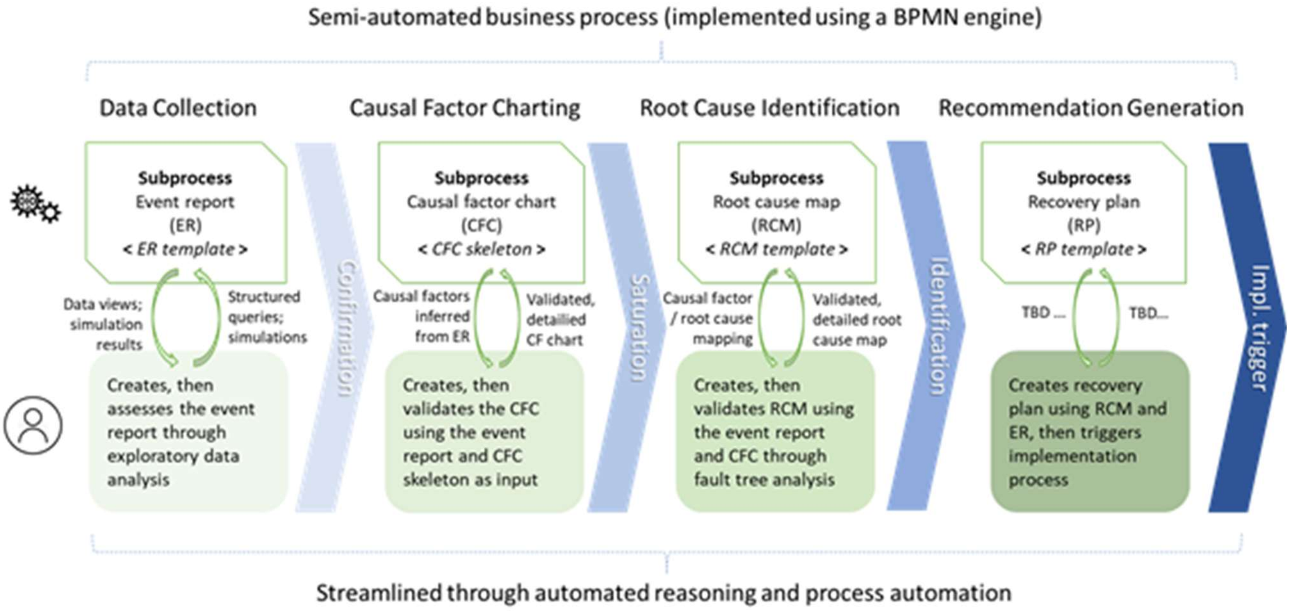


Figure 77: RCA as a four-step business process.

These tests were focusing on step 1 and step 2. The first RCA process step is dealing with automatically generated event reports. In this field, the team made valuable experiences regarding the applicability of change point detection (CPD) methods. CPD methods use time series of measured power grid data (e.g., U, I, Q, P) to identify the timestamps (i.e., positions) at which significant changes in the statistical properties of the timeseries being monitored have occurred.

An example is shown in Figure 78. When clicking on an event marker in the map, a list of the detected events for a specific location is presented. The color intensity of the marker is adapted to the number of detected events for the selected timespan. This provides the user with a quick overview of the monitored grid section with respect to the dynamics of the power consumption patterns. The locations which yield more change points are those were the consumption patterns are more dynamic and irregular. The user can investigate the exact causes of these events in the next step of the RCA – the causal factor charting.

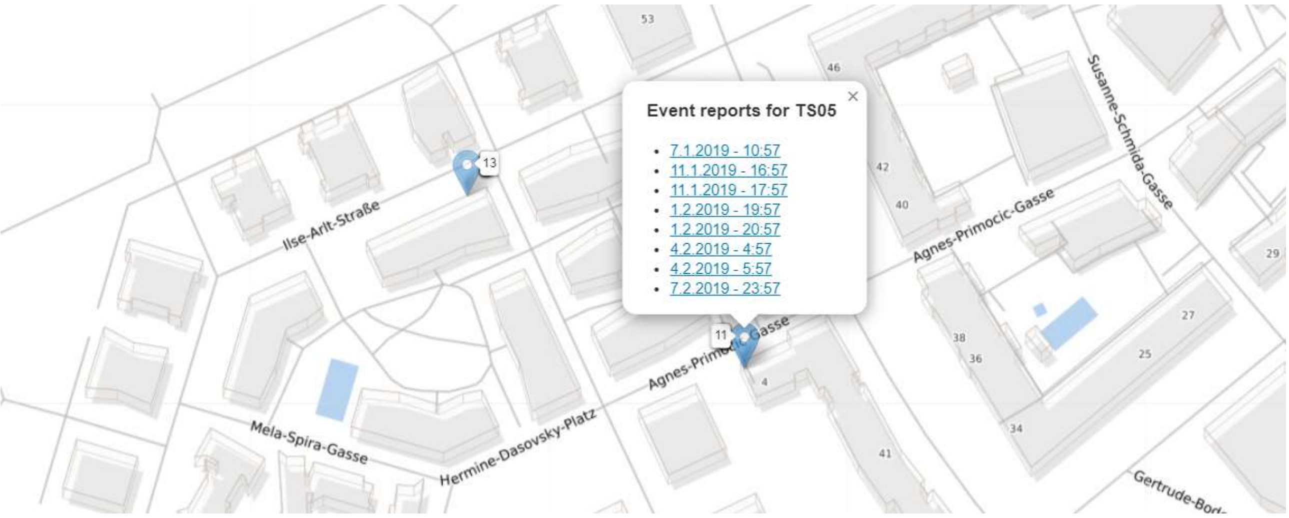


Figure 78: Event report list for a specific location for a given timespan.

While working on RCA step 2 the findings concerning the determination of causal factors for a specific event are of high importance because that is the main part of the creative work of human technicians in the state-of-the-art scenario. It relies on the exploitation of the statistical features of the time series being monitored as well as on other endogenous and exogeneous factors and criteria. For example, the nature and significance of an event can be determined by investigating whether events have occurred in several places (i.e., consumption points) at (approximately) the same time.

Figure 79 shows the workflow of tasks performed by an expert and an operator to enable operative event detection. A detailed description of the single tasks is provided in Deliverable D6.2. An expert is required to create the CPD ensemble for unsupervised labelling of events in a data stream. The CPD ensemble consists of 7 different or differently configured methods for the detection of change point detection methods. The cp.np.PELT method is sensitive and thus detects even fine changes in the time series. The other 6 methods are configured to detect changes in mean or variance, or both, that is, mean and variance. Due to the different configurations and/or heuristics, it is possible that the statement of each of these CPD methods can be combined with a specific system-specific expert explanation. In this working mode, the CPD ensemble behaves like a clustering method.

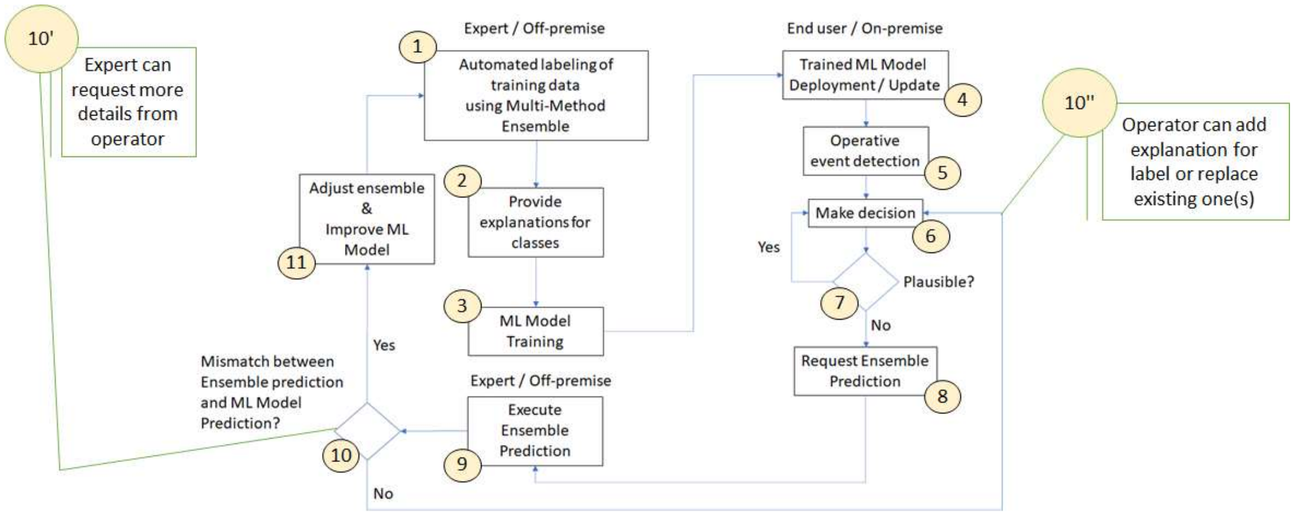


Figure 79: workflow of tasks performed by an experts and an operator to enable operative event detection.

The ensemble of CPD methods, which is used to detect events with high confidence and to infer a first set of causal factors, can be extended to include additional dissimilar approaches in order to provide more information. Initially, a 7-method ensemble was used. Some of the methods were redundant in terms of the statistic being used as a criterion for detecting changes (e.g., mean, variance, etc.), but dissimilar in terms of the heuristic used to detect those changes. An ensemble should be built around (n) dissimilar approaches and contain at least (2n+1) methods. That is, there should be at least two methods looking for the same kind of changes (e.g., in mean or variance) in order to ensure the possibility of providing a statement concerning the confidence of the prediction with respect to a certain statistical property being monitored.

Depending on the data, the ensemble can contain any number of methods (e.g., dozens). While such an ensemble works in an unsupervised mode and thus does not require any expert input to cluster the events, it might require high computational resources since many methods have to be executed for a single input data set (i.e., a time series sequence). In a sliding window process, the computational cost of running a multi-method ensemble is high. Therefore, the ensemble should be used to train a ML model, such as a random forest or neural network, having as input the time series sequences and the statistical labels produced by the ensemble for those sequences. Figure 80 shows the results of an experiment in which a random forest (RF) model was trained using a 7-method ensemble. After training, the RF model was able to produce the correct SL, when given an arbitrary time series sequence, in over 96% of the cases. The model was able to predict both the severity of the events as well as the statistical causal factors. This proves that an ensemble of dissimilar, hand-coded CPD methods can be successfully used to train a much faster ML model to perform the same task as the ensemble. Such a ML model can then be used for operational event detection and causal factors inference in real time.

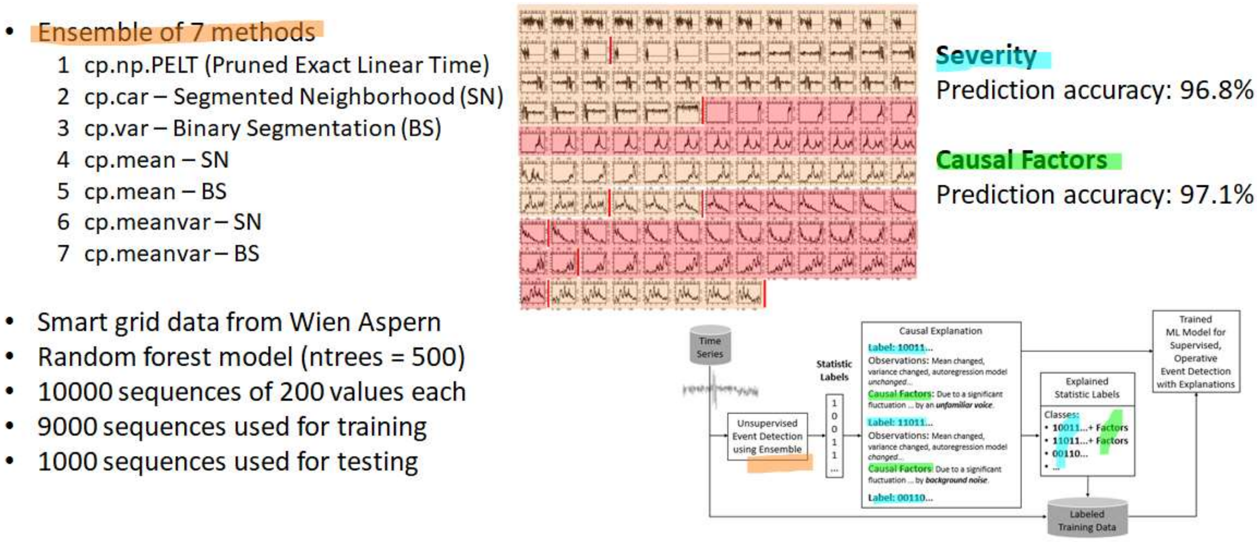


Figure 80: Training and testing a Random Forest model using a 7-method CPD ensemble.

The work within the PoSyCo RCA represents a first step in many possible future applications. Problems, errors and complaints will increase significantly, especially in the lower network levels. Network operators are increasingly confronted with this and need technical support to be able to answer these queries in a (partially) automated way. Manual processing will simply no longer be manageable by the existing staff.

4.5.3.2 Application of Root Cause Analysis on real data

This is the logical extension of the “understanding events” test case. Historical data of grid events from Aspern testbed are used to improve the robustness of UC2 solutions. Initially, it is possible to validate the event / alarm concept and the mapping to causalities improving semi-automated root cause analysis as described in the previous case. In this test case, the third step of the 4-step approach, introduced in the previous test case, is in focus.

To support the human analyst, in PoSyCo, two main tools are used: Granger causality analysis and semantic search.

<u>The Granger causality test</u> is a statistical hypothesis test for determining whether one time series is useful in forecasting another. This approach is based on the principles that (i) a cause occurs before its effect and (ii) knowledge of a cause improves prediction of its effect. In a nutshell, a variable X is said to G-cause a variable Y if the past of X fused with the one of Y helps predict the future of Y more accurately than only using the past of Y. Moreover, Granger-causality aims to quantify directed functional connectivity by means of a statistical description of fused observed responses. Figure 81 depicts the Granger causality determination principle.

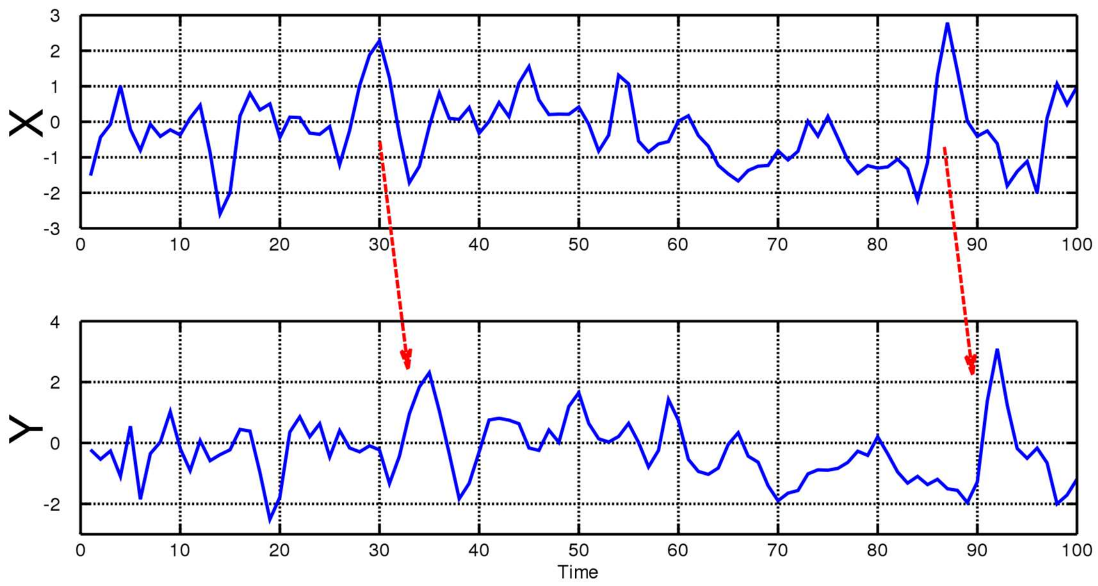


Figure 81: When time series X Granger-causes time series Y, the patterns in X are approximately repeated in Y after some time lag (two examples are indicated with arrows). Thus, past values of X can be used for the prediction of future values of Y.

While the Granger causality has been initially used to analyze econometric data, it has also recently been successfully applied to low-voltage power transformer data.[10]

To visualize potential causal relationships between measurements in PoSyCo, Sankey diagrams are used. Sankey diagrams allow for the visualization of energy flow, voter flows, etc. The Sankey diagram in Figure 82 suggests that, for a particular time series segment in which a significant number of CPD methods have identified change points, some of the meteorological parameters may have Granger-caused those change points. Figure 83 shows the relevant time series plots for the respective case. While the Sankey diagram provides the analyst with a suggestion concerning a possible root cause of an event, the time series plots help the analyst to validate that suggestion. For this subset of analyzed measurements it appears that the significant changes in relative humidity and dew point temperature may have caused the change points in P1 at TS06.01. Another possible cause is the high global radiation level in combination with a dramatic drop in the air pressure.

[10] Rodriguez-Rivero, J., Ramirez, J., Martínez-Murcia, F. J., Segovia, F., Ortiz, A., Salas, D., ... & Górriz, J. M. (2020). Granger causality-based information fusion applied to electrical measurements from power transformers. *Information Fusion*, *57*, 59-70.

Figure 82: Sankey diagram of Granger-causal relationships between Aspern measurements (P1) at two measurements points (TS06.01 and TS08.01) and meteorological measurements (GL - global radiation, RH2M - relative humidity, TD2M - dew point temperature, P0 means sea level pressure). The causal factors are displayed on the left side of the plot.

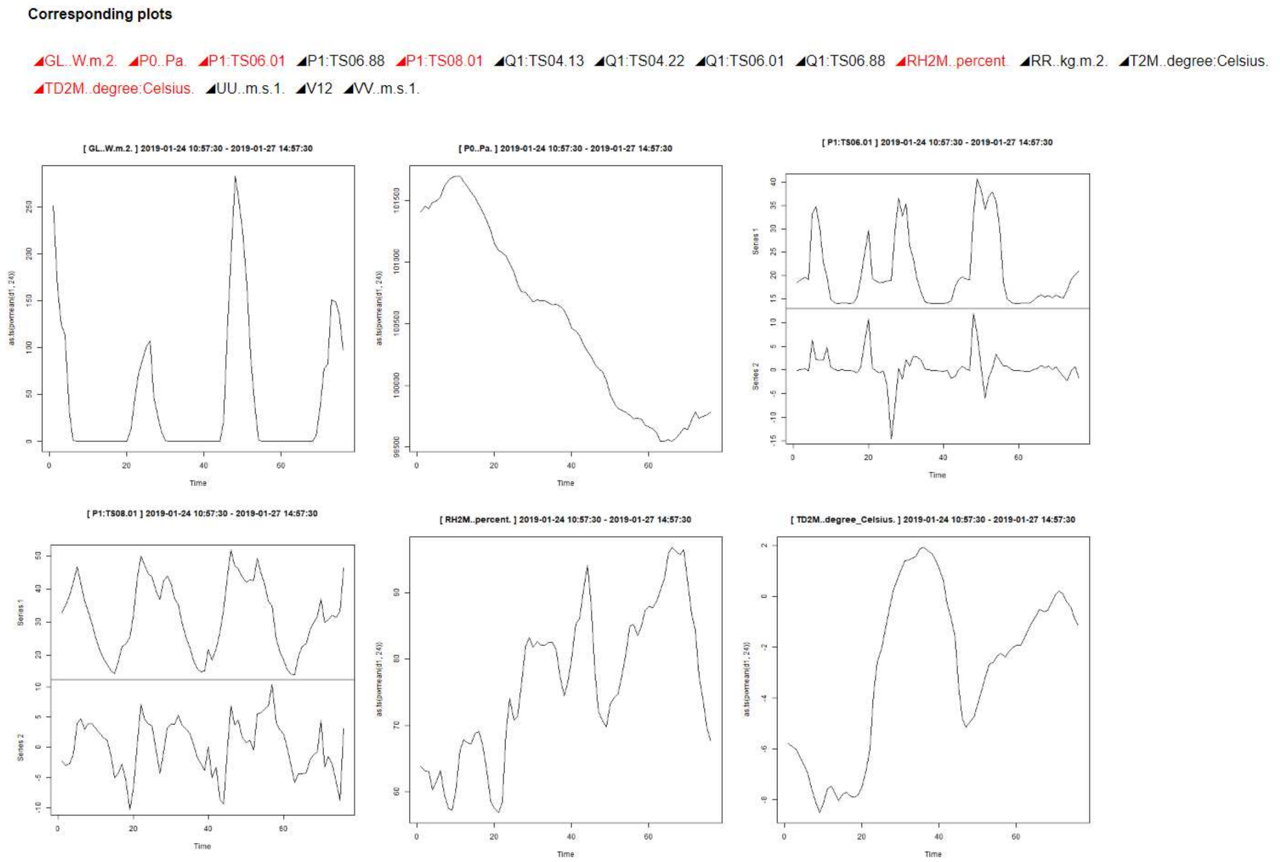


Figure 83: Relevant measurement plots corresponding to the Granger-causality diagram. The smart grid measurements are plotted in two versions: the top-level plot represents the original data and the bottom-level plot represents the data after seasonality and trend have been removed.

The second method, semantic search in time series data, is a novel approach that enables an analyst to search for similar events in the past based on a currently detected grid event. By comparing current events with past events, an analyst or operator is able to better understand current events since the past events, if significant, must have additional information associated with them. For example, if a certain event is detected by a CPD ensemble, there are several ways of searching for past events in a data base or a message bus; or to generate explanations of the events using a knowledge graph.

In PoSyCo, a knowledge graph-based approach was conceived (denoted Automated Explanation Provisioning (AEP) system) for generating an explanation for a binary or probabilistic statistical label (SL) provided by an ensemble learner. This is achieved by means of automatically generating a query that can be used to perform searches in a domain-specific knowledge graph or in another structured database (e.g., graph, NoSQL or relational database) to retrieve information pertinent to the explanation of the SL. The results of such queries are converted into natural language and associated with the original SL.

The function of the AEP system is thus to generate explanations for unique classes or categories of events, determined by an ASL system, which consumes and stores a continuous stream of time series data received from an ASMO platform.

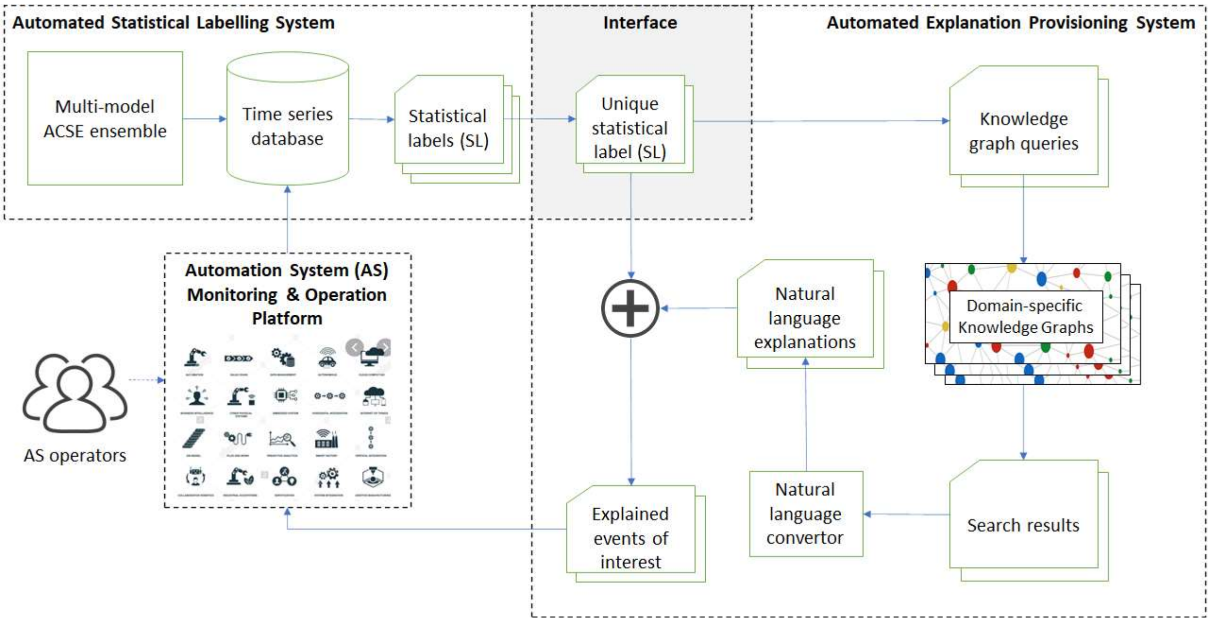


Figure 84: Schematic of the AEP system.

The ASMO platform collects data from measurement devices installed in various automation systems (e.g., low voltage digitalized power grid, a smart building, a digitized factory, a local or city-wide transportation system, etc.). Users of the ASMO platform are automation system operators, who monitor and control various automation systems remotely.

The third step in the classical RCA approach presented in this chapter is root cause mapping. Theoretically and already part of advanced AI application projects, this also can be done automatically. In the case of the power grid, taking the learnings of WP6’s wide ranging test cases into account, the expectation that an RCA can be fully automated is naïve. When introducing this step in real-life environments, PoSyCo choose a human-in-the-loop approach. A human supported by a decision-support system (DSS) leverages their domain knowledge as well as the information provided by the event report and the causal factors chart to determine a possible root cause for an event. This strategy can increase the acceptance of RCA as a supportive system.

Supplementary to the outlook regarding step 1 and step 2, the degree of automation, especially regarding the third step, will increase in parallel with the increasing application of RCA applications. Combined with a self-learning ability of technical realizations the causalities and the initial root cause of more and more known events can be detected automatically.

4.5.4 Use Case 3: Overload prevention by customer activation

4.5.4.1 Dynamic utilization of available grid capacity of an EVCS hub – BIFROST simulation

For this test case, the dynamic utilization of available grid capacity of an electric vehicle charging Station hub is implemented in the BIFROST simulation environment. Hence, EV-charging stations receive an enable signal from the grid operator through the transformer, which allows them to charge incoming cars with maximum charging power. Without the enable signal, charging is not possible. Different scenarios are considered to emulate transformer overloads and transmission losses on the communication line to see what happens if the enable signal is not received by the charging stations. The graphical representation in Grafana gives the user insights about the loads on the cables and effective enable signals, arriving at the EV stations.

A visualization of a test result is given in Figure 85 and Figure 86. For this scenario, the first two days are normal, showing no reduced connection quality and no overload (other EV stations are disabled). Then the quality of node 1 is reduced to 75% for two more days. It can be seen that the signal is frequently not getting through, and the charging power is then always briefly reduced. In the next two days, the connection quality of node 2 is reduced to 10%. At the EV station, it is now only 7.5% and the enable signal never comes through. For the last two days the connection quality is increased to 100% again, but the other stations are activated. This overloads the transformer during the day; the transformer actively does not send the enable signal anymore and sets a reduction factor >1.

The idea behind the design of this test case was to investigate the behavior of SOFTprotection applications in connection with the first ideas for generating reduction signals according to Austrian Technical and Organisational Rules - TOR (discussions as of autumn 2021) and the influence of the quality of the connection. In addition, the real implementation of the charging and energy management of a smart charging hub in the testbed Seestadt Aspern was simulated. The influence of the signal quality in combination with the fallback behavior in the event of a communication interruption was particularly interesting.

Simple reduction signals have not been prescribed in this way after the TOR review process (discussions as of spring 2021). However, the implemented Proof-of-Concepts can now be further developed according to the findings of the working group on the Digital Customer Interface at ÖE (Österreichs Energie). The SOFTprotection application for estimating the grid bottleneck remains of interest, regardless of how the potential control of flexibilities will be realized.

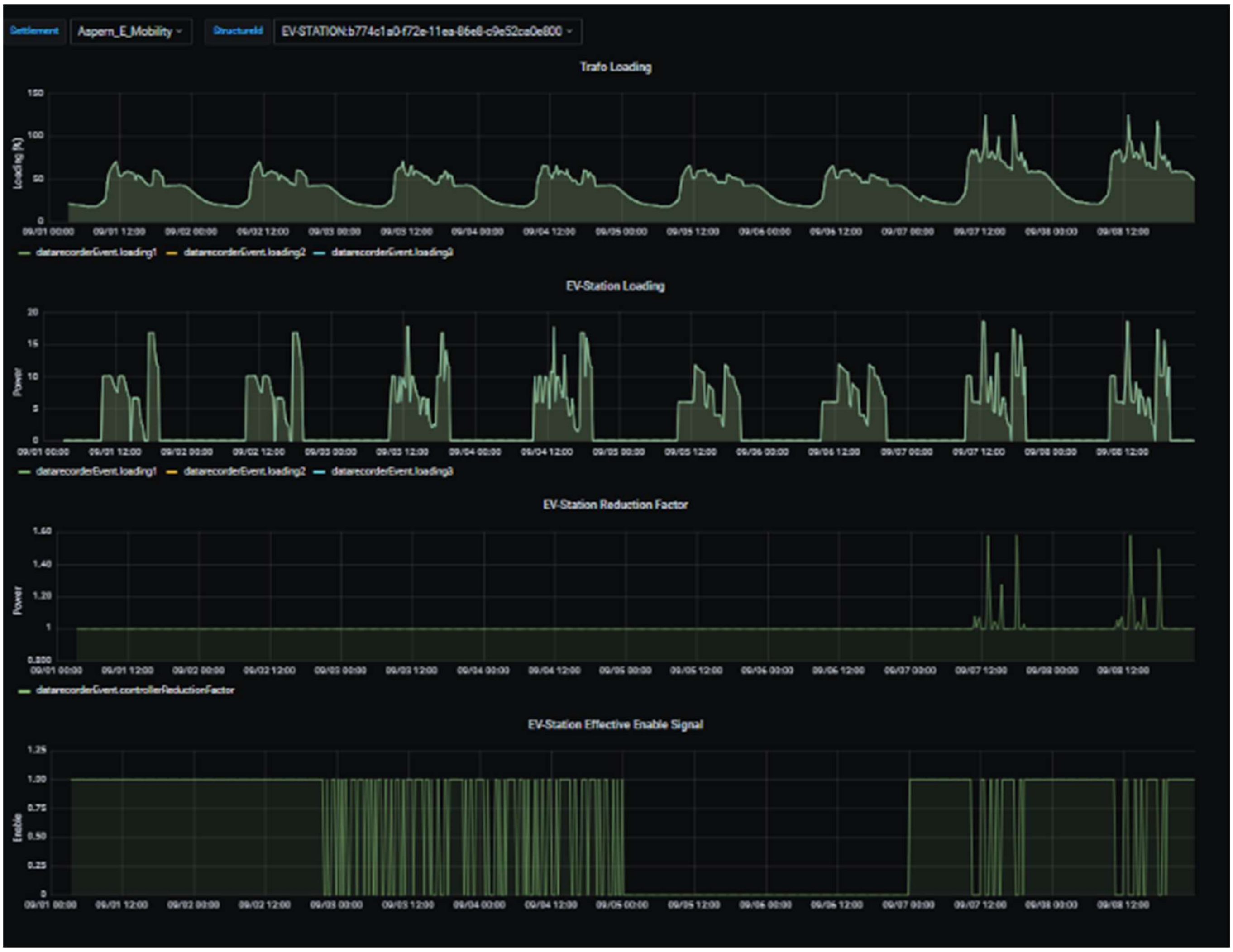


Figure 85: Grafana output for UC3, part 1
(From TOP to BOTTOM: Trafo Loading at the main cable, EV-Station Loading, EV Station Reduction Factor, EV-Station Enable Signal)

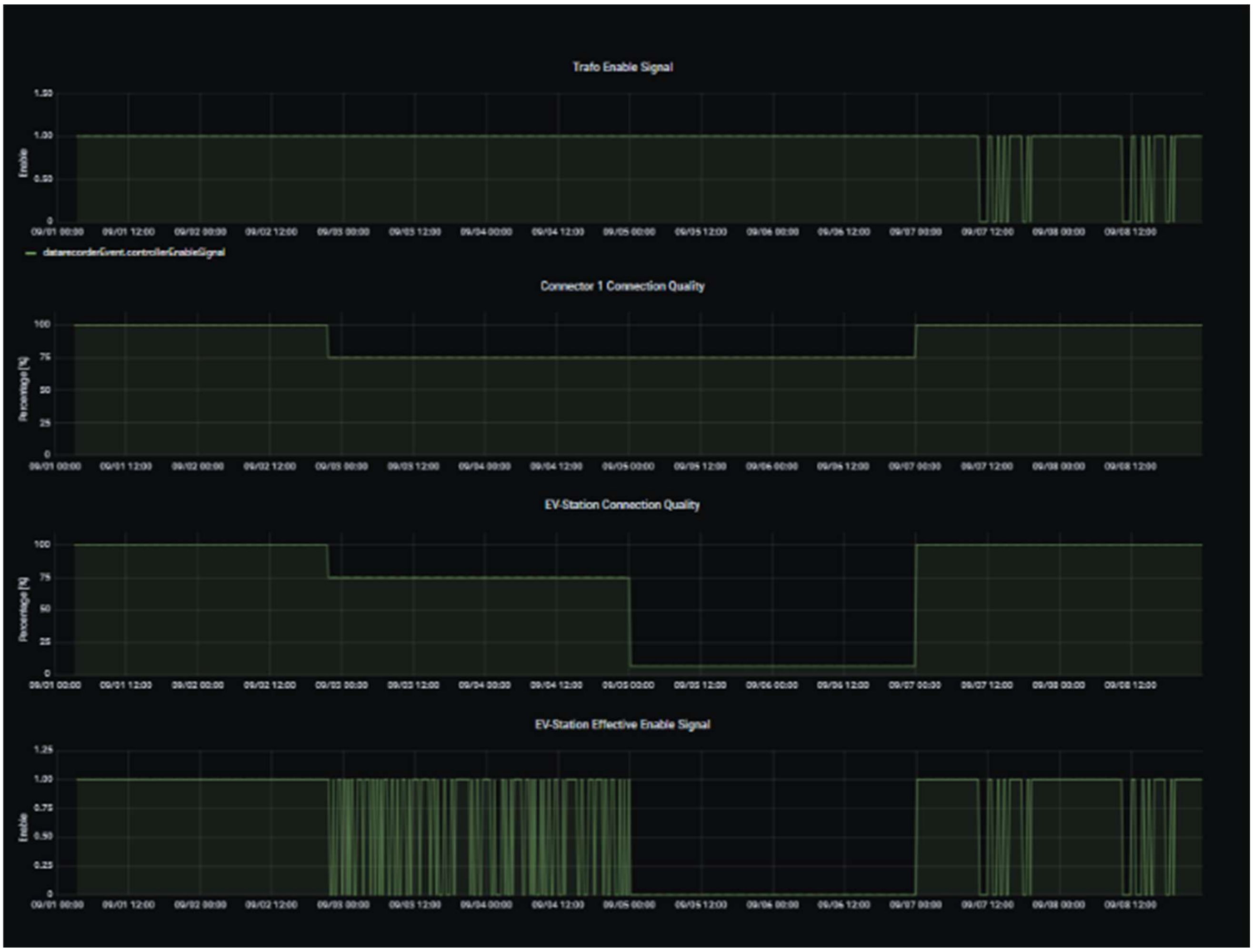


Figure 86: Grafana output for UC3, part 2; Showcase to visualize the effect of poor connection quality
TOP: Enable signal sent out by the transformer to allow EV charging.
MIDDLE: Emulated connection quality
BOTTOM: Real (at the EVCS arriving) Enable signal

4.5.4.2 Parameter optimization using a BIFROST based digital twin

For this test case, an adapted variant of the SOFTprotection algorithm is running as a SIAPP application at a C-HIL system setup on a Siemens SICAM A8000-CP8050 hybrid LV grid controller, which is depicted in Figure 53. BIFROST was used as a virtual testbed/environment and different scenarios were simulated for the ASPERN test grid TS10. The setup is shown in Figure 87. Test scenarios, such as single-section and transformer current overload, as well as a long-section high-voltage drop, are simulated and the proof of functionality and the parameter optimization for the sub-functionalities assuming an application in Testbed Aspern was successfully evaluated.

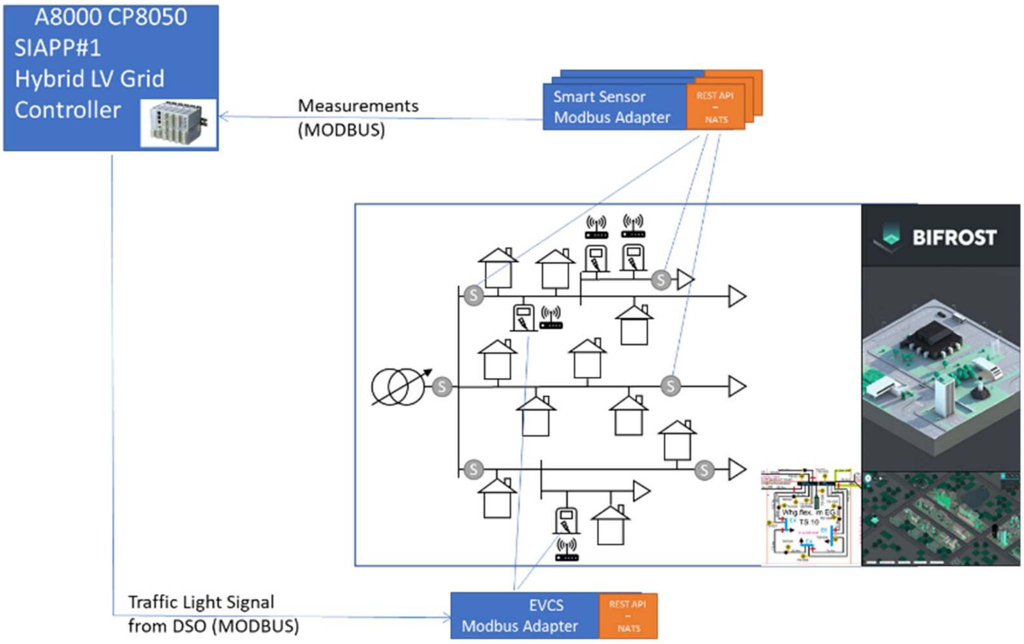


Figure 87: C-HIL system Set-Up with SIAPP on A8000 and BIFROST as virtual testbed

As a kind of decentralized SOFTprotection functionality, a "Hybrid LV Grid Controller" (HLVGC) as a SIAPP has been implemented based on the algorithms addressing the PoSyCo physical dimension. The advantage of testing the algorithm in the real hosting system - so called "Intelligent Secondary Substation Node (ISSN)" with A8000-CP8050 (a Siemens product) with a Linux-based Container Framework – is, that parameters of the (sub)controllers can be optimized in a -real-world system. The three sub-functionalities of HLVGC -

- Transformer overload prevention by e-car charging reduction,
- Cable/line overload prevention by e-car charging reduction in selected branches,
- Avoiding voltage band violation by e-car charging reduction in selected branches,

were validated in a Controller-Hardware-in-the-loop scenario using the BIFROST virtual Testbed. The simulation/emulation control to enable accelerated simulations considering digital twins of Modbus devices like charging stations and measurement devices was challenging but the set-up was able to fulfil the requirements.

The DSO involved in the project was so convinced by the results of the C-HIL simulations that a field test will now be carried out on the campus using one of the transformers and charging stations as actuators to investigate the extended practical suitability of the solution.

4.5.4.3 Implementation of grid friendly charging management in a SIL environment

The aim of this test case was to evaluate how a prototypical implementation of the grid-friendly charging management performs in combination with realistic real-time simulations, using a so-called software-in-the-loop setup. For this purpose, the charging management algorithm previously developed in Matlab was translated into Python and coupled with a simulated distribution system running on AIT's real-time-simulator. The test setup is shown in Figure 88 and is described in more detail in chapter 3.2.2.3.

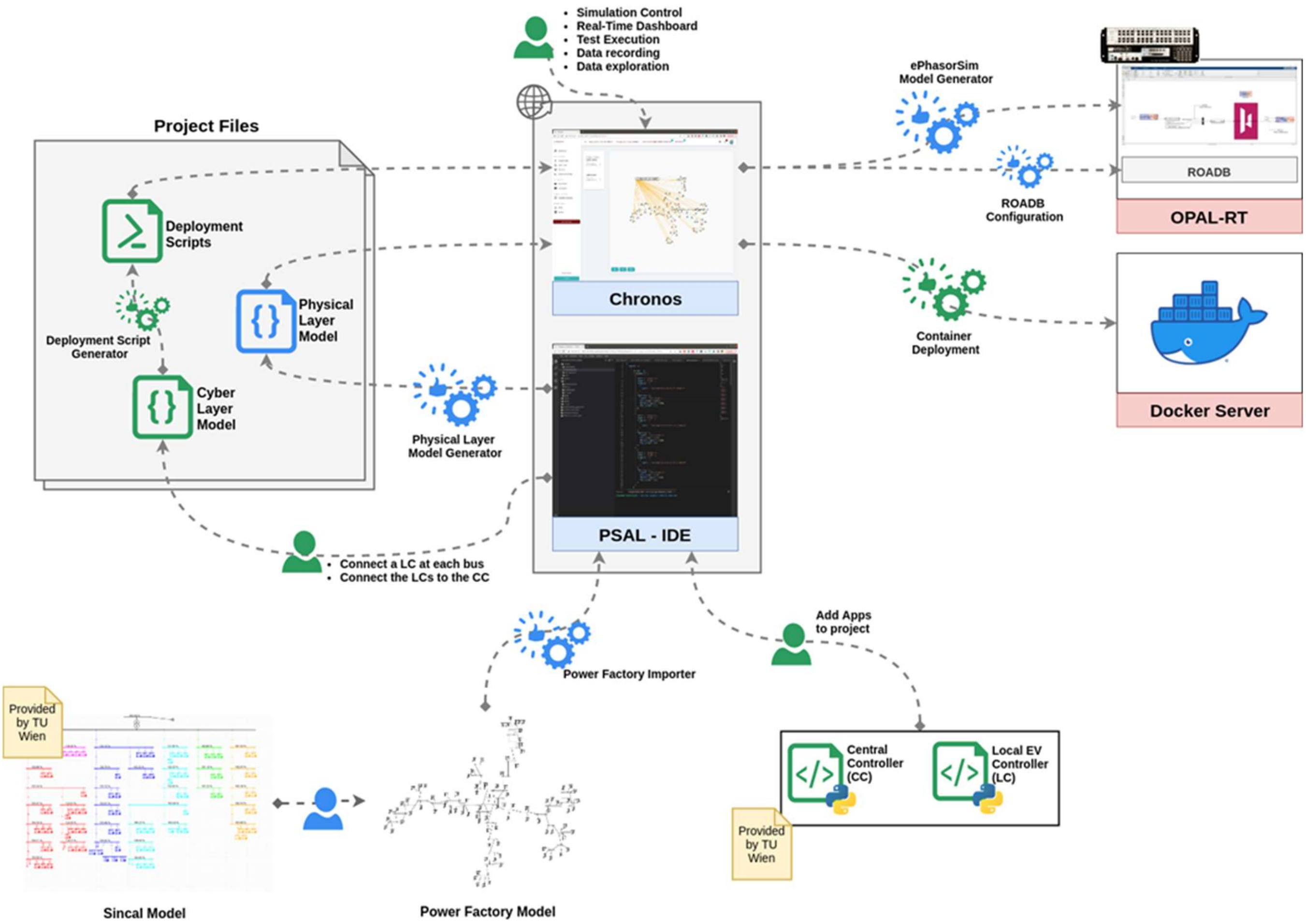


Figure 88: AIT PSAL-Chronos Validation Environment applied to PoSyCo UC3.

The results that were achieved indicate that the prototypical implementation acts according to the proof-of-concept that was developed earlier in the project. One scenario is shown in Figure 89. In this scenario the EVs are set to charge in the evening starting around 06:00 pm. The coordination algorithm that was used calculates the loading of each feeder and at the transformer. If an overload is detected the EVs on that feeder—or all EVs if the overload is at the transformer—are forced to reduce their charging active power. This is visible as the spikes that are fluctuating shortly after 06:00 pm on the first day. This oscillating behavior is due to the controllers always acting on the current measurement. Similar results to the ones presented in D3.3 were obtained.

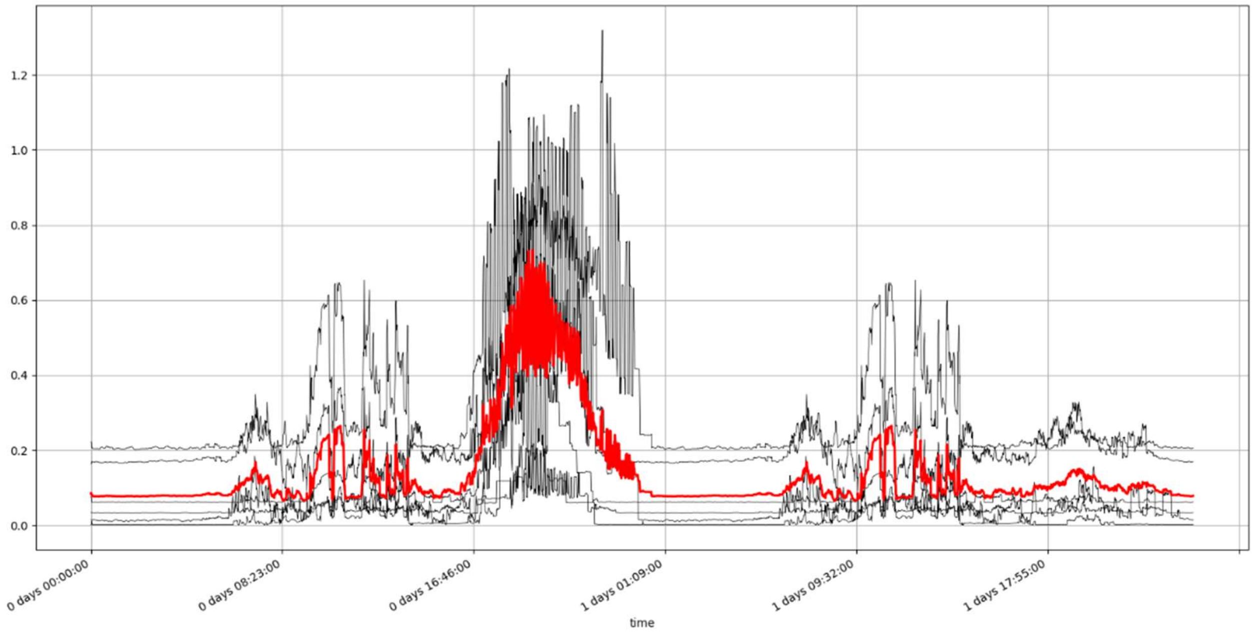


Figure 89: Results of a SIL simulation of the small urban grid using coordination and reduce charging until next permission. Red line shows the loading at the transformer in p.u.

The tests showed that with the approach used, it is possible to rapidly iterate between development and testing. Thus, implementation issues can be caught and correct with very small effort. Using the same setup, more tests can be made looking into different real-time aspects, such as communication issues or the possible negative impacts which a deployment of hundreds or thousands of these controllers could have on each other or the energy system. This can then be followed by further development and testing of the algorithm on its target system using a controller-hardware-in-the-loop setup.

4.5.4.4 Distributed LV control by SOFTprotection and DSO Interface

This real-life test case is based on the successful application of the SOFTprotection set-up in a C-HIL (Controller-HW-in-the-Loop) test (see D6.2. chapter 3.4.2) scenarios using the virtual testbed modelled in BIFROST. Now this test case is being realized and tested in the newly built e-car charging outdoor laboratory installed at the Siemens site in Vienna. The test bed is shown and described in chapter 3.2.2.4. The test case itself was separated into two parts.

Part 1 is focusing on the SIAPP running within the HW and SW framework A8000, a charging station and an e-car. The SIAPP generates and transmits control signals to the charging station to avoid overloading. Part 2 is focusing on the interpretation of the reduction signal at a certain customer installation. With reference to the discussions within “Österreichs Energie” a simplified, unidirectional DSO-2-customer interface was realized.

<u>Part 1:</u>

As shown in Figure 90, only the left part (DSO Back-End, ISSN Control, EVCS) of the whole chain is tested. The "Hybrid LV Grid Controller" detects overloads at the transformer, at the feeders or even violations of the voltage band by connected measuring devices. The permissible current for the feeder, to which only one charging station is connected in this case, was set to 12A per phase. Specifically, relative reduction signals between 100% and 40% (around 6A per phase) are generated depending on the grid load, e.g. measured at a feeder or transformer. The Hybrid LV Grid Controller now attempts to bring the current in the individual phases back into the permissible range by gradually reducing the permissible charging power per charging station in 10% steps (based on the maximum charging power).
In a first demo, a corresponding implementation of the "DSO" request is transmitted here in the form of current specifications via Modbus to the charging station. The reduction of the charging power can be monitored on a dashboard. This behavior, as observed at one of the charging points in the outdoor laboratory when charging an VW ID4, is shown in Figure 91.

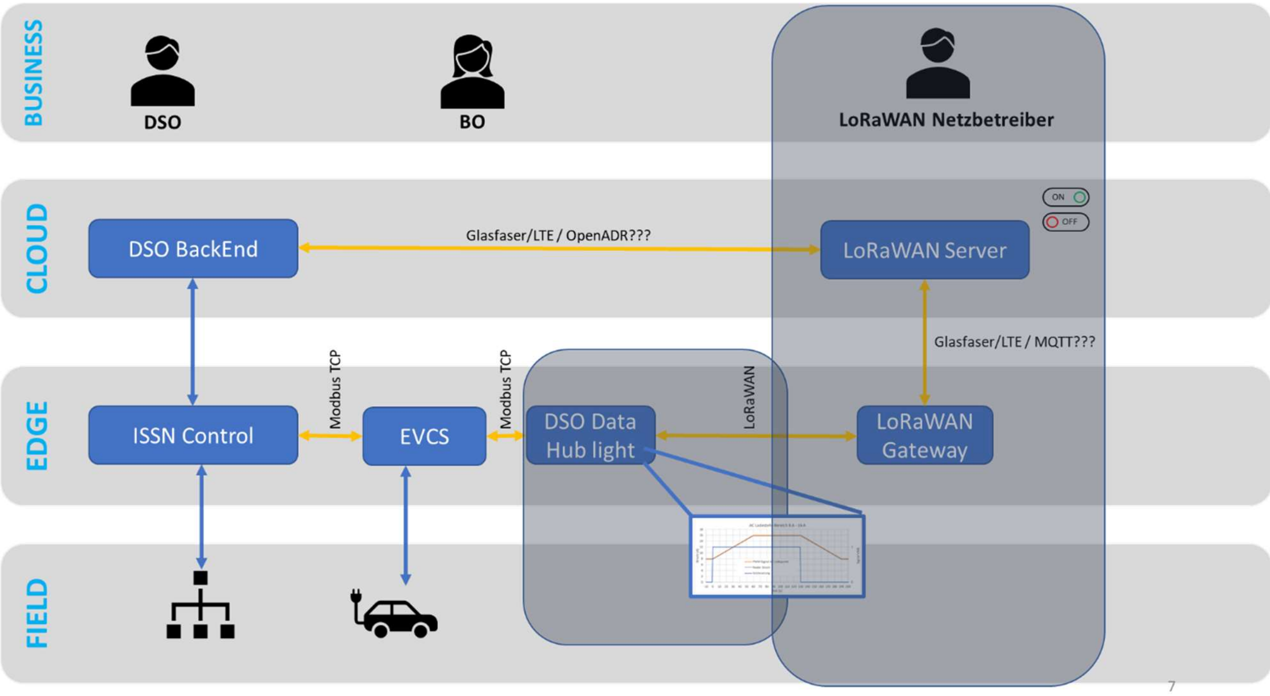


Figure 90: Test Case Part 1 „HLVGC and charging infrastructure" (the reduction signal distribution by LoRaWAN and the DSO Data Hub light was fabricated in this test to reduce complexity)

Figure 91: Gradual (10%) reduction of the charging power of a VW ID4; top: overall course of the charging event; bottom: detail view of the reduction

Even after the transfer from the C-HIL environment to a real testbed, the function of the HLVGC could be evaluated positively. In order to achieve the appropriate reaction on a lightly loaded line with only one charging station, the limits had to be lowered considerably, of course. The configuration of the SIAPP also proved to be user-friendly in this respect. In addition, the remote terminal unit (RTU) part of the A8000 had to be used to translate the relative reduction signal from % to the current values of the charging station to be specified via Modbus. This means that if the whole chain were closed, the reduction signals would be sent according to the infrastructure as described below in Part 2. These intermediate steps with the conversion into concrete current values for the charging station are a consequence of the division into the previously mentioned parts 1 and 2.

Part 2:
Part 2 is focusing on the interpretation of the reduction signal at a certain customer installation. With reference to the discussions within "Österreichs Energie", a simplified, unidirectional DSO-2-customer interface was realized. The setup with DSO interface, ramp and fallback function is shown in Figure 92. Only the left part of the whole chain is tested. The assumption is that overloads in a certain feeder of an LV network are detected and then the charging stations placed and "registered" in this feeder receive a reduction signal as demonstrated in part 1. According to association guidelines (later TOR), a 0/1 signal is assumed to come from a DSO system. This is manually generated in a suitable form at the LoRaWAN server. The Proof-of-Concept realization was using NodeRed to generate the defined ramp up and ramp down so also this technology stack could be evaluated as well as an open-source Modbus stack for the downstream connection to charging station. The signal and resulting current at the EVCS are shown Figure 93.

As one promising technology for a cost-efficient downstream connection, the LoRaWAN infrastructure provided and operated by project partner Wien Energie was tested. Due to difficulties regarding the availability of LoRaWAN devices, this part of the test case was finished successfully in the last days of the project.

Outlook for future standardization

The reaction of charging stations controlled by 0/1 reduction signals has not been prescribed in this way after the TOR review process (discussions as of spring 2021). However, the implemented PoCs can now be further developed according to the findings of the working group on the Digital Customer Interface at ÖE (Österreichs Energie). The SOFTprotection application for estimating the grid bottleneck and generating adequate reduction requests remains of interest, regardless of how the potential control of flexibilities will be realized.

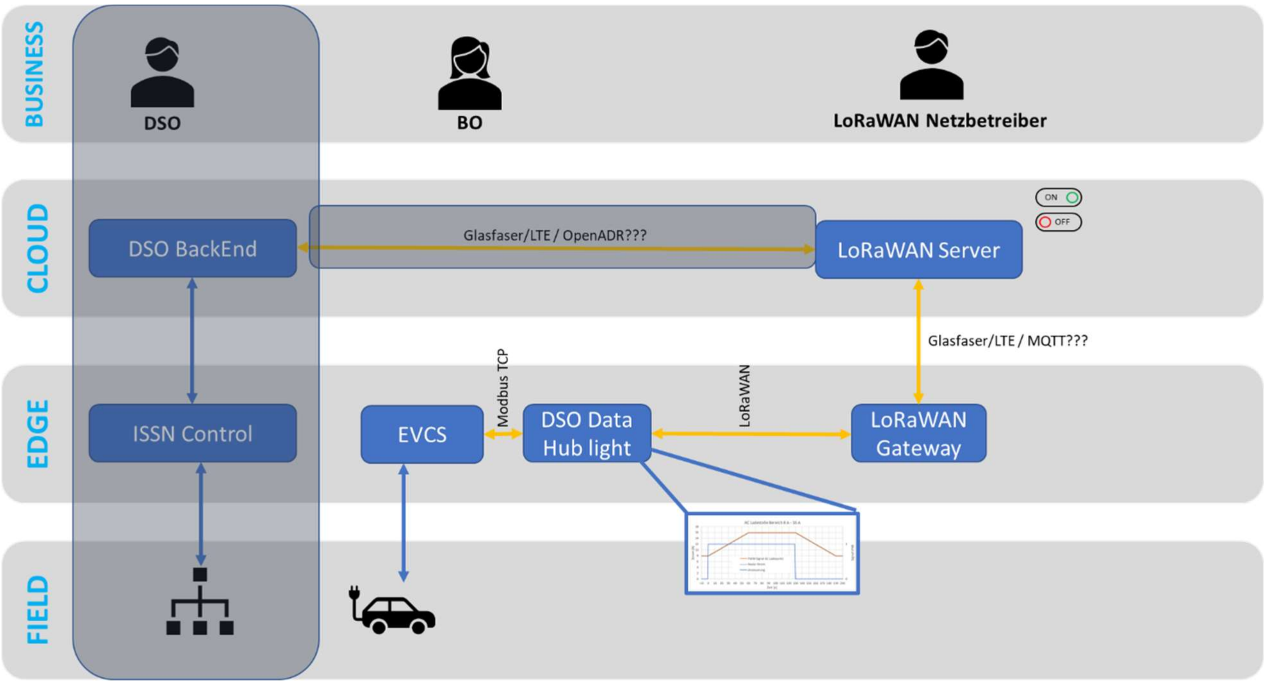


Figure 92: Test Case Part 2 „LoRaWAN infrastructure and DSO Data Hub light" (the DSO related part of the infrastructure to generate the reduction signal was mocked in this test to reduce complexity)

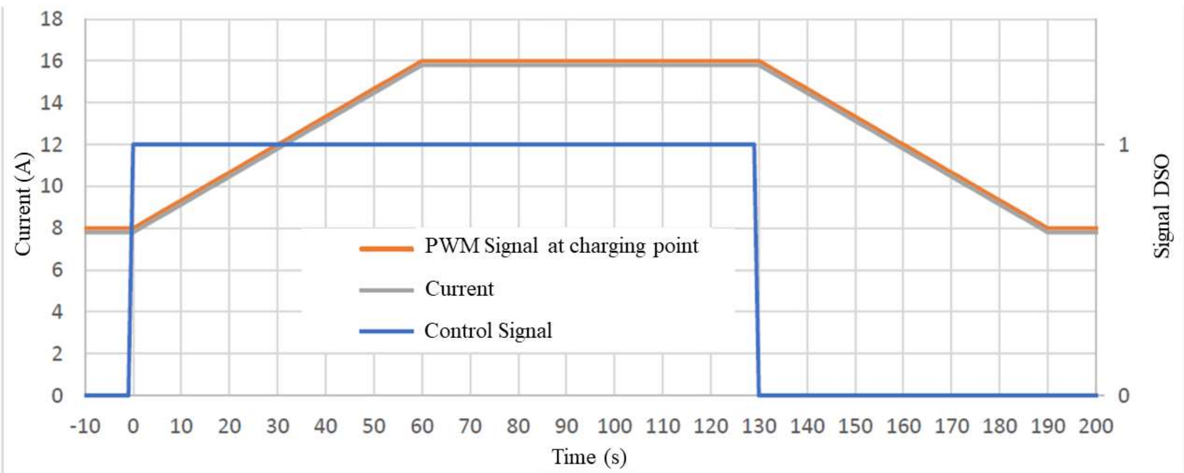


Figure 93: Definition of charging station reaction after reduction signal: AC charging point 8A – 16 A

The reaction of charging stations controlled by 0/1 reduction signals have not been prescribed in this way after the TOR review process (discussions as of spring 2021). However, the implemented PoCs can now be further developed according to the findings of the working group on the Digital Customer Interface at ÖE. The SOFTprotection application for estimating the grid bottleneck and generating adequate reduction requests remains of interest, regardless of how the potential control of flexibilities will be realized.

4.5.4.5 OCPP infrastructure and local interaction

PoSyCo UC3’s public charging infrastructure, such as the ASCR Testbed at Seehub garage in Aspern, connects a promising group of actors to ensure grid stability. Beside the local load management controlling numerous charge-point devices, they are also controlled by a backend via Open Charge Point Protocoll (OCPP). OCPP is usually used to maintain charge points and to control the charge process including user access administration, authentication, reservation up to billing and monitoring the availability, energy usage and managing issues. To gain experience with this type of connection, this testcase was focused on evaluating local control vs. backend control using an already existing, prototypical OCPP implementation.

A main interest of setting up this test case was research on the potential dependencies of a centrally managed, public charging infrastructure with decentral requirements for load management considering grid constraints as supervised by SOFTprotection. It has been evaluated that the limits for the charging current are specified with OCPP from a CPO perspective and, additionally, that the charging current or power can be influenced with Modbus within these limits. Therefore, a local controller would be able to influence OCPP-managed charging stations as well. Such a local controller could also operate as kind of fallback in case the connection to the OCPP back-end is lost.

The base functionalities such as authorization, transactions and metering data transfer, configuration, remote control, and remote updates for the charge point devices are already in place at most charge point operator systems with OCPP v1.6 implemented. With the increasing numbers of new e-car models equipped with IEC15118 communication, as well as charging stations implementing new features regarding smart charging, inductive charging, and plug&charge, the upgrade of existing systems using OCPP v2.0 is likely to happen in the near future.
The “local controller” described in OCPP v1.6 specification is not able to operate OCPP communication on a local level in case of communication failure to the back-end. Issues such as authentication, billing, sending/receiving messages after reconnection must be investigated and specified in the future.

4.5.5 Use Case 4: Overload prevention through temporary meshing

4.5.5.1 Functionality of the Switching Management System algorithm, executed at a laboratory demonstrator

For testing the practicality of the developed SMM algorithm (Switching Management Module) for the temporary reconfiguration of low-voltage grids, a laboratory demonstrator was developed and set up. With this demonstrator, it is possible to operate different loads and generation units on two feeders. Through a corresponding Ethernet-based communication system, these can be automatically reconfigured via three of the four circuit breakers using the SMM algorithm.

Figure 94 shows a simplified overview of the laboratory demonstrators with a transformer as source, its 4 circuit breakers (CB), 4 line modules (LM, connectors to emulate cable lengths) as well as 6 possible load resp. source connections. In the final configuration of the laboratory demonstrator, the four compact circuit breakers mentioned are connected in the form of an open ring structure with outlets for sources/feeders and loads/consumers located at different points. The laboratory setup with the hardware used is shown in chapter 3.3.2.2.

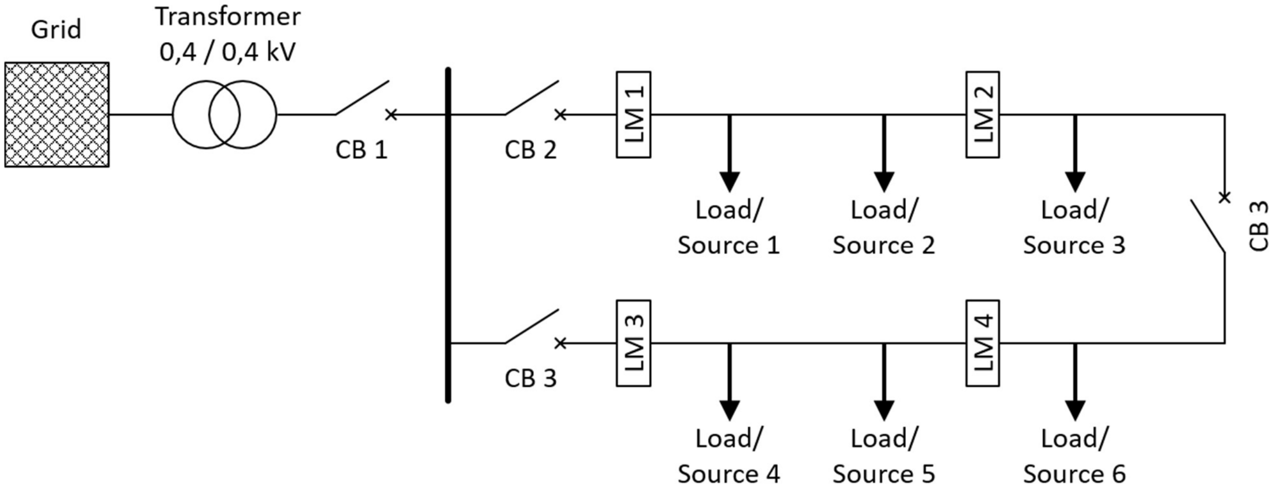


Figure 94: Overview circuit diagram of the laboratory demonstrator

The 4 CBs are able to communicate with the data concentrator via specific communication modules and a prefabricated bus cable. From the data concentrator onward, communication works via Profinet to a PLC which converts the corresponding data to Ethernet protocol. The rest of the communication then works with normal Ethernet via LAN whereby the Display as well as the control PC are addressed. The PC itself is hosting the whole development environment which consists of the control algorithm performed in Python and the related grid simulation software for carrying out the necessary load flow calculations. A schematic diagram of the described communication is shown in the chapter of the test bed description in Figure 8.

One of the biggest challenges during the commissioning and initial testing of the laboratory demonstrator was the communication of the circuit breakers. In detail, this included firmware updates and related interoperability issues of the individual components (e.g. circuit breakers, communication modules, data concentrator) or software interoperability challenges between the configuration software and the control tool via Python (the SMM algorithm is Python-based). After initial adaptation measures (e.g. installation of a PLC as an "adapter" between different communication protocols), the first tests of the algorithm in combination with the laboratory demonstrator were successfully completed.

With the help of the laboratory demonstrator, further investigations with different loads or feeders are now to be carried out to identify possible weaknesses of the SMM algorithm. Furthermore, an upgrade of the demonstrator regarding integrable line modules is conceptualized, with which more realistic line lengths of the individual feeders can be emulated.

4.5.5.2 Robustness of the SMM algorithm at unfavorable environment conditions

The objective of this test is to assess robustness of SMM algorithm in face of unfavorable environmental conditions. These environmental conditions could be data loss during transfer in the form of missing or incomplete input data for SMM algorithm. Missing or incomplete data is defined as data missing a subset of data points compared to the full set of input data. The subset data is assumed to be still valid with respect to its format and schema. If the data subset is malformed because of environment conditions, the error must be handled in the data layer and would not lead to a successful SMM algorithm execution. During this test, input data for the SMM algorithm is changed and a comparison is done with unchanged input data reference results. Changes to input data represent information loss due to communication problems or incomplete data transmission.

For this test, robustness was found even for worst-case information losses. As the tests are done only for one test grid, an evaluation on more test grids should be done in the future.

4.5.5.3 Robustness of the SMM algorithm at changing environment conditions during the algorithm runtime

The objective of this test is to assess robustness of the SMM algorithm in the face of changing environment conditions during algorithm runtime. These environment conditions could be a change in operational conditions such as load or generation conditions. This change in conditions cannot be picked up by the SMM algorithm during runtime, so the SMM algorithm results might not reflect the changed physical reality. Changed operating conditions with respect to line loading would be an increase of load on a different lines terminal, which would, in turn, decrease line loading of the line deemed critical prior to load increase. Each sub-test is defined as a load increase happening during a different SMM algorithm internal iteration, reflecting different instances of time during SMM algorithm runtime.

During this test, grid load parameters are changed during the SMM algorithm operations and the results are compared with unchanged grid load parameters reference results. Changes to grid load parameters represent operational deviation of forecasts or renewable generation.

Robustness was found for realistic grid load parameter change ranges. As the tests are done only for one test grid, an evaluation on more test grids should be done in the future.

4.5.6 <u>Use Case 5: Stakeholder-overarching system interaction and process adaptation</u>

4.5.6.1 SoftProtection for ensuring grid friendly flexibility requests

For this test case, it is verified whether flexibility requests of the market are limited by the SoftProtection mechanism and if they would trigger transformer overloads. This is verified within the BIFROST virtual test bed for different events and scenarios.

One scenario is that a new community arises and wants to offer flexibilities on the market. This offer (of both positive and negative flexibilities) should then be visible in BIFROST. Flexibility Requests come from a Flex aggregator, which are fulfilled by the community, as well as possible. BIFROST visualizes how these requests are fulfilled. It can become problematic if the requested flexibility suddenly causes an local overload at the transformer. This has negative consequences for grid performance and constitutes a potential downside of community flexibility.

To overcome these arising problems, following the introduction of "SOFTProtection", a protection mechanism ensures that a flexibility request which would bring the transformer to the overload, may not be fulfilled at all or only partially. An implementation is done in BIFROST for validation purposes: As soon as SOFTProtection is activated, the "available" flexibility decreases so that the transformer can never be overloaded by flexibility requests. A detailed description of the implementation and test results is given in Deliverable D6.2.

The implementation demonstrated that the SoftProtection can protect transformers and line segments from overloads. Especially future challenges, when flexibilities in the lower grid levels are actively offered on markets, will lead to selective overloads for the grids due to the assumed simultaneities. As the selected scenario shows, the demand is met most of the time, apart from a sequence towards the end where the demand can only be partially met. By examining this in the virtual testbed, it becomes clear that this is probably since the battery cannot be charged with even more power. Its limit is set at 60 kW, and even if it is empty, a more powerful inverter and thus more negative flexibility is not possible.

Due to the developments in energy prices in the last months of the project duration, the topic of flexibilities and how the future assistance systems for grid operation deal with them will become of increasing importance. It is suddenly no longer an option of the future but a real given that solutions will have to be available in a few years, ideally within months. The inputs from these studies also flow directly into the working group at ÖE on the topic of digital customer interface.

4.5.6.2 Overload prevention support due to community flexibility activation

Similar to the UC5 SoftProtection test case, BIFROST is used as virtual test bed. Whereas the previously described SoftProtection limits flexibility requests the scenario “overload support” looks for additional flexibility at the market to reduce overloads. For example, if the transformer compensation is activated in BIFROST, the community will attempt to avoid an overload at the transformer by "providing" flexibilities.

As this case is an extension of the case before, the learnings are identical considering the role of flexibilities in overall system operation. What was interesting in this case is that, on the one hand, flexibilities are pro-activly used as additional actors for SOFTprotection to avoid limit violations, but on the other hand, that this will not work all the time. As shown in the scenario, firstly a negative request occurs, which aggravates the situation which is then solved by SOFTprotection. Nevertheless, the transformer load increases continuously due to the demand from other customers connected. Now the community steps in and provides positive flexibility on request of SOFTprotection. The flexibility is provided by the battery, which is discharging. Since the battery level was low at the time, the transformer load can only be regulated to 100% for a short time. As soon as the battery is empty, the community has no more positive flexibility and can no longer support the transformer.

This scenario shows that there may be dedicated “grid serving” flexibility operation schemes which have to be foreseen (e.g. by aggregators) or additional possibilities (e.g. the already mentioned digital DSO interface to customer) have to be introduced and become mandatory.

5 Summary

5.1 System tests in outdoor labs and Aspern Seestadt Hybrid LV Grid Controller

Over the course of the three-and-a-half-year project period, the conventional grid protection concept was expanded to include intelligent add-ons. This „SOFTprotection“ system now represents a function to avoid grid overloads. Accordingly, in the Show Case “Grid Supervision”, the method of active capacity management has been chosen, adapted (over the course of the project it has been to now focus on the grid friendly charging of electric vehicles) and has been implemented as so called SIAPP on an automation system of the SICAM A8000 series by using a Docker-like container framework. The “Hybrid Grid Controller” runs in the SIAPP-Container as a distributed SOFTprotection solution.

It monitors the load of the transformer, in the individual outgoing circuits and the voltage level in the low voltage grid. If the predefined limit values are violated and the problem cannot be solved by the adjustable local network transformer, the algorithm begins to reduce the permissible charging power step by step.
For demonstration purposes, a first, a very simple test case was carried out in the real laboratory. The charging process of the test vehicle exceeded the permissible power in one of the outlets, which was identified by the Hybrid LV Grid Controller. The Hybrid LV Grid Controller then attempted to bring the electrical power back into the permissible range in the individual phases by gradually reducing the permissible charging power per charging station in 10 % increments (related to the maximum charging power). After the successful tests on the laboratory test site, tests can now also be carried out in the garage in Aspern Seestadt, e.g. with ASCR’s own Tesla.

5.2 IoT sensor system as One-Device-Solution

Over the years, the assumption that an increasing amount of load information down to the low-voltage range will be required for efficient and safe operation of the distribution grids has been substantiated. Analyzes have shown that a combination of data from smart meters with precise measurement data from a few sensors distributed in the low-voltage network as well as the transformer stations is the best and cheapest combination to create the necessary transparency regarding network utilization. However, the question now arises as to how the existing network infrastructure can be easily and inexpensively retrofitted. For this, the “Enhanced Grid Sensor” (EGS) has been developed as part of PoSyCo as a “One Device Solution”. It contains a measuring mechanism that has 3 voltage and 3 current measuring inputs, a powerful data processing unit for determining all derived variables such as P, Q, U, cos phi, frequency and a configurable averaging function, a power supply and an LTE / Bluetooth LP communication unit.

Another research question covered the topic of the interaction with sensor networks. Wireless temperature measuring sensors or e.g. door opening sensors can be integrated via Bluetooth low energy communication. For applications in which only one voltage measurement, but several current measurements (e.g. busbars with several outlets) are required, the concept of a cost-effective current measurement module as an extension of the EGS is currently being researched. This module will scan the measured current values and makes them available to the EGS after synchronizing via the phase zero crossings. In order to make the EGS future-proof, it is equipped with a container framework and two Ethernet interfaces, so that in the future higher-level functions or communication protocols than SIAPP (see highlight Hybrid LV Grid Controller) can be loaded. This makes it easy to integrate such sensors into various IoT environments, but also into classic automation systems.

5.3 Findings from Economic Evaluations

The economic assessments in the PoSyCo project primarily examined Show Case 1 and 2 on an exemplary network section. One of the main results is that timely grid digitalization can definitely result in economic advantages in the operation of a distribution grid. These arise primarily from delayed grid expansion measures and avoided customer complaints (e.g. in the event of a grid failure due to excessive charging). However, the extent of these advantages is highly dependent on the age of the individual grid components and thus on the selected period under consideration. For example, advantages compared to conventional grid expansion could be high in 2040, but significantly lower in 2050, since the technical service life of the cables would have been reached and they would then have to be replaced anyway.

Other parameters (e.g. the number of new personnel roles in network operation, the cost of installing cables, the digitalization rate of network sections, component availability or inflation) also have a significant impact on profitability. Investments in network digitalization must therefore be carefully considered. A SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) in the project showed that in addition to increased efficiency in network operations, customers could also be offered new services in the future. In order to take a closer look at this, the following measures appear to be central:

- DSOs should act as enablers to support future customer needs (e.g. for energy communities, prosumers, flexible load sharing). Only then can new customer services be offered (e.g. data insights into the voltage quality, warning messages as soon as the connected load reaches e.g. 80 %, flexible tariffs, etc.). Internal processes and roles must be adapted to this vision;
- Set up a proactive external discussion process with stakeholders (e.g. energy communities, prosumers, charging station operators, aggregators, etc.), regulators and politicians to identify and develop the correct digital and grid-related services;
- Use the additional income from new services to ensure affordable basic services in the long term;
- Build a “Safe and Secure by Design” architecture with little dependence on external actors;
- Establish an appropriate recruitment process for well-trained employees, e.g. through tailor-made trainee programs for digitalization.

5.4 A day in the Digitalization Lab

The Show Cases described above show the idealized process for the integration of new SOFTprotection applications. The PoSyCo project analyzed how to integrate the developed SOFTprotection into existing DSO processes. The focus was not only on the technical integration, but also very much on the topic of the interaction of modern tools with employees. The design of the Use Cases and the definition of the roles has shown that many more people with different perspectives, information needs and previous knowledge will have to interact with the envisioned SOFTprotection system.

In the Wiener Netze digitalization laboratory, created specifically for this purpose as part of PoSyCo, the primary aim is to make the added value visible to the newly identified users. There, the Show Cases can now be implemented as prototypes with the help of the technical functions and representations via user interfaces, embedded in the future "workplaces" – a "cockpit of SOFTprotection". An important requirement is real interaction, meaning that instead of PowerPoint presentations, videos or static dashboards, for example, a sensor can be picked up and the process integration from installation and connection to visualization and processing of the data can be experienced firsthand. This is intended to ensure well-founded feedback with regard to the operating processes that will be required in the future.

5.5 Exploitation of the results

As a result of this project, it is now clear how a network operator can implement and control the extended network protection both technically and in the organizational processes. The information sources created for this purpose enable improved analysis and faster clarification of faults. As a result, future energy systems with a high proportion of renewable, volatile generation and flexible loads such as e-mobility or battery storage systems can be operated more reliably and safely. In this way, the ultimate goal of every network operator – to ensure security of supply – can continue to be achieved, also with regard to the many future challenges such as the integration of energy communities.

Based on the findings of the completed economic case study and the further SWOT analysis, strategies and measures were identified that can support the energy transition through grid digitalization. The knowledge gained from the project forms the building blocks for future standards and guidelines, standardized components, and business cases. Thanks to the know-how built up in the project team in recent years, the partners were able to implement and test the „SOFTprotection" approaches in their testbeds. The results of PoSyCo will contribute to further projects and through the associated dissertations, diploma theses and the ASCR DemoCenter, they will be disseminated among stakeholders of various kinds and enrich the overall scientific know-how in the areas of energy transition and intelligent power grids.

At first glance, it may look as if many pieces of the SOFTprotection puzzle have been worked on in the course of the project, but the overall system remains unclear. But here, the work on the project has shown that the multi-dimensional complexity – represented by physical, ICT and process dimension - requires a step-by-step approach based on vertical use cases. Since both the internal adaptation of the network operator and the development of the offer portfolio of the technology suppliers will not be completed over the next few years, PoSyCo provides valuable insights for this transformation process without the necessity of defining the overall system right at this point.

6 Outlook and Recommendations

In continuation from the last paragraph of the summary, a SOFTprotection overall system for a DSO could not be defined at present and therefore could not be specified for a corresponding tender. Not only are the technical and operational adaptation processes still ongoing, but also the framework conditions (e.g. energy prices, diversification of energy production, alternatives to natural gas, e-mobility, energy communities) are still undergoing massive changes. These framework conditions must then be incorporated into corresponding legal framework conditions for regulated grid operators. If this results in corresponding control options in the future, e.g. for e-car charging or heat pumps, SOFTprotection is precisely the solution that can then be productized for its use. Nevertheless, as explained below, there are, of course, also many project-specific findings that allow the derivation of recommendations or outlooks on the necessary further developments.

The project shows that Smart Grid rollout with automatized deployment of Smart Grid devices (such as sensors, novel gateways, intelligent EV charging controls) on a large scale is possible. Thus, electricity grid planners can plan and organize the rollout with dedicated tools and keep track of progress. The deployed devices register with the system autonomously whenever possible and send data without any manual interaction with the system. The user interface for the planning process of the Smart Grid rollout accordingly collects all necessary information from the grid planner to commence the deployment process.

To achieve such “grid friendliness”, a system for explaining events that occur in smart grids was also developed within the project. Thus, a basic version of an explanation generation engine was implemented. The current implementation is based on a simple causality model and explanation generation algorithm. This explainability system relies on Knowledge Graph technology as a basis to aggregate various data sources and derive explanations. The system was tested in tandem with the powerful smart grid simulator BIFROST, and it has been concluded that such an approach to explanations is feasible.

In the future, it is intended to explore the improvement of the causality and performance of the algorithm on one hand. On the other hand, for sure, the challenge of porting the system to real-life scenarios will be the future work beyond the PoSyCo project. As a start, the first prototype of a Hybrid LV Grid Controller - implemented as an SIAPP and hosted by a future proof automation system - was integrated in the Siemens E-Mob Outdoor Laboratory and successfully tested in terms of the PoSyCo validation activities. The application in this grid-friendly charging scenario will now build the base to provide information about the practical applicability of the explainability system.

Developments by the scientific community and the industry during the PoSyCo project confirm that the combination of a flexible data model with communication adapters is a state-of-the-art solution to enable semantically rich communication between devices. Specifically, the use of Semantic Web technologies and the systematic consideration of dependability distinguish the PoSyCo communication and information framework from existing solutions. While the framework can already be used to implement Smart Grid use cases, it should be integrated with Smart Grid planning tools to automate the configuration process. Other objectives that will be addressed in the future are additional communication adapters and the use of the framework in other areas, such as smart manufacturing, by adapting the domain-specific data models.

Furthermore, economic as well as sensitivity analysis showed the project team that several parameters (e.g. cable prices, OPEX or inflation rate) significantly influence the profitability of the developed grid digitalization solutions. Thus, long term investment strategies towards network digitalization must be evaluated in depth by DSOs before decisions are made. An additional SWOT analysis derived DSO-specific internal and external measures as well as strategies for the development of new services enabled by grid digitalization. These strategies and measures will be pursued by the PoSyCo project partners to trigger further developments towards Smart Low Voltage Grids.

7 References

7.1 PoSyCo Deliverables

Deliverable D2.1 – Use Cases and Required Components, 2022
Deliverable D3.1 – Developed Concepts, 2020
Deliverable D3.2 – Mathematical Models, 2021
Deliverable D3.3 – The Interaction of Models in Grid Model Operation, 2021
Deliverable D4.1 – System Architecture Specification, 2020
Deliverable D4.2 – Dependable Communication and Information Framework for SOFT Protection, 2021
Deliverable D4.3 – Communication and Information Framework Validation, 2022
Deliverable D5.1 – Optimised Process and Interface Description, 2020
Deliverable D5.3 – Recommendations for Process Integration, 2022
Deliverable D6.1 – Test Cases and KPIs, 2021
Deliverable D6.2 – UC specific lab validation: Test- and experiment specifications; results and insights
Deliverable D6.3 – UC living lab proof of concept: Test- and experiment specifications; results and insights

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7.3 PoSyCo Journal Publications

- M. Sabou et al: “Semantics for Cyber-Physical Systems: A Cross-Domain Perspective; Semantic Web Journal”; 2019
- D. Schultis et al: “Sparse measurement-based coordination of electric vehicle charging stations to manage congestions in low voltage grids”; Smart Cities (ISSN 2624-6511); 2020
- D. Herbst et al: “Development and evaluation of an algorithm for the automated reconfiguration of low-voltage grids”; e & i Elektrotechnik und Informationstechnik volume 138, pages 525–537 (2021)
- F. Knorr: “Framework for the Design and Automatic Deployment of Smart Grid Applications”; EPSR 2022; *https://www.journals.elsevier.com/electric-power-systems-research*
- T. Frühwirth: “Dependable multi-agent systems for smart grid applications”; PhD Thesis, TU Wien, 2021

- G. Steindl: "Digital Twinning for Industrial Energy Systems Utilizing Semantic Web Technologies"; PhD Thesis, TU Wien, 2021

A full overview of PoSyCo conference publications is presented in deliverable D7.2.

8 List of Abbreviations

AEP	Denoted automated explanation provisioning
ACS	Advanced Current Sensors
AI	Artificial Intelligence
AIT	Austrian Institute of Technology
API	Application Programming Interface
ASCR	Aspern Smart City Research
ASL	Automated statistical labelling
ASMO	Automation system monitoring and operation
CA	Communication Adapter
CAM	Context Aware Monitoring
CAPEX	Capital Expenditures
CB	Circuit Breaker
CBA	Cost Benefit Analysis
CEE	Commission on the Rules for the Approval of the Electrical Equipment
C-HIL	Controller Hardware in the Loop
CIM	Common Information Model
CP	Costumer Plant
CPD	Change Point Detection
C-PHIL	Controller Power Hardware in the Loop
CPS	Cyber Physical System
C-SIL	Controller Simulation in the Loop
DER	Distributed Energy Resrouces
DSO	Distribution System Operator
DSS	Decision Support System
DTR	Distribution Transformer
EGS	Enhanced Grid Sensor
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
GIS	Geographic Information System
GMD	Grid Monitoring Device
GPRS	General Packet Radio Service
HLVGC	Hybrid Low Voltage Grid Controller
HP	Heat Pump

HW	Hardware
ICT	Information and Communication Techology
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IT	Information Technology
iSSN	Intelligent Secondary Substation Node
KG	Knowledge Graph
KPI	Key Performance Indicator
LF	Load Flow
LV	Low Voltage
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
NPV	Net Present Value
OCPP	Open Charge Point Protocoll
ÖE	Österreichs Energie
OPC	Open Platform Communications
OPEX	Operational Expenditures
OT	Operational Technology
PLC	Power Line Communication
PoC	Proof of concept
PoSyCo	Power System Cognification
PV	Photovoltaic
QDS	Quasi Dynamic Simulation
RCA	Root Cause Analysis
RCD	Residual Current Devices
RF	Random forest model
RTU	Remote terminal unit
SCADA	Supervisory Control and Data Acquisition
SED	Supervision and Event Detection
SEPA	SPARQL Event Processing Architecture
SG	Smart Grid
SGAM	Smart Grid Architecture Model
SGTB	Smart Grid Toolbox
SL	Probabilistic statistical label
SMM	Switching Management Module
SoC	State of Charge
SOSA	Sensor Observation Sample Actuator
SWOT	Strengths Weaknesses Opportunities Threats
TOR	Technical and Organizational Rules
TUG	Technical University Graz

UA	Unified Architecture
UC	Use Case
WACC	Weighted
WB	Wall Box

9 Contact Details

Project Leader: DI Helfried Brunner, MSc
Institution/Company: AIT Austrian Institute of Technology
Contact: Giefinggasse 2, 1210 Vienna, Austria, +4350550-6382; helfried.brunner,@ait.ac.at; AIT Website: www.ait.ac.at; Project Website: https://www.ascr.at/power-system-cognification-posyco/?msclkid=d1fada4fcf8f11ecbb6e8179472d3a2c