



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

Technical Report TA User Project

Z-NET – ERIGRID

Pre-normalisation of grid impedance measurement in the power line communication frequency band - Grid impedance impact on PLC

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Abbreviations

| | |
|----------------|--|
| <i>DC</i> | Data Concentrator |
| <i>FDGI</i> | Frequency Dependant Grid Impedance |
| <i>HES-SO</i> | Haute École spécialisée de Suisse occidentale |
| <i>HEVS</i> | HES-SO Valais-Wallis |
| <i>PLC</i> | Power Line Communication |
| <i>RSSI</i> | Received signal strength indication |
| <i>SM</i> | Smart Meter |
| <i>SNR</i> | Signal to noise ratio |
| <i>TA</i> | Trans-national Access |
| <i>TSR</i> | Tratamiento de la Señal y Radiocomunicaciones research group at UPV/EHU |
| <i>UPV/EHU</i> | Universidad del País Vasco / Euskal Herriko Unibertsitatea (University of the Basque Country, Spain) |

Executive Summary

The large-scale deployment of smart meters relies widely on the usage of power line carrier technology for data communication (PLC). On top of various interferences, the Frequency Dependent Grid Impedance (FDGI) measured on the low voltage network greatly influences the propagation of the power line signals and can thus impact the reliability and speed of the communication for smart meters. The precise measure of the frequency dependent line impedance is presently ill defined and only possible with some experimental instruments. This issue motivated the Swiss Federal Office of Energy SFOE to support the Z-NET project: 'Pre normalization of grid impedance measurement in the power line communication frequency band. The impact of time constant FDGI on PLC has been studied and well documented by the partners of the Z-NET project. But so far, no consensus could be found about the actual influence of Time Variant Grid Impedance on the robustness of advanced PLC systems. How much do strong variations of the grid Impedance due to commutation of semi-conductors, occurring repetitively within one fundamental cycle at 50 Hz impact on PLC communication channels? The question can only be answered after further tests are conducted in laboratory conditions, in the absence of non-controlled perturbation sources.

The ERIGrid Z-NET measuring campaign is part of pre-normalisation activities for grid impedance measurement in the frequency band 9 to 500 kHz, with focus on Advanced Metering Infrastructure based on power line communication (PLC) and dedicated to future functionalities of Smart Grids. The measuring campaign aimed to gain a better understanding of the communication process and of which parameters or type of electronic loads affect the most the communication channels for advanced PLC systems. This knowledge will help the authors finalizing the specification of a time variant frequency dependent grid impedance standard to be developed in the frame of the Z-NET project.

TECNALIA premises emulate a LVAC distribution grid with two 500m line sections connected in series and several distribution cabinets equipped with Smart Meters (SM) which can be connected to the lines in a flexible manner. The cabinet at the head of the distribution line is equipped with a PRIME PLC Data Concentrator (DC) while the other cabinets are equipped with 10 Smart Meters provided by different suppliers. Perturbating loads with a specific time variant frequency dependent impedance were connected to the distribution line at the level of the Smart Meter cabinets. The impact of the loads on the transmission quality of Wide Band PLC in the CENELEC A frequency range were measured with two different types of 'Packet Sniffers'. Successful measurements of Frequency and Time Dependent Grid Impedance (FTDI) up to 500 kHz, signal attenuation along the line, as well as electric noise at the loads coupling points were realised in complement to transmission quality for each load configuration.

Additionally, a Line Impedance Stabilizer device and an EMC filter, both developed by Schaffner, the industrial partner of Z-NET project, were connected in series between the electronic loads and the Smart Meter. The purpose of this impedance stabilizer is to modify actively the access impedance at the Point of Common Connection of Smart meter within the CENELEC A band in order to improve the quality of PLC communications. The tested impedance stabiliser brought very positive results, improving significantly the communication in case of noisy environment [1].

The partners of the Z-NET project did not only find in TECNALIA the appropriate infrastructure for the demanding measurement campaign; they could also rely on the support of TECNALIA team.

1 General Information of the User Project

| | |
|--|--|
| User Project acronym | Z-NET - ERIGRID |
| User project title | Pre-normalisation of grid impedance measurement in the power line communication frequency band – Grid impedance impact on PLC |
| Name of the ACCESS PROVIDER | TECNALIA |
| INSTALLATION name | Smart Grid Technologies Laboratory |
| Name of the ACCESS PROVIDER representative | Emilio Rodríguez |
| Name of the User Group Leader | Dominique Roggo (HES-SO) |
| User Group | Dilan Ben M'Rabet (HES-SO), Cédric Pellodi (SIG-GE), Noelia Uribe Perez (TECNALIA), Prof. David de la Vega, Igor Fernández, Mikel Martínez (UPV/EHU) |
| Home Institution of the User Group Leader | University of Applied Sciences and Arts, HES-SO Valais-Wallis, Switzerland (HEVS) |
| Access period | 12.10.2019 – 22.11.2019 |
| N° of Access Days | 7 |

2 Research Motivation

The trend of our society is to continuously improve and increase the performance of the different technologies available. The electrical network is not lacking in this respect. In the United States, 86.8 million smart meters were already installed in 2018, 88% of which were installed in private households. [2]

Smart Meters play a decisive role in the energy transition as they allow to monitor energy consumption or production at the grid users and thus determine which devices and actions are the most effective in terms of energy-consuming, a concrete way to save costs. Smart meters are part of a wider range of energy-saving measures updating the Swiss electricity grid with a view to rationalising energy. [3] With the energy supply act and its ordinance (LApEI and OApel) defining the framework for the deployment of intelligent measurement systems, 80% of the conventional meters installed in Switzerland should be replaced by smart meters by 2028. [4]

Power Line Communication Systems (PLC) is a critical enabler for the roll-out of Advanced Metering Infrastructure in Europe. Smart Meters with regular data exchange capacity are dedicated to a more efficient management of consumption and use of Distributed Energy Resources and in fine to energy savings. Mains communicating systems are considered as a cost-effective solution to read out smart meters as the grid infrastructure is owned by the Distribution Systems Operators, avoiding cost for third party communication.

Two main alliance in Europe provide modern and advanced Power Line Communication protocols in the frequency range between 34 and 92 kHz, according to the rules defined by CENELEC : PRIME and G3-PLC.

Power Line Communications signals are affected by the injection of electrical noise by the various power electronic equipment used in renewable sources or electronic loads. Additionally, low grid impedances also contribute to signal attenuation. Grid impedance is strongly affected by resonances in EMC filters integrated in electronic devices and converters. The so-called 'notching effect' by resonances is well described but is not yet considered in the standardisation process.

The Figure 1 represents a simplified schematic of the communication channel for PLC. The attenuation effect on the communication signal, due to the so-called 'access impedance' $ZA(t)$ is well represented on the example displayed in the following picture. Even if we have a relatively clear picture through measurement or simulation on the effect on signal attenuation due to EMC filters built with passive components, it is difficult to anticipate their effect on the communication system and the possible impact on communication robustness.

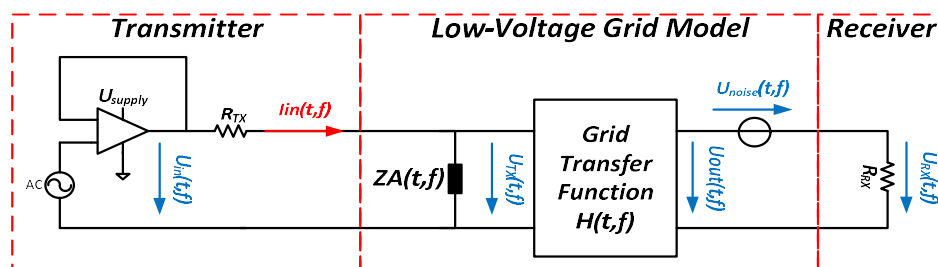


Figure 1: Schematic representation of a PLC communication channel

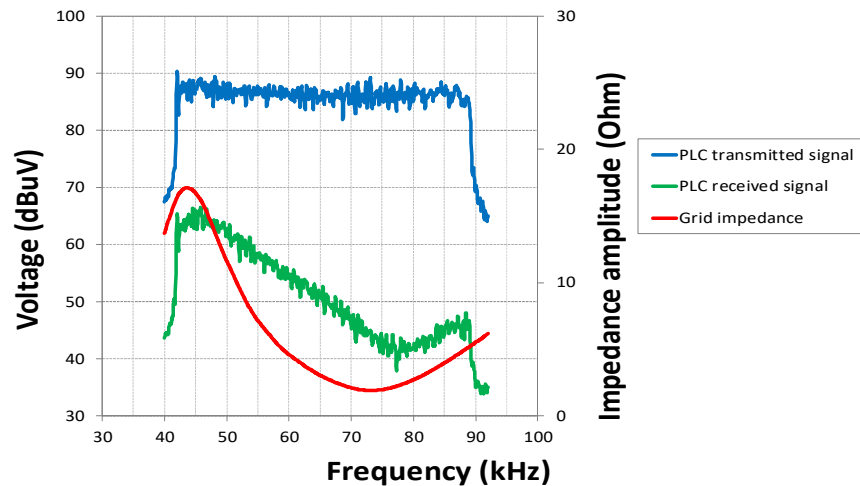


Figure 2: Example of the effect of Access Impedance on the signal levels [5]

We are facing much larger difficulties when trying to anticipate on the impact of nonlinear loads based on semiconductors, like power supplies, on the communication robustness. The objective of the proposed measuring campaign is to get a better understanding of the attenuation process and on the impact on communication robustness due to nonlinear commuted loads. A better understanding will help us to create a model and finally to specify a standard impedance for the calibration of Impedance meter. According to the discussion we had with industrial supplier of Advanced PLC communication solutions integrated in dedicated chip, the fast variation of spectral grid impedance with a 50 Hz cycle can significantly reduce the communication robustness or speed. However, this issue has not been systematically analysed yet.

Effect of linear and non-linear access impedances on communication robustness will also depend on the length and type of cables connecting the smart meters together and to the data concentrator, according to the scheme represented on Figure 3.

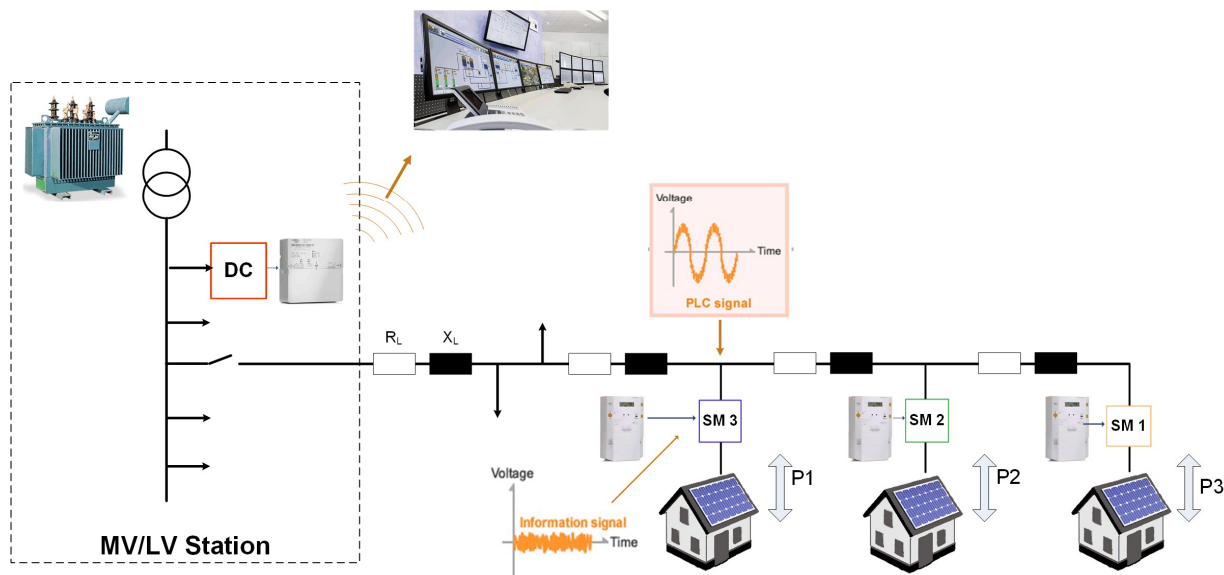


Figure 3: General test set-up for the assessment of PLC systems quality

The large-scale deployment of smart meters relies widely on the usage of power line carrier technology for data communication. The precise measure of the frequency dependent line impedance is presently ill defined and only possible with some experimental instruments. This issue motivated the

Swiss Federal Office of Energy SFOE to support the Z-NET project: 'Pre normalization of grid impedance measurement in the power line communication frequency band'. [1]

2.1 Objectives

1. Determine the effect that different electronic charges may have on the quality of communication channels for advanced PLC systems and which ones further impact the network.
2. Test the impact of the impedance stabilizer developed by the Schaffner company on the network impedance and check that it contributes to the improvement of PLC communication.
3. Analyse the signals sent by smart meters to better understand the effect of different loads on them.

2.2 Scope

Two measurement campaigns were carried out together with UPV/EHU, Schaffner and SIG-GE in the frame of the ERIGRID Z-NET action at the TECNALIA laboratory for PLC communication in Bilbao, Spain. The objective of the measuring campaign was to assess the impact of Time Variant Grid Impedance on advanced Power Line Communication systems. The test results will serve as a basis for the specification and the design of the Time Variant Grid Impedance reference standard which has to be developed in the frame of WP3 of Z-NET project.

A three days preliminary measuring campaign was organized with the participation of HEVS and UPV/EHU in October 2019 in order to evaluate the existing TECNALIA test bench, suggest possible modifications and check the available equipment. Preliminary measurements of a Time Variant Grid Impedance were realized with the help of the impedance meter developed by UPV/EHU with different equipment. Some tests realized with diode rectifier and capacitive load built with discrete components showed the limitation of such a circuit and provided requirements for the circuit realized by TSR for the main test campaign. See Figure 4.

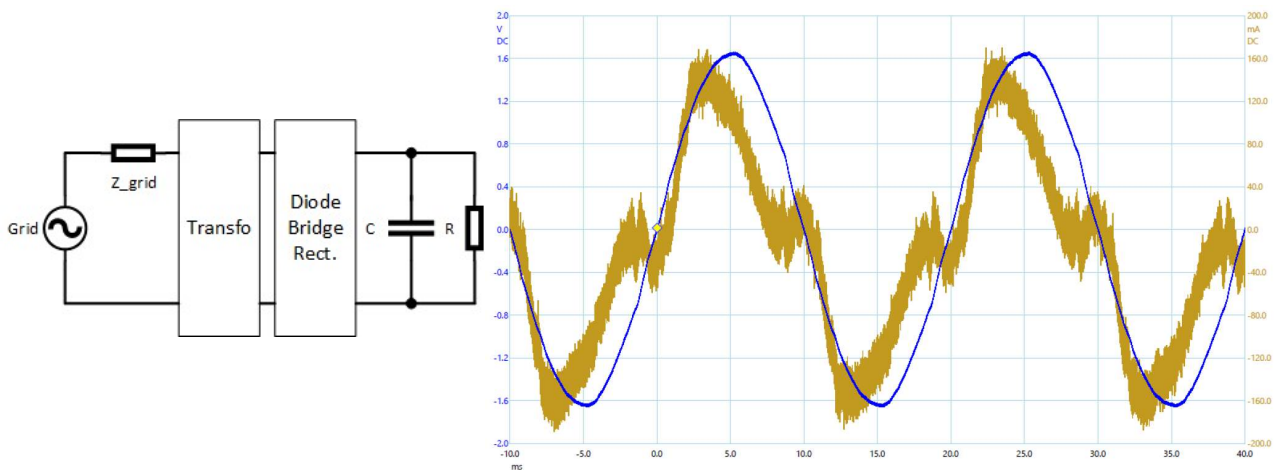


Figure 4: Example of a load generating a time varying impedance with non-linear a current waveform

Based on preliminary results, a test protocol and specifications for the different scenarios for the 5 days main measurement campaign in November 2019 were established, with the participation of UPV/EHU, HEVS, SIG-GE and Schaffner. The aim of this measurement campaign was to measure the effects that the different loads can have on the available PLC Network and consumers loads available. With these loads, several configurations could be analysed by combining them or placing them at different points in the circuit. For each given configuration, several measurements have been performed.

3 State-of-the-Art/State-of-Technology

Techniques and instrumentation to measure frequency dependent grid impedance have been developed within several research institutions the last decades. Objectives, methods and results vary greatly. HES-SO Valais-Wallis has been actively working on the development of an impedance-meter since year 2010. A first prototype was functional in 2012. [6]. The TSR team at UPV/EHU has also developed an impedance meter in order to evaluate the communication channels for advanced PLC [7]. When defining specifications for their impedance meters, most institutions put an emphasis on the analysis of EM interferences between power electronics devices in laboratory or on the field: accurate measurement of magnitudes and phase on a large frequency range, with a light portable equipment. For most of them, the measuring process is time consuming and a fast measurement of time varying FDGI within a 50Hz cycle stay challenging.

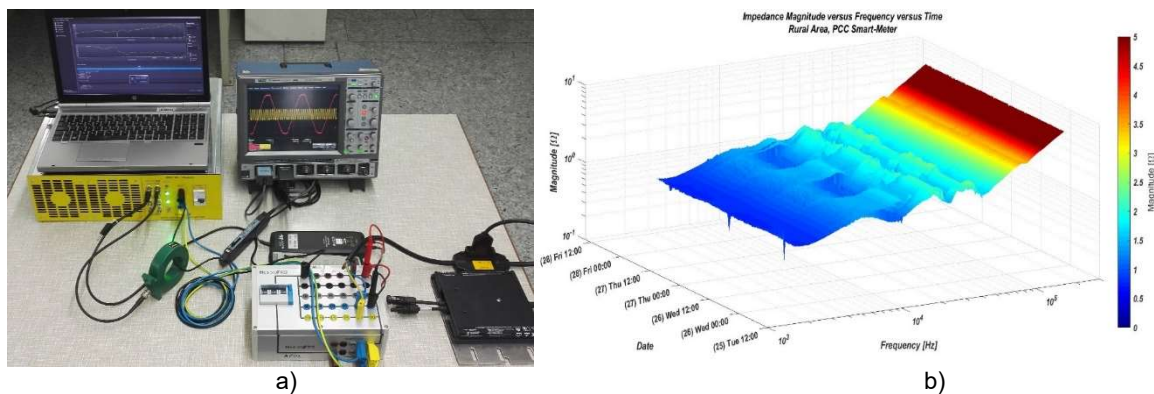


Figure 5: a) On-line grid impedance meter 1 to 500 kHz 'IGOR V' developed at HES-SO Valais for CEM-Smart Grids research activities. b) Variation in time of the spectral grid impedance measured at the common point of connection of PV installations in a rural area (REMIGATE Project)

It was however possible for both named institutions to establish a model of the interference process between PLC communication and converters, based on the measurement of FDGI on Pilot-sites where both Smart Meters and renewable Energy production or energy storage were installed. [8], [9], [10]. The results of these investigations show clearly the influence of spectral grid impedance in PLC signals and harmonics propagation.

Another research institution, TUD in Germany, is very active in the domain of specifying FDGI and its impact on communication signals or conducted EM interferences. The Grid Impedance Meter developed by TUD is however able to measure fast time variations. The example presented in [11] show significant variations within a 50Hz cycle. It was however not possible to prove the variations impact on the robustness PLC systems.

These results were reported to standardization working groups in charge to define compatibility levels and immunity tests methods for PLC devices [12]. However, a common definition of Spectral grid Impedance is still missing in order to pursue research and further collaborations. An equivalent and traceable standard impedance for the comparison of the different proposed measuring methods is missing as well.

In practice, the absence of useful spectral grid impedance definitions and references is slowing down the development of more robust and efficient PLC systems tests, as well as the design of efficient EMC filters for converters. For this reason, the Swiss Federal Office of Energy has granted HES-SO Valais-Wallis and METAS for the research project Z-NET in 2018.

The project consortium has come to a crucial point where specification for the passive and the Time

Varying FDGI standards should be finalised. A good picture of the FDGI trends at transformer stations, distribution cabinets and installations points of coupling was gained with the help of Measuring campaigns in Switzerland and Europe [13]. However, the parameters affecting mostly the communication with Power Line Carrier need to be taken into consideration. The specification of the standard samples can only be confirmed after a final laboratory test campaign with a large number of smart meters with recent technology and a realistic distribution grid model. This is particularly valid for the time varying frequency dependent grid impedance.

TECNALIA is among the most advanced laboratory for the evaluation of PRIME smart meter Power Line Communication with a variable number of smart meters, variable line configuration and appropriate communication diagnosis tools. The team at TECNALIA has conducted several research projects in the domain of Smart Metering and PLC communication.

The Signal Processing and Radiocommunication Group (TSR) of University of Basque Country (UPV/EHU) brought in their expertise on PLC systems and on-site measurements, and they provided their own developed state-to-the-art Time Variant Grid Impedance meter.

The results of the large number of measurements and tests carried out are completed with communication quality analysis with the help of the packet sniffer configured and handled by the partner DSO expert. The results correlation was programmed by the same expert in Python language before the measuring action. They deliver a great base for the specification and the design of Grid Impedance reference samples to be designed in the frame of the Z-NET project.

4 Executed Tests and Experiments

Access to TECNALIA facilities, technical support by TECNALIA personal and travel expenses for all participants were granted by the H2020 ERIGRID Project presented in Annex 1. Working hours for HEVS, SIG-GE and Schaffner are accounted in the frame of the Z-NET project.

TECNALIA premises emulate a LVAC distribution grid with two 500m line sections connected in series and several distribution cabinets equipped with Smart Meters according to Figure 6. The main distribution cabinet at the head of the distribution line is equipped with a data concentrator DC while the other cabinets are equipped with 10 Smart Meters (SM) each. The cabinets 1 and 4 are equipped with Smart Meters from the same supplier. The cabinets 2 and 3 are each equipped with SM from different PRIME compatible suppliers (3 suppliers in total). The Wideband PLC communication protocol PRIME version 1.3.6 is used between DC and all SM, covering the frequency band between 42 and 89 kHz. The original test plan and a description of TECNALIA facilities can be found in the ERIGRID Z-NET project application in the Annex 2.

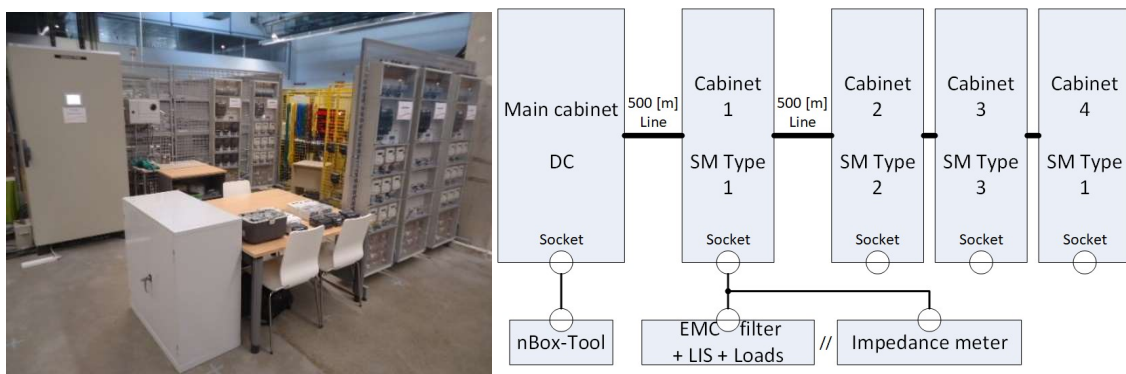


Figure 6: Representation of the TECNALIA laboratory installation

The experiments carried out are described in chapter 4.1. They require several measurements applied to different loads listed below.

The results of the large number of measurements and tests carried out are completed with communication quality analysis with the help of the packet sniffer handled by the partner DSO expert. The correlated results deliver a great base for the specification and the design of Grid Impedance reference samples to be designed in the frame of the Z-NET project.

Selected loads for the tests:

- Five Standby laptops chargers from different brands
- A LED light bulb switch board
- Single-phase EMC filters
- Noise generator with noise injection capacity
- A full wave rectifier

Types of measurements performed:

- Noise measurement
- Impedance measurement
- Attenuation measurement
- Communication performance

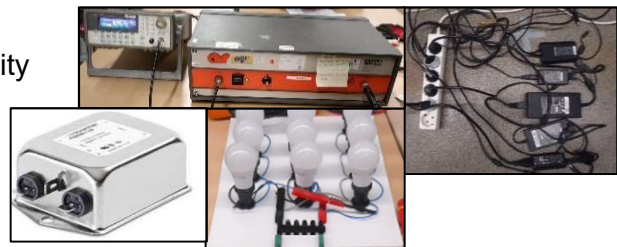


Figure 7: Loads used during the ERIGRID Z-NET project

Schaffner participated to the ERIGRID Z-NET and tested their new active Line Impedance Stabilizer (LIS) developed with the objective to improve the environment for PLC communication. This LIS has been tested for almost every given situation.



Figure 8: Testing the impedance stabilizer and the set of batteries used for the measurements

Finally, some tests were performed in the form of islanded grid. The islanded grid consists on disconnecting the microgrid from the main power transformer of the laboratory, and then, connecting the microgrid to a feeder composed of three power inverters and a battery rack, which form an islanded AC grid. Hence, all the devices and loads considered in this scenario are powered directly by the batteries and not by the connection to the external LV grid.

4.1 Test Plan

The original test plan and a description of TECNALIA facilities can be found in the ERIGRID Z-NET project application in the Annex 2.

4.1.1 Day 1 (18.11.2020) PLC network and measurement set-ups

- ERIGRID Z-NET PLC network set-up
 - PLC communication performance
- Noise measurement set-up
 - Noise with and without communication at main cabinet, cabinet 1 and cabinet 2
- PLC signal attenuation over the line, measurement set-up
 - Signal attenuation over a 500-1000 m line section
- Preparation of different loads
 - Grid impedance without equipment
 - Impedance of each equipment
- Measurement results collection and short reporting.

4.1.2 Day 2 (19.11.2020) PLC network interference with market equipment and EMC filter

- EMI interference and impact on PLC for loads
 - PLC communication performance
 - Noise at DC and at the connecting points except for the EMC filter
 - PLC signal attenuation
 - Grid impedance at the connecting points
- Same with impedance stabilizer
- Measurement results collection and short reporting.

Loads tested: Power adaptors for laptops / Single phase EMC filter / LED light bulbs

4.1.3 Day 3 (20.11.2020) PLC network improvement with impedance stabiliser (Schaffner)

- EMI interference and impact on PLC for loads
 - PLC communication performance

- Noise at DC and at the connecting points
 - PLC signal attenuation
 - Grid impedance at the connecting points
- Same with impedance stabilizer
- Measurement results collection and short reporting.

Loads tested: UPV/EHU rectifier / Perturbation signal generator combined

4.1.4 Day 4 (21.11.2020) Tests on islanded grid and Reserve

- Repeat failed tests or measurements
 - PLC communication performance
 - Noise at DC and at the connecting points
 - PLC signal attenuation
 - Grid impedance at the connecting point of the devices
- Preparation of Islanded grid
 - PLC communication performance
 - Grid Impedance at the connecting point
- Tests in islanded grid generated by converters
 - PLC communication performance
 - Noise at DC and at the connecting points
 - PLC signal attenuation
 - Grid impedance at the connecting point of the devices
- Measurement results collection and short reporting.
- Final reporting

Loads tested: Power adaptors for laptops / LED light bulbs / UPV/EHU rectifier

4.2 Test Set-up(s)

4.2.1 Measurements without loads

At first, the voltage noise produced by the PLC communication of the SM was measured by connecting a PQBox300 to the socket of every cabinet with and without communication provided by the SM. These measurements allow a real comparison between the level of the signals sent by the SMs and the ambient noise on the circuit.

One of the experiments carried out has been to connect PRIME modems, visible on Figure 9, producing signals in the frequency range of conventional SM on the main cabinet. The first unit produces a signal between 42 and 89 kHz while the second unit produces a signal between 424 and 471 kHz.

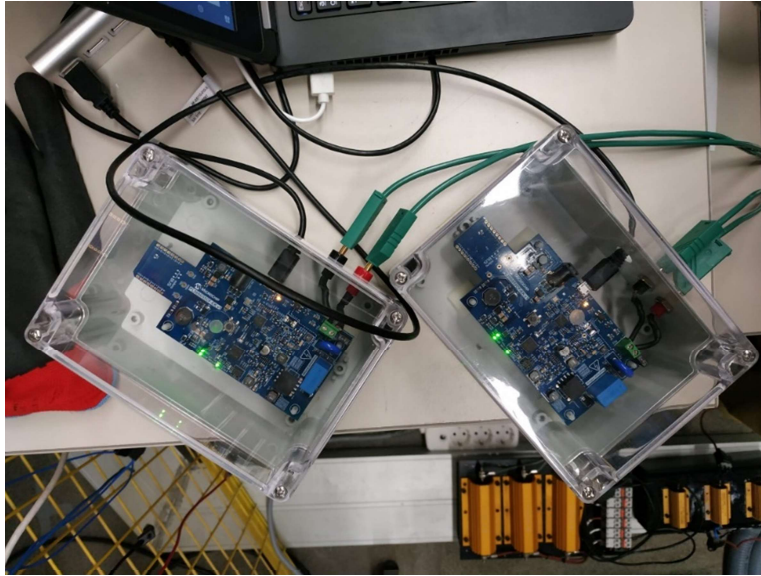


Figure 9: Primes modems used to inject signals

A PQBox was then connected to the main cabinet and a second one to cabinet 1 followed by cabinet 2 to test different configurations.

- Attenuation of the 500 [m] line with communication CH1 (42 -89 [kHz])
- Attenuation of the 500 [m] line with communication CH2 (424-471 [kHz])
- Same course with a line of 1000 [m]

An overview of the attenuation measurement setup is shown in Figure 10.

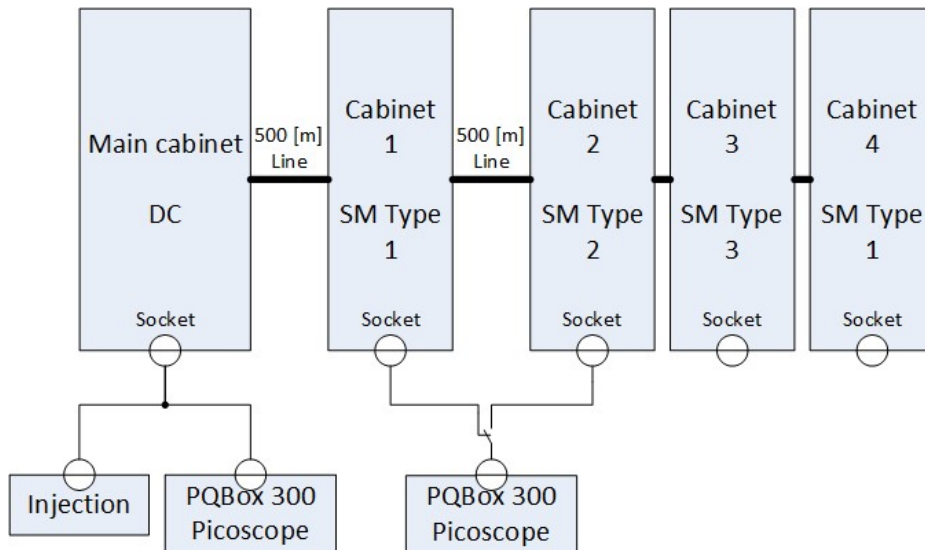


Figure 10: Representation of the TECNALIA laboratory line attenuation test setup

4.2.2 Measurement with loads

As stated earlier in the chapter 4, the same measurements were made for each given situation. For each condition, the tested load was connected to the cabinet 1 followed by the cabinet 2. For the different positions, the load was connected with and without the stabilizer.

Initially, the tests were carried out without load and without communication from the MS in order to have a reference for the next measurements.

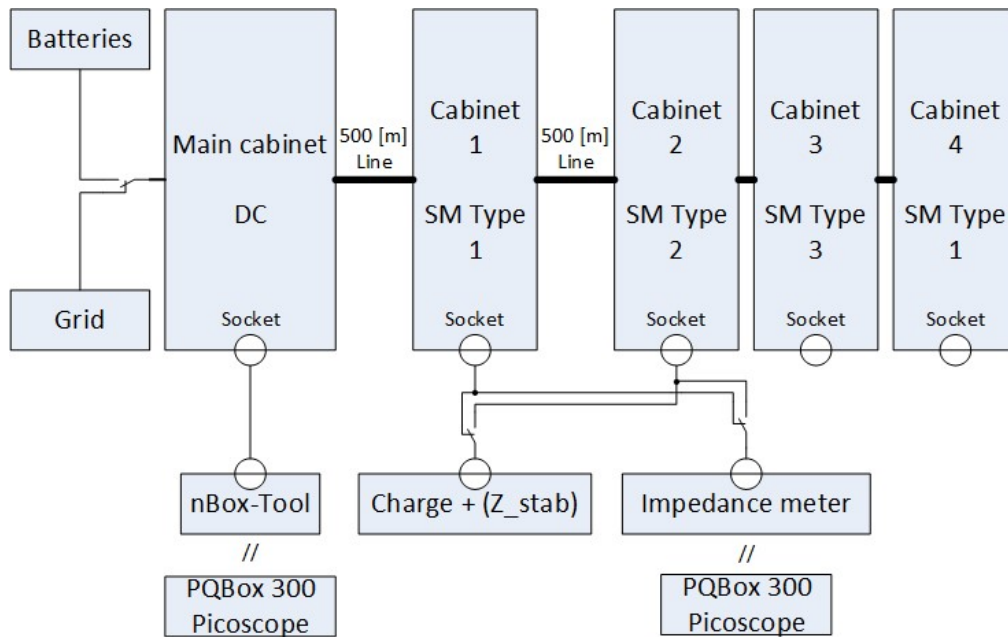


Figure 11: Representation of the TECNALIA laboratory loads test setup

During the measurements, the filter, which is part of the Line Impedance Stabilizer (LIS, 'Z-Stab' on Figure 11), was always connected between the SM cabinets and the perturbing loads, so the total load is composed by the elements described in the previous section (power adaptors, LED bulbs, etc.) in series with the LIS filter and some cables for the connections. When comparisons of transmission losses, noise and impedance of different scenarios were performed with and without the stabilizer, in fact, only the current probe of the stabilizer was included or excluded in the setup. The LIS filter was excluded only for the tests with full wave rectifier, due to the smoothing effect of the LIS on fast impedance variations.

For the measurements made with batteries replacing the grid, noise and attenuation measurements were only taken with USB-Oscilloscope (Picoscope).

An overview of the measurement setup is shown in Figure 11.

4.3 Standards, Procedures, and Methodology

4.3.1 Course of action

The following loads were connected to the cabinet 1 and cabinet 2, in order to generate two different effects: sub-cycle variations in the grid impedance and a high level of noise and non-intentional emissions, both in the frequency range assigned to Power Line Communications (35 kHz – 500 kHz):

- Five Standby laptops chargers from different brands
- A LED light bulb switch board (composed of twelve led light bulbs)
- Single-phase EMC filters
- LED light bulbs switch board, together with 5 laptop chargers and a noise generator with an amplifier
- A full wave rectifier from UPV/EHU with a theoretical low impedance load between 1 and 2 ohms in the analysed band.

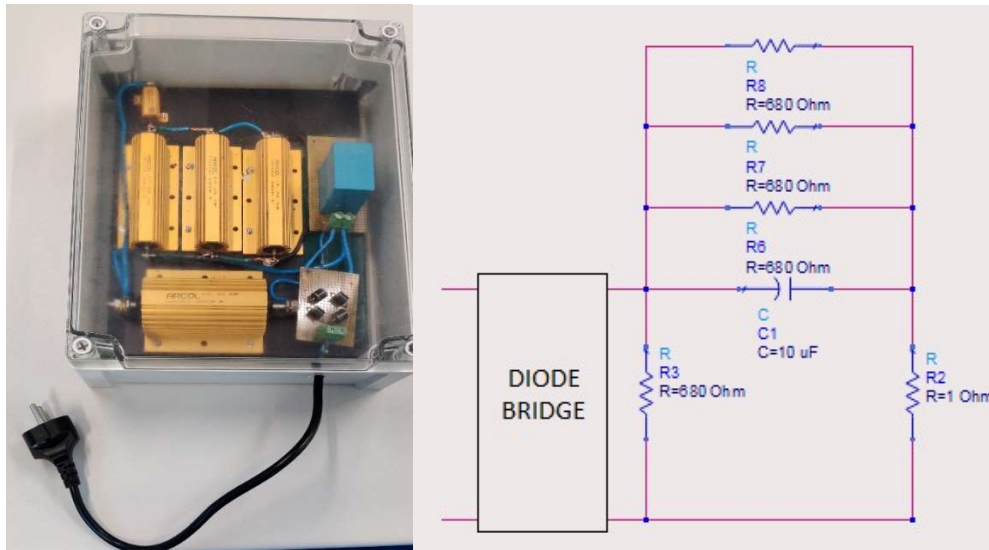


Figure 12: UPV/EHU full wave rectifier

The fourth load is, in fact, a combination of loads, in order to disturb the communications between the smart meters hosted in the cabinets. The total load was a combination of the LED bulbs and the laptop power supplies, together with a noise generator connected to an amplifier, in order to generate a high level of non-intentional emissions, and hence, degrade the performance of the communications.

For each load, all the measurements mentioned in Chapter 4 have been carried out. In each case, the load was tested firstly alone and secondly with the impedance stabilizer. A picture of the impedance stabilizer is available on Figure 13.

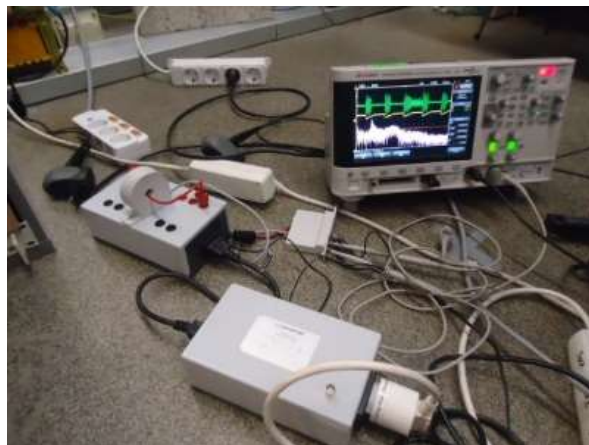


Figure 13: Impedance stabilizer with filter from Schaffner

After testing all loads, the main cabinet was disconnected from the external LV grid and a battery set was connected to power the circuit. Unfortunately, the impedance stabilizer was no longer available for the experiments on islanded grid.

With the little time remaining, the three most promising loads in terms of results were measured.

- 5 power adaptors for laptops.
- A LED light bulb switch board (composed of twelve led light bulbs)
- A full wave rectifier from UPV/EHU with a theoretical low impedance load between 1 and 2

ohms in the analysed band.

For each load, the same measurement made without the battery set have been carried out.

4.3.2 Use of devices

The communication performance has been evaluated based on the frames recorded by the PRIME version of the NEURON nBox at the measurement point. In this case, the measurement point is the socket from the main cabinet, close to the DC. The measured phase is the black one corresponding to the first phase. It's possible to extract the RSSI, the SNR, and some identification information from each recorded frame. By cross-checking the data it's possible to assign each frame to the smart meter who has emitted it and therefore to know the phase and the cabinet.

To evaluate the impact of the loads on the communication performance, several scenarios have been run. For each scenario, the frames were recorded and then analysed in time by grouping them by cabinet, phase or smart meter.

For the noise measurements done with the USB-Oscilloscopes, the quasi-peak and peak voltage noise levels have been recorded in the central cabinet, cabinet 1 and cabinet 2 depending the situation. The noise was measured between 35 and 500 kHz. [14]

The noise measurements done with the PQBox 300 were performed at the same points as the Picoscope measurements. The average harmonics levels were recorded in time between 9 and 170 kHz. The PQBox 300 regroups the harmonics in 2 kHz bands.

For the attenuation measurements done with the Picoscope, the average voltage spectrum levels have been recorded. The transmission losses measurements were carried out between the Main Cabinet and the Cabinet 1, and between the Main Cabinet and the Cabinet 2. The voltage spectrum was measured in dBV. The attenuation was measured between 35 and 500 kHz.

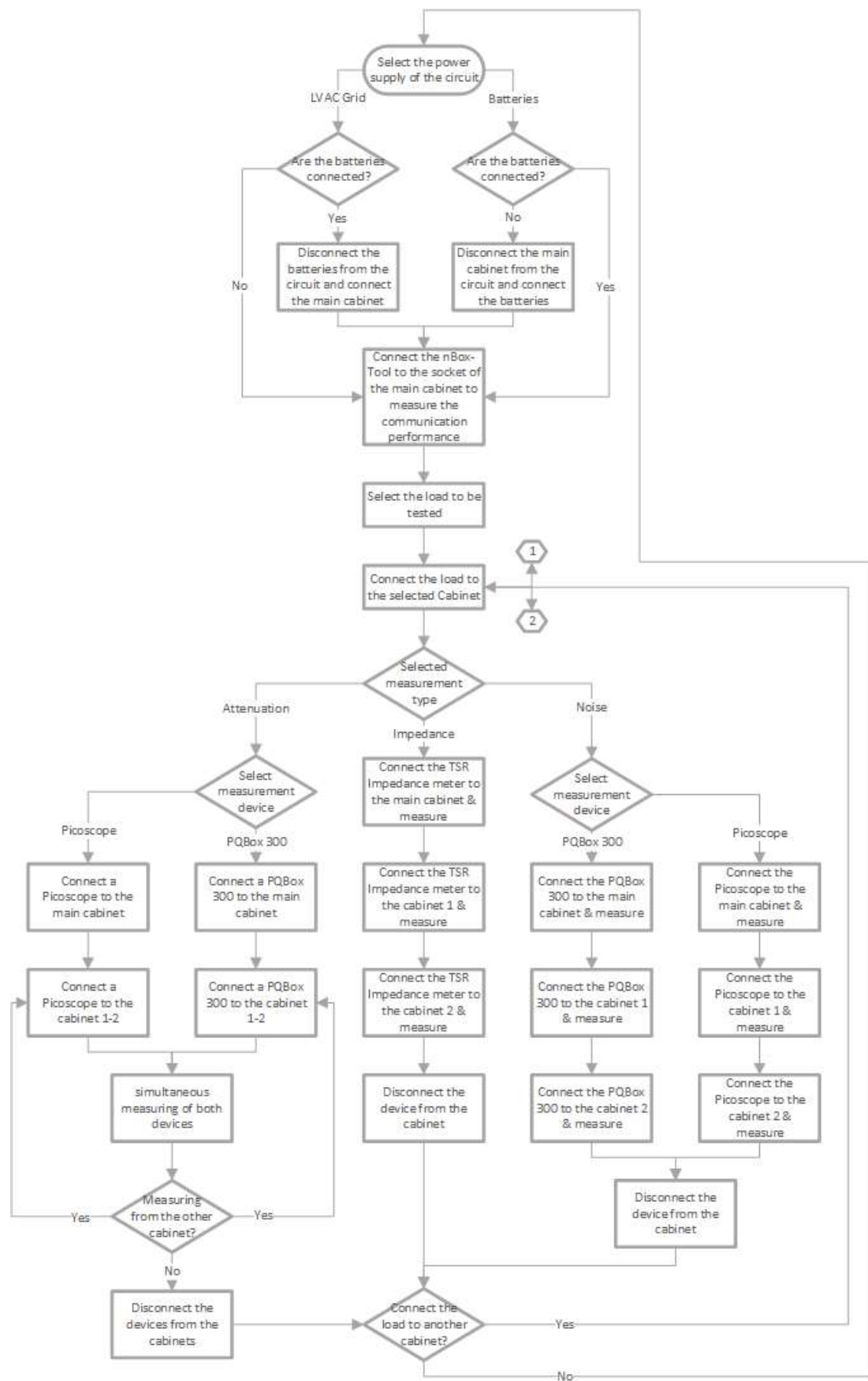
The attenuation measurements done with the PQBox 300 were performed at the same points as the picoscope measurements. The average harmonics levels were recorded in time between 9 and 170 kHz. The PQBox 300 regroups the harmonics every 2 kHz.

The current was measured with the USB-oscilloscope with the help of PEM CWT Rogowski probe cutting the fundamental up to 500 Hz.

The impedance measurements were made using the TSR Group Impedance meter. The TSR laboratory at University of the Basque Country (UPV/EHU) recently developed a measurement system to characterize the noise and the impedance variations of electrical grid and isolated loads, even below the mains period, up to 500 kHz.

Further information about their impedance meter can be found on the publication [14]. Impedance levels have been recorded in the Main Cabinet, Cabinet 1 and Cabinet 2 depending the situation.

4.3.3 Flow chart



4.4 Data Management and Processing

Noise and attenuation measurements performed with the PQBox300 are directly exported from the box with the WinPQ Mobil application provided by the supplier. The measurements are then processed using a MatLab script to sort the measured harmonics and present them in user-configured graphics.

Noise and attenuation measurements performed with USB-oscilloscope are directly exported from the computer with the Picoscope 6 software provided by the supplier. The measurements are then processed using a MatLab script to sort the measured spectrums and present them in user-configured graphics.

To calculate the attenuation between two cabinets, we simply retrieve the noise measurements taken at the same time on the two cabinets involved and subtract them after processing.

The PLC communication performance measurements are exported from the NEURON nBox with the web interface provided by the nBox itself. The measurements are then processed using Python language, the web based Jupyter Notebook environment and the Bokeh visualization library (all these tools can be freely downloaded and used). A script was written to sort the measured frames and their characteristics and present them in user-configured graphics.

Impedance measurements performed with the TSR Impedance Meter are directly exported from the box with the Picoscope 6 software. The measurements are then processed using a MatLab script to sort the measured spectrums and present them in user-configured graphics.

5 Results and Conclusions

5.1 Preliminary measurements of noise in the circuit

5.1.1 Attenuation measurements

5.1.1.1 Attenuation for CH1 signal (42 – 89 kHz)

An attenuation is visible but around 90 [kHz] an increase of the signal is observed.

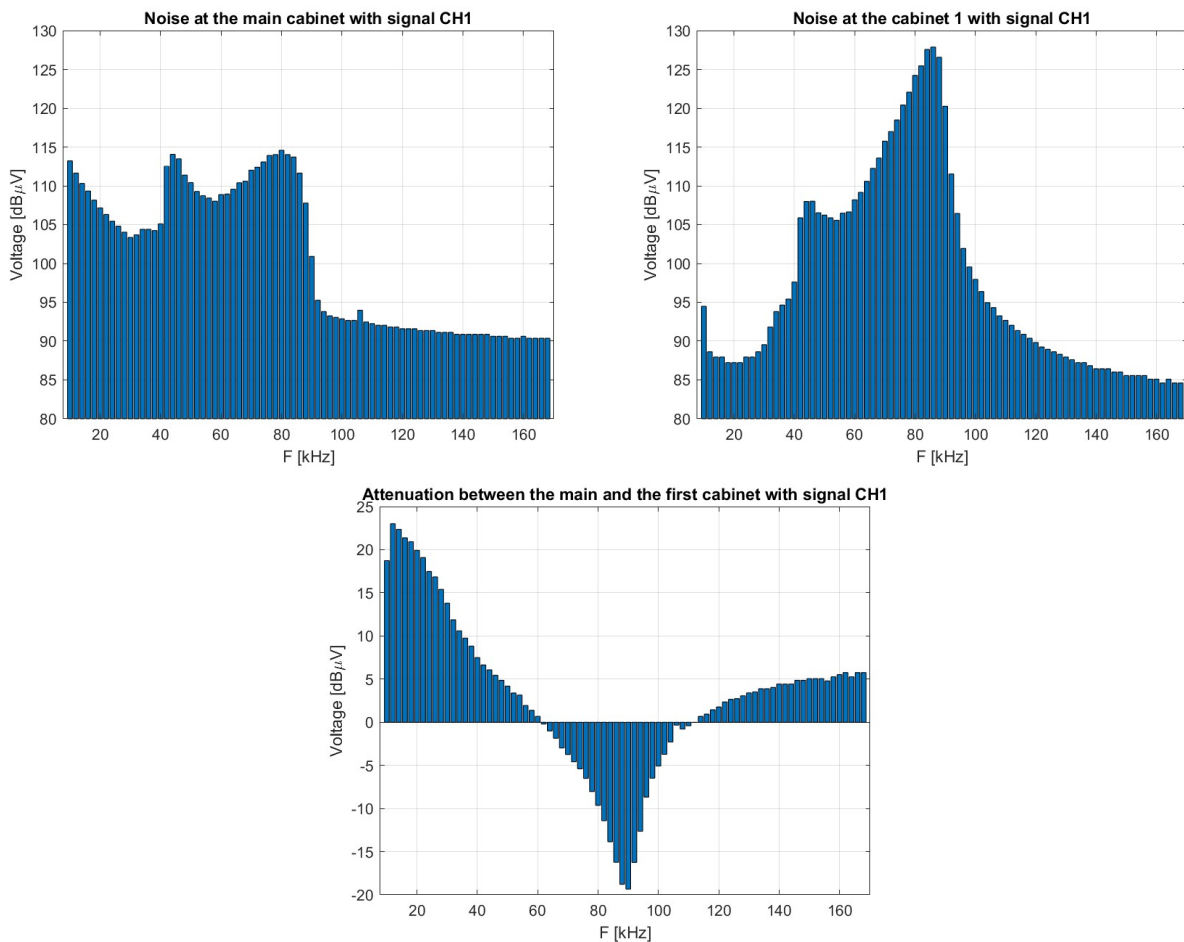


Figure 14: Attenuation of a CH1 signal on a 500 [m] line with PQBox 300

As seen in Figure 14, attenuation ranges from -20 to 23 dB μ V.

Unfortunately, measurements made with Picoscopes do not give the same results as measurements made with the PQ-Box 300. Figure 15 shows the attenuation measured with Picoscopes under the same conditions.

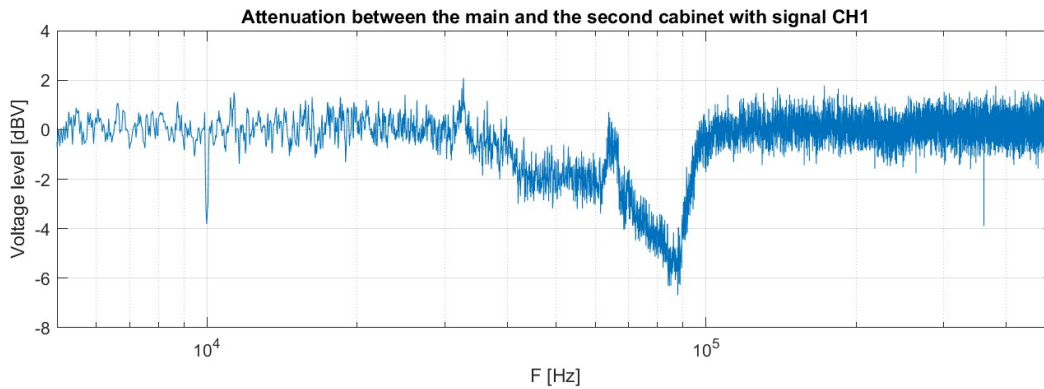


Figure 15: Attenuation of a CH1 signal on a 500 [m] line with Picoscopes

For a 1000 m line Roughly the same observation is made as for a 500 m line. Except that this time, the signal increase is around 40 kHz as seen in Figure 16.

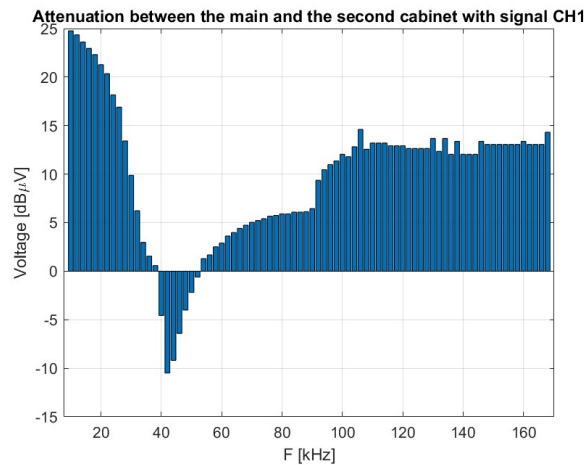


Figure 16: Attenuation of a CH1 signal on a 1000 [m] line with PQBox 300

Again, the measurements with Picoscopes do not give the same attenuation at all. The difference in the signal analysis methods and the frequency grouping methods for both equipment can explain the lack of coherence in the results. Or then the parametrisation of the measurements or difference in voltage probes. This will still be investigated with laboratory trials.

5.1.2 Attenuation for CH8 signal

The measurement made with a high frequency signal in the FCC frequency band have been performed with two Picoscopes, as the PQBox 300 is limited at 170 kHz.

The results in Figure 17 show that for any line length, the signal does not attenuate but increases between 424 and 471 kHz.

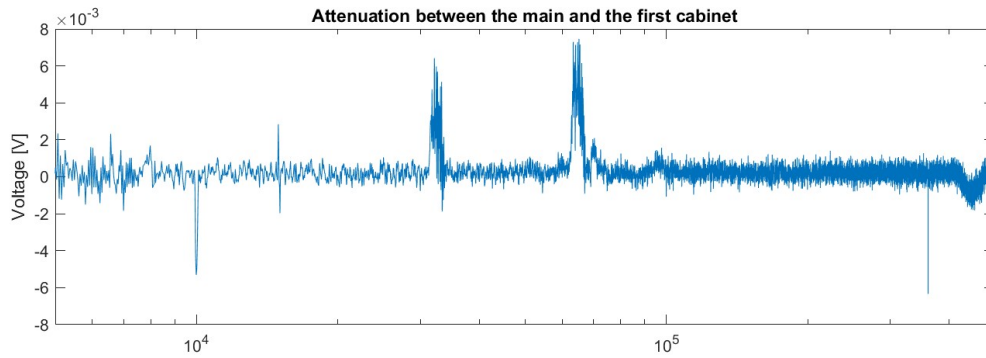


Figure 17: Attenuation of a CH8 signal on a 500 [m] line with Picoscopes

5.1.3 Noise measurements

Preliminary measurements were done in order to have a reference of the noise floor of the grid.

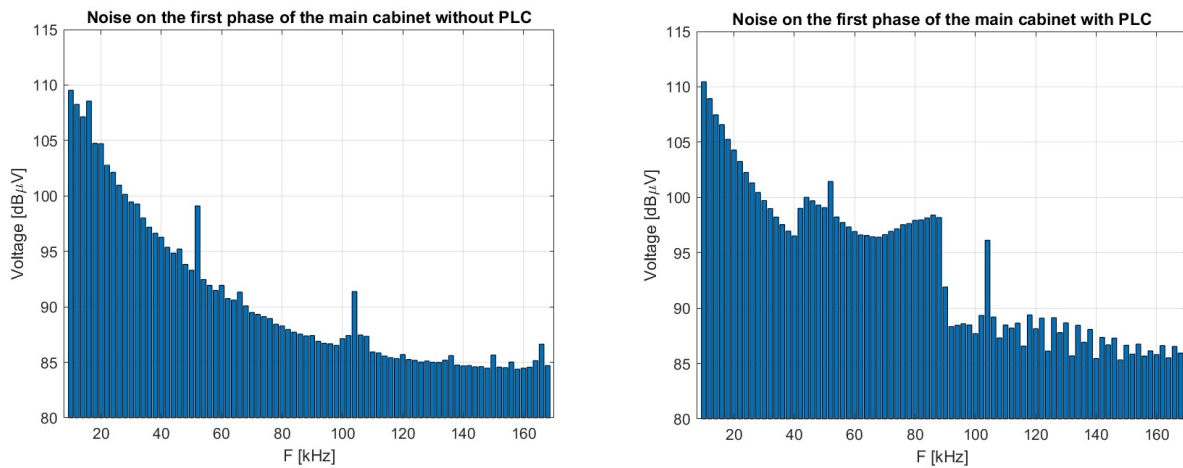


Figure 18: Noise measurement with a PQBox 300 at the main cabinet with & without communication

PLC communication is clearly visible in Figure 18 between 40 and 90 kHz. High frequency noise is also higher with communication even though the level is still acceptable.

The noise on cabinets 3 & 4 is like the one in the main cabinet. On the other hand, the noise in cabinets 1 and 2 has a lower amplitude.

5.2 Interference from PLC measurements

It's during this part that the charges were tested on the circuit.

5.2.1 Impedance measurements

A high variation in frequency in the access impedance values is obtained within the fundamental period along the frequency band in the three cabinets without the presence of communications between the smart meters. Moreover, no loads were connected in the grid. See Figure 19.

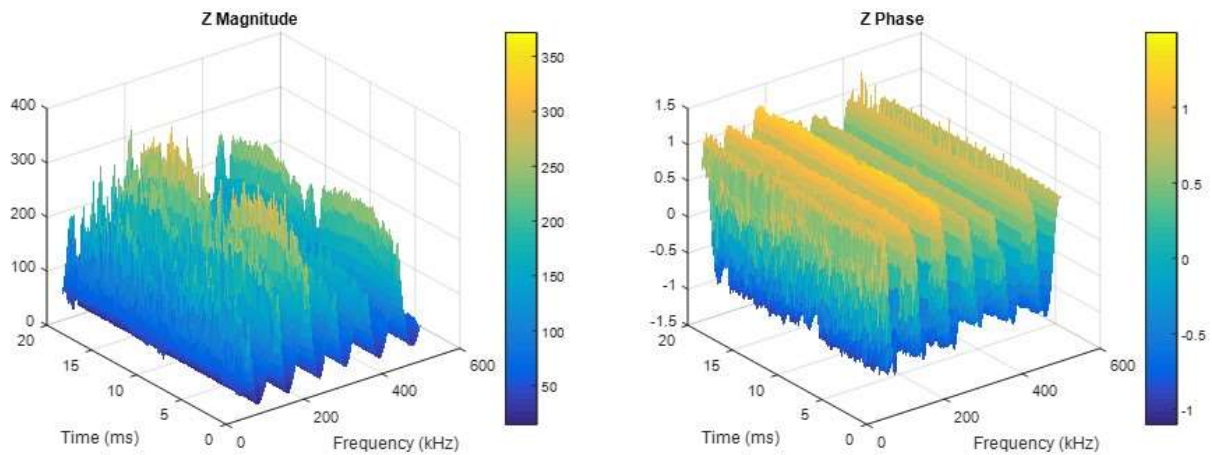


Figure 19: Grid impedance in the Cabinet 2, without any load connected in the grid

When the power adaptors are connected to the cabinet 1 or 2, the access impedance at that point is reduced considerably in all the frequency band, as it is shown in Figure 20, and amplitude values below 20 ohms are obtained for the whole frequency range. However, the low impedance values obtained in specific frequencies at cabinet 1 or 2 when no load was connected to the grid (Figure 19) can be distinguished also in this scenario.

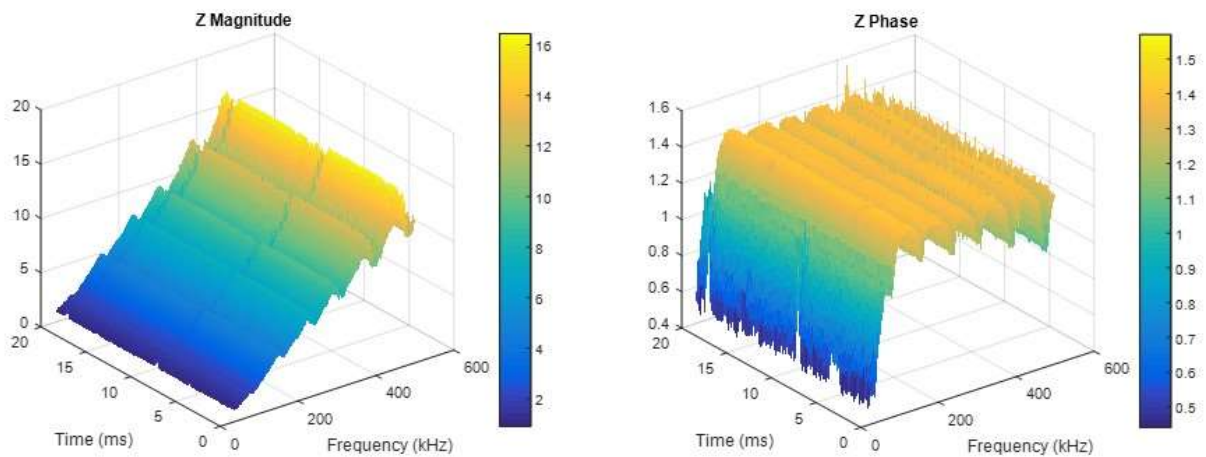


Figure 20: Grid impedance in the Cabinet 2, with the power adaptors connected in the Cabinet 2

When the impedance stabilizer of Schaffner is added to the load, the impedance in Cenelec A band is increased for lower frequencies up to 12 ohms, as it can be seen in Figure 21. The phase is also increased from around 0.4 radians to around 1 radian.

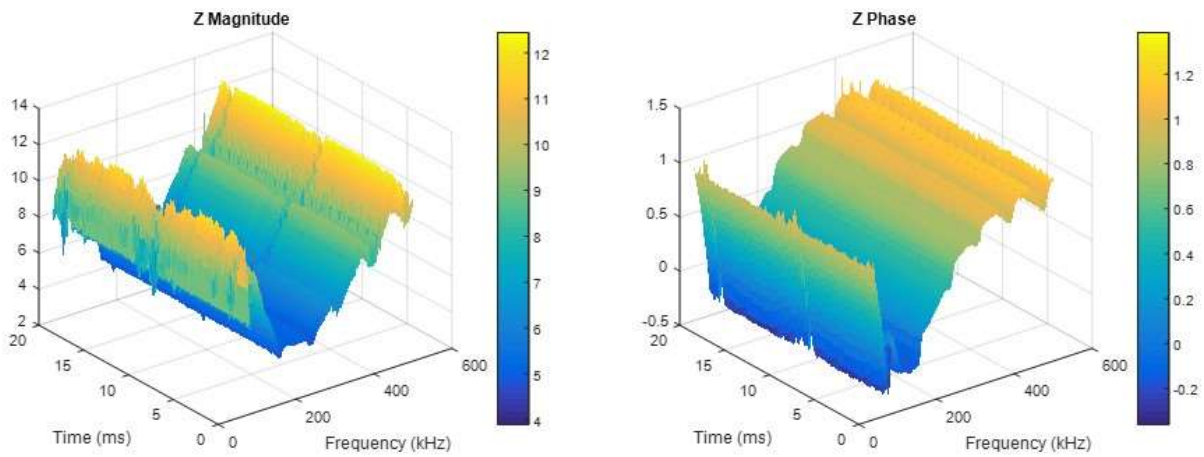


Figure 21: Grid impedance in the Cabinet 2, with the power adaptors and the stabilizer connected in the Cabinet 2

In terms of impedance, similar results were found between the laptops chargers and the other loads tested. Only the rectifier gives different results.

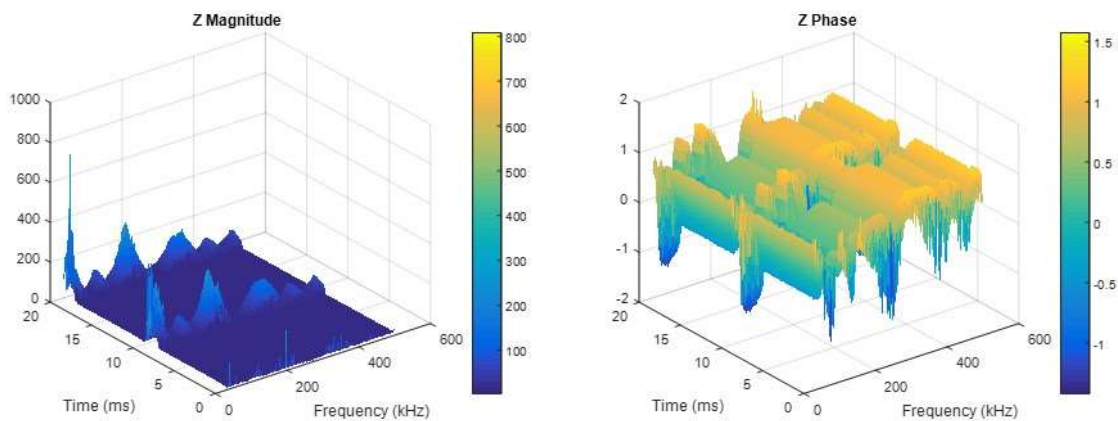


Figure 22: Grid impedance in the Cabinet 1, with the rectifier and the stabilizer connected in the Cabinet 1

The access impedance when the stabilizer is included increases up to around 12 ohms in Cenelec A band, as in previous setups (see Figure 21), although it cannot be distinguished in Figure 22, due to the scale needed to represent the high impedance values seen during the short periods around the zero-crossings. Several sections of the impedance magnitudes in the frequency domain have been represented in Figure 23 in order to see the difference of the impedance of the device when the diodes are on, with and without the stabilizer.

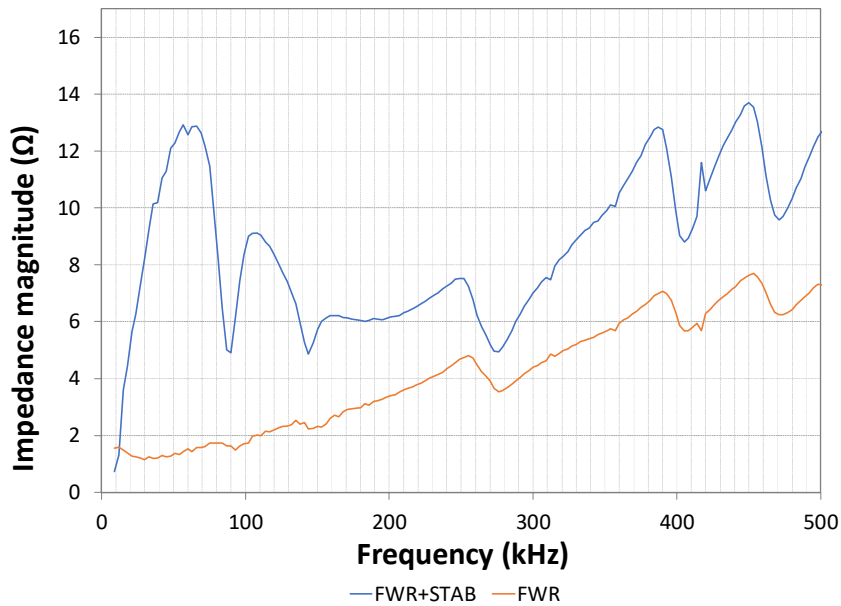


Figure 23: Grid impedance in the Cabinet 1, with the rectifier connected in the Cabinet 1 and the diodes on, with and without the stabilizer

The result is conclusive and corresponds to the measurements carried out on the other loads.

5.3 Noise & attenuation measurements

Due to the modification in the impedance, the use of the Line Impedance Stabilizer LIS in the grid also affects the transmission losses in Cenelec A band. Figure 24 and Figure 25 show the comparison of the transmission losses between Main Cabinet and Cabinet 2, with and without the stabilizer connected to the grid. As it can be observed, the use of the impedance stabilizer reduces the transmission losses for frequencies below 170 kHz.

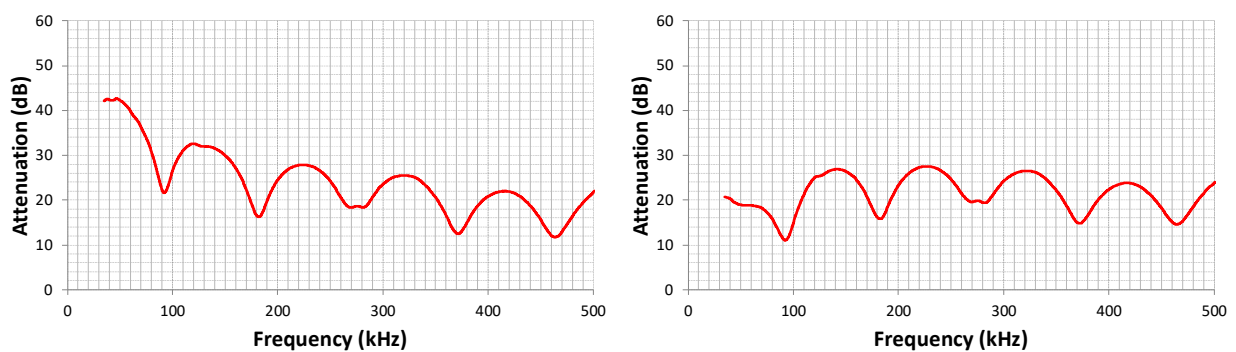


Figure 24: Transmission losses measured with Picoscopes between the main cabinet and cabinet 2, with the power adaptors connected in the cabinet 2. Left: without stabilizer; right: with stabilizer

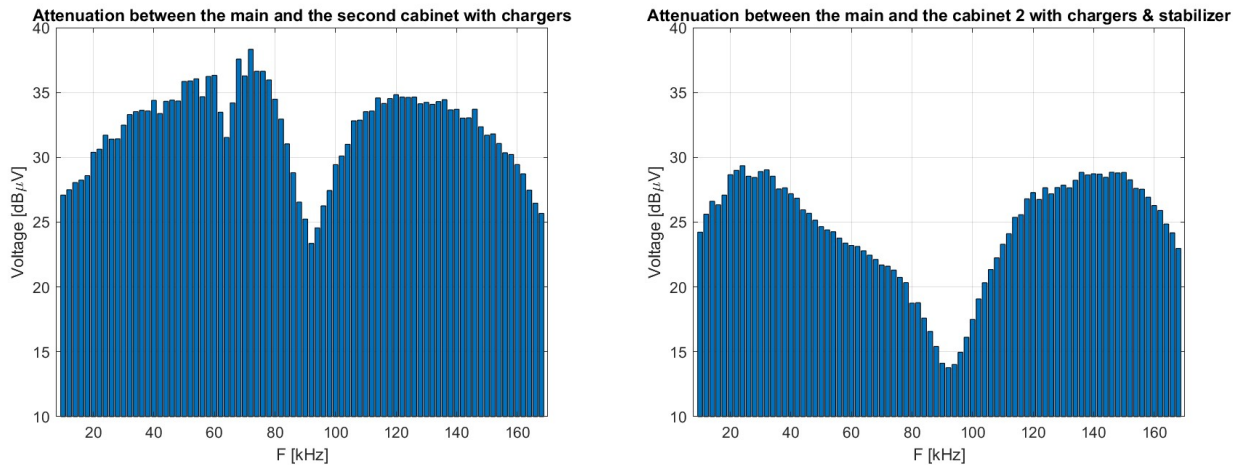


Figure 25: Transmission losses measured with PQ-Box 300 between the Main Cabinet and Cabinet 2, with the power adaptors connected in the Cabinet 2. Left: without stabilizer; right: with stabilizer

When the LIS stabilizer is added to the load, the attenuation in Cenelec A band varies around 20 dB, whereas when the LIS stabilizer is not connected to the grid, the transmission losses are around 35 dB in the whole Cenelec A band. In frequencies higher than 170 kHz, the transmission losses are similar for both cases.

The same results can be derived from the attenuation measurements on other loads.

For all the measurements, no significant differences are observed in the noise levels when the stabilizer is connected

There is a noticeable reduction in the noise level for frequencies up to 180 kHz when the LED bulbs were connected, with respect to when the power adaptors were connected. The insertion of the stabilizer does not alter the noise levels.

With the combined load, the noise was obviously increased due to the noise generator and the amplifier, but no significant difference was appreciated in the levels obtained with and without the LIS stabilizer.

5.3.1 Communication performance

The Figure 26 shows an example of the measured communication performance in Cabinet 2 for different situations.

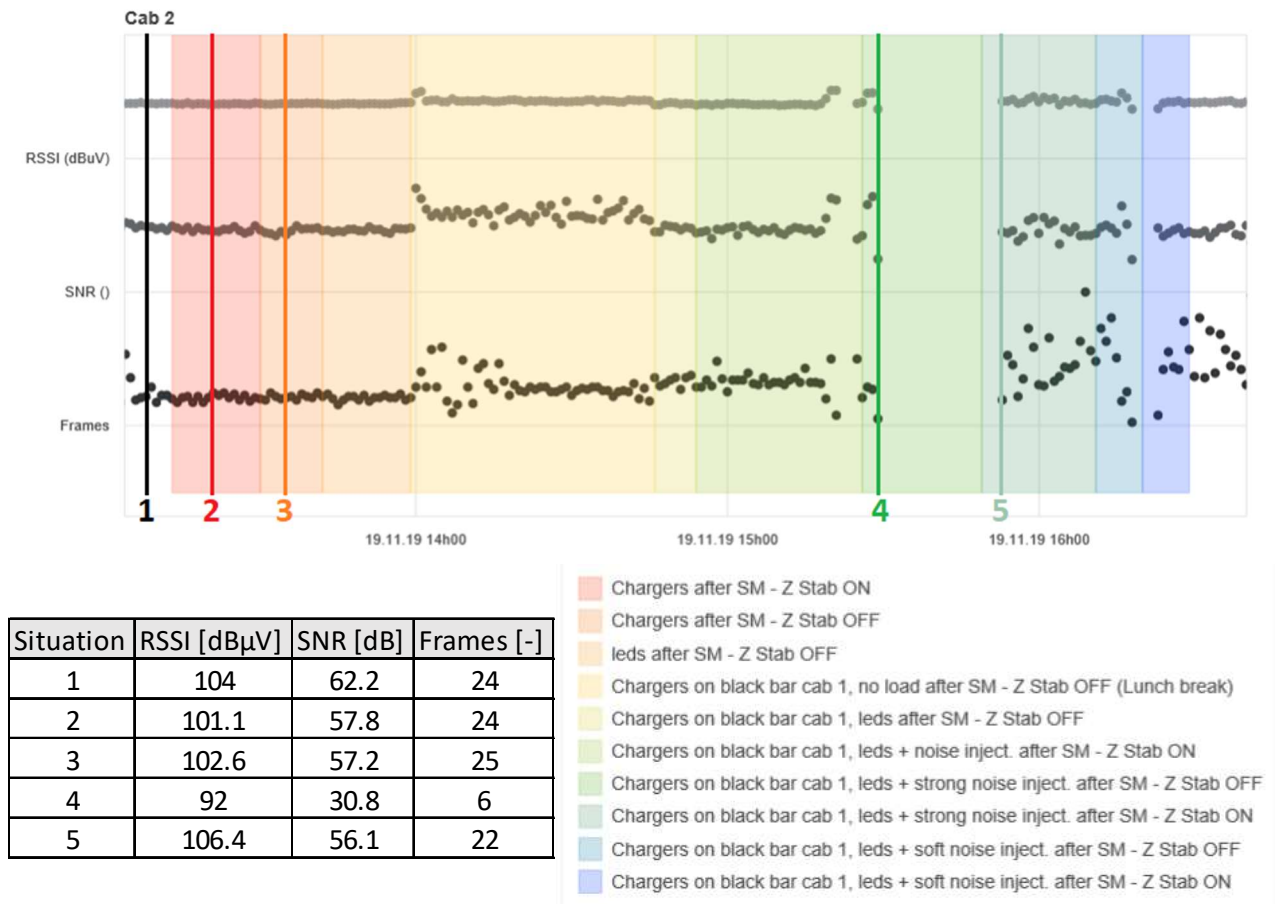


Figure 26: Communication performance of the SM in the second cabinet

The first situation is a measurement with no load connected to the cabinets. It gives a perspective on communication when the system is undisturbed.

The SNR always has a smaller value than in step 1 due to the noise generated by the loads connected.

At step 4, almost no frames pass because the conditions are too harsh to be processed by the data concentrator. Communication breaks down because of the high noise level generated.

In general, the impedance stabilizer improves PLC communication. Even when communication is cut off at situation 4, the LIS stabilizer allows the signal level to be raised to an acceptable level.

5.4 Islanded Grid

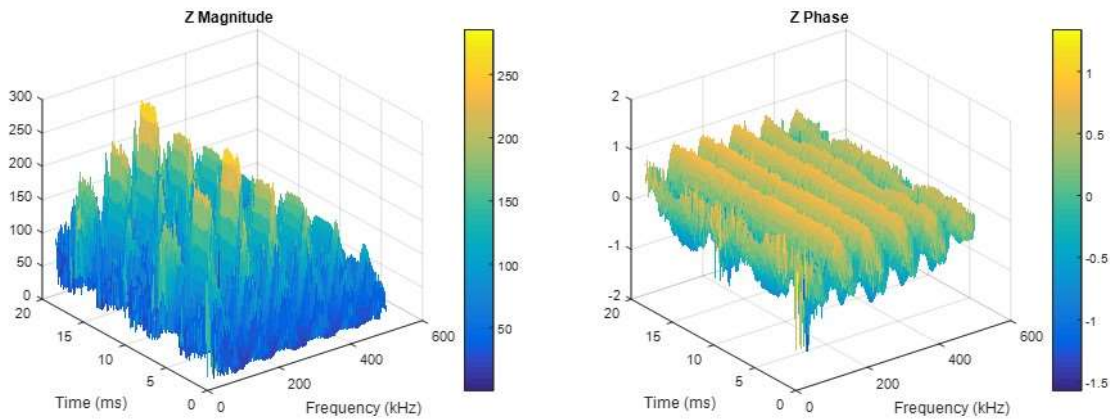


Figure 27: Grid impedance in the Cabinet 2, without any load connected in the islanded grid

A strong variation in the frequency domain in the impedance values is obtained also in this setup, for all the frequency band, although not the exactly same shape is obtained in any case as when the islanded grid was not used (Figure 19).

The influence of the loads does not bring an important difference in the islanded grid measurements. Only the noise levels vary, as the power supply of the system is no longer the same. The noise level in the measurement points without any additional load connected to the grid are higher than levels measured with connected main AC-grid, at least for frequencies below ca.300 kHz.

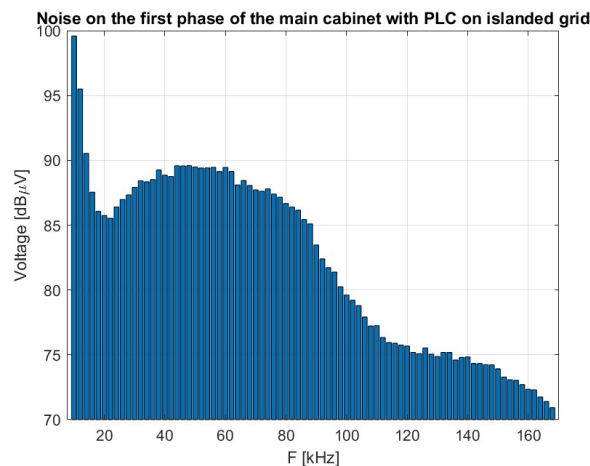


Figure 28: Noise measurement at Main Cabinet with no loads and with PLC on an islanded grid

The noise levels are similar when the load is composed of the LED light bulbs, but there is a significant change in the access impedance when this load is connected to the grid in Cabinet 2, with respect to the results obtained without the islanded grid (Figure 20). Since the filter of the LIS stabilizer is not connected in this case, the impedance of the LED light bulbs (in parallel with the grid) shows a time-variant behavior, similar to the rectifier. In fact, the access impedance is the impedance of the grid during most of the fundamental period, and only a low access impedance is obtained around the maximum and the minimum values of the mains (during around 2.5 ms). This low impedance varies from 2 ohms for low frequencies to around 10 ohms for the highest frequencies. See Figure 29.

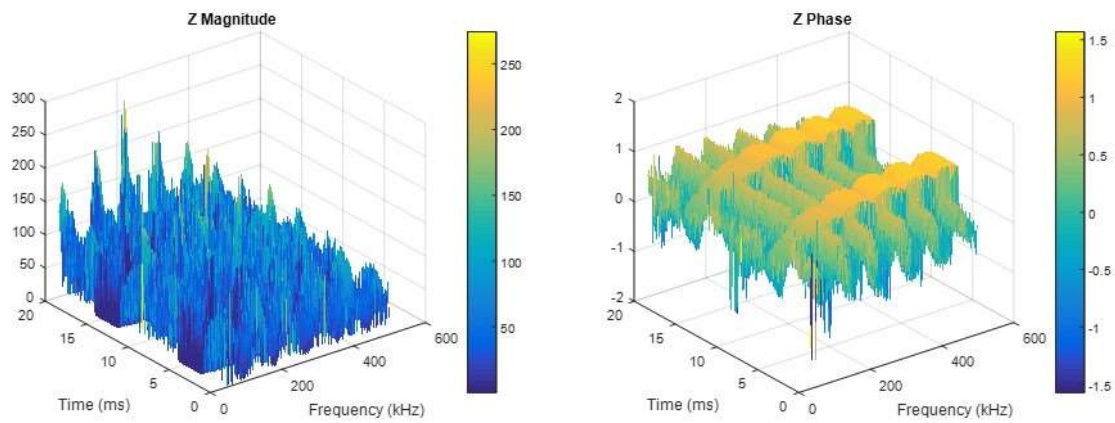


Figure 29 : Grid impedance in the Cabinet 2, with the LED bulbs connected in the Cabinet 2 (islanded grid)

Measurements taken in islanded mode do not add much to the project. However, by processing and analyzing them, they allow a better specification of the time-varying load to be developed. With all the tested cases, a valuable information is available to determine the impedance response with different scenarios.

6 Open Issues and Suggestions for Improvements

Overall, the measurements carried out at TECNALIA went very well. All parties involved in the project are satisfied with the results. Thanks to the good preparation, the availability and the complementary spectrum of competences found within the different partners, the measurement protocol could almost be followed in its entirety.

All scheduled scenarios could be realized at the exception of:

- Measurements with a Line Impedance Stabilizer could be carried out in islanded grid. It would have been interesting to see the effect of the stabilizer when the impedance of the network varies.
- Impact of Frequency and Time Variant Grid Impedance on latest released version of PLC systems protocols, in particular PRIME version 1.4, working in the frequency range up to 500 kHz (FCC band). A comparison in term of robustness with current protocol working in CENELEC A-Band could be an important follow-up in the frame of an ERIGRID 2.0 measuring campaign.

In order to achieve the objectives of the ERIGrid Z-NET measuring campaign, it is necessary to properly process all the measurements carried out in order to find a correlation between the different effects produced by the different loads. Data analysis work is only partially done at the time this report is delivered.

Issues with the correlation of measuring results presented by different equipment need to be investigated in respective academic institutions laboratories. Even this is not the main scope of the Z-NET project, the impact of different signal treatment methods is a key issue in the current development of standardized emission measuring methods.

It will be interesting to analyze the impact of the Line Impedance Stabilizer in real advanced smart metering installations with PLC in order to deduce its field of use and its effect in a precise manner. One suggestion would be to redo measurements with elements producing more noise on the network or inject specific harmonics in order to analyse how communication performance decreases with noise.

A suggestion for improvement in the Smart Grid Technology Laboratory would be the addition of grid lines sections with different length, in particular shorter ones, in order to increase flexibility in test scenarios. The authors are aware that this would however represent a significant investment for the hosting laboratory. Migration to FCC frequency range up to 500 kHz would be a very valuable contribution as well.

7 Dissemination Planning

The preliminary results of the work developed in this project are promising and interesting for the scientific community. A dissemination plan has been developed by the working team, in order to organize the dissemination of the main outcomes of the project in relevant peer-reviewed scientific journals and international conferences.

The topics that have been identified for the development of future publications are the following:

- New measurement methodology for the characterization of the access impedance sub-cycle variations in the LV grid for frequencies up to 500 kHz
- Impact of the fast variations of the access impedance of the LV grid on the performance of NB-PLC
- New technique for the impedance stabilization against fast variations of the access impedance of the LV grid up to 150 kHz
- Effects of the impedance stabilization on the performance of NB-PLC

The scientific journals selected for the dissemination of the results are:

- IEEE Transactions on Smart Grid
- IEEE Access
- IET Smart Grid
- Elsevier – Measurement
- Elsevier – International Journal of Electrical Power and Energy Systems
- MDPI – Energies
- MDPI – Applied Sciences

All the publications in scientific journals will be under Open Access conditions.

The international conferences selected for the dissemination of the results are:

- Preliminary results of the characterization of the fast variations of the access impedance of the LV grid
- Characterization of the impedance variation of representative devices connected to LV grid for frequencies up to 500 kHz
- The international conferences selected for the dissemination of the results are:
- IEEE SmartGridComm (International Conference on Communications, Control, and Computing Technologies for Smart Grids)
- IEEE ISPLC (IEEE International Symposium on Power Line Communications and its Applications)
- EMC Europe
- IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)
- International Workshop on Applied Measurements for Power Systems (AMPS)

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9 Annex

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