Received May 27, 2019, accepted June 16, 2019, date of publication June 21, 2019, date of current version July 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2924253

Field Trials for the Empirical Characterization of the Low Voltage Grid Access Impedance From 35 kHz to 500 kHz

IGOR FERNÁNDEZ[1], AMAIA ARRINDA[1], ITZIAR ANGULO[1], (Member, IEEE), DAVID DE LA VEGA[1], NOELIA URIBE-PÉREZ[2], AND ASIER LLANO[3], (Member, IEEE)

[1]Bilbao Engineering College, University of the Basque Country (UPV/EHU), Bilbao ES-48013, Spain
[2]TECNALIA Research & Innovation—Digital Labs, Derio ES-48160, Spain
[3]ZIV Automation, Derio ES-48170, Spain

Corresponding author: David de la Vega (david.delavega@ehu.eus)

This work was financially supported in part by the Basque Government under the grants IT1234-19 and KK-2018/00037 and the Spanish Government under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER-UE).

ABSTRACT The access impedance of low-voltage (LV) power networks is a major factor related to the performance of the narrow-band power line communications (NB-PLCs) and, in a wider sense, to electromagnetic compatibility (EMC) performance. Up to date, there is still a lack of knowledge about the frequency-dependent access impedance for frequencies above 9 kHz and up to 500 kHz, which is the band where the NB-PLC operates. The access impedance affects the transmission of the NB-PLC signal, and it determines the propagation of the non-intentional emissions that may disturb other electrical devices, including malfunctioning or reduced lifetime of equipment. This paper presents the results of field measurements of the LV access impedance up to 500 kHz in different scenarios, with measurement locations close to end users and near transformers. The results provide useful information to analyze the characteristics of the LV access impedance, including variation with frequency, ranges of values for different frequency bands, and analysis of specific phenomena. Moreover, the results reveal a diverse frequency-dependent behavior of the access impedance in different scenarios, depending on the grid topology, the number of end users (that is, number and type of connected loads), and the type of transformation center. Overall, the results of this paper offer a better understanding of the transmission of NB-PLC signals and EMC-related phenomena.

INDEX TERMS Impedance measurement, measurement techniques, electric variables measurement, transmission line measurements, communication channels, communication networks, electromagnetic compatibility and interference.

I. INTRODUCTION

In the frequency range below 9 kHz, it is well known that the access impedance of LV networks is a major factor for setting Electromagnetic Compatibility (EMC) requirements. Accordingly, reference values for the network impedance are given in IEC/TR 60725 [1] for fundamental frequency and in the appendix to IEC 61000-4-7 [2], [3] for frequencies between 2 kHz and 9 kHz.

By contrast, there is still limited knowledge about the access impedance and load impedances of LV grids for frequencies above 9 kHz. However, there are many EMC aspects where the frequency-dependent grid impedance may have an impact. First, the impedance in the supply network affects the propagation of non-intentional emissions in this frequency band and, therefore, the possibly disturbing effects of these emissions to other electrical devices, including malfunctioning or reduced lifetime of equipment [3]–[5]. Second, impedance is a key aspect for Narrow Band Power Line Communications NB PLC, on CENELEC A band (3 kHz to 95 kHz for energy providers) currently used in Europe, ARIB band (155 kHz to 403 kHz) in Japan and on FCC (155 kHz to 487 kHz) for the United States and the rest of the world. For example, end-user equipment may represent a low-impedance path at frequencies used for NB PLC, resulting in attenuation of the intentional signal, which might

The associate editor coordinating the review of this manuscript and approving it for publication was Andrea M. Tonello.

disturb or interrupt communication [3]. In addition to this, the proper design of power frontends of the NB-PLC equipment requires an estimation of the impedances to be expected on the LV grid for this frequency band, in order to avoid impedance mismatching effects [6], [7].

Therefore, it is important to investigate about typical impedance values for this frequency range. Since the access impedance value depends on the grid topology, type of cable and the connected loads, extensive field trials in different scenarios are needed, in order to be able to perform a statistical approach for finding typical impedance values [1], [3].

Some previous measurements have been reported in the literature. The measurements included in [6] are performed in laboratory installations. In [7], there are some examples of measurements on three-phase low-voltage distribution grids, where the measurement equipment was connected as close as possible to the house connection box. In [8], some measurements in a typical urban residential area with underground power cable are analyzed. Additionally, [9] and [10] show some more examples of impedances of connected devices and access impedance in indoor scenarios.

The results included in this paper provide further insight into this topic, with an empirical analysis based on field measurements of LV access impedance values. In Section II, the field trials, including measurement locations and methodology, are described. In Section III, results are presented and analyzed according to the characteristics of the measurement scenarios. Finally, Section IV gathers the main conclusions of the work.

II. OBJECTIVES

The main goal of this study is the analysis of empirical values of the access impedance of the LV electrical grid. For this purpose, a measurement campaign in representative scenarios of the grid topology was scheduled in coordination with the DSO Iberdrola.

The analysis methodology developed for this project was based, first, on the definition and implementation of an accurate and validated measurement system, then, on the use of ad-hoc software for the data processing of the registered data, and last, on the thorough analysis of the field results, considering the particularities of the grid topology and the measurement areas. The measurements and the data processing were adjusted to obtain values of the grid impedance up to 500 kHz, in order to characterize in detail the frequency-dependent behavior of the access impedance in different scenarios.

III. METHODOLOGY

The study described in this paper is based on the analysis of a set of grid impedance measurements in rural (overhead cable) and urban (underground cable) scenarios, with locations close to end users but also near transformers. This section describes the analysis methodology of the recording and processing of the data registered in the measurements.

A. MEASUREMENT METHODOLOGY

The measurement method used in the field trials has been developed by the TSR Group of the University of the Basque Country (UPV/EHU), specifically for the characterization of the impedance of the LV electrical grid in the frequency range up to 500 kHz. This measurement method has been tested in the laboratory [11] and presented in CENELEC SC 205A Working Group 11 [12].

As these trials were planned in coordination with Iberdrola, the measurement methodology was adjusted to the frequency range of the NB-PLC technologies used by this DSO for Smart Metering services in the LV distribution network: 35 kHz - 500 kHz, for PRIME 1.3.6 [13] and PRIME 1.4 [14] transmission technologies.

The method is composed by, first, the recording of voltage and current values in a specific point of the grid, and second, the signal processing of the recorded values, in order to assess the frequency response of the grid impedance [11], [12]. The measurement system injects ad-hoc test signals into the grid, and then, it acquires the voltage and current values synchronously (see Figure 1). The ratio between voltage and current values for each particular frequency bin provides the variation of the amplitude and phase of the grid impedance, and the post-processing of the registered data provides the spectral characterization of the impedance for the whole frequency range, from 35 kHz to 500 kHz.

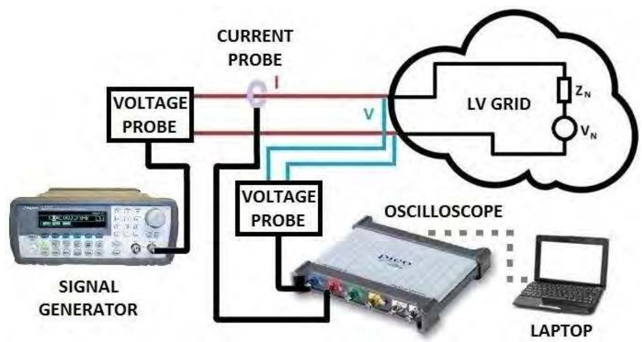


FIGURE 1. Measurement system for the characterization of the grid impedance.

The system is prepared to inject two types of ad-hoc signals into the grid: a single frequency sweep or NB-PLC signals. In the first case, the level of the transmitted signal, the sweep time and the frequency range are configurable by the user in the signal generator; in the second option, the signal level and the frequency channel can be selected by the user. In both cases, the injected signal level should be at least 10 dB higher than the level of the noise present in the grid. The sweep signal allows the measurement for the whole frequency range, while the use of NB-PLC signals provides results only for the frequencies of the NB-PLC channels.

For synchronous measurement of voltage and current, a high-resolution oscilloscope (Picoscope series 5000) digitizes the acquired signals at a high sampling rate. In particular, the sampling frequency used in these measurements is 3.9 Msample/s with a resolution of 15 bits/channel. The measurements were then decimated to 1.95 Msample/sec to alleviate the data processing; this sampling frequency is high enough to avoid aliasing effects.

The decoupling of the generated signal from the LV grid is carried out by a commercial capacitive probe and a current probe (see Figure 1). The voltage probe must reject signals below 2 kHz (mainly 50/60 Hz component and low order harmonics), in order to protect the measuring equipment, but also reject signals above 500 kHz to avoid coupling of radio signals and aliasing effects. The fundamental and the low order harmonics are filtered out by the voltage probe with an attenuation greater than 107 dB. This suppression of high amplitude signals significantly increases the resolution of the system, since the amplitude resolution is completely adapted to the voltage range used to measure the grid impedance, which is considerably lower than the voltage level of the fundamental. The frequency response of the coupler in the frequency band of interest should be as flat as possible for the wide range of typical expected grid impedance values (from 1 Ω to 50 Ω) [3].

In order to couple the generated signal into the grid, a capacitive probe has been specifically designed for this system. This coupler does not modify the characteristics of the generated signal, and it protects the signal generator against overvoltages caused by fast transient disturbances.

B. DATA PROCESSING

The processing of the recorded signals is the core of the assessment procedure of this method. It is based on three main steps: signal windowing, Fourier analysis and impedance assessment.

Once the voltage and current values generated by the injected signal have been recorded, the software applies a sliding windowing in time domain to these recordings. Then, Fourier analysis is applied separately to each set of (V, I) samples, in order to obtain spectral characterization. The Fourier analysis does not take into account the frequency bins below 35 kHz, and therefore, the attenuated component at 50 Hz is not considered in the data processing. Last, the impedance is calculated by dividing the voltage and current values of all the frequency bins.

One of the main strengths of the method is that different resolutions in time and frequency domains are possible, simply modifying the configuration of the signal processing of the recorded measurements [11], [12]. The frequency resolution depends on several parameters of the assessment procedure: the time duration of the acquisition of voltage and current signals, the length of the sliding window and the configuration of the FFT; the time resolution is related to the sweep time of the injected signal. As all these parameters are configurable by the user, both frequency and time resolutions can be determined by the configuration of the measurement system and adapted to different approaches. A typical configuration is composed of an injected sweep time of 1 s length, a sliding windowing of 20 ms/5 ms and the use of a FFT to each subset of 20 ms, which provides a resolution of 50 Hz in frequency. Better resolutions can be obtained with different configurations of the system, up to 5 Hz in frequency.

The resolution in amplitude is determined by the specific configuration used in the measurements. Considering that the sampling resolution of the oscilloscope is 15 bits/sample and the quantization error depends on the dynamic range used in the measurement configuration, the maximum error in the amplitude resolution is 0.61 mV. Since the dynamic range used in the field trials was always between 2 and 20 times lower than the maximum, the error in amplitude resolution is much lower than 0.61 mV in all cases.

For the sake of accuracy, only the V and I levels with a margin of 10 dB above the noise level are considered in the calculation. For that, the noise levels in the frequencies where there is no presence of the injected signal sweep are calculated and compared to the (V,I) levels. Moreover, the current probe and the equipment for voltage measurement (including connecting cables, voltage probe and oscilloscope) were carefully characterized and measured values are applied for calibration in the post-processing software [11].

The ad-hoc software provides the instantaneous values of the frequency response of both amplitude and phase of the grid impedance.

IV. PLANNING OF THE EMPIRICAL TRIALS

A. MEASUREMENT SCENARIOS

Four representative scenarios of the LV distribution grid in the Basque Country (Spain) were selected for the field trials. All the selected scenarios include a transformer substation and the corresponding downstream last-mile distribution grid to the homes. In particular:

- Two urban areas composed of building blocks of 4-6 floors and underground grid distribution.
- Two rural areas with very low density of detached houses and aerial grid distribution.

In the urban areas selected for the analysis, the distribution grids include a high number of short tri-phasic branches, providing service to a high number of homes in a limited area. Therefore, the density of the users' loads is high and they are located at short distances from the transformer station, in a grid topology composed of a high number of short cable sections (see Figures 2 and 3).

On the contrary, in the rural areas, the distribution grids under analysis are composed of a low number of branches, connecting a reduced number of detached houses, separated several tens of meters, with separately distributed phases in different branches. Therefore, the cable sections between houses are mono-phasic, long and aerial (see Figures 4 and 5).

B. MEASUREMENT CAMPAIGN

The measurement campaign was developed with the collaboration of authorized staff, who was in charge of connecting the measurement system to the selected points in the LV distribution grid. Measurement points were located both at the

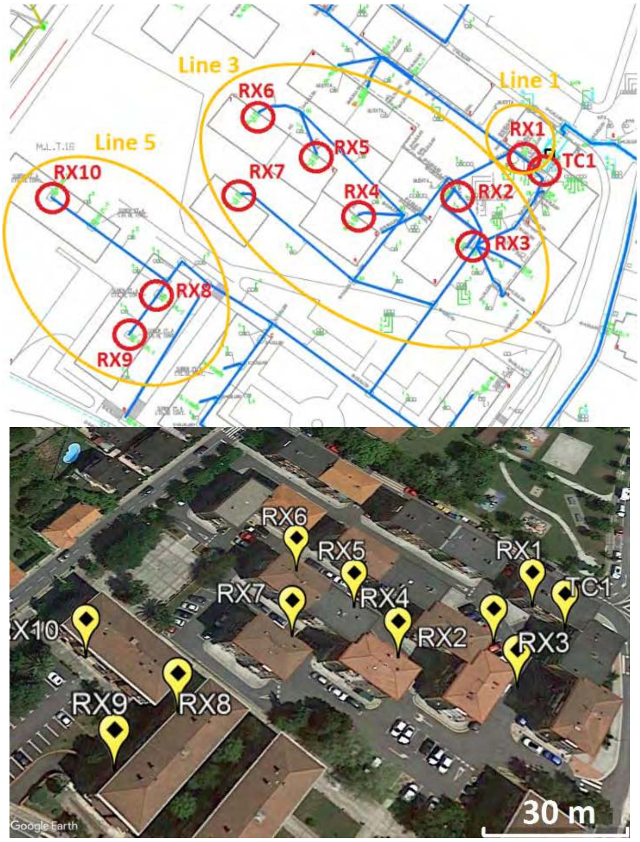


FIGURE 2. Measurement locations in scenario Urban-1: Top, scheme of the distribution grid; bottom, aerial view.

FIGURE 3. Measurement locations in scenario Urban-2: Left, scheme of the distribution grid; right, aerial view.

transformer stations (labeled as TC in Figures 2 to 5) and at a set of access points within the distribution grid between the substations and the homes (labeled as Rx in Figures 2 to 5). The only exception was the scenario Rural-2, where the TC was not accessible to connect the measurement equipment, and it was no possible to measure the access impedance at

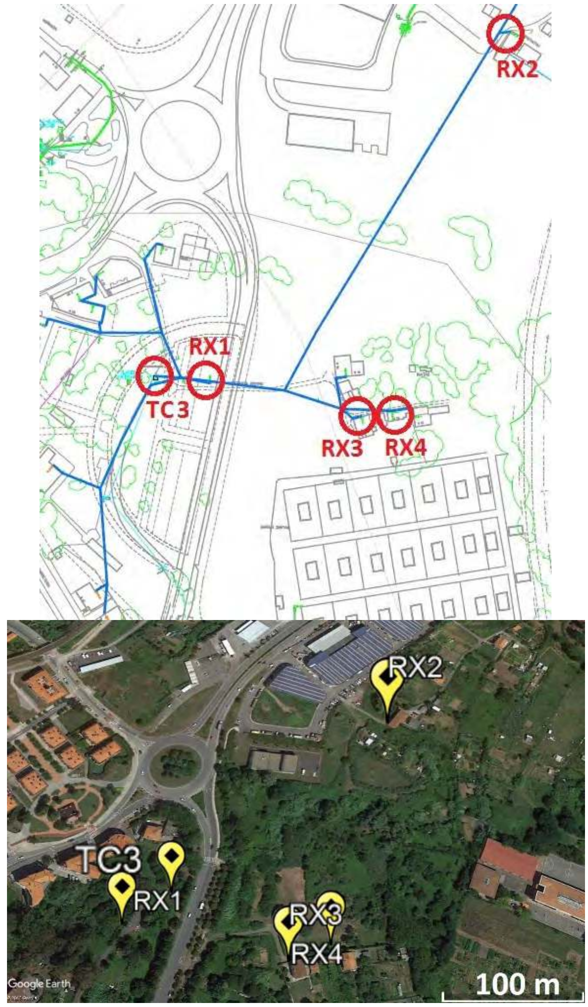


FIGURE 4. Measurement locations in scenario Rural-1: Top, scheme of the distribution grid; bottom, aerial view.

this point. In all the measurement locations within tri-phasic grid distribution, the impedance for each of the three phases was measured.

As the recording of each measurement requires only a few seconds, several measurements were registered at each phase of each measurement point, in order to evaluate the short time-variability of the grid impedance.

V. RESULTS AND ANALYSIS

A. IMPEDANCE AT THE TRANSFORMER STATION

The frequency response of the access impedance at the transformer substation of urban (Urban-1/TC1, Urban-2/TC2) and rural (Rural-1/TC3) scenarios are shown in Figure 6. The registered values are lower than 20 Ω for the whole frequency range.

In general, results of the impedance amplitude show a linear increasing tendency with frequency f due to the inductive nature of the electrical lines. Therefore, the impedance of the power line depends on the inductance of the cable L and the length of the cable according to $j\omega L$, with $\omega = 2\pi f$.

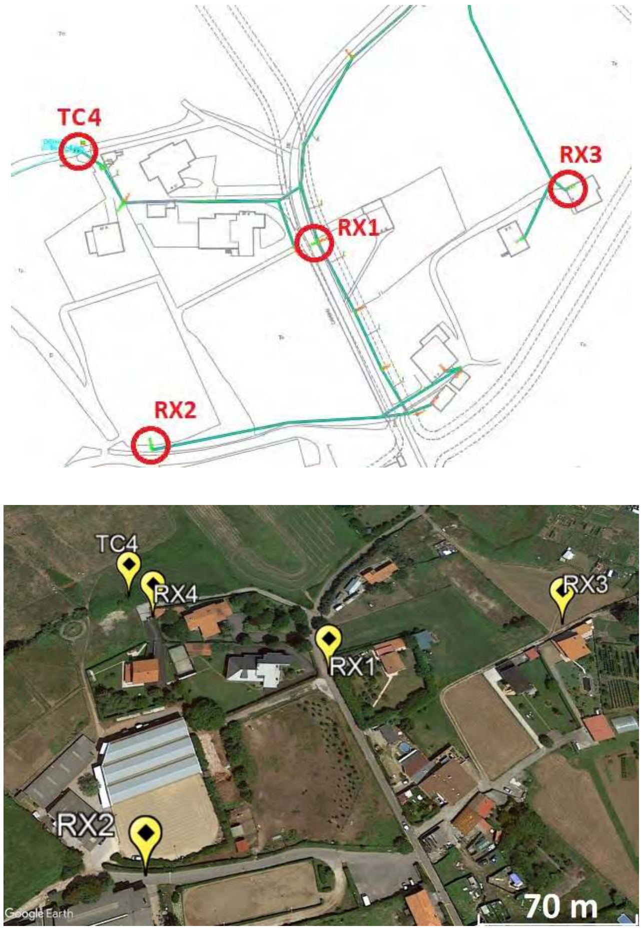


FIGURE 5. Measurement points in scenario Rural-2: Top, scheme of the distribution grid; bottom, aerial view.

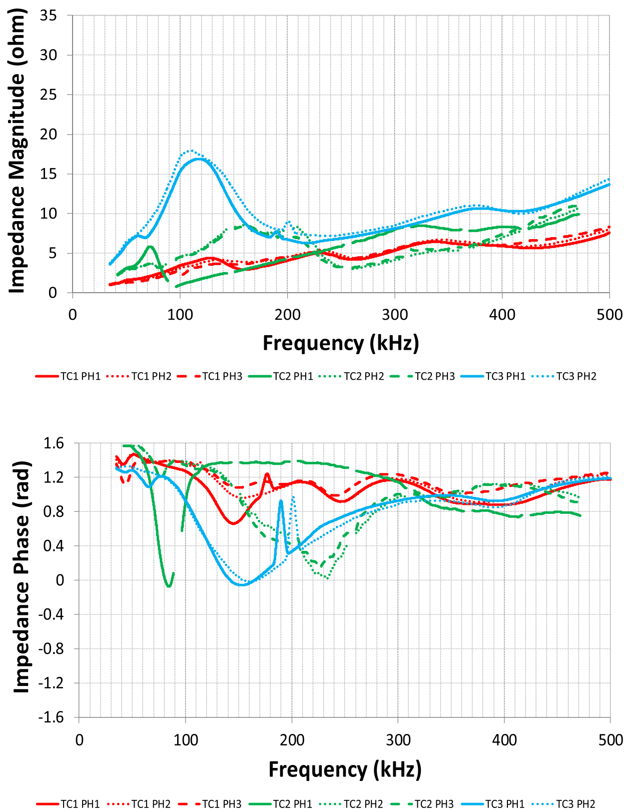


FIGURE 6. Results of access impedance in the transformer substations of scenarios Urban-1 (TC1) Urban-2 (TC2) and Rural-1 (TC3).

Apart from this linear trend, no significant variations with frequency are shown, except for Rural-1 (TC3), where a local maximum at 110 kHz shows values above 15 Ω. According to this inductive behavior, the phase of the impedance is close to 90° (1.57 rad) for most of the frequency range.

However, some significant changes at specific frequencies that reduce the inductive behavior are also observed.

In [15], the authors describe and summarize the results of impedance measurements of several converter and nonconverter transformers as a function of frequency. From measured impedance, it can be concluded that the profiles of the impedance change both in terms of magnitude and phase angle as a function of frequency. Each profile shows the presence of resonant frequencies that alter the linear tendency of the impedance, but all of them show an increasing tendency with frequency; the amplitude and frequencies of these resonant frequencies depend on transformer design features and on terminal conditions. The increasing tendency is also observed in the measurements developed in [16], with maximum magnitude values between 5 and 10 Ω for transformers located in residential and rural areas. Moreover, [8] and [17] describe measurements in transformers that show that the impedance is mainly inductive and resistive. According to the conclusions of the above-mentioned references, the results shown in Fig. 6 seem to be influenced by different types of transformers for each location, as well as different number, type and distance to connected loads.

The curves of the three electrical phases of each measurement location match quite well in amplitude for Urban-1 (TC1) and Rural-1 (TC3), which implies similar overall behavior for all the frequencies up to 500 kHz. On the contrary, some variations are observed in Urban-2 (TC2), both in impedance amplitude and phase of PH1, with respect to PH2 and PH3. It should be noted that the absolute values depend on the number of outgoing feeders, due to the fact that each feeder represents a parallel connection to the access point and therefore decreases the resulting impedance [17].

B. URBAN ENVIRONMENT

The access impedance values at the measurement locations along the distribution grid between the TC and the end users in the scenario Urban-1 are shown in Figure 7. The curves in the figure show clear differences between electrical phases at the same measurement point.

Moreover, two different behaviors can be observed. For frequencies up to approximately 250 kHz, some variability

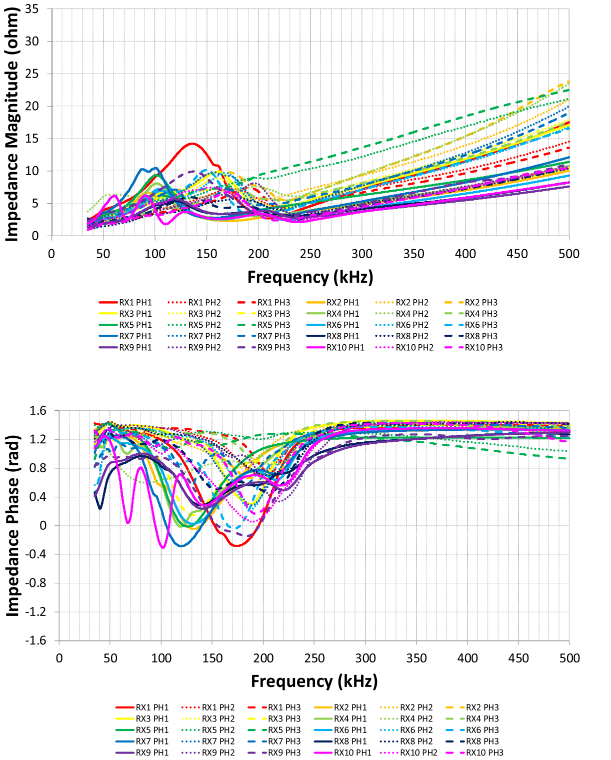


FIGURE 7. **Results of access impedance in the measurement points at the distribution grid of Urban-1: Up, impedance amplitude; bottom, impedance phase.**

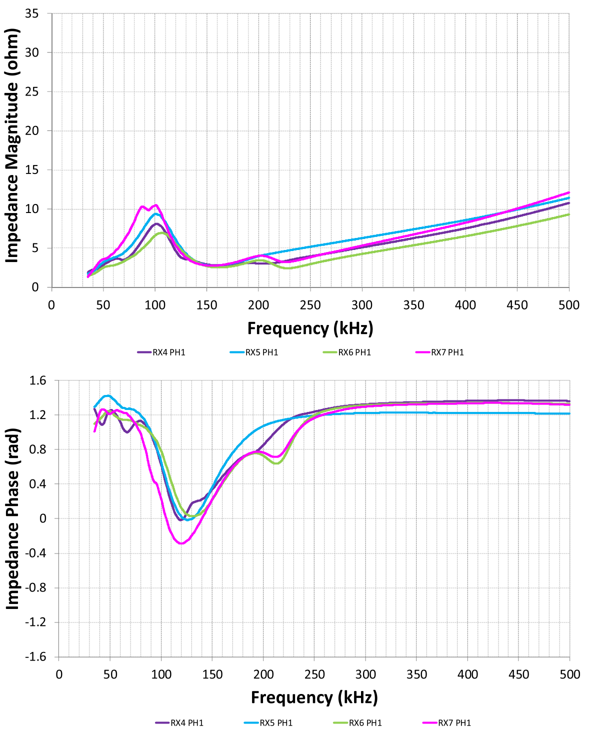


FIGURE 8. **Access impedance at one of the phases for a set of measurement points separated by a short distance, in Urban-1.**

both in amplitude and in phase is present at all the measurement points. In this frequency range, the total impedance seem from a certain point of the distribution

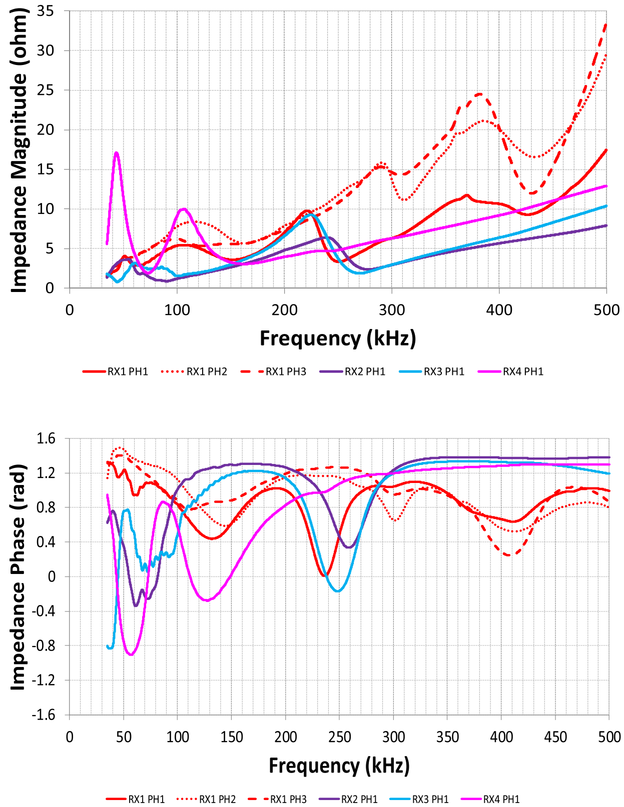


FIGURE 9. **Access impedance in the distribution grid of Rural-1: Up, impedance amplitude; bottom, impedance phase.**

grid strongly depends on the loads connected to the grid. It should be mentioned that many household devices have an EMC filter with a capacitor connected between phase and neutral, which results in low impedances at high frequencies [19].

The variability at lower frequencies is shaped as local maxima of impedance amplitudes and impedance phases close to 0° (resistive behavior), at specific frequencies. These specific frequencies differ at each measurement point, although they may be present in the same phase for measurement points separated a short distance (see Figure 8).

By contrast, for frequencies from approximately 250 kHz to 500 kHz, a clear inductive tendency is shown, this is, a linear increasing tendency with frequency in amplitude and phase values close to 90° (1.57 rad). The inductive behavior of the impedance and its tendency to increase with frequency is supported by the conclusions in [18]. This seems to be caused by the prevalence of the inductive frequency response of the lines in the overall response of the grid for this frequency range.

These observations match the conclusions obtained in [8] and the measurements in close vicinity to a hospital and a shopping center included in [18]. It should also be noted that the impedance amplitudes are higher than those recorded in the transformer station (up to 15 Ohm below 150 kHz and up to 25 Ohm above 150 kHz).

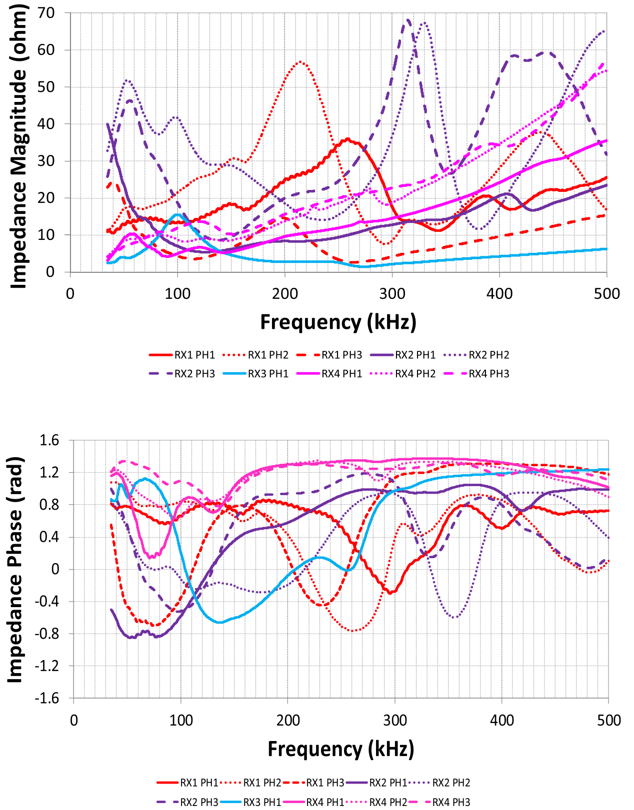


FIGURE 10. **Access impedance in the distribution grid of Rural-2: Up, impedance amplitude; bottom, impedance phase (notice that the vertical scale of the impedance magnitude is considerably larger than in the rest of the figures).**

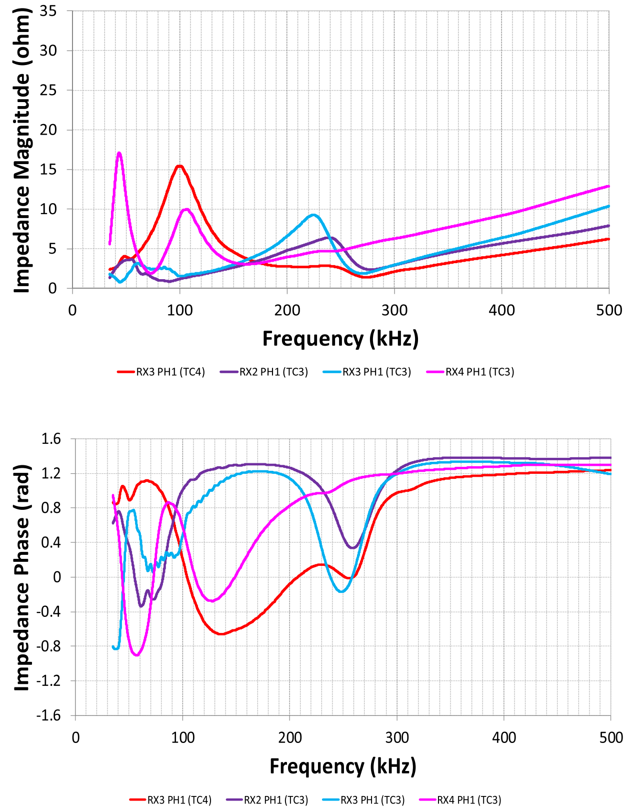


FIGURE 11. **Access impedance at Rural-1 and Rural-2 areas, located near a home: Up, impedance amplitude; bottom, impedance phase.**

C. RURAL ENVIRONMENT

The results for the measurement locations located at the rural distribution areas are shown in Figure 9, for Rural-1, and Figure 10, for Rural-2.

Although the results obtained in rural environment do not follow a common pattern, they can be grouped into two types of observations. All the measurement points located nearer the end users (for Rural-1: RX2, RX3, RX4; for Rural-2: RX3) show more similar results to those obtained in urban areas. This is, amplitudes between 1 Ohm and 10 Ohm for most of the cases, and lower than 20 Ohm in any case, and a clear inductive behavior for frequencies above 250 kHz. As in the urban scenarios, local maxima of impedance amplitude arise for specific frequencies, with values lower than 20 Ohm.

These results are in line with conclusions in [7], where, in rural scenarios, the impedance is usually low and irregular, as it strongly depends on connected devices. By contrast, in urban scenarios with bigger buildings, the general behavior is more regular.

On the contrary, measurement points located at a certain distance of any home show considerably higher values of impedance [7], in particular, higher than 30 Ohm for a wide set of situations and frequencies, and up to 70 Ohm in some specific cases; moreover, no inductive behavior is observed for any frequency range. The variability with frequency of amplitude and phase values is significantly higher for all the frequency range. This variability is different for all the phases, therefore, the frequency response for different phases differs noticeably; this is due to the monophasic distribution of the grid in these areas, at least for some of the sections. This aspect can be clearly observed if the results of rural areas are grouped regarding the distance to a home (see Figures 11 and 12). Only measurement points at a certain distance from any home show greater amplitudes, higher variability and a behavior that does not follow an inductive trend with frequency.

The reason of this different behavior may be based on the type of impedances of cable sections (inductive behavior, increasing with frequency), homes (low impedance values) and other types of loads in the grid (non-inductive behavior). Moreover, the impedance of overhead line twisted cable, typical of rural areas, is considerably higher than the impedance of underground cables, most common in urban scenarios [20].

Hence, a measurement point located near a home will be highly influenced by a low impedance in parallel with the rest of the grid, which leads to low values and inductive behavior for higher frequencies. On the contrary, in measurement points located at a certain distance from end users, the effect of inductive (cable sections) and non-inductive (other loads

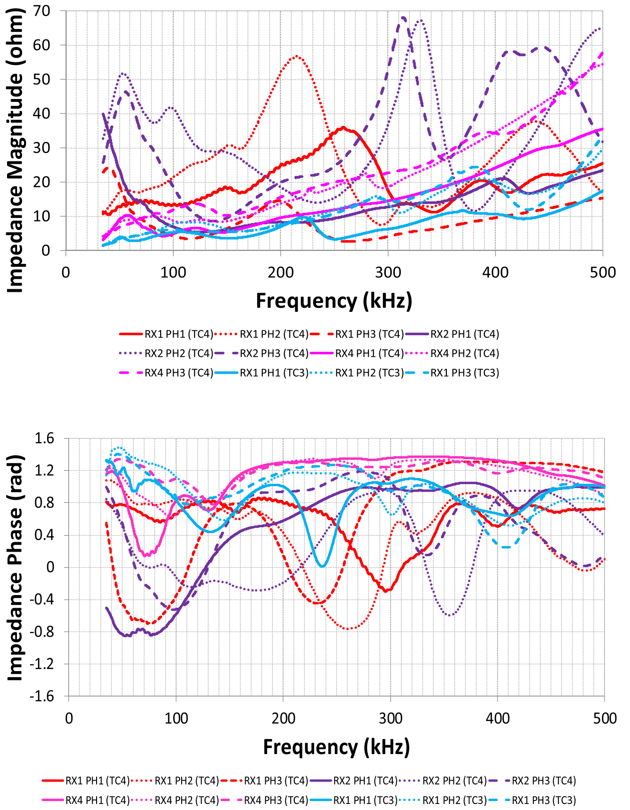


FIGURE 12. **Access impedance at Rural-1 and Rural-2 areas, at a certain distance from a home: Up, impedance amplitude; bottom, impedance phase (notice that the vertical scale of the impedance magnitude is considerably larger than in the rest of the figures).**

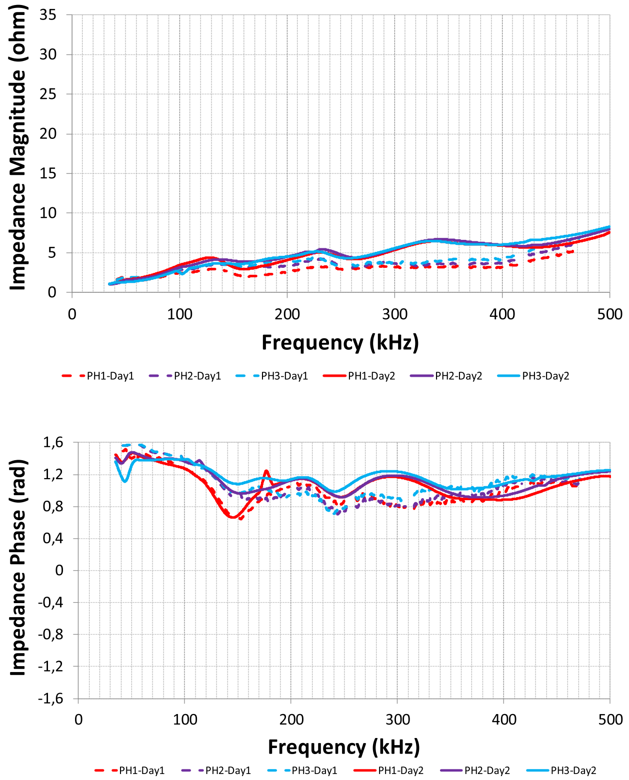


FIGURE 13. **Long-term time variability of the grid impedance, for measurements carried out in two different days, in the TC-1 (Urban-1).**

in the grid) elements leads to higher impedance amplitudes and a frequency response with increased variability.

D. TIME-VARIABILITY OF THE GRID IMPEDANCE

Impedance measurements were repeated in two separate days at TC-1 (Urban-1), in order to evaluate the long-term variation of the impedance, due to the connection and/or disconnection of the home loads. In this case, both types of injected signals were used (single-tone sweep and controlled NB-PLC transmission, as described in section III.A). Results in the frequency response show small variations in absolute values of the magnitude (if compared with the disparities between rural and urban scenarios), but they represent high relative variations (see Figure 13). This goes in line with the conclusions in [7], [8], and [21].

Variations within one mains cycle depend mainly on the nearby appliances, which are located further away from the measurement location in the case of block of flats, and therefore not observed in these measurements. Moreover, since the number of loads connected in parallel is larger, the relative contribution of one of the loads is less relevant in the measured overall access impedance at that specific point.

VI. CONCLUSIONS

A field measurement campaign has been developed in Spain, in order to evaluate the frequency response up to 500 kHz of the impedance of the electrical grid in different scenarios. Representative scenarios of rural and urban environments were selected, where the access impedance was characterized by using a measurement method tested in the laboratory [11] and presented in CENELEC [12]. This work contributes with on-field measurements, as demanded by several working groups from CENELEC and IEC.

According to the results obtained in these trials, the urban distribution may be considered as a particular scenario of short cable sections and numerous homes. In most of the potential interesting points for Smart Grids applications (near the users or near the transformer substations), the expected impedance values would be of low amplitude (lower than 25 Ohms at any frequency within the evaluated range) and inductive behavior for frequencies above 250 kHz.

The analysis of the results highlights the need of additional measurements, in order to have a statistically significant sample size of empirical data. In particular, two new aspects should be covered: first, measurements in different scenarios, including dense urban and industrial environments; second, measurements in the same location in different moments of time (hours of the day, day of the week, several days...) in order to perform a more complete and thorough analysis of the time variability of the access impedance.

ACKNOWLEDGMENT

The authors would like to thank Iberdrola for the availability and the collaboration of authorized staff for carrying out the field trials.

REFERENCES

[1] *Consideration of Reference Impedances and Public Supply Network Impedances for use in Determining Disturbance Characteristics of Electrical Equipment Having a Rated Current ≤75 a Per Phase*, Standard IEC/TR 60725, 2012.

[2] *Electromagnetic Compatibility (EMC)—Part 4-7: Testing and Measurement Techniques and Interharmonics Measurements*, Standard EN 61000-4-7, 2009.

[3] *Study report III. Electromagnetic Interference Between Electrical Equipment/Systems in the Frequency Range Below 150 kHz*, Standard SC205A/Sec0400/R, CENELEC, Oct. 2015.

[4] N. Uribe-Pérez, I. Angulo, L. Hernández, T. Arzuaga, D. de La Vega, and A. Arrinda, "Study of unwanted emissions in the CENELEC-a band generated by distributed energy resources and their influence over narrow band power line communications," *Energies*, vol. 9, no. 12, p. 1007, Nov. 2016

[5] I. Fernandez, N. Uribe-Pérez, I. Eizmendi, I. Angulo, D. de la Vega, A. Arrinda, and T. Arzuaga, "Characterization of non-intentional emissions from distributed energy resources up to 500 kHz: A case study in Spain," *Int. J. Elect. Power Energy Syst.*, vol. 105, pp. 549–563, Feb. 2019. doi: 10.1016/j.ijepes.2018.08.048.

[6] G. Hallak, C. Nieß, and G. Bumiller, "Accurate low access impedance measurements with separated load impedance measurements on the power-line network," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 10, pp. 2282–2293, Oct. 2018.

[7] M. Sigle, W. Liu, and K. D. Karlsruhe, "On the impedance of the low-voltage distribution grid at frequencies up to 500 kHz," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, Beijing, China, Mar. 2012, pp. 30–34.

[8] G. Chu, J. Li, and W. Liu, "Narrow band power line channel characteristics for low voltage access network in China," in *Proc. IEEE 17th Int. Symp. Power Line Commun. Appl.*, Mar. 2013, pp. 297–302.

[9] S. Zhu, C. J. Kikkert, and N. Ertugrul, "Software for control and calibration of an inductive shunt on-line impedance analyzer," in *Proc. IEEE Int. Symp. Power Line Commun. Appl. (ISPLC)*, Austin, TX, USA, Mar./Apr. 2015, pp. 53–58.

[10] C. J. Kikkert and S. Zhu, "Resistive shunt on-line impedance analyzer," in *Proc. Int. Symp. Power Line Commun. Appl. (ISPLC)*, Bottrop, Germany, Mar. 2016, pp. 150–155.

[11] L. Capponi, I. Fernández, D. Roggo, A. Arrinda, I. Angulo, and D. De la Vega, "Comparison of measurement methods of grid impedance for narrow band-PLC up to 500 kHz," in *Proc. IEEE 9th Int. Workshop Appl. Meas. Power Syst. (AMPS)*, Sep. 2018, pp. 1–6.

[12] I. Fernández, A. Arrinda, I. Angulo, M. Alberro, J. Montalbán, and D. de la Vega, "Measurement method for the characterization of the grid impedance of LV networks for the frequency range for NB-PLC up to 500 kHz," document SC205A_WG11_Conv0032c_RM.pdf, CENELEC SC205A WG11 6th Meeting, Oct. 2018

[13] PRIME Alliance Technical Working Group. *Draft Specification for PoweRline Intelligent Metering Evolution*. Accessed: Jul. 1, 2019. [Online]. Available: http://www.prime-alliance.org/wp-content/uploads/2013/04/PRIME-Spec_v1.3.6.pdf

[14] PRIME Alliance Technical Working Group. *Specification for PoweRline Intelligent Metering Evolution*. Accessed: Jul. 1, 2019. [Online]. Available: http://www.prime-alliance.org/wp-content/uploads/2014/10/PRIME-Spec_v1.4-20141031.pdf

[15] Y. Liu, S. A. Sebo, R. Caldecott, D. G. Kasten, and S. E. Wright, "Power transformer resonance-measurements and prediction," *IEEE Trans. Power Del.*, vol. 7, no. 1, pp. 245–253, Jan. 1992.

[16] E. Takmaz, "Impedance, attenuation and noise measurements for power line communication," in *Proc. 4th Int. Istanbul Smart Grid Congr. Fair (ICSG)*, Istanbul, Turkey, Apr. 2016, pp. 1–4.

[17] K. Dostert, M. Zimmermann, T. Waldeck, and M. Arzberger, "Fundamental properties of the low voltage power distribution grid used as a data channel," *Telecommun. Transmiss.*, vol. 11, no. 3, pp. 297–306, May/Jun. 2000.

[18] M. Wolkerstorfer, B. Schweighofer, H. Wegleiter, D. Statovci, H. Schwaiger, and W. Lackner, "Measurement and simulation framework for throughput evaluation of narrowband power line communication links in low-voltage grids," *J. Netw. Comput. Appl.*, vol. 59, pp. 285–300, Jan. 2016.

[19] S. K. Ronnberg, M. Wahlberg, M. H. J. Bollen, and C. M. Lundmark, "Equipment currents in the frequency range 9–95 kHz, measured in a realistic environment," in *Proc. 13th Int. Conf. Harmon. Quality Power*, Wollongong, NSW, Australia, Sep./Oct. 2008, pp. 1–8.

[20] M. A. O. Kharraz, P. Jensen, V. Audebert, A. Jeandin, C. Lavenu, D. Picard, and M. Serhir, "Experimental characterization of outdoor low voltage cables for narrowband power line communication," in *Proc. Int. Symp. Power Line Commun. Appl. (ISPLC)*, Bottrop, Germany, Mar. 2016, pp. 138–143.

[21] Ł. Chruszczyk, "Low-voltage grid impedance measurements in 10 kHz–1 MHz frequency range," in *Proc. IEEE 3rd Workshop Adv. Inf., Electron. Elect. Eng. (AIEEE)*, Riga, Latvia, Nov. 2015, pp. 1–6.

IGOR FERNÁNDEZ received the M.S. degree in telecommunications engineering from the University of the Basque Country, Spain, in 2001, and the Ph.D. degree in the characterization of signal and noise for digital radio mondiale (DRM) in the medium wave band in indoor environments, in 2011.

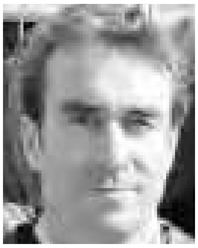
In 2003, he joined the TSR (Radiocommunications and Signal Processing) Research Group, Department of Communications Engineering, University of the Basque Country, where he is currently an Assistant Professor. His current research interests include new digital broadcasting technologies and power line communications (PLC).

AMAIA ARRINDA received the M.Sc. degree in telecommunications engineering from the University of the Basque Country (UPV/EHU), Spain, in 1993, and the Ph.D. degree. In 2001, she presented her doctoral thesis (Ph.D. degree) dealing with interferences between terrestrial analogue and digital TV transmissions. In 1993, she joined the Department of Electronics and Telecommunications, UPV/EHU, where she is currently an Associate Professor. She has stayed at ENST Bretagne and CNET, France, for one year, and the Wireless Networks and Communications Research Centre, Brunel University, U.K., for four months.

She has been involved in research projects related to measurements for several purposes (human exposure, digital broadcasting, radio noise, and so on) for more than 15 years. She is a coauthor of more than 25 papers in journals of the best third of the JCR Index and more than 40 contributions to international conferences. Her current research interests include digital broadcasting systems, and signal propagation, measurements, and simulations.

ITZIAR ANGULO (S'09–M'10) received the M.S. and Ph.D. degrees in telecommunications engineering from the Bilbao Engineering College, University of the Basque Country, Spain, in 2007 and 2013, respectively.

Since 2005, she has been a part of the TSR (Radiocommunications and Signal Processing) Research Group, University of the Basque Country, where she has been involved in several research projects in the digital terrestrial television and digital radio broadcasting area. After five years of Postdoctoral experience, she is currently an Associated Professor with the Department of Applied Mathematics, University of the Basque Country, and continues with the research activities within the TSR Group. She is also involved in the characterization of the electrical grid as a communication channel for PLC and the study of new data transmission techniques for smart metering, monitoring, and management of the future smart grids.



DAVID DE LA VEGA received the M.S. and Ph.D. degrees in telecommunication engineering, in 1996 and 2008, respectively.

Since 1998, he has been an Associate Professor with the Department of Communications Engineering, University of the Basque Country (UPV/EHU), Spain. He has been the Head Researcher of the Competitive Research Projects funded by European, National, and regional calls and by industries. The results of his work are published in 36 indexed papers, and part of them are included in the reports of regulatory and standardization bodies. His research interests include the analysis of the signal propagation and, mainly, the analysis of the effects of different types of interferences and disturbances on the quality of the data transmission. Within the area of smart grids, he researches on the characterization of the electrical grid as a propagation medium for data transmission and on the effects of noise and emissions on the smart grid communications.

NOELIA URIBE-PÉREZ received the B.S. degree in telecommunication engineering from the University of Cantabria, in 2009, the master's degree in energy renewable energy, fuel and hydrogen cells from the Spanish Scientific Research Council (CSIC) and Menéndez Pelayo International University (UIPM), in 2011, the master's degree in smart cities from the University of Girona (UdG), in 2015, and the Ph.D. degree in telecommunications engineering from the University of the Basque Country (UPV/EHU), in 2017.

From 2013 to 2017, she was a member of the Energy Department, CIEMAT, developing research work related to the management of electric micro-grids with renewable energies and storage systems. Since 2017, she has been a part of TECNALIA, where she further develops her career in topics related to the investigation of PLC communications protocols and their practical application in controlled environments. She is a coauthor of seven publications in international scientific journals, 13 articles in international congresses, and three in national congresses.

ASIER LLANO (M'11) was born in Bilbao, Spain, in 1980. He received the M.S. degree in telecommunications engineering and the M.S. degree in information technology on wireless networks from the University of the Basque Country (UPV/EHU), Bilbao, in 2003 and 2013, respectively.

He is currently an Research and Development Manager of the Metering Business Unit, ZIV Automation, Bilbao. He has been contributing to reshape the utilities of the future by creating the next generation of devices to support the advanced metering and e-mobility infrastructure. He is part-time working on this research thesis on power line communications. His professional experience is in the design and development of embedded devices for the industrial sector. His technical knowledge is in embedded software, industrial electronics, communications, and RF and signal processing. He is the author of more than 15 articles. His research interests include power line communications, smart grids, signal processing, and open standards evolution. He holds one patent.

Mr. Llano is an Active Member of PRIME TWG, G3-PLC Alliance, and Meters & More Alliance.