European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project

HOLISTICA

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Executive Summary

Background

In previous projects, some technical restrictions were encountered, openning the opportunity for further research with the idea to include not only PV inverters but also distributed storage units (batteries) and EV charging control in an unbalanced LV network with dynamic loads and a higher reactive power presence.

The HOLISTICA project, carried out at Syslab of DTU, takes into account all the above technologies and more advanced characteristics of the network.

Test scenarios and control strategies

Rural and urban grid scenarios using four voltage control strategies based on real-time measurements from different nodes are considered: no control (NC), tap control (T-control), reactive power control (Q-control) and holistic combinated tap and reactive power control (QT-control).

Results comparison

The impact of each approach is evaluated by comparing the hosting capacity of the network, the reduction of power losses and the increment of grid stability, whilst streamlining the number of OLTC operations.

Control strategy	Hosting capacity (pu)	Energy losses (%)	Losses reduction (%)	Number of operations
NC	1.93	4.78	0.00	0
T	3.12	4.66	2.56	19
Q	3.05	4.42	6.31	0
QT	3.16	4.33	9.35	20

Comparison results between the different control strategies

The table above shows the performance of the control strategies. While enabling a better voltage and overloading contraint management, the application of OLTC operation increases up to 61.65 % the nominal hosting capacity; and, by adding a centralized reactive power control of distributed generation, the efficiency of the electrical grid can improve a 9.35 %.

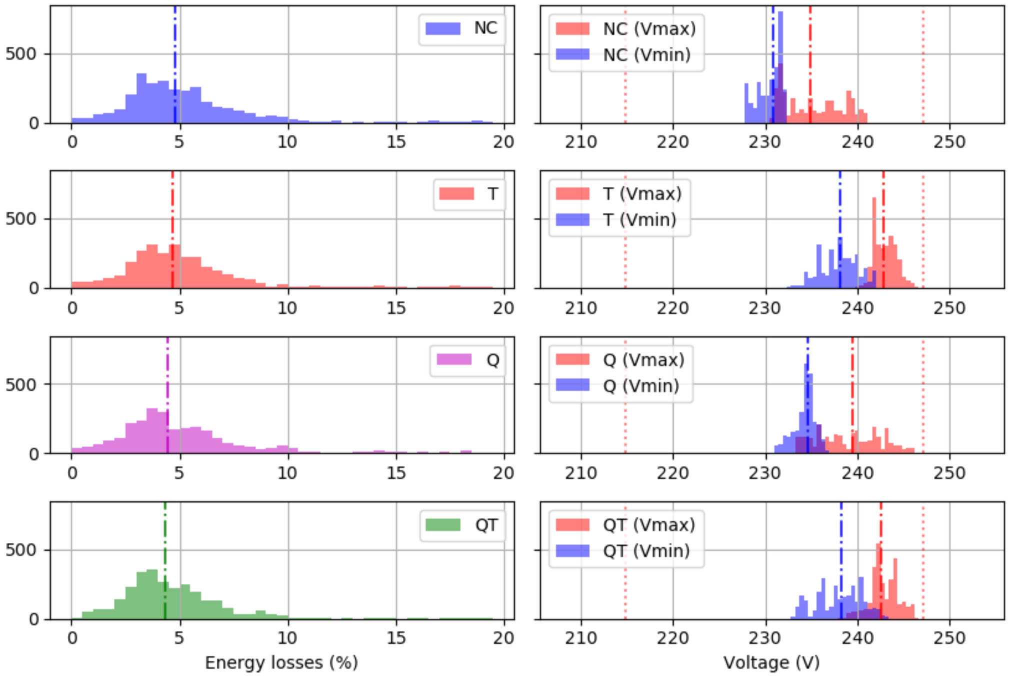

Figure 1: Losses and voltage profiles

Conclusions and future work

Results show that the smart distribution transformer with OLTC can be considered an essential element of distribution networks that provides optimal grid flexibilities and reliability, thus maximizing the integration of renewables whilst delaying expensive and long-term grid reinforcement - especially when it is coordinated with existing distributed generation, batteries and EV.

In previous works, the control system included an optimal power flow implementation using the topology and measurements from all the devices in the network. This information is not usually available or it is difficult to ensure in a real production environment. Thus, additionally to the inclusion of batteries and EV, the topology of the network was omitted in the control system, and the optimal power flow was reduced to follow simpler and closer to real-time control rules. The latest assumption resulted in a reduction of the benefit in energy losses savings with respect to the complete (OPF) version of the control system.

In the near future, we intent to take the control a little further by omitting also the availability of measurements on the feeder, thus, estimating the voltages and current limits based on the transformer or secondary substation measurements. Moreover, including new functionality to the control system, such as flexibility, secondary services, or energy optimization using energy storage systems.

1 General Information of the User Project

USER PROJECT	
Acronym	**HOLISTICA**
Title	**Holistic Optimization of Losses using an Improved Synergy of Technologies under an Innovative Coordination Algorithm**
ERIGrid Reference	**05.008-2018**
TA Call No.	**05**

HOST RESEARCH INFRASTRUCTURE			
Name	**PowerLabDK, SYSLAB** **Department of Electrical Engineering, Technical University of Denmark (DTU)**		
Country	**Denmark**		
Start date	**17/06/2019**	**Nº of Access days**	**6**
End date	**20/09/2019**	**Nº of Stay days**	**16**

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2 Research Motivation

2.1 Objectives

The HOLISTICA (**H**olistic **O**ptimization of **L**osses using an **I**mproved **S**ynergy of **T**echnologies under an **I**nnovative **C**oordination **A**lgorithm) project will be the first to physically test an innovative proposal (control algorithms) for the holistic technical management of the Low Voltage Cell (from the *”Web-of-Cells*” architecture), proposing the MV/LV Transformer Substation as a control and communication hub for the Low Voltage Grid.

Voltage rise is the most critical constraint for the integration of DG in rural electric distribution networks. The DSO is responsible for maintaining voltage limits, however DSO does not have direct access to the DGs.

Coordinated voltage control concepts, as the proposed for research in the HOLISTICA project, can delay expensive and long-term grid reinforcement while increasing the DG hosting capacity of electric distribution networks.

2.2 Scope

The scope of the proposed research is to test different voltage control concepts allowing a cost-efficient integration of high shares of DG. These concepts have to maintain a high level of quality of supply while achieving economic benefits in comparison to network reinforcement. This project proposes a coordinated voltage control architecture between MV/LV distribution transformer with OLTC, solar inverters and distributed storage units (EV with V2G capabilities or batteries).

First, a conventional control will be tested with a local voltage control for the distribution transformer with OLTC, the PV-inverters and the distributed storage units. There is no communication between the grid controller and the mentioned electric resources. Each local resource works on his own, taking into account local available voltage measurements and try to balance it with the help of a local controller.

Afterwards, the integration of voltage measurements (smart meters and/or remote sensors) along the LV network with a simple optimization algorithm for distribution transformer tapping will be tested. PV-inverters and distributed storage units will be working on their own.

Next step will be to test an integrated coordination between the distribution transformer with OLTC and the inverters. Distributed storage units will be still working on their own.

Finally, a holistic coordination algorithm will be tested with the aim to enhance the renewable hosting capacity of the LV distribution grid and to reduce losses, whilst reducing inverters curtailment and enhancing health-index of distributed resources. In this case there will be a coordinated voltage control architecture between MV/LV distribution transformer with OLTC, solar inverters and distributed storage units (EV or batteries).

3 State-of-Technology

In previous projects, some technical restrictions were encountered, openning the opportunity for further research with the idea to include not only PV inverters but also distributed storage units (batteries) and EV charging control in an unbalanced LV network with dynamic loads and a higher reactive power presence.

The HOLISTICA project will be the first to physically test an innovative proposal (control algorithms) for the holistic technical management of the Low Voltage Cell (from the *”Web-of-Cells*” architecture), proposing the MV/LV Transformer Substation as a control and communication hub for the Low Voltage Grid.

The proposed research will improve the current knowledge regarding the coordination of the technologies capable of providing a distributed voltage balance in the LV distribution network, avoiding technologies miscoordination that can cause undesired additional losses and curtailment, the limitation of the hosting capacity of electrical networks and the over operation of distribution transformers with OLTC, distributed batteries or inverters.

4 Executed Tests and Experiments

This section covers the test protocol or plan for proving the control strategies feasibility and efficiency. Although the principles have already been proven in mathematical models and power flow simulations, the laboratory tests a step forward towards a industrial product.

First, the testing consists in a strategy comparison that will provide a complete steady state profile of the strategies' performance in different distribution networks and load/generation scenarios.

Provided the control strategies works properly in the comparison tests, a validation test is proposed using a more realistic and dynamic approach. In this validation, a flexible distribution network will be configured to ensure that the control strategy is able to perform well in an unbalance situation.

4.1 Test Plan

As SYSLAB is a LV laboratory, a back-to-back connection of a conventional transformer plus a distribution transformer with OLTC, inside a ship container, is proposed. LV enters to the container and it is elevated to MV by means of the conventional transformer. Then, a grounded connector is used to join the MV of the conventional transformer with the MV of the distribution transformer with OLTC, that reduces voltage to LV out of the container. Therefore, MV is confined inside the container.

The smart distribution transformer can be connected to the following resources:

- Distributed Energy Resources: 2 wind turbines (11kW and 10kW), 3 PV plants (10kW, 10kW and 7 kW), Diesel generator set (48 kW / 60 kVA).

- Energy storage: 15 kW / 120 kWh vanadium redox flow battery.

- Energy loads: Controllable loads (75 kW, 3 x 36 kW). Connected to the PowerFlexHouse facility, an intelligent office building as well as two domestic houses with controllable loads (10 to 20 kW). The SYSLAB facility is further interconnected with the NEVIC electrical vehicle test facility at DTU/Risø. The NEVIC facility includes chargers for electrical vehicles and has access to an increasing fleet of electrical vehicles used for test purposes and internal transport between PowerLabDK facilities.

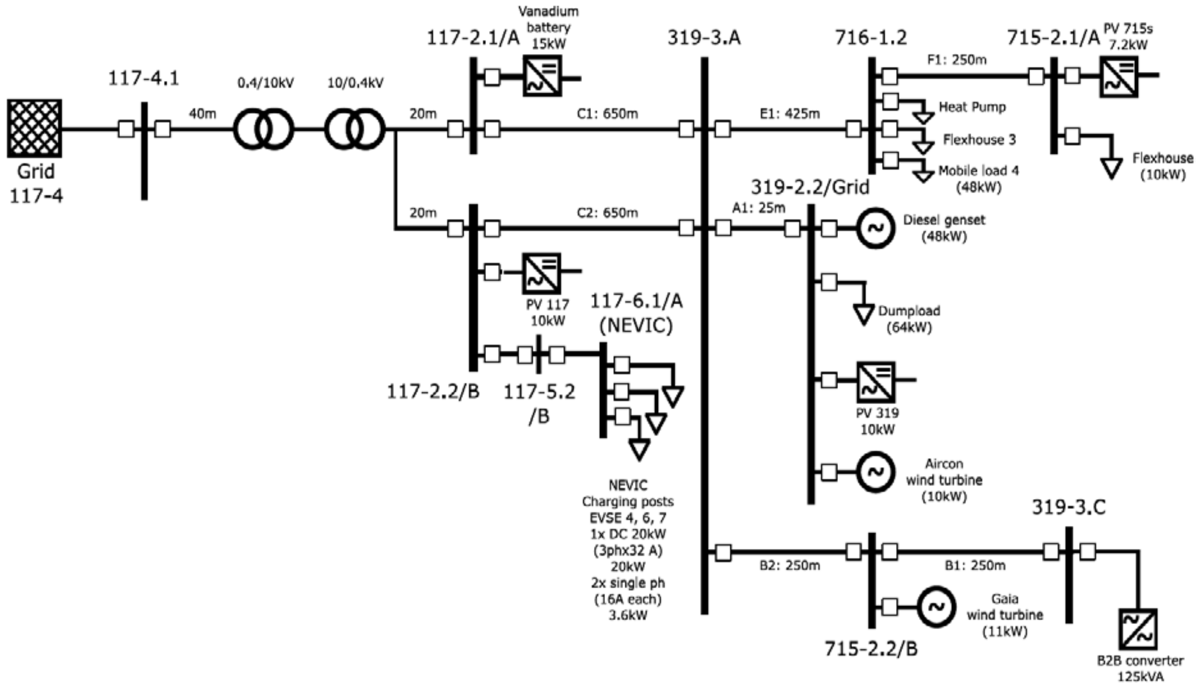

Figure 2: Distributed energy sources and load are all connected in one distributed control and measurement system that enables very flexible setup with respect to experimental configuration.

The coordination of MV/LV distribution transformer with OLTC, solar inverters and distributed energy storage units (batteries or EV with V2G capabilities) will be assessed under different coordination levels. Different control algorithms (normal, advanced) will be checked under a set of different operation conditions.

In addition, reverse power flow conditions, in the case that distributed DG excess the LV loads, will be tested along with remote sensors devices. Besides, the relation between voltage, LV load characteristics (ZIP model) and power consumption will be assessed.

There are different levels of coordination:

1. First, a conventional control will be tested with a local voltage control for the distribution transformer with OLTC, the PV-inverters and the distributed storage units, including electric vehicles with V2G capability. There is no communication between the grid controller and the mentioned electric resources. Each local resource works on his own, taking into account local available voltage measurements and try to balance it with the help of a local controller.

2. Afterwards, the integration of voltage measurements (smart meters and/or remote sensors) along the LV network, with a simple optimization algorithm for distribution transformer tapping, will be tested. PV-inverters and distributed storage units will be working on their own.

3. Next step will be to test an integrated coordination between the distribution transformer with OLTC and the inverters. Distributed storage units will be still working on their own.

4. Finally, a holistic coordination algorithm will be tested with the following objectives:

   - To reduce LV losses.
   - To improve the hosting capacity (RES and EV) of the LV distribution grid.
   - To reduce the curtailment of inverters.

- To reduce the number of the operations and/or the operating times, in order to improve the health-index of the distributed devices.

In this case, there will be a coordinated voltage control architecture between MV/LV distribution transformer with OLTC, solar inverters and distributed storage units (EV and/or batteries and EV with V2G capabilities).

4.2 Standards, Procedures, and Methodology

The test procedure is intended to be composed of two factors:

1. Test configuration: the topology and control strategy to be tested.
2. Load-generation case: power consumption and generation, and grid voltage.

Test configuration

Each test configuration will consist in a combination of the following parameters:

- Laboratory scenario (η): two configurations were proposed, the rural network (R) and the urban network (U), defined below.

$$\eta \in \{R, U\}$$

- Control strategy (ζ): the three control strategies, no control (NC), tap control (T), reactive power control (Q), reactive power and tap control (QT).

$$\zeta \in \{NC, T, Q, QT\}$$

- Distributed generation penetration (σ): a percentage of distributed generation penetration with respect to the peak load (maximum load in the laboratory scenario). This penetration will be emulated using the laboratory resources.

$$\sigma \in [0, 2]$$

For testing purposes, the values will be limited to $\sigma \in \{0, 0.5, 1.0, 1.5\}$.

Load-generation case

For every test configuration, a full load-generation profile grid will be tested, by modifying the total power consumption percentage (α), and limiting the total active power generation percentage (β). This will allow the analysis of different realistic load and generation profiles based on other studies and actual measurements.

$$\alpha \in [0, 1] \ \beta \in [0, 1]$$

For testing purposes, the values will be limited to $\alpha, \beta \in \{0, 0.2, 0.4, 0.6, 0.8, 1\}$.

A load-generation case will be generated by dispatching α and β proportionally to the nominal power between the generators and loads available in the test configuration. Thus, provided the testing limitation, there will be a maximum of 36 load-generation cases.

4.3 Test Set-up(s)

Three different networks are proposed for the testing: rural, urban, and flexible. Rural and urban networks will work as a control performance measurement, while the latest serves as a validation case.

Rural network

The main purpose of the use of a typical rural network is to analyse the differential contribution for each control element. Ideally, there will be cases where the network voltage is out of limits in the last bus during no control operation, and the control strategies will be able to avoid these situations. In cases where the limits are correct, not only should the algorithm keep the technical requirements within limits, but also optimize the losses of the network.

After the DTU laboratory review, the proposed network is shown below.

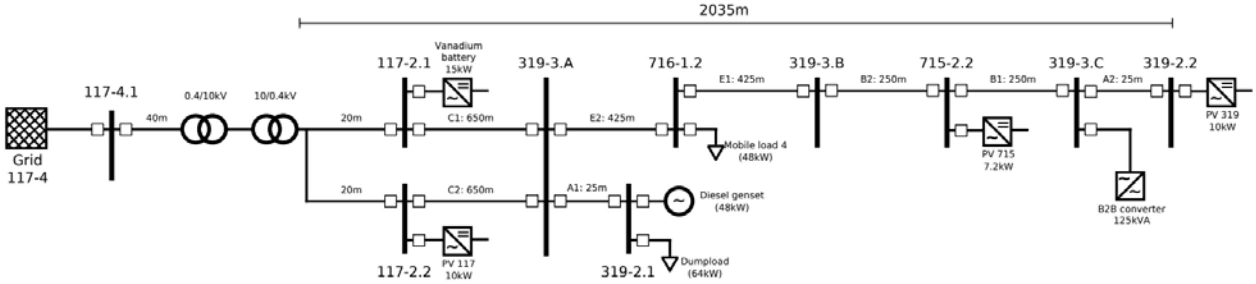

Figure 3: Rural network single line diagram.

The rural network contains 2 load units (Mobile load and Dumpload) of 112 kW, 3 generation units (Diesel, Vanadium battery, and B2B converter) of 188 kW, and 3 extra possible generators (PV) for reactive power control. The power will be limited to 35% of the power transformer, thus, the maximum load consumption will be 58 kW, and the maximum generation will be 86.9 kW.

Urban network

The main purpose of the urban network is to test the control system stability when multiple control elements affects different feeders. As per tested in simulation, this should difficult the voltage control and system optimization, but provide a better insight of the limitations of a possible industrial product. After the DTU laboratory review, the proposed network is shown below.

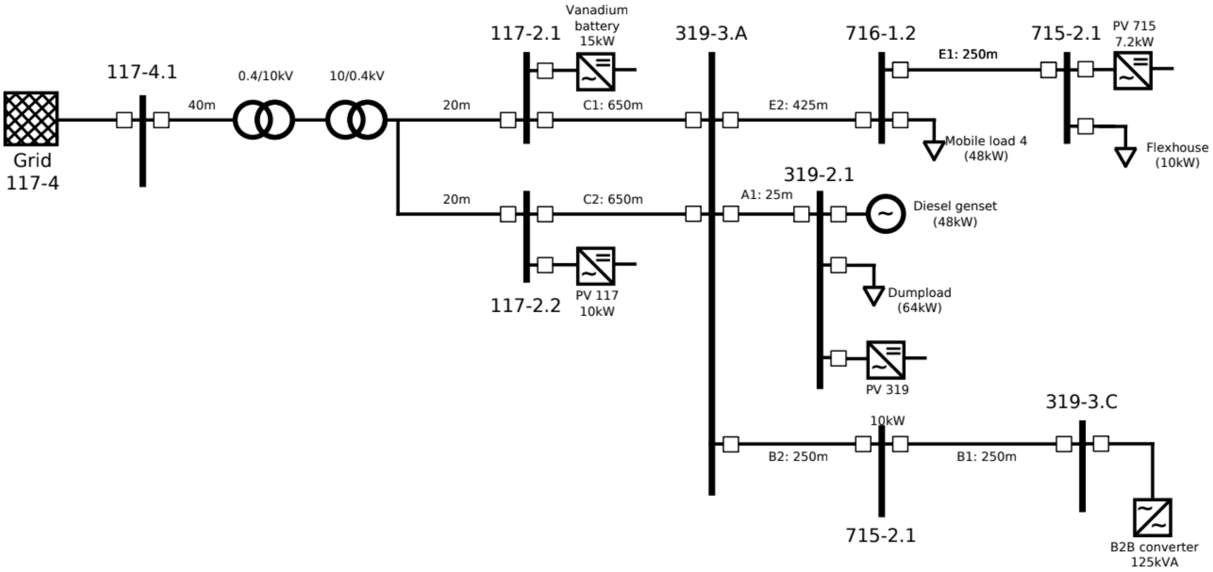

Figure 4: Urban network single line diagram.

The rural network contains 3 load units (Mobile load, Dumpload, and Flexhouse) of 122 kW, 3 generation units (Diesel, Vanadium battery, and B2B converter) of 188 kW, and 3 extra possible generators (PV) for reactive power control. The power will be limited to 35% of the power transformer, thus, the maximum load consumption will be 58 kW, and the maximum generation will be 86.9 kW.

Flexible network

Once the differential control strategy comparison and analysis has been performed, a dynamic validation case is necessary to approve the implementation of an industrial product. In order to archive the validation, a complex unbalanced laboratory scenario will be implemented, and the load and generation units will act freely. The objective is to obtain realistic results about the efficacy of the control system.

Tentatively, the T and QT control strategies will be tested during a 24-hour period. However, depending on the time limitations, this could be restricted to the reactive power and tap control strategy, and to the laboratory schedule.

After the DTU laboratory review, the proposed network is shown below.

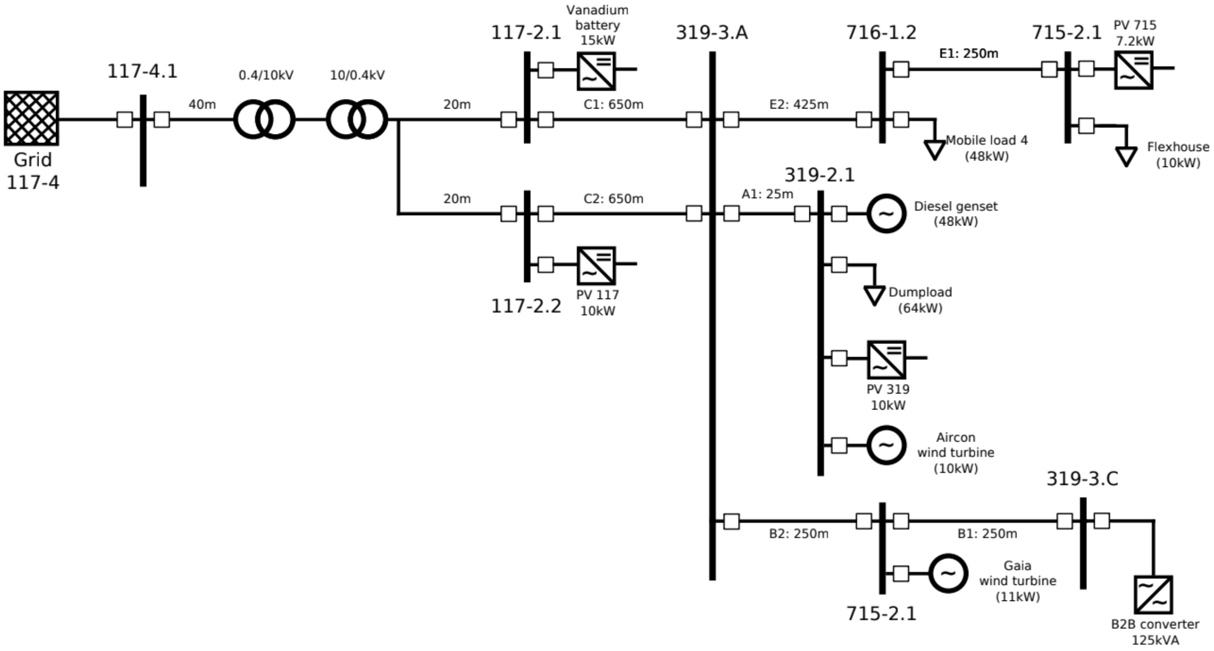

Figure 5: Flex network single line diagram.

The rural network contains 3 load units (Mobile load, Dumpload, and Flexhouse) of 122 kW, 3 fixed generation units (Diesel, Vanadium battery, and B2B converter) of 188 kW, and 5 renewable generation units (PVs, wind turbines) of 48.2 kW. Further limitations could be performed depending on the power flow.

Test summary

In total, 28 test configurations will be implemented, and 2 free recording cases. In total 888 scenarios will be tested, and a 48h validation test is planned. The test cases are summarized in the table below.

Table 1: Test case summary

#	η	ζ	σ	α	β	Total
1	R	NC	0	-	all	6
2	R	NC	0.5	all	all	36
3	R	NC	1	all	all	36
4	R	NC	1.5	all	all	36
5	R	T	0	-	all	6
6	R	T	0.5	all	all	36
7	R	T	1	all	all	36
8	R	T	1.5	all	all	36
9	R	Q	0.5	all	all	36
10	R	Q	1	all	all	36
11	R	Q	1.5	all	all	36
12	R	QT	0.5	all	all	36
13	R	QT	1	all	all	36
14	R	QT	1.5	all	all	36
15	U	NC	0	-	all	6
16	U	NC	0.5	all	all	36
17	U	NC	1	all	all	36
18	U	NC	1.5	all	all	36
19	U	T	0	-	all	6
11	U	T	0.5	all	all	36
21	U	T	1	all	all	36
22	U	T	1.5	all	all	36
23	U	Q	0.5	all	all	36
24	U	Q	1	all	all	36
25	U	Q	1.5	all	all	36
26	U	QT	0.5	all	all	36
27	U	QT	1	all	all	36
28	U	QT	1.5	all	all	36
29	F	T	-	-	-	24h
30	F	QT	-	-	-	24h
						888 + 48h

4.4 Data Management and Processing

All communications will be handled by the DTU's DERLab API, which standardizes the communication within the laboratory. The control system and the OLTC tap changer will communicate via Modbus/TCP.

All control and measurement variables were recorded during the tests with a frequency of 200 ms per sample. The data was treated afterwards to generate a result for each test case. The precision was defined to the most detailed value allowed by the measurement device and the DERLab API.

During the project, some communication drivers were in development or outdated, in these cases, the communication was handled by the control system using Modbus/TCP directly to the laboratory equipment.

5 Results and Conclusions

Rural and urban grid scenarios using four voltage control strategies based on real-time measurements from different nodes are considered: no control (NC), tap control (T-control), reactive power control (Q-control) and holistic combined tap and reactive power control (QT-control).

The impact of each approach is evaluated by comparing the hosting capacity of the network, the reduction of power losses and the increment of grid stability, whilst streamlining the number of OLTC operations.

Table 2: Comparison results between the different control strategies.

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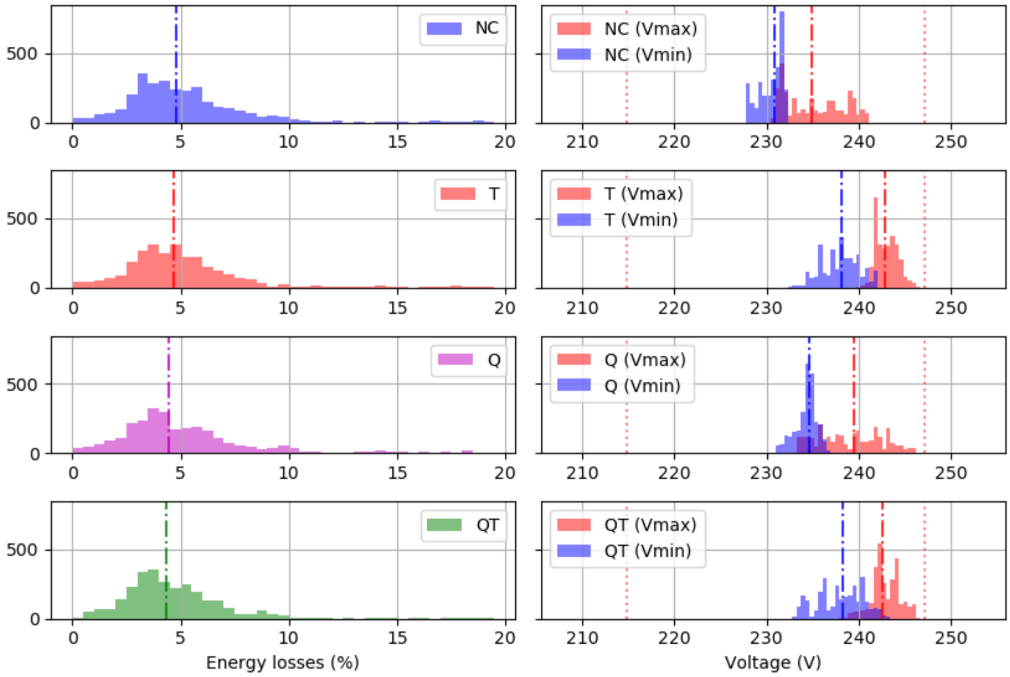

Figure 6: Losses and voltage profiles.

Results show that the smart distribution transformer with OLTC can be considered an essential element of distribution networks that provides optimal grid flexibilities and reliability, thus maximizing the integration of renewables whilst delaying expensive and long-term grid reinforcement - especially when it is coordinated with existing distributed generation, batteries and EV.

In previous works, the control system included an optimal power flow implementation using the topology and measurements from all the devices in the network. This information is not usually available, or it is difficult to ensure in a real production environment. Thus, additionally to the inclusion of batteries and EV, the topology of the network was omitted in the control system, and the optimal power flow was reduced to follow simpler and closer to real-time control rules. The latest assumption resulted in a reduction of the benefit in energy losses savings with respect to the complete (OPF) version of the control system.

6 Open Issues and Suggestions for Improvements

In the near future, we intent to take the control a little further by omitting also the availability of measurements on the feeder, thus, estimating the voltages and current limits based on the transformer or secondary substation measurements. Moreover, including new functionality to the control system, such as flexibility, secondary services, or energy optimization using energy storage systems.

7 Dissemination Planning

The project results were presented at ERIGrid final event. A success story was published on the ERIGrid website.

The project results will also be presented at the CIRED 2020 Berlin Workshop on 4-5 June 2020, reference [1], both as presentation and as a paper in the conference proceedings.

8 References

[1] A. Ulasenka, A. Gastalver-Rubio, et al., “Coordinated Operation of Distributed Energy Resources to Enhance Local Flexibility”, in *CIRED 2020 Berlin Workshop*, paper 130, 2020.

9 Annex

9.1 List of Figures

9.2 List of Tables