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Final report dated 14.01.2022

Z-NET

Pre normalization of grid impedance measurement in the power line communication frequency band

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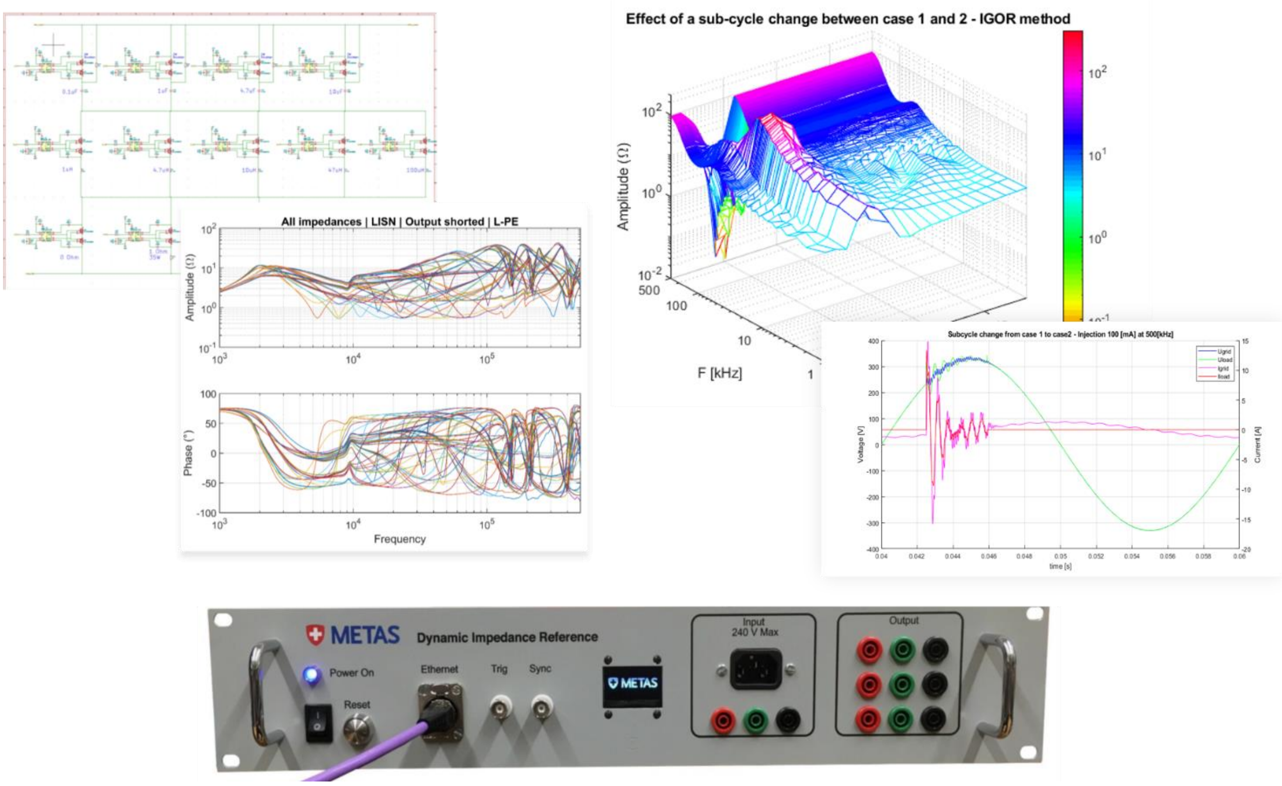

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Zusammenfassung

Der weit verbreitete Einsatz von intelligenten Zählern hängt in hohem Maße vom Einsatz der Power Line Communication (PLC)-Technologie für die wirksame Übertragung von Messdaten ab. Die auf dem Niederspannungsnetz zwischen Phase und Neutralleiter gemessene Impedanz als Funktion der Frequenz (FdGI) beeinflusst die Signalausbreitung auf den Leitungen stark. In den schlimmsten Fällen kann sie sogar die Zuverlässigkeit einschränken und die Übertragungskapazität von intelligenten Zählern reduzieren. Die genaue Messung der Leitungsimpedanz ist derzeit schlecht definiert und nur mit sehr wenigen Geräten möglich. Darüber hinaus führen die verschiedenen vorgeschlagenen Methoden nicht immer zu vergleichbaren Ergebnissen. Ziel dieses Projekts ist es, eine Referenz für eine messtechnisch nachvollziehbare Netzimpedanz zu etablieren, die den objektiven Vergleich der vorgeschlagenen Messtechniken ermöglicht und den Weg zur Normung eröffnet. Die Standardisierung einer gemeinsamen Messmethode soll die Entwicklung und Einführung effizienter Impedanzmessgeräte erleichtern. Dieser erste Schritt wird die Aufstellung und Verbreitung von Methoden zur Analyse der Übertragung von PLC-Signalen im Verteilungsnetz ermöglichen. Somit können diejenigen Geräte ermittelt werden, die nicht unbedingt Rauschen erzeugen, deren Frequenzeigenschaften aber für die PLC-Übertragung ungünstig sind. Ein Hersteller von EMV-Filtern und Partner im Z-NET-Projekt schlägt vor, einen Impedanz Stabilisator zwischen kritische Verbraucher und das Verteilnetz einzufügen, um solche Situationen zu beheben.

Für die Kalibrierung von Netzimpedanz-Messgeräten sind standardisierte Prüfmuster erforderlich. Im Rahmen des Projekts Z-NET hat das Schweizerische Institut für Metrologie METAS auf der Grundlage der gemeinsam mit der HES-SO Valais-Wallis erarbeiteten Spezifikationen mehrere Standard-Netzimpedanzmuster erstellt und charakterisiert:

- ein statisches Prüfmuster bestehend auf einer standardisierten Netznachbildung (LISN), das für Elektromagnetische Verträglichkeit (EMV) Akkreditierungstests verwendet wird.
- ein Prüfmuster mit programmierbaren Frequenzkennlinien, um Flexibilität für umfassendere Labor- oder Feldtests zu gewinnen.
- Basierend auf dem oben genannten Prüfmuster, eine programmierbare dynamische Variation der Frequenzeigenschaften, synchronisiert mit der Grundfrequenz des elektrischen Verteilungsnetzes, um eine periodische Impedanzvariation zu bewirken.

Das Projekt Z-NET fand im Jahr 2020 einen neuen Impuls, und die Bemühungen der Hauptpartner wurden durch das Erscheinen von zwei Geräten auf dem Markt belohnt, die in der Lage sind, die spektrale und zeitliche Netzimpedanz zu analysieren. Die Messergebnisse dieser Geräte mit dem statischen Prüfmuster wurden bereits verglichen und die Ergebnisse werden in diesem Dokument vorgestellt. Es ist interessant festzustellen, dass trotz der Verwendung unterschiedlicher Netzanregungs- und Datenverarbeitungsmethoden alle verglichenen Geräte ähnliche Ergebnisse in dem von Powerline-Kommunikationssystemen verwendeten Frequenzband erzielten.

Schließlich erweitert sich der Kreis der nicht geförderten Projektpartner um drei deutsche Universitäten, die während einer Präsentation des Z-NET-Projekts auf einer vom Netzimpedanz Interessenverband im Oktober 2020 in Hamburg organisierten Konferenz getroffen wurden.

PLC-Kommunikationsanalysemethoden für intelligente Zähler, die auf Impedanzmessung basieren, wurden ebenfalls durch hochentwickelte Werkzeuge zur Messung von Übertragungspegeln und der zeitlichen Entwicklung der Kommunikationsqualität ergänzt. Es wird spannend sein, diese Methoden bei den schweizerischen Verteilnetzbetreiber systematischer anzuwenden.

Résumé

Le déploiement à grande échelle de compteurs intelligents repose largement sur l'utilisation de la technologie de communication par Courant Porteur en Ligne (CPL)pour la transmission de données mesurées. L'impédance mesurée entre Phase et Neutre sur le réseau basse tension, en fonction de la fréquence (FdGI), influence grandement la propagation des signaux sur les lignes. Elle peut même dans certain cas limiter la fiabilité et réduire la capacité de transmission des compteurs intelligents. La mesure précise de l'impédance de ligne est actuellement mal définie et n'est possible qu'avec quelques rares équipements. Par ailleurs, les différentes méthodes proposées ne donnent pas toujours des résultats comparables. L'objectif de ce projet est d'établir une norme d'impédance de réseau traçable du point de vue métrologique qui permette la comparaison objective des techniques de mesure proposées et ouvre la voie à la normalisation. La standardisation d'une méthode de mesure commune devrait faciliter le développement et l'introduction d'instruments de mesures de l'impédance efficaces. Cette première étape permettra l'établissement et la dissémination de méthodes d'analyse des conditions de transmission des signaux CPL pour les compteurs intelligents sur le réseau de distribution. Les appareils qui ne génèrent pas nécessairement du bruit, mais dont les caractéristiques en fréquence sont défavorables à la transmission CPL pourront être localisés. A titre d'exemple, un fabricant de filtres CEM partenaire du projet Z-NET, propose d'insérer un stabilisateur d'impédance entre les appareils consommateurs critiques et le réseau de distribution.

Des échantillons normés sont nécessaires à la calibration d'instruments de mesure d'impédance du réseau. Dans le cadre du projet Z-NET, l'Institut suisse de métrologie METAS a construit et caractérisé plusieurs échantillons standard d'impédance de réseau sur la base du cahier des charges établi conjointement avec la HES-SO Valais-Wallis :

- Un échantillon statique basé sur un réseau d'impédance de ligne stabilisé normalisé (LISN), tel qu'utilisé pour les tests d'accréditation de Compatibilité électromagnétique (CEM).
- Un échantillon aux caractéristiques en fréquence programmables, afin de gagner en flexibilité pour des essais plus complets en laboratoire ou sur site.
- Basé sur l'échantillon précédent, une variation dynamique programmable des caractéristiques en fréquence synchronisée à la fréquence fondamentale du réseau de distribution électrique, pour provoquer une variation d'impédance périodique.

Le projet Z-NET a trouvé un nouvel essor en 2020 et les efforts concédés par les partenaires principaux ont été en quelques sorte récompensés par l'apparition sur le marché de deux équipements dédiés à l'analyse spectrale et temporelle de l'impédance du réseau. Les résultats de mesure de ces équipements avec l'échantillon statique ont déjà été comparés et les résultats seront présentés dans ce document. Il est intéressant de noter que malgré l'utilisation de méthodes d'excitation du réseau et de traitement des données différents, l'ensemble des équipements comparés ont donnés des résultats semblables dans la bande de fréquence utilisée par les systèmes de communication par courant porteurs en ligne.

Finalement, le cercle des partenaires non financés du projet s'élargit à la suite de la rencontre avec trois universités allemandes à l'occasion d'une présentation du projet Z-NET dans le cadre d'une conférence organisée par la Netzimpedanz Interessen Verband à Hamburg en octobre 2020.

Les méthodes d'analyses des réseaux de communication par CPL pour compteurs intelligents basée sur une mesure d'impédance ont aussi été complétées avec des outils avancés pour la mesure des niveaux des signaux et l'évolution de la qualité de la communication dans le temps. Il sera intéressant d'appliquer ces méthodes de manières plus systématiques avec les gestionnaires de réseaux de distribution suisses.

Summary

The large-scale deployment of smart meters relies heavily on the use of Power Line Communication (PLC) technology for the transmission of measured data. The impedance measured between Phase and Neutral on the low voltage network, as a function of frequency (FdGI), greatly influences the propagation of signals on the lines. It can even in some cases limit the reliability and reduce the transmission capacity of smart meters. Accurate line impedance measurement is currently poorly defined and is only possible with very few devices. Moreover, the various methods available do not always give comparable results. The objective of this project is to establish a metrologically traceable network impedance standard that allows objective comparison of the proposed measurement techniques and paves the way for standardization. The standardization of a common measurement method should facilitate the development and introduction of efficient impedance measuring instruments. This first step will allow the establishment and dissemination of methods for more systemic analysis and improvement of line carrier current signal transmission conditions for smart meters on the distribution network. Devices that do not necessarily generate noise, but whose frequency characteristics are unfavorable to PLC transmission will be located. As an example, a manufacturer of EMC filters, a partner in the Z-NET project, proposes to insert an impedance stabilizer between critical consumer devices and the distribution network.

Standardized samples are required for the calibration of network impedance measuring instruments. Within the framework of the Z-NET project, the Swiss Metrology Institute METAS has constructed and characterized several standard network impedance samples based on specifications established jointly with the HES-SO Valais-Wallis:

- A static sample based on a standard stabilized line impedance network (LISN), as used for EMC accreditation tests.
- A sample with programmable frequency characteristics, to gain flexibility for more comprehensive laboratory or field testing.
- A very fast programming of the latter, synchronized with the fundamental frequency of the network, to create a variable impedance over a period of the network.

The Z-NET project found a new momentum in 2020 and the efforts of the main partners were somewhat rewarded by the appearance on the market of two pieces of equipment dedicated to the spectral and temporal analysis of the network impedance. The measurement results of these equipment with the static sample have already been compared and the results will be presented in this document. It is interesting to note that despite the use of different network excitation and data processing methods, all the equipment compared gave similar results in the frequency band used by power line carrier communication systems.

Finally, the circle of unfunded project partners is being extended following a meeting with three German universities with a presentation of the Z-NET project at a conference organized by the Netzimpedanz Interessen Verband in Hamburg in October 2020.

The methods for analyzing PLC communication networks for smart meters based on impedance measurement have also been supplemented with advanced tools for measuring signal levels and the evolution of communication quality over time. It will be interesting to apply these methods in a more systematic way with the Swiss Distribution System Operators.

Acknowledgments

The presented research activities and outcomes would not have been taking place without the support of Swiss Federal Office of Energy representative, who did not only help to make the Z-NET project viable financially but coached us and followed the project from the beginning of the application process to this final report.

We wish to express our gratitude to all the partners of the project for the active collaboration.

We thank industrial and academic partners who voluntarily joined the project without direct financial contribution or contractually defined missions.

Contents

Abbreviations

AC	Alternating Current
AN	Artificial Network
AMN	Artificial Mains Network
ARAMIS	Administration Research Actions Management Information System (information system operated by the Swiss federal government)
BFH	Berner Fachhochschule
CEM	Compatibilité Électromagnétique
CENELEC	Comité européen de normalisation en électronique et en électrotechnique
CISPR	Comité International Spécial des Perturbations Radioélectriques
CPL	Courants Porteurs en Ligne
CSV	Comma Separated Values
DUT	Device Under Test
EUT	Equipment Under Test
DFT	Discrete Fourier Transform
DPD	Dual Phase Demodulation, so called 'Lock-In amplifier technique'
DSO(s)	Distribution System Operator(s)
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMV	Elektromagnetische Verträglichkeit
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FCC	Federal Communications Commission
FdGI	Frequency dependent Grid Impedance
FTdGI	Frequency and Time dependent Grid Impedance
FFT	Fast Fourier Transform, efficient algorithm to implement DFT
GUM	Guide to the expression of Uncertainty in Measurement
HDF	Hierarchical Data Format, a set of file formats designed to store and organize large amounts of data.
HES-SO VS	HES-SO Valais-Wallis, Haute Ecole Spécialisée de Suisse Occidentale Valais-Wallis (University of Applied Sciences and Arts Western Switzerland Valais-Wallis)
LCR meter	Electronic test equipment used to measure the inductance (L), capacitance (C) and resistance (R)
LED	Light-Emitting Diode
LISN	Line Impedance Stabilization Network
LV	Low Voltage
METAS	Federal Institute of Metrology METAS
MCE	Mains Communication Equipment
N	Neutral
NIE	Non-Intentional Emissions
PE	Protective Earth

PCC	Point of Common Coupling
PLC	Power Line Communication
PLRI	Programmable Line Reference Impedance
PTVLRI	Programmable and Time Variant Line Reference Impedance
RF	Radio Frequency
RSSI	Received Signal Strength Indication
SCCER	Swiss Competence Center for Energy Research
SFOE	Swiss Federal Office of Energy
SIG	Services industriels de Genève
SLRI	Static Line Reference Impedance
SNR	Signal to noise ratio
SPICE	Simulation Program with Integrated Circuit Emphasis
TSR	Tratamiento de la Señal y Radiocomunicaciones research group at UPV/EHU
TUD	Technische Universität Dresden
UPV/EHU	Universidad del Pais Vasco/Euskal Herriko Unibertsitatea
V-AMN	Artificial Mains V-network
VSE	Verband Schweizerischer Elektrizitätsunternehmen

1 Introduction

1.1 Background information and current situation

The large-scale deployment of smart meters relies heavily on the use of Power Line Communication (PLC) technology for the transmission of measured data. This method represents significant advantages for the Distribution System Operators (DSOs) in term of investments and operation costs. A frequency band between 3 and 98 kHz was defined by the CENELEC (Comité Européen de Normalisation en Électronique et en Électrotechnique) for the use of PLC dedicated to Smart Meters. Two large alliances of DSOs and equipment manufacturers in Europe developed and established advanced technologies and communication protocols for PLC. This was before recognizing that the CENELEC A band was in fact perturbed by active in-feed converters, power adapters, LED lights and other battery chargers. The interference between electronic equipment and PLC has trigged an impressive effort of normalization for the limitation of conducted Non-Intentional Emissions (NIE) in the frequency range 2 to 150 kHz since then. In parallel, a similar effort is on-going for the standardization of emissions measuring technique in the 2 to 150 kHz frequency range.

Research activities conducted at HES-SO VS (HES-SO Valais-Wallis, Haute Ecole Spécialisée de Suisse Occidentale Valais-Wallis) and at other European based universities have showed that not only noise present on the line could affect the quality of PLC transmission. The frequency dependent and in some cases the time variant impedance measured between Phase and Neutral at the connecting point of communicating devices, so-called access impedance, plays a significant role in the reliability and the transmission capacity of smart meters.

Accurate line impedance measurement is currently poorly defined and is only possible with very few devices. However, the interest for a standardized method to measure impedance has been growing during the past years, not only for the issues linked with communication systems but also for the stability analysis of current controllers in renewable energy in-feed converters. Several universities in Europe have developed different types of analyzers for frequency dependent and time variant grid impedance. In 2020 two German companies have commercialized their own products.

The Industrial Electronics & Drives team at the HES-SO VS has been researching on these topics with the realization of Power Line Impedance meter covering a frequency range up to 500 kHz. Thanks to the support of Swiss Federal Office of Energy (SFOE) and Swiss Competence Center for Energy Research (SCCER), research activities in the domain of PLC for the Advanced Metering Infrastructure could be conducted during the past five years. The impact on Power Line Communication systems of converters dedicated to renewable energy production and energy in-feed to the grid could be addressed during the REMIGATE [1] and OptiQ [2] and other projects in Europe [3], Numerous measurements of Power line impedance were conducted in collaboration with our project partners at several type of sites in the frame of those projects. The specification for the standard impedances is based on this important data.

1.2 Purpose of the project

A common definition of Frequency dependent Grid Impedance (FdGI) or Frequency and Time dependent Grid Impedance (FTdGI) should be established, based on existing references. A grid impedance definition will represent a significant step in the EMC standardization process. It will make it possible to define coherent measuring and calculating methods. Impedance limits for PLC communication immunity and impedance conditions for PLC performance tests bench can then realistically be defined. An important question to solve in this matter is the relevance and how to define time varying grid impedance, in particular, how should the sub-cycle variations within a 50Hz grid cycle be considered. Definition of Time and frequency resolutions for the measurement of spectral impedance need also to be harmonized. The on-going process for the definition of measuring method for intentional and non-intentional conducted emissions in the frequency range 2 to 150kHz will have a certain impact and should be considered.

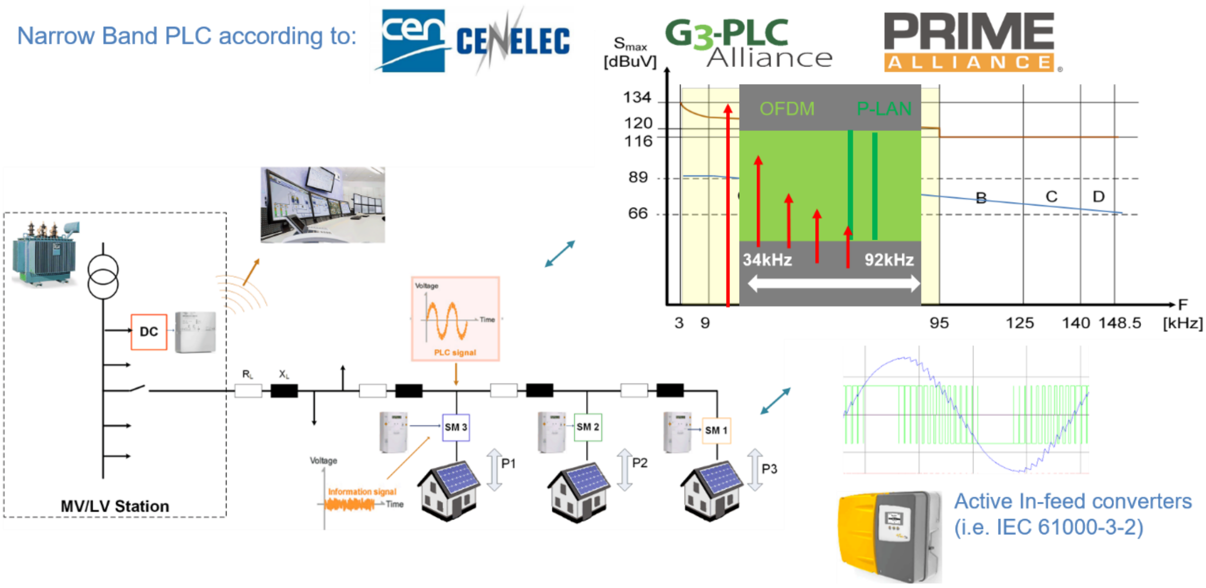


Figure1: Power Line Communication for Smart Grid Infrastructure in Europe

The goals of this project are threefold:

- The establishment of a metrological base for the grid impedance measurement.
- Contribute to the standard definition of the grid impedance and the initiation of the normalization effort of the frequency grid impedance measurement.
- Time dependent grid impedance measurement.

The results of the project will be shared with standardization instances in charge of defining the environment in term of electromagnetic compatibility where power line communication is planned to be used, as well as standardization committees in charge of specifying the working conditions and immunity of PLC for smart meters at the physical layer. This process can only be achieved through an international collaboration with experts in the domains of Power Quality, Radio and Telecommunication and industrial partners involved in the Smart Metering business, instrumentation for Power Quality and Smart meter users, like Distribution Systems Operators. International partners can help us collecting measured data on the tendency with FdGI in European grids. They will help us to review and compare existing measuring methods. We are also intending to collect information and to realize further tests about the impact of sub-cycle variation of the access impedance on PLC systems.

Due to its impact on propagation of non-intentional conducted emissions, Power Line Communication Systems, passive filters components aging or converter controllers' stability, we expect the FdGI to be considered or used more often in standards in the future.

1.3 Objectives

The main targeted outcome is a deterministic standard sample of frequency and time dependent grid impedance. The standard sample will be practically usable for the calibration of grid impedance meters in the CENELEC A and FCC (Federal Communications Commission) bands (3 to 500kHz). The standard sample will be determined in magnitude and phase with values corresponding to those found on Low Voltage Alternating Current (LV AC) distribution grids in Europe. Impedance values can be varying in time within a 50 Hz cycle. It will be connected parallel to a low voltage AC source and will shape the impedance of that source.

Based on a traceable standard impedance, different measuring methods can be validated. A comparative analysis of results of measurements realized with different existing on-line grid impedance meters will be available. The report will indicate how adequate is the developed sample for the calibration of different grid impedance measurement tools. The designers of grid impedance meters will find out if measuring methods give coherent results and if they are useful for the analysis and reduction of Electromagnetic Interference (EMI) with PLC systems.

A participation to the standardization activity is one of the targeted outcomes.

A comparison of the various grid impedance measurement techniques developed by key research organizations in Switzerland and Europe will be made possible with such an impedance standard and will constitute the first significant step towards a standardization of the measuring method. The project report will be completed with recommendation to the Power Quality instrumentation industry for the realization of accurate and affordable high frequency range Power Line Impedance Analyzers.

2 Project partners and research facilities

An overview of the project partners, with competences, responsibilities in the project and standardization activities related to the Z_NET project is presented on Table 1. The two main partners for the project are METAS, the Swiss Federal Institute of Metrology, located in Bern-Wabern, and the Institute of Systems Engineering at HES-SO VS. METAS has realized and characterized the Static Line Reference Impedance (SLRI) (WP1) as well as the Programmable Line Reference Impedance (PLRI) (WP 3). Beside coordinating the project, HES-SO VS has specified and evaluated both SLRI and PLRI devices (WP1 and WP2) and evaluated the PLRI in its function as dynamic impedance reference for the subcycle impedance variations (WP3). HES-SO VS has also taken the main role in specifying and coordinating the Z-Analyzers intercomparison campaign, established recommendations, mainly for the standardization working groups involved in PLC or quality of the grid voltage.

METAS	HES-SO Valais-Wallis	SCHAFFNER	SIG	Camille Bauer Metrawatt
Swiss Metrology Institute	University of Applied Science, Institute System Engineering	EMC Filters design, production and slaes	DSO in Geneva	PowerAnalysers Design and production
Laboratory Electrical Energy and Power	Industrial Electronics & Drives Lab	R&D Unit (B. Stauffer, S. Pasko)	Power Quality Group (Cedric Pellodi)	R&D Unit (Thomas Naef) & Management (Max Ulrich)
Realisation SLIR (WP1) Realisation VLIR (WP2 - 3)	Project Leader	Development of Line Impedance Stabiliser	Power Quality measurements with PQ-Box on sites with DER and e-Mobility, Heat Pumps, etc.	Interest to integrate FdGI in their equipement
Uncertainty evaluations EMPIR projects	Specification and evaluation of SLIR and PLIR (WP 1-3) Intercomparison Z-Analysers and recommendations (WP4)	Participation to ERIGrid measuring campaign in Bilbao	Smart Metering implementation pilot projects with G3-PLC	Involved in several Research projects with field measuring campaigns of grid impedance
Standardisation comitees TC 85, ...	Recommendations (WP5) Standardisation comities (WP6) TC 77A, TC 219, TC 8X	Standardisation committee TC 77A, WG8 ...	Member of GRUT : Technical uniformization WS	Standardisation activities TC 85, TC 8x, DACH-CZ ...

Table 1: Overview of main partners to the Z-NET project with responsibilities and related standardisation activities

Three industrial partners participate to the Z-NET project with the main objective to work on the application of Power Line Communication or Frequency and time dependent grid impedance and measuring techniques:

METAS and HES-SO VS could benefit from a funding from Swiss Federal Office of Energy. The industrial partners collaborated on their own costs. Three European academic and industrial partners have joined the project for the two last years:

TU Dresden	UPV/EHU	morEnergy
Chair of Electricl Power Supply	University of Basque Country, Bilbao	PQ laboratory Equipments
Power Quality Group (Jan Meyer)	TSR Group	R&D Unit (Trung Do, M. Jordan)
Conception of FTdGI measuring device (IMD 300)	Design of FTdGI measuring device	Development of Line Impedance Analyser for LV and MV
Numerous PQ research activities with FTdGI measurements on site and in lab	Research activities with PRIME PLC and impact of DER on PLC	Participation to Z-meters intercomparison
	Intercomparison Z-Analysers , Participation to ERIGrid measuring campaign in Bilbao	
Standardisation comitees and WGs, TC 77A WG8, WG9, TC 219 WG 11, DACH-CZ …	Standardisation comitees and WGs, TC 219 WG11…	Netzimpedanz Interessen Verband (Stefan Hoffmann)

Table 2: overview of European academic and industrial partners with competences and related standardisation activities

Most of the development and testing activities were realized in existing laboratories of the partner research institutions:

Some developments and measurements were realized at the facilities of our international partners

Figure 2: Location of Z-NET partners facilities for static standard intercomparison

3 Procedures and methodology

The project activities were organized in 7 work packages:

3.1 WP0: Reference impedance specifications

Lead: HES-SO VS

Participants: TUD, TSR, METAS

The following parameters need to be checked and agreed upon:

The impact of a Frequency and Time dependent Grid Impedance (FTdGI) on harmonics and supra-harmonics propagation has already been proven. However, the impact of this FTdGI on PLC communication still has to be proven and better described. Therefore, simulations and impedance measurements on several power supplies with rectifiers and EMI filters will be performed in this preliminary study.

Those simulations and measurements will provide data to establish a static impedance reference profile.

3.2 WP1: Design and characterization of a static reference impedance

Lead: METAS

Participants: HES-SO VS

This WP consist in the design and the characterization of a reference impedance network that can be used in conjunction with a LISN (Line Impedance Stabilization Network). Together they can be used as comparison standard for most grid impedance meters with a minimum of special equipment.

This first impedance reference will be designed and built by METAS, based on the specifications jointly defined by METAS and HES-SO VS. Once built, the reference will be fully characterized by METAS, and an uncertainty budget will be written and calculated to allow an intercomparison.

The fact that a special impedance network is used with a LISN enables the start of a preliminary inter comparison in most facility with basic EMC capabilities.

3.3 WP2: Design and characterization of a programmable impedance

Lead: METAS

Participants: HES-SO VS

This WP consists in the design of a programmable reference impedance, based on the specifications established in WP0. The programmable impedance allows the selection of a wide variety of resonances and damping values, to allow the measurement and the comparison of different spectrum of interest.

Just like in WP1, once designed and built by METAS, all the impedance configurations of the network will be fully characterized, and an uncertainty budget will be calculated to allow the intercomparison of each impedance value of the network.

The original idea to modify METAS iSimulator used for the calibration of RLC meters is discarded.

3.4 WP3: Design and characterization of a time varying impedance

Lead: METAS

Participants: HES-SO VS, TUD, TSR (for the Specification), Schaffner

The goal of this WP is to design a time varying impedance network, based on the programmable impedance designed in WP2. In this WP, the programmable impedance network gains the ability to vary within a 50 [Hz] or 60 [Hz] period. This behavior allows emulating electronic loads and devices which impedance varies in the cycle. The time varying impedance reference will be synchronized to the fundamental frequency of the network it is connected to.

As for the last WPs, all impedances values will be fully characterized with their uncertainty budget to allow an intercomparison.

3.5 WP4: Comparison of impedance meters measuring the references impedances

Lead: HES-SO VS

Participants: TUD, TSR, morEnergy

Several Frequency dependent impedance meters were developed in Europe during the last years. At least four of them will be compared in term of measuring ranges, accuracy in amplitude and phase as well as in functionality. The comparison will be based on tests realized in laboratory with the standard impedance sample designed by METAS. The test conditions and scenarios will be very carefully agreed upon and will reproduce measuring conditions on site. Number of measurements, tests duration, available power supply and temperature conditions have to be considered for instance.

It will be decided with the owners of the equipment if the comparison tests should be done in one single laboratory (HES-SO VS for instance). In case of reduced availability and transportability the comparison will be done in different laboratories and the standard impedance sample will be transported. A comparative test report will be established. Information about the measuring methods and used signal treatment algorithms will complete the measurement results. The report will indicate if measuring methods give coherent results and if they are useful for the analysis and reduction of EMI with PLC systems.

3.6 WP5: Recommendations for grid impedance measurement method

Lead: HES-SO VS

Participants: TUD, TSR, Camille Bauer Metrawatt AG

Based on the comparative tests results the most reliable and effective grid impedance method will be selected and improved. Selection criterions include costs, robustness and stability. Emphasis will be put on the effectiveness and usefulness of the measuring method to facilitate and accelerate the deployment of smart meters with reliable PLC on the grid. Grid impedance measurements can be used at the planning stage: optimal number of repeating devices and used technology can be defined when the characteristics of the grid section are known. Grid impedance measurement can also be useful after installation of smart meter in the so-called ‘clean-up’ process. Finally, the impedance characteristics of grid components or equipment’s can be done before their installation, respectively connection to the grid at equipment’s suppliers or at DSOs laboratory.

The best method will be established in collaboration with all the partners of the project. The signal processing is an integral part of the FTdGI measuring method (sample frequency, time steps, frequency grouping and harmonics cancellation). The definition and specification of signal processing has to be agreed upon with the project partners and standardization experts in EMC and PLC communication.

3.7 WP6: Collaboration with standardization committees and experts working groups

Lead: HES-SO VS

Participants: All the academic partners

The project partners will continue their contribution to the standardization effort linked to electromagnetic Interferences in the PLC frequency band all along the duration of the project. The project partners are currently involved in the following committees and working groups:

The idea to create a definition and to define a standard sample of the ‘frequency and time dependent grid impedance’ will be shared within working groups in a first priority. A definition will be proposed based on the Z-NET project results. Due to FTdGI impact on PLC in the 2 to 500kHz band, limits will be proposed for corresponding EMC product standards and for PLC immunity test.

3.8 Project coordination and results dissemination

Lead: HES-SO VS

Participants: All the partners

Coordination meetings with all the project partners are organized on a yearly basis, to share preliminary results with all partners, to review specifications for equipment, to develop and to agree upon further project activities. Complementary funding solutions for the research activities are studied in a coordinated manner.

4 WP0: Specifications for standard impedance

One of the main objectives of the Z-NET project is to define a common specification for future standardized impedance circuits to be used when testing On-Line frequency dependent grid impedance measuring instrumentation or as a standardized reference sample with an emphasis on FdGI impact on narrow band and wide band PLC systems in the frequency ranges covered by the CENELEC A and FCC standards. The objective of the WP0 was to establish preliminary specifications for the Static Line Reference Impedance (SLRI) (WP1), the Programmable Line Reference Impedance (PLRI) (WP2) and the Programmable and Time Variant Line Reference Impedance (PTVLRI) (WP3) prototypes. Both static and programmable impedances networks are specified based on existing Artificial Mains Network (AMN) or Line Impedance Stabilization Network (LISN) modified to achieve impedance levels matching to grids reality and offering sufficient dynamic ranges for instrumentation testing. The time variant impedance network will be specified according to laboratory test results on the impact of different equipment and circuit on advanced PLC technique realized in the frame of the ERIGRID Z-NET action.

Our objective is not to reproduce or to create a compromise between existing standards. But a comparison and inspiration from these standards seems relevant, as all had followed the common objective to reproduce the grid behavior in a statistical approach.

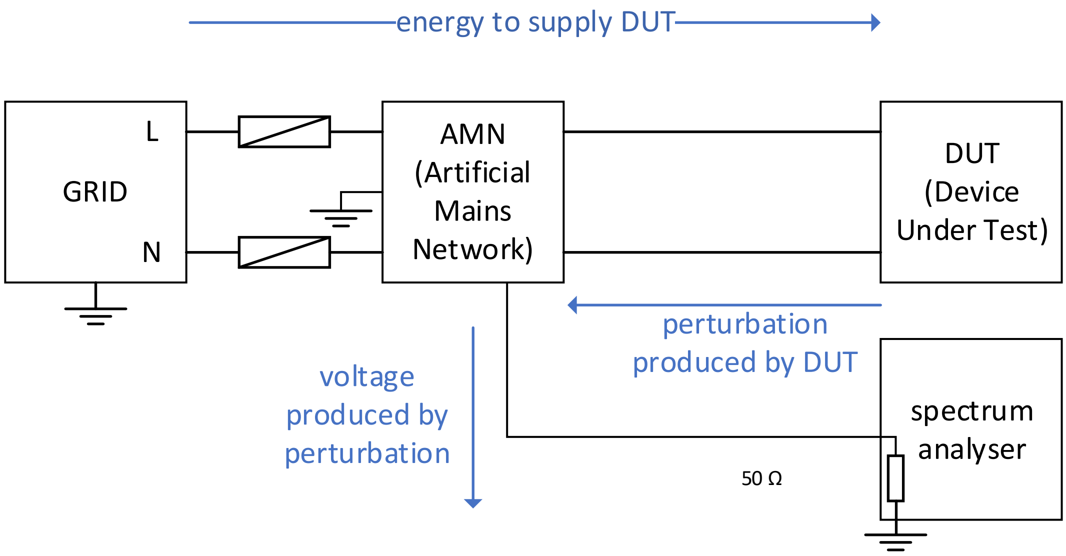


Figure 3 : AMN usage scheme

Several standards and technical reports deal with normalization on impedance, to achieve comparable measurement results, independently of the variable grid conditions and location of the tests. As example, Figure 3 illustrates how an AMN is used.

Figure 4 summarizes the EMC standards with reference to standardized or modified standardized impedance networks to be implemented between DUT and grid for conducted emissions tests or immunity tests.

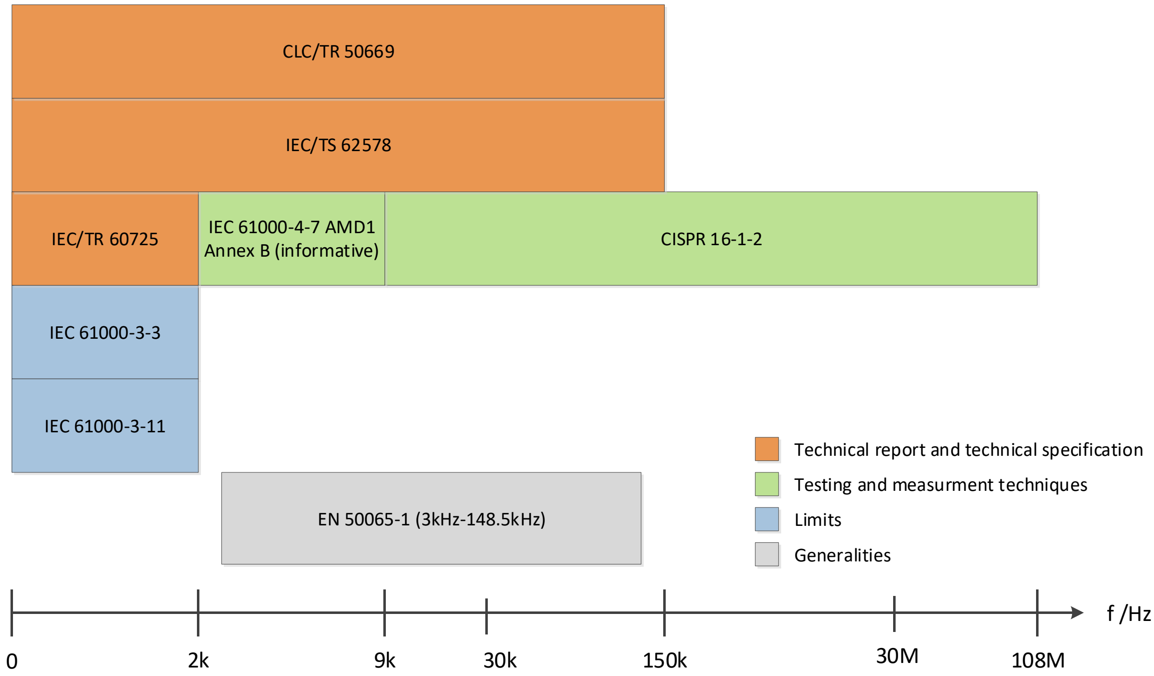


Figure 4 : Set of EMC standards with reference to standardized or modified standardized impedance networks

The IEC 61000-3-3 [4] (Z_{REF}), IEC 61000-3-11 [5] (Z_{TEST}) and IEC/TR 60725 [6] define impedance for frequencies measurement below 2kHz (flicker measurement). The CISPR 16-1-2 [7] defines among other artificial mains network V-network (V-AMN) for frequencies above 9kHz, up to 108MHz (conducted emission measurement). The IEC 61000-4-7 - AMD1 [8] defines an AMN for emission assessment in frequency range 2kHz to 9kHz, but this proposal is informative only. No AMN according to this standard is available on the market.

All impedances specified in the standards present a higher amplitude than usually measured in the low voltage distribution grid across Europe.

Other standards, technical reports and technical specification like CLC/TR 50669 [9], IEC TS 62578 [10] and EN 50065-1 [11] mention the usage of modified normalized impedance to be more representative of the actual grid impedance.

4.1 Summarize of impedance spectrums in relevant standards

Figure 5 represents impedances calculated on basis of schematic or table values proposed in EMC standards. The spectral reference impedances are considered from EUT point of view. Excepted for the V-AMN CISPR 16-1-2, all impedances seen from the EUT side have been calculated or estimated with a short-circuit on the grid side. Due to the normative frequency range above 9kHz, applying for V-AMN CISPR 16-1-2, the spectral reference impedance is calculated with an open circuit on the grid side. The calculated behavior in frequency domain under 9kHz trends toward 4.5Ω and diverge significantly from real grid impedance behavior.

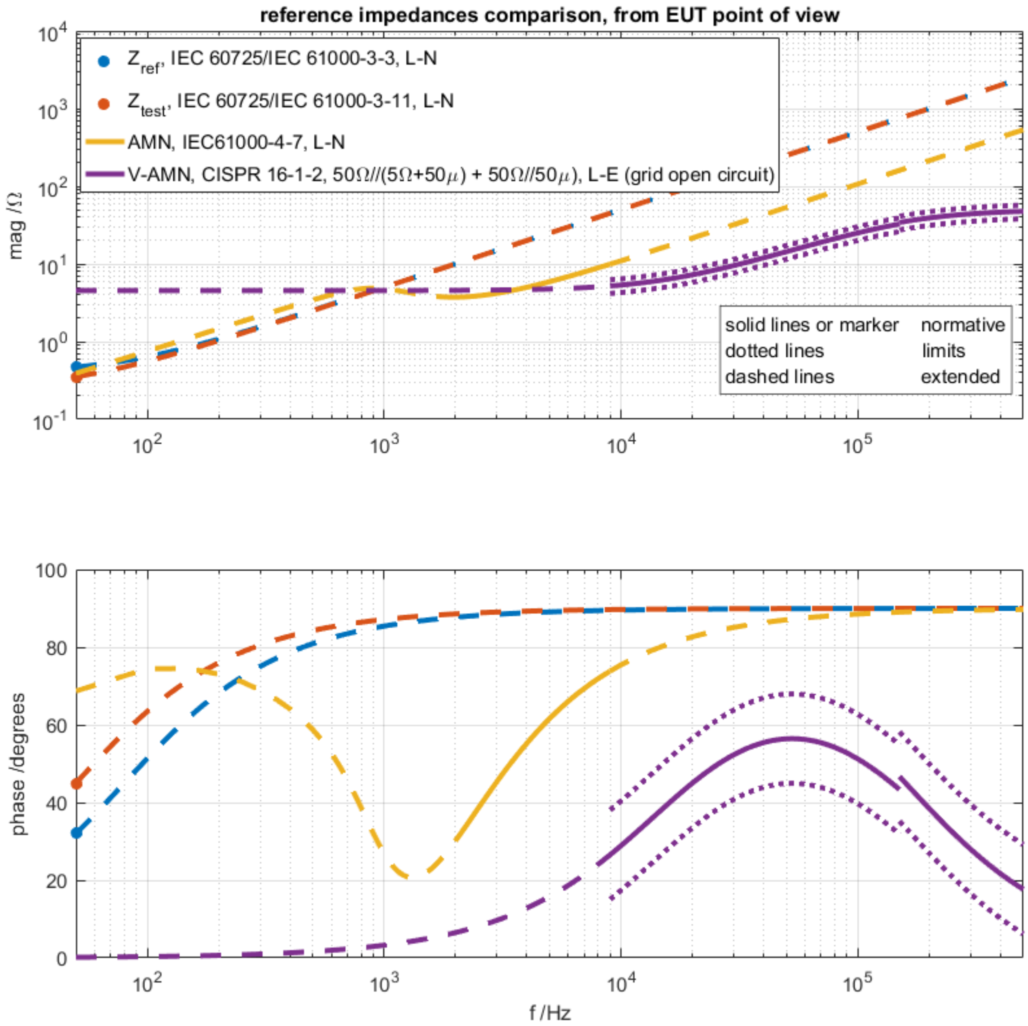


Figure 5 : Reference impedance calculated from CEM standards

In real situation, the V-AMN CISPR 16-1-2 is connected to the 50 Hz grid, through a low impedance path. The characteristic of the grid impedance, related to the short-circuit power at the point of common coupling (PCC), depends on the grid configuration and equipment. It plays an important role in the propagation of conducted harmonics and emissions in real installations and in tests set-ups. Three representative situations have been considered: grid side shorted (the ideal case), strong grid (industrial or urban locations) and weak grid (rural locations). The D-A-CH-CZ 2007 [12] was used to define representative values of grid impedance. The retained values are listed in the Table 3.

type of distribution location	RGRID	LGRID
Shorted	0	0
strong (industrial or urban)	3 mΩ	31 µH
weak (rural)	196 mΩ	572 µH

Table 3 : Characteristics of the grid impedance for different cases

Figure 6 illustrates the desired spectral impedance behavior, for the three cases calculated.

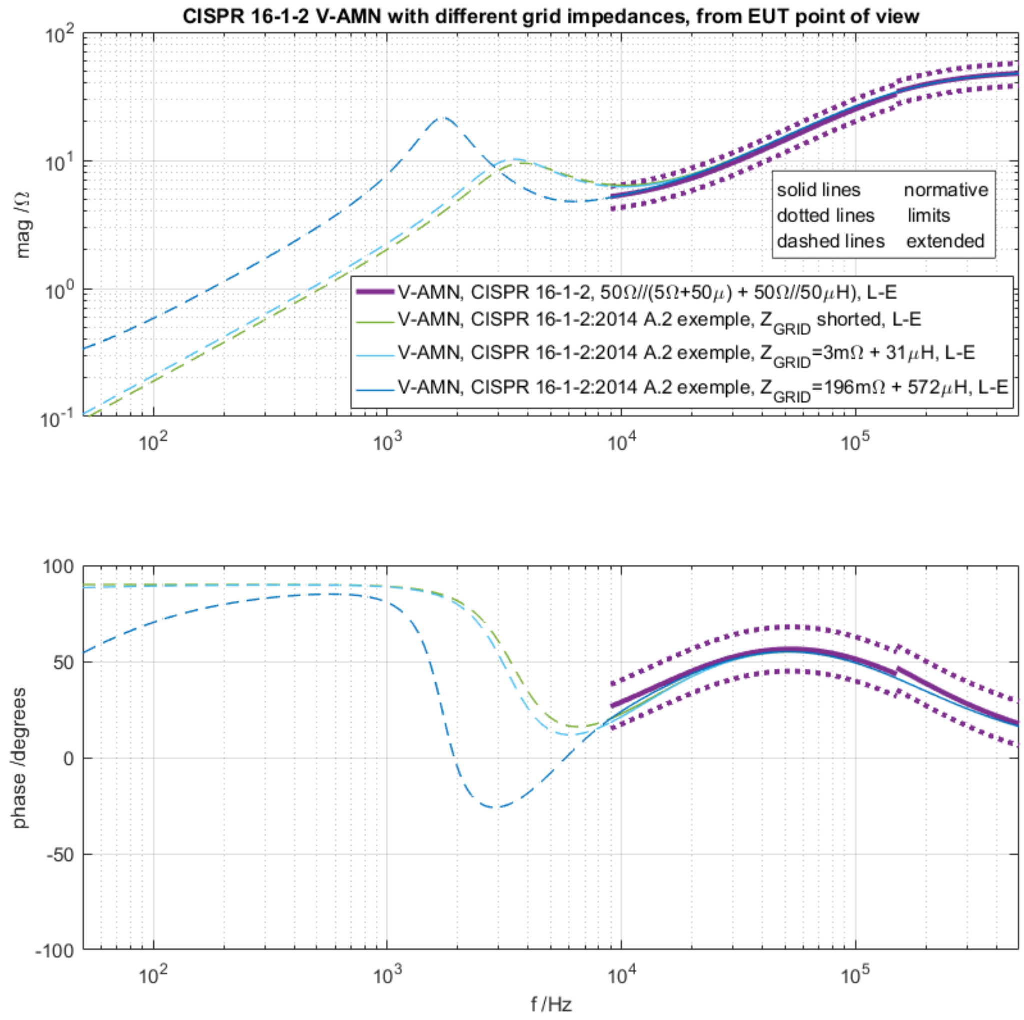


Figure 6 : Impedance spectrum with different grid strength according to CISPR 16-1-2

4.2 Comparison CISPR 16-1-2 V-AMN with actual impedance field measurements results

If the CISPR 16-1-2 seems to be the most interesting impedance due to its large usage for emission measurement in EMC laboratories and its lower magnitude in high frequencies, it is necessary to compare its behavior with real on-field measurements, to evaluate if and how to modify the basic impedance with external components.

Figure 7 represents measurements results of the D-A-CH-CZ campaign 2018, compared to the impedance CISPR 16-1-2 standard (with grid shorted, magnitude between line and earth). The yellow curve published in bulletin.ch [13] is the median 50% of all measurements realized by TUD (with measurement in Germany and Austria too). The blue curve is the mean value of all measurements realized by the HES-SO VS. The measured impedance is always lower as the CISPR 16-1-2 standard impedance.

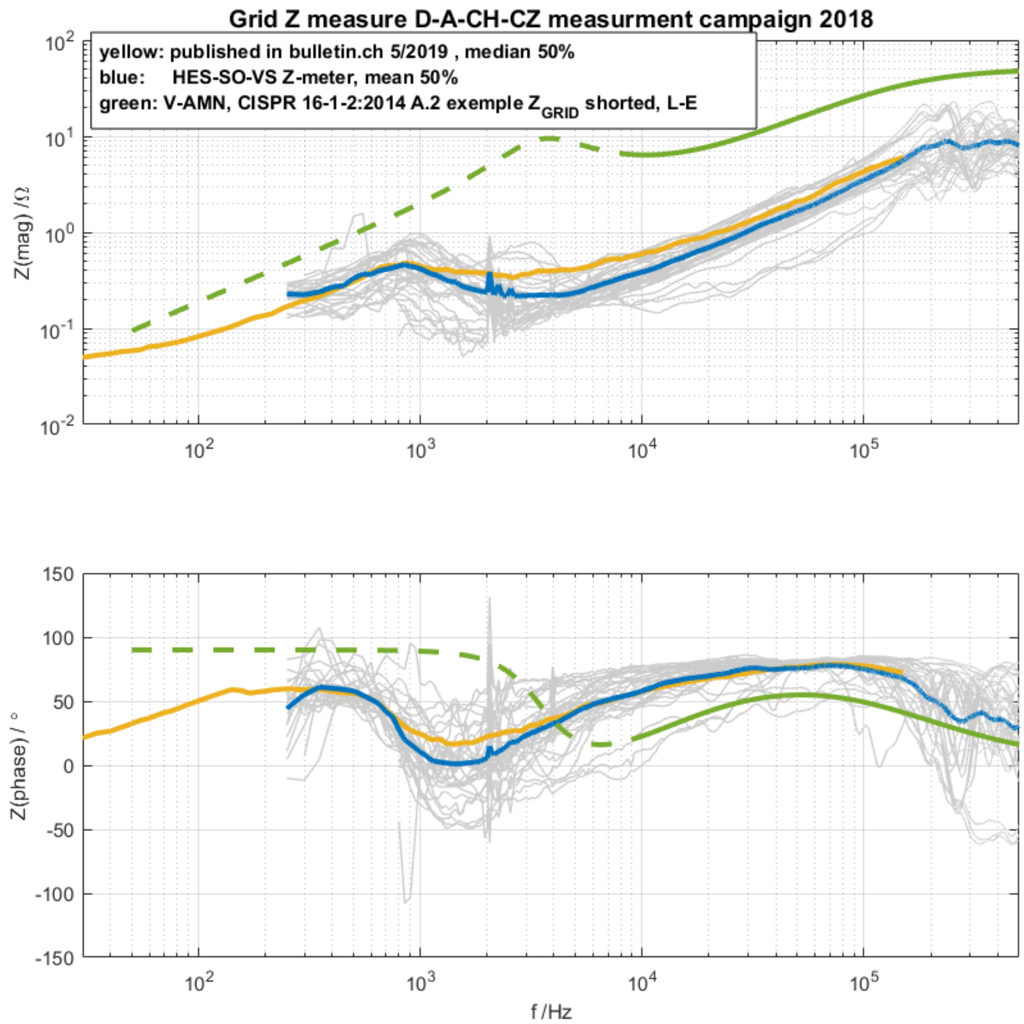


Figure 7 : Measurements results of the D-A-CH-CZ campaign 2018

4.3 Final target for the Static Line Reference Impedance (SLRI)

The standard reference impedance defined in the Z-NET project should not only be representative of the average frequency behavior of LV AC grid found in Europe. The reference should include some important dynamic range of impedance with some stronger variations of magnitude and phase over the considered frequency range to emulate some damped resonances. This feature is relevant for instrumentation testing. On the other hand, the line impedance reference needs to be easy to use and its frequency behavior must not depend on working environment.

To test the impedance-meters with realistic values, it was decided to get an easily affordable standard CISPR 16-1-2 V-AMN as a basis and to build external components to lower its average magnitude over the frequency range (RLC series resonant circuit for lower frequencies, RC series circuit for high frequencies). To allow the evaluation of impedance-meters in more challenging situations, a second RLC series resonant circuit with high quality factor was added, working close to the upper limit of the CENELEC A-band. Figure 8 illustrates the results for the modified V-AMN, compared to the unmodified standard and the mean values of D-A-CH-CZ measurement campaign 2018 (results from measurements at HES-SO VS).

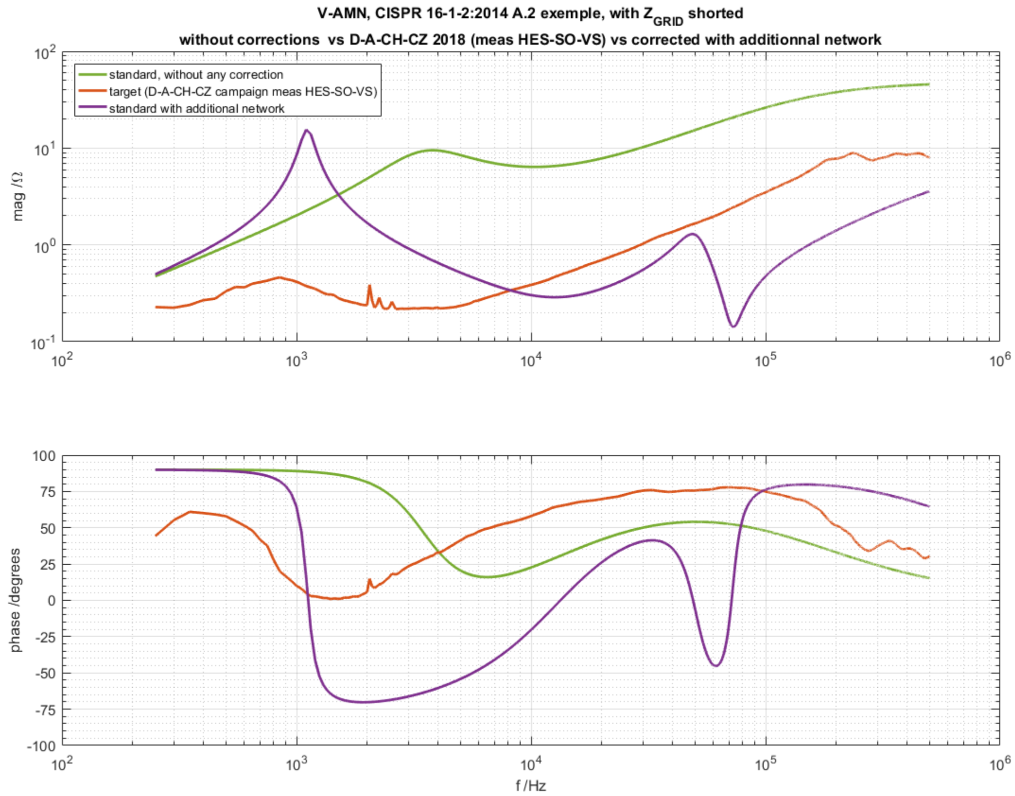


Figure 8 : Modified standard CISPR 16-1-2 to achieve the Static Line Reference Impedance (SLRI)

5 WP1: Design and characterisation of a static reference impedance

In WP0, the specifications of an impedance reference standard were discussed and set. The goal of WP1 was to design and characterize a Static Line Reference Impedance (SLRI) according to WP0's specifications.

METAS approach for the design of the SLRI was the following:

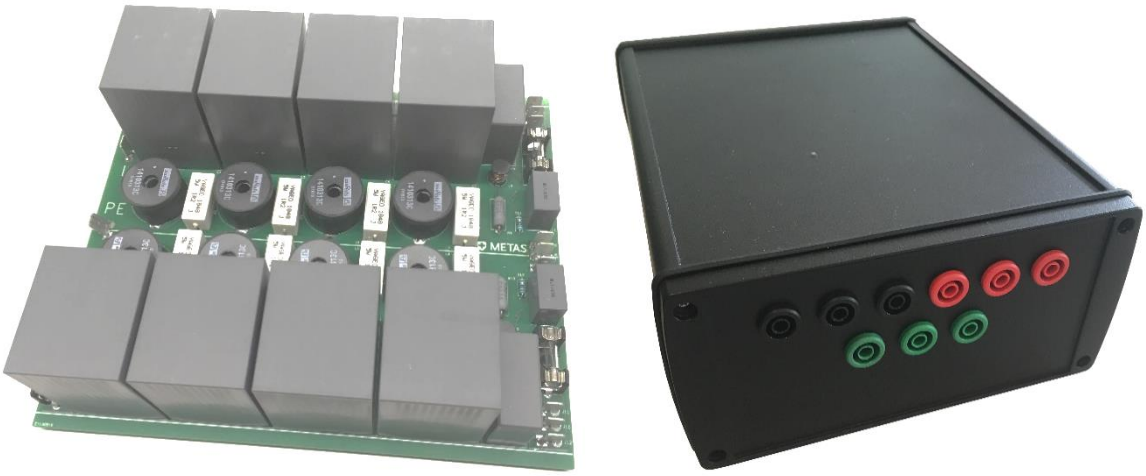


Figure 9: Static line reference impedance additional network PCB (left) and packaged (right)

After designing and simulating the LISN and the RLC network, METAS designed the printed circuit board and the enclosure for the SLRI. Once built, the impedance of the device was measured over the 1-500 kHz frequency range (Figure 10) with a calibrated precision impedance measurement bridge. All the impedance measurements were performed at low voltage and current, disconnected from the grid.

Once the device fully characterized over the frequency range of interest, an uncertainty budget was established for the measurements.

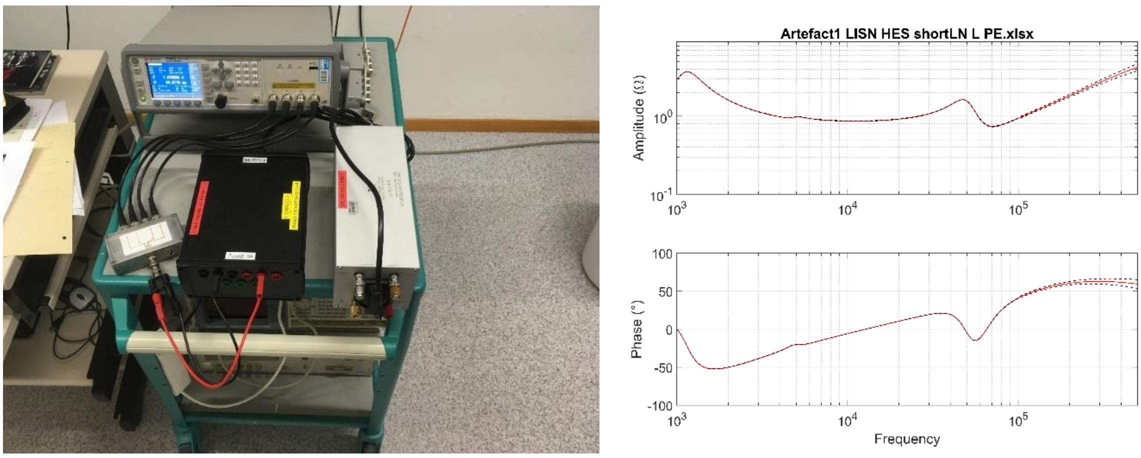


Figure 10: Impedance measurement setup (left) and impedance response (right)

Once the SLRI built and characterized, the intercomparison started in January 2020 and successfully finished its course around Europe in June 2020 after being measured by all the partners. The results of the intercomparison of impedance meters are dealt with in the chapter 8.3

6 WP2-WP3: Design and characterization of programmable and time variant reference impedance

The goal of WP2 is similar to the WP1, but this time by realizing a programmable impedance network in parallel with the LISN. Based on the experience acquired by measuring the static impedance network, it was decided that the programmable impedance standard would be based on the same principle:

The RLC circuit is based on the same principle as the SLRI, but in the Programmable Line Reference Impedance (PLRI), several values of the RLC components were placed on the PCB and could be switched on or off by using MOSFET-based AC switches. Components of the programmable impedance network were carefully selected to permit a large selection of resonances all over the spectrum of interest, as illustrated by Table 4 and Figure 14.

C (µF)		0.1	1	4.7	10		
L (µF)			1	4.7	10	47	100
R (Ω)	0		1		10		

Table 4: RLC matrix components in programmable line reference impedance

After several simulations, METAS built the PLRI in two parts:

The power circuit is based on high current discrete components, allowing the use of large excitation current for the grid impedance meters. The PCB traces were designed accordingly, and some passive cooling was added when necessary.

The control circuit is based on an AM3358 ARM Cortex-A8 processor with a lightweight Linux distribution running on it. METAS wrote a control software providing a web-based user interface over Ethernet to select individually the discrete components in the PLRI.

As the user interface is based on simple http-requests, it was then easy to automatize the characterization of many impedances based on various combinations of RLC components. This was done in the same manner as for the SLRI in WP1, with an additional programmable script (Figure 11).

Figure 11: Programmable line impedance reference (left) and automated characterization setup (right)

For all RLC combinations, an uncertainty budget was automatically calculated in the calibration script, in accordance with the Guide to the expression of Uncertainty in Measurement (GUM) and the Keysight E4980AL RLC bridge user manual. The uncertainty budget on all measurements is a condition to be able to reliably compare the measurements made in all partners institutes.

Since WP3 was closely related to WP2, METAS decided to develop the PLRI with the WP3 goals in mind. As the goal of the latter is to allow the variation of a programmable impedance within a mains frequency cycle, the PLRI hardware contains already almost everything necessary to allow the fast switching.

The only thing that was added for WP3 is a synchronization circuit, based on an isolation transformer, a band-pass filter tuned at 50 Hz and a zero-crossing detector. This circuit is implemented on the power PCB of the PLRI.

Since the main control processor is running a Linux operating system and a webserver not optimized for real-time applications, a real-time micro-controller was also implemented in the control circuit.

The main processor programs the micro controller according to the user inputs and then let the real-time side handle the switching of the impedance.

To add flexibility, some BNC interfaces were added for an external trigger signal as well as a synchronization signal for the impedance switching.

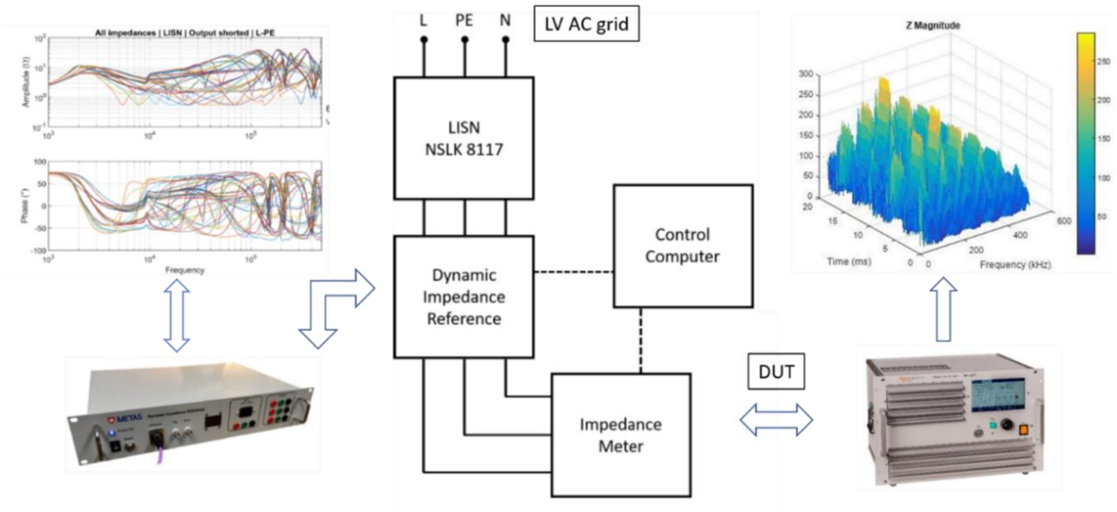


Figure 12: Test set-up with programmable and time variant line reference impedance

Figure 12 illustrates the system schematic to test the various impedance meters. The impedance meters are not necessarily connected to the same control PC as the PLRI. The device is connected to the output of the LISN, where the EUT is normally connected during EMC testing. There are no series components in the programmable impedance network, so the total measured impedance is the parallel impedance of the LISN from EUT point of view and the programmable impedance network itself. Finally, it should be remembered that since the LISN is not used for its primary purpose (EMC testing), it is imperative that both RF outputs are terminated by 50 Ω.

Both static and dynamic modes of the device can be selected and configured in the web-based control interface. The user can also synchronize the impedance switching with an external TTL signal to allow further flexibility. Figure 13 illustrates the easy control interface to configure the programmable interface and a zoom on time variant timing if the dynamic mode is chosen.

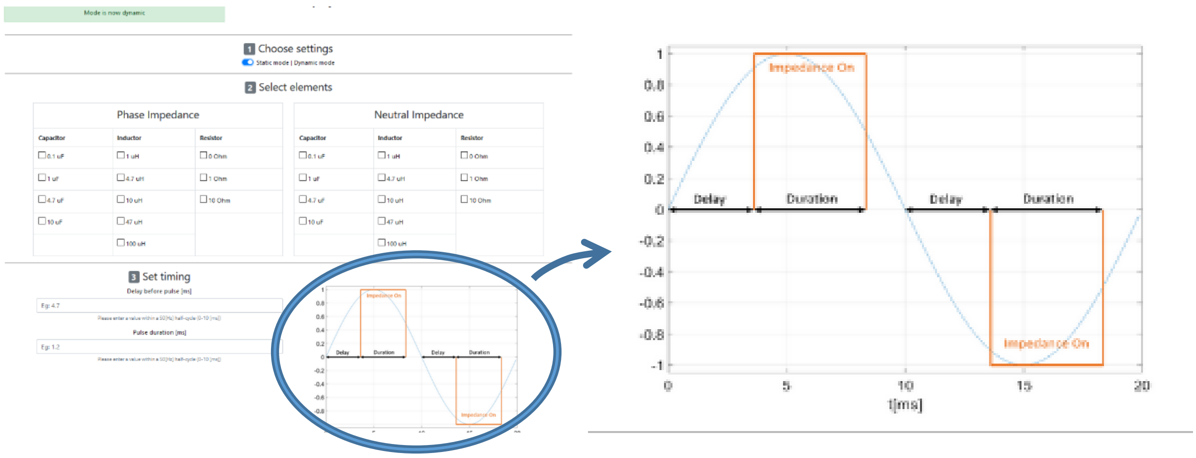


Figure 13: Programmable and time variant line reference impedance control interface and zoom on time variant timing

The discrete components combinations of programmable and time variant impedance network constructed by METAS can set hundreds of spectral impedance characteristic curves. As it is not possible for METAS to characterize the time varying impedances, the results from WP2s characterization campaign were used as a reference. Figure 14 shows the result of one of those characterization campaigns. The measurement curves as well as their associated uncertainties were saved in excel format and were shipped along with the PLRI, allowing the partner institutes to directly compare their measurements with METAS.

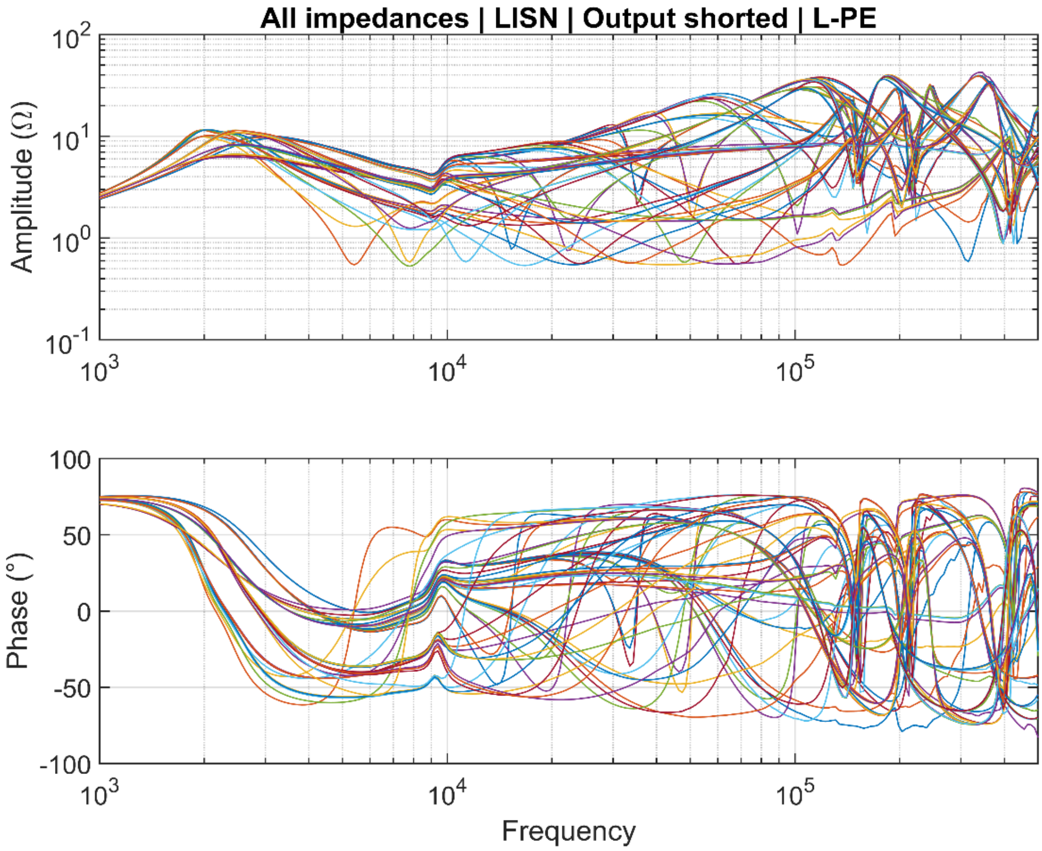


Figure 14: Characterization of programmable set of parameters

The programmable line impedance reference was sent to HES-SO VS in September 2020 for preliminary testing and debugging purpose. It was then sent to other partners across Europe for trials and intercomparison.

7 Preliminary validation by simulation

The schematics of the SLRI and PLRI/PTVLRI circuits supplied by METAS were simulated with the LTspice® software [14] at HES-SO VS, to evaluate first the functional compliance with Z-NET project.

LTspice is a SPICE (Simulation Program with Integrated Circuit Emphasis) [15] analog electronic circuit simulator, developed by Linear Technology now part of Analog Devices. This software was chosen for two reasons:

Of course, LTspice also allows to realize ac analysis simulation, for purely linear circuits as well as for linearized circuits. Depending on the reference impedance modeled, the simulations were performed in two ways:

7.1 AC analysis mode

AC analysis simulation calculates the frequency response of linear circuits. This method will first use operating point analysis to gather linear, small-signal models for all nonlinear components. The snapshot of this circuit is then analyzed based on a defined frequency range. Figure 15 illustrates the schematics realized to perform the AC analysis simulation of SLRI.

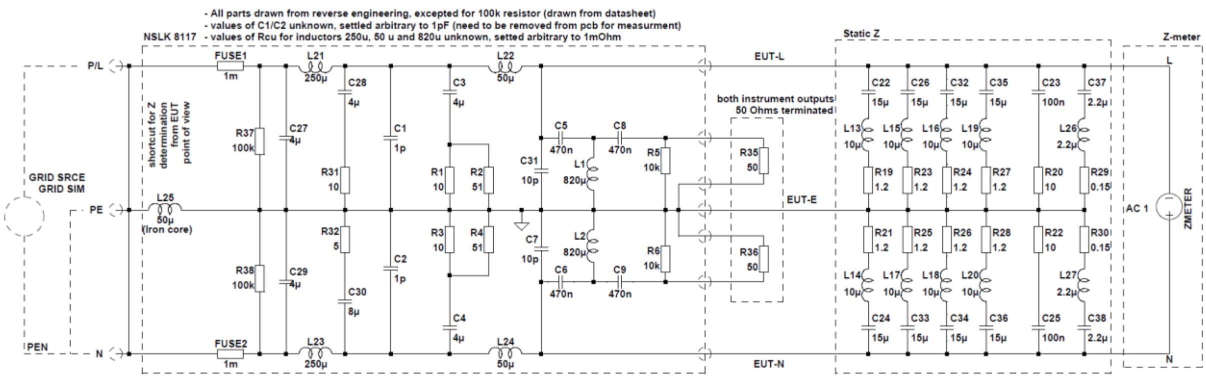


Figure 15 :Schematic to perform simulation in AC analysis mode

The nature of the simulated SLRI circuit is fully linear. In this case, solving the model in Laplace's space should provide the same result (e.g., with Matlab®, GNU Octave).

7.2 Transient analysis mode (time domain)

Transient analysis simulation considers non-linear components. The simulation model is completed with a simplified model of the IGOR impedance analyzer to perform a dual-phase demodulation [16] [17] Figure 16 illustrates the schematic realized to perform the transient analysis of PLRI. The circuit model matches with the one used to perform AC analysis simulations. The grid is connected to the V-AMN input. The additional network and the current source of the IGOR-meter are connected to the EUT terminals. The circuit is completed by the dual-phase demodulation and post processing, to calculate the impedance.

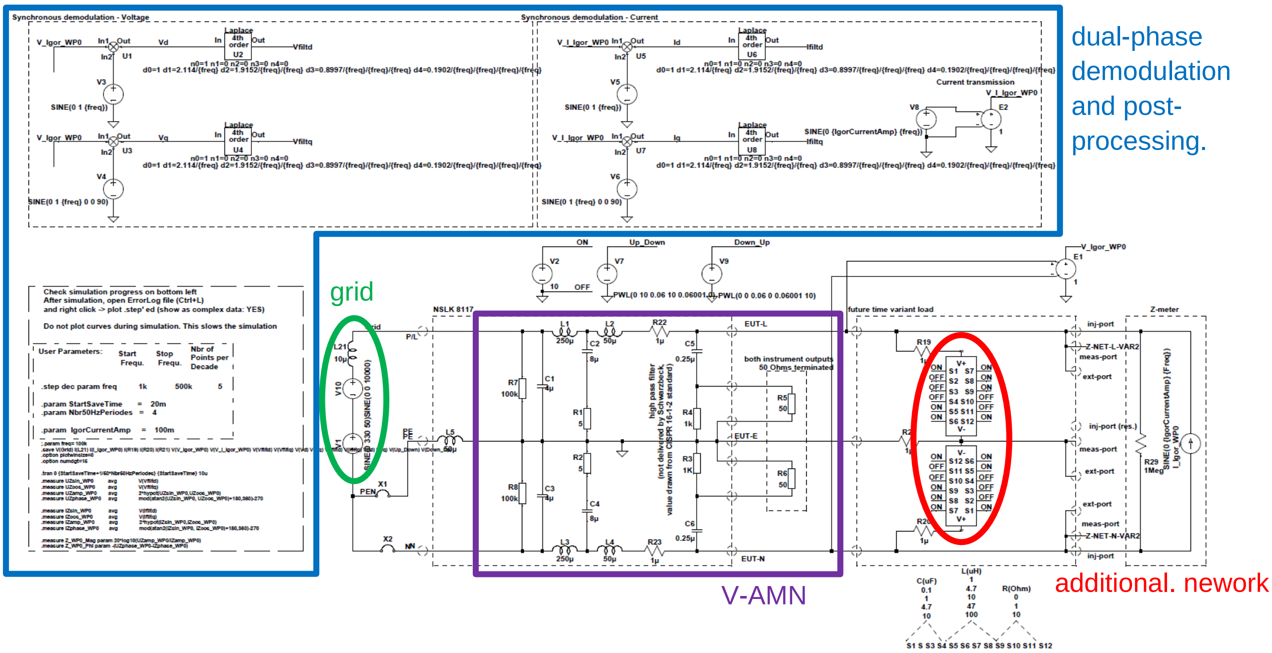


Figure 16 : Schematic to perform simulation in transient analysis mode with dual-phase demodulation

The current passing through the circuit and the resulting voltage are measured and converted into a d-q referential frame for each frequency step of the transient analysis to perform the dual-phase demodulation (Figure 17).

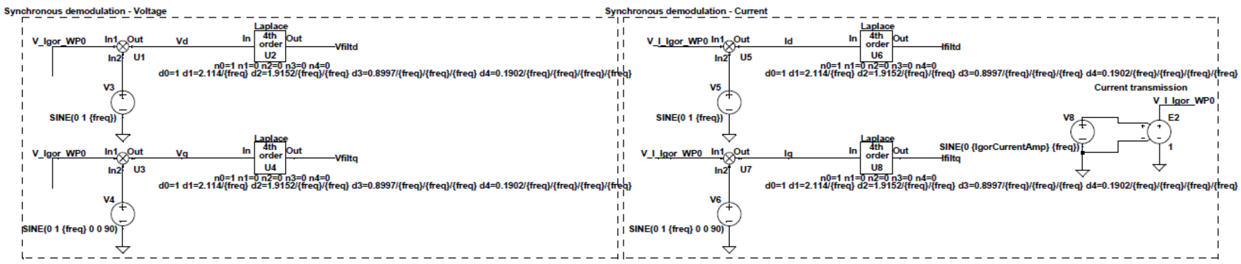


Figure 17 : Dual-phase demodulation part of the simulation in transient analysis mode

The resulting d-q components contain a useful DC component and unwanted higher frequencies modulated by the main frequency, as illustrated on Figure 18.

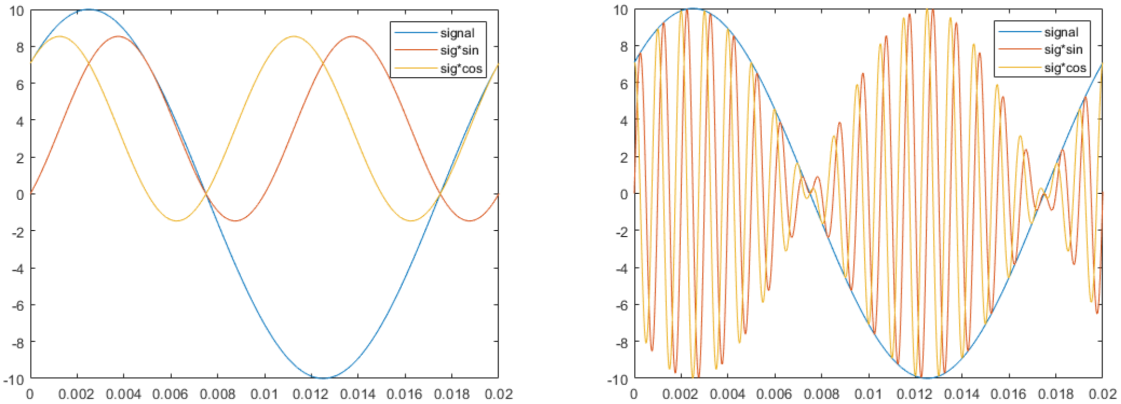


Figure 18 : Examples of resulting's d-q components of a dual-phase demodulated signal (before filtering)

An adaptive fourth-order filter, depending on the analyzed excitation frequency suppress the unwanted high frequencies and keep the DC component. Finally, the resulting's DC components of voltage and current, averaged other a full number of periods of excitation frequency are post-processed to calculate the impedance at the considered frequency. Measurement results of simulated circuits are presented in chapters 7.3 (SLRI), 7.4 (PLRI) and 7.5 (PTVLRI).

7.3 Simulation results for the SLRI

The static line reference impedance was simulated first, to validate the dual-phase demodulation and post-processing stage. The AC analysis is used as reference, while the transient analysis is performed to verify that the added components work fine. The result is illustrated on Figure 19. The simulated dual-phase demodulation works correctly and allows to extend its usage also to PLRI and PTVLRI.

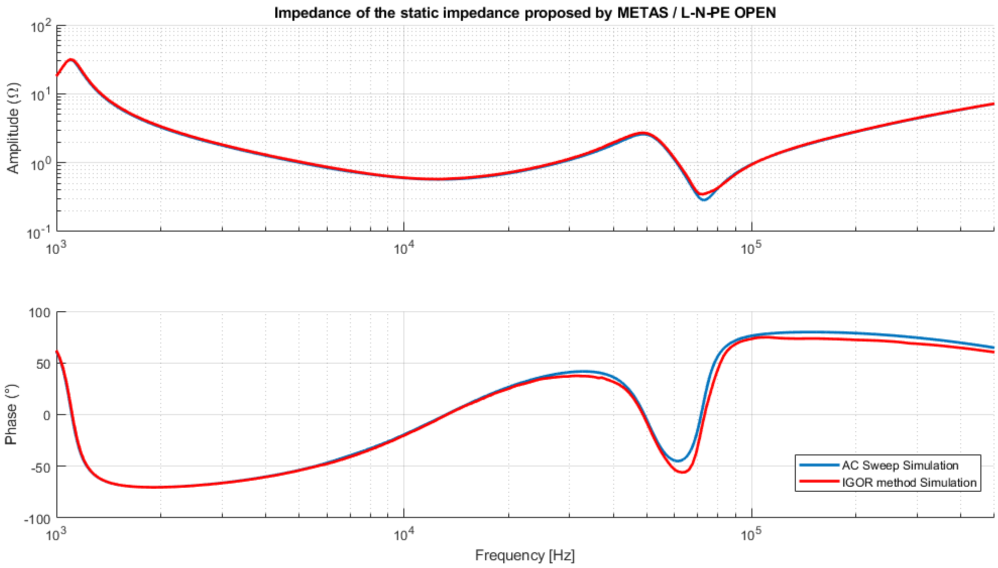


Figure 19 :AC versus transient analysis results of SLRI circuit simulation

7.4 Simulation results for the PLRI

To prepare the intercomparison measurements done by all the partners of the project, simulations of the different cases proposed by the programmable impedance have been made.

For simplicity, only certain cases of interest have been chosen to be tested.

Case 1: LISN alone

Case 3: C 0.1u – L 1u – R 1

Case 4: C 1u – L 47u – R 1

Case 7: C 10u – L 10u – R 10

The cases chosen are simulated in AC Analysis mode and with the IGOR meter demodulation method described in the previous chapter.

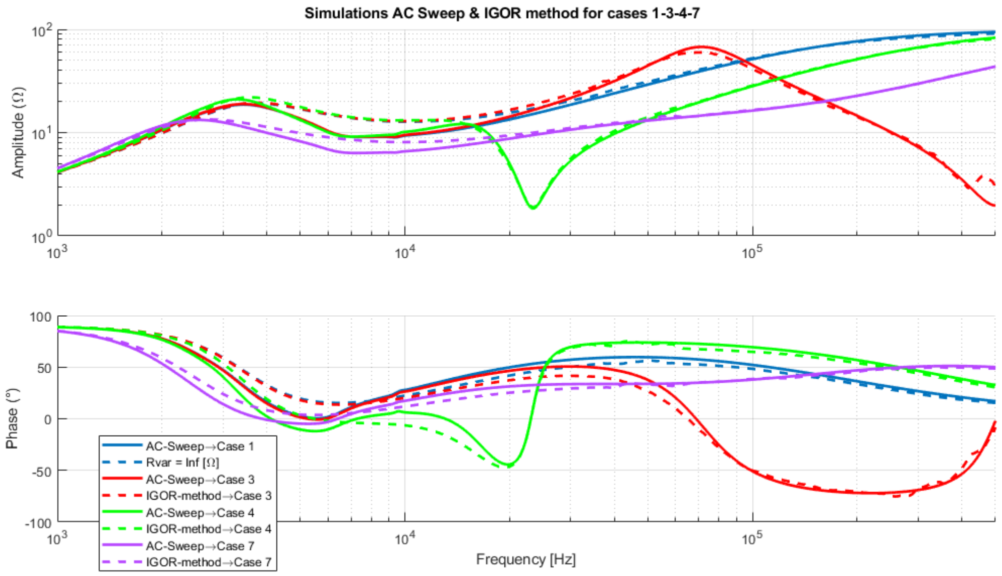


Figure 20 : Simulations of the cases 1-3-4-7

The Figure 20 shows the similar results obtained with both simulation methods. Differences result from the fact that in case of the IGOR-Meter method, the circuit is supplied by the Line to Neutral voltage. According to the simulations, the intercomparison measurements should give us satisfying results.

7.5 Simulation results for the PTVLRI

Only the cases that did not result in strong instabilities were retained. As an example of cases that leads to instability, the transition from case 1 to case 2 cannot be ‘emulated’ properly, as can be seen on Figure 21: the excitation current signal at 500 kHz can barely be recognized. In opposition, a strong and damped oscillation appears at 1.5 kHz.

Although the excitation current is generated at 500 kHz, an oscillation at 1.8 kHz appears and is maintained for at least 5 ms after the dynamic switching. In this case, the Dual Phase Demodulation cannot detect voltage and current, neither calculate accurately the impedance for the time before stabilization. Determining impedance at frequencies close to the resonance frequency represent the worst case to be considered.

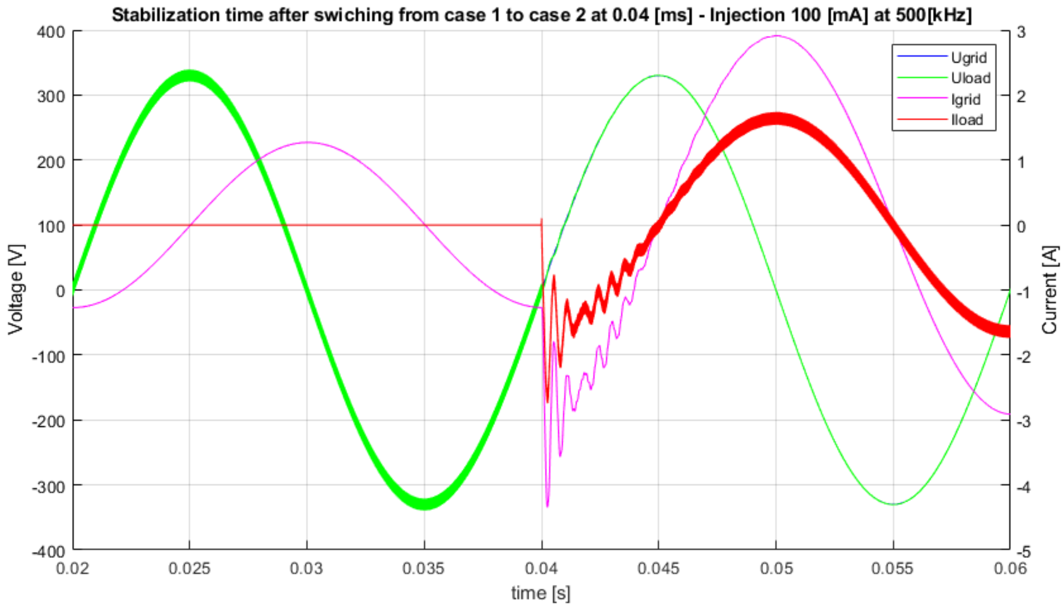


Figure 21 : example of a case that cannot be used for the evaluation due to long stabilization time: case 1⇨2

The damped oscillation looks like the transient phenomena linked to the sudden switching of a large capacitor together with the ca. 700 uH total inductance measured in serie with the LISN and the grid. A capacitance in the order of 16uF, would result in a serie resonance at 1.5kHz. However, the lowest frequency with serie resonance presented in Figure 14 has a frequency close to 5 kHz. These phenomena can theoretically occur in case of the Turn-on of diodes in a rectifier bridge, though such a high current and slow damping requires a very low resistivity of the circuit.

Three tested cases for the sub-cycle measurements have been selected, respecting the limitations due to the resonant circuits of the time variant test impedance, and in accordance with the measurements realized in the previous chapter:

Simulations helped to estimate in advance results obtained with the measurements.

The conduction angles were carried out according to the test 8 of the technical report IEC TR 61000-4-37:2016 [18].

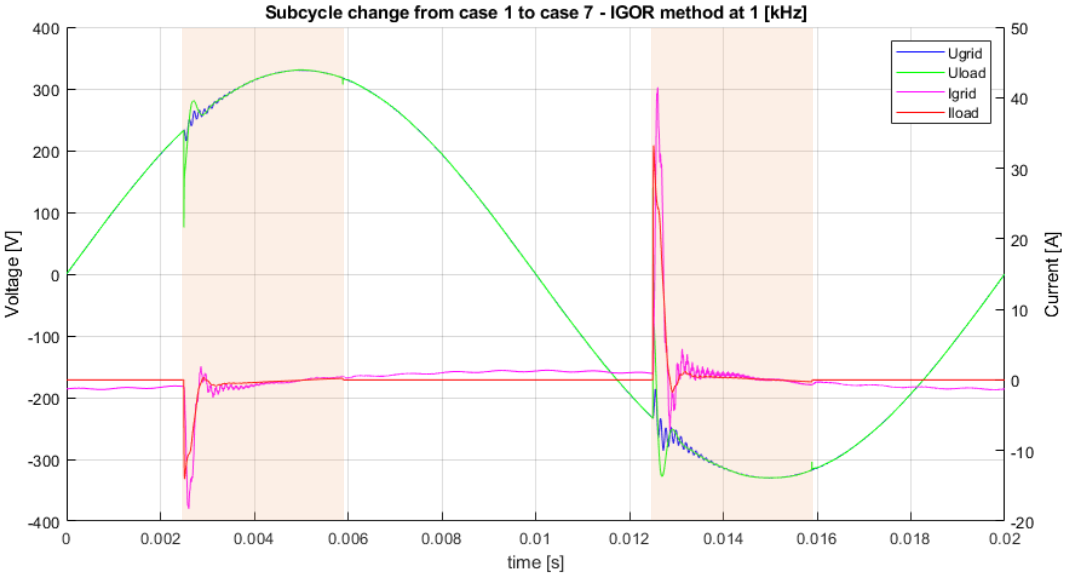
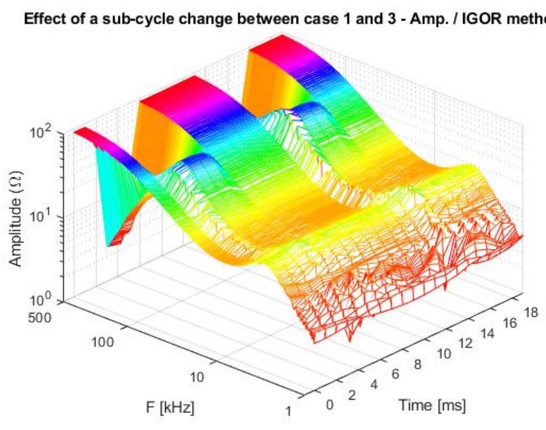
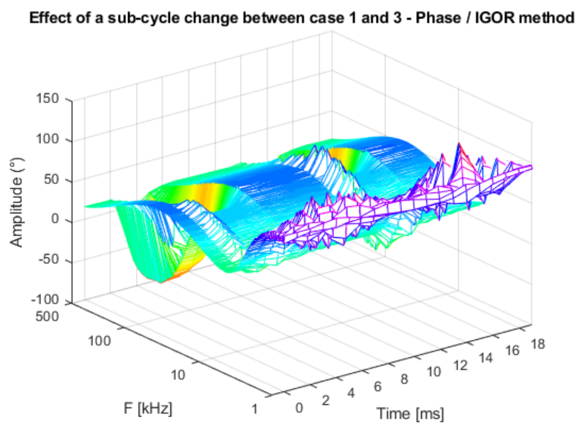


Figure 22 : Result of simulation when switching from case 1 to case 7. (1⇒7)

A conduction angle between 45° and 106° electrical is considered. The reference impedance is set to the case 1 (no load). During the conduction phase, the programmable impedance is connected on the circuit. For this test, the simulation model used in chapter 7.4 has been adapted to simulate a sub-cycle impedance. In this case, the time interval is split in multiples intervals and the frequency dependent impedance is calculated for each time step within the considered period: the analyzed fundamental cycle is split in 1 ms intervals and the impedance is calculated for each time interval from 1 kHz to 500 kHz.





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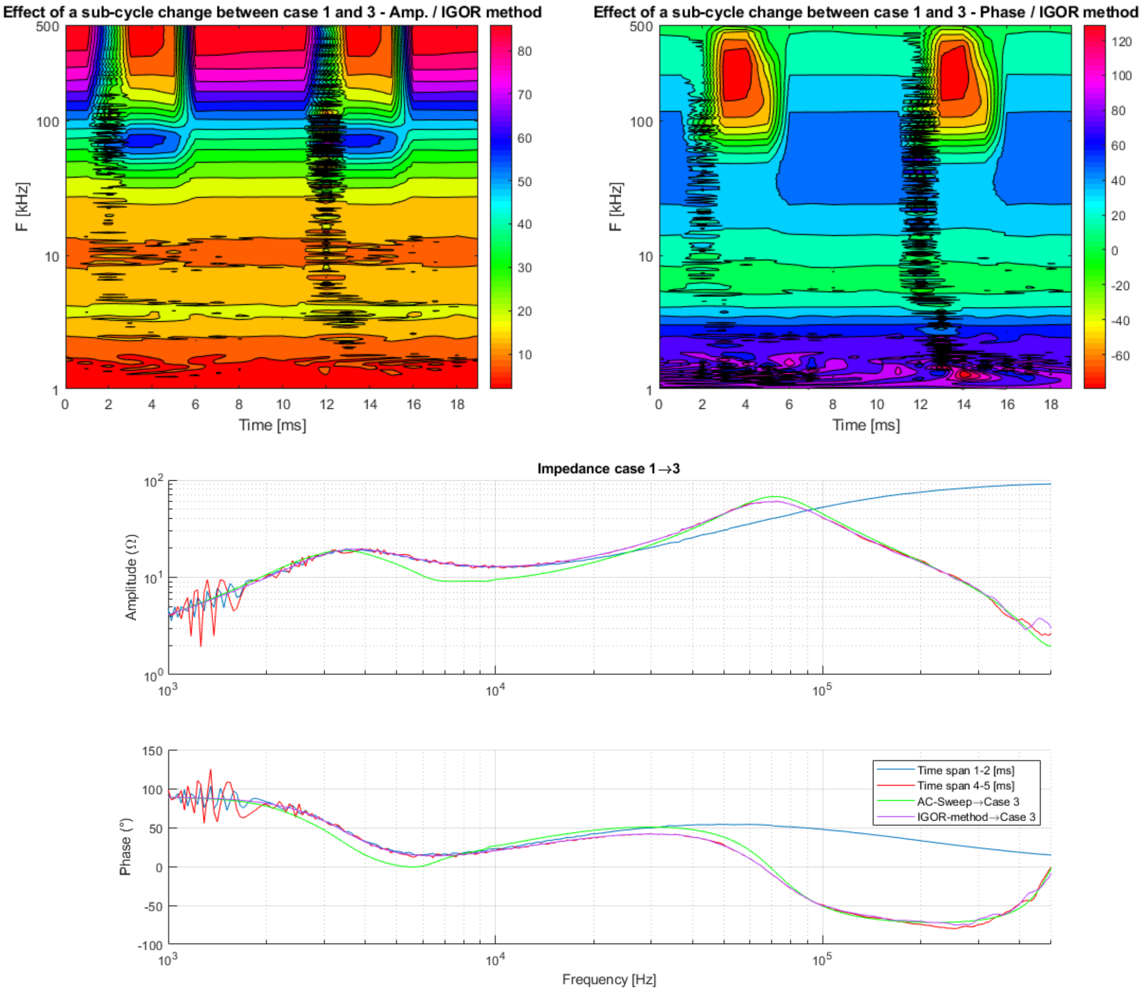


Figure 23 : 3D representation of simulated Sub-Cycle impedance of case 1⤇3

The simulation above shows satisfying results. The results of Figure 23 shows that within specific limits, the sub-cycle variation could theoretically be detected using the impedance analysis method applied with the IGOR-meter. However, the resources to reprogram the equipment were not available for this project.

8 WP4: Intercomparison of impedance meters

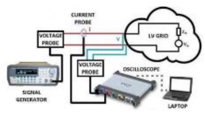
Both static and programmable/time variant reference impedances constructed by METAS were characterized using a calibrated LCR-meter. They were then disseminated and measured at facilities of the project partners owning a high frequency range impedance analyzer. The chapter 8.1 reviews the equipment used during the intercomparison measurement campaign. The chapter 8.2 relates the importance of coordination between the teams to build a matching test setup. The chapters 8.3, 8.4 and 8.5 review the results of respective static, programmable and time variants impedance references measurements.

During the project, the advantages of using a calibrated reference impedance could be effectively demonstrated: One of the project partners obtained results that diverged with the other measurements carried out in 2020. The issues with this measuring equipment could be fixed and better results were obtained during a second measurement campaign in 2021.

8.1 Devices used for benchmarking

The references impedances were measured by the various partner institutes and one company. Thanks to the close contacts with the University of Dresden, ‘morEnergy’, an additional spin-off company related to Hamburg Technical University and active in engineering was invited to measure the reference impedance. In total four impedance meters were evaluated and compared:

The review of equipment’s and their major characteristics are reported on Table 5.

Manufacturers Institutes / **Characteristics**	**TUD (Spitzenberger & Spies IMD300)** 	**morEnergy ONIS-690V** 	**UPV/EHU** 	**HES-SO VS IGORMETER IV** 
Coupling to grid	Direct	Direct	Capacitive	Direct
Connection for measurement	4-wire	4-wire (controllable load)	4-wire	4-wire
Excitation source	Current (3 A_{RMS})	Switched controllable load	Voltage (up to 3.5V_{RMS})	Current (90 mA_{RMS})
Frequency sweep	Single frequency steps	Random switched (broadband)	Single sweep	Single frequency steps
Suppression of fundamental	None	None	Yes	None
Signal processing	Fourier analysis (DFT)	Fourier analysis (DFT)	Fourier analysis (FFT)	Dual-Phase Demodulation
Time windowing	Rectang., 200 ms (10 fund. cycles)		Rectang., 20 ms, 5 ms sliding win.	--

Bandwidth	0 kHz -200 kHz	0 kHz - 150 kHz	20 kHz - 500 kHz	1 kHz - 500 kHz (250 Hz - 2 MHz)
Frequency resolution	5 Hz	Configurable best 5 Hz	Configurable, typ. 50 Hz best 5 Hz	Configurable (log or lin step)
Measurement time	Several minutes		Configurable typ. 2 seconds	From 1 to 10 minutes

Table 5: Review of equipment's and their major characteristics

It is interesting to note that the equipment's have very different excitation principles: the ONIS-690V from morEnergy is the only device that operates a controlled load; the other devices use active current or voltage sources. Some excitation methods are optimised to reduce the measuring time: the UPV-EHU device performs a single frequency sweep and the ONIS-690V excites the load at broadband; the last two devices (IMD 300 and IGORMETER IV) use slower single frequency steps. Direct coupling of the excitation source to the Line voltage is advantageous to increase the bandwidth, but at this stage of the study it is by no means a determining criterion.

For signal processing, the majority of devices use the Discrete Fourier Transform (DFT) or the computer optimised Fast Fourier Transform algorithm (FFT). Only one device, the IGORMETER IV uses a completely different technique, namely the dual-phase demodulation.

After the reference has been returned to the HES-SO VS in Switzerland and measured too, the data were collected and compared. The results and their analysis are presented in chapters 8.3 to 8.5.

8.2 Test protocol

The different possible circuits for the test setup demonstrate the importance of coordination between the institutes and companies. During the project, a test protocol was developed and improved to clarify two major connection methods for the energized reference impedance: one for measurement to the real grid, the other for measurement with a EUT supplied by a grid simulator. A third connection method should also be determined, for the unenergized measurement.

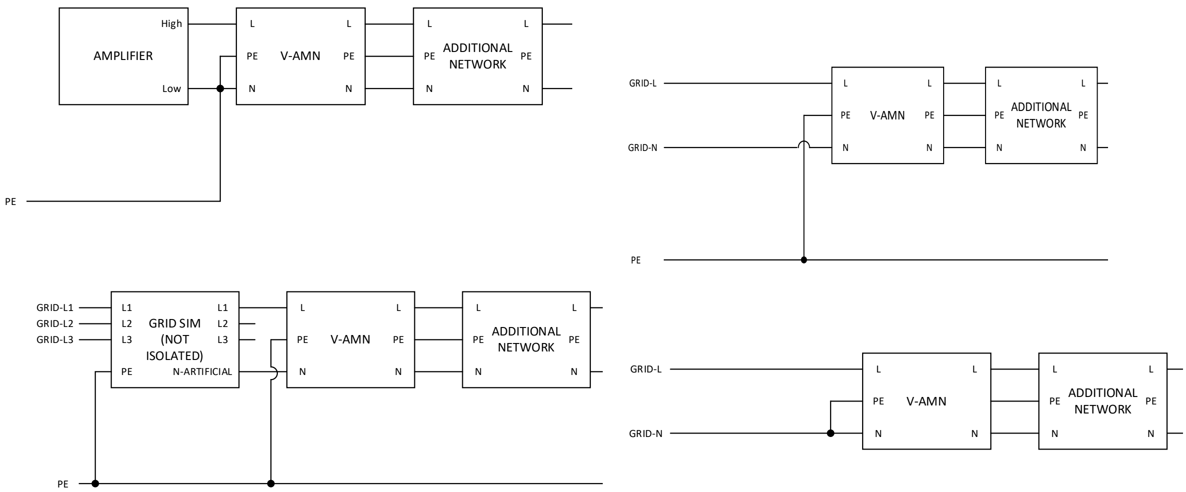


Figure 24: Measurement setups: many ways to connect the reference impedance

The data exchange format still needs to be harmonized. The institutes owning equipment able to measure the time variant spectral impedance need to deliver data that can be easily processed by other project partners for intercomparison. In addition to the data exchange format, the file type needs to be defined. The most currently used formats are Excel and CSV. An evaluation of other formats, like the HDF (Hierarchical Data Format) as example could be considered.

8.3 Results of measurements on the Static Line Reference Impedance (HES-SO VS, TUD, morEnergy and TSR)

The impedance meters were compared in two measurement modes: unenergized and energized (230 V / 50 Hz). The unenergized mode allows the user to quickly verify that the static reference impedance is functional. The energized mode ensures the correct operation of the impedance meter and its performance, as the 230 V / 50 Hz component and its possible harmonics are much more important than the signals generated at variable frequencies. The energized mode is ultimately the mode of operation that impedance meters will encounter in the field. Regardless of the measurement mode, the results are always compared with those obtained by METAS using the calibrated LCR meter.

The following figures show the results for unenergized and energized measurement modes. The frequency band of interest defined in the Z-Net project is colored green.

Figure 25 shows the results obtained by the impedance meters in unenergized mode. The correlation between results with different equipment's is good. The magnitude at resonance (Q-factor) differs slightly. The serial resonance measured by the ONIS-690V diverges in frequency and magnitude. This might be linked to the insertion losses due to a 50 Ω shunt resistor used internally in the ONIS 690V.

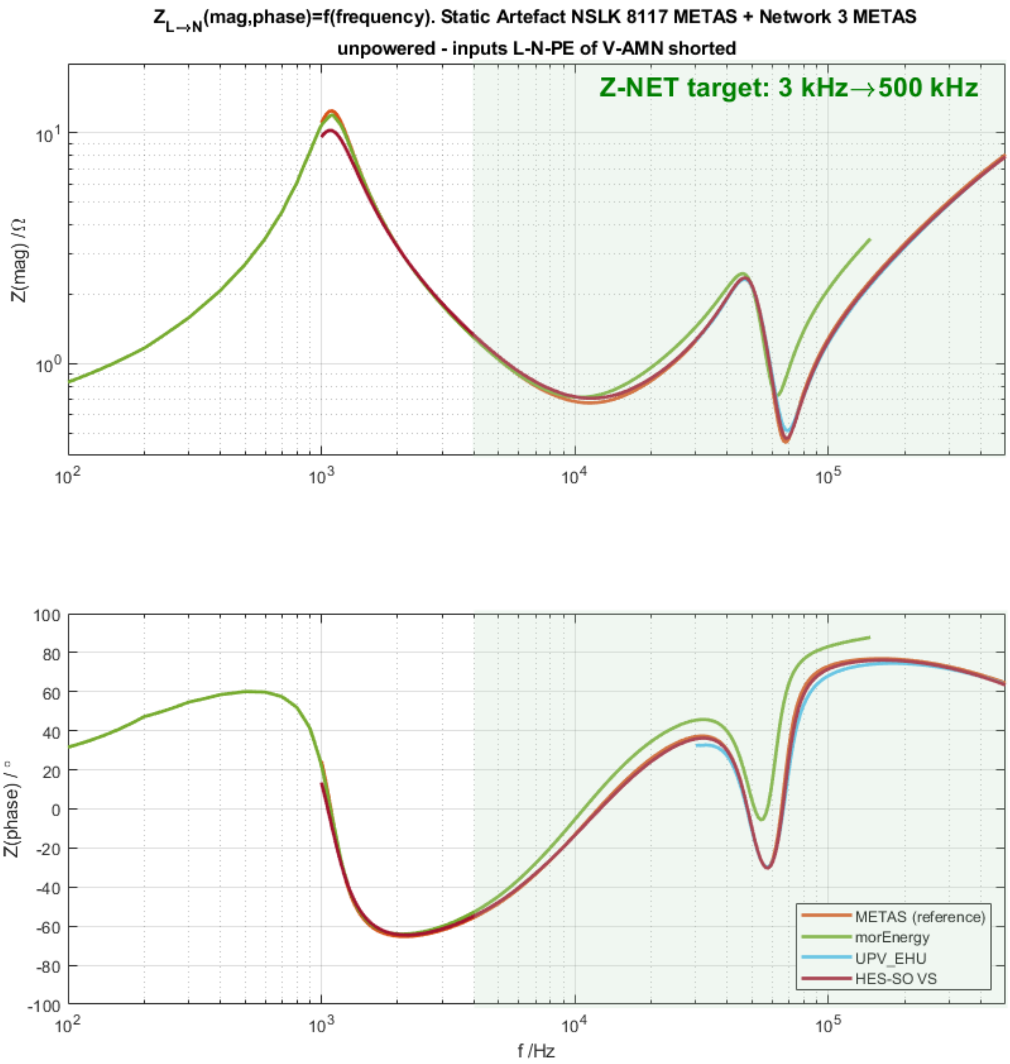


Figure 25: Unenergized static reference impedance intercomparison of impedance meters results

Figure 26 shows the results obtained by the impedance meters in energized mode. There are two ways of feeding the static reference impedance: the use of an electrical grid simulator (solid lines) or the direct use of the electrical grid (dashed lines). Unfortunately, many ways to handle the PE and N conductors can be considered, this could lead to small differences, but not marked in frequencies of interest. For Z-NET target frequency range, as for the unenergized measurement, the magnitude at resonance (Q-factor) differs slightly. Small differences in the resonances measured with the ONIS-690V compared to those of other devices are always to be observed.

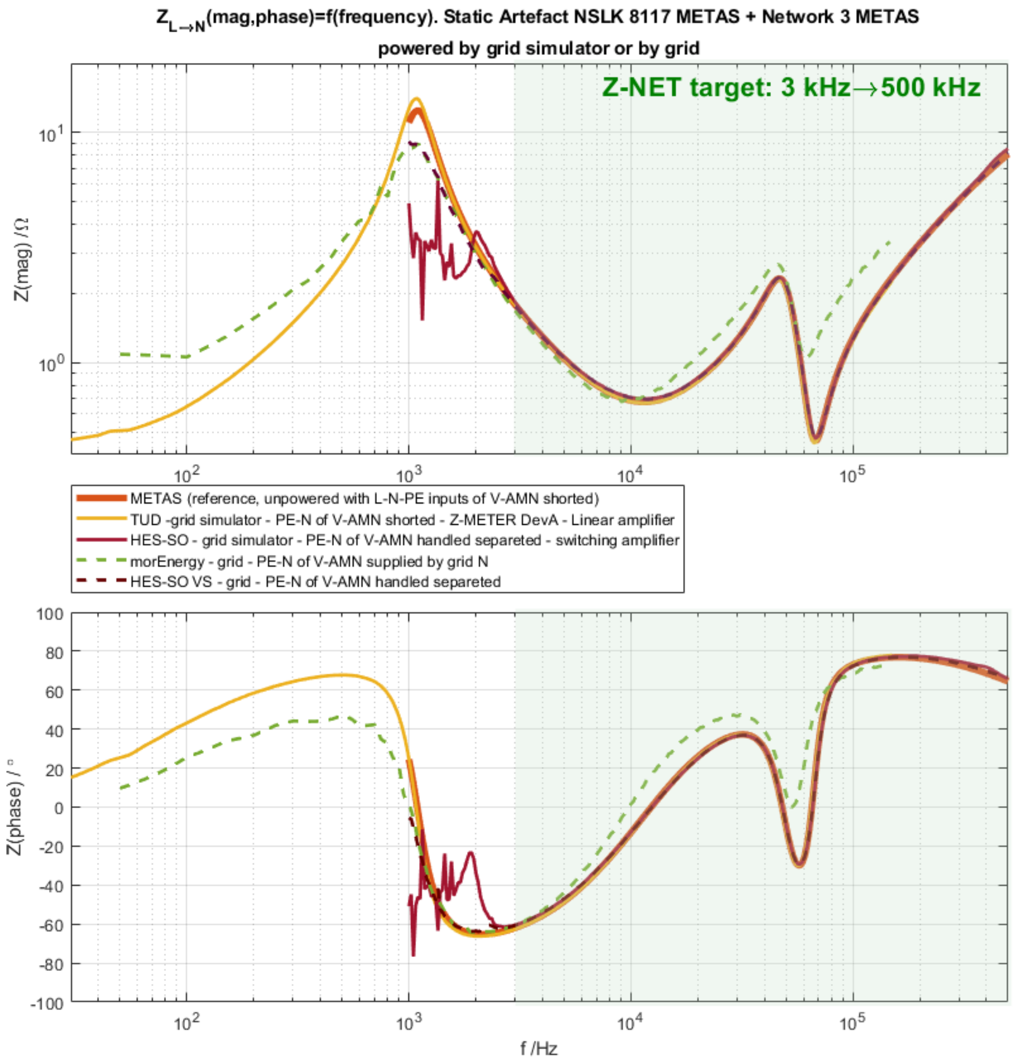


Figure 26: Energized static reference impedance intercomparison of impedance meters results

Based on these findings, morEnergy was able to isolate the source of the error and correct it. A second set of measurements provided much better results. The Figure 27 illustrates the results obtained during the second campaign. In the case of grid measurements, the differences in the frequency range of interest are really contained. Variation in damping is however observed in case of supply with the grid simulator. The internal impedance and the current controller of the simulator are a possible reason for this deviation.

Out of the frequency range of interest (1 → 3 kHz), the results are matching better with the METAS reference when the reference impedance is fed from the network simulator rather than from the real electrical network.

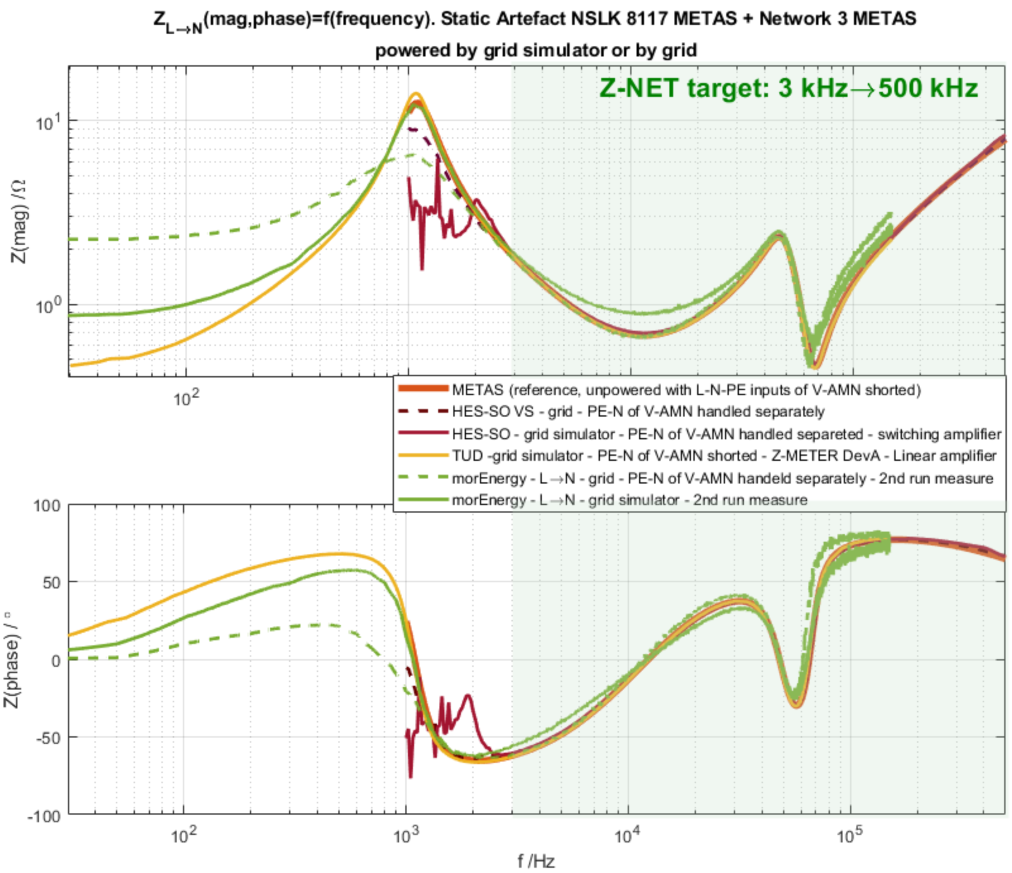


Figure 27: Energized static reference impedance intercomparison of impedance meters results (partial second run)

The use of an electrical grid simulator does not seem to be necessary for the validation of an impedance analysis method in the frequencies under consideration for PLC applications. This would definitively simplify the test procedure and requirements for the test set-up, and give opportunity to smaller institutes or companies to contribute to this standardization effort.

8.4 Measurements with the Programmable Line Reference Impedance (HES-SO VS, TUD, morEnergy and TSR)

METAS calibrated 61 scenarios (components RLC combinations) for every possible measurement on the EUT side (L→PE, N→PE, L→N) and for two short circuit cases on the LISN input side (L-N-PE, L-N), making a total of 366 calibration curves!

Among these combinations, a first criterion was selected: between which ports of EUT should the impedance be measured. The choice was made for the measurement between phase and neutral (L→N), which is the simplest measurement that can be made in the laboratory. This criterion reduces the choice to 61 scenarios that will have to be carefully chosen by the partners.

After some tests, 9 cases were retained initially for the intercomparison: S1 to S9 in Table 6. Of these 9 cases, 4 cases were rejected that did not allow any objective comparison (R = 0 Ω) and would have required more investigations. Finally, the comparison set is reduced to 5 scenarios, S1, S3, S4 S7 and S8 summarized in Table 6

Static test number	C [F]	L [H]	R [Ω]
S1	no value settled	no value settled	no value settled
S2	0.1e-6	1e-6	0
S3	0.1e-6	1e-6	1
S4	1e-6	47e-6	1
S5	4.7e-6	4.7e-6	0
S6	10e-6	10e-6	0
S7	10e-6	10e-6	10
S8	10e-6	100e-6	10
S9	All C settled (CEQU = 15.8e-6)	All L settled (LEQU = 744e-9)	0

Table 6: Static test scenarios final selection

The impedance meters were compared in two measurement modes: unenergized (unpowered) or energized (230 V / 50 Hz) by the grid or a grid simulator). The unenergized mode allows the user to quickly verify that the static reference impedance is functional. The energized mode ensures the correct operation of the impedance meter and its performance, as the 230 V / 50 Hz component and its possible harmonics are much more important than the signals generated at variable frequencies. The energized mode is ultimately the mode of operation that impedance meters will encounter in the field. Regardless of the measurement mode, the results are always compared with those obtained by METAS using the calibrated LCR meter. Figure 28 illustrates the test setup to measure the programmable impedance at the HES-SO VS.

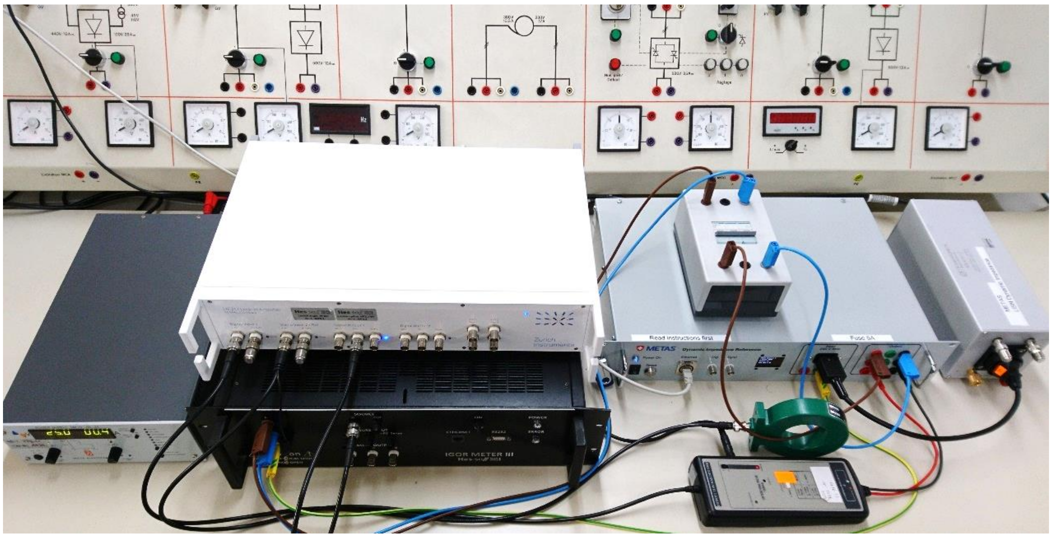


Figure 28: Test setup at HES-SO VS for the measurement of programmable impedance

The following figures show some measurement results for unenergized and energized measurement modes. The frequency band of interest defined in the Z-Net project is colored in green. Unfortunately, the programmable line reference impedance could not be measured in this configuration with the ONIS 690V. The reason for this issue still needs to be investigated and alleviated. The programmable impedance was instead shipped to UPV/EHU where the measurement succeeded but revealed a surprising behavior.

8.4.1 Programmable test impedance: unenergized tests

The non-energized measurements could only be performed by the HES-SO VS and UPV/EHU meters. Their results were compared to the METAS reference curves.

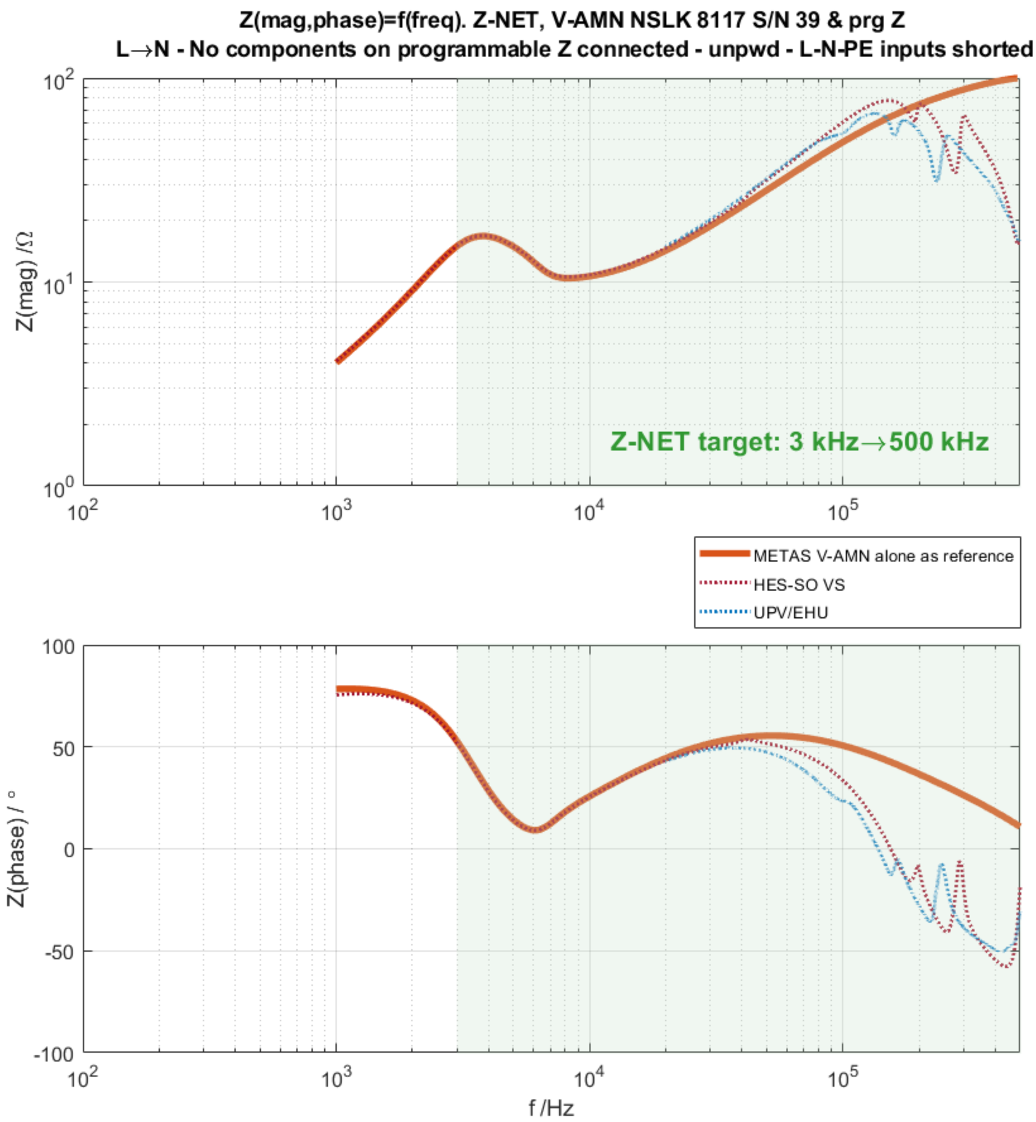


Figure 29: Unenergized programmable test impedance: test S1

Figure 29 shows the results for test S1, obtained by the impedance meters from HES-SO VS and UPV/EHU. A similar impedance characteristic as the one of CISPR 16-1-2 was expected. Case S1 was not measured by METAS. Instead, the reference curve of the V-AMN NSLK 8117 alone is represented. Above 100 kHz, the results of HES-SO VS and UPV/EHU diverge from the METAS reference and tend towards a capacitive behavior. This behavior is probably produced by parasitic capacitors of the programmable test impedance. The results of the HES-SO VS and UPV/EHU measurements show a similar trend in over all the frequency range, even in the upper frequency range. The same number of resonances appear in the frequency range between 100 and 500 kHz. However the resonances frequencies are clearly shifted from each other. One explanation for the differences could be the interaction between parasitic components in the PLRI and the different excitation circuits used by UPV and HES-SO VS impedance meters.

Figure 30 show the results for test S7. For both impedance meters from HES-SO VS and UPV/EHU, the resonances match approximatively with those measured by METAS. The meter of UPV/EHU diverge more in amplitude as the meter of HES-SO VS. The supposed parasitic effects above 100 kHz are identifiable again.

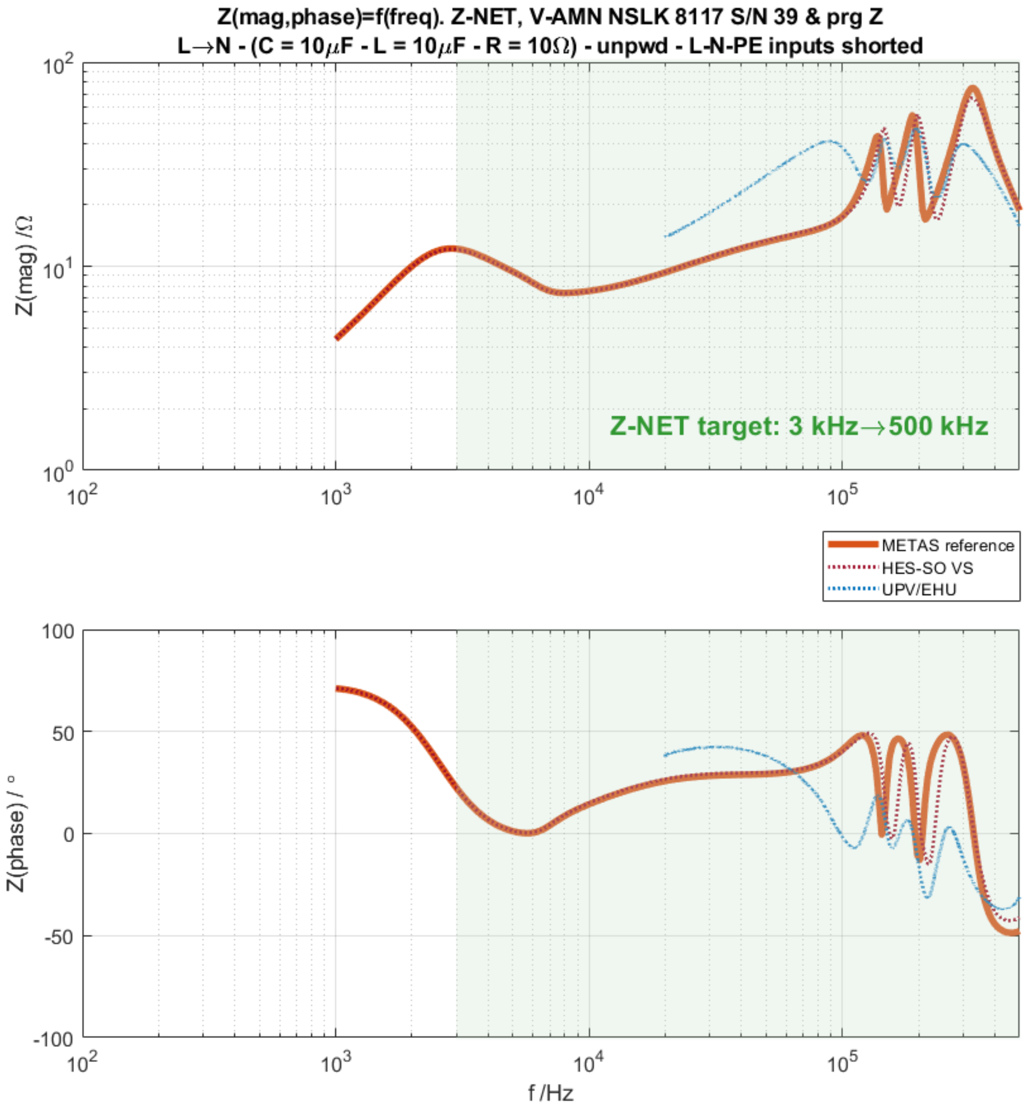


Figure 30: Unenergized programmable test impedance: test S7

A study of Table 5 let's suppose that the excitation current could vary from one impedance meter to the other. A test was made with 2 different excitation currents for the same impedance meter and same programmed impedance. Figure 31 shows the comparative results. In the lower frequency, where the V-AMN is prevailing, no variation could be observed. The programmed discrete components (C = 1 µF, L = 47 µH)) force the serial resonance as awaited to 23 kHz. But in the upper frequency range (above 100 kHz), we could clearly observe that a lower excitation current results in a shift of the resonance frequencies toward lower frequencies.

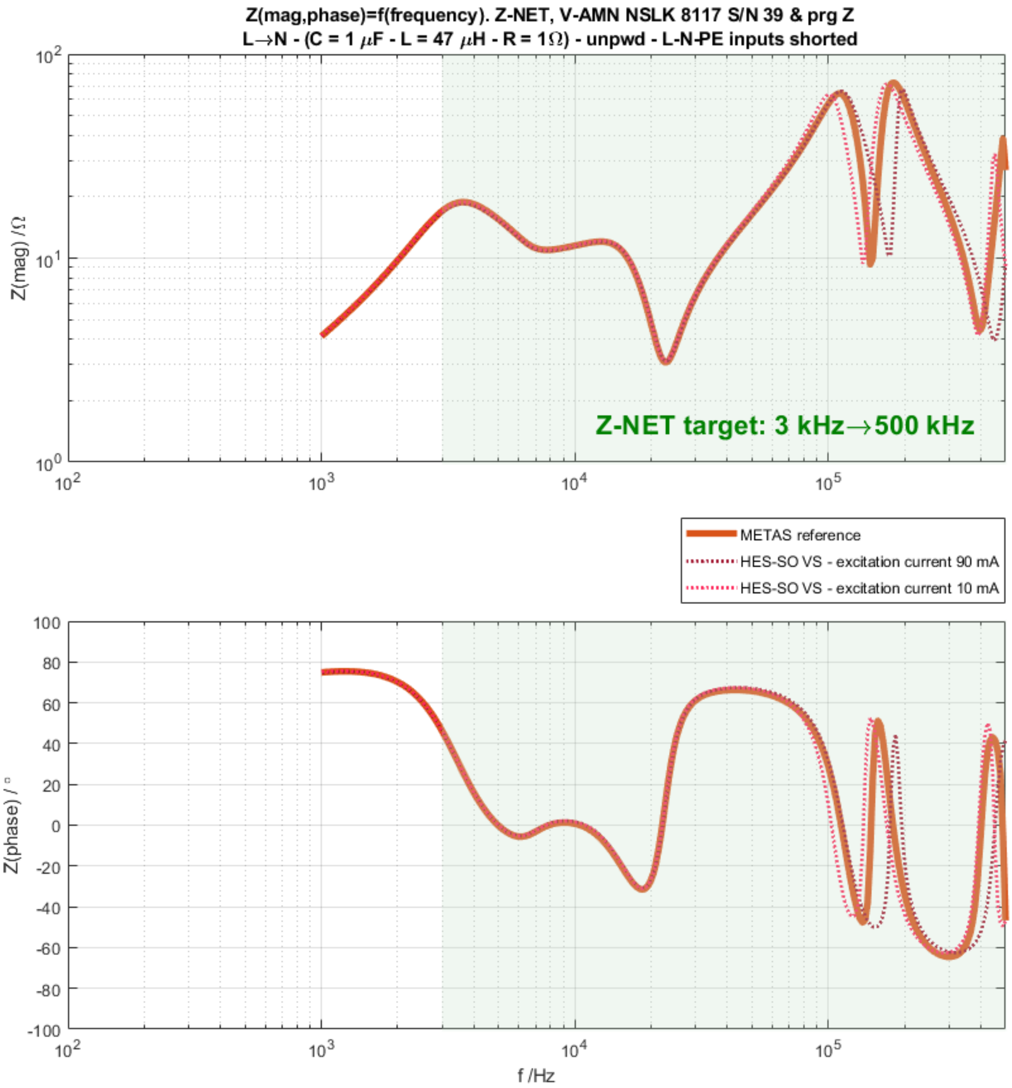


Figure 31: Unenergized programmable test impedance with 2 different test currents: test S4

Before drawing any conclusions, it seems important to repeat the tests in the energized mode for which the PLRI is actually designed.

8.4.2 Programmable test impedance: energized tests

The energized measurements could be carried out with two different set-ups, once fed by the grid, once fed by an artificial grid. The measurements were performed by the HES-SO VS, TUD and UPV/EHU meters, their results were compared with the METAS reference curves.

Figure 32 shows the results for test S1, obtained by the impedance meters from HES-SO VS, TUD and UPV/EHU. As for non-energized mode, a similar impedance curve as the well-known CISPR 16-1-2 characteristic was expected. The reference curve of the V-AMN NSLK 8117 alone, measured by METAS, is represented with plain red line. As expected, above 100 kHz, the results of HES-SO VS and TUD diverge from the METAS reference and tend towards a capacitive behavior. This behavior is probably produced by parasitic capacitors of the programmable test impedance. The measurement of UPV/EHU presents an unexpected and interesting behavior. The comparison was also done with the S7 impedance setting and show the same behavior (Figure 33). All tests performed with the UPV/EHU impedance meters all measures present the same issue.

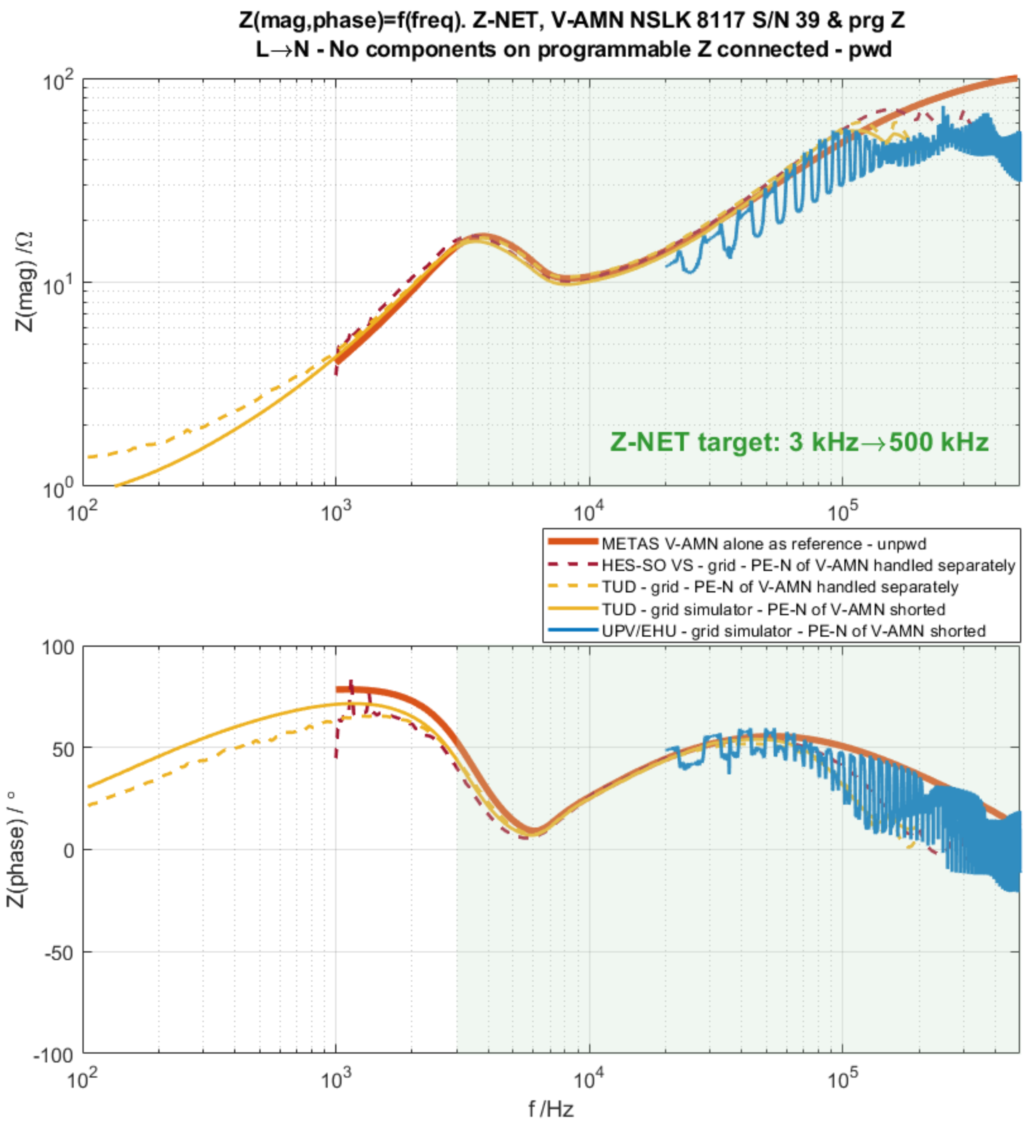


Figure 32: Energized programmable test impedance: test S1

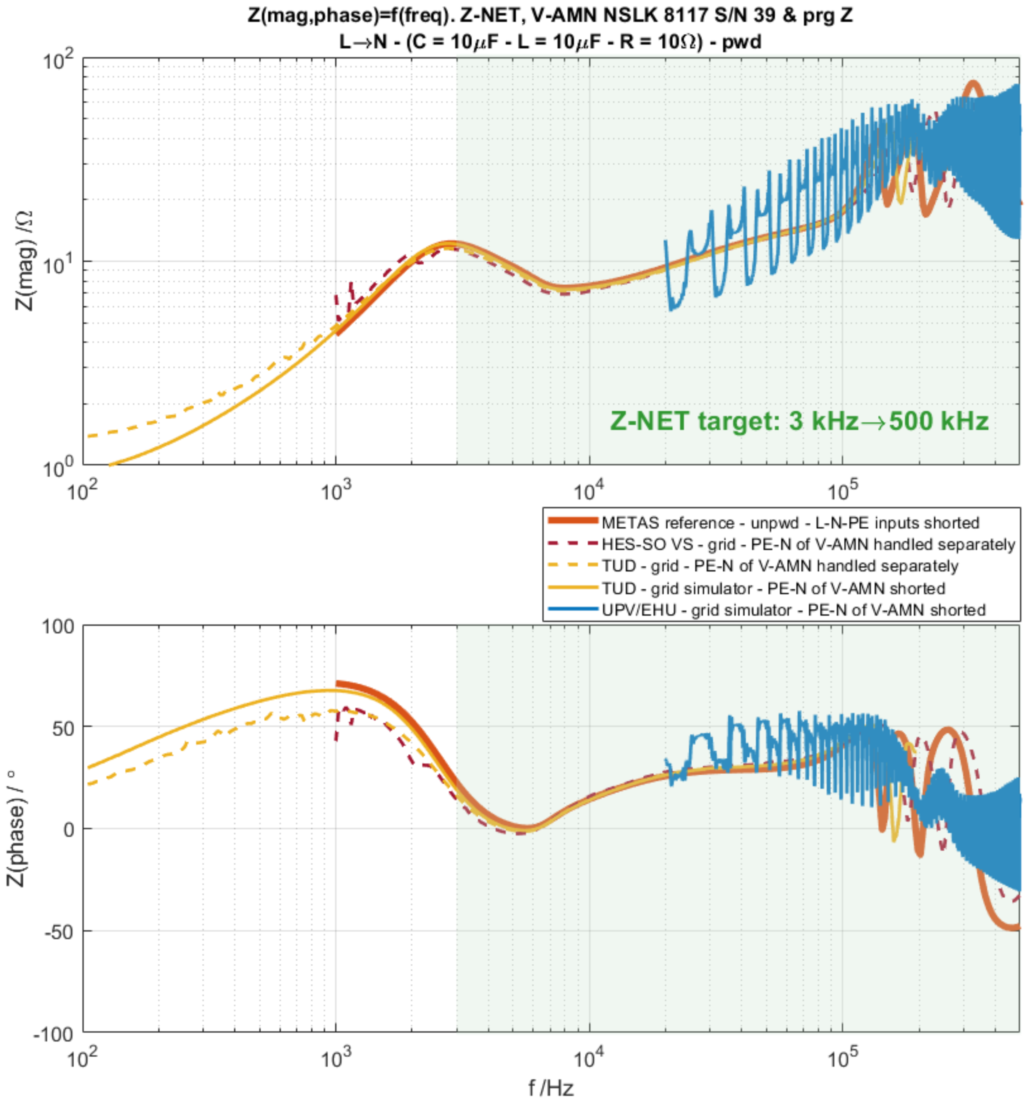


Figure 33: Energized programmable test impedance: test S7

A careful observation of the results pattern suggests an impedance variation depending on the half cycle of the electrical network. The investigation for the source of malfunction is based on:

The UPV/EHU measurements could be compared to those previously performed at the HES-SO VS with the different input ports. The measurements carried out at the HES-SO VS showed that the magnitude of impedance L→N is twice the magnitude of impedance L→PE or N→PE. This can be explained by the symmetrical construction of the reference related to the PE. Figure 34 shows that the amplitude of the impedance measured by UPV/EHU varies periodically from simple to double for one half-period, the magnitude is comparable to the magnitude L→N; for the other half-period, the measured magnitude is comparable to the magnitude L→PE or N→PE. Already by the HES-SO VS measurements, an unexpected difference between L→PE and N→PE occurs above 100 kHz, which suggests that the problem is to be found on the neutral port.

The periodicity of the variation could be explained by the methodology applied by UPV/EHU. The measurement method, based on a single frequency sweep of 1 second from 5 kHz to 530 kHz results in a frequency variation of 525 kHz/s. The portions of spectral impedance where the magnitude is high are about 5 kHz wide. This corresponds to a time slot of about 10 ms at the given frequency gradient.

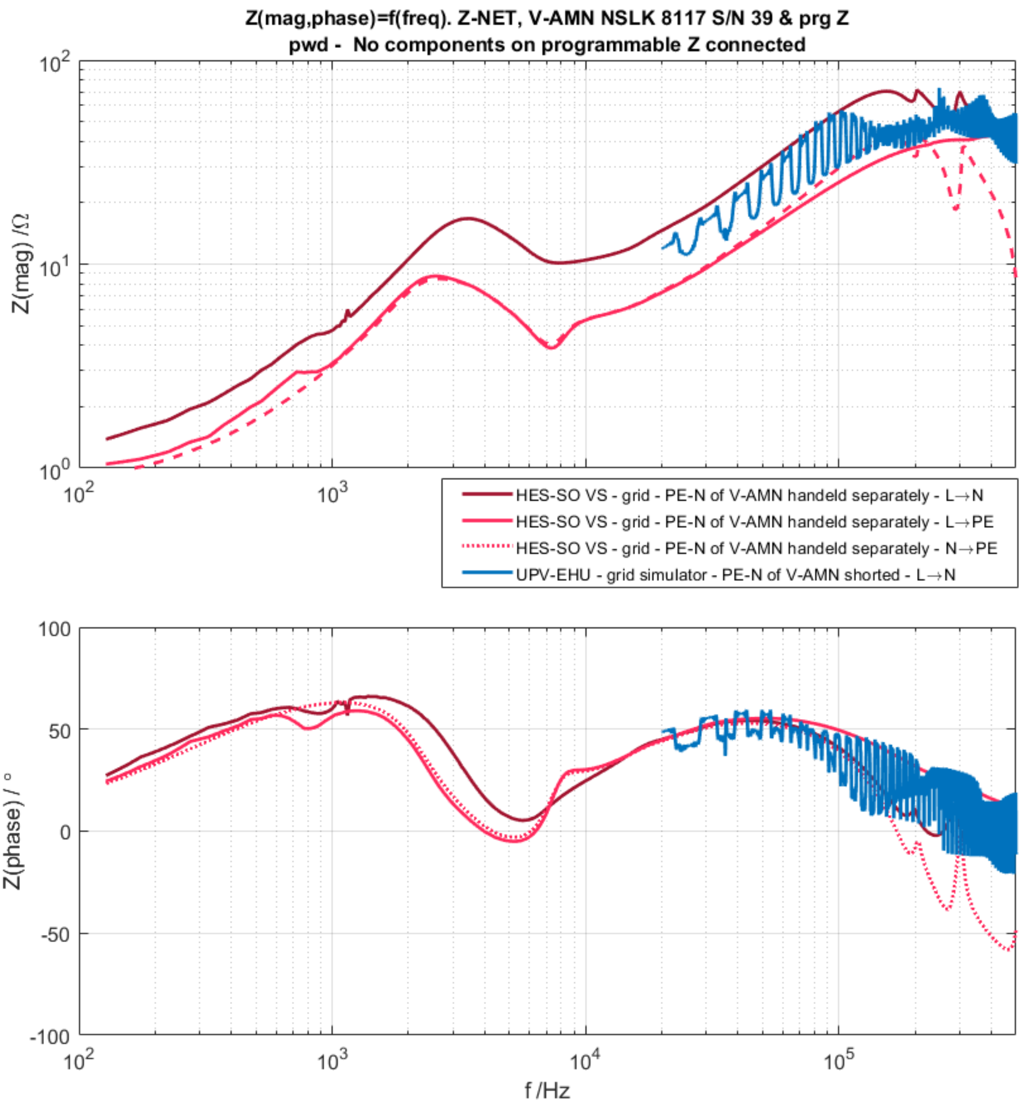


Figure 34: Energized programmable test impedance, comparison HES-SO VS ⇔ UPV/EHU: test S1

HES-SO VS and TUD that calculate impedance based on averages measured over several cycles of the electrical network may not lead to the same results, because this phenomenon is masked.With these findings in mind, it is not reasonable to make a further comparison of the various impedance meters for use with the programmable impedance. Investigations on the programmable line reference impedance itself should be conducted before a new measurement and comparison campaign is launched.

8.5 Time variant test impedance (HES-SO VS, TUD, morEnergy and TSR)

The programmable test impedance was also developed with the objective to work as time variant impedance. To achieve this, the programmable configurations can be switched dynamically and synchronized with the mains supply fundamental waveform. The switching times are freely configurable with the web-based control interface.

Based on preliminary simulations, only the cases that did not produce strong instability were considered for the intercomparison tests (D2 to D9)Table 7Table 7. Indeed, cases with an important recovery phase would not allow to determine the impedance in a reliable way. The three retained cases D3-D4-D5 are summarized in Table 7. Outside the section when the time variant impedance is active, the static test "S1" (no value settled, only LISN connected) prevails. The time variant impedance therefore always switches between test S1 and test Sx (for x = 3, 4, 7).

Dynamic test number	C /F	L /H	R /Ω	Pulse delay /ms	Pulse duration /ms
S1	no value settled	no value settled	no value settled	n/a	n/a
~~D2~~	~~0.1e-6~~	~~1e-6~~	~~0~~	~~n/a~~	~~n/a~~
D3	0.1e-6	1e-6	1	2.5	3.39
D4	1e-6	47e-6	1	2.5	3.39
~~D5~~	~~4.7e-6~~	~~4.7e-6~~	~~0~~	~~n/a~~	~~n/a~~
~~D6~~	~~10e-6~~	~~10e-6~~	~~0~~	~~n/a~~	~~n/a~~
D7	10e-6	10e-6	10	2.5	3.39
~~D8~~	~~10e-6~~	~~100e-6~~	~~10~~	~~n/a~~	~~n/a~~
~~D9~~	~~All C settled (C_{EQU} = 15.8e-6)~~	~~All L settled (L_{EQU} = 744e-9)~~	~~0~~	~~n/a~~	~~n/a~~

Table 7: Dynamic test scenarios final selection

The impedance meters accuracy was only compared in energized mode (230 V / 50 Hz) as the mains voltage measurement is used for the synchronization of both the time variant impedance and the impedance meters. The PLRI was either supplied directly from the grid or through a grid simulator.

As for the programmable test impedance, the time variant test impedance could not be measured with the ONIS 690V. The instrument of HES-SO VS is not yet programmed and ready for time variant measurement. Instead, HES-SO VS made the effort to simulate the dynamic behaviour, which on the one hand allowed the selection of stable simulation sets and on the other hand prepared the way for the attention that must be paid to the instability of the network in case of load switching. (Chapter 7.3)

The comparison between curves represented by each institute according to their own convention was tedious. As the data exchange format had not been originally specified, the data were provided to

HES-SO VS in a nonhomogeneous way. An optimal number of processing steps were applied. Two different graphical representations were used: 3D plot and $2^{1/2}$D plot (a xy plot with colormap for the third dimension).

The first comparison is conducted between the simulation results at the HES-SO VS and the UPV/EHU measurements on a 3D graph, as shown in Figure 35. The comparison is difficult, because the simulation is performed for an ideal model and the measurement with real time variant impedance and its limitations. Moreover, the simulation step, chosen for reasonable simulation times is limited to 1ms or more. The second comparison, shown in Figure 36, is conducted between the simulation results of the HES-SO VS and the TUD measurements on a $2^{1/2}$D graph. The comparison is again very difficult. Moreover, the measurement with the device of TUD ends at 150 kHz, which reduces the frequency range for the comparison.

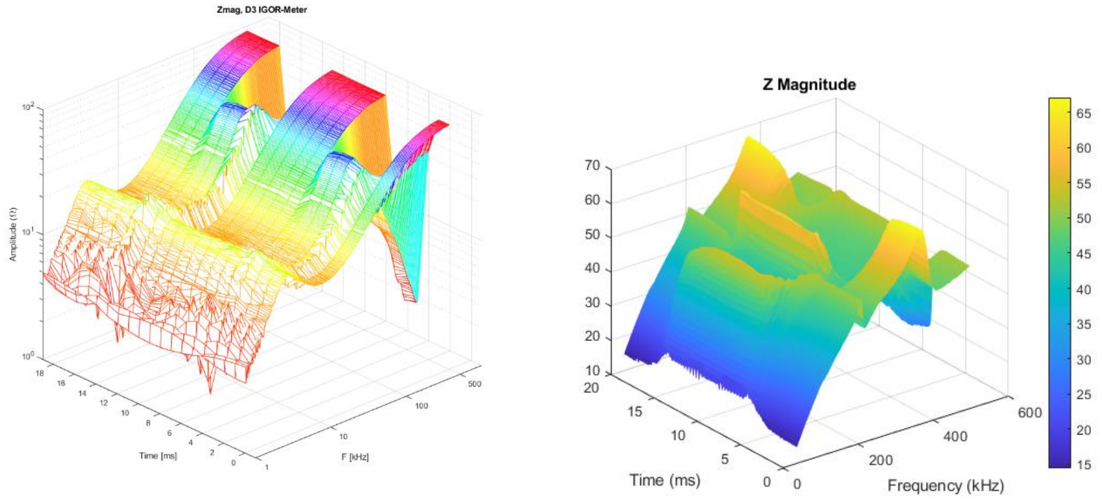


Figure 35: Time variant impedance, 3D representation, HES-SO VS (left), UPV/EHU (right): test D3

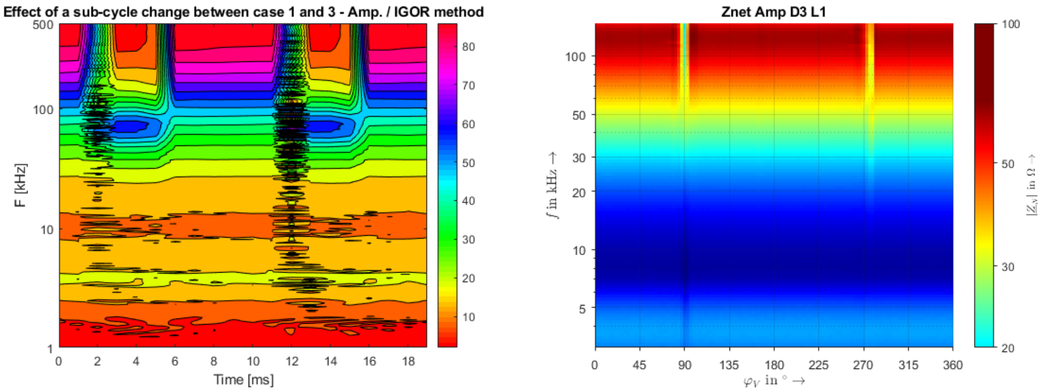


Figure 36: Time variant impedance, $2^{1/2}$D representation, HES-SO VS (left), UPV/EHU (right): test D3

A fixed data exchange format would help importing the data from other partners in a simple manner. This should still allow each institute to display the data according to their own standards.

9 WP5: Recommendations for grid Impedance measurement method

9.1 Recommendations for grid Impedance measurement method

The WP5 'Establishment of a method' aimed at the selection and the improvement of a reliable and effective grid impedance measuring method. Recommendations for an optimal method were discussed together with all the partners of the project. The signal processing is an integral part of the FTdGI measuring method (sample frequency, time steps, frequency grouping and harmonics cancellation). Advantages and challenges encountered with different signal processing were also discussed with the project partners and standardization experts in EMC and PLC communication. .

9.1.1 Criterias and specifications

The criteria to be considered in priority are listed and commented hereafter

- **Time resolution for the sub-cycle measurement of grid impedance**.
  In order to track sub-cycles FdGI variations, a time step of 1ms is to be considered as an absolute maximum (10 values within half cycle)**Frequency resolution:**
  For G3 PLC application with OFDM modulation, the frequency spacing between carriers is typically 1 to 2 kHz. A frequency resolution of 1 kHz seems sufficient. The accuracy in frequency has indeed a great importance, when measuring a resonance for instance. 1/20th of a decade in logarithmic scale seems already as an important error.**Accuracy in amplitude and phase measurement**ccuracy of +/- 5% in Z magnitude and +/-10 degree in phase are fairly enough for PLC application and troubleshooting.**Power of the excitation signal**
  If an excitation current or voltage source is required, the power required for the excitation should be as small as possible. Excitation power has an impact on equipment size and autonomy, as well as on some sensitive equipment connect to the grid. E**Equipment stability and robustness**
  Stability in measurements is relevant, as equipment are transported and used on a wide range of locations and climate conditions. On-line calibration at any location on the grid is not possible. A calibration with a passive standard sample could already compensate for a part of the instabilities due i.e., to temperature variations or magnetic offsets. . Impedance measurement with the rise of smart meters communicating via PLC implies a reflection on the measurement methodology for the understanding of signal transfer (multiphase communication and crosstalk in particular). The preparation phase of the measures in partnership with the DSO is essential to identify the connection of smart meters prior to the campaign.

9.1.2 Recommendations for the measuring method: support with software simulation

The Z-NET research team is facing large or small size companies with a long experience in developing and marketing instruments for the qualification of electrical grid or smart meters. We have no authority in this matter and must consider a modest role to play here. It is neither possible to evaluate all the measuring equipment coming to the market.

In order to make this task easier and to achieve results which are less depending on the test condition, we suggested at the beginning of Fall 2020, that the different partners would realize an **accurate software simulation** of their measuring method. For better comparability, the simulation should be executed on a common simulation software. LT Spice simulation software, available free of charge would be a good candidate. Treatment of results can be collected and treated in any mathematical solver, Matlab for instance.

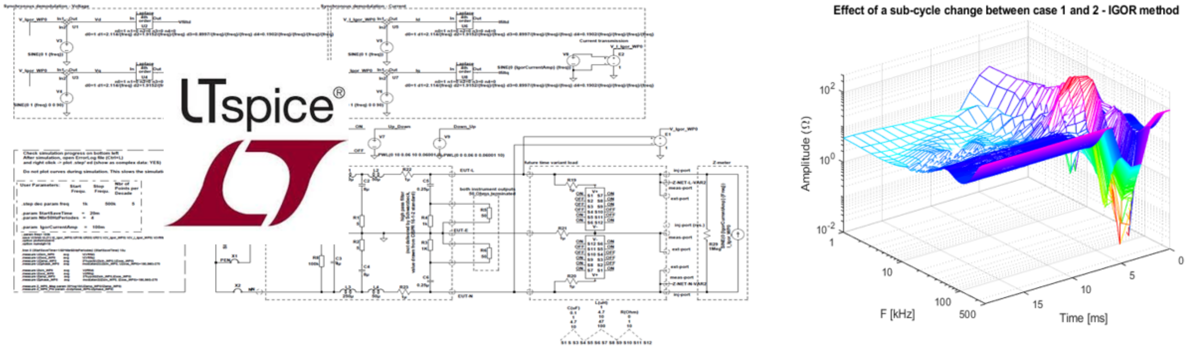


Figure 37: Simulation model and results grid impedance measuring method based on DPD with the help of LT-Spice software

Software simulation is of great support in evaluating the capacity of impedance measurement methods, particularly in the case of sub-cycle or time variant impedance. The Dual Phase Demodulation process was implemented in LT-Spice by the Z-NET. Simulation trials with the Static Line Reference Impedance developed during the project were realized.

As an example, the outcome of the first simulations have shown some limitation of the applied DPD method to measure impedance in the lower frequency range, below 10kHz with strong variations in short time and required minimal time steps, tmes<1ms. (See Chapter 7.3)

A synthesis of required performances and optimal methods for line impedance measurement are presented in an annex to his document.

9.2 Recommendations for comparison and assessment of impedance analyzers with reference impedance

The passive as the programmable impedance reference were measured by 4 institutes and 1 engineering company. These two measuring campaigns have highlighted certain points that require attention in preparation towards future standardization. These include, among others:

Uniformization of test set-up and data formats of results of energized samples in different laboratories have challenged the intercomparison process. The few options are presented in order of difficulty or satisfaction:

In any case a very clear attention must be put on output current controller of the used artificial grid converter. The Z-NET partners are currently discussing these options, to find the most efficient and accurate compromise.

9.2.1 Comparison of the Impedance analyzers with programmable and time variant impedance

9.3 Prototype of a low-cost impedance meter

In the context of a master's thesis, Mr. Dilan Ben M'Rabet Assistant at the HES-SO of Sion as developed and realized a prototype of low-cost impedance meter.

The idea is to offer a low-priced measurement device using off-the-shelf equipment and ingenious techniques to maintain quality measurements. The challenge is to create a device that is competitive with systems already developed on the market while working with cheaper components.

After analyzing the various devices developed by the Z-NET project collaborators, the impedance meter developed by the UPV/EHU team stood out. This device is designed to be simpler and more economical. It is based on the measurement of the amplitude variation of the voltage and current of

PLC signals in frequencies up to 500 kHz. For this purpose, these signals are injected in a controlled way into the network.

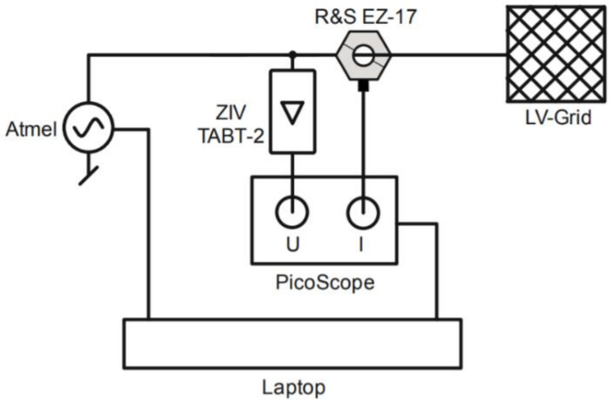


Figure 38 : Configuration of the impedance measurement according to the method proposed by the UPV/EHU

The voltage and current of the signals are acquired synchronously. The ratio between the voltage and current levels of the PLC signals provides the variation with time of the amplitude and phase of the network impedance.

The proposed impedance meter is also inspired by the operation of the IGOR meter by being equipped with an amplifier to amplify the signal injected on the measured load. The idea of processing the measurements with synchronous demodulation to calculate the impedance was also discussed during this work.

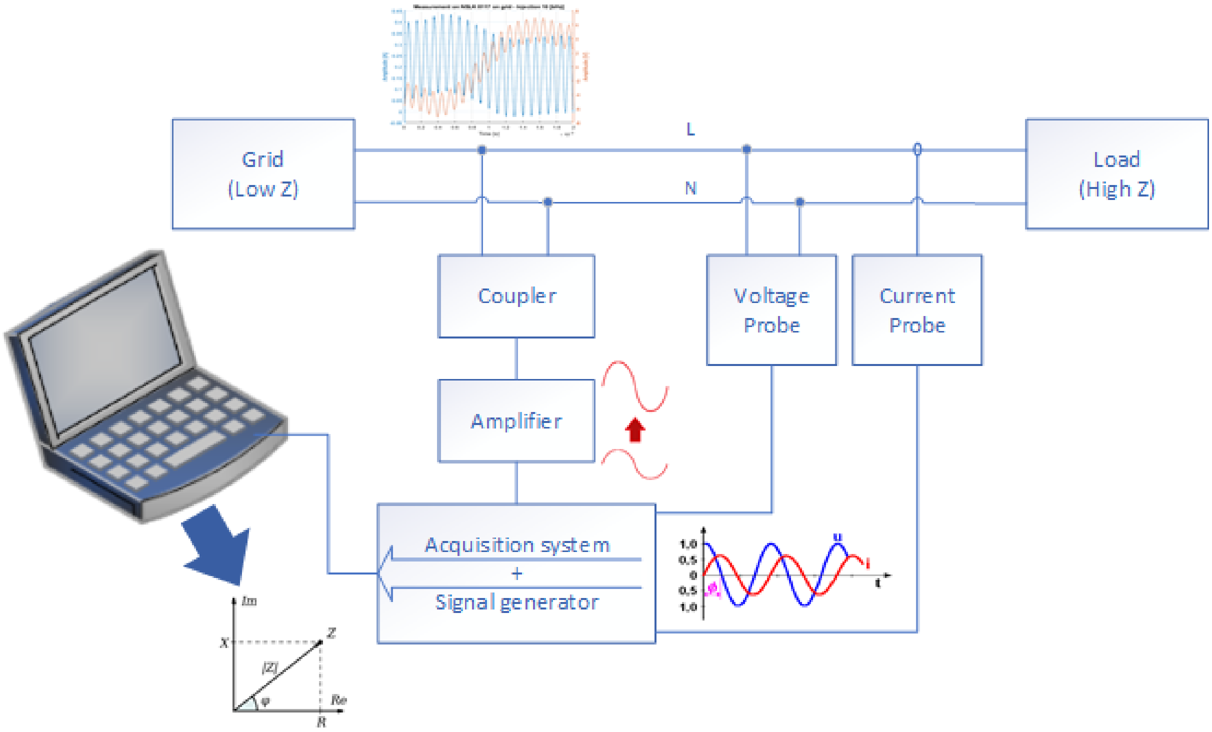


Figure 39 : Schematic of the GIA low-cost impedance meter

Impedance meter final characteristics:

- Measurement range: 1 [kHz] to 1 [MHz].
- Resolution: 14 bits
    - Increasable via oversampling and averaging (not yet developed)
- Measurable impedance range: 0.01 to 100 [Ω]
- Phase measurement range: ±180 [°]
- Measurement time on battery: 24 [h]
- Measurement time without iteration: ~40 [s]
- Price GIA : 778.16 [CHF]
- Price voltage probe : 395 [CHF]
- Price current probe : 1227 [CHF]
- Battery price : 569 [CHF]

The proposed device challenges all impedance meters with its low price. Considering the measurement probes, the cost of the impedance meter does not exceed 3000 [CHF]. Its accuracy remains relatively good despite resonances that sometimes are added to the measurements and its voltage filter that partially modifies the impedance at low frequency. The device has an excellent measurement range by offering a measurement up to 1 [MHz]. It will be possible to exceed these limits in the future by improving the oversampling and averaging method implemented. This provides an advantage for observing possible impedance changes at higher frequencies. A user-friendly interface with a wide range of parameters for the measurements to be performed could be offered. This allows users to enjoy a lot of freedom while providing optimal parameters.

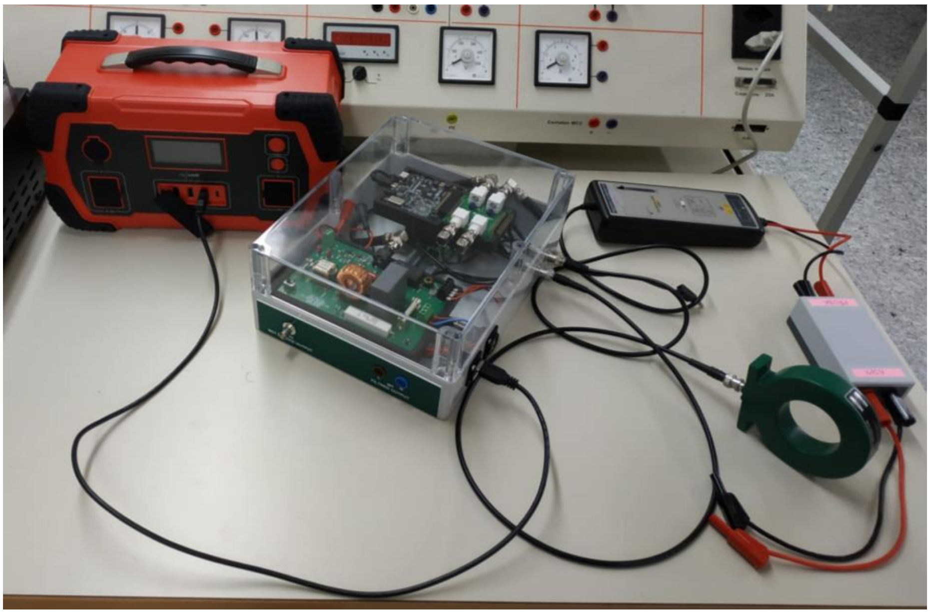


Figure 40 : Picture of the GIA low-cost impedance meter with its battery and probes

For now, the measured data are processed with a customizable FFT in post processing. The Digilent Analog Discovery 2 oscilloscope used in our system offers an option of acquisition by synchronous demodulation that must be learned and implemented in the system operation.

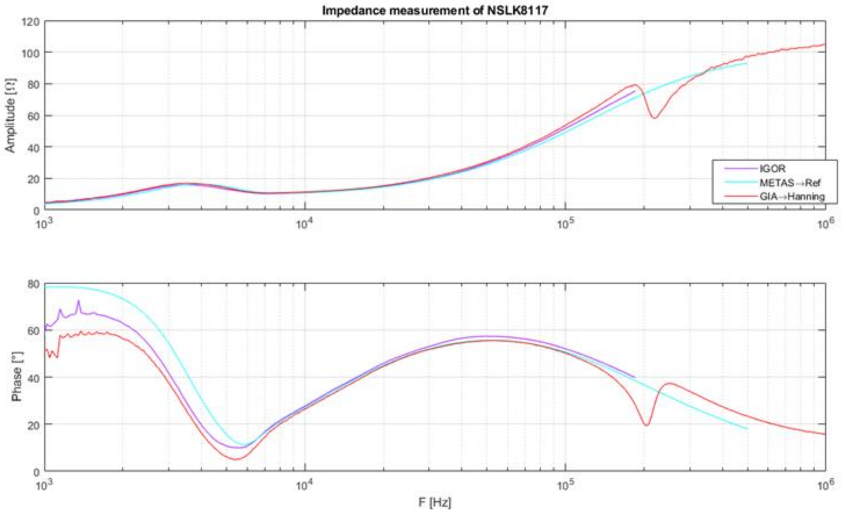


Figure 41 : Measurement oft he NSLK8117 connected tot he grid

10 National and international cooperation

10.1 Cooperation with standardization committees (WP6)

According to activities planned under the WP 6, the results of the research activities in the frame of the Z-NET project are reported to and discussed with standardization working group in form of presentations at the occasion of meetings:

- CENELEC TC 219 (ex-SC 205A), 'Mains Communicating Systems', Working Group WG 11 'Immunity', (participation of TUD, TSR and HES-SO VS, overview on Table 8
- IEC TC 77 A, EMC Low Frequency Phenomena, Working Group WG8, 'Description of the electromagnetic environment associated with the disturbances present on electricity supply networks" (participation of HES-SO VS, TUD and Schaffner, overview on **Erreur ! Source du renvoi introuvable.**)

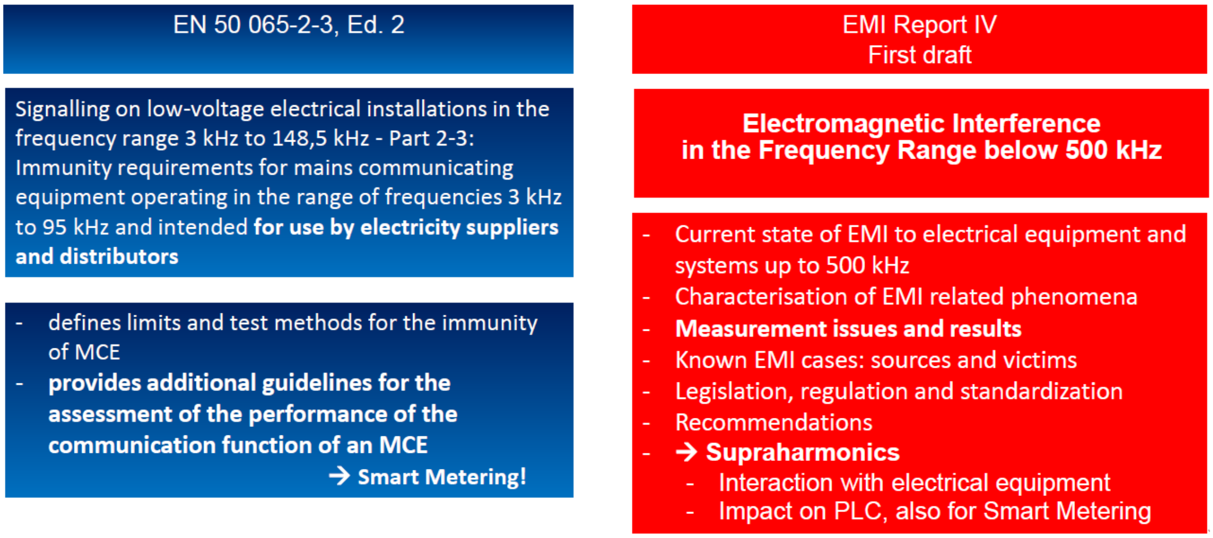


Table 8: overview of main activities within the WG11 of CENELEC TC 219 'Mains Communicating Systems

The expertise acquired with the Z_NET project activities give us the possibility to participate to the elaboration of new standards or to the maintenance of existing standards maintenance in form of comments. This is the case for the EN 5005-2-3 Ed. 2, 'Signalling on low voltage electrical installations in the frequency range 3 kHz to 148,5 kHz Part 2 3: Immunity requirements for mains communicating operating in the range of frequencies 3 kHz to 95 kHz and intended for use by electricity suppliers and distributors'.

The standard defines i.e., limits, test method and conditions for the Immunity of MCE. It provides guidelines for the assessment of the performance of the communication function of an MCE. The general test set-up defined on ANNEX A of the standard started from a system which did not define any specific or variable access impedance, in parallel to the test bench communication channel simulation. The focus was on the propagation of a stimulus over a simplified model of the lines. The final version for issued in Fall 2021 includes in Annex B additional guidelines for an optional assessment of the MCE communication performance which may be measured during the EMC tests and documented in a test report. The test set-up circuit presented in the ANNEX A3 of the final draft for vote includes the parallel connection to the transmission channel of a perturbation generator. The perturbation signals are transmitted to the communication channel via a coupling/decoupling network with a **frequency dependent impedance** as defined by the IEC 61000-4-19 immunity standard. This proposal is in the line with the recommendations issued among others from the Z-NET project.

The Working Group WG11 ‘Immunity’ of CENELEC TC 219 has started working to an up-date or complement of previously published EMI reports. The future report ‘Electromagnetic Interference in the Frequency Range below 500 kHz’ aims at addressing the following topics:

- Current state of EMI to electrical equipment and systems up to 500 kHz
- Characterization of EMI related phenomena
- Measurement issues
- Known EMI cases: sources and victims
- Legislation, regulation, and standardization

Our objective is to include some of the results and recommendations issued from the Z-NET project results a Technical Report entitled. A contribution related to line impedance measurements on the grid have been submitted by our partners from UPV/EHU for the development of this Technical Report.

EN 61000-2-2 AMD1 + AMD2	TR 61000-2-5 First draft
Electromagnetic compatibility (EMC) - Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems	**Description of the characteristics of networks with high penetration of power electronics equipment**
- Compatibility levels are specified for EM disturbances for guidance in: - the limits to be set for disturbance emission - the immunity limits to be set for the equipment exposed to the conducted disturbances… → conducted disturbances in the frequency range from 0 kHz to 9 kHz, with an extension up to 148,5 kHz specifically for mains signalling systems **→ Supraharmonics vs PLC for Smart Meter!**	- describes the main phenomena which affect the power quality of a modern Distribution Systems with high penetration of power electronics converters - focused on the following main aspects, as resonances in LV network, impact of increased number of power electronic converters, instability issues for the equipment to be connected to the LV networks - **→ Impact of FdGI on propagation and stability**

Table 9: Overview of main activities within WG8 of IEC TC 77A ‘EMC Phenomena’

The Working Group 8 of IEC Technical Committee TC 77A oversees the description of the electromagnetic environment associated with the disturbances present on electricity supply network. During the time of the Z-NET project, WG 8 fulfilled the mission to establish typical environmental levels (compatibility levels) to which emission and immunity levels can be related, in the frequency range 2 to 150 kHz. (IEC 61000-2-2 AMD1 + AMD 2) [20]. This frequency range, between harmonics and radio frequencies is typically used for Power Line Communication dedicated to smart metering applications. The advanced metering industry and DSOs have initiated the process to define compatibility levels. They have also influenced the WG to define low levels, to ensure good PLC transmission over the power lines.

WG8 is currently preparing the first draft of a technical report ‘Description of the characteristics of networks with high penetration of power Electronics equipment’. (TR 61000-2-15). The scope of the report is to address phenomena, which affect the power quality in modern distribution systems with high penetration of power electronics converters. The report focuses on modelling and understanding the resonances phenomena in network, propagation, and measurement of supraharmonics, instability issues with connected equipment with an increasing presence of power electronics converters. The FdGI plays a key role in the described phenomena.

TU Dresden and HES-SO VS representatives are member of WG8 and participated actively to the preparation of the report, in particular with information issued from the Z-NET and OptiQ projects with the support of SFOE. The Taskforce 'Instabilities' aims at publishing the report in the Year 2022.

10.2 Collaboration with the Interessenverband Netzimpedanz (WP5)

Understanding the role of Frequency dependent Grid Impedance in Power Line Communications, for conducted emissions propagation and for the stability of in-feed converters controllers, among others, a group of academic research instances and companies has launched in 2020 the initiative to form the 'Interessenverband Netzimpedanz' association in Germany. The Z-NET Project team was kindly invited to present their activities at the occasion of the first event organised by the NI Verband in October 2020 (see Chapter 8). Following a very interesting On-Line Conference, we answered positively to the invitation to integrate the board of the Association.

Link to the web page of the Interessenverband Netimpedanz: https://www.netzimpedanz.com/

Two further conferences were organized so far. The main outcomes of the Z-NET were presented at the occasion of the 3rd conference.

10.3 Cooperation with industrial partners (WP5)

Collaboration with industrial partners within the Z-NET consortia is on-going.

A collaboration with **Camille Bauer Metrawatt** supported by a Check Innosuisse allowed us to create a stronger link with them and to prove we could collaborate in excellent and efficient terms. Sharing our respective expertise in laboratory measurements or evaluation of a technology with their competences in signal treatment would be of great benefit. Discussions are on-going about a proposal to work on simplified Power Line Measurement technique accessible to existing or new CBM measuring platform. A measuring campaign was organized together with CBM at a transformer substation and at a micro hydro power plant located in the vicinity of the ski resort of Siviez at an altitude of 1730 meter. Our objective was to measure line impedance and harmonic perturbations between the transformer substation and the renewable energy production installation, at a time of the year when ski lifts and cable cars are still running. The reason for the measurements was the failure of a blocking inductance in the reactive power compensation bank connected in parallel to the induction generator of the hydro power plant. We expect that a resonance between lines and capacitors would result in the amplification of a 7th to 11th harmonics and hope to find the proof for the resonance phenomena with line impedance and harmonics perturbations measurements.

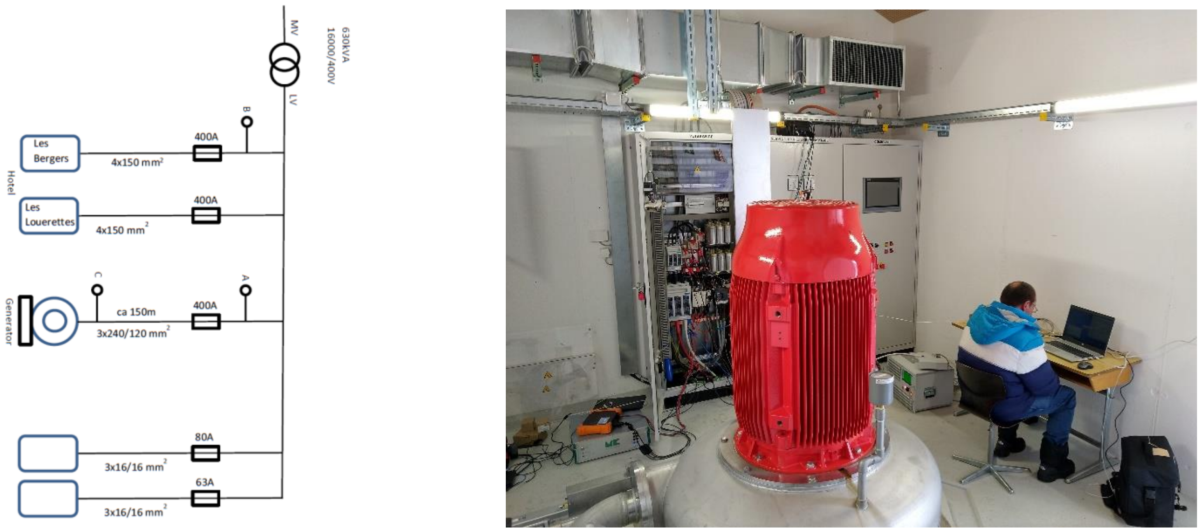


Figure 42: Grid impedance and power quality measurement at the RE installation in the Alps (grid configuration on the left)

At the occasion of this campaign, grid impedance on a frequency range between 1 and 150 kHz could be measured with 3 different impedance analysers at the transformer station of ‘Dents Rousses’ located North of Siviez. The total parallel impedance measured directly at the distribution bus bars is represented on Figure 43. This is is in our knowledge the first comparative on-site measurement of 3 impedance analysers on the CENELEC A band frequency range dedicated to Power Line Communication systems. We can observe a relatively good match of results between 1 and 150 kHz for the 3 phases, despite the quite different measuring techniques and signal treatments used in each device.

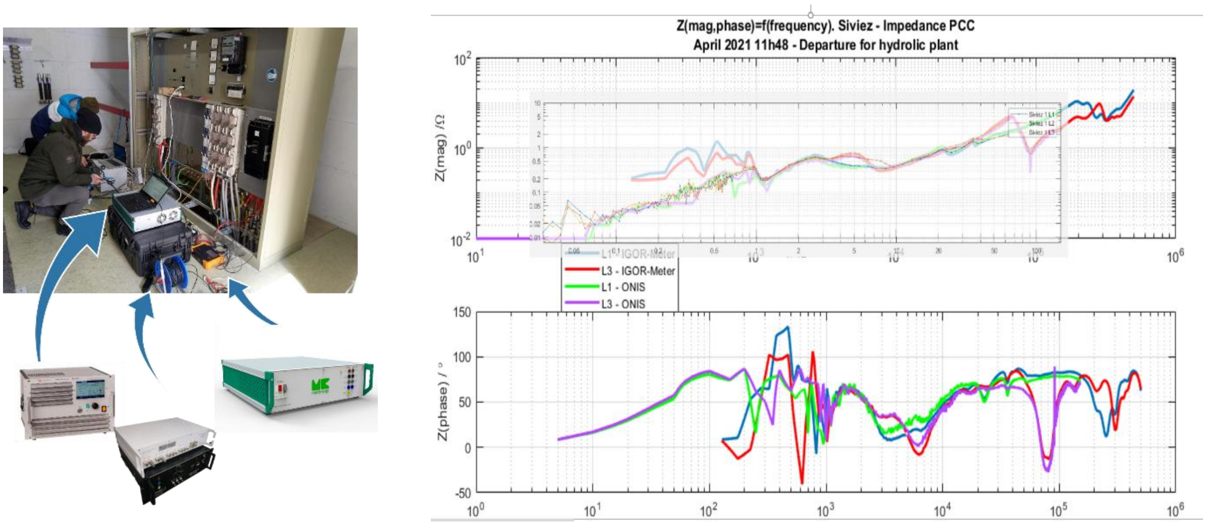


Figure 43 Line impedance measured at a transformer substation in the Alps with 3 different impedance analysers

The CBM team is also involved in the iREF-Grid project with the objective ‘Improvement of the Reliability and Efficiency of Grid operation through continuous monitoring of system perturbations caused by customer installations’, where impedance measurement are considered as a important help to assess the propagation of perturbations on LV distribution grids.

The German company **morEnergy** is issued as a start-up out of the Department of electrical power systems at Helmut-Schmidt-University in Hamburg (Prof. D. Schulz). morEnergy has developed and is commercializing the Online Network Impedance Spectrometer ONIS 690V for the measurement of line impedance and for the detection of resonances up to 50 kHz in the LV distribution networks. The company is together with the Helmut Schmidt University among the mains initiators for the NetzImpedanz Interessenverband. The ONIS 690V was used for intercomparison of Line Impedance analysers, with Static and programmable Line Impedance references in laboratory and on the field for the measurements with CBM.

The Z-NET partner company **Schaffner EMV AG** has developed a very promising technology in order to compensate for the negative impact of some EMC filter and electronic loads on the Access Impedance for PLC transmission chanel. One of the first Line Impedance Stabiliser (LIS) prototype was tested on the PLC test bench at HES-SO Valais-Wallis, where its beneficial interaction with one Smart Meters connection could be proven. Further on, Schaffner took a very active role in the ERIGRID Z-NET measuring campaign realised at the facilities of TECNALIA close to Bilbao (Spain) in collaboration with the TSR Group of the University of Basque Country. The positive effect of the LIS on communication robustness of complete Smart Metering infrastructure could be shown at the occasion of the ERIGRID Trials. The proof that a dynamic and active modification of the deteriorated access impedance could improve communication represented one of the most interesting out-come of the Z-NET ERIGRID project.

Since 2019, Schaffner developed new versions of the Line Impedance Stabilizer (LIS) which achieves significantly higher series line impedance within the CENELEC A band, when compared to the version tested in 2019. This will further improve the LIS influence on attenuation reduction, to greatly assist PLC signals to reach the minimum level for stable communication.

More specifically, the higher LIS impedance serves to diminish the negative influence of perturbating loads and to positively enhance PLC signal levels. The overall effect is to significantly improve the PLC signal to noise ratio and thus to provide reliable communication. The new LIS version can discriminate between common and differential mode signals. This enables the LIS to provide an exclusively differential mode impedance which works more directly to enhance the reliability of the inherently differential mode PLC signals.

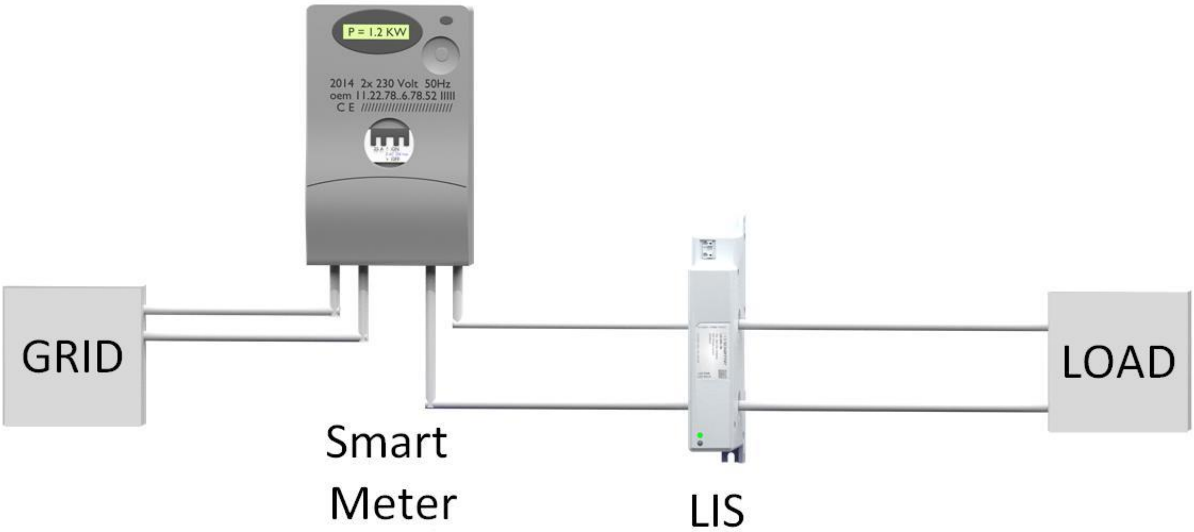


Figure 44: Circuit configuration for the application of the Line Impedance Stabiliser (LIS) (Source: Schaffner)

The new LIS version was packaged into one convenient DIN-rail mounted housing, which facilitates installation. It was integrated in the last laboratory trials on impact of Sub-Cycle time varying spectral line impedance scheduled in 2020 at HES-SO Valais-Wallis in the frame of Z-NET project.

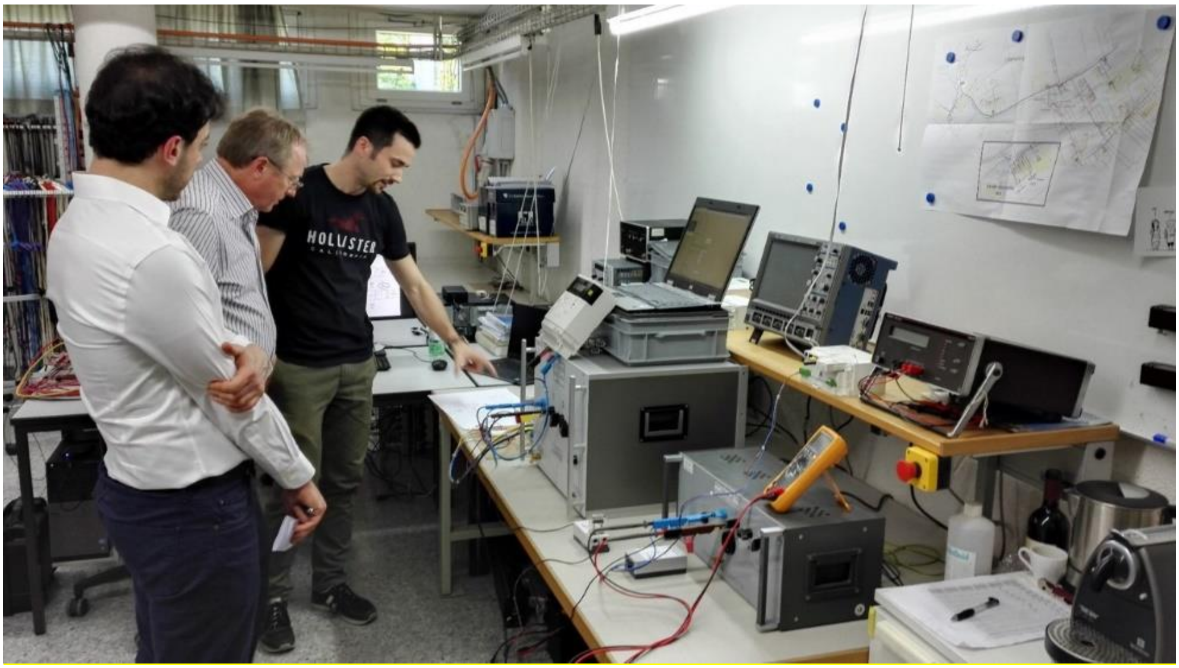


Figure 45: First prototype of LIS tests realized on the PLC test bench at HES-SO Valais-Wallis.

10.3.1 Deployement of Smart Metering infrastructure at SIG

The Power Quality Group at SIG, give technical support to other departments of the company in the frame of the deployment of the Smart Metering Infrastructure. Apart of the communication between smart meters and data concentrators is based on PLC in the CENELEC A Band (G3-PLC). The Power Quality group realizes i.e., measurement of nonintentional emissions in the 2 to 150 kHz frequency range. They also acquired and have developed advanced skills to use the 'N-Box' PLC communication analyser from Neuron.

One the pilot installations located in La Servette District is undergoing very unstable and poor-quality communication yields. Bad communication quality is related to a permanently high noise level generated by an unknown source. Surprisingly, the noise level is attenuated during activity time at the nearby shops. This attenuation could find its origin in a low impedance of some electronic loads in the shop. Unfortunately, the impact on noise comes together with impact on communication quality. A trial with Schaffner's LIS together with FdGI would be of great interest on this site.

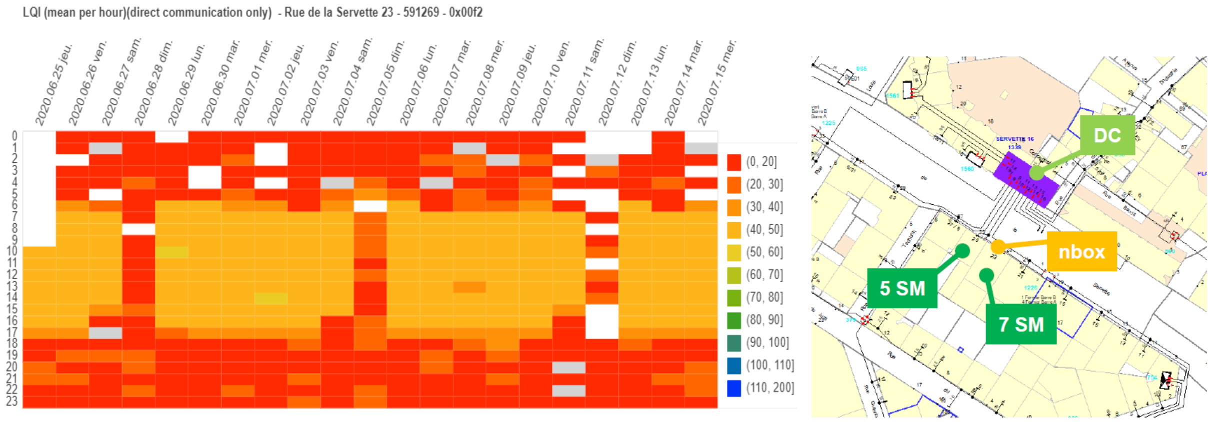


Figure 46: Smart Metering infrastructure and Hourly distribution of PLC Quality Index at La Servette (SIG) within one week

10.4 Activities with academic partners

10.4.1 Activities related to Z-NET, Working Group Power Quality at TU Dresden, Dr Jan Meyer

The research in the Power Quality working group focuses on noise emission and immunity in the frequency range below 2 kHz (harmonic) and in the frequency range between 2 kHz and 150 kHz, so-called supraharmonics. They have published an impressive number of papers on the topics of harmonics and suprahamonics propagation as well as Grid impedance role and measurement techniques. Dr Jan Meyer is involved in numerous standardization committees and Working Groups, within CIGRE, CENELEC, DACH-CZ and IEC. He also invested countless hours in the development of the CIRED conference, as a member of technical committee of Session 2 Power Quality and EMC.

For almost a decade now they have worked together with Spitzenberger+ Spies on the development of a Grid impedance analyzer (IMD 300), which is now available on the market. Our first collaboration with TUD comes back to 2015 in the frame of the SCCER project ‘Swinging Grids’, where FdGI field measurements were realized with both impedance analyzers, IGOR and IMD 300.

The Power Quality group has taken an important role in the intercomparison of Static and Programmable Line Reference Impedances. They have shared their experience with recommendations and relevant presentations on the topic of supraharmonics of grid impedance measurement at the occasion of each partner meetings.

10.4.2 Activities related to Z-NET at TSR Group, UPV/EHU (Spain)

The experience and the knowledge obtained in previous projects [4], as the projects Z-Net (SFOE) and ERIGRID.Z-Net (H2020) projects, provided a valuable background to move forward in this research topic and start new activities in higher frequency ranges, up to 10 MHz. The collaboration with the members participating in these projects (Z-Net and ERIGRID.Z-Net) has been also of great interest in the development of this new proposal

TSR Group was granted support from Basque government for a new large-scale project (>0.5 MEuro) in the domain of PLC which could impact on the standardization activities for Power Line Impedance measurement. The project “Design and analysis of a new technology for broadband data transmission in Smart Grids” in collaboration with TECNALIA, University of the Basque Country (UPV/EHU), ZIV Automation has as objective to define, design, develop, and realize lab trials and field trials of a new technology for broadband data transmission in Smart Grids. Although the project aims at the development of new transmission technologies, one relevant aspect is that these technologies must been adapted to overcome the difficulties caused by the electrical grid as a propagation medium. For this reason, the Work Package 1 of this project is focused on the characterization of the main parameters of the electrical grid for the data transmission. Hence, the characterization of the impedance in the frequencies up to 10 MHz is one of the main tasks in this Working Package.

In order to achieve this goal, a new impedance measurement system was designed, developed and calibrated. Additionally, new processing algorithms for the analysis of the data registered in future measurement campaigns are being developed. Information regarding the new impedance measurement system and the first outcomes were shared in the frame of the Z-Net project. The shared information is very valuable as HES-SO VS will continue activities in the domain of Broad-Band PLC in the frequency range 1.6 to 30 MHz.

10.5 ERIGRID Z-NET project

10.5.1 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 semiconductors, occurring repetitively within one fundamental cycle at 50 Hz impact on PLC communication channels?

10.5.2 Objectives

The objective of the proposed measuring campaign is 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 should help us finalizing the specification of a time variant frequency dependent grid impedance standard to be developed in the frame of the Z-NET project.

The question can only be answered with further tests conducted in laboratory conditions, in the absence of non-controlled perturbation sources.

10.5.3 Setup

TECNALIA premises emulate a LVAC distribution grid with two 500m line sections connected in series and several distribution cabinets equipped with 10 Smart Meters each. 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 provided by 3 different suppliers. The Narrowband PLC communication protocol PRIME version 1.3.6 is used between DC and all SM, covering the frequency band between 42 and 89 kHz. 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 those electronic loads on PLC can be analyzed with the help of a dedicated data network analyzer (‘packet sniffer’).

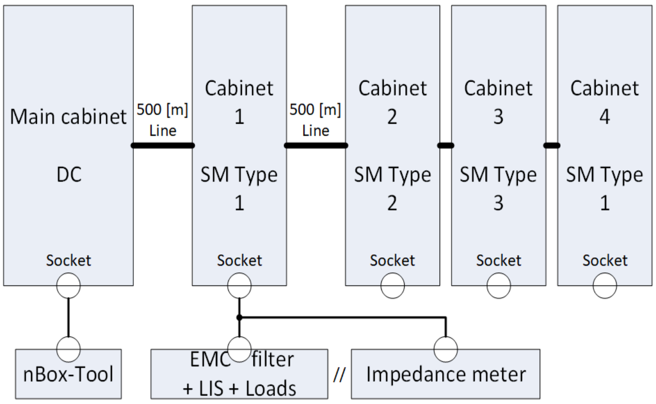


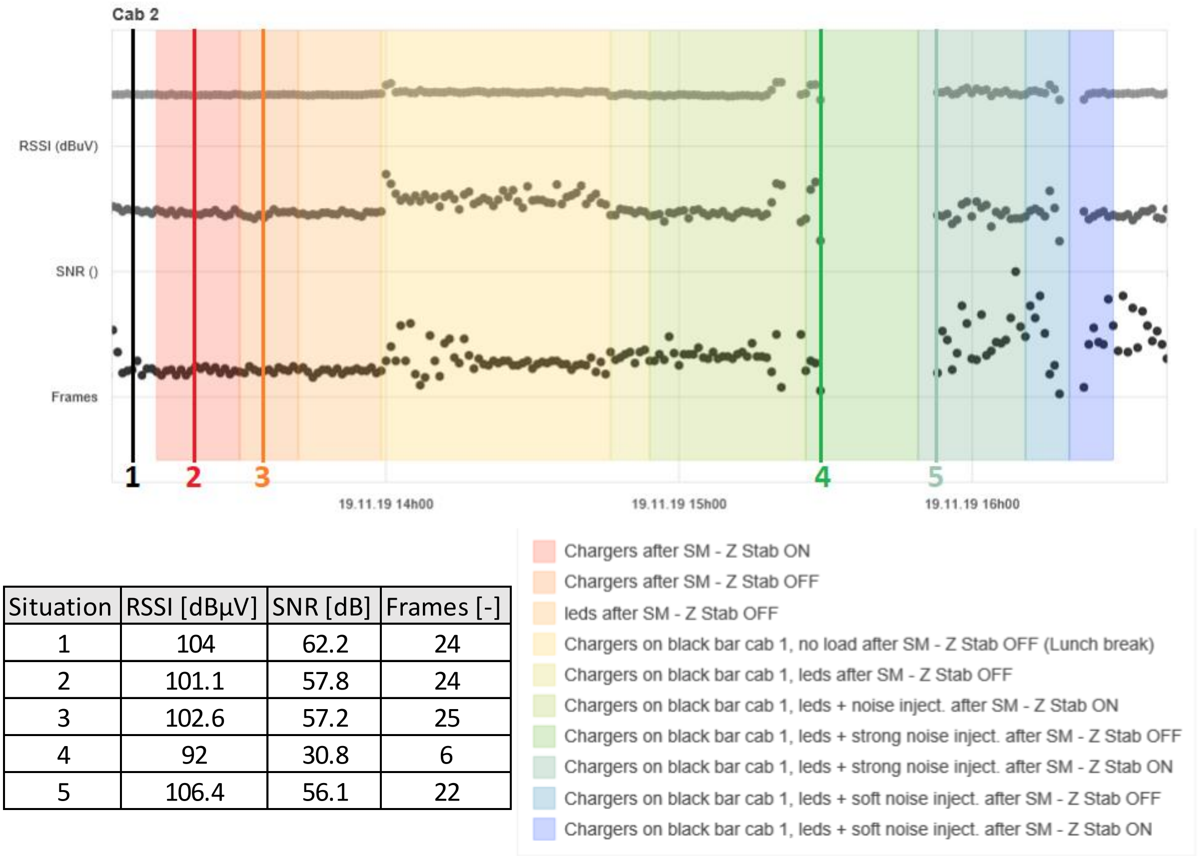
Figure 47: Picture and scheme of the TECNALIA permises

10.5.4 Results

Various measurements were done to see the impact of different loads on the communication and the impedance. However, it is difficult to find a correlation between the quality of the communication and the impedance of the circuit.

The Figure 48 shows the communication performance of the signals sent by a DC to a SM separated by a 1 km line in different situations.

A nBox by Neuron was used to measure the communication quality of the signals passing through the SM. Many configurations were tested during the day, the nBox was connected all day to see the changes on the communication.



Situation	RSSI [dBµV]	SNR [dB]	Frames [-]
1	104	62.2	24
2	101.1	57.8	24
3	102.6	57.2	25
4	92	30.8	6
5	106.4	56.1	22

Figure 48: Communication performance of a SM communicating with DC separated by a 1km line

As presented on the above scheme, the communication seems to be a bit worse when loads are connected. The situation 1 shows the communication quality without loads. The RSSI and the SNR is a bit better when no loads are connected. The measurements with PLC performance analyser Neuron N-Box, the analysis of the measuring results, and the smart representation of the communication performances in time was one of the main contributions of SIG during the project. (Figure 48)

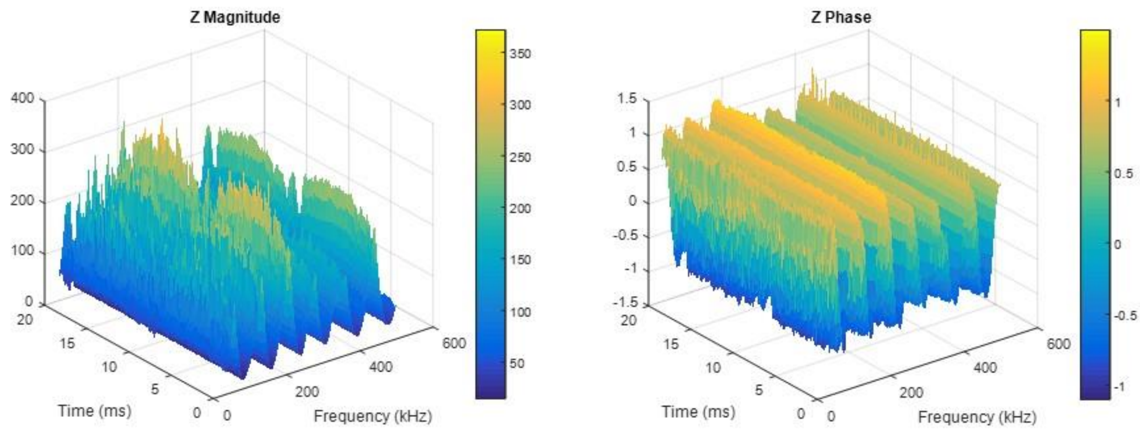


Figure 49: Grid impedance in the cabinet 2, without any load connected in the grid

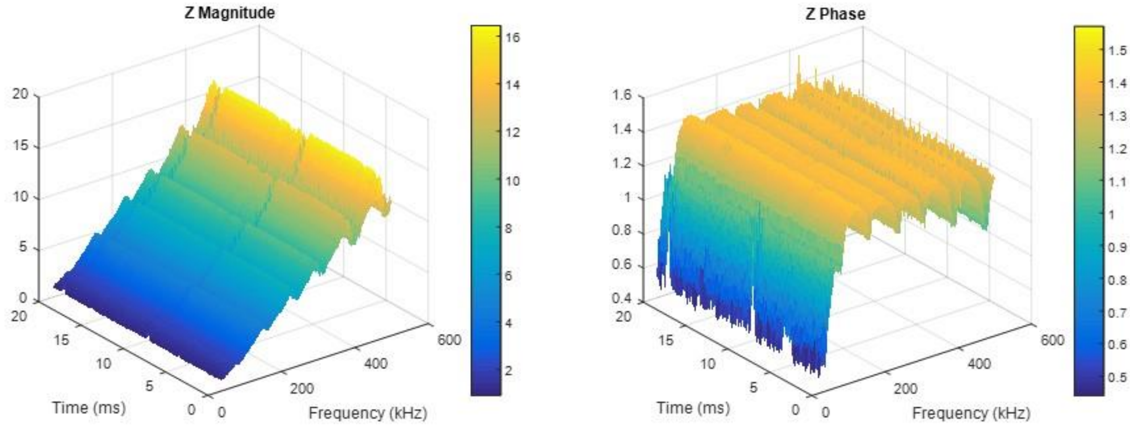


Figure 50 : Grid impedance in the cabinet 2, with the power adaptors connected in the cabinet 2

As presented in Figure 49 & Figure 50, the impedance measured on cabinet 2 seem to have a lot of resonances. When the load is connected to the cabinet, the impedance seems to stabilize while keeping the resonances.

10.5.5 Line Impedance Stabilizer LIS

As said in the Chapter 10.3, one of the first version of the Line Impedance Stabilizer combined with an EMC filter were tested during the measurement campaign done at TECNALIA in Bilbao. They were connected in series between the electronic loads and the Smart 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.

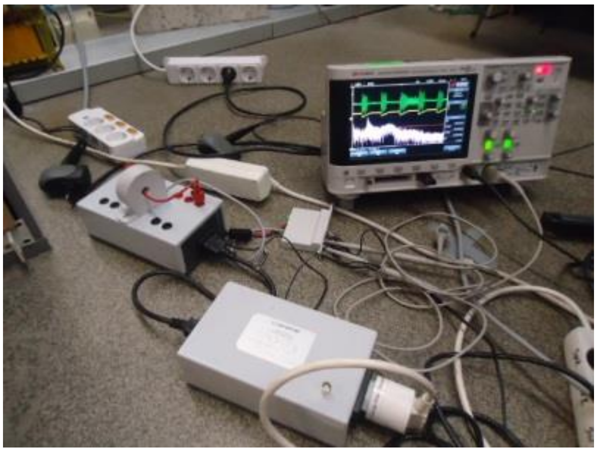


Figure 51 : Impedance stabilizer with filter from Schaffner.

The positive effect of the LIS on communication robustness of complete Smart Metering infrastructure could be shown at the occasion of the ERIGRID Trials. The proof that a dynamic and active modification of the deteriorated access impedance could improve communication represented one of the most interesting out-come of the Z-NET ERIGRID project.

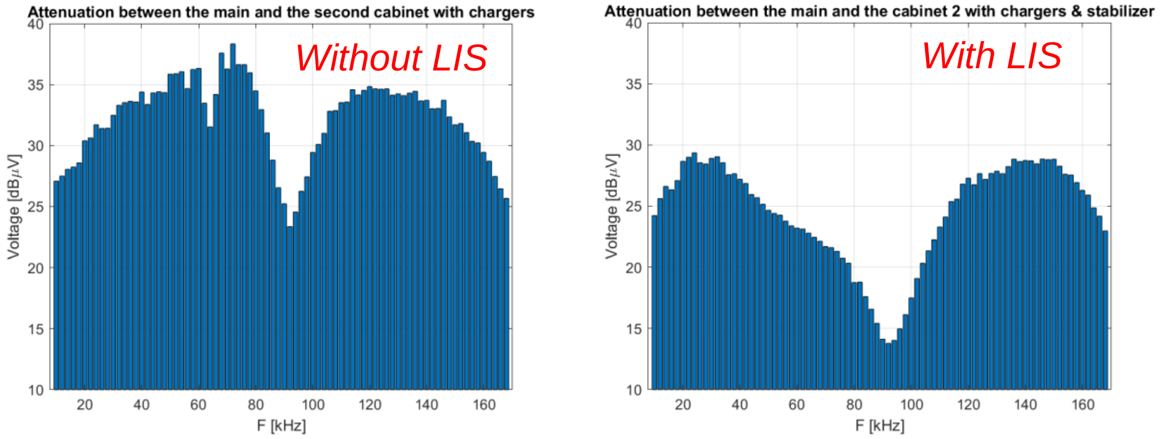


Figure 52 : Transmission losses measured with PQBox 300 between a DC and a SM separated by a 1 km line, with power adaptors connected on the SM side.

When the stabilizer is added to the load, the attenuation in Cenelec A band varies around 20 dB, whereas when the 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.

In the Figure 48, 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 stabilizer allows the signal level to be raised to an acceptable level.

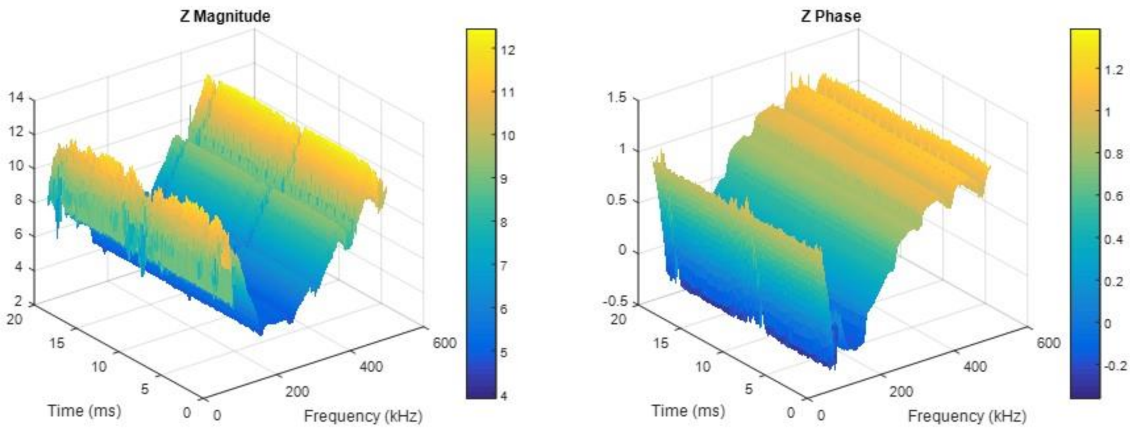


Figure 53 : Grid impedance in the cabinet 2, with the power adaptors and the stabilizer connected in the cabinet 2

11 Laboratory trials with PLC test bench

11.1.1 Summary

The European Telecommunications Standards Institute has proposed a standard defining a guide to test the communication of narrow band transceivers in the range of 9 kHz to 500 kHz on power lines. This is a key possible application of Line Impedance Analyzers in the domain of standardization

As presented earlier in the report, the impedance of a line and the communication quality of transceivers is related. Therefore, the test setup described in the ETSI TS 103 909 guideline has been mounted.

11.1.2 Objectives

Since the ETSI bench is designed to allow efficient analysis of the state of the PLC communication, it was decided that it would be a good idea to set up the bench and carry out tests under several configurations. For each case analysed, a measurement of the communication and impedance would be made to try to find a correlation between the two.

11.1.3 Setup

The installed setup was taken from the ETSI standard.

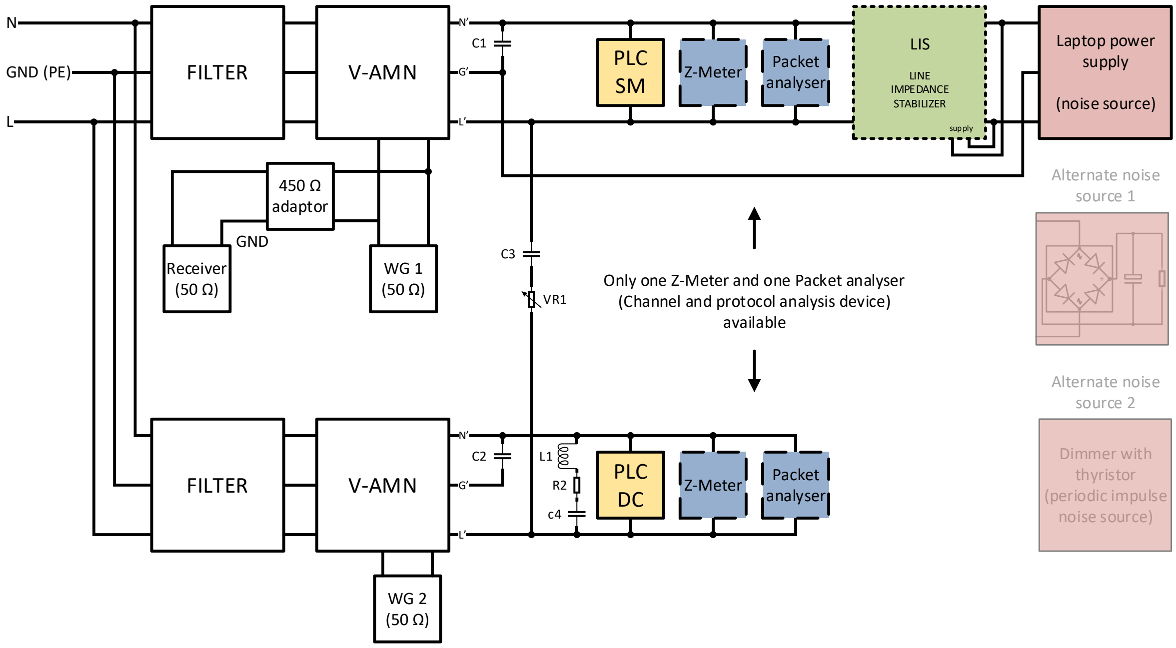


Figure 54 : Setup of the test bench proposed on the ETSI standard

The LIS, an impedance meter and a packet analyser were added to the circuit to measure the different values required.

List of equipment

V-AMN DC side:	NSLK8121
V-AMN SM side:	NNLA8120
Packet analyser:	nBox-Tool from Neuron
Z-Meter:	IGOR-Meter from HES-SO & ONIS from MorEnergy

Load:	Dell Charger 90 [W]
PLC DC-SM:	Landis+Gyr G3-PLC

VR1 is presented as R_var in the report. The passage through R_var represents the only path where communications can cross between the DC and the SM.

The system will be tested with different values for R_var from ∞ to 0 [Ω]

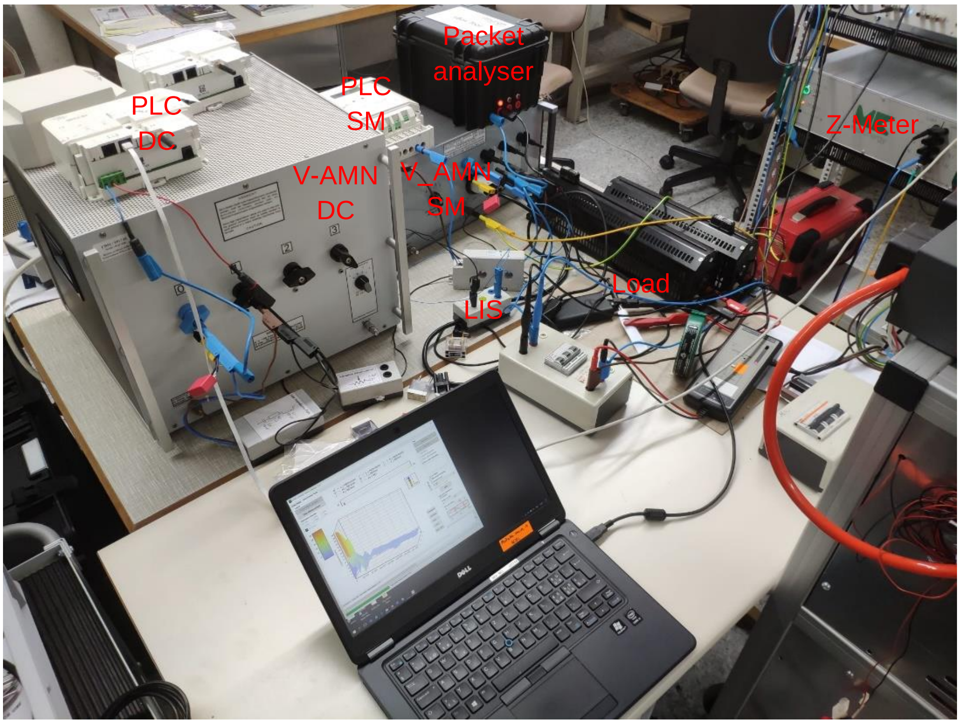


Figure 55 : Picture of the ETSI bench mounted

The load used for the tests is a laptop charger (Dell 450-19040) loaded one time with 15 [Ω] and another with 6 [Ω].

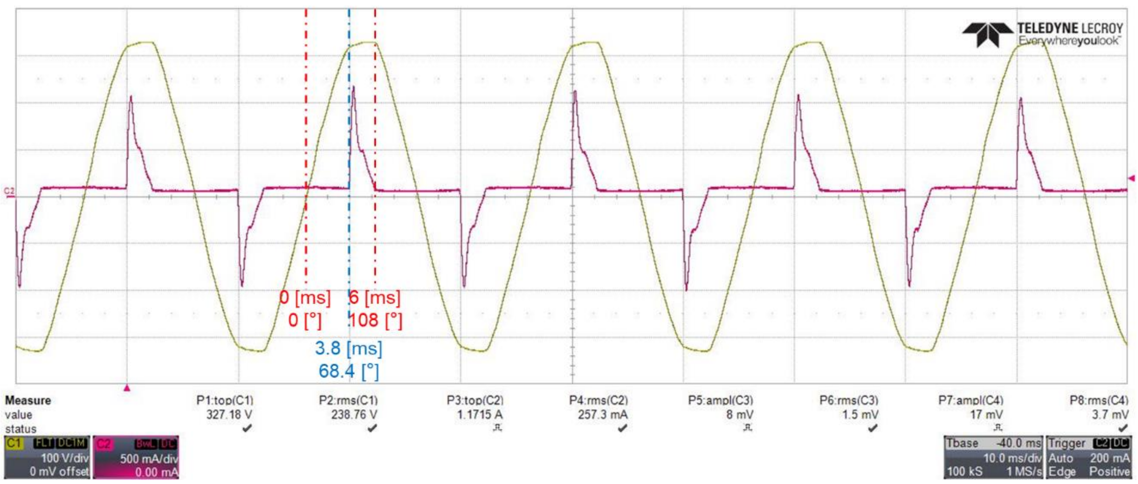


Figure 56 : Current consumed by the laptop charger loaded with 15 [Ω] (25 [W])

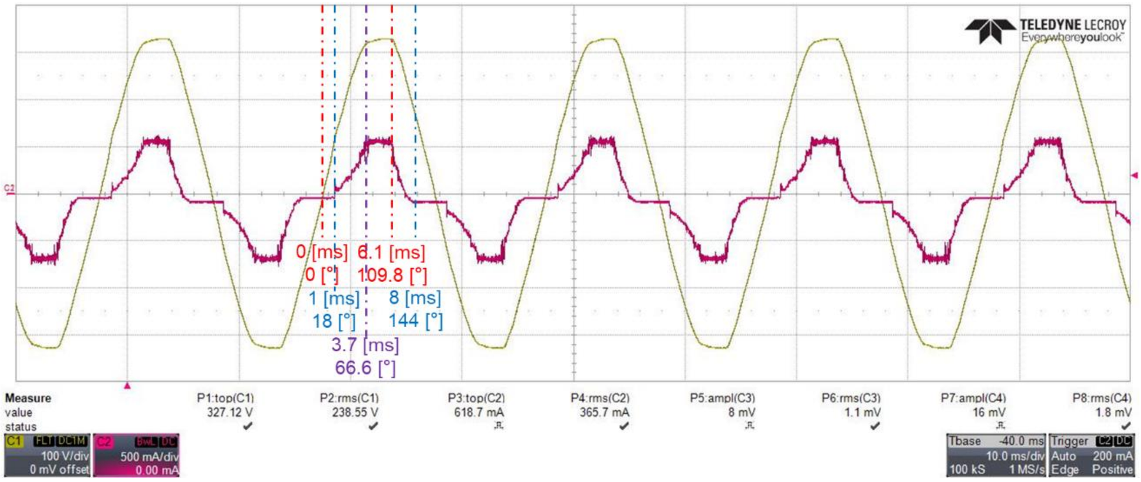


Figure 57 : Current consumed by the laptop charger loaded with 6 [Ω] (63 [W])

When the consumed power exceeds ~65 W the charger regulates its consumption by limiting the pic current produced. This comes from the normalization instilled by the IEC 61000-3-2 standard that define the limits for harmonic current emissions for equipment input current ≤16 A per phase.

11.1.4 Results

The test bench used for the measurements has been modelized on LtSpice to see if the behavior of the system would respect the reality on simulation.

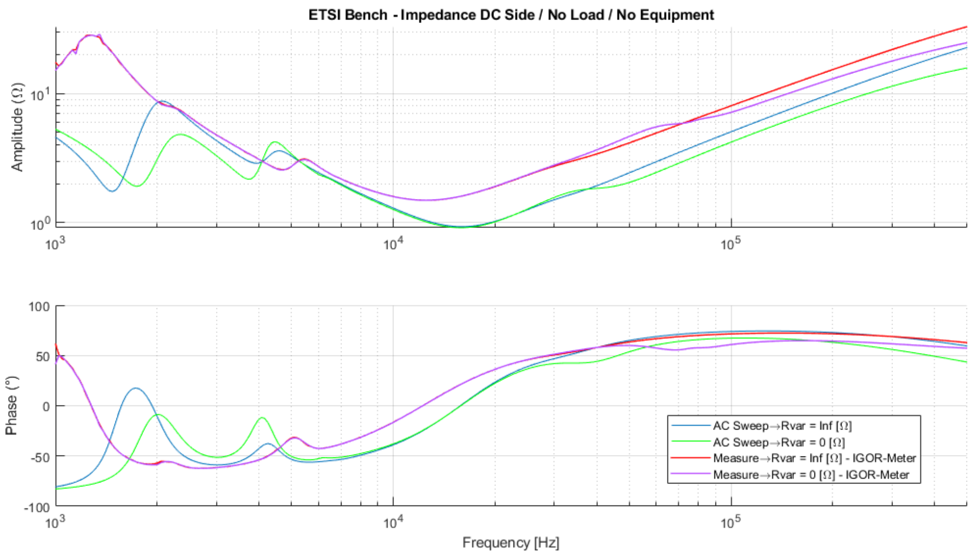


Figure 58 : Comparison of impedance measured and simulated on DC Side

The simulated impedance seen from the DC side is relatively correct. Under 10 [kHz], the resonances observed aren't placed the same way. The magnitude is also different. Above 10 [kHz] the curves are similar. There is a difference going from 1 to 5 [Ω] between the reality and the simulation.

For the SM side, the impedance shape is totally different but the differences between the measure and the simulation are approximately the same

The resonances are not at the same place but seem to be related.

With these results, it can be assumed that the model simulated can be used if some small analysis shall be made. If something accurate must be determined, the model cannot be used in its current state.

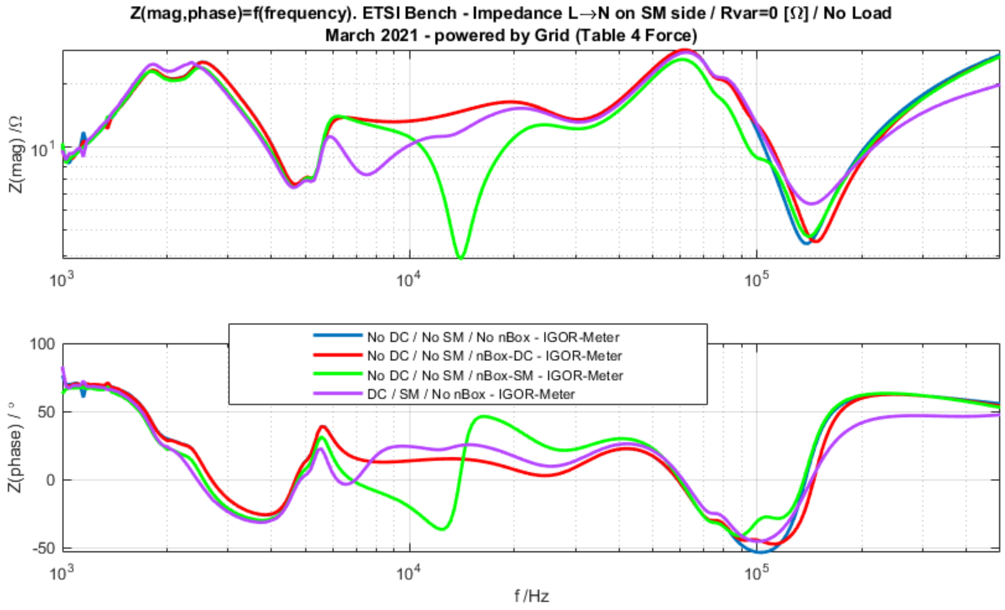


Figure 59 : Impact of the different devices connected on the circuit on SM Side

It is interesting to see on the Figure 59 that even the devices used to communicate or to measure the communication can make the impedance of the grid variate and therefore decrease the communication quality. In this case, we can see that between 30 and 500 kHz the impedance stays relatively similar.

The real meaning of the performed tests is to see the relation between the changes on the impedance and the communication of smart meters.

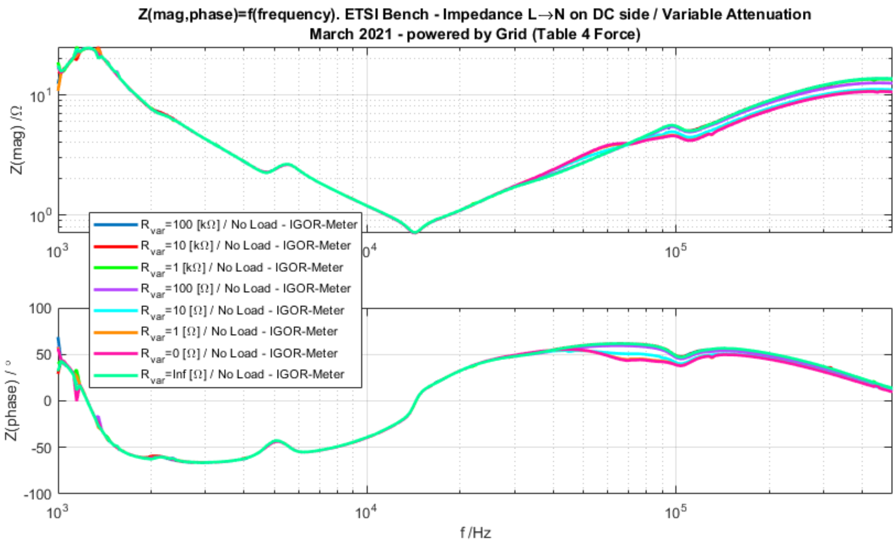


Figure 60 : Impedance of the circuit viewed from the DC Side with variation on Rvar & no load

As seen on the Figure 60, the change of Rvar doesn't make a real difference on the impedance of DC side when no loads are connected. The impedance on the SM Side will be analysed because the change with Rvar is more visible.

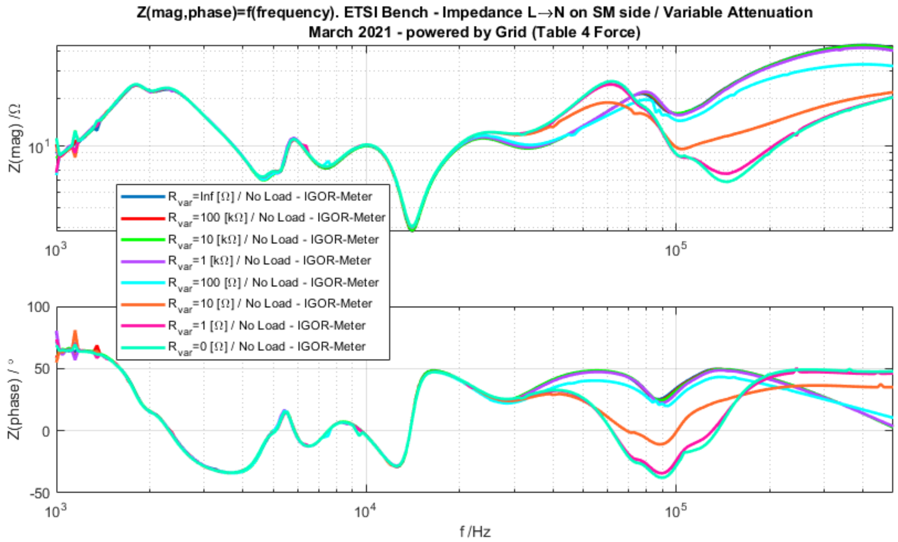


Figure 61 : Impedance of the circuit viewed from the SM Side with variation on Rvar & no load

This time, a real change occurs on the impedance when Rvar is modified.

To measure the quality of the communication, a nBox was connected on the circuit as shown on the Figure 54. The ETSI test Bench was designed with LISNs and filters. They are here to block the high frequency perturbations coming from the grid. The only way for the packages to pass is through the Rvar line. So, when Rvar is too high, the DC and the SM fails to communicate so no packages are exchanged.

DC view / No load					
Time [hh-mm]	R_var [Ω]	RSSI SM [dBμV]	LQI_Min	LQI_Max	LQI_Mean
10h10	INF	/	/	/	/
10h30	100000	/	/	/	/
11h01	10000	51	70	122	108.3
12h31	1000	75	54	143	105.1
12h52	100	90	105	145	128.9
13h18	10	103	121	139	129.2
13h35	1	105	115	136	125.5
13h56	0	105	117	135	126.6
SM view / No load					
Time [hh-mm]	R_var [Ω]	RSSI DC [dBμV]	LQI_Min	LQI_Max	LQI_Mean
8h20	INF	/	/	/	/
8h46	100000	/	/	/	/
9h05	10000	/	/	/	/
9h30	1000	82	79	139	111.4
9h55	100	100	115	140	125.9
10h05	10	112	111	150	123
10h35	1	115	112	134	119.9
10h53	0	117	107	127	115.8

Table 10: Communication quality on both sides of the circuit with variation on Rvar

As seen on the Table 10, the RSSI decreases when R_{VAR} increases. It's possible de see the mean LQI level present online when no loads are connected to the circuit.

The results presented on the Table 10 are showing the quality of the signals sent from the SM to the DC measured on the DC side.

Looking from the DC side, no relevant change on the RSSI can be seen. Its's visible that the mean LQI level is a bit higher when no loads are connected (Table 10). But the change isn't so relevant and won't affect the communication significantly.

DC view / Dell Charger 90 [W] - 15 [Ω]					
Time [hh-mm]	R_var [Ω]	RSSI SM [dBµV]	LQI_Min	LQI_Max	LQI_Mean
12h20	INF	/	/	/	/
14h21	100000	/	/	/	/
14h27	10000	52	82	111	104.9
12h46	1000	72	74	124	97.1
13h08	100	91	103	119	112.6
13h23	10	105	107	123	115.4
13h47	1	108	83	117	107.1
14h08	0	109	98	112	106.4
DC view / Dell Charger 90 [W] - 6 [Ω]					
Time [hh-mm]	R_var [Ω]	RSSI SM [dBµV]	LQI_Min	LQI_Max	LQI_Mean
7h45	INF	/	/	/	/
8h02	100000	/	/	/	/
8h11	10000	/	/	/	/
8h20	1000	/	/	/	/
8h45	100	91	101	126	115.8
9h50	10	104	87	122	113.0
10h08	1	108	106	118	110.4
10h29	0	108	74	127	108.8

Table 11: Communication quality of the packages coming from the SM measured on the DC Side

However, when we look at the SM side that is directly connected to the load, a real change occurs.

SM view / Dell Charger 90 [W] - 15 [Ω]					
Time [hh-mm]	R_var [Ω]	RSSI DC [dBµV]	LQI_Min	LQI_Max	LQI_Mean
7h15	INF	/	/	/	/
7h43	100000	59	0	0	0
7h52	10000	64	0	48	22.5
7h57	1000	83	46	78	62.4
8h24	100	100	63	85	76.9
8h38	10	108	71	90	80.5
8h55	1	110	57	89	76.4
9h11	0	111	69	85	77.3
SM view / Dell Charger 90 [W] - 6 [Ω]					
Time [hh-mm]	R_var [Ω]	RSSI DC [dBµV]	LQI_Min	LQI_Max	LQI_Mean
10h38	INF	/	/	/	/
10h59	100000	/	/	/	/
11h19	10000	/	/	/	/
12h20	1000	/	/	/	/
12h57	100	/	/	/	/
13h22	10	/	/	/	/
13h40	1	112	80	152	93.8
15h37	0	113	52	94	82.3

Table 12: Communication quality of the packages coming from the DC measured on the SM Side

This time, the LQI decreases significantly compared to the cases without loads. It's possible to see that less frames could be measured with dell charger at 63 [W] connected. This is an excellent case to see if the LIS from Shaffner can improve the communication.

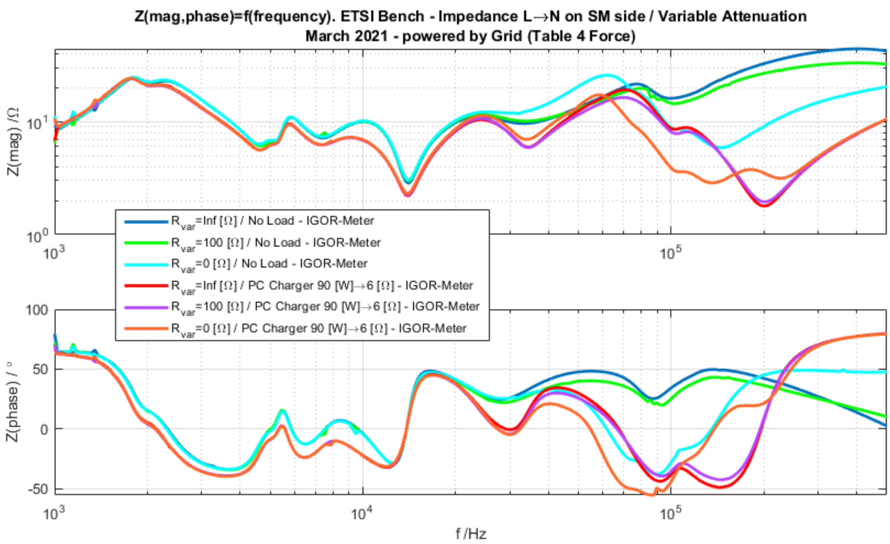


Figure 62 : Impedance of the circuit viewed from the SM Side with variation on Rvar & on the load

The Figure 62 shows the impedance difference between the circuit with no load and with the Dell charger at 63 [W] connected. The impedance is a bit lower under 70 [kHz] with the load connected. Above 70 [kHz], The amplitude of the impedance decreases consequently when the load is connected.

11.1.5 Line Impedance Stabilizer LIS

The version LIS140C-1 of the LIS released in 2020, is presented in the Figure 63 and the frequency dependent characteristics on Figure 64.

Figure 63 : 2020 version of the Line Impedance Stabilizer by Schaffner

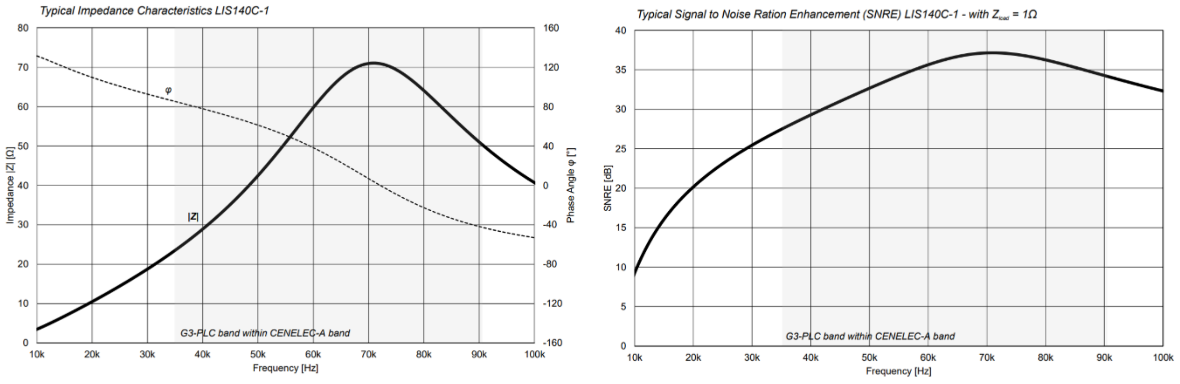


Figure 64:Frequency dependent characteristic curves for LIS140C-1 (2020), as tested during Z-NET project.

Left: FdGI. Right: Signal Noise Ration Enhancement

As presented on the previous chapter, the measurements done with loads on the circuit were repeated with, this time, the LIS added upstream of the load

SM view / Dell Charger 90 [W] - 15 [Ω]					
Time [hh-mm]	R_var [Ω]	RSSI DC [dBµV]	LQI_Min	LQI_Max	LQI_Mean
7h15	INF	/	/	/	/
7h43	100000	59	0	0	0
7h52	10000	64	0	48	22.5
7h57	1000	83	46	78	62.4
8h24	100	100	63	85	76.9
8h38	10	108	71	90	80.5
8h55	1	110	57	89	76.4
9h11	0	111	69	85	77.3
SM view / Dell Charger 90 [W] - 15 [Ω] & LIS					
Time [hh-mm]	R_var [Ω]	RSSI DC [dBµV]	LQI_Min	LQI_Max	LQI_Mean
8h45	INF	/	/	/	/
9h20	100000	/	/	/	/
9h39	10000	67	0	0	0
9h55	1000	80	0	88	64.5
10h23	100	98	96	112	104.8
10h30	10	110	92	120	108.6
10h38	1	112	23	118	86.1
10h45	0	112	68	117	100.6

Table 13: Communication quality of the packages coming from the DC measured on the SM Side

The main difference, visible on the Table 13, comes from the LQI. The LIS doesn't seem to improve the strength of the signals transmitted on the circuit. However, the mean LQI presented above is clearly better when the LIS is present. This improves the communication

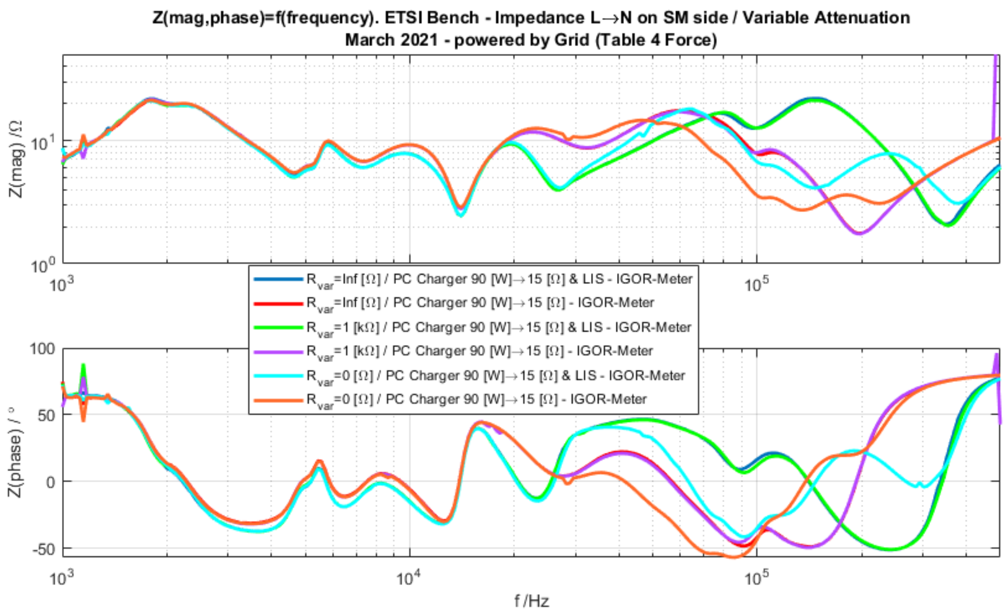


Figure 65 : Impedance of the circuit viewed from the SM Side with & without LIS & with Dell Charger at 25 [W]

The Figure 65 demonstrate the impedances differences with and without LIS connected to the circuit. We can say that under 70 [kHz] the impedance seems to decrease when the LIS is connected. Above 70 [kHz], it's difficult to find a correlation between the impedance

11.1.6 Example of Measurements of the Time Variant Grid impedance with the LIS

The impact of Sub-Cycle time varying frequency dependent line impedance (FTdGI) on the transmission channel for PLC was analyzed with the help of the ETSI test bench. The impact on the communication performance of a power electronic load (laptop charger) connected in parallel to the Smart meter is evaluated with the help of FTdGI measurements We need for that an impedance analyzer with capacity to measure sub-cycle variations of the Impedance of energized line. The following figures represent measurement results with and without the LIS connected between the load and the PLC transmission channel. The behavior in time domain of the Laptop power adapter are represented on Figure 56 (15 Ohm or standby mode) and on Figure 57 (6 Ohm, PFC mode).

The impact of electrical angle resolution on Sub-cycle grid impedance measurements is presented on Figure 66 with examples 10° and 30° angle resolutions. FTdGI measured with 30° electrical angle resolution at the connecting point of a Smart meter communicating with PLC without LIS are presented on Figure 67 and with LIS on Figure 68. The transmission channel is emulated with a 1 kOhm resistor. The perturbation source is connected either directly to the transmission channel or through the Line Impedance Stabiliser (LIS) developed by Schaffner. An instant view of the line impedance profiles with high resolution in frequency, at a defined time within the 50 Hz cycle (90° electric in this case) are represented on Figure 69. More detailed results and impact of the LIS discussed directly with the project partner (Schaffner) are not reported here.

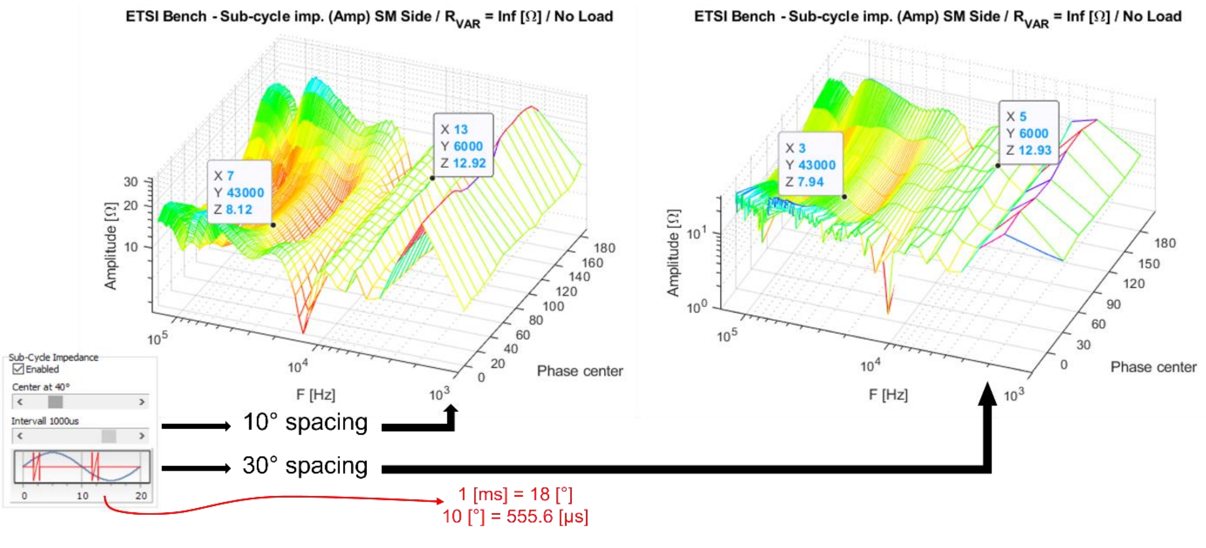


Figure 66: FTdGI measurment results at SM point of connection with different time resolutions. Starting situation: no load and line off

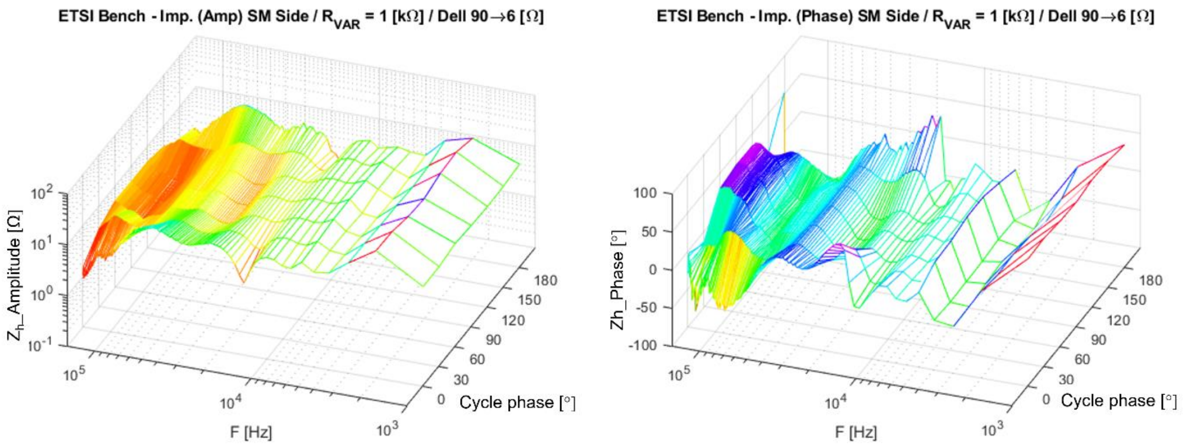


Figure 67: FTdGI measured with a laptop AC power supply in PFC mode, directly connected in parallel to SM point of connection

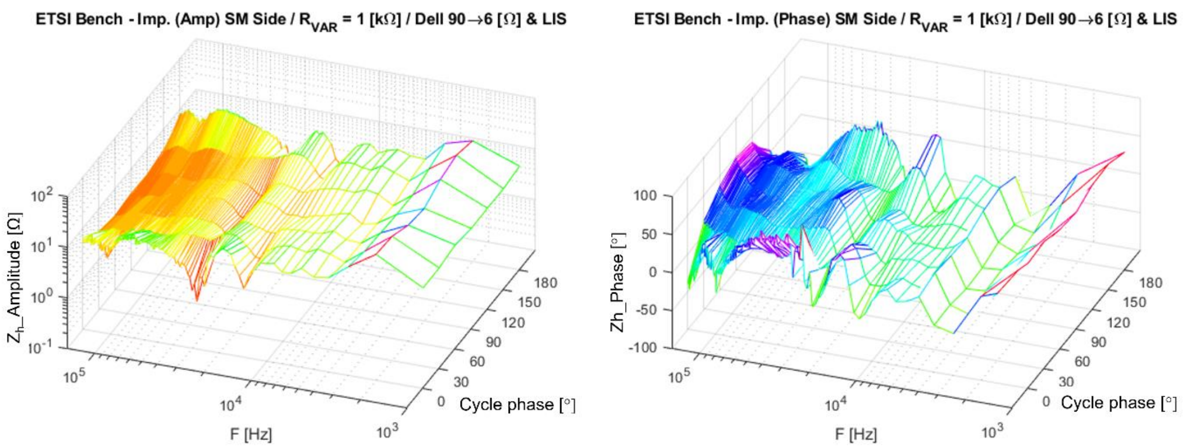


Figure 68: FTdGI measured with a laptop AC power supply working in PFC mode and connected in parallel to SM through LIS

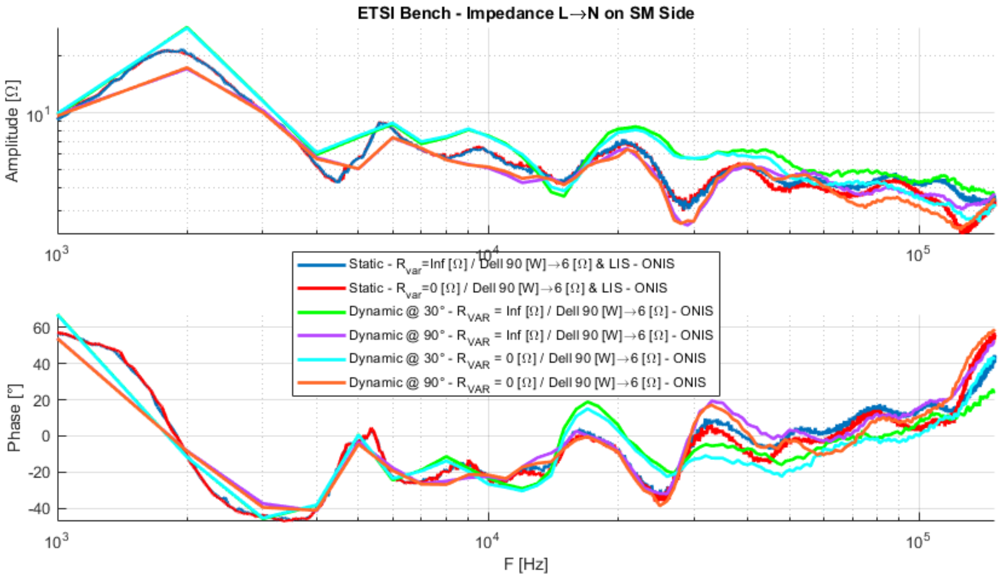


Figure 69: FTdGI measurement result at 90

12 Communication

Following the sanitary crisis, few conferences were able to maintain their original program this year. In fact many conferences and events were replaced by webinars or on-line workshops. Initially, our institute with its competence in the field of power grid quality, was invited to present an update on PLC deployment and reminding technical challenges at the bi-annual VSE conference on power grid quality 'Versorgungsqualität Tagung' in Brunnen in November 2020. The event is postponed to 2021. Two other very events gave us the opportunity to present the activities and results of Z-NET this Year:

12.1 ERIGRID Final Conference, April 1st 2020:

Presentation 'Impact of Time variant Grid Impedance on Power Line Communication System'
Session "Facilitating Effective Laboratory Testing by Lab Users"

The ERIGRID Z-NET measuring campaign realized together with UPV TSR Group and Schaffner at TECNALIA facilities in Bilbao (Fall 2019) was selected among 5 to represent the European ERIGRID research program supporting access to European Smart Grid Testing Infrastructure.
https://erigrid.eu/dissemination/

12.2 Interessenverband Netzimpedanz Conference, 29.10.2020

Presentation 'Pre-normalisation of grid impedance measurement in the power line communication frequency band'. The founders of the recently created Interessenverbandes Netzimpedanz about Grid Impedance invited us to present the Z-NET project activities and results. Emphasis was put on the specification and realization of the impedance standards (WP1 to WP3) and on the first results of the intercomparison (WP4). The event gave us a great opportunity to increase our visibility and for networking.

A summary of the final results of the Z-NET project were presented at the occasion of the 3rd NI Interssenverband Conference, 2nd of November 2021. The link to the presentations is not available at the time of the finalization of this report.

https://www.netzimpedanz.com/presentations

12.3 VSE Veranstaltung: Leistungsqualität Tagung 2021

A Questionnaire about evolution of PLC for smart metering addressed to the Swiss DSOsIn order to assess the current status of the deployment and acceptance of the Power Line Communication technology for Smart Metering Applications, an online questionnaire was prepared for this purpose in the frame of the SFOE funded project OptiQ in collaboration with BFE in Biel. Only few questionnaires were returned by the end of the OptiQ project. It was therefore decided to pursue the initiated effort in the frame of Z-NET project. More than 15 DSOs have responded at this date which represents already an interesting portion of the Swiss electricity distribution. The results will be presented at the occasion of the next Versorgungsqualität Tagung organised by the Verband Schweizerischer Elektrizitätsunternehmen VSE during the Fall 2021.

Figure 70: On-line questionnaire for PLC deployment and acceptance

13 Publications

The following conference papers and journal articles were published in collaboration with the Z-NET project partners:

I. Fernández, D. de la Vega, D. Roggo, R. Stiegler, L. Capponi, I. Angulo, J. Meyer, A. Arrinda, 'Comparison of Measurement Methods of LV Grid Access Impedance in the Frequency Range Assigned to Nb-Plc Technologies', MDPI, Journal of Electronics, October 2019

L. Capponi, I. Fernández, D. Roggo, I. Angulo, A. Arrinda, D. de la Vega,' Comparison of Measurement Methods of Grid Impedance for Narrow Band-PLC up to 500 kHz', AMPS conf. 2018

D. Roggo, J. Braun, J. Meyer, D. de la Vega, B. Evequoz, C. Blaser, R. Stiegler, I. Fernandez, 'Pre-normalization of grid impedance measurement in the power line communication frequency band' CIRED 2021 Conference, Paper No 1150

14 Perspectives and conclusions

In the scope of WP1, METAS designed, constructed, and characterized a static line impedance reference, which was used to compare all partners' grid measurement devices. This reference raised an interest in another project focused on the measurement of supra harmonics on the grid: the EURAMET project ‘supraEMI’. The reference is now used at NPL where additional characteristics are measured to allow further intercomparisons.

In WP2 and WP3, METAS designed, constructed, and characterized a programmable and time-dependent impedance reference. Just like the static impedance, this reference device was sent to and measured by the different project partners owning a grid measurement equipment. As this reference is significantly more complex than the static one, some stability issues were discovered on the prototype when measuring it with different excitation currents. At least some parts of the reference leading to the stability issues were identified and could relatively easily be corrected in a possible future iteration of the prototype. For the moment, however, the device is being evaluated to be used as a programmable load in the scope of the supraEMI but no further modification or improvement is foreseen in a near future.

The comparison of equipment’s dedicated to on-line measurement of Frequency dependent Grid Impedance, realized in several laboratories in the frame of WP4, has brought considerable and valuable information about capability, functionalities, and performance of the different measuring methods. The comparison of measurement with the Static Line Reference has brought very positive results. The uncertainty applying to the measured samples developed in the framework of the project and measuring conditions are not assessed and a quantitative statement about the accuracy of measurements results cannot be done. But results in both Magnitude and Phase presented in chapter 8.3 prove consistent on a wide frequency range. A comparative measurement of FdGI realized together with CBM partner at a MV/LV transformer station with three different equipment’s produced very similar results as well.

A comparison between different equipment’s and methods for the measurement of time variable frequency dependent grid impedance (FTdGI) was only possible with a limited number of equipment’s and scenarios. Despite the availability of the programmable line reference impedance developed in the frame of the WP3, producing similar test conditions in different laboratories proved very challenging. Harmonized data treatment and results presentation would facilitate the comparison of performances.

Uncertainty assessment for the Static Line Reference Impedance (SLRI) in function of working conditions (i.e., variable ambient temperature) could be realized in the framework of the SupraEMI or another future project. A similar evaluation of the Programmable Line Reference Impedance (PLRI) seems much more challenging and is not planned at this time.

On the basis of the gained experience and results, recommendations about FdGI measuring methods for the industrial partners and standardization committees are presented in Chapter 9.1 (WP5). Proposals and recommendations for the definition and the application of frequency and time dependent grid impedance in future standards are at the disposal of standardization committees. (WP6).

An industrial product aiming at actively stabilizing the grid impedance and reducing the possible negative impact of EMC filter on performances of Power Line Communication systems was developed by SCHAFFNER, one of the Z-NET project partners. A successful evaluation of the first LIS prototypes in two different Smart Meters communication testbeds represented a valuable contribution for all the project partners.

Several publications present the developments and the main outcomes of the Z-NET project. Several project partners took the opportunity to present and communicate about the project activities and results in presential or on-line conferences.

Further efforts in research and industrial developments in the domain of Frequency and time dependent grid impedance measurement are necessary. The impact of FTdGI on performance of Power Line Communication systems dedicated to smart energy metering justifies partly this effort. Measurements on a smart metering site deployed at SIG in Geneva, where the performance of the power line communication increases during working hours is a good example for this.

Today, Narrow Band PLC systems working in the frequency range between 30 and 150 kHz are widely deployed. Energy distribution systems operators and smart metering industrial actors are actively looking for an extension of the frequency range or even moving to the Broad Band PLC in the MHz range. Another application of FdGI measurement is to evaluate the role of grid impedance on propagation of non-intentional emissions generated by switched mode power supplies and the many other equipment interfaced to the grid with power electronics converters: energy saving lighting devices, household appliances, renewable energy production plants, climatization, just to name a few of them. The concept of frequency dependent grid or spectral line impedance was cited a countless number of times during the Power Quality & EMC sessions at the last CIRED conference in September 2021. Finally, the influence of grid impedance on stability of converters controllers in the frequency range of harmonics (0 to 2 kHz) needs further consideration and measurements as well.

Despite all the possible applications, a very few industrial companies are developing, producing, or commercializing equipment dedicated to field measurement of grid or line impedance. According to our experience, an equipment that covers all mentioned applications and required frequency ranges is still difficult to find. The few industrial actors and research institutions active in this domain would greatly benefit of harmonized FdGI definition or of tools and calibration methods for their developments. This statement also applies more generally to the industrial companies active in Power Quality and EMC.

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