Interoperable solutions for implementing holistic **FLEXI**bility services in the distribution **GRID**

REPORT ON MODULES PROGRESS ACHIEVED

Deliverable 4.7

WP4

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4			
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7			

ACRONYMS

A	Current in Ampere
3R2C	Three Resistance Two Capacitance
AC	Air Conditioning
ACO	Ant Colony Optimisation
AeS	Average estimation of savings per stakeholder
BaU	Business as Usual
CAIDI	Customer Average Interruption Duration Index
CNN	Convolutional Neural Network
DAF	Demand Available Flexibility
DE	Distributed Energy
DER	Distributed Energy Resources
DER	Distributed Energy Resource
DHW	Domestic Hot Water
DR	Demand Response
DSO	Distribution System Operators (DSO)
EC	Energy Consumption
ENS	Energy Not Supplied
EWH	Electric Water Heater
EXL	Exchange of Information with sub-DSOs
FA	Forecasting Accuracy
FAT	Flexibility Actions Taken
GP	Gaussian Process
GRU	Gated Recurrent Unit
HV	High Voltage
HVAC	Heating Ventilation Air Conditioning
IML	Information Management Layer
IMRR	Island Mode Reliability Rate
IoT	Internet of Things
KPI	Key Performance Indicator
LFM	Local Flexibility Manager
LSTM	Long Short-Term Memory
LV	Low Voltage
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MILP	Mixed Integer Linear Programming
ML	Machine Learning
MV	Medium Voltage
NGE	Number of Grid Events
OLTC	On-load Tap changer
OPC	OLE for Process Control
P2H	Power to Heat
PCR	Plant Central Regulator
PLC	Programmable logic controller

PLRed	Peak Load Reduction
PV	Photovoltaic system
R&D	Research and Development
RE	Reactive Energy Consumptions
ReLU	Rectified Linear Unit
RES	Renewable Energy Sources
RMS	Root Mean Squared
RMSE	Root Mean Square Error
RNN	Recurrent Neural Network
RTO	Research & Technology Organisation
RTU	Remote Terminal Unit
SAIDI	System Average Interruption Duration Index
SAX	Symbolic Aggregate Approximation
SCADA	Supervisory Control and Data Acquisition
SCRt	Self-Consumption Rate
SERI	Successful event reading index
SGC	Smart Grid Controller
SMRI	Successful Meter Reading Index
SoC	State of Charge
SS	Secondary Substation
SSG	Rate of successful switching operations to reconnect to grid
SSR	Switching success ratio to islanded mode
SSRt	Self-sufficiency ratio
TDRP	Time-Domain Reflectometry
TP	Technical Partner
TSO	Transmission System Operator
UML	Unified Modelling Language
V	Voltage in Volts
VES	Virtual Energy Storage
VLV	Voltage Limits Violations
VPP	Virtual Power Plant
VTES	Virtual Thermal Energy Storage
WP	Work Package

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EXECUTIVE SUMMARY

The FLEXIGRID project explores some of the many benefits of using smart grid technology. Three major structures are developed throughout the project, a web-based harmonisation platform (WP5), a hardware solution that locally addresses the needs of the demos (WP3) and finally a complete set of software modules (WP4) whose development is outlined in this document. Work package 4 will carry out six different tasks, led by technical partners and covering key aspects which take advantage of the capabilities of the smart-grids. The main objectives of these tasks are:

- T4.1 Software upgrade for advanced operation, fault detection and self-healing of MV distribution grid: led by CIRCE, mainly deployed in the Spanish demo.
- T4.2 Software upgrade for demand/generation forecasting: led by VERD and deployed in the Greek demo.
- T4.3 Improved control technologies for the smart operation of grid assets: led by CIRCE, mainly deployed in the Spanish demo.
- T4.4 Software upgrade for congestion management and peak-shaving: led by VERD and deployed in the Greek demo.
- T4.5 Dynamic thermal modelling of buildings and energy storage specifications: led by HYPERTECH and deployed in the Croatian demo.
- T4.6 Tools for the distribution grid dispatching and operating in islanded mode: led by EDYNA and deployed in the Italian demo.

The result of all these tasks were different modules and implementations which are collected in this document as a summary of the technical approaches and, the adaptation based on the demo needs. The latter is found in sections 2 to 7, and the final comments and lessons learned by each developer are summarised in section 8.

TABLE OF CONTENTS

1 INTRODUCTION

The FLEXIGRID project contemplates the use of innovative solutions to provide flexibility under different use cases and configurations of electrical networks. Proposed solutions will allow the distribution grid to operate securely and reliability when a large share of renewable generation is connected to low and medium voltage grids.

FLEXIGRID proposes a three-level approach aiming at Flexibility, Reliability, and Economic Efficiency through the development of innovative hardware and software solutions. These solutions will be demonstrated in four Demo-Sites across Europe ensuring their interoperability through its integration into an open-source platform able to harmonize the data flow between the FLEXIGRID solutions and the actual grid.

The following lines explore the developments that were completed in WP4, involving the various software modules that will be used in the demonstrations, each of which covers a unique and relevant aspect of the active use of smart grid technology to solve a problem or improve a particular use of existing resources.

1.1 Work package description

Work package 4 takes care of the software developments to be implemented in the demos, at the same time defining the exchange of information from the field devices, the FUSE platform and the software modules that determine the behaviour and control of the controllable assets.

Main Objective: To develop innovative operation, control and management strategies for the distribution grid, addressing its architectural and interoperability challenges.

Specific objectives:

- To improve current security algorithms towards grid security and resilience increment.
- To improve current demand/generation forecasting algorithms towards grid control and management increment.
- To improve current control algorithms towards grid control increment.
- To improve current management algorithms towards grid congestion reduction.
- To develop network thermal models towards the creation of synergies between networks.
- To develop an operation tool for the island mode operation of the distribution grid.

It has been implemented from month 7 to 30 of the FLEXIGRID project and is composed of six main tasks, the correlation with the use cases is shown in Table 1.

Table 1. Use cases and solutions matrix correlation

Task	Description / Leader	Algorithm / Module	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8
T4.1	Software upgrade for advanced operation, fault detection and self-healing of MV distribution grid / CIRCE	(A) Fault location and self-healing	X							
		(B) Optimal operation of the distribution network					X			
		(C) DC-link capacitors for inertia								X
T4.2	Software upgrade for demand/generation forecasting / VERD	(A) Demand/generation forecasting	X		X					
		(B) Machine learning algorithms (day-ahead forecast)	X		X					
T4.3	Improved control technologies for the smart operation of grid assets / CIRCE	(A) Flexibility Assets Operation	X							
		(B) Predictive optimization algorithms				X		X		
T4.4	Software upgrade for congestion management and peak-shaving / VERD	(A) Congestion management and peak-shaving				X				
		(B) analyse pricing strategies				X				
T4.5	Dynamic thermal modelling of buildings and energy storage specifications	(A) Virtual energy storage (VES) demand response/flexibility module						X		
		(C) Sizing and siting of electrical batteries module								
T4.6	Tools for the distribution grid operating in islanded mode	(A) Dispatching module							X	
		(B) Operating in islanded mode								X

1.2 Relation to other work packages

The main interactions of WP4 are with WP3 where the hardware solutions are designed, WP5 which covers the information exchange architecture through the FUSE platform and finally with WP6 where the complete set of solutions are deployed and tested, this is reflected in Figure 1.

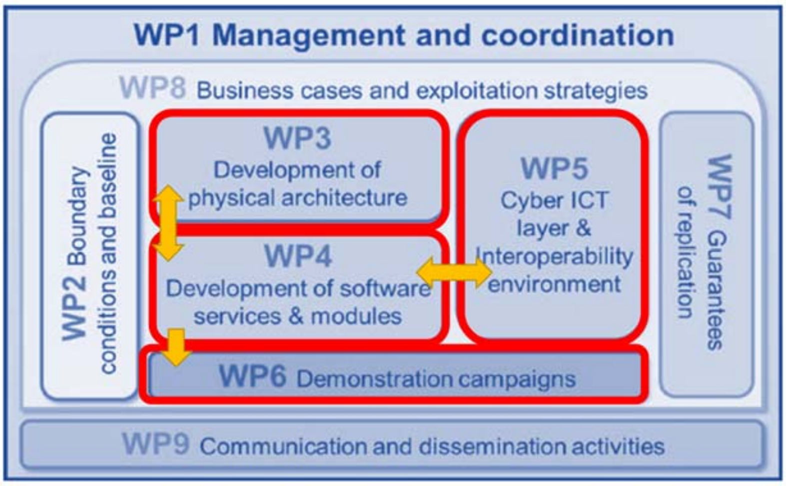

Figure 1. WP4 relation to other work packages

1.3 Scope and Structure of the deliverable

Being a compendium of the different software developments resulting from the work done in WP4 of the FLEXIGRID project, it will show the relevant technical aspects and particular considerations in each of the tasks that are part of the work package.

The document is composed of eight sections, the first one covers the general aspects, sections 2 to 7 correspond to the results of tasks 4.1 to 4.6 respectively and finally section 8 is a contribution from the developers where they summarise their experiences during the execution of the tasks.

2 T4.1. Software upgrade for advanced operation, fault detection and self-healing of the MV distribution grid

This task consists of two main submodules which are shown in Figure 2

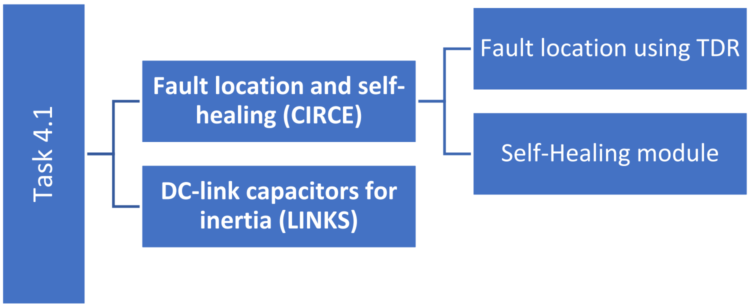

Figure 2. Submodules in the task 4.1

2.1 Fault location using TDR (CIRCE)

As part of the FLEXIGRID project, a medium voltage network monitoring device is proposed that autonomously locates the fault on the line indicating the distance, reducing the time of specialised personnel to identify the location. For this purpose, the TDR signal injection principles are used together with the traveling wave principles, comparing pre-fault and post-fault signals into the power grid to have information on the state of the grid in both cases. This solution only requires the installation of one device in the transformation centre, avoiding the installation of multiple devices, which makes its implementation difficult.

2.1.1 Operation and features

2.1.1.1 technical approach

Among the technologies and solutions developed under the FLEXIGRID project is the implementation and testing of a fault locating and self-healing system, which aims to significantly improve response times to problems in medium voltage networks, by more accurately indicating where the fault is located, and reconfiguring the network to ensure maximum provisioning and connectivity of subscribers or devices, isolating the faulty part, and minimizing network topology modification.

FLEXIGRID's integral solution is carried out from two complementary techniques, the first is based on the use of advanced reflectometry studies, which allows, thanks to the injection of a high frequency signal and the comparative analysis of this signal over time, to infer the distance in magnitude to the fault (see Figure 3). The second method is fault location based on the identification of the affected line sections by means of fault passage detectors.

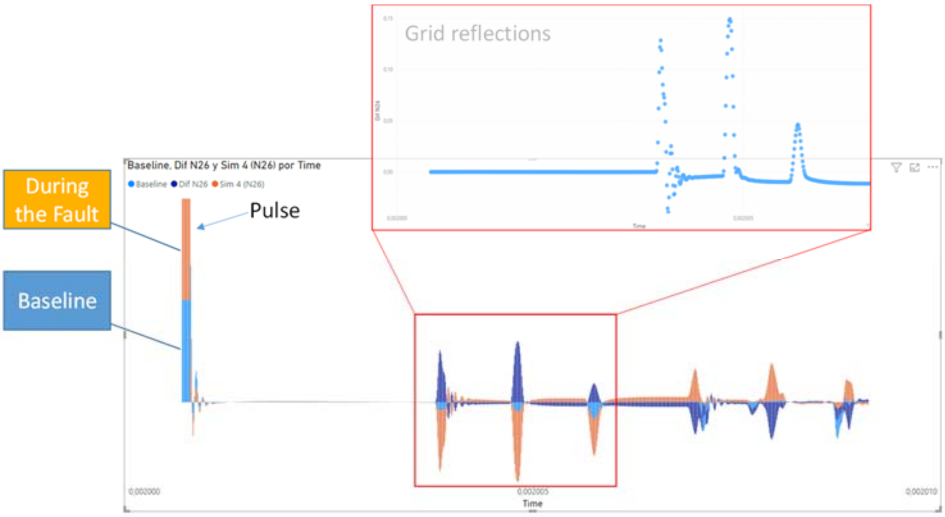

Figure 3. Sum of reflected waves

For the first method, the response of the power grid to pulse injection in normal operation is different from the response when a fault has occurred. In case of a fault, the impedance is changed at some point in the network. The pulses reaching that point are reflected differently than they were before the fault. when an impedance change occurs, part of the injected signal is reflected, and part of the signal propagates forward continuing its path through the rest of the electrical network. During a fault event, part of the injected pulse will be reflected at that point and return to the TDR differently than before the fault. Based on this fact, the distance from the TDR to the point where the fault occurred can be determined.

2.1.1.2 Actors and scenarios

Table 2. Submodule actors and scenarios

Name	Type	Description
TDR	Actor	The TDR is a subsystem that periodically injects high frequency pulses into the network. These pulses travel through the network and reflections are produced depending on the impedance at each bifurcation. These reflections return to the TDR where they are recorded and processed to calculate the distance at which the fault occurred.
Fault detector	Actor	The fault detector is a subsystem that detects that a fault has occurred at some undetermined point in the network by measuring the currents and voltages of the network.
Fault detected	Scenario	A protection device detects a fault and sends the signal to the TDR, which emits a new pulse and starts analysing the difference in the reflection.
Normal operation	Scenario	The system sends pulses to the network continuously and records the response.

2.1.1.3 Main flowchart

During normal operation, the TDR periodically generates pulses and records feedback from the grid. After the fault occurs, pulses are generated again to record the response of the downed grid, then the data is processed by an algorithm and the distance between the TDR and the fault is obtained as shown in the Figure 4.

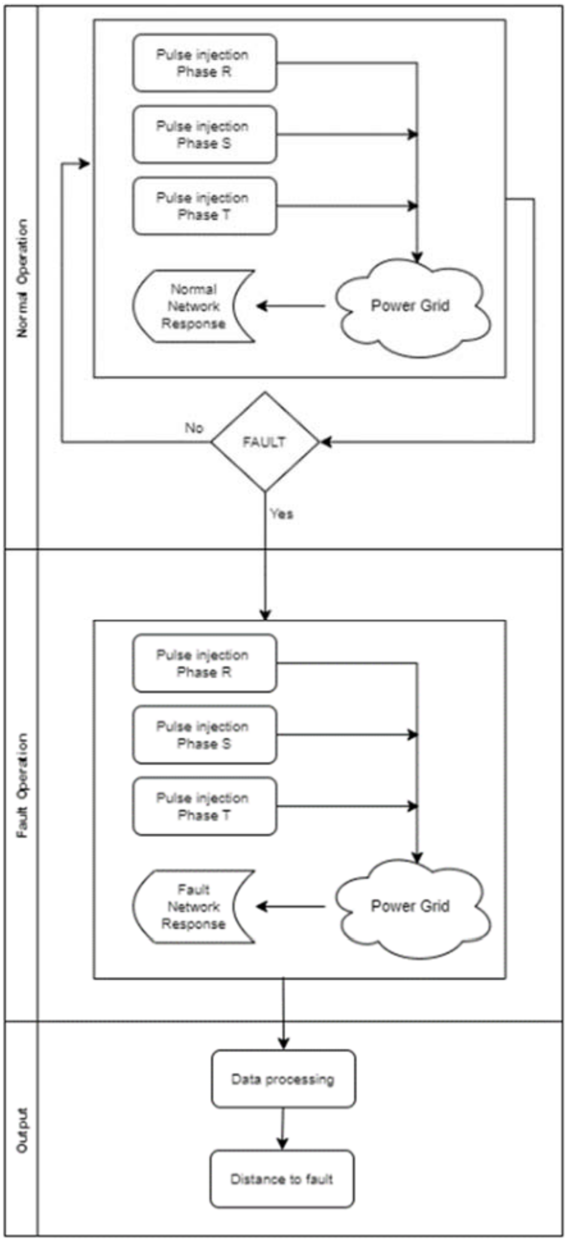

Figure 4. Main flowchart

2.1.2 Modelling and testing considerations

2.1.2.1 Description of the demo

The configuration is formed by pulse injection and coupling as shown in the Figure 5.

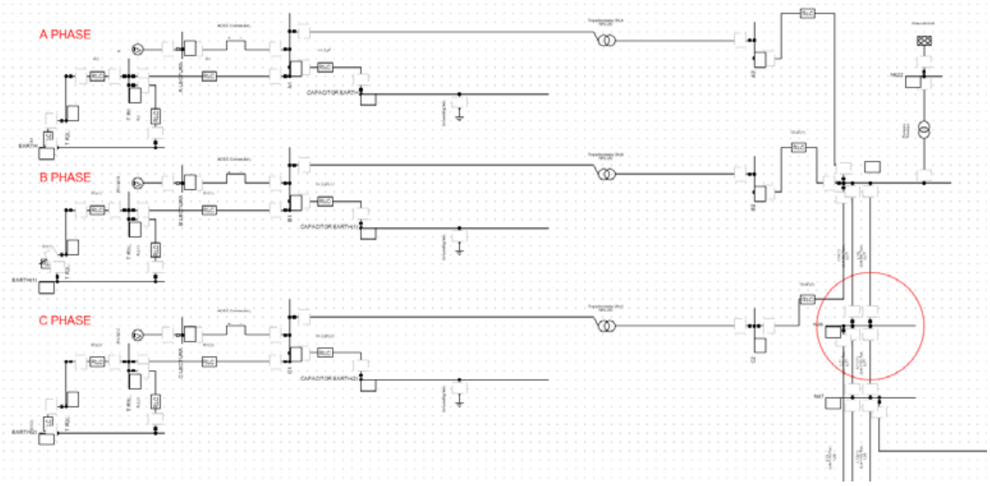

Figure 5. TDR configuration in DIgSILENT

Modelling the injection of a DC voltage pulse within an AC network was the most laborious work in the DIgSILENT. At first, the connection of an AC voltage source was made, varying the wave through the internal programming language (DPL). Finally, in the latest version of DIgSILENT it is possible through a new element called “AC/DC connector” to connect the generation of a DC voltage pulse within an AC network.

The coupling from the pulse injection to the connection point with the 12 kV network is based on the prevalent model CAMS-10C.

The coupling, localized between the generation of the pulse and the connection to the network, is formed by a group of resistors, a capacitor in parallel, a transformer (1:2 ratio) and a capacitor before reaching the connection point.

2.1.2.2 Devices installed in the field

The installation of the physical elements in the medium voltage network are shown in Figure 6.

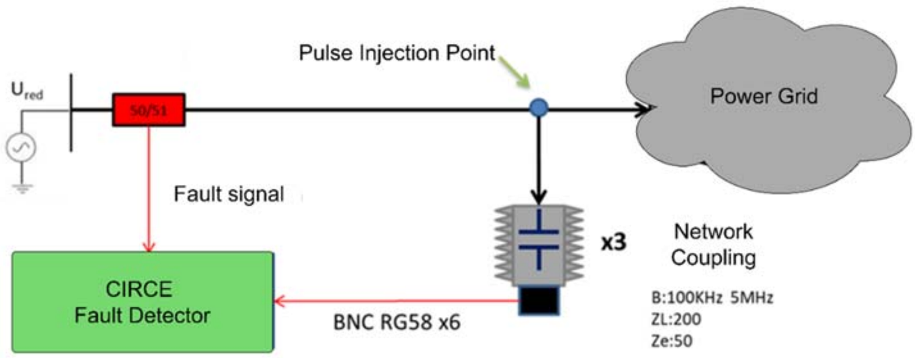

Figure 6. Field Device Connection

The description of the pulse generation and signal acquisition stages are shown in Figure 7, the elements that constitute the generation and injection system are:

- **Main processing unit**: Generates the pulses, samples the network response and processes the information obtained.
- **Pulse power signal conditioner:** Transforms low-energy pulses into high-energy pulses to be injected into the grid
- **Signal adaptation conditioner**: Transforms the response signal from the network to valid levels for processing.
- **Medium voltage network couplers:** provides an electrical isolation for the equipment (TDR) from the medium voltage grid and allow the injected high frequency pulses to travel from the TDR to the grid and from the grid back to the TDR.
- **Fault occurrence signal:** This signal is sent to the TDR to indicate when a fault has occurred from a IED. This system can determine if a fault has occurred on either phase by measuring the voltage/current on the power grid. When a fault occurs, the fault signal alerts the TDR and it injects a new pulse with the mains in that fault state. Thus, the signal stored before the fault and the signal stored after the fault are compared by the algorithm to determine the distance to the fault.

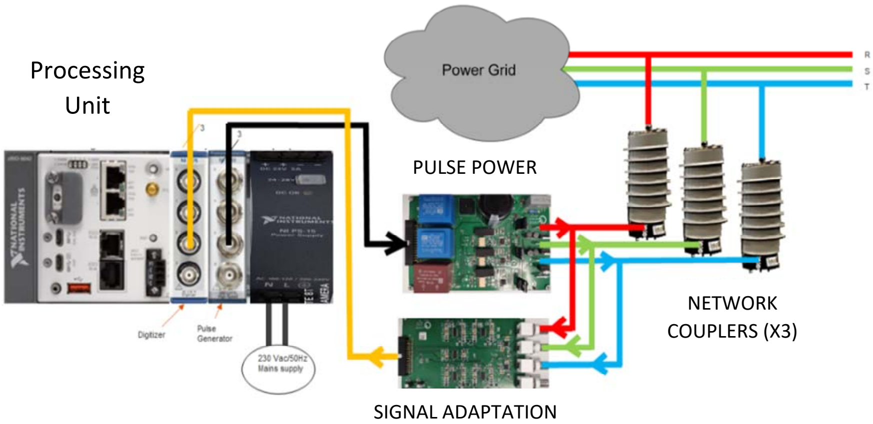

Figure 7. Detail of Physical Devices

2.1.2.3 Main processing unit

The script that generates the pulses and processes the signals received in response from the power grid runs inside a National Instruments (NI) module. This script is also capable of formatting these signals by effectively join them and saving them in a file that can be post processed.

Each file are sent to the PC where the fault detection algorithm is processed. This developed algorithm may contain parts of "traditional" signal processing and/or even other types of algorithms based on e.g. neural networks. Moreover, these data can be obtained remotely through the connection of the system to the internet using a 4G router represented in Figure 8.

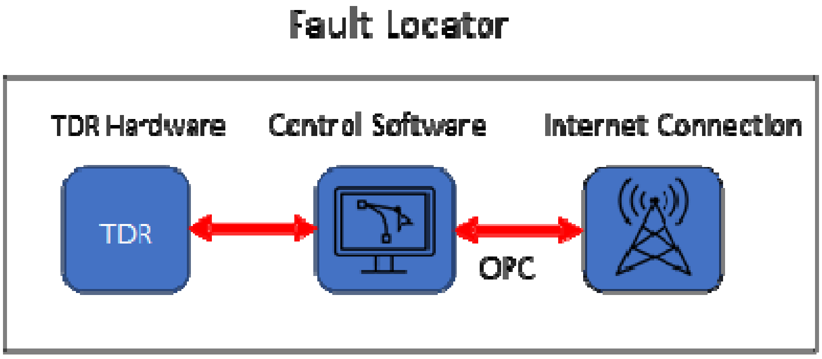

Figure 8. Fault locator communication scheme

2.2 Self-Healing Module (CIRCE)

2.2.1 Operation and functionalities

2.2.1.1 Technical approach

The aim of this tool is to locate faults in the electrical network. To do this, a network model is obtained that is equivalent to a real network where through fault detectors (TFD) are integrated. These devices make it possible to know whether the fault has occurred downstream of the point in the network where they are located, which helps to locate the fault by ruling out other areas. The fault will have occurred between the last breaker that has seen the fault and the first breaker that has not seen the fault. With this it is possible to determine the affected section of the line, the resolution is limited by the number of TFDs, once the faulty section is defined the module determines an optimal reconnection sequence if possible.

2.2.1.2 Main actors and scenarios

Table 3. Main actors and scenarios

Name	Type	Description
Through fault detectors	Actor	By reading the fault detection switches it is possible to limit the fault possibilities.
TDR locator	Actor	By knowing the distance from the fault, it is possible to limit the fault possibilities.
Network model	Scenario	Network model with voltage, load, and generation profile. Fault detection switches and TDR integrated.

2.2.1.3 Functional diagram

To run the self-healing algorithm, it is necessary to import a network model that includes the location of the fault detection switches, which will increase the possibilities of locating faults. In addition, with the TDR device, the distance from the substation to the point where the fault has occurred must be known. Thus, with both tools together, fault location will be possible. The general scheme is represented in Figure 9.

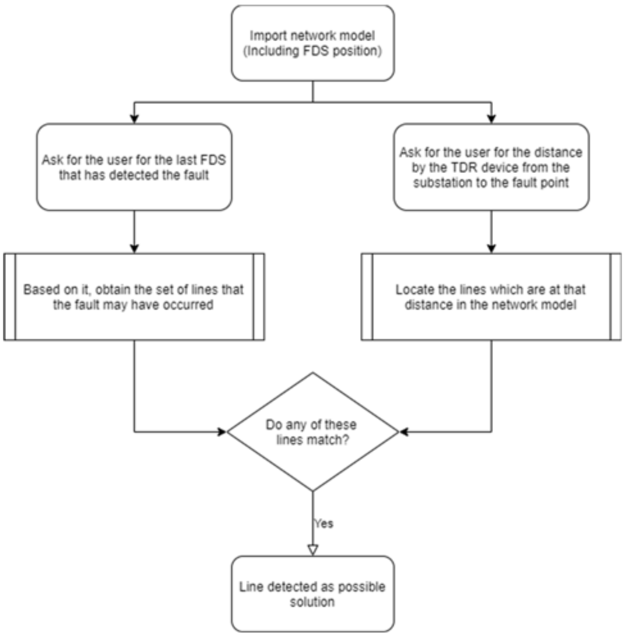

Figure 9. Main flowchart

2.2.2 Modelling and testing considerations

2.2.2.1 Description of the selected demo

The "Toranzo" network (Figure 10) is in Luena, Cantabria, Spain and is a 12 kV medium voltage network, which has a 12 MVA transformer (55/12 kV) with connection YNyn0. It has a set of fault detection switches integrated along the network, as well as a protection element that records voltage and current measurements on the transformer's MV bus.

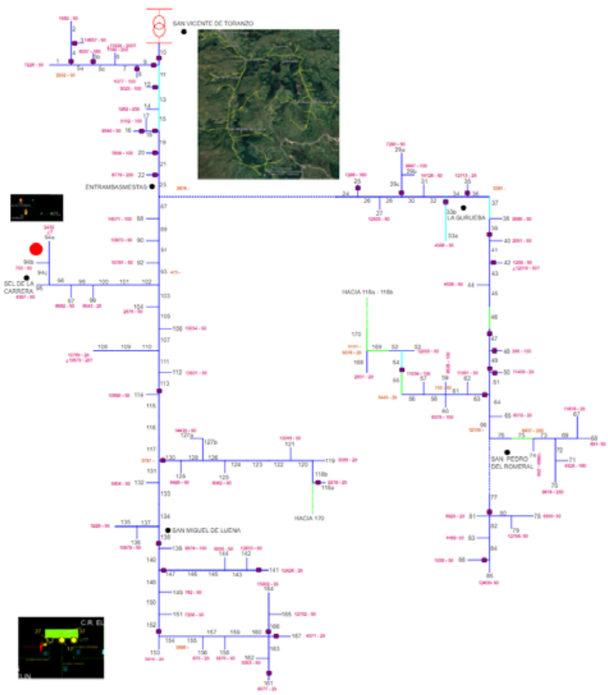

Figure 10. Toranzo network

2.2.2.2 Devices installed in the field

Due to VIESGO's internal security policies, the self-healing algorithm will be tested using virtual elements instead of acting directly on real equipment, this approach was an agreement in coordination with CIRCE and VIESGO. In this way, point-to-point tests can be performed in a safe and controlled environment, with the possibility of testing on real elements in the future at VIESGO's discretion. These virtual elements will represent devices that can be controlled by the self-healing module in situ, taking advantage of the computational power of the Energybox it is possible to emulate the behaviour of the switches and through fault detectors (TFD) of the Toranzo network.

The description of the virtual assets and their signals and commands is shown in Table 4.

Table 4. Virtual Assets description

On site Element	Virtual Asset	Description	Signals
Energybox	TFD	Through fault detector	• Fault detected: [bool] • Timestamp
	Breaker	MV circuit braker	• Status [Open/Close] • Timestamp
	IED	Main Feeder protection	• Maximum fault current [float] • Timestamp

2.2.2.3 Integration with the FUSE platform

FUSE system as a data integrator provides different methods to communicate with devices in the field, for the specific case of virtual assets the chosen protocol was OPC a well-known industrial IoT (IIoT). Thus, For the upstream information exchange, the unified REST API developed by ATOS will be used. The conversion procedure between the API and the OPC will be carried out internally in the FUSE platform acting as a gateway and this abstraction layer means that the system can easily scale.

The entire scheme is shown in Figure 11.

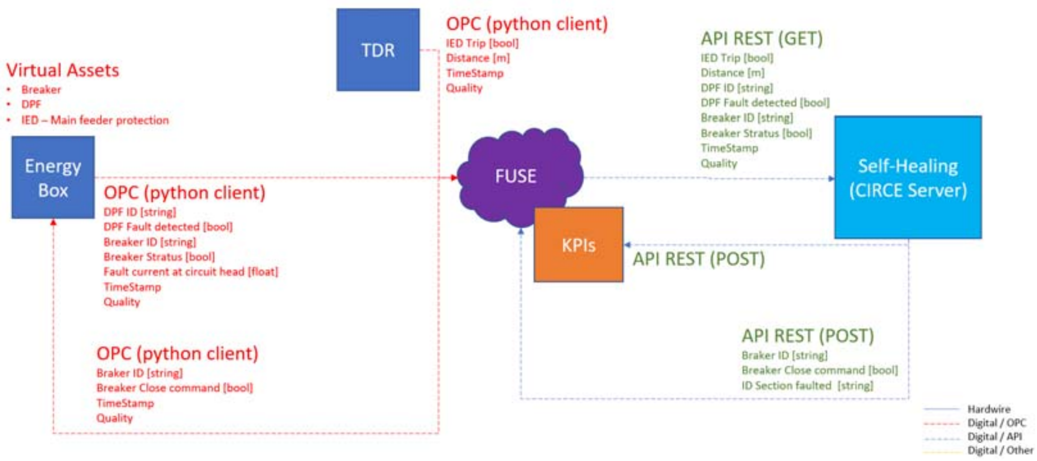

Figure 11. Main communication scheme with FUSE

2.3 DC-link capacitors for inertia (LINKS)

Inertia of the electricity system is the reluctance of the system itself against changes in frequency of complex system due to unbalance events such as breakers' trips, load insertion, generation disconnection etc. The self-healing of the power system in dynamic is essential to guarantee service continuity, as according to predefined standards, the system unable to meet normative limits in term of frequency in a determined amount of time, will be disconnected automatically e.g. IEEE/NERC 2018. That in turn means economic losses and complicated condition for service black start. Matter of stability in distribution systems is more complicated and yet this can be a crucial task in islanded grids. Although strong studies have been ongoing in recent years for forming appropriate methods [2], still there is a need for further exploration regarding frequency stability in new paradigm of electricity system.

The frequency dynamics, transient behaviour and small signal stability must be analysed in dynamic domain, and this requires relevant modelling. In this section, the developments have been oriented on simulations.

2.3.1 Power system inertia

The ability of power system to oppose instantaneous variations comes from moment of the inertia of generators and turbines and therefore the rotational masses, predominantly [3].

The inertia constant H definition comes from stored kinetic energy in the rotational mass. The unit of inertia constant is MWs/MVA and therefore is a time parameter with second unit.

$$H = \frac{E_k}{S_n}$$

With S_n representing the nominal power of the generator and $E_k$as the total kinetic energy stored in the rotational mass, where:

$$E_k = J\frac{\omega_n^2}{2}$$

Where *J* represents the total moment of inertia from the turbine (or blades) plus the generator in [kg.m^2], and ω_n is the angular speed of generator. The moment of inertia *J* is in fact given by the weight and the dimension of the flywheel (equivalent rotating mass):

$$J = Mr^2$$

With *M* explicitly points to the weight and *r* stands for radius, represents the dimension. In other words, the total inertia of a single generator group (including turbine and/or blades) is shown as:

$$H = J\frac{\omega_n^2}{2 \times S_n}$$

In which J and S_n are the dimensional variables and for a certain network with fixed frequency thus ω_n. Physical meaning of *H* is the time that the kinetic energy can be delivered to the system without primary source.

Neglecting other minor contributions from energetic elements in power system such as complex capacitive and inductive elements of the distributed power lines, and other rotational components such as functioning electromotors, the total mechanical inertia of an interconnected power system with *N* generators is approximated as [3]:

$$H_{tot} = \frac{\sum_{i=1}^{N} S_{n_i} \times H_i}{\sum_{i=1}^{N} S_{n_i}}$$

Based on this constant, the dynamic of frequency can be approximated as:

$$\frac{df}{dt} = \frac{f_n^2 \times (P_m - P_i)}{2f \times H_{tot} \times \sum_{i=1}^{N} S_{n_i}}$$

With f as frequency, f_n as nominal frequency, P_m and P_i mechanical power applied to the turbine shaft and electricity power at generator terminals, respectively.

Intuitively, the sensitivity of frequency to the load change, i.e. temporary unbalance between P_m and P_i given the faster changes in P_i, is inversely proportional to the total inertia of the interconnected system and systems with lower inertia become more sensitive to load balance.

2.3.2 Inertia of distribution systems

Most of the rotational inertia, comes from rotational generators among which thermal generators are dominant, at the time being. Given the trend of growth in power generation from green resources, the amount of static converter interfaced generators is gaining momentum. It is expected this trend [4] continuous as it is strongly fuelled with international and European targets [5]. In such paradigm, there must be a reliable transient stability roadmap. Therefore, there have been many studies over the **control** strategies and **dimensioning** of the inverters itself to accommodate natural disturbances with declining rotational masses.

2.3.2.1 Inertial Calculation

The first step to analyse virtual inertia control and provision, is to obtain constant of the inertia as described in the previous section. Calculation of inertia in power system might be a cumbersome task given that it is not possible to obtain the model of whole contributing power generators and beside that, this value is constantly changing. State-of-the-Art studies suggest main approaches for inertia estimation as data-driven methods [6]:

Estimation based on data: Rate of Change of Frequency (RoCoF) calculation, system identification, numerical approaches such as machine learning would also correlate the rate of changes in frequency with the certain amount of load. Methods such as estimation based on centre of inertia after events similarly is data-driven method.

These methods need online measurement and/or measurement campaigns. In [6] there is an interesting work to approximate the inertia constant based on rating power and voltage of the system, the method that current work is stablished on which.

2.3.3 Dimensioning

The DC-link capacitor dimensioning for inverters essentially deals with voltage ripple that in turn is given by the current (power) need of the downstream application, for Voltage Source Inverters (VSIs) [7]. However, to give additional support to the electricity system inertia, the sizing —subject to cost optimization as well— needs to be oversized. Oversizing depends strictly on the study case and cannot be extended as a global value, as [8] shows for the subject use-case the 9% oversizing would be needed, while the study in [9] shows a need for adding much more (supercapacitors) to the DC-link for managing frequency drops.

Instantaneous energy in DC-link is given by:

$$E_{\mathrm{DC-LINK}} = C \times V_{\mathrm{DC-LINK}} \times \frac{dV_{\mathrm{DC-LINK}}}{dt}$$

This value corresponds to the power from primary source P_p minus delivered instantaneous power in inverter's terminal P_t:

$$E_{\mathrm{DC-LINK}} = P_p - P_t$$

A naïve assumption for the current calculation can be such as the whole energy in DC-link would be delivered as the inertia support. If whole inertia was expected from DC-link, the C would satisfy constant inertia formula, thus:

$$H_{\mathrm{DC-LINK}} = \frac{C \times V_{\mathrm{DC-LINK}}^2}{2 \times S_{\mathrm{n}}}$$

By using the integral of power and this yield:

$$C = \frac{J\, \omega_n^2}{V_{\mathrm{DC-LINK}}^2}$$

In fact, it is needed to examinate the needed additional constant inertia by observing extreme cases of violation:

- How many times the frequency limit is violated per year,
- How much energy injection would reduce the recovery time?

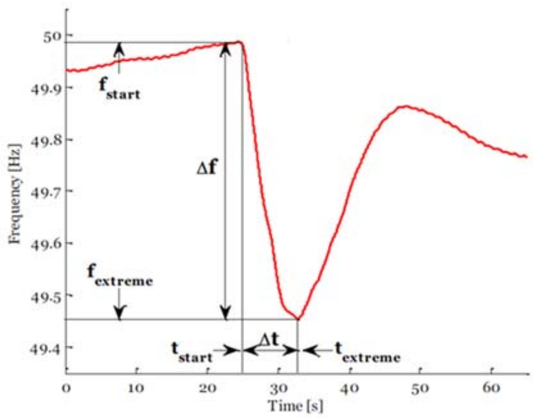

Figure 12. Example of frequency drop extremes.

The example brought from [10] represents the mentioned extremes. Given the changing state of the network, and the cost of additional capacitor, relevant grid code for the network and cost of frequency violation (e.g. energy supply interrupt and system restart) the capacitor can be optimally calculated.

2.3.4 Control

The control of virtual inertia is a critical task in low inertia distribution systems, especially in islanded grids. Frequency oscillation and centre of inertia displacement can cause serious consequences:

- Loss of synchronism
- Power swing between generators thus loss of energy and possible damage to generators and loads
- Growing oscillation and instability
- And more…

Fastest response to the disturbances is related to the passive response of the generators which is directly tied with the inertia and rotational mass of machines. First control loops to be activated are related to the machines and are Automatic Voltage regulator and Power System Stabilizer [11].

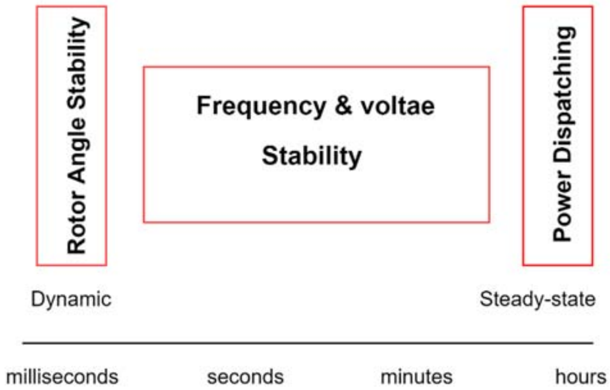

Figure 13. Control paradigm for stability problem.

Synchronous generators are controlled in sequence of passive, secondary and tertiary response and there are many schemes for control logics for field excitation and mechanical torque applied to the turbine shaft. The subject of small signal stability i.e. rotor angle and frequency, concerns the fast control loop. The fastest control acts on field excitation and thus field voltage via power electronics and their PWM control. Yet, this control can be a combined feedback control of:

- Automatic Voltage Regulator (AVR): feedback of generator's terminal voltage will activate AVR controller and then PWM is set for power electronics modulation.
- Power System Stabilizer (PSS): Frequency (rotor angle) measurement by governor and PSS controller set the PWM for power electronics modulation.

These are combined controller and therefore an optimization can find the best compromise for keeping the system stable.

In practice, the controllers of generators are tuned optimally, and the coefficient of control parameters couldn't be changed but by manufacturer.

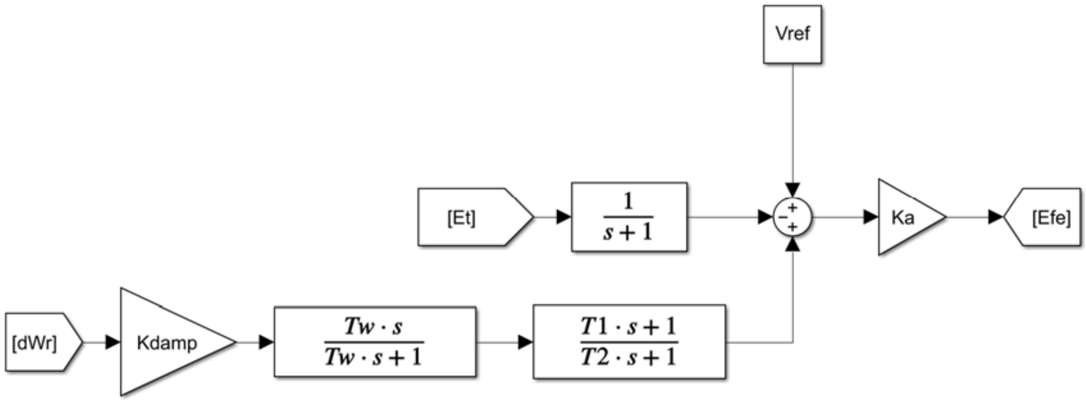

Figure 14. Kundur's PSS and AVR controllers.

Although this method is mature and there are many schemes for control already tested and functioning, the challenge comes from the new paradigm of low rotational inertia systems, with multiple rotating machines. In context of FLEXIGRID, Italian demo site intends to study and develop control methods for frequency stability in islanding mode operation. The Italian pilot site is characterized by several synchronous generator machines that normally are not controlled centrally. As such, the risk of instability in islanded mode is high in case of load balance changes.

The proposed method in current study case, was to focus on usage and application of innovative methods based on Artificial Intelligence to cope with the matter.

2.3.4.1 Frequency and Voltage Stability

The frequency and voltage stability as brought in Figure 13, is considered by steady-state modelling. However, dynamic aspects for control are considered implicitly.

The experimental control method is to use Reinforcement Learning (RL) method for job of coordinating various generators. This scheme separate optimization and decision making into different phases of learning and inference. Therefore, the immediate advantage is that the speed of real-time calculation becomes faster, while in traditional paradigm, optimizer needs several iterations and solving to converge towards optimal solution. Implementation scheme is depicted in Figure 15. The agent starts to explore and then exploits how to vary its freedom degree of the control the best.

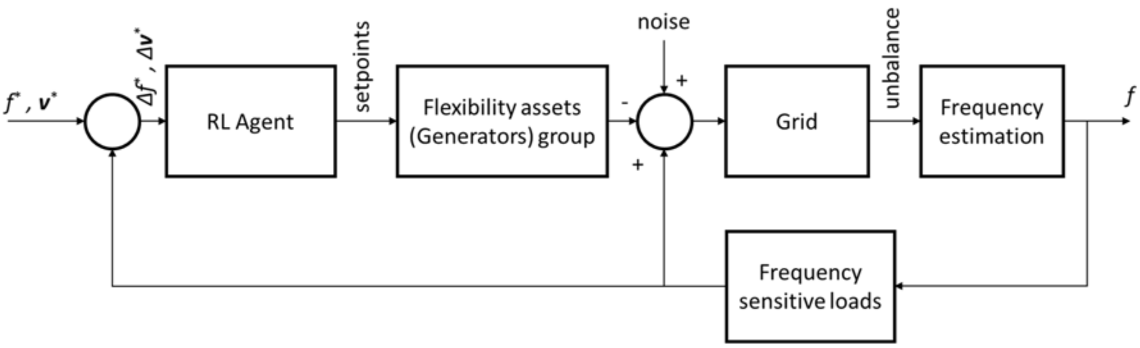

Figure 15. Logical scheme for RL Agent control.

Given the discrete search (action) space, the DQN approach is accommodated. The crucial phase of this work is to how to implement the reward function. The reward function is set as part of the so-called environment.

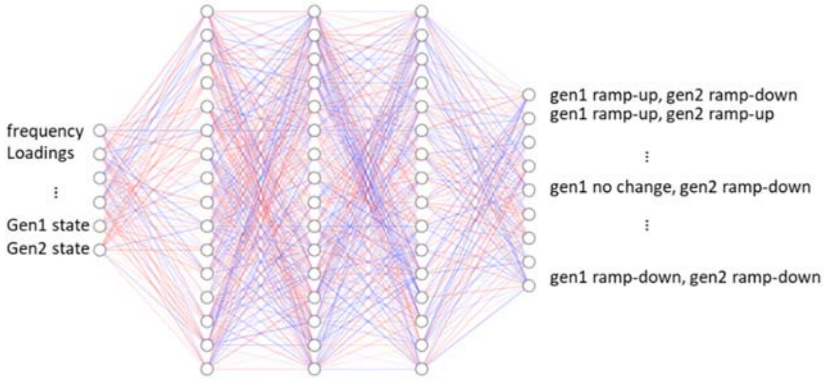

Figure 16. Control by AI graphic representation.

Environment handles the sessions of simulation by calling reset function:

1. **environment.reset**: the scale factor for all non-controllable loads and generators (and state of switch) is set by random values. These values are set between meaningful range. A power flow calculation is run.
2. **environment.get_observation**: state variables of interest are calculated:
   a. P_I total unbalance of the islanded system is calculated. The trick is that actually in simulation, a node is selected as slack, and the unbalance at that node, becomes an indicator of islanded grid unbalance.
   b. V_{std} Voltage deviation among all nodes.
   c. P_{loss} Total line and transformers losses,
   d. L_L Maximum loading of lines,
   e. L_T Maximum loading of transformers,
   f. I_C center of inertia to evaluate frequency stability in an implicit way
   g. P_{osc} Powe swing between generators. To evaluate the latter ones, it memorizes the power values for calculation of last step
3. **environment.step**: to prune control variables according to the physical limits of generators (flexible assets), and apply them, then calculate again observation with above mentioned function,
4. **environment.reward**: to calculate the reward, the most important function for steering RL agent, based on which goodness of action is evaluated. There has been in fact major focus on developments in that part, and final version includes the following items:

$$r = -\alpha_1 \frac{d^2|P_i|}{dt^2} - \alpha_2 \frac{d|P_i|}{dt} - \alpha_3 P_i - \alpha_4 P_{\text{osc}} - \alpha_5 \Psi_{\text{th}} + \alpha_6 f_c^*$$

With;

$$\mathrm{P_{osc}} = 1 \text{ if } \mathrm{L}_L \; or \; \mathrm{L}_T > \text{thermal limits}, 0 \text{ otherwise}$$

and

$$\Psi_{\text{th}} = 1 \text{ if } \mathrm{V_{max}} \leq \mathrm{V} \leq \mathrm{V_{min}} \lor f_{\max} \leq f \leq f_{\min} \land \mathrm{Tv} \geq \mathrm{T}^* , 0 \text{ otherwise}$$

Where Tv and T^* are time of limits violation and maximum tolerance time respectively, defined by the grid code, as well as limits for voltage and frequency.
And when a control action brings the frequency close to reference value, with a tolerance of ε.

$$f_c^* = 1 \text{ if } f*(1-\varepsilon) \leq f \leq f*(1+\varepsilon)\text{ , 0 otherwise}$$

Coefficient α_j for j={1, ...,n} is tuned based on various trials and can be different for another use-case. In this study they are set to {5, 5, 1, 1, 100, 50}.

Any specific objective such as Optimal Power Flow (OPF) could be plugged into the agent decision making by adding a relevant item. In case of OPF, cost of generator usage might be added to the reward, with negative sign:

$$r = r - \sum_{j \in N_G} \beta_j P_{\mathrm{j}} + \gamma_j Q_j$$

The weighted item $\frac{d^2|P_i|}{dt^2}$ penalizes fast changes in power of generators, to avoid overshoots and oscillations. This item gains more dominancy when the second term and third items become lower, i.e., when actually there is the risk of overshoot and thus oscillation. Second item $\frac{d|P_i|}{dt}$ actually measures if the direction of power change in generators is correct or not. P_i directly says the unbalance amplitude. Once the model is tuned efficiently, these items would perfectly balance themselves in a recovery scenario; starting with a severe event, 3rd item is heavier probably, in control phase, second item gains dominance and in last moments of transient, first item becomes more dominant.

Agent; the core AI responsible for decision making and learning.

The agent is responsible to choose action base on greedy strategy. The greedy strategy in short handles a balance between decision making based on exploiting its experiences or explore the search space. If the choice is based on exploitation, it follows the term:

$$a_{\mathrm{k}} = \max_a(Q\ (s_{\mathrm{k}}, a))$$

Q is the q-function and nothing but neural network instance.

This action is applied to the network and the observation of the environment are received again. Agent estimates the target (best action) from a neural network that is the cloned network to the prediction network and gets updated every T_U (a hyperparameter of the problem) steps. Agent gets the target reward by:

$$R_{\mathrm{T}} = R(s_k, a_k) + \gamma \max_a(Q\ (s_{\mathrm{k+1}}, a))$$

This occurs for a batch *B* in practice. The learning process is applied to certain batch size at each learning event. This batch size is retrieved randomly from a memory replay.

Then the loss gets calculated over the batch:

$$L_{\mathrm{B}} = \frac{1}{2}\sum_B \left[R(s_{k_B}, a_{k_B}) + \gamma \max_a(Q\ (s_{k_{B+1}}, a_{k_B}))\right]^2$$

This error then is backpropagated through neural network.

As a result, the agent successfully learns the actions to get more rewards, which in this is stability of the network by optimal power flow. The Figure 17 shows the beginning of the learning process, which agent takes random actions with no knowledge.

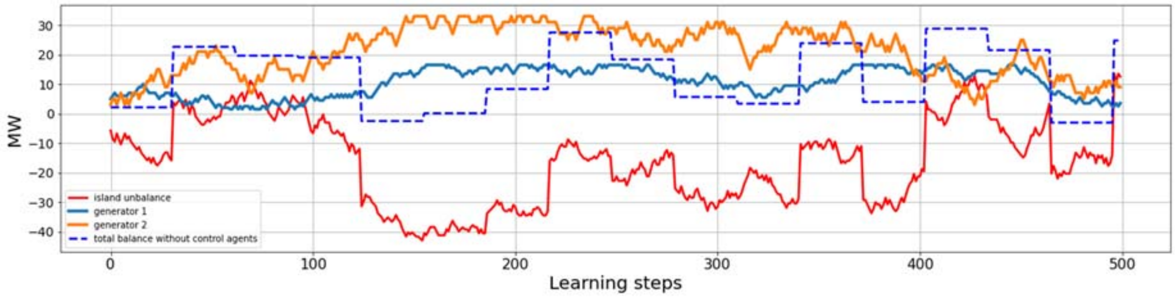

Figure 17. Example of the online learning process, in the first epochs (beginning).

Then after 1000 epochs, the agent starts to learn from experience. Agent is able to send right setpoints to the generators in order to follow the load changes.

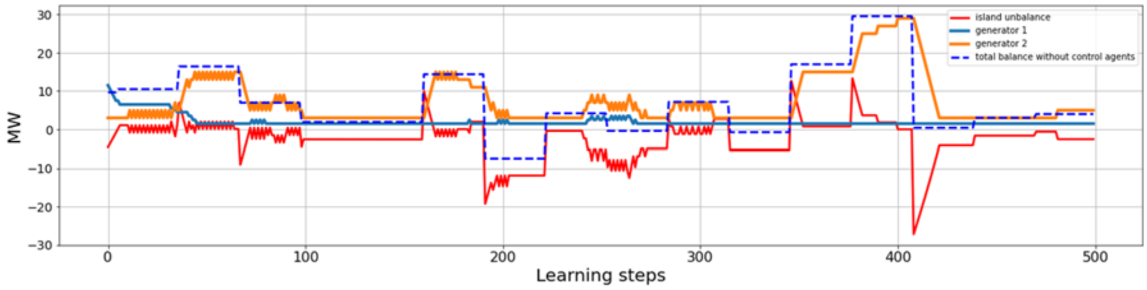

Figure 18. Learning process after 1000 epochs.

Agent continues to learn and after 2000 epochs, it confidently follows the network dynamics.

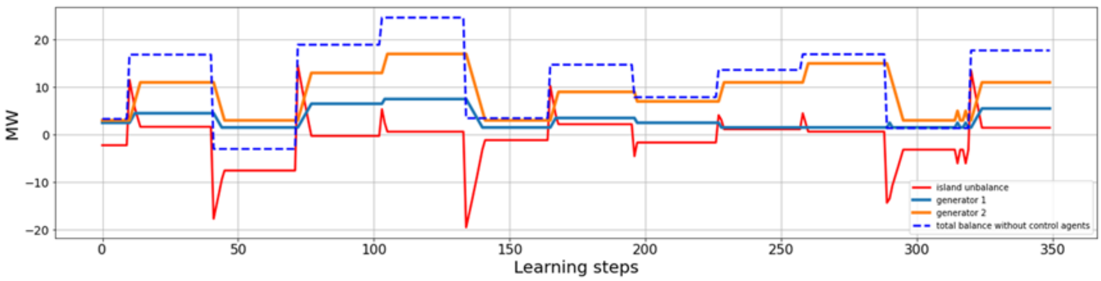

Figure 19. Learning after 2000 epochs.

Dispatching of the total power between the generators is depicted in Figure 20 as sum of the power generated from all groups. The generators as mentioned have the maximum and minimum of power generation, therefore in some extreme cases cannot zero the unbalance of the grid.

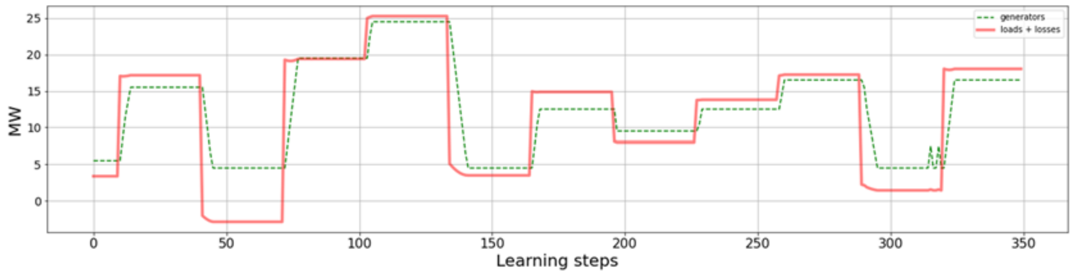

Figure 20. actions after 2000 epochs.

Pseudocode of learning

For this study, for sake of the physical system (environment) model, the complete MV model of the Italian demo has been used, thanks to the developments in T4.6 as can be seen in Figure 21. Italian MV pilot network. The software developed in Task 4.6, already converts the model of the network retrieved from SCADA to a model usable for power flow solver. The steady-state solver i.e. power flow solver being used in the development is open-source python library Pandapower[1].

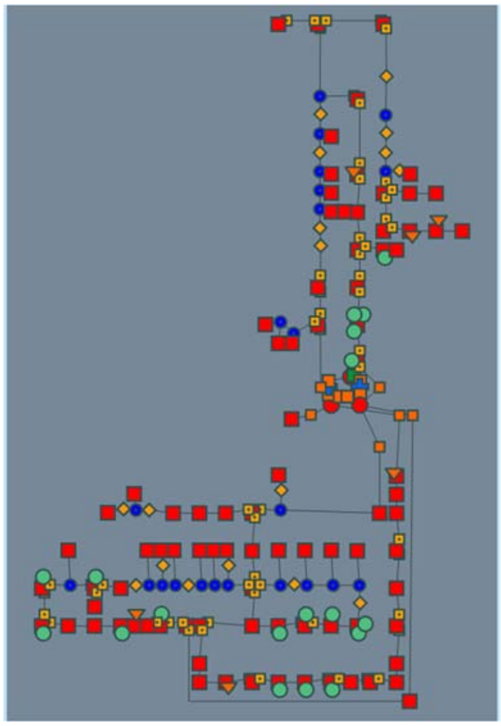

Figure 21. Italian MV pilot network.

To summarize, the steps after initialization, at each time step can be presented as followings:

1. environment is reset. This means all loads and generators are given new (random) values.

[1] http://www.pandapower.org/

2. Q-values are predicted
3. Action is selected
4. Reward is calculated and reach to next state
5. The transition $T_K(s_K, a_K, R_K, s_{K+1})$ is stored in replay memory
6. A random batch *B* of memory is selected
    a. For all transitions of the batch a prediction and a target is calculated by the twin networks
    b. Loss calculated
    c. Back propagation is applied

The DQN implemented agent, might be a good exercise with many use cases. In essence application of reinforcement learning control is corresponding to optimal control in classic paradigm, with the difference that machine learning approach decouples decision-making process to a long time for training but very quick inference whereas the classic optimization calculation needs shorter time for finding the best solution however the process gets repeated for each calculation thus the decision making becomes slower and less efficient. This cannot be tolerated for distribution system with low inertia and high number of active elements. An example of RL application in frequency and voltage regulation is to distribute the load between different flexibility assets.

2.3.4.2 Small signal stability (rotor)

In a low inertia system, the major critical issues can be classified as rotor angle stability. This means the risk of loss of synchronism, instability and growing oscillation and inertia continuous displacement between rotational machines. Such issues might be addressed by analysis in small signal stability domain.

This required analysis and implementation in an electrodynamic simulation environment. The simulation and modelling have been implemented in OpenModelica, using OpenIPSL package. A simplified network is modelled representing Italian main elements. Simplified because of the nature of dynamic calculation, each additional element brings major complexity into state-space matrix and makes the calculation heavier, for a little additional precision. Load insertion simulation has been applied after 10 seconds of simulation, in order to let the model gets to its stability. The unstable behaviour comes from the initial values of power flow calculation, coming from Pandapower. It is natural that these don't match since the model in Pandapower is automatically generated and includes more details.

Simulation structure can be seen in Figure 22.

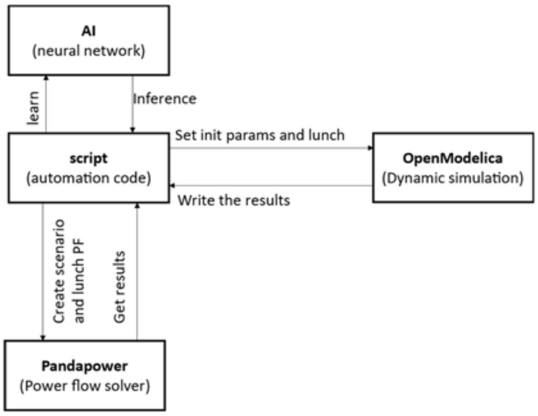

Figure 22. Automated dynamic simulation.

As mentioned, the first 10 seconds are being considered only for stabilization of the system, then random load change in random bus is applied, as can be seen in Figure 22.

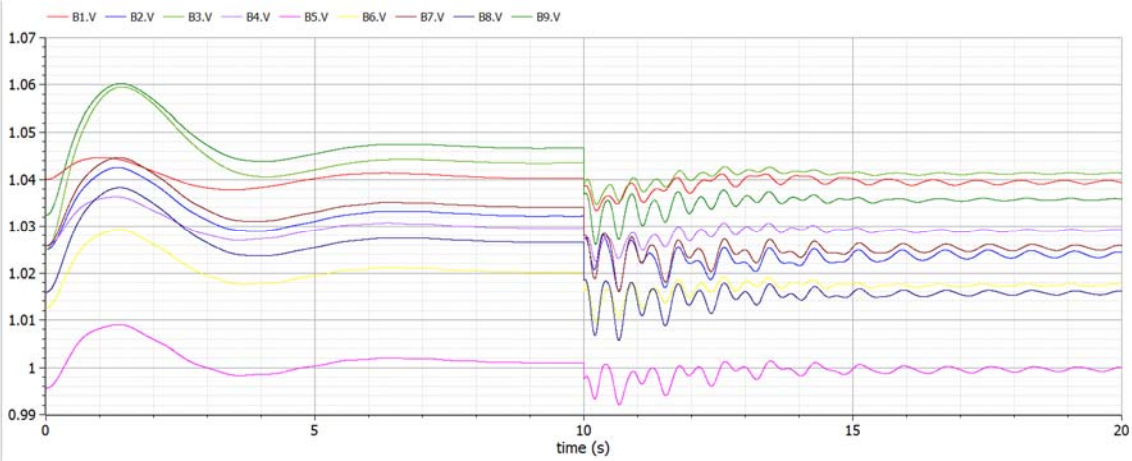

Figure 23. Voltage variation in a subset of buses.

For a load change, both generators react by passive control and thanks to AVR and PSS, they stabilize the oscillation. The transient behaviour of generators are shown in Figure 24.

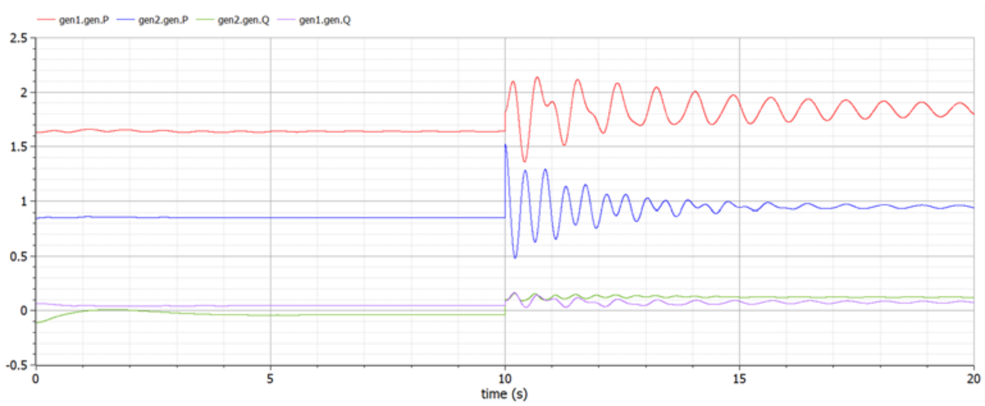

Figure 24. Generators dynamics for load change.

The control is designed to be made by distributed inverter-interfaced RES. The objective is to implement the logic based on which inverters react as inertia providers to reduce the minimum frequency and rate of change after variations, and then act as damping for securing the non-coordinated generators don't enter in oscillation.

Therefore, individual inverters act upon the voltage variation on their connected buses. The voltage variation as state-variable is reasonable since the distribution grid is mainly linear as this can be seen in Figure 25.

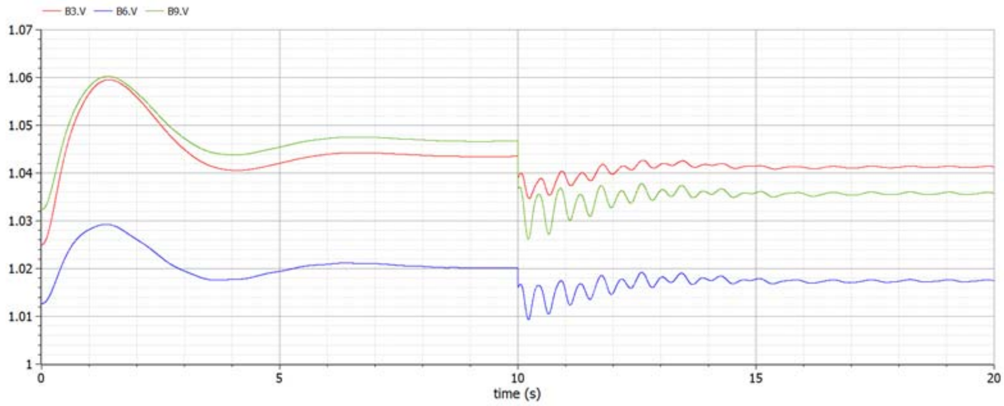

Figure 25. Voltage variation upon load change.

The RL model adopted for this use-case is a policy-based method. In this implementation, solving of each problem iteration needs a huge computation power with respect to the steady-state case (around 30 seconds of solving in dynamic versus 0.02 of steady-state with a personal computer). Therefore, the online learning is changed to offline learning in this case. The simulations are generated first in OpenModelica and the learning process takes into account stored transitions, similar to DQN case.

The control and learning scheme is reported in Figure 26.

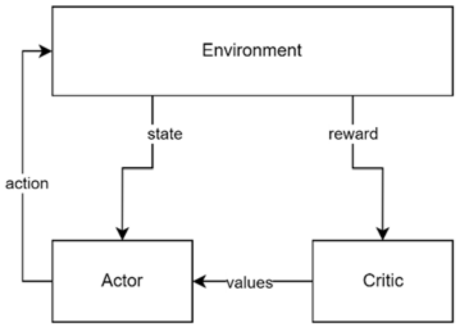

Figure 26. Continuous space RL model.

3 T4.2. Software upgrade for demand / generation forecasting

The modules developed within this task can be categorised as per below:

1. Demand/Generation forecasting for the Greek pilot

In the context of the developments deployed in the Greek pilot, forecasting is an essential component for the optimal operation of renewable resources. It mainly includes prediction for two different variables:

a. Generation of Renewable Energy Sources (RES) with a specific focus on the solar PV technology and
b. Electricity demand of the non-controllable loads.

These modules are analysed separately in sections 3.1 and 3.2.

2. Demand forecast for the Croatian pilot

Croatian pilot develops grid optimization tools for the day ahead operation. The renewable generation share is not particularly high and therefore the required prediction subject is the aggregated load (which includes in turn distributed generation).

This module is analysed in section 3.3.

3.1 Generation forecasting for the Greek pilot (VERD, LINKS)

3.1.1 Implementation approach

The implemented approach exploits two different neural network architectures to enable two features that can be combined to predict renewable generation and load consumption. The first component uses a Multilayer Neural Network (with no feedback) to address long-term solar power forecasting, while the second one exploits the potentiality of Recurrent Neural Network (RNN) and Convolutional Neural Network (CNN) to tackle short-term forecasting.

The first component is always active, while the second one is triggered as a corrective measure whenever the difference between the long-term prediction and the current irradiation is greater than a pre-defined threshold. This enables the field devices to take appropriate countermeasures against the uncertainty coming from weather forecasting.

<u>Long-Term Neural Network Design</u>

A Baseline Neural Network generates the long-term forecasting which characterizes the first baseline for the approach. It is used in the system to infer a single float value for sun irradiation for every hour in the 48-h, based on weather prediction provided by OpenWeatherMap [1] in real-time. The third-party data are wide but some are relevant to the forecast such as Temperature (C), Pressure (hPa), Humidity (%), UV index (UV), Clouds (%).

The baseline layer of the network is the core part of the architecture and it is composed of a regular densely connected neural network layer with a specific hidden size and activation function, a layer for batch normalization and a dropout one.

The optimal architecture of the ANN was defined following a number of extensive tests detailed in D4.2.

To conclude, the best performing architecture used to implement this component comprises 5 layers, with a hidden size of 512, a dropout rate of 0.3, and a batch size in the training of 64.

<u>Short-Term Neural Network Design</u>

The second core component of the architecture is short-term forecasting. The candidate architectures chosen to implement this feature are:

- Long Short-Term Memory (LSTM): a key recurrent neural network architecture that outperformed vanilla RNNs by solving the vanishing gradient problems by the usage of additive components and forget gate activations;
- Gated Recurrent Unit (GRU): a type of recurrent neural network similar to an LSTM. The main difference is that it has only two gates (reset gate and update gate) and no output gate. Generally, it is easier and faster to train than the LSTM architecture.
- WaveNet: it is a type of convolutional neural network developed in the context of the homonymous audio generative model. The architecture is based on dilated casual convolutions, which unveil a very large receptive field suitable to deal with long-range temporal dependencies.

As per the Long-Term Neural Network Design, the optimal architecture was defined as described in D4.2.

3.1.2 Final architecture and information exchange

For the final architecture, the hyperparameter tuning was set on the following factors:

- LSTM and GRU
  - Layer Hidden Size - hidden_size Є {64, 128, 256}
  - Number of Layers - n Є {5, 10, 15}
  - Dropout Rate – d_r Є {0.1, 0.3}
- WaveNet
  - Layer Hidden Size – hidden_size Є {64, 128, 256}
  - Dropout Rate– d_r Є {0.1, 0.3}

The number of hidden layers in the WaveNet architecture was not the object of the grid search because the dilation rate set of the convolutions was fixed to {1, 2, 4, 8, 16, 32}.

27The information exchange process consists of the elements presented in Table 5 and depicted in Figure 28.

Table 5 Information exchange for the solar and demand forecasting process

#	Input/Output	From	To
1	Substation load	Energy Box (through FUSE)	Demand forecasting module
2	Weather data	Open Weather map	Demand and Generation forecasting modules
3	Generation and consumption data	Energy Box (through FUSE)	Demand and Generation forecasting modules
4	PV generation	Energy Box (through FUSE)	Generation forecasting module
5	Technical inputs (technical characteristics and constraints of the assets, energy tariffs, etc.)	Static inputs (IOSA)	Optimisation and congestion management module
6	Demand forecast	Demand forecasting module	Optimisation and congestion management module
7	Generation forecast	Generation forecasting module	Optimisation and congestion management module
8	Optimum set-points for flexibility assets	Optimisation and congestion management module	Energy Box (through FUSE)

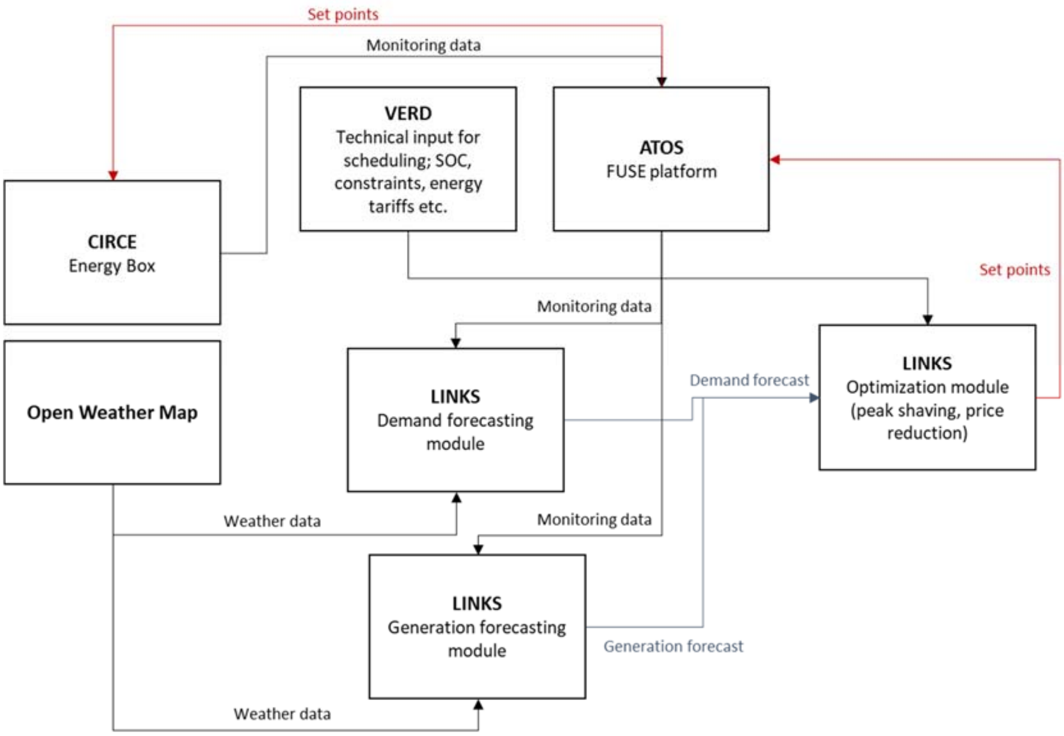

Figure 28 Information exchange

3.1.3 Testing of technologies

In a first stage of training and development the model has been evaluated from data retrieved from the field. Performance metrics used for this valuation are Mean Absolute error (MAE), and the application of this metric is applied after normalization (z-score normalization) of data, both observed and predicted. The evaluations are made on test set that hasn't been seen by the model. Figure 29 depicts two sequences of forecast (predictions) and its evaluation versus actual data (labels). Note that night time is dropped from all datasets to optimize learning process. In Figure 4, the line inputs denote the long-term forecast that the short term forecaster seeks to improve.

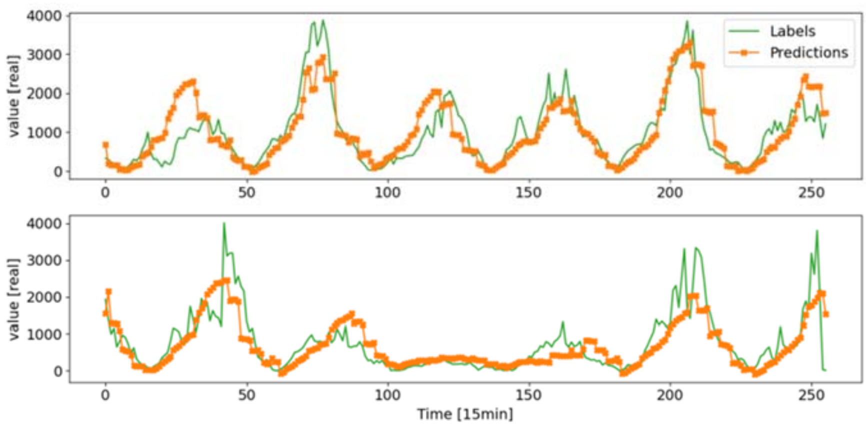

Figure 29. Long-term forecast for solar power.

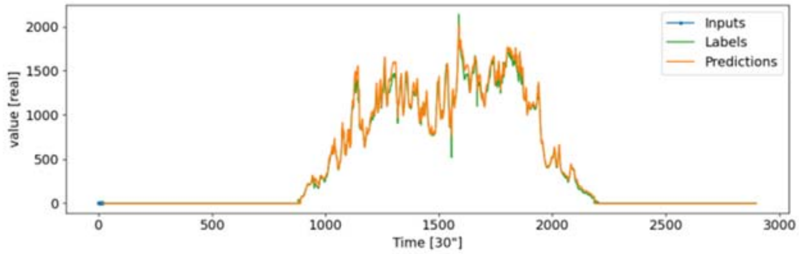

Figure 30. Short term (corrective) forecast of the solar power.

3.2 Demand forecasting for the Greek pilot (VERD, LINKS)

3.2.1 Implemented approach

Real energy consumption data was used in the present work to develop, train, and validate the proposed holistic forecasting and control methodology. The data come from VERD's commercial customer, which is a summer resort connected to the Medium Voltage (MV).

Main factors impacting on load (e.g., number of booked clients) are not available to the forecast model development, and therefore a direct correlation is obtained from the recent evolution. Therefore, a recurrent model may fit this problem efficiently. Data properties of interest are identified as power, energy, and ambient temperature in different windows.

The final architecture of the module is defined in section 3.1.2 as per the previously analysed generation forecasting module and more details are provided in D4.2.

3.2.2 Testing of technologies

Models have been tested and validated during development, in offline way. The results of the forecast are brought in the Figure 31 and Figure 32 to provide a visual impression, since standard error calculation for a custom dataset (non-state of the art exercise) would not provide enough information.

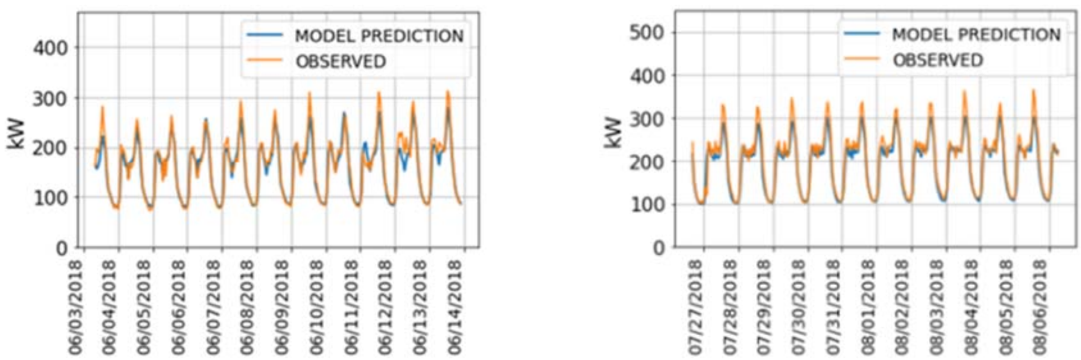

Figure 31. Load forecast for high-season of business activities

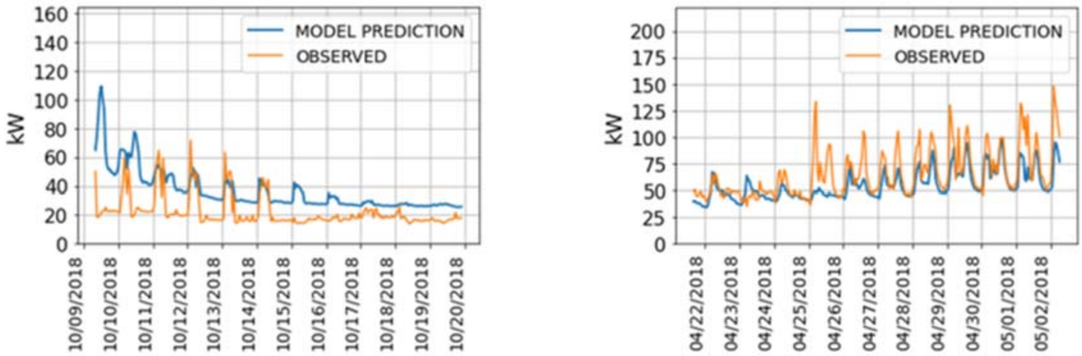

Figure 32. Load forecast for transition period, from and to high season.

3.3 Demand forecast for the Croatian pilot (LINKS)

Demand forecast in Croatian demo has been based on substations' historical data and context data for corresponding time. Classic pre-processing for removing outliers and data correction has been carried out.

3.3.1 Operation and functionalities

In this section the development rationale and steps taken to achieve a reasonable forecast are provided.

3.3.1.1 Conceptual approach

Once the data (two substations' active and reactive power) is cleaned and processed, partial correlation with external temperature reveals as can be perceived in Figure 33.

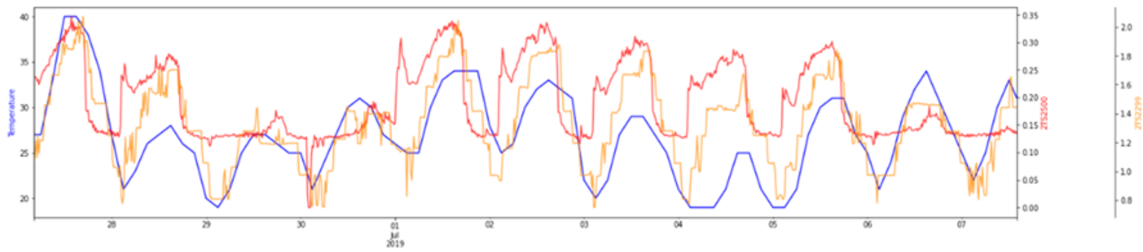

Figure 33. Initial analysis and correlation with context data.

Other particular aspect, is the seasonality of data and weakly frequency components that can be observed via visual inspection. To integrate that information, time is presented as the cosine of days and hours, as depicted in the Figure 34.

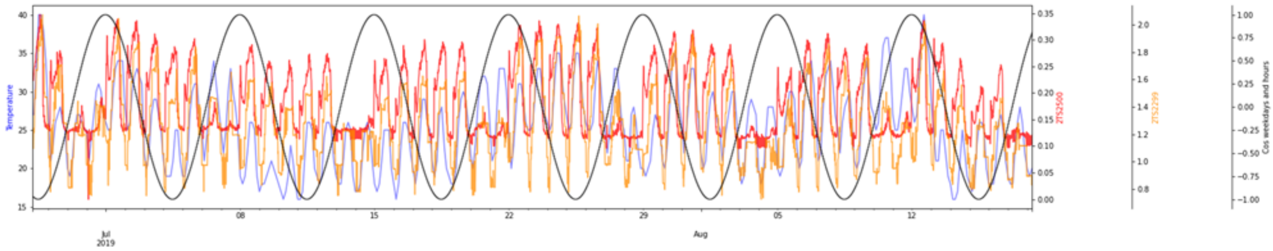

Figure 34. Periodicity of demand pattern and correlation with external temperature.

3.3.2 Modelling and testing premises

The neural network used to develop this module, is a light model with one recurrent layer composed of 64 GRU (memory cells) and recurrent dropout of 0.2, together with a final layer with size of forecast indices, namely active and reactive power for substations.

3.3.2.1 Description of the demo

The demo site includes a distribution network defined in UC5. A demand forecast module is used to predict consumption of the MV/LV substations in the defined networks. The demo infrastructure of the forecasting algorithms comprised the modelling and testing premises of LINKS (as described above), and an interface between UNIZGFER and HEP-ODS, that will provide the data needed for the forecasting algorithms.

3.3.2.2 Actors and scenarios

In the case of the Croatian demo site, where the developed forecasting algorithm is being used, a model for predicting the substations load has been trained and afterwards implemented for forecasting the real-world data. The forecast follows a rolling horizon fashion with 24-hours length and 15-minute intervals. The resulting demand forecasts are used together with the network data in the modules for the operation of the grid, developed for the network reconfiguration and voltage-led demand response modules, defined in UC5.

The scenarios and actors where this module will be used and their link to the trials that will be performed in the Croatian demo site are presented in Table 6.

Table 6 Actors and scenarios – Croatian demo site

ID	Use Case Name	Trial Name	Primary Actor	Triggering Event	Pre-Condition	Post-Condition
UC05T01	UC5	Optimal topology of MV distribution network	Demand forecasting modules	The forecast and scheduling optimisation modules are used for the detection of extreme, unwanted events that can be resolved by changing of the network's topology Network reconfiguration	Establishment of the necessary data streams. Communication with the HEP-ODS platform that streams the necessary demand data	Battery setpoint applied for the duration of the trial period and the cost reduction benefits are calculated based on the usage of the PV and battery systems

				will be performed periodically upon request form HEP-ODS's side.		
UC05T02	UC5	Voltage led demand response in distribution networks	Demand forecasting module	The forecast and scheduling optimisation modules are used for the detection of extreme, unwanted events that can be resolved by rescheduling the operation of DSO's assets and providing the Q-U regulation Cost reduction estimation will be performed periodically upon request from VERD's side	Establishment of the necessary data streams. Communication with the HEP-ODS platform that streams the necessary demand data	Battery setpoint applied for the duration of the trial period and the network charges are calculated based on the usage of the PV and battery systems and compared to BAU charges

3.3.2.3 Information exchange

All the data necessary for the training of the demand forecasting model is exchanged with HEP-ODS, through the developed platform based on the Restful API protocol.

Connection to the FUSE platform is also established and the data is streamed to the platform.

3.3.3 Testing of technologies

The results of testing are brought in Figure 35 where the active and reactive power observed and predicted values can be inspected visually, both for active and reactive powers.

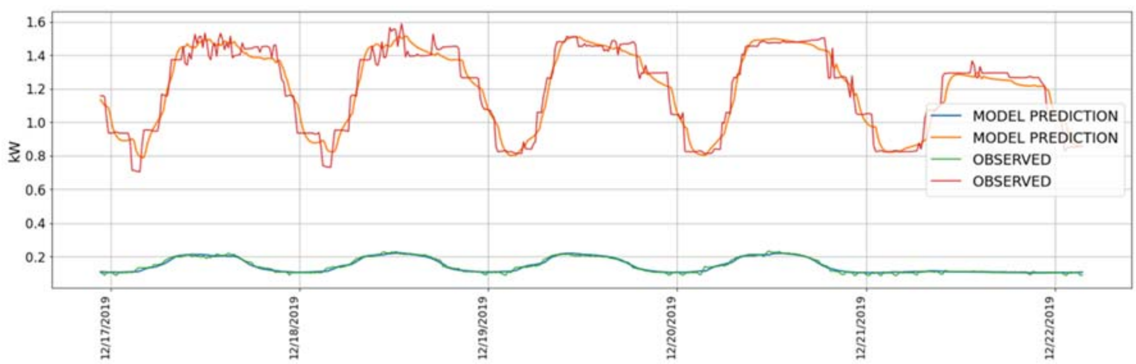

Figure 35. Forecast results for active and reactive power demand.

4 T4.3. Improved control technologies for the smart operation of grid assets

This task contain three main submodules which are shown in Figure 36, each led by a technical developer partner and focusing on:

- Flexible asset control - Spanish demo
- Predictive optimisation - Spanish and Italian demo
- Optimal operation of the distribution network - Croatian demo.

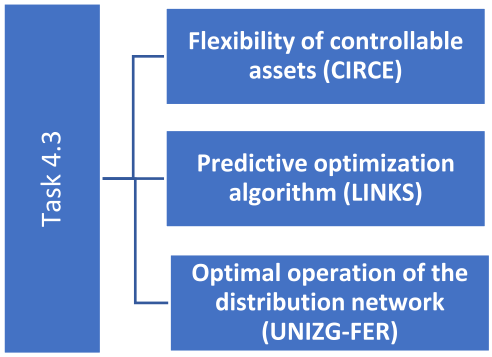

Figure 36. Submodules in the task

4.1 Flexibility of controllable assets (CIRCE)

4.1.1 Operation and features

4.1.1.1 Technical approach

Flexible asset operation is based on the ability to send setpoints in a coordinated manner to different controllable assets in the distribution system to avoid or reduce congestions and to maximise operational efficiency. The operation of the network will be provided by some modules that supervise the grid status and take actions in consequence.

4.1.1.2 Actors and scenarios

Table 7. Submodule actors and scenarios

Name	Type	Description
Contingency Operation	Scenario	This module will use a monitoring tool to know the grid state. Depending on the values of network congestion and voltage problems, different instruction sets will be generated and send to the controllable assets to avoid or minimize the effects.
Optimal Operation Module	Scenario	Setpoints are sent to assets based on an optimal power flow that is generated every 24 hours and adjusted according to predicted demand and generation.

Name	Type	Description
Setpoint Dispatcher	Actor	Is the interface that sends the setpoints to each asset in a coordinated way, at an early stage of the project it only shows suggestions to the network operator.

4.1.1.3 Functional diagram

Figure 37 shows the flowchart of all actors and scenarios.

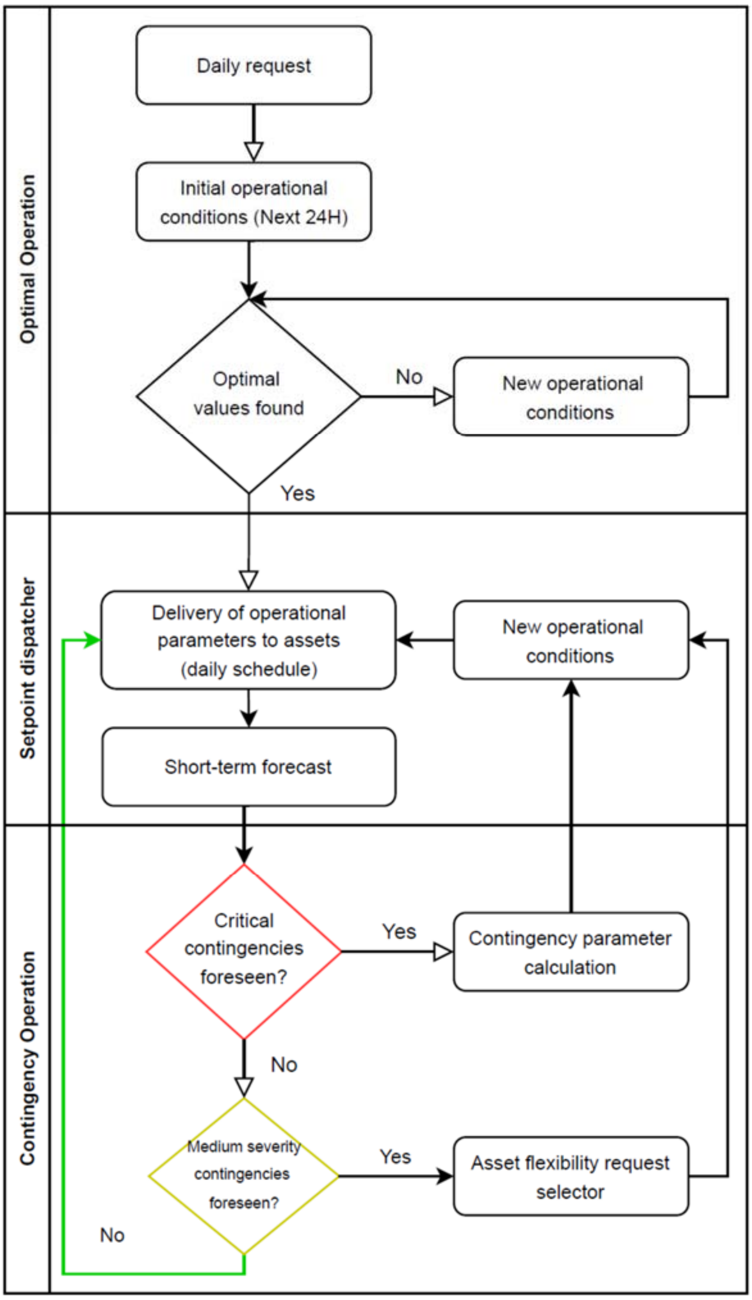

Figure 37. Main flowchart

4.1.2 Modelling and testing considerations

4.1.2.1 Description of the selected demo

The network to be evaluated is that of Villabermudo (see Figure 38), it is a 20 kV circuit, where there will be two areas with controllable elements, in the Villabermudo 1 and 2 transformer stations (EB1 and EB2).

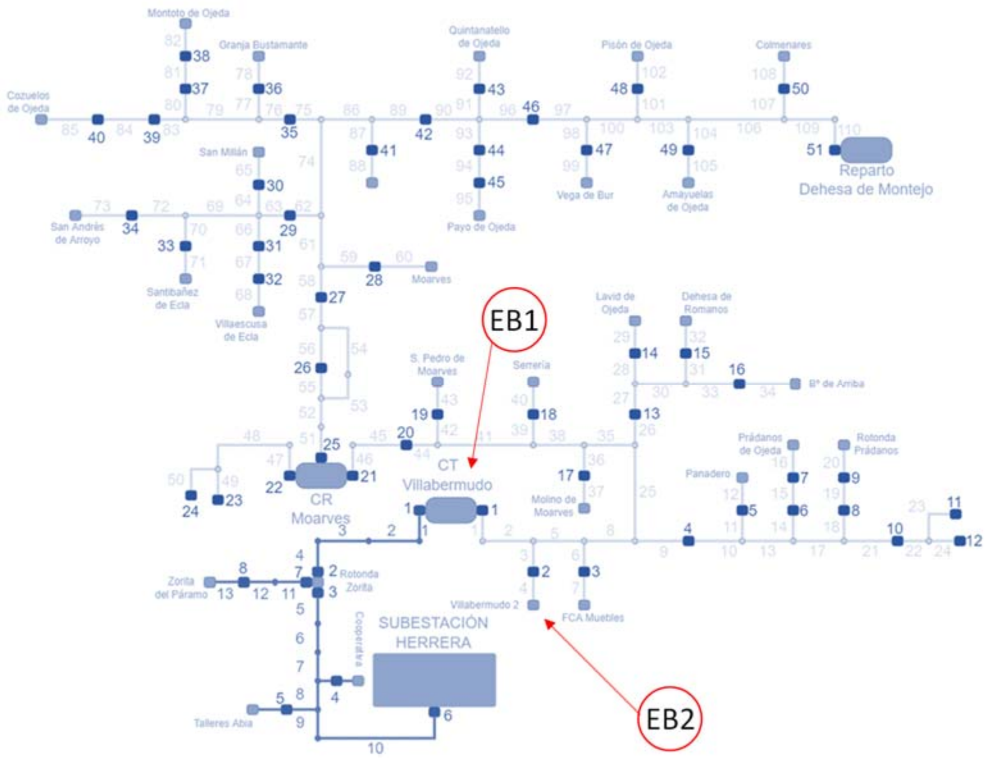

Figure 38. Villabermudo's network and Energybox location

4.1.2.2 Devices installed in the field

Two Energy boxes will be installed in the Villabermudo 1 and 2 transformer substations, in these devices the scripts of the virtual assets will be executed, in this way it will be possible to send setpoints from the flexibility module to virtual devices in the field, such as PV, batteries and an OLTC.

Table 8 shows the virtual assets in each transformer substation.

Table 8. Virtual assets in Villabermudo transformer substation

Substation	Virtual assets
Villabermudo 1	• Battery • PV generation • OLTC • Controllable Load
Villabermudo 2	• Battery • PV generation • Controllable Load
Herrera	• IED

All the virtual assets have been generated by code and will be executed in the Energy boxes.

4.1.2.3 Integration with the FUSE platform

The integration with FUSE is done in two ways. The right side in Figure 39 shows the connections with the field devices, these connections are made with OPC. The Energyboxes generate data from the virtual assets (Batteries, PV generation and OLTC) and DIgSILENT is used to know the state of the grid.

Then, this data is sent to FUSE with "OPC_1". The left side of Figure 39 represents the connections with flexibility modules Optimal Operation and Contingency Operation. The optimal operation uses "OPC_2" to communicate DIgSILENT and the algorithm that calculates the optimal operation point setpoints. These setpoints are sent by "OPC_2" to the flexibility tool (light signal) to determine the status of the network (normal or contingency) and send the setpoints to the controllable assets.

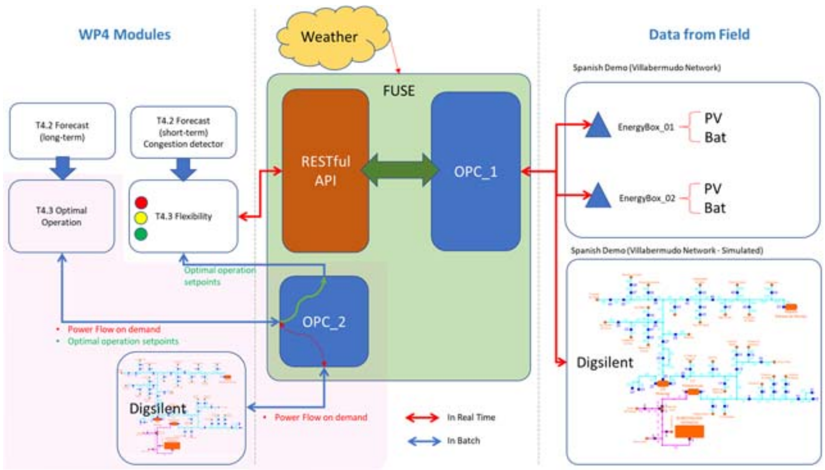

Figure 39. Integration with FUSE

4.2 Predictive optimization algorithm (LINKS)

Actual requirements from grid operators, highlights the necessity of general-solver/optimizer without plain grid modelling. Therefor alternative methods have been analysed to provide problem solving through artificial intelligence methods namely reinforcement learning. Such method can use lowest possible time for solving problem, at the same time prevent constraints' violation with anticipating corrective actions.

4.2.1 Operation and functionalities

4.2.1.1 Conceptual approach

The distribution system in Villabermudo is subject to changes in load and distributed generation. Expected evolution in RES integration would cause excess of local power generation and thus reverse power flow scenarios, which is not desired for the system operator. From other hand, the dynamics of intermittent RES generation can be fast and sharp, as it all depends on the non-controllable natural primary energy. The solar power (irradiation on flat surface) in Villabermudo, in a high generation season can be seen in image Figure 40.

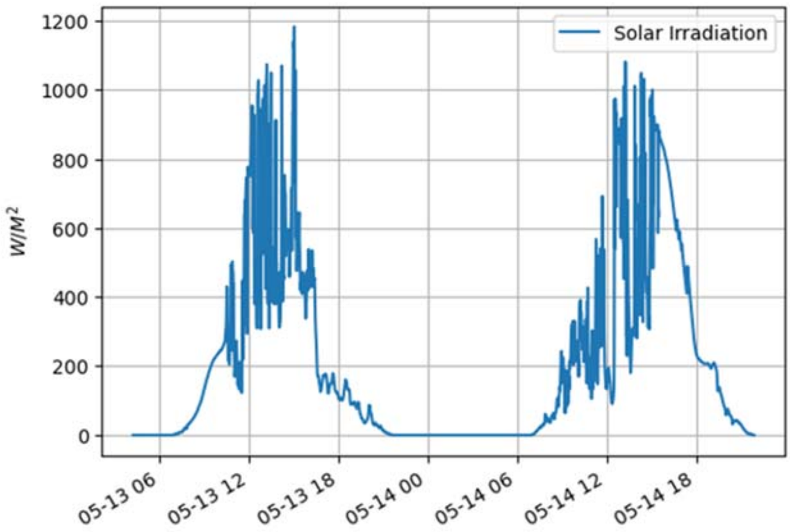

Figure 40. Villabermudo solar capacity and intermittent power generation.

This variation means up to 90% lose of power generation from solar energy in just one minute. Once the increase in photovoltaics is predominant, such situation can easily cause voltage instability and thus breaker trips.

The requirement for handling such condition is to implement the control for flexible assets through a predictive optimization.

The challenges for online control of the assets is:

- Time constraints for corrective decisions. This means, given that errors in forecast and long-term optimization is inevitable, the optimizer must continuously correct and update the instructions.
- Access to the explicit model of the network. Highly restricted security measures, prevent fully integration of software (optimization module) to the SCADA and this means explicit model of the implementation of explicit model of the network. Adding to this, the fact that grid model can be subject to continuous variation e.g. changes in state of the switches, tab-changer etc.

To address these challenges a predictive optimization based on Artificial Intelligence (AI) is implemented, that can learn from experiences.

The module will build a sort of discretized search space, with best predefined steps / actions depending on any state of operation. A simplified example is shown in the following figure, in which starting from any state (St), the decisions (based on a pre-calculated probability distribution) always lead successive states towards system stability.

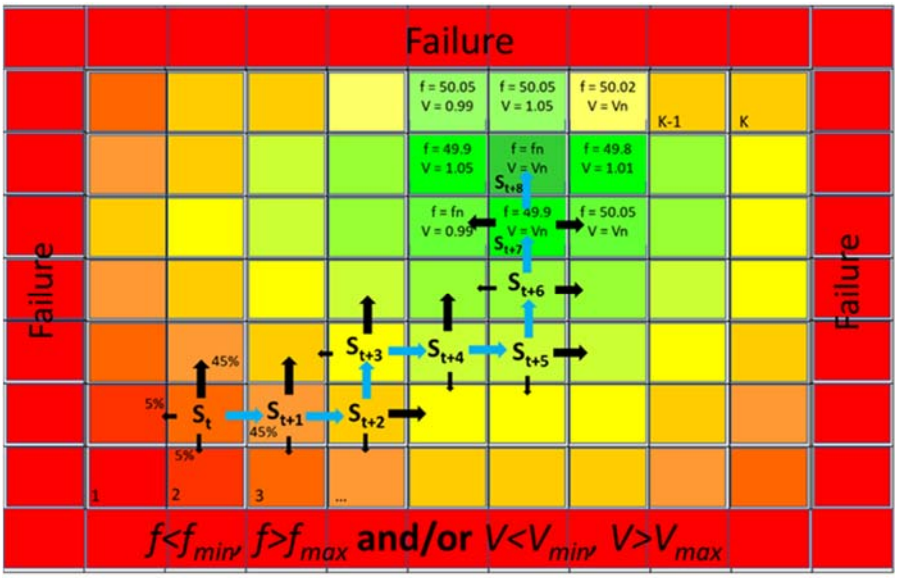

Figure 41. Simplified decision making process by AI.

The decision vector could be of any desired size, normally equal to the degree of freedom of control. In the above case for the sake of clarity and simplicity, the decision vector dimension could be considered with only one element; active power of a generator, which can only be modulated to four actions. In practice, the decision vector can be constituted by active / reactive power for various generators, state of switches, state of variator under load of the various transformers, etc., each on an admissible and feasible range. The table below provides further information for the example shown.

Reinforcement learning methods are perfectly suited to solve this problem topology. Then various mathematical models can be applied to this problem to obtain the distribution table, such as Dynamic Programming or Q-Learning. The latter is a widely used approach for cases with discretized search space, in that context. "Q" stands for "Quality" and in essence this method downstream of numerous iterations of calculation finds the goodness (Quality) of each decision depending on the state in which you are.

The benefit of applying these methods is that the process of calculating and making decisions is decoupled, so off-line calculations can take hours and even days, but once the so-called table is built, making the decision is immediate.

The problem could arise due to the number of decision variables and also a large search space, which also requires a not very limited memory, which again in turn reduces the calculation speed. At this point the method does not guarantee to provide efficient operation.

Deep Q-Learning (Network)

Thanks to neural network application, solving a problem of this nature becomes more efficient. The Deep Q-Learning method which is also referred to as Deep Q-Network (DQN) uses the results of various simulations but also real examples (so-called Experience Replay or Replay Memory) to train the neural network in such a way that providing a sequence of events (states) as an input to the model, can generate decisions (actions) to be performed as the best output. The training process is repeated periodically with new observations to improve the model results.

4.2.2 Modelling and testing premises

For modelling and test, as mentioned before, to comply with security requirements of the system operator, the simulation of the network is being executed by a remote server.

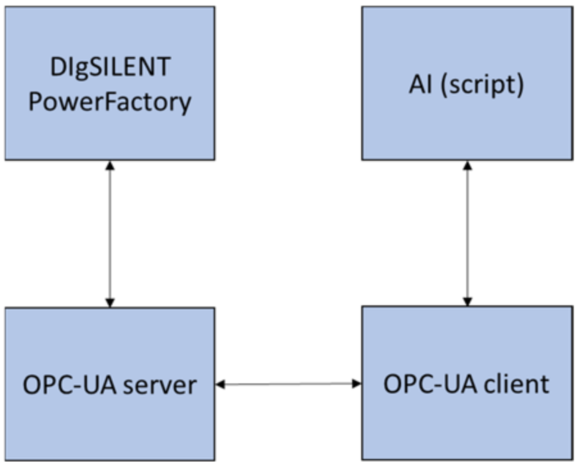

Figure 42. Implementation of control via simulation as service (remote simulation server).

The remote server is a OPC-UA server hosted by CIRCE. The asynchronous OPC server is communicating with the power system simulator DIgSILENT PowerFactory[2] as part of its native communication support. To guarantee the proper simulation a simple semaphore logic has been applied between simulator clients and server.

This solution for simulation and execution allows to develop on-line logic creation without the need for accurate modelling of the network in a decision-making side (e.g. aggregator) and improves security of the subjected system.

Below in Pseudo-code 1 the high-level process of reinforcement learning application is described.

[2] https://www.digsilent.de/en/powerfactory.html

```
initialize_replay_memory(1e6)
policy_net = build_neural_network()
target_net = copy(policy_net)
For e = 1 to episode_number
      Loads <- ℕ⋂[P̄min,P̄max]
      RES <- ℕ⋂[P̄min,P̄max]
      state <- simulator(list_of_KPIs)
      action <- exploration_exploitation()
      reward, transition <- simulator(action)
      replay_memory(state, action, reward, transition)
      sample = get_batch_replay_memory()
      processed_data = process()
      loss  <- train(policy_net, target_net, processed_data)
      gradient_descent(policy_net)
      if e % 5 = 0
            copy_weights(taret_net, policy net)
```

Pseudo-code 1. Reinforcement learning applied to battery management.

In the beginning, the replay memory is created. Replay memory is basically a dataset containing the whole transitions; state, action taken, next state, reward and done. Done here means if some KPI is violated and couldn't be recovered in allowed time specified by grid code. It can be defined as specified steps of an episode for not-continuous scenarios.

Next step of initialization is to create a neural network with randomly generated weights. The size and feature of network is a subject of analysis. Here is set to 3 hidden layers with 64, 128, 64 neurons. Then this network is cloned to another network as target network which have same weights only in the beginning.

The loop starts and the simulation management script selects random values between minimum and maximum values per load. These limits are given by vector of lower and upper constraints per node/asset. Simulation management also selects random values between minimum and maximum values per generator, in this case PVs.

Then the KPIs are evaluated. Here in this draft the KPIs are introduced as congestion and voltage level.

Agent selects action based on exploitation and exploration criterion. The action is also an array with dimension of freedom degree of control components (here is set to one; a battery system).

Action is the same dimension of freedom degree of control per element (here is set to 3, only charge, discharge with maximum power or idle. Action is the same dimension of freedom degree of control per element (here is set to 3, only charge, discharge with maximum power or idle. The environment in this context is handled by the simulator that execute power flow simulation by considered action (here DIgSILENT PowerFactory via OPC command).

When the replay memory is filled up with transition number more than batch size of training, the script of simulation management selects random batches from replay memory and pass it through neural networks. The loos is calculated between two networks of policy and target, and then is back-propagated through policy network. After certain epochs (here 5) the policy network is updated by the policy network's weights.

4.3 Optimal operation of the distribution network (UNIZG-FER)

4.3.1 Operation and functionalities

4.3.1.1 Conceptual approach

In traditional distribution network, voltage and current congestions were mitigate by the network reinforcement, i.e., current cables and lines were replaced with those of more suitable characteristics. However, most of the problems occur only in extreme events, making an expensive solution such as the network reinforcement unnecessary.

The integration of electric vehicles (EVs), photovoltaics (PVs), and other distributed energy resources (DERs) but also the increased electricity consumption, in general, create new technical challenges for Distribution System Operators (DSOs). New technologies integrated into distribution networks, together with end-users equipped with smart infrastructure present great potential. Methods that include smart charging of EVs, Volt/Var control of PVs, demand response programs, exploitation of end-users flexibility, etc. have been widely used in the mitigation of technical problems and increasing the hosting capacity of DERs but also these methods replace traditional methods such as network reinforcement, which presents a significant decrease of costs in the planning and operation of distribution networks.

Three different software modules have been created and tested in order to fully exploit the potential of end-users and DSO's assets installed in a network:

- Optimal topology module
- Third-party flexibility module
- Voltage-led demand response and providing flexibility from DSO's assets module

Despite the fact that distribution networks are in most cases operated as radial, they are planned as meshed which enables the change of a network's topology in case of extreme events. The same situation is at the Croatian demo site defined in UC5, where four installed relays enable the change of topology when necessary. Based on the signals received from a DSO, relays trip and reconfigure a network when voltages or currents in a network violate defined technical constraints.

The network reconfiguration module is developed using Python programming language with the Gurobi[3] optimization solver. The network reconfiguration module is based on the common non-linear optimal power flow model, with additional constraints that ensure the radiality of the network. The network reconfiguration module will provide information about the optimal topology in the observed demo site. The algorithm is based on the statical data about the gird, such as resistance and reactance of cables and lines and the dynamic processing and billing data (e.g., loading of a substation). The output of the algorithm is the proposed topology of the

[3] https://www.gurobi.com/

radial distribution network which satisfies all defined constraints and ensures minimal technical losses or some other objective, defined in a formulation.

The developed tool is validated against the NEPLAN commercial software for different simple and more complex benchmark distribution networks. The result of the computation is the proposed network topology with minimal losses (optimal topology). Also, when compared to the examples from the literature, the developed tool reconfigures all benchmark networks in the same way.

The operational scenario will consist of the following steps:

- An algorithm will be ran at frequency according to the agreement with a DSO
- In order to minimize losses or improve voltage magnitude, an algorithm will propose a new network topology
- After the proposal of the topology, all necessary information are streamed through the HEP ODS platform
- If unwanted events occur, the switching state will be changed, and the new topology will be determined

Other potential objective functions include maximizing the reliability of supply for end users, enhancing the resilience of the network, enabling the provision of flexibility from network users etc.

The logic of the algorithm is as follows: a distribution network is normally operated without any technical or other violations. After the unwanted or extreme event happens, e.g., network losses increase or current or voltage congestion occurs, a DSO activates the network reconfiguration algorithm that analyses all possible solutions and proposes an optimal one, based on the goal function. After the network is reconfigured, a new normal operation state is introduced. Described steps are then repeated if needed.

The location of relays in a network is predetermined, the same as the allowed frequency of the tripping. Four relays are installed in a network defined at the Croatian demo site, i.e., only a limited number of lines can be switched, leading to the exact number of possible configurations. Also, to avoid tripping of relays every time when another network topology ensures lower network losses, a maximum number of relays tripping in a certain period, e.g., one day or one week, are defined. This constraint will secure the premature failure of installed relays.

Before the development of technology and integration of DERs in distribution networks, end-users were mainly passive and oriented toward satisfying their own electricity needs with a minimum number of interruptions. Nowadays, the high share of DERs has caused different changes in distribution networks, leading to the need for more active participation of end-users in the provision of ancillary services and helping in the reduction of the violation of technical limitations in a network. In order to investigate the potential of end-users in the mitigation of voltage and current problems in a network, an algorithm that based on the network needs activates the flexibility of end-users is developed.

The first step of the developed tool includes determining the end-user's flexibility profile. Each end-user has different devices, with different flexibility potential. Consequentially, not every end-user can increase or decrease their consumption for the same amount, even if a DSO requires so. Therefore, determining the flexibility potential is a prerequisite for the successful performance of the tool. The second step includes the detection of time periods in which an unwanted event such as excess PVs production or uncoordinated EVs charging leads to the lines' congestion, transformers overload, overvoltage, or undervoltage. After such a problem is detected, an OPF-based solution determines the amount of needed flexibility and also determines which end-users are based on their potential most suitable for the provision of the flexibility service that will lead to the improvement of technical conditions in the network. After the calculation is finalized, the signals for the increase or decrease of the consumption are sent to end-users who finally participate in the improvement of network conditions.

In certain cases, the amount of flexibility provided by end-users can be insufficient to solve the issues that occur in a distribution network, and a DSO must observe the other possibilities for minimizing the effect of the problems caused by current and voltage congestion. One of the possibilities is to exploit DOS's assets, e.g., on-load tap changer transformers.

As mentioned before, end-users are not always capable to provide the needed flexibility in order to prevent negative effects of extreme events in a network. However, the effect of such events must be prevented, and DSOs must find other solutions other than only relying on the potential of end-users. Such solutions include the utilization of physical devices that are already installed in a network. An example of such solution is already described network reconfiguration achieved with the tripping of relays installed in a network. Other solutions rely on other assets such as on-load tap changer transformers, power electronics or shunt devices.

Same as two previous tools, the tool in which DSO's assets are used to provide flexibility services is developed based on the OPF formulation. Two different OPF-based problems are formulated: the first includes determining of the capability chart for distribution network flexibility provision, while the second determines the ability to set the used controlling devices so that the desired setpoint within the aforementioned chart could be achieved.

As the results, the developed algorithm proposes a P-Q curve that quantifies distribution network's ability to change its power injection at the TSO-DSO interface. The P–Q curve is defined as a set of all possible active and reactive power values that can be achieved by controlling the voltage dependent loads, on load tap changer transformers, capacitor shunts positions, and distributed generators. An example of such curve is shown in Figure 43.

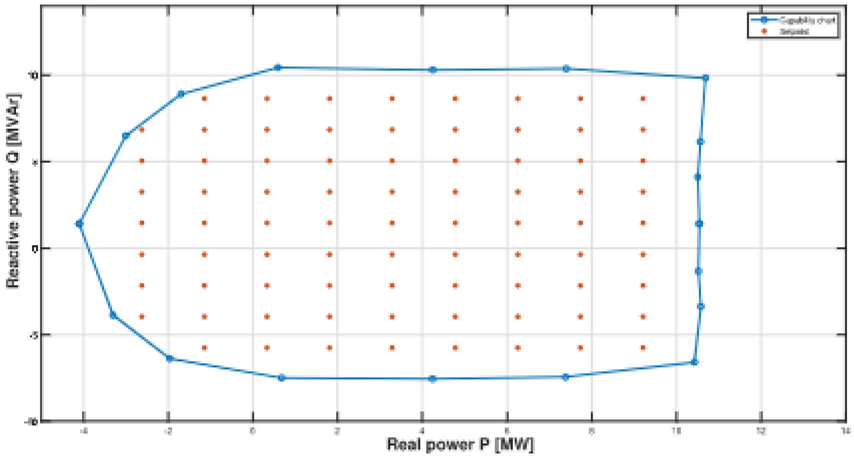

Figure 43 Proposed P-Q curve

The developed model is implemented for the distribution network defined in UC5. The initial parameters of the OPF-based problem are defined in a way that a situation in which the activation of DSO's assets is needed. As the result of a simulation, a P-Q curve with the set of all possible power values is proposed. The advantage of this approach is that a DSO can rely on its assets, instead of additional payments for the third-party flexibility services.

4.3.1.2 Main flowchart

Figure 44, defined as a flowchart, presents the logic behind the development of all three modules and the activation of services needed after the occurrence of an unwanted or unplanned event.

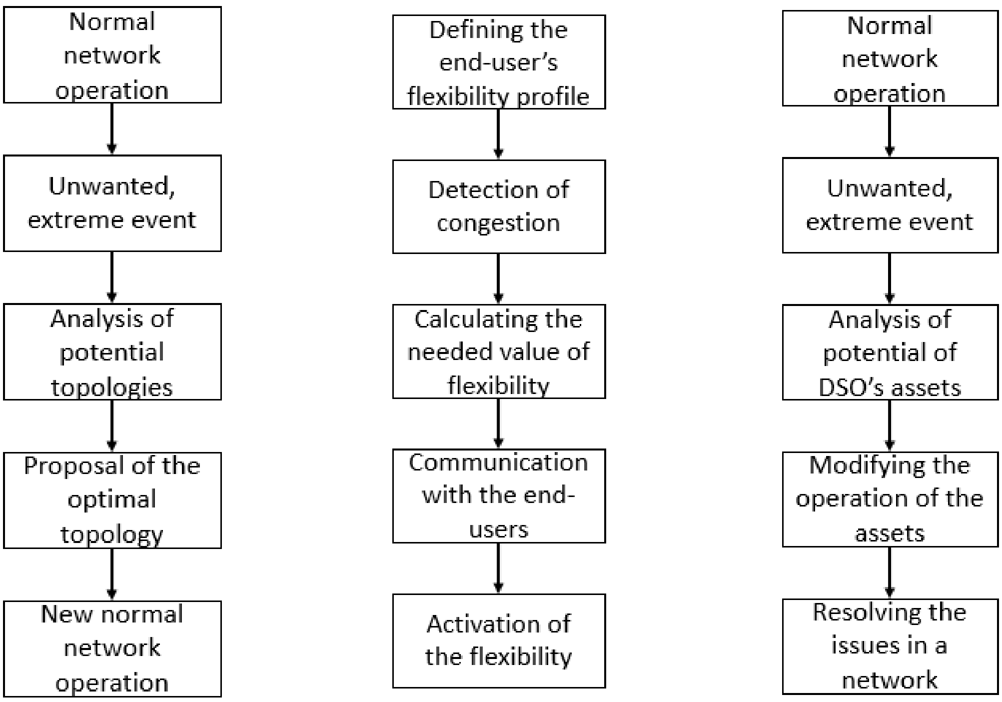

Figure 44 Developed modules description

4.3.2 Modelling and testing premises:

4.3.2.1 Description of the demo

Figure 45 shows the functional schematics for the automated part of the grid defined in UC5. Lines for automated operation, adaptive protection, and manually operated supporting connection lines are defined with the locations of installing the relays.

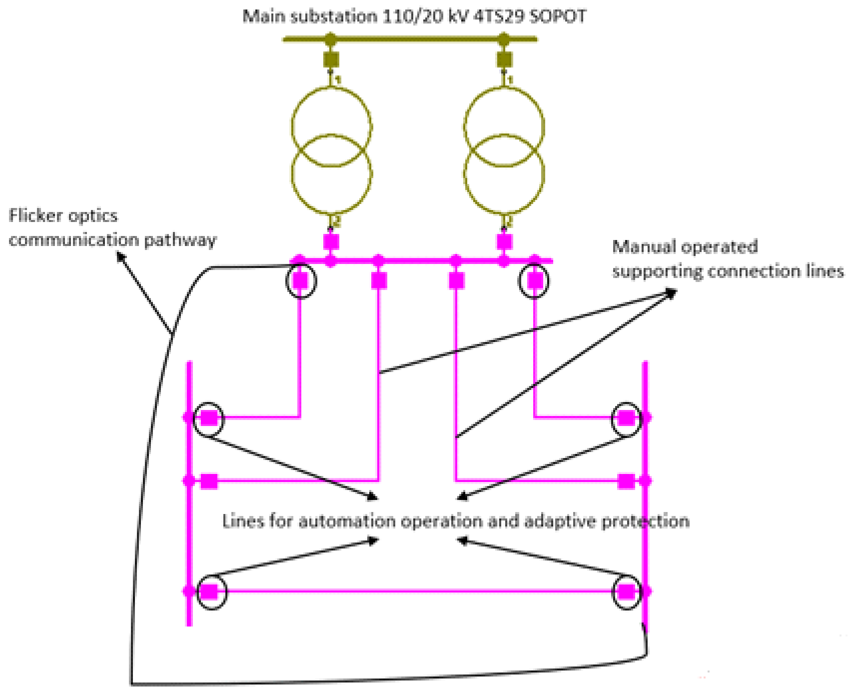

Figure 45 Functional schematics for the automated part of the grid

The prerequisite for using the tool on the defined demo site is verified on benchmark networks and successful lab tests. Additionally, the communication that will enable the exchange of needed data is needed.

On the Croatian demo-site defined in UC6, an end-user is fully equipped with smart meres and the infrastructure that enables him to provide the flexibility services when needed.

A representation of the architecture of the pilot is depicted in Figure 46.

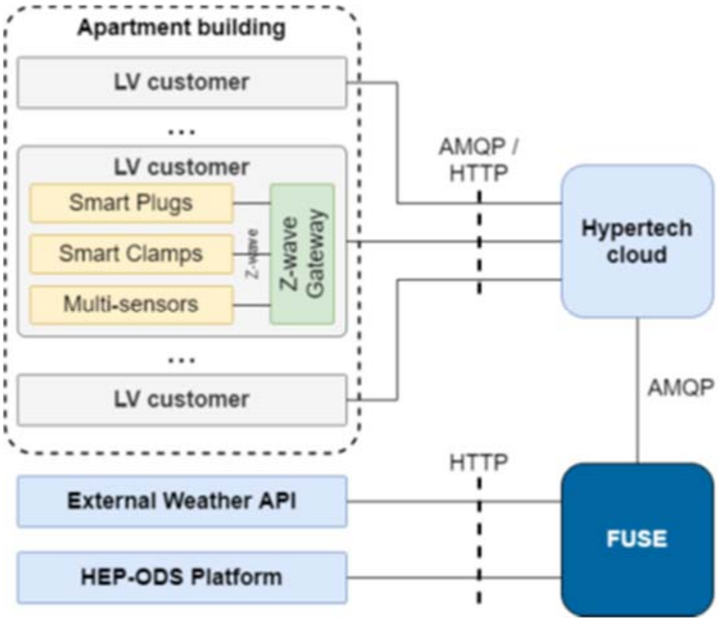

Figure 46 Croatian demo site architecture of components – LV customer level

Figure 47 shows the MV distribution network located in Croatia. The network is used for the analysis and the flexibility calculation. The end-user equipped with the smart metering infrastructure is connected to an LV part of the network and is supplied with energy from the MV/LV substation.

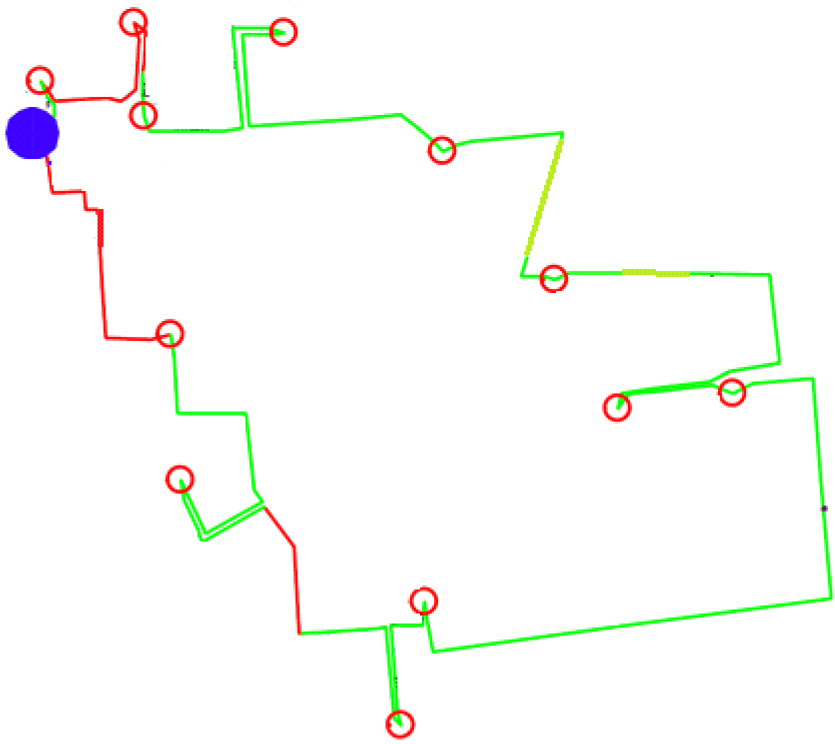

Figure 47 MV distribution network - UC6

4.3.2.2 Integration with other platforms and tools

The third-party flexibility module is based on the VTES module developed by Hypertech. Hypertech participated in defining the architecture of the communication module which will be used in activities defined in UC6, which are related to activation of flexibility services provided by an end-user. The architecture and the establishment of the communication are presented in Figure 48. Based on the equipment installed on-site and the modified forecasting module developed by LINKS flexibility profiles of an end-user will be defined.

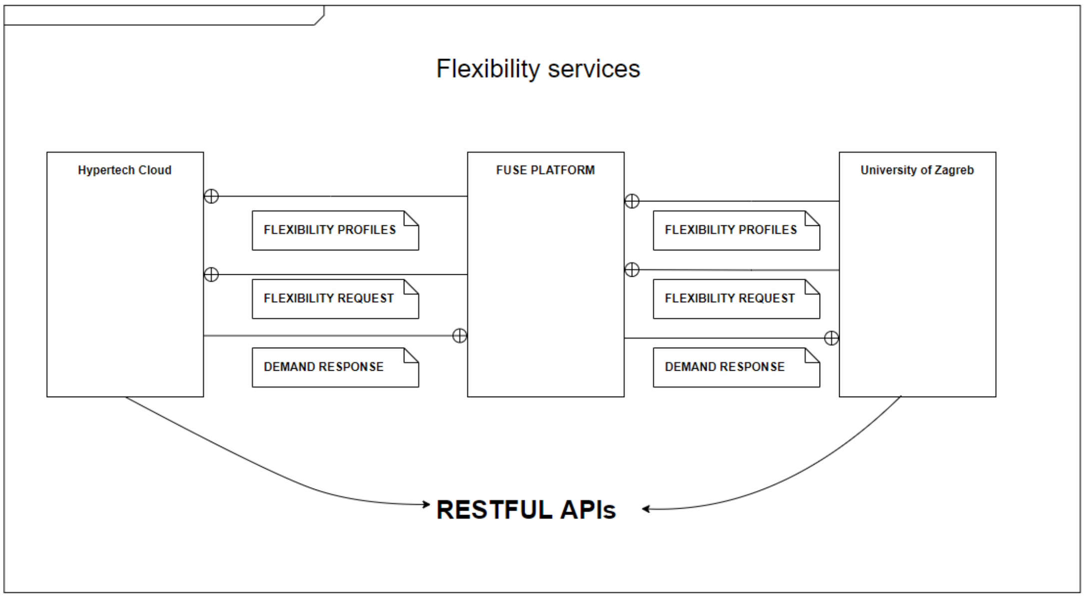

Figure 48 Communication with Hypertech Cloud

5 T4.4. Software upgrade for congestion management and peak-shaving

The module developed within this task is described below:

3. Congestion management and peak shaving

Decreasing cost of photovoltaic and battery systems, together with the variability and inherent uncertainty of electricity prices, increased the interest for such localized energy systems by commercial customers for business-as-usual operations, which may address reliability, whilst providing cash flow certainty and reducing overall environmental impact. Microgrids are typically operated in Low Voltage (LV) in both grid-connected and islanded modes.

The main control-related state-of-the-art applications for a system similar to Figure 49 are the forecasting and the optimization/scheduling functions of the microgrid energy management systems, whose requirements are driven by the business objectives and the revenue streams of the commercial microgrids application.

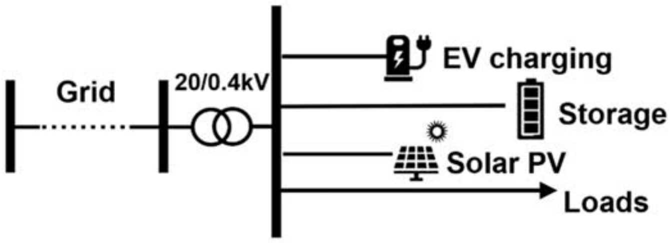

Figure 49. Component-wise view of use-case's local system.

The module is further analysed in section 5.1.

5.1 Congestion management and peak shaving

5.1.1 Implemented approach

The preliminary analyses, assessment of use-case and analysis of the state-of-the-art highlighted important facts to design an integrated chain of applications—mainly forecast and optimization—that can be assembled as the following:

- Hybrid long- and short-range forecast and optimization are needed to better exploit resources ahead-of-time and deal with uncertainties.
- It is necessary to reduce unnecessary complexity of the calculations where possible to make separate modules more flexible in terms of time and computation.
- Regressive model with and without recurrence units can handle long- and short-range forecasting, respectively. An evolutionary algorithm and a greedy one can handle long- and short-range optimizations, respectively.

The current work's case falls into combined problem type demanding to be treated by designing two distinct modules of forecast and optimization. The Forecast module is designed and developed as a hybrid forecast method by the integration of:

- A baseline regressive model to generate a forecast with long horizon H and big granularity, e.g., 48 h and 30 min, respectively.

- A recurrent model, for smaller time horizon and steps, e.g., 5 min ahead and 10 s steps, which gets activated upon errors between observed values and long-term forecast model.

5.1.2 Final architecture

The Optimization module follows the same hybrid approach since its input is fed directly from the forecast module. The current application is rendered with low complexity, where possible, to ease the integration within a chain of components from the physical field devices, gateways, and cloud service with continuous back and forth data flow. The hybrid approach is a combination of:

- Longer horizon and wider step optimization, matching baseline forecast (same time window and step) and triggered by that forecast updates. This optimization uses the meta-heuristics method as it deals with a complex problem, while it is less constrained in terms of calculation time.
- Spot decision-maker, namely greedy optimization, for very close actions, triggered by the recurrent forecast model.

The optimization process responds to the relevant forecast submodule, meaning that for the H hours ahead battery system scheduling, an evolutionary method—namely Ant Colony Optimisation (ACO)— solves the problems, as it can return the results in a reasonable calculation time. In the following sections, an implementation of the classic ACO approach for battery system management is described, and furthermore, an extension is presented to accelerate calculations. Thereafter, the used Greedy logic for near steps ahead (corrective submodule) is made. The control process of the full control chain is described in detail in D4.4

The information exchange process consists of the elements presented in in chapter 3.1.2.

5.1.3 Testing of technologies

The modelling has been tested in development phase with a number of datasets including real-billing scheme, load profile and various PV generation profiles. Further details on the test results are provided in D4.4.

The testing of the scheduling and optimisation module was conducted in LINKS premises in conjunction with the forecasting modules as described in D4.4. However, as the output of the scheduling module (i.e. the actual setpoints for the field devices) could not be communicated to the field devices, due in part to delays in the delivery of the FUSE infrastructure, the end-to-end testing of the scheduling and optimisation module will be conducted in the following months of the project and reported accordingly in WP6 deliverable reports.

6 T4.5. Dynamic thermal modelling of buildings and energy storage specifications

This chapter presents the development of accurate thermal energy storage profiling models that are used for individual spaces and devices within buildings, with the aim to define the flexibility that individual buildings can provide in the context of optimized demand response strategies.

This work was carried out within Task 4.5 of the FLEXIGRID project ‘Dynamic thermal modelling of buildings and energy storage specifications’. This section presents a summary of these activities as they are described in detail in Deliverable 4.5 ‘Building dynamic thermal model’ [1].

6.1 UC and Solutions correlation

This task is responsible for the designing and implementation of software modules that will define and create the Virtual Thermal Energy Storage module in terms of the FLEXIGRID project. The VTES’s main purpose is to provide demand flexibility services to the energy providers to facilitate the stability of the Low Voltage electric grids and to raise awareness of the demand response events and the energy markets to the end users. For each examined pilot site grey box optimized algorithms will be implemented that will simulate the buildings thermal characteristics. Comfort profiling algorithms will reflect and forecast the temperature preferences of the occupants. In addition, black box data driven models will estimate and model the energy patterns of each thermal building asset. Combining the aforementioned modelling approaches the VTES module will be capable of providing flexibility services for individual buildings avoiding the “one solution addresses all cases” approach.

As shown in Table 1. Use cases and solutions matrix correlation, engaging the VTES module the FLEXIGRID project is able to address Use Case 6. The main module comprises of three submodules: The Comfort Profiling Modelling Module, the Building Thermal Modelling Module and the Distributed Energy Resources (DER) Modelling module.

6.1.1 UML representation

Figure 50 presents the information exchange between the VTES module and the different partners’ software modules in terms of UC6 of the FLEXIGRID project. In addition, it includes the procedure of flexibility generation per pilot site and how the submodules communicate with each other to achieve it. As presented in Figure 50, the FUSE platform acts as a communication channel between the HYPERTECH Cloud and the UNIZG-FER platform. The flexibility requests and responses will be forwarded through the FUSE platform to allow UNIZG-FER to run simulation tests according to the data provided by the HYPERTECH Cloud.

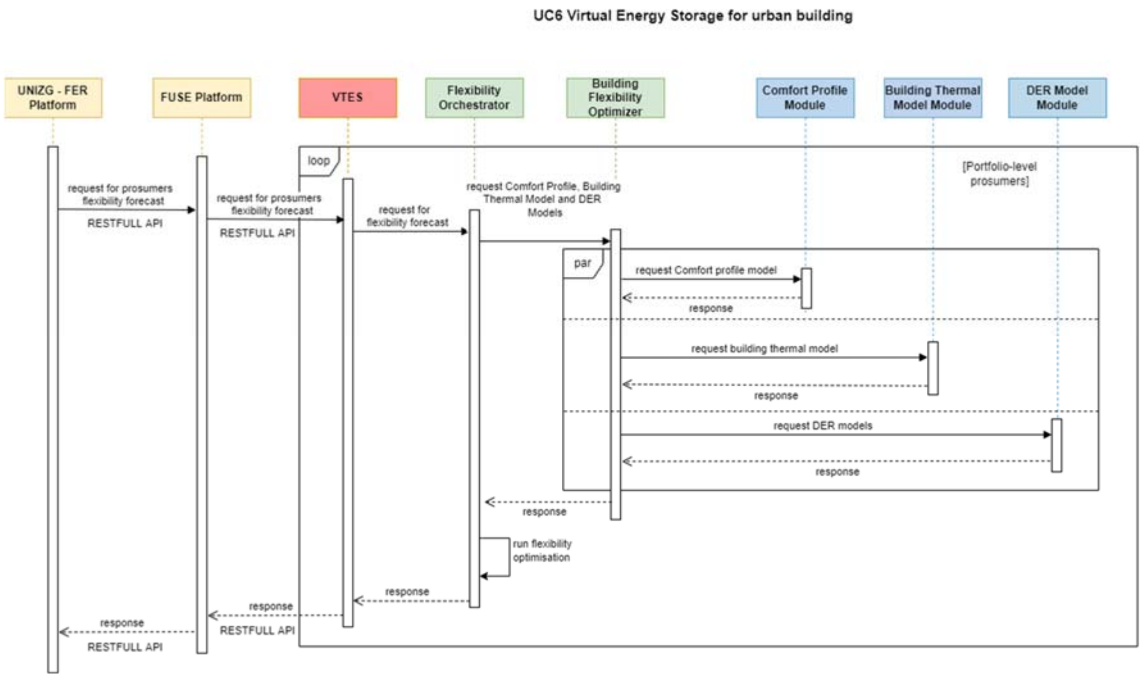

Figure 50. Use Case 6 UML Sequence Diagram

The following two deployment plans of the Croatian pilot sites, (Figure 51 and Figure 52) display the IoT equipment infrastructure that is installed in the respective pilots and the loads that are monitored and controlled. Through the installed IoT equipment, the user is able to monitor the energy consumption for each building asset as well as the total energy consumption. In addition, the prosumer can observe the indoor ambient conditions that occur per building zone. The deployment plans were described in detail in [2].

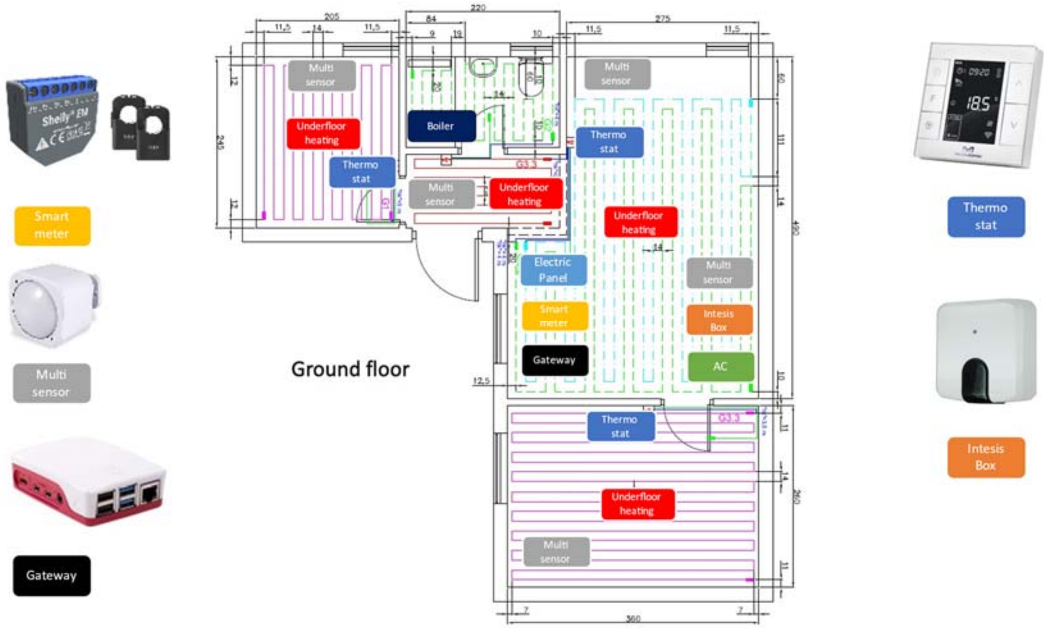

Figure 51. Deployment plan of the first pilot site

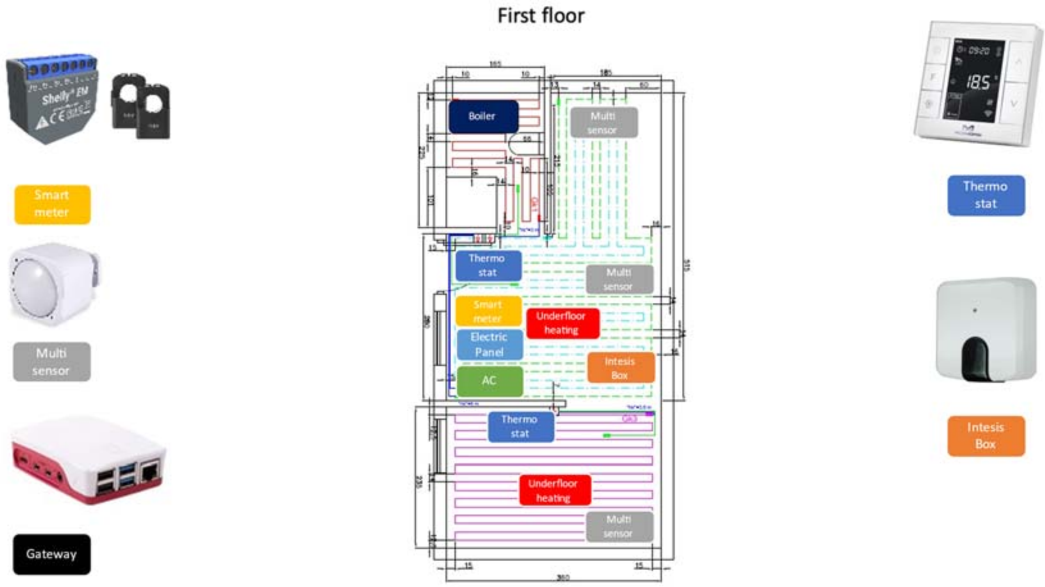

Figure 52. Deployment plan of the second pilot site

6.2 Comfort Profile Modelling Module

The main function of the Comfort Profile Modelling Module is to extract information about the pilot site's indoor temperature and create a pattern that corresponds to the preferred conditions of the occupant. These conditions are translated into two dynamic limits, based on which the flexibility forecasting and demand response dispatching is created. As a consequence, the model can modify the energy needs of the building without affecting the indoor thermal comfort. The ambient conditions are monitored by the installed IoT sensors and provided as input to the Comfort profile modelling module that uses this information to generate comfort profiles for each building zone. If more than one sensor is included in an investigated building zone, the average value of the installed sensors is used.

The raw IoT data undergo a pre-process procedure in order to omit outliers, create 15 minutes interval aggregates and then normalise then in a common scale. This pre-processed data serves as input of the comfort profile Machine Learning (ML) algorithm. The latter uses a Symbolic Aggregate Approximation (SAX) learning algorithm to analyse indoor temperature per building zone and correlate it with specific actions of the occupant (HVAC usage, etc.). As a result, the algorithm will provide an indoor temperature pattern with upper and lower limits for each zone. Lastly, the profile extractor subcomponent will generate a set of timeseries including the extracted occupant's preferred temperatures. Python 3.7 libraries have been applied for the development of the module.

Residential buildings were used as test cases to examine and validate the suggested methodology, using indoor temperature data for a period of one month, as shown in the following figures for aggregated data. Figure 53 presents the normalized indoor air temperature during a weekday period, while Figure 54 for a weekend period.

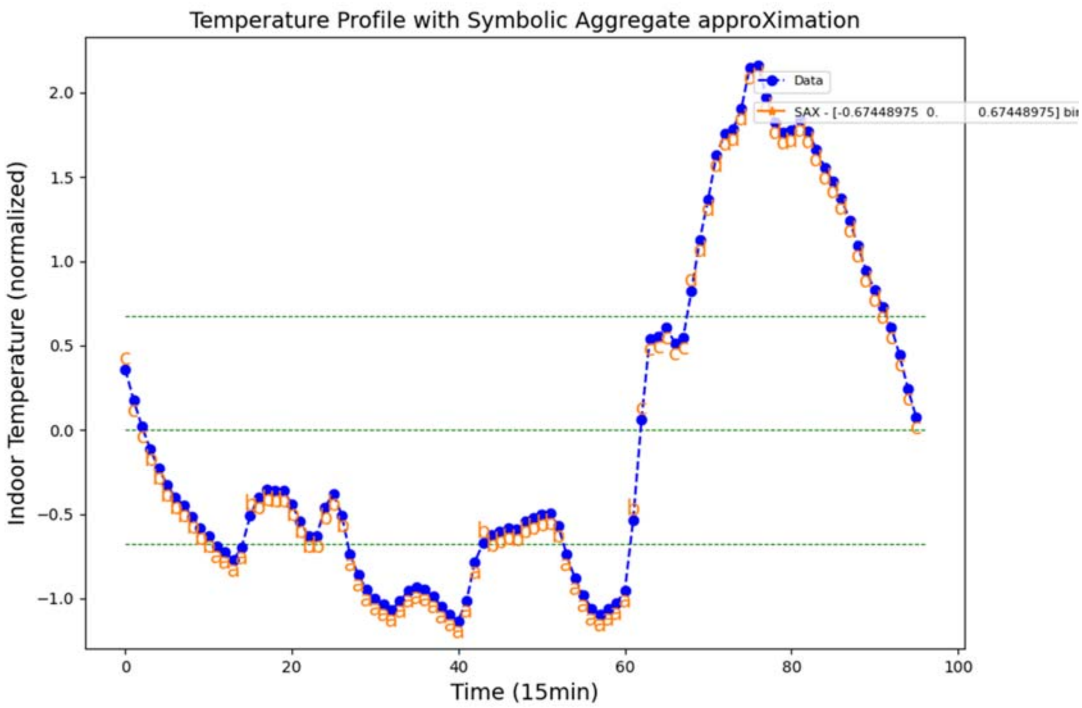

Figure 53. SAX's profile extraction for residential user during weekdays

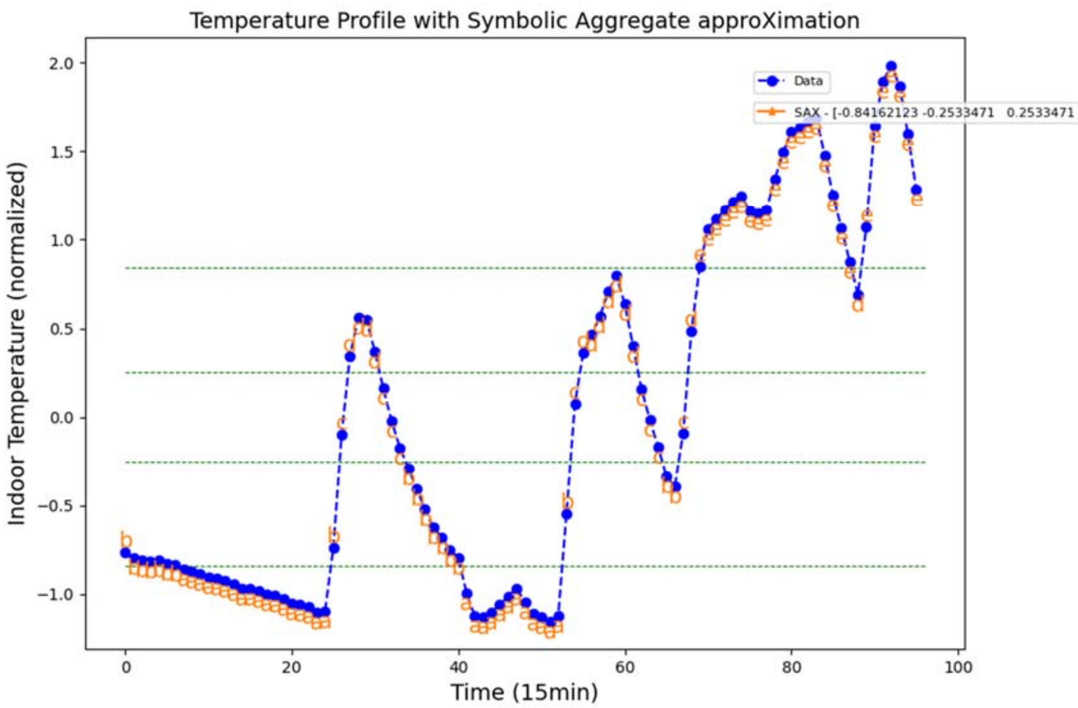

Figure 54. SAX's profile extraction for residential user during weekends

6.3 Building Thermal Model Module

The Building Thermal Model is developed based on a grey box modeling approach, allowing to simulate the performance of different buildings, not requiring extensive information on the building while avoiding a "one-size-fits-all" paradigm.

The developed 3R2C model receives as input the main heating and cooling loads power consumption and external environment conditions (temperature and solar radiation) in order to calculate the indoor temperature at each zone. In doing so, the VTES module can correlate the internal conditions of each zone with the load affecting the zones in question.

Preliminary tests were carried out on residential test cases. Figure 55 shows the parameters that were used for the simulation during, while Figure 56 presents the results of the model and compares them to measured data.

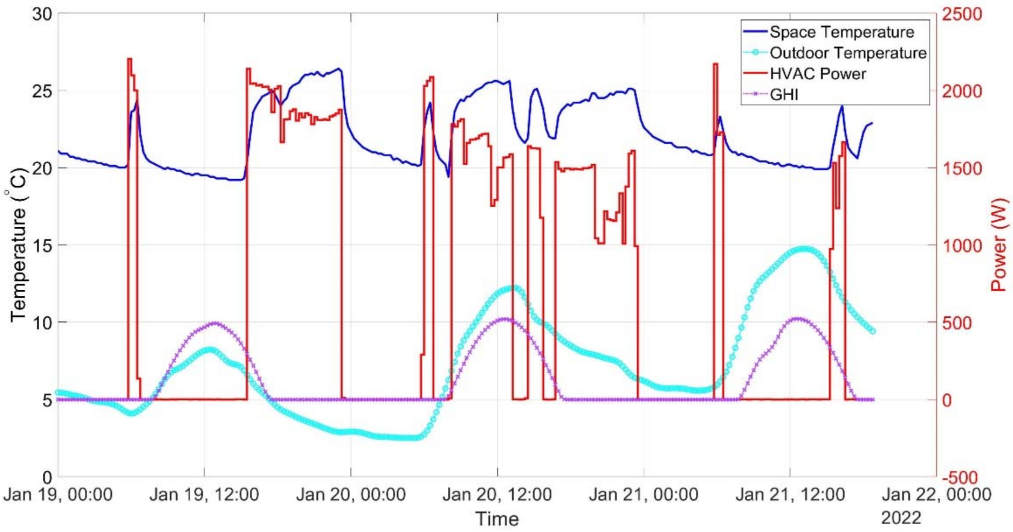

Figure 55. Building Thermal Model's inputs

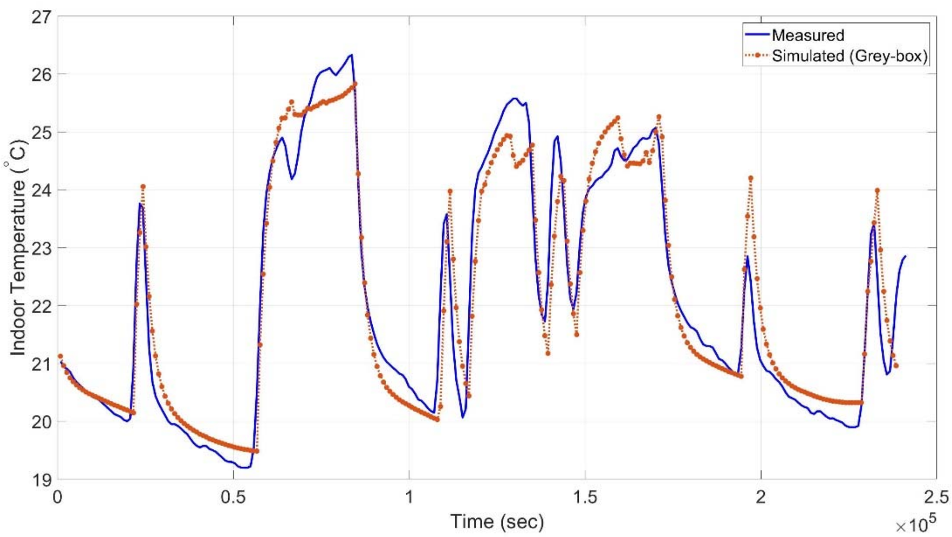

Figure 56. Building Thermal modelling results

6.4 Distributed Energy Resources (DER) Modelling Module

Similarly to the Building Thermal Model Module, the Distributed Energy Resources (DER) Modelling Module is based on data driven methods. The module simulates the performance of different types of HVAC and DHW energy systems, namely electric underfloor heating systems, AC units with inverter and electric water heaters. These devices were selected for the FLEXIGRID project based on audits.

6.4.1 HVAC system: electric underfloor heating system

Electric underfloor heating systems follow a discrete-step consumption pattern and can be treated as a resistive load of K levels of consumption. Their performance can therefore be simulated using an unsupervised ML algorithm K-Means, as is the case for other resistive loads, such as EWH systems. Specific Python libraries were used for this purpose, namely pandas for data analytics, scikit-learn for data pre-process and K-Means. The optimal number of clusters was predefined using two additional modeling methods, the Silhouette Coefficient and the Elbow methods. The developed model requires as input the energy consumption and the operational status (i.e., on/off) of the device.

The findings of this DER module will be given in future deliverables of the project, due to the inability to test and validate the underfloor electric systems.

6.4.2 HVAC system: AC with inverter

Air-Condition split units are now widely used to cover heating/cooling needs of the building sector and the ones using inverter modules are gaining a growing share of the market, as they offer accurate temperature control by altering the compressor speed and consequently their capacity.

Gaussian Processes (GP) are used to simulate the operation of these units within the FLEXIGRID project, stated as a non-parametric supervised ML algorithm, able to effectively solve regression problems. Due to their capacity to fit their parameters in diverse HVAC systems, non-parametric algorithms may handle instances where a model remains the same for varied conditions. The model is based on a dynamic dimensional vector with increasing dimensions as more data is collected.

Using input parameters such as the device’s power consumption, status operation and set point, outdoor and indoor air temperature, the GP algorithm evaluates the mean and variance values of the AC inverter loads at predefined time intervals.

The proposed methodology was evaluated during the winter period in residential test cases, with the obtained results presenting a good agreement between measured and estimated power consumption for the investigated AC systems with inverter integrated units. Results are illustrated in the following figure, comparing measured and forecasted power consumption of an AC device with inverter during the winter period.

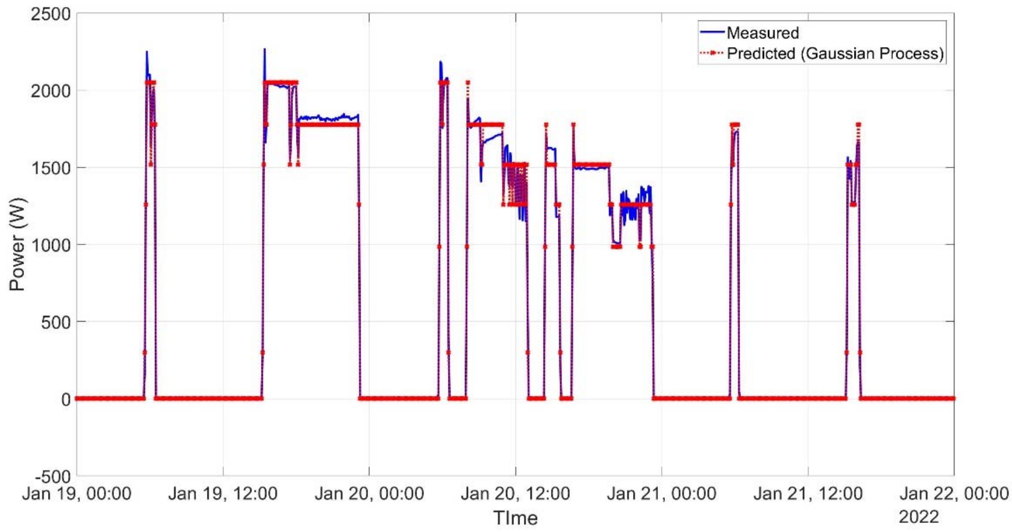

Figure 57. DER AC with inverter modelling results

6.4.3 EWH modelling

Electric Water Heaters are responsible for a significant portion of a household's daily total energy consumption. They offer several advantages regarding the FLEXIGRID solution, as they represent a controllable resistive load and they incorporate thermal energy storage tanks that provide the possibility to shirt part or whole of their hot water heating production.

Data driven methods were used for the modelling of EWH systems as they do not require intrusive actions for the installation of IoT equipment. It was therefore selected to distinguish and forecast the status and future power consumption of such devices using clustering ML algorithms. Various ML unsupervised models were tested, leading to the selection of the K-Means algorithm, as EWH present similarities with electric underfloor heating systems (electric consumption is divided into discrete power consumption levels).

The EWH's status and energy usage are used as inputs for the unsupervised ML algorithm, however before the EWH DER module is deployed, further processes are executed. The energy consumption data will be adjusted using the normalization technique offered by Python's SciPy module to help the K-Means algorithm divide the training dataset into two groups. Next, the dataset is separated into two partitions: the first covers weekday energy usage, while the second includes weekend energy consumption.

The EWH model was evaluated using data from the aforementioned residential test building. It presents a good fit with the measured values, with slight deviations, mainly during peak demand periods. Results are illustrated in the following figure, comparing measured and forecasted power consumption of an EWH device during the winter period.

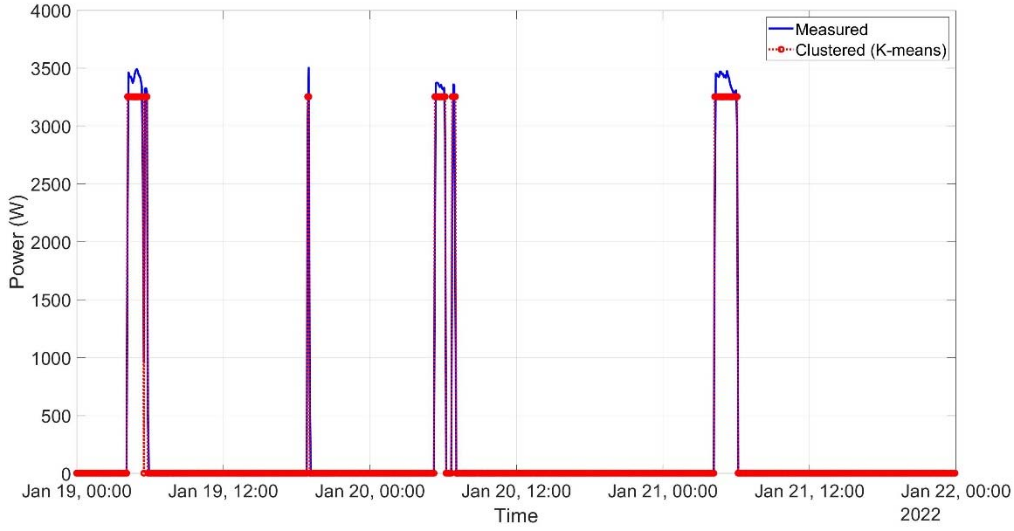

Figure 58. DER DHW modelling results

6.5 Virtual thermal energy storage flexibility framework

The VTES Flexibility Framework is in charge of supplying flexibility forecasts. There are two sorts of flexibility signals: downward flexibility and upward flexibility; the first signal is sent to reduce electricity usage, whereas the second is sent to increase electricity consumption.

The Building Flexibility Optimizer is used by the VTES flexibility framework to extract required input, including information provided by the previously described models (comfort profile model, building thermal model, DER models) and weather data. The flexibility framework uses Mixed Integer Linear Programming formulations with mixed integer and continuous parameters to estimate the baseline, upwards and downwards flexibility energy consumption for each investigated device and the building in total. It is created in Python 3.9 based on a widely used MILP solver, CPLEX

The validation of the model was conducted through evaluation tests in the previously considered test building. Figure 59 presents the baseline forecasted energy consumption, the solar radiation, the outdoor air temperature, the indoor air temperature and the comfort zone. Figure 60 and Figure 61 shows the same parameters, however in this case for the downwards and upwards flexibility scenarios.

Compared to the baseline and downwards flexibility scenarios, the HVAC unit operates for longer times in the event of an upwards flexibility scenario, this leading to higher indoor temperature. During the downwards flexibility scenario, the operation of the HVAC unit is limited, while the indoor temperature approaches the lower temperature comfort boundary.

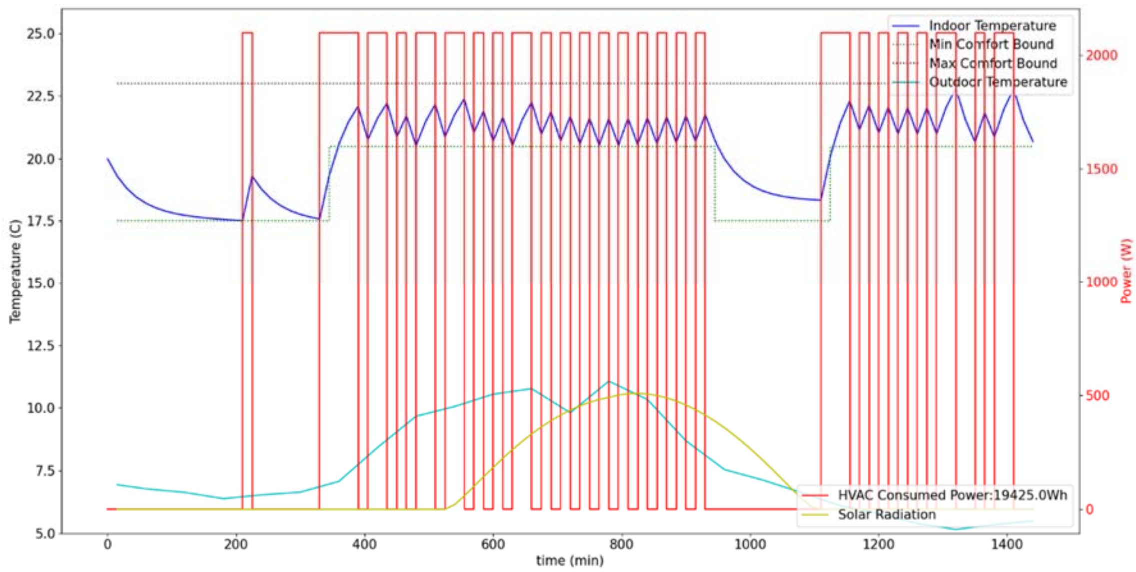

Figure 59. HVAC forecasted baseline power consumption.

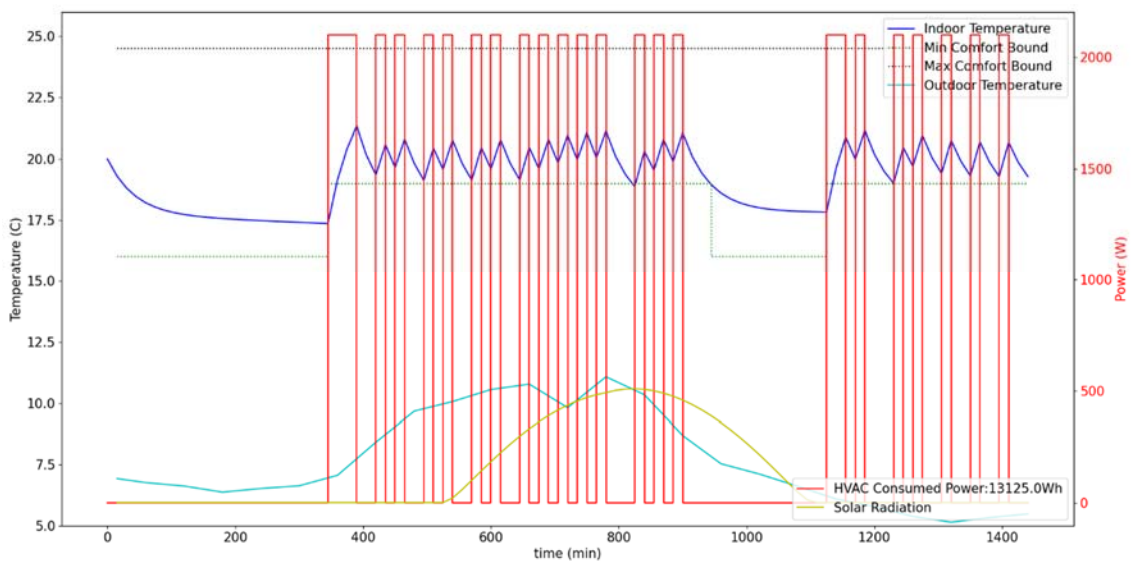

Figure 60. HVAC forecasted downwards power consumption.

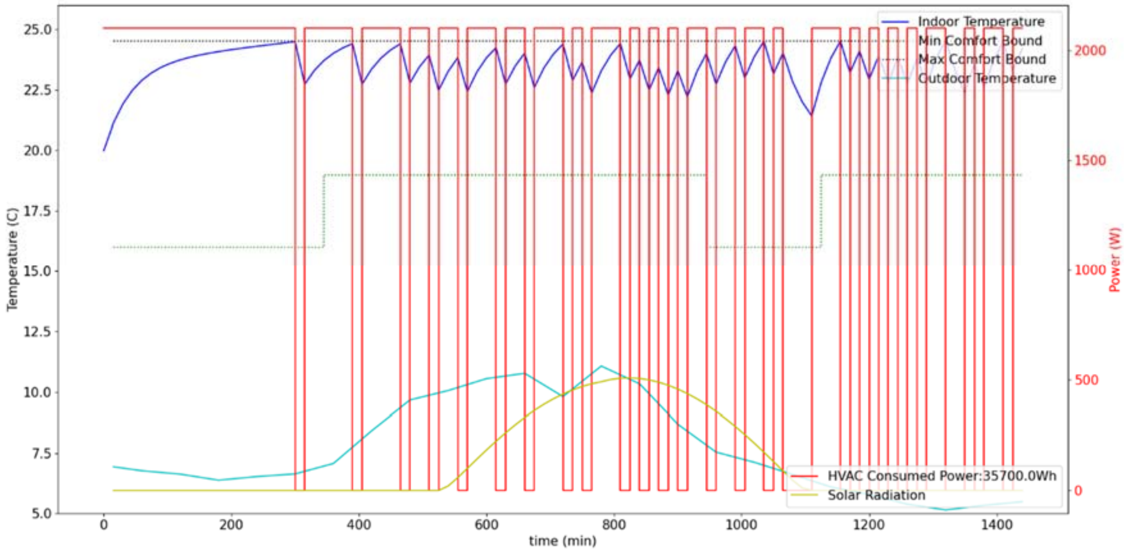

Figure 61. HVAC forecasted upwards power consumption.

6.6 Standalone Sizing and Siting module

The Sizing and Siting module was developed and tested for electrochemical battery storage systems, but its principles may be applied to any other flexibility devices. The developed technique employs an evolutionary optimization method to obtain the optimal configuration of a multi-objective function, with lowest time consumption. The proposed module can be exposed as a service and integrated as third party software; it can be made available as a web service to authorized clients and only requires the proper configuration of inputs without any prior knowledge of optimization setup being needed.

7 T4.6. Tools for the distribution grid operating in islanded mode

The developed modules for Italian demo are divided to dispatching platform and islanding model operation or Smart Grid Controller (SGC). Each of these modules incorporate various submodules for handling various tasks.

7.1 Dispatching Platform

The dispatching platform for MV generation represents the basic functionality of SGC. In fact, in practical execution and development of the Task 4.6, this platform has been incorporated as part of SGC. However, in this section, there will be description focused and oriented on the functions and rationale of the dispatching platform.

The DSO needs to have observability on the peripheral portion of its grid and the increasingly request to provide ancillary services from the distributed energy resources leads to consider crucial having an automatic central controller.

The dispatching platform represents the basic functionality of SGC. The DSO needs to have measures from its grid, in particular estimation of voltage profile and power flow along the MV feeders. The increasingly request of providing ancillary services from the distributed energy resources leads to consider as critical issue to adopt an automatic centralised estimator and controller.

We can summarize the main goals as follow:

- Improvement of distribution networks flexibility through the exploitation of Dispersed Generation units' flexibility capabilities.
- Real-time smart load flow calculation and predictive state estimation of the distribution networks in order to allow the DSO to identify and solve in advance possible issues.
- Increase of distribution network hosting capacity for RES, by innovative features based for example on congestions relief and voltage control strategies.
- Improvement of data exchange between DSO and sub-DSOs.
- Possibility to deliver useful data about MV grid to the TSO (Terna) in real-time.

From functional point of view, a dispatching platform or the DT of the distribution system of Italian demo should make it possible to:

- Retrieve latest state and valid information from the electricity system topology
- Retrieve real-time monitoring data from SCADA system for the RTU enabled elements
- Estimate in real-time the missing states of the power system elements
- Fast power flow calculation with the valid model of the network
- Based on the above-mentioned functionalities, to add various power system control and analysis algorithms.

Such a flexible platform would practically build a secure and valid test bed for many analyses that otherwise would come to high costs of system upgrade. Based on requirement analysis launched in the beginning of the project, following feature for the DT have been established:

- Relying on open-source tools:
    - power system analysis: Pandapower
    - Artificial Intelligence libraries: Tensorflow
    - Connectors: open-source OPC-UA python library
    - User-interface: React.js
    - Back-end: python scripts, python FastAPI

- Local management of interfaces and connectors:
    - Host server to be placed physically in the Edyna ICT infrastructure
    - Communication with Oracle Database (static data of the network) and SCADA (dynamic data of the network) within network of Alperia (no entry to internet)

- Flexibility of the platform for additional functions:
    - Backend support for various communication protocols

7.2 Frontend

First function of the dispatching platform is to build the latest state of the electricity system. The easiest and most valid way of extracting grid information has been to *export from SCADA*. System operator can perform this operation at any time and obtain the overall topology of the system alongside the static information as an XML file. This file, which is SCADA's standard export and therefore replicable for other cases, contains also the required tags for real-time data queries from OPC server. Then the XML file should manually be uploaded to the DT via a frontend. This frontend will also be the base of any interaction between the operator and DT.

An essential requirement from the Italian pilot (and any other) is to avoid exit points to internet or other non-proprietary networks, and implement the software locally. Based on this rationale, as initial developments an executable application is developed as the front end, as can be seen in Figure 62.

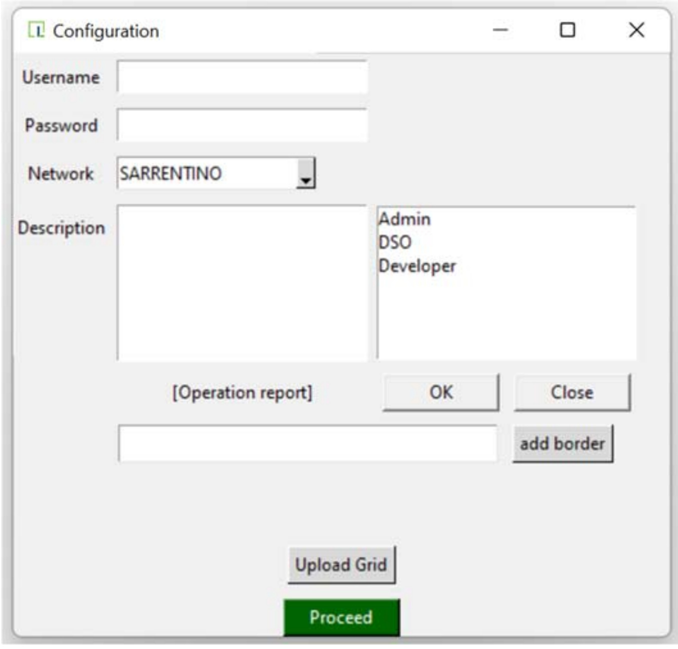

Figure 62. Executable front-end application.

The basic required functionalities of rebuilding network model automatically, is to limit the portion of system (as is explained in next paragraphs). This application allows to perform selection of network and its borders.

This can be proceeded for next steps of network validations.

An alternative to this, is a browser application that is more flexible for integrating further functionalities and visualizations, that has been under development after desktop application. Figure 63 shows a preview of the prototype interface and the base functionality.

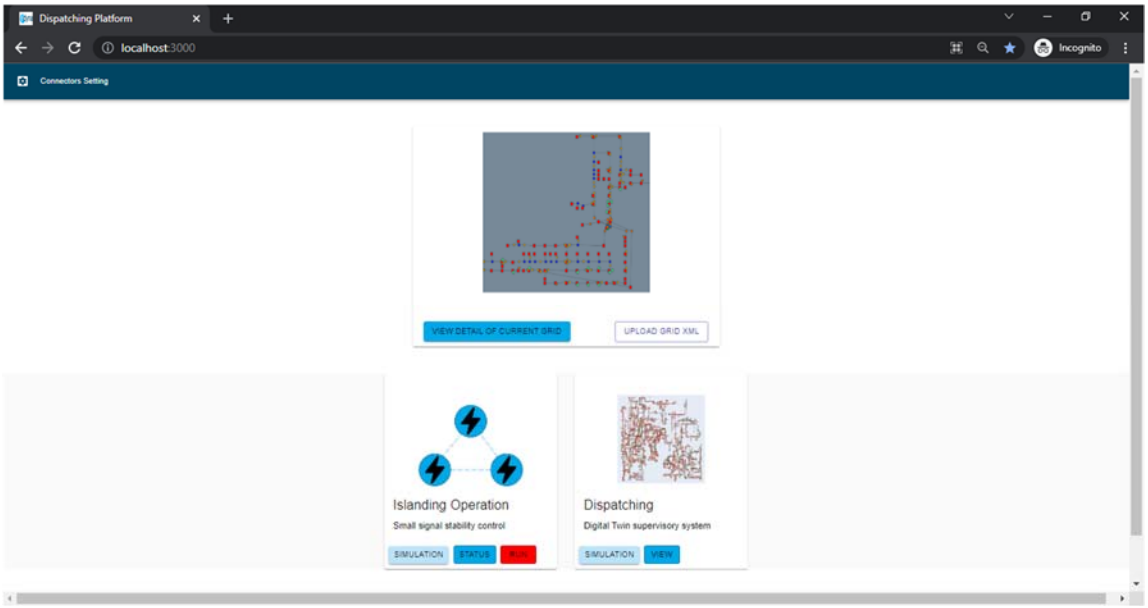

Figure 63. Dispatching Platform interface.

The operator is able to see the latest uploaded system configuration. If it is believed that this configuration has been subject to the changes in previous hours, it is possible to upload the new XML file. It is possible to check all the detail by pushing on view button, either each node and connections. This can be seen in the example brought in Figure 64.

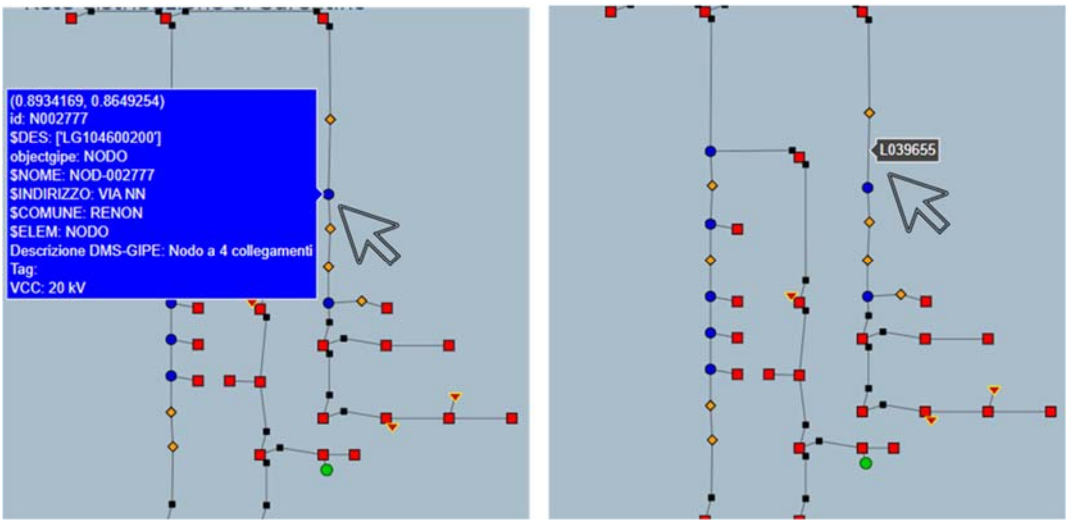

Figure 64. Network topology tab.

7.3 Grid model re-building

Main data being extracted from XML are:

- Topology of the network as a graph
- Electrical characteristic of the components
- OPC-UA tags

The logical process of modelling the grid is as following.

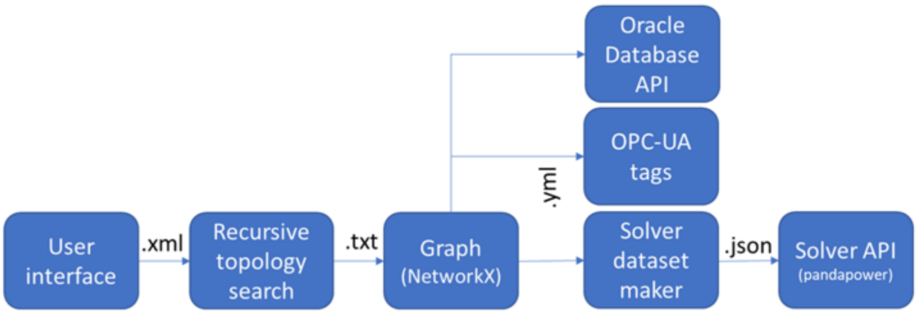

Figure 65. Logical process of automatic grid modelling.

Since the process of selecting a portion of the network from SCADA might be time consuming and perhaps not possible in many cases, a feature is added to module that user can select the portion of interest, by defining the *borders*. Figure 66 shows the case in which no border is defined.

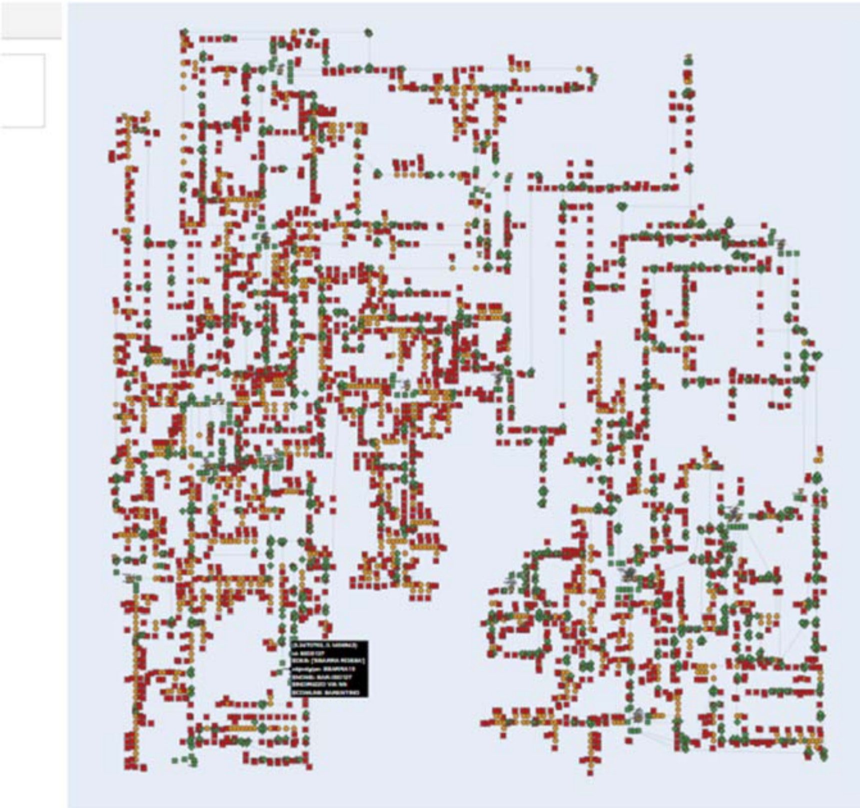

Figure 66. Re-construction (modelling) of the network of the whole province.

Once the modelling of the grid structure is confirmed by visual inspection from topology tab, the user can access to Dispatching functions as well. In the final version of the software, user is able to see the monitoring data from the SCADA and the missing information that have been estimated, in real-time.

Figure 67 shows an example of calculation through platform. The module builds successfully the structure of the network and makes it possible to perform a visual inspection as the geo-location of components is respected with same retrieved from SCADA.

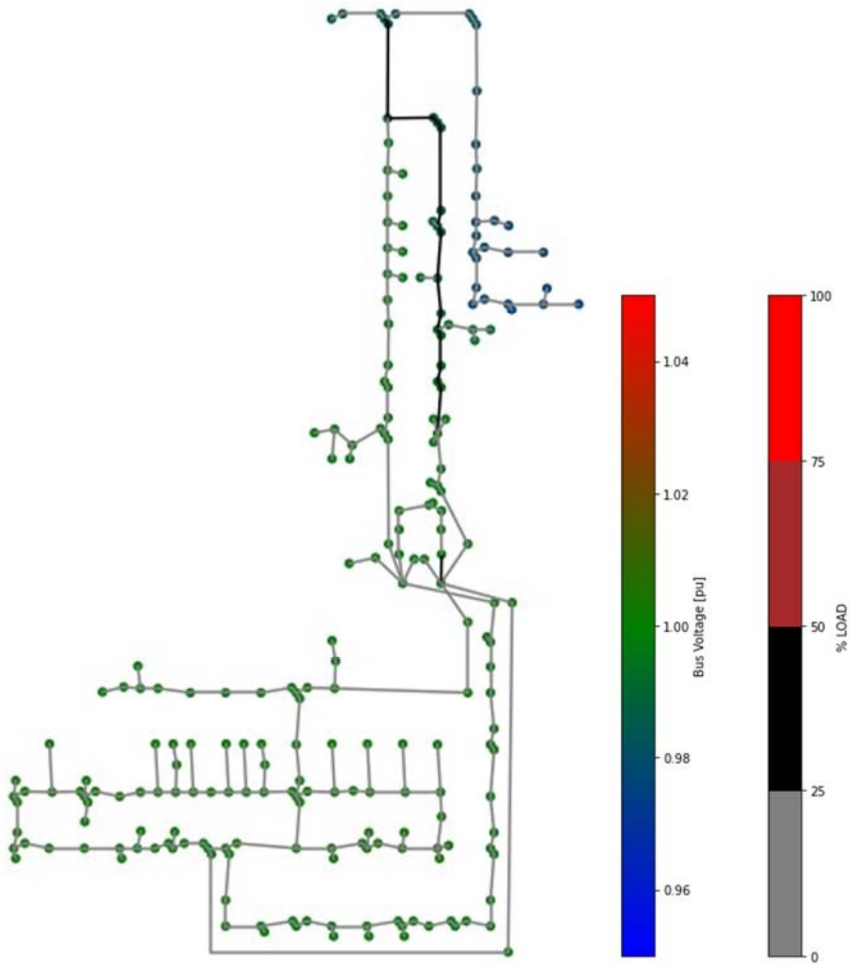

Figure 67. Execution of calculation on re-build network model in SGC's power flow solver.

The missing data is built by the DT of the network estimation through Deep Neural Network. The AI model has been developed as the prototype version, with simulation data. The model gets some available data from:

- RTU elements in substations, with a comprehensive range of measurements such as active and reactive powers, voltage and current of the starting and ending lines,
- Partial data such as voltage that can be obtained by extending the DT to integrate sparse IoT devices such as LV metering

The DT model mixes these data and estimate the missing ones, somehow inverse of the load-flow calculation and also load flow calculation by obtaining complex correlation matrices of the variables in the grid.

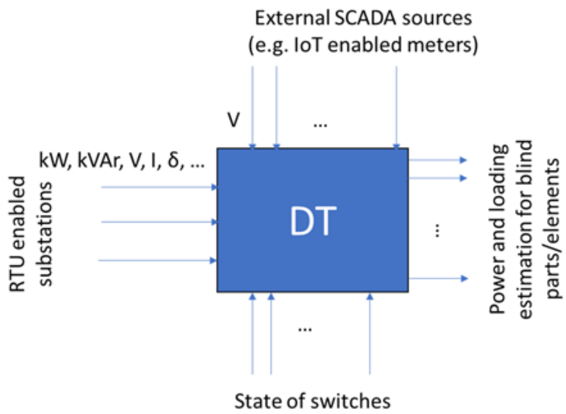

Figure 68. DT estimation scheme.

The partial rationale behind this scheme is to exploit as much as possible available metering and, thanks to innovative methods, reduce the expenses for upgrading the network automation level whereas can be avoided.

The Figure 69 shows a modest model of neural network able to estimate balance power in different nodes which are not monitored.

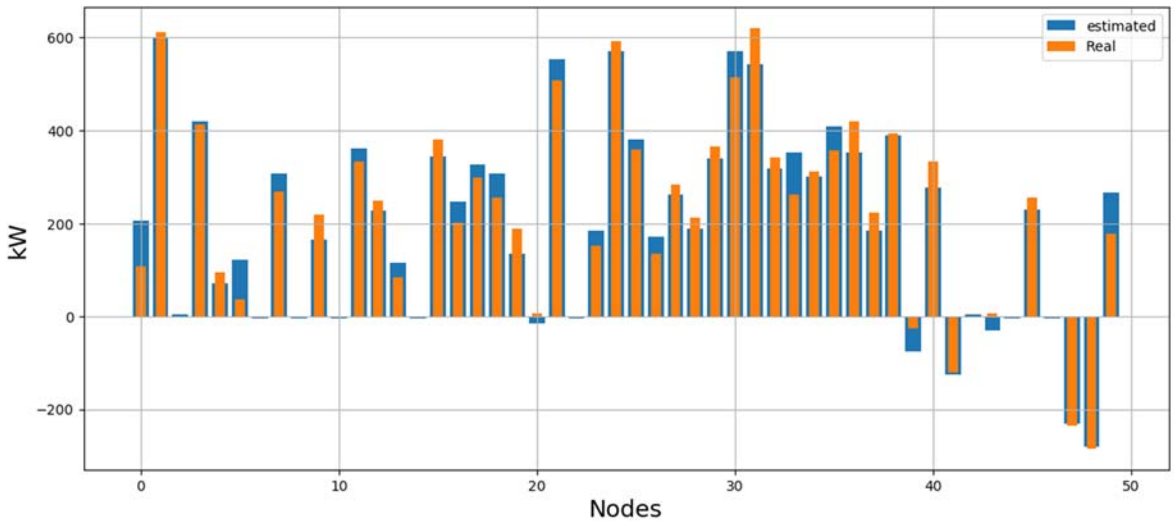

Figure 69. Power estimation at non-monitored nodes, based on other information from grid.

DT provide statistical power flow modelling of the network as well. The immediate advantage of these schemes is the speed of calculation and avoiding divergence in iterative calculations.

Thanks to the fast estimation, operator can obtain estate of the network in real-time with high accuracy.

7.4 SGC

The Smart Grid Controller (SGC) is located at a telecontrol centre and it is responsible for the system dynamic management on the occurrence of a load unbalanced.

Its main tasks are:

- To guarantee the stability of the involved Smart Grid;
- To coordinate the balance between requested and generated power;
- To implement the algorithms for power and voltage regulation;
- To operate the power dispatch of distributed energy resources (DERs);
- To perform the transition from on-grid to off-grid and vice versa, avoiding to create disease to connected loads.

In order to reach the above goals, SGC needs to monitor the electrical quantities related to loads and generators, as well as the status of every component displaced within the Smart Grid.

These data are collected thanks to a communication network able to link the central control system and the remote terminal units.

Therefore, SGC is able to run an optimal real time dispatching, allowing a continuous operation of the grid. The communication network and SGC can interact among themselves through the Alperia platform/SCADA where the data coming from delocalized devices converge.

7.4.1 Architecture

SGC is a software application (entirely based on Python language) installed in a dedicated server —as can be seen in Figure 70— which is hosted at the Control Center of the DSO, operating on a Windows Server2019 platform. Its aim is to implement function in order to add functionalities to the already existing SCADA in a flexible way.

Figure 70. Physical server hosting SGC (left) deployed in EDYNA (Alperia) premises (right).

The communication stream between deployed field devices, SCADA and SGC is reported in Figure 71.

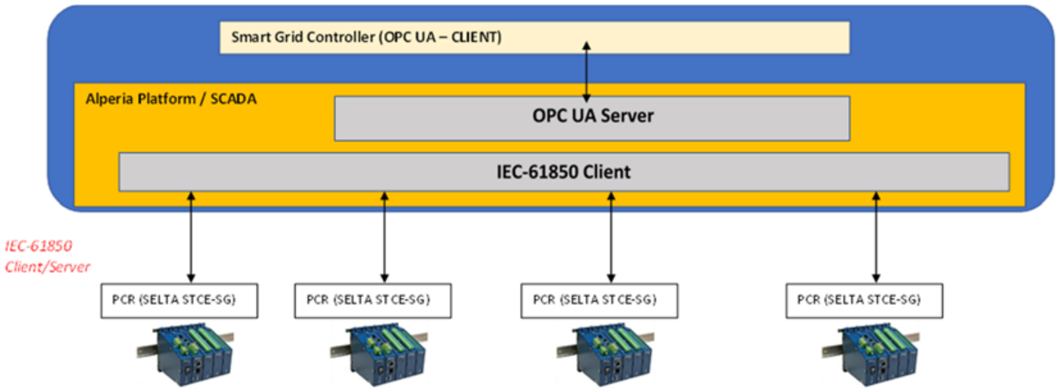

Figure 71. Communication scheme between SGC, SCADA and RTU devices.

The real time data, coming from the Selta Plant Central Regulators (PCRs) and other monitoring devices, are managed by the SCADA system of Alperia. About PCRs, the communication protocols used for the bi-direction information exchange is the IEC-61850 standard.

The only real time interface of SGC is represented by SCADA, and the sw connector consists in the OPC UA standard: the SGC plays the role of Client and on the SCADA the server instance is configured.

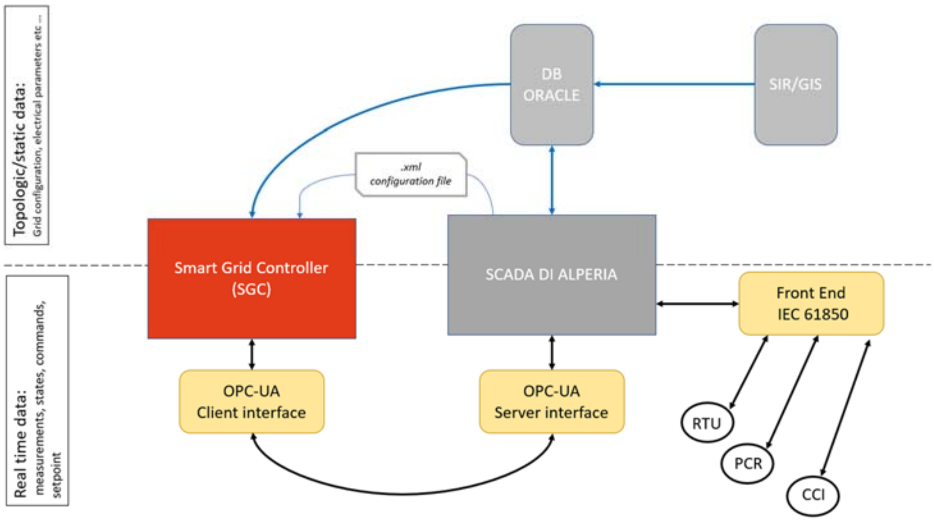

Figure 72. Data acquisition by category.

As shown in Figure 72 the SGC data acquisition can be sub-divided in two different sections:

- The external one consists in the interface for data exchange and the loader modules:
  - The real time data, measurements and breakers status, come from the SCADA throw the OPC UA interfaces. Moreover, also the set point and the results of SGC elaboration can be read by SCADA thanks the same front-end.
  - The DSO grid schemes is elaborated by SGC by the use of xml files that SCADA generates. In this file, it is also possible identify the keywords for grid elements matching.

- The electrical parameters and other static information about the grid elements are requested by the SGC to the DSO database one-off. This communication channel allows to maintain the SGC aligned with real conditions of the distribution systems.

- The core calculator is composed by several modules and its purpose is to elaborated data and to take real time decisions according to the functions pre-activated:
  - The state estimator is based on Pandapower libraries; using real time data and the updated structure of the grid, rapid load flow calculations run in order to obtain real time measures monitoring the whole portion of the MV grid involved.
  - SGC algorithm includes different functionalities that the operator can activate. In particular SGC calculates the setpoints for distributed generators within the Q/V regulation or P regulation/balance. The decisions are taken in compliance with the DSO requirements and constraints. The island mode check module allows to simulate specific scenarios with the purpose of transmitting information and advises to operators.

7.5 Islanding mode control

7.5.1 Main goals

The islanding mode control represents the most innovative functionality of SGC. The DSO needs to be able to manage specific conditions that can happen during the normal grid operation. In particular, the field experience teaches that in mountainous valley grid, where often electrical power flows up from distributed generation, if islanding conditions occur, some portions of the grid can continue in the service.

We can summarize the main goals as follow:

- Improvement of the security of supply for MV/LV grids.
- Increase of the resilience against major weather events (e.g., snowfalls) that could cause major black-outs having duration also of many hours and consequently arising safety concerns.

The operation of a MV network portion in islanded mode can be studied and tested on field. The islanded operation will be possible thanks to the use of power capabilities control of Distributed Generators displaced on the MV network in the area of the experiment (e.g. hydro power plants).

To this purpose, issues refer to power balancing and the voltage profiles control will be explored in the pilot. The key solution is the proper selection of the grid portion to be enabled for the islanded operation. Suitable control logics needs to be developed, taking into account the dynamic aspects.

In addition, power fluctuations have to be predicted in advance and managed by proper algorithms implemented by SGC.

The aim of this investigation is to enable a MV network portion on the islanded operation, exploiting the support of the MV Distributed Generators, and to guarantee the efficient disconnection and re-connection from/to the main power system.

7.5.2 Functions

SGC, after the data elaboration, is able to send detailed reports about the actual situation of the grid, therefore it suggests optimal procedures in order to support the telecontrol technical operators during the islanding operation mode. Under certain conditions, SGC can also activate automatic commands and setpoints to SCADA and the distributed devices.

The Master/Slaves configuration has been selected in order to control an isolated portion of the grid. This solution allows to directly manage the main electrical variables but it needs a robust and real time communication system.

The Master Distributed Generator (MDG) is chosen among the set of the available power plants, and it has the following features:

(c) Ability to vary own active and reactive power.
(d) Ability to connect itself in no voltage condition on MV grid.
(e) Ability to automatically implement the primary/secondary frequency regulation and the Q/voltage regulation.
(f) Power plant size that ensures the majority of the islanded portion of the grid.

It can be useful to remind few theoretical concepts about power/frequency regulation:

- Primary regulation: its aim is to restore instantaneously and automatically the power balance avoiding the frequency drifting. It is an intrinsic feature of a rotating generator.
- Secondary regulation: its aim is to restore the system frequency to the nominal setpoint (normally 50 Hz), varying the power of adjustable generators. It has to react in few seconds, starting from the end of the primary regulation.
- Tertiary regulation: its aim is to control the total power flow in order to fulfil the dispatching requirements and to guarantee an optimal spinning reserve on the grid and a proper operation of the distribution lines.

When the islanding operation mode is activated, MDG is voltage controlled, the so-called “forming” function: only one generator of the grid can be set in this mode, and just for the islanding operation.

MDG plays the role to maintain the reference voltage and frequency values. It works as “slack node” of the involved grid. Indeed, MDG adjusts its output current by varying the total load consumption.

For the system, it is needed that MDG could rely on always available power. In the case of hydroelectric power plants, the steady-state power setpoint can be at 50%, in such a way that, at every instant, the generator could react maintaining the grid operation stable and secure. This condition is guarantee, in terms of energy, if MDG doesn’t work at its limits of capability, so that it could react to power load peaks.

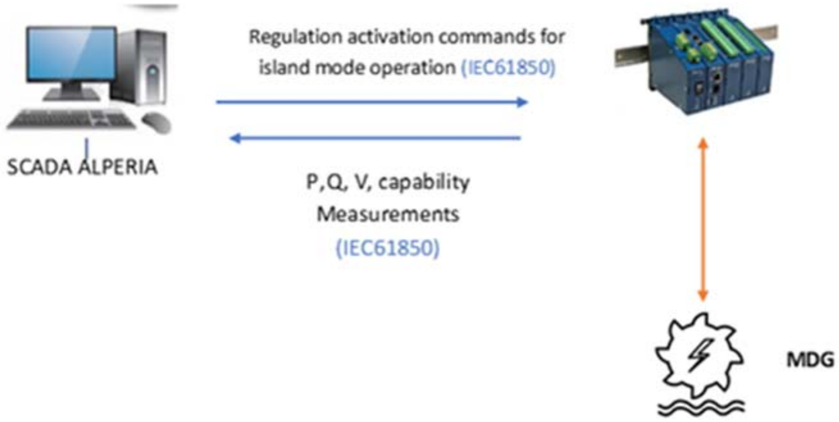

Figure 73. Instruction (setpoints) communication with field devices.

At the same time, during the configuration of the grid components, the Slave Distributed Generators (SDG) are selected, and they have the following feature:

- Ability to vary own active and reactive power, following the set points coming from the control centre.

To ensure the operation of the MDG around 50% of its power capability, it is necessary to balance the total power flow through the use of SDGs (they can be passive users too) that are involved in the islanded portion of the grid and that has been enabled to this kind of regulation.

When the islanding operation mode is activated, SDGs are current controlled, the so-called "following" function: the generators vary their power setpoints.

Usually, in normal grid connected operation, SDGs provide all the available power (it depends on the primary energy source); by the way, they have to be able to decrease and increase the power output based on remotely setpoints and taking in consideration their own capability.

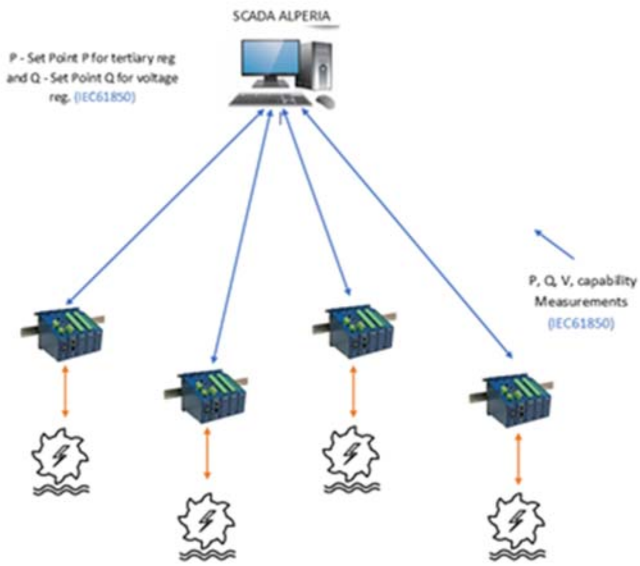

Figure 74. Instruction (setpoints) communication with SDG

As part of developments of algorithms, for control and resilience of the system through AI application in Task 4.1, there has been some tests and evaluations on the Italian pilot. The control uses the DQN method and successfully learns the load dispatching between two generators, on the basis of the costs of generators activation and also the state of the network (based on where the unbalance is heavy, the dispatching can be different to avoid line congestions.) The simulation environment is based on steady-state discrete snap calculation. There is a limit of minimum and maximum power generation for the groups (as it is in reality), therefore in some cases of excess of power consumption or generation form RES, full compensation of unbalance by generators is impossible. Examples can be seen in Figure 75 and Figure 76.

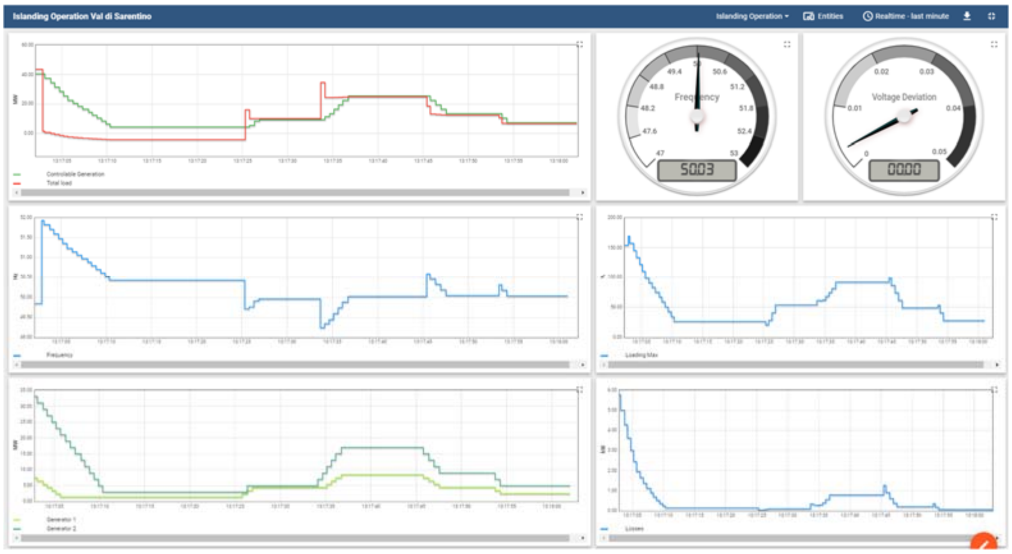

Figure 75. AI action against the load change.

Main indicators such as total unbalance, linear estimation of frequency, total lines' and transformers' losses, voltage deviation, maximum loading (congestion) and dispatched power among generators can be observed in the dashboard.

Figure 76. dispatching example by AI.

Successful implementation of the AI allows to examine various scenarios of automatic control in critical conditions with large search space and restricted calculation time.

7.6 Demo adaptation

Below a brief description of use cases and demos involved and their implementation in the modules:

7.6.1 UML representation

In figure 78 a graphical representation of the interaction between the module and involved actors:

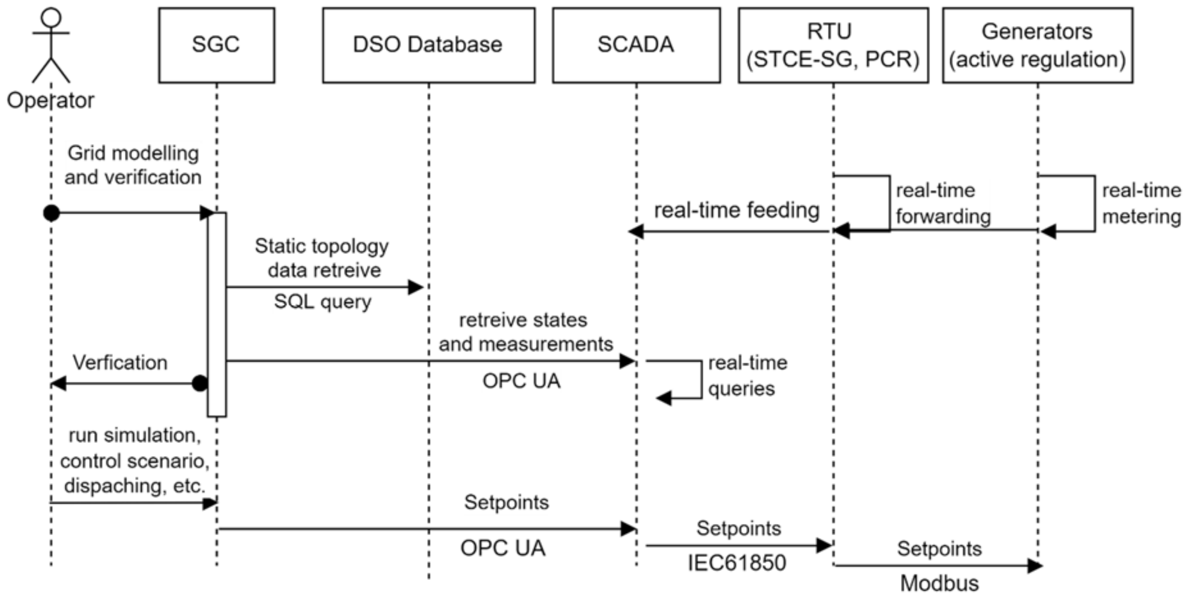

Figure 7778. Modules and actors interactions.

7.6.2 Scenarios

The main scenarios for the Italian pilot are of two types:

- In the first scenario (standard scenario) only the dispatching platform is foreseen, where commands for voltage management and reactive power management are provided;
- In the second scenario the function of the grid in island mode is foreseen.

8 FINAL REFLECTIONS AND LESSONS LEARNED

8.1 CIRCE

A smart grid is composed of three main elements. The intelligent devices (IEDs), whose function is limited to a specific area (a battery, an OLTC, etc.), then we have a communication and data exchange structure, and finally we have the control algorithms which orchestrate the IEDs in a wider context. In the specific case of FLEXIGRID, this orchestration was focused on the flexibility algorithm and the self-healing algorithm. Part of our experience during the development of these systems can be summarized in the following key aspects:

- The modelling of the network, which required a complete understanding of the topology and the elements that were present in the Villabermudo and Toranso networks. In general, the distribution networks are modelled in the DSO management systems, but it is not always possible to "export" them to formats that allow them to be represented in analysis programs such as DIgSILENT or Pandapower, so manual conversion work is still required. For mass or scalable implementations of these technologies over time, a common information framework will be required, some of which has been explored in the CIM models, but much work remains to be done to promote these technologies to DSOs and integrators.
- The behaviour of network elements, usually represented as a generation or demand profile, which depending on what is to be analysed may require a sampling frequency from minutes to hours, and a record usually spanning a whole year. Decision-making requires a significant volume and quality of data, so it is essential that the network has an adequate number of sensors and telemetry to generate a history to help identify problems. In this respect, the legal framework must be in line with the technical development, since in the case of distribution networks an important part of the data is obtained or can be deduced from individual customers, this directly implies that reasonable and respectful use of data must be ensured.
- Controllable assets that provide flexibility also have their particularities, starting with the large number of different protocols used (OPC, MQTT, IEEE-104, etc.) and the technologies involved (inverters, batteries, motors, lighting, HVAC, heat pumps, etc.), which make integration into a unified control system difficult. But perhaps the biggest challenge lies in the interaction with users, who must be motivated to offer flexibility and above all trust that centralised control is safe and fair. In that sense, exploring the future use of technologies such as blockchain and smart contracts is interesting.
- As for the TDR, the network where the installation was to be carried out was modelled and the pulse injector device (TDR) was also modelled. Numerous fault generation simulations had to be carried out and several parameters had to be modified (signal amplitude, pulse width, sampling frequency) until the solution could be validated at a theoretical level and a first approximation of the fault location algorithm could be developed, which will later be fine-tuned with the data obtained in the field. With this data extracted from the modelling and simulation stage, the physical prototype of the injector was built, which has been equipped with 4G modem communication to be able to be monitored remotely and thus be able to modify any parameter of the pulse injection and the localisation algorithm, as well as to be able to download the signals captured in the field.

Automation is a process that has been with us for many years, and over time it has covered more and more aspects of our lives. One of the latest frontiers in this movement is precisely distribution systems, where the benefits are diverse, from saving on bills, optimising the use of existing installations to promoting the incorporation of technologies that convert the energy distribution network into an active energy exchange network.

8.2 LINKS / VERD

For the load and generation forecasting algorithms as well as the congestion management and peak shaving modules that have been developed within tasks 4.2 and 4.4 of FLEXIGRID, our key outputs can be summarised as per below:

- For the identification of the requirements for controlling a set of flexibility asset, the preliminary simulation and analysis found that if a control based on global vision were not in place, the storage system would increase the monetary payment cost for the whole system. Drawing such a picture, the possibility of external control was evaluated.
- Regarding the characteristics of the hybrid inverters (with interfaces towards local load, RES, and feeding system), such an external control should disable the default control logic and rather implement a control based on a time-domain optimization. The optimization process itself is dependent on an accurate forecast, which can either foresee RES generation and load consumption in the range of a couple of days, while it can manage any unwanted errors in a rolling horizon fashion.
- Among different methods, using artificial neural networks was promising and therefore, different architecture and hyper-parameters have been tested to deduce the best ones. In a chain of resource management applications, optimizations based on Ant Colony Optimization and Greedy methods are set to comply with the forecast module.

8.3 EDYNA

In order to be able to manage an islanding operation mode of a portion of the distribution grid, particular tools have been designed within the tasks 4.6 and 6.5 of FLEXIGRID. A structured dispatching platform has been developed and the experience of trial tests has shown important lessons, that can be summarised as per below:

- Front-end and architecture
  The front-end is the interface between the operator and the system. For the security of the SCADA system the front-end must be in a local system, without connection with internet or other public or private networks.
- Grid Model rebuilding
  In previous projects (e.g., SmartNet) the importance to have the model of the grid always updated was learned. So, in this project the Grid Model rebuilding is the base for all modules developed. In this manner we do not have the problem to update the model of the grid manually, with a large waste of energy and the risk to have a model different from the real grid.
  The difficulty was in the understand and automatically acknowledge the SCADA code to rebuild the grid in the new model.
- Smart Grid Controller (SGC)

This is the core of the system: it manages the grid on the base of the measures and the estimation of the states. It was built on the experiences gained in previous project (e.g. SmartNet) and it represents an evolution and updates of that system.

- Islanding mode control algorithm
  This is the most innovative part developed for the Italian pilot inside FlexiGrid project. The need to develop this tool was born from real necessities in EDYNA. Sometimes, for works or failures, it is not possible, or with big difficult, re-feed portion of MV grid. In the traditional approach the solution is the use of generators. But now, with a lot of dispersed producers, mainly hydroelectric, we can think to use these generators already connected to the grid to solve the problem of re-supply.
  In the past EDYNA has already done some tests, also with TERNA (the Italian TSO). A lot of information was collected in these occasions, and the idea to have a tool to help the operators to manages the grid in islanded mode was born.
  The tool developed in FlexiGrid project manages the whole information to send the corrects set-point to the generators involved and gives the needed information to the operator to start and maintain the island without problems (voltage, frequency, power failure).

8.4 HYPERTECH

Summarizing, the VTES module comprises three submodules. The Comfort profiling model, the Building Thermal model and the Distributed Energy Resources models. The first one is responsible for the identification of the occupants' forecasted indoor temperature preferences. The dry bulb temperature data of the building's zones, that are responsible for the training of the submodule are obtained through IoT multi-sensors. Next, the Building Thermal module recreates a virtual modelling of the building, based on the extracted information of the IoT devices, predicting the appropriate amount of electrical energy to meet the building's needs and to provide adequate comfort to the residents. Last but not least, the DER modules include forecasting algorithms that model and estimate the energy consumption of the building thermal assets, like Heating Ventilation Air Conditioning and Electrical Water Heaters.

Combining these three submodules, the VTES module provides upwards and downwards flexibility profiles per controllable building loads in order to adjust the energy consumption in the pilot sites without disrupting the occupants' preferences. The training of the VTES module requires one-month seamless historical data with fifteen-minute interval granularity from the installed IoT devices in the premise. Also, there is a two-week validation period to evaluate the quality of the data.

As a consequent, the selection and the proper installation of the IoT device plays a vital role for the proper deployment of the VTES module. Since the modules are mainly data driven models, the success of the FLEXIGRID solution is based on them. For the stable and constant information exchange between the gateway and the HYPERTECH cloud it is prerequisite that there is access to the internet and that the Wi-fi signal is strong and stable at the pilot site.

Regarding the comfort profile modeling module, it is assumed that the occupants remain the same, which means that the same individuals interact with the building systems. The eventual introduction of new people will lead to the creation of inaccurate values in what concerns the comfort profile limits.

Finally, the VTES module was deployed in friendly user's premises which have similar building characteristics with the examined pilot sites. Therefore, the methodology was tested in similar environments to establish the integration of the VTES module to the project's pilot sites.

8.5 UNIZG-FER

The operation of smart distribution networks defined in UC5 and UC6 is improved with three developed tools: optimal topology module, third-party flexibility module, and voltage-led demand response and providing flexibility from DSO's assets module. All three modules are based on the optimal power flow formulation, which is modified according to the wanted functionality of each module. The lessons learned from the development of tools and provided tests can be summarized as follows:

- There are multiple ways in which DSOs can improve network conditions. Even though there are numerous positive impacts of the DERs integration, they could lead to different problems including congestion, overvoltage, and undervoltage. Both end-users flexibility and the flexibility of DSOs assets show great potential in the mitigation of the issues in a grid.
- Installation of automatic relays enables the reduction or even complete mitigation of technical issues in distribution networks by changing the network's topology. Even though a predetermined location of relays and allowed frequency of tripping limits the possible number of topologies, reconfigurations that occur help DSOs in resolving technical challenges but also allow further integration of DERs.
- End-users equipped with smart meters and advanced communication infrastructure have great potential in providing flexibility services by increasing or decreasing their electricity consumption after receiving a signal from a DSO. Based on the results of the OPF-based tool, the amount of flexibility of each end-user is calculated. After the flexibility needs are calculated, the communication with the equipment installed at end-users sites enables the increase or decrease of consumption.
  In some time periods, the flexibility provided by end-users is not enough to completely mitigate the problems in a network. In those cases, DSOs must find other solutions. One of the solutions is relying on the assets and physical devices already installed in a network. The developed module shows that changing the operating schedule of on-load tap changers, shunt capacitors, and other assets can change the injection of power on a TSO-DSO interface and that way provides a service that will lead to the improvement of network conditions.

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