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Abstract: Voltage measurements in the frequency range from 10 kHz to 500 kHz are used to quantify the level of the Narrow Band Power Line Communication transmitted signals, the noise and the non-intentional conducted emissions generated by the devices connected to the Low Voltage grid. Considering that the voltage levels within this frequency range are very small if compared to measurements below 2 kHz, measuring equipment of higher precision is needed, but existing standards do not currently cover this frequency band. In this paper, a voltage adapter with improved performance at the 10 kHz–500 kHz frequency range for field measurements in LV networks is presented. Moreover, a measurement setup and methodology for the frequency-dependent characterization of this type of voltage adapters is described, which is used to demonstrate the outperformance of the designed probe with respect to four commercial devices.

Keywords: Frequency response; Low voltage networks; NarrowBand power line communications; Power system measurements; Voltage measurement; Voltage probes

A new voltage probe with improved performance at the 10 kHz – 500 kHz frequency range for field measurements in LV networks

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Abstract*— Voltage measurements in the frequency range from 10 kHz to 500 kHz are used to quantify the level of the Narrow Band Power Line Communication transmitted signals, the noise and the non-intentional conducted emissions generated by the devices connected to the Low Voltage grid. Considering that the voltage levels within this frequency range are very small if compared to measurements below 2 kHz, measuring equipment of higher precision is needed, but existing standards do not currently cover this frequency band. In this paper, a voltage adapter with improved performance at the 10 kHz – 500 kHz frequency range for field measurements in LV networks is presented. Moreover, a measurement setup and methodology for the frequency-dependent characterization of this type of voltage adapters is described, which is used to demonstrate the outperformance of the designed probe with respect to four commercial devices.

***Index Terms*— Frequency response, Low Voltage networks, NarrowBand Power Line Communications, Power system measurements, Voltage measurement, Voltage probes.**

I. INTRODUCTION

Traditionally, power quality studies have been focused on lower order harmonics (<2 kHz). Therefore, power electronics converters with active switching using Pulse Width Modulation (PWM) are designed to reduce non-intentional emissions below 2 kHz. In return, this is leading to higher emissions at PWM switching frequency and its multiples, in the RF range (>10 kHz) [1]. It is precisely within this frequency band (10 kHz to 500 kHz) where Narrow Band Power Line Communications (NB-PLC) are extensively used for Advanced Metering Infrastructure and other Smart Grid applications [2]. The interaction between high non-intentional emissions from end-user equipment and NB-PLC equipment might lead to communication problems. However, the given EMC problem due to emissions above 10 kHz is a broader issue, not focusing solely on the coexistence of general equipment with NB-PLC systems, but also featuring with effects like malfunction or loss of function of electronic devices, and hidden effects like ageing of electronic components and reduction of lifetime of equipment [3],[4]. Therefore, it is necessary to establish a new consistent framework for measurement and assessment of voltages and currents in the higher frequency range [5].

Measurements in this frequency band are challenging since noise levels are very small compared to common measurement values below 2 kHz, where harmonics of the fundamental are present. For measurements in the LV networks, special broadband voltage and current probes are available, but as presently the standard IEC 61000-4-30 does not cover this frequency band, there are no certified devices able to perform this type of measurements [5]-[7]. These commercial probes for the NB-PLC frequency range have been designed mainly for NB-PLC signal injection or communication testing (connecting a NB-PLC sniffer to the grid), but not for accurate voltage measurements in the field. For this reason, transducers with high accuracy for both amplitude and phase angle over a wide frequency range are needed, along with appropriate filters in order to avoid aliasing and leakage effects, and protection against high voltages for the sensitive measuring equipment [8]-[10].

Therefore, the work at this frequency range has just started and more research is needed to find suitable ways for quantifying emissions in this frequency range. Moreover, measurement campaigns are needed to provide information on existing levels of emissions in this frequency range, including the level of the NB-PLC signals, the conducted noise and the non-intentional emissions from the grid-connected devices [1].

In this context, this work presents the design and modelling of a voltage transducer with improved performance at the 10 kHz – 500 kHz frequency range for field measurements in LV networks. The better performance of this novel voltage adapter is demonstrated by characterizing its frequency-dependent behaviour for the above-mentioned frequency range and comparing these results with those obtained for four commercial voltage probes. To do so, a test measurement setup and a methodology for the frequency-dependent characterization were defined and implemented in this study.

The changing conditions of the LV network in real scenarios, this is, the varying impedance values of the electrical grid due to the different loads that are connected and disconnected over time, were also considered in this comparison. For that, the wide range of typical expected grid impedance values for this frequency band (from 1 Ω to 50 Ω) was considered in the comparison.

II. Relevant Issues on the Accuracy of Voltage Probes

A measurement campaign was developed by the authors in the distribution grid of their lab at the University, in order to evaluate the influence of the probes when measuring non-intentional emissions in the frequency band of interest. In the trials, the conducted emissions in the distribution grid were assessed, with the measurement system described in [11] and using the voltage probes evaluated in this work and described in Section III. Fig. 1 shows a representative example of the influence of the voltage probes in the field measurements for the frequency range 10 kHz – 500 kHz. Results of the registered measurements demonstrate that the amplitude of the samples differ in more than 10 dB for the whole frequency range, depending on the voltage adapter used in the measurement system, for most of the measurement points. This difference is strictly due to the voltage probe used for each signal recording, since several measurements were carried out successively in order to confirm that there was no significant time-variability in the measured emissions.

Ideally, characteristics of voltage probes for this frequency band should show high-pass filter behaviour to reject signals below 2 kHz (mainly 50/60 Hz component and low order harmonics, in order to both protect the measuring equipment and allow high resolution for the higher frequency band) and low-pass filter behaviour to reject signals above 500 kHz (radio signals that might be coupled by the connecting cables). In between, the frequency response should be as flat as possible.

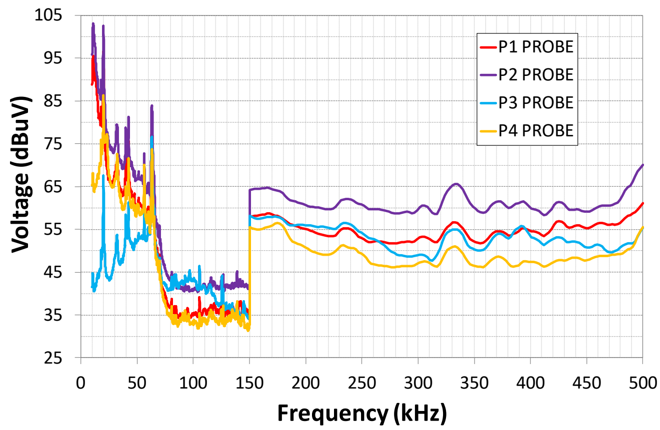

Fig. 1. Conducted emissions in the frequency range 10 kHz-500 kHz measured with different voltage probes in the same measurement location.

It should be also taken into account that the access impedance of the LV grid varies with frequency and time according to the network topology and the number and type of the grid-connected devices. Accordingly, the frequency-dependent access impedance varies between different points of the grid, and additionally, it varies with time at a specific location, depending on the devices connected at each moment [12]. Therefore, it is not possible to know in advance the impedance mismatching that a voltage adapter device will face, and the above-mentioned ideal flat response should apply for a wide range of typical expected grid impedance values (from 1 Ω to 50 Ω) [5],[13].

Some previous works present coupling devices for the frequency band of interest [10],[14],[15]. However, these works do not characterize the frequency response of the device for different access impedance values [10],[15] or show poor performance for low grid impedance values [14].

III. Measurement Setup and Methodology

Considering the above-mentioned issues (frequency range, typical grid impedance values and filter behaviour to reject fundamental and radio signals), a measurement setup and methodology were designed to analyse the voltage measurement accuracy as a function of a wide range of grid impedance values and for the whole frequency range 10 kHz - 500 kHz.

First, in order to emulate the voltage and access impedance of the grid for the frequency band of interest, both a signal generator, which provides a controlled voltage, and a set of known resistances (R_{test}), are used , as shown in Fig. 2. As the internal impedance of the signal generator (R_{gen}) has a constant value of 50 Ω [16], the varying impedance of the grid (R_{grid}) is emulated by adding a known resistance R_{test} in parallel to R_{gen}. This implies a Thevenin's equivalent circuit with equivalent voltage V_{grid} and equivalent impedance R_{grid} given by:

$$V_{grid} = \frac{R_{test}}{R_{gen} + R_{test}} \cdot V_{gen} \tag{1}$$

$$R_{grid} = \frac{R_{gen} \cdot R_{test}}{R_{gen} + R_{test}} \tag{2}$$

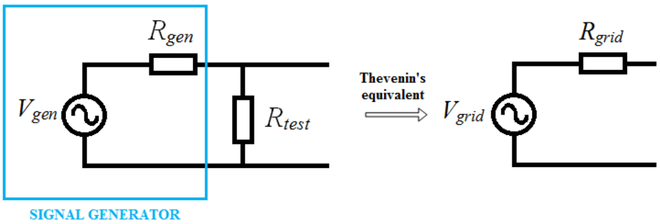

Fig. 2. Setup for emulating the voltage and access impedance of the grid for the frequency band of interest.

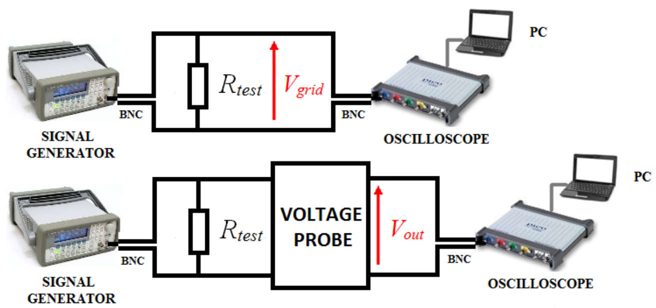

Fig. 3. Measurement setup for the characterization of the voltage probes. The accuracy of the probes is represented as the V_{out}/V_{grid} ratio.

A single-tone sweep is the best way to measure the frequency response of the voltage adapters. The frequency of the generated signal V_{gen} is stepwise increased and the step size changes adaptively along the whole frequency range [17].

A set of R_{test} values has been used in the measurements, in order to obtain six R_{grid} representative values within a range of typical grid impedance values (1.7 Ω, 11.8 Ω, 25 Ω, 33.3 Ω, 40 Ω, and 50 Ω) [5],[13]. This range of impedance values allows the analysis of the response of the voltage probes for different grid access impedance values, and therefore, for different levels of the impedance mismatching between the electrical grid and the voltage probe.

The characterization of the different voltage probes is represented as the ratio between the voltage measured at the probe output (V_{out}) and the reference voltage (V_{grid}), expressed in dB (see Fig. 3). In order to measure the voltages, a high-impedance oscilloscope is used to digitize signals with 16 bits sampling resolution, as shown in Fig. 3 [18]. Ideally, this ratio should be 0 dB for the whole frequency range and independently of the access impedance of the grid R_{grid}.

Additionally, the line side impedance of the voltage probes was determined by simultaneously measuring voltage and current, and then applying frequency domain processing of the captured signals. To do so, a signal sweep in the frequency band of interest was injected into the line side of each probe, terminating the output of the probes in a 50 ohms impedance. An arbitrary waveform generator [16] was used for the signal sweep injection and a digital oscilloscope [18] was used for synchronously digitizing the voltage and current. The current was measured using a current probe [19], whereas the voltage was directly measured using the required cables to connect the input terminals of the probes to an oscilloscope channel. A Fourier analysis was carried out so that the ratio between voltage and current values provided the variation of the impedance of the probes in the frequency domain.

Four probes were selected for the analysis: two insulated capacitive PLC couplers designed for NB-PLC signal injection or communication testing (connecting a NB-PLC sniffer to the grid), with different line side impedance (P1 50 Ω and P2 12.5 Ω) [20]; a commercial hand-held adapter for power lines with a frequency response starting in 30 kHz and low line side impedance – not numerically specified by the manufacturer - (P3) [21]; and a probe designed by a research centre as part of a system for detecting noise in the electrical grid (P4) [22].

As the low-pass filtering characteristics of probes P1 and P2 were not restrictive enough to avoid aliasing effects in further signal processing, an additional external filter was implemented and included for these probes. This 6th order low-pass filter was designed with Advanced Design System of Keysight Technologies (see Fig. 4) with a cut-off frequency of 4.46 MHz in order to reject commercial radio signals in the FM band, while maintaining a flat response for the frequency band of interest (10 kHz to 500 kHz).

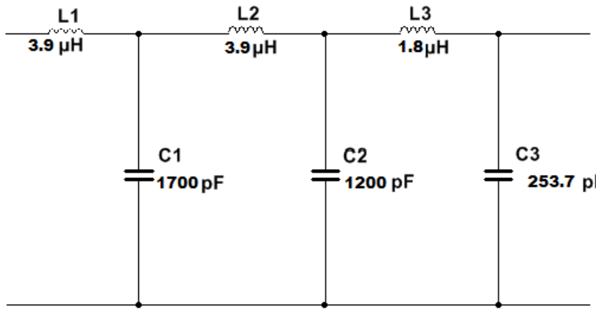

Fig. 4. Implemented external 6th order low-pass filter for P1 and P2 probes in order to avoid aliasing effects.

IV. Characterization of Commercial Voltage Probes

A. *Characterization of the input impedance*

First, the frequency-dependent input impedance measured according to the methodology described in the previous section is shown in Fig. 5 for the four commercial probes P1 to P4, in order to be compared to their nominal input impedance.

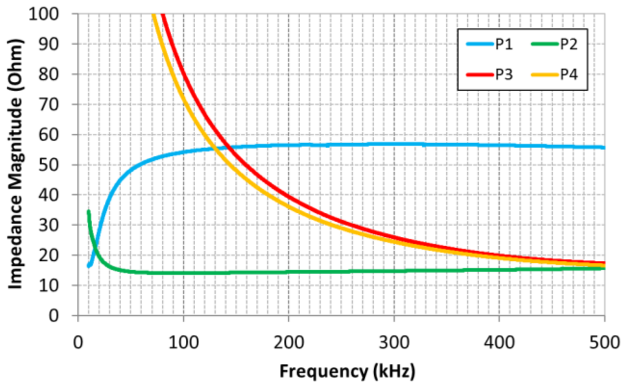

Fig. 5. Measured frequency-dependent input impedance of the commercial probes P1-P4

According to the measurements, the impedances of P1 and P2 are quite stable with frequency from 100 kHz and 40 kHz respectively, but slightly above their nominal values of 50 Ω and 12.5 Ω. The measured input impedances of P3 and P4 are very similar to each other, showing a noticeable decreasing tendency with frequency, and featuring values above 100 Ω below 100 kHz and values around 15 Ω for the highest frequencies.

B. *Characterization of the frequency-dependent response*

The frequency-dependent response of each voltage probe, for a set of representative values of grid impedance (R_{grid} in the measurement setup), is shown in Fig. 6 to Fig. 9. The results for probes P1 and P2 include the frequency response of the external filter specifically designed for these probes.

Results show that the voltage probes may provide quite different levels of accuracy, with error values from 0 dB to more than 20 dB, including both negative values (that will result in an attenuation of the measured emission levels) and positive values (measured values higher than real emission levels).

The frequency-dependent behaviour of the voltage adapters shows distinctive resonance points that vary significantly between the different probes. The location and rise of resonance points depend on a complex system of influencing factors including internal or external filtering design, manufacturing tolerances, etc. [13]. These resonance points are located from 10 kHz to 25 kHz for P1, P2 and P4, whereas for P3 are located in a higher frequency band from 40 kHz to 90 kHz. If these frequencies are within the frequency band of interest, errors of great magnitude will occur in the measurements of non-intentional emissions or NB-PLC signals at these specific frequencies.

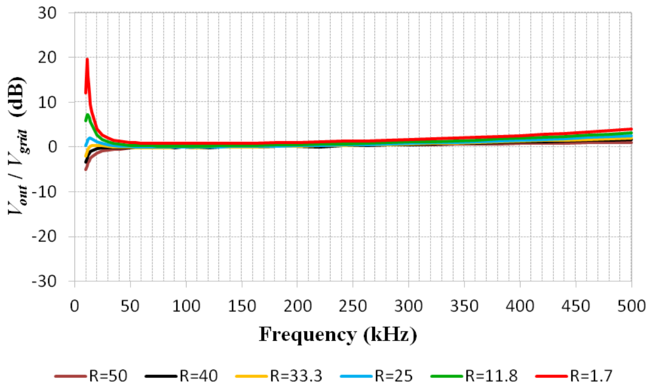

Fig. 6. Accuracy obtained in the measurements carried out with probe P1 and external low-pass filter, for six different grid impedance values (R_{grid}).

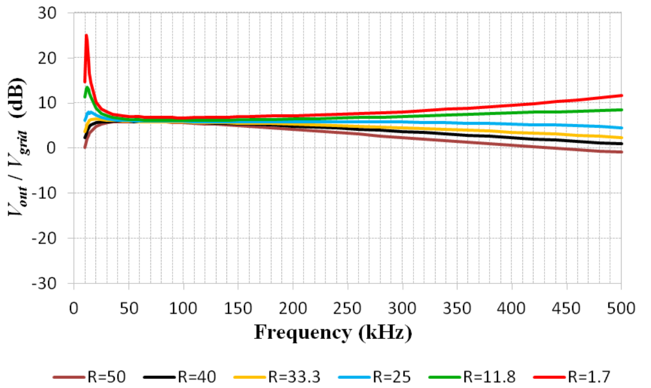

Fig. 7. Accuracy obtained in the measurements carried out with probe P2 and external low-pass filter, for six different grid impedance values (R_{grid}).

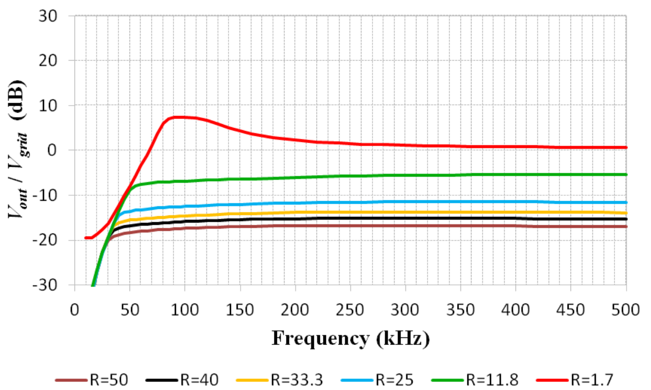

Fig. 8. Accuracy obtained in the measurements carried out with probe P3, for six different grid impedance values (R_{grid}).

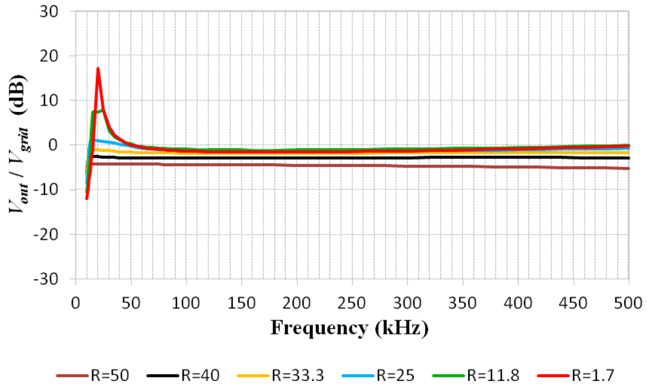

Fig. 9. Accuracy obtained in the measurements carried out with probe P4, for six different grid impedance values (R_{grid}).

Some voltage adapters do not show a flat response for the whole frequency band, e.g., P2 for the highest frequencies and P3 for frequencies below 100 kHz. In addition, impedance mismatch effects are more significant for some adapters, especially for P3. It should be reminded that actual grid impedance values for this frequency band are unknown and highly varying, so it is not possible to compensate the measurement error of a voltage adapter even if the characterization is performed. Therefore, it is important for a certain voltage adapter to have an as flat as possible response for the whole range of expected grid impedance values.

In order to quantify the accuracy of voltage adapters for measuring purposes, the frequency band of operation where the accuracy is limited to ±3 dB is calculated for all the analysed impedance values. The only voltage adapter that complies with this criterion is P1, obtaining a frequency band of operation from 25 kHz to 420 kHz. Within this frequency band of operation, the mean absolute error of the probe is 0.55 dB and the standard deviation of the error 0.65 dB.

Finally, it does not seem to be a direct influence of the input impedance with the measured voltage when using an oscilloscope (high impedance equipment). For example, P3 and P4 have very similar patterns of input impedance, whereas the accuracy they provide for different grid impedance values is very different.

V. Voltage Probe with Improved Performance at the 10 kHz – 500 kHz Frequency Range

A. Design of the voltage probe TSR

The designed coupling circuit for voltage measurement in the 10 kHz - 500 kHz frequency range is shown in Fig. 10. The circuit contains a second-order high-pass filter, composed of C_1 and the primary of the transformer, with -3 dB cut-off frequency in 4 kHz and a seventh-order low-pass filter, with -3 dB cutoff frequency in 4.6 MHz. The characteristic impedance of the filter is 50 Ω. The combination of both filters rejects the signal components of the fundamental frequency 50Hz/230V and results in a flat passband for the frequency band of interest.

Between both filters, there is a transformer with a ratio of 1 to 1 between the primary and secondary windings to provide galvanic isolation between the power line and the instrumentation. The 1:1 transformer features primary and secondary inductances of 1.4 mH, high saturation current and low total harmonic distortion. The internal impedance of the transformer has to be considered properly in order to design an effective coupling interface.

In order to protect from overvoltages from the LV grid, a Gas Discharge Tube (GDT) and a Metal Oxide Varistor (MOV) are used across the power line terminals (phase-neutral). The placement of both elements in series enhances surge protection, since varistors show low impedance and GDTs show high impedance for the frequency band of interest [23],[24]. For limiting transient disturbances and discharging the high voltage series capacitor, a high value protection resistor is used.

Finally, the measuring equipment is protected from power lines transients by means of a bidirectional Transient Voltage Suppresor (TVS). When there is a transient voltage event, the TVS diode conducts to clamp the transient voltage using the Avalanche effect. The bidirectional TVS is placed in parallel to the secondary of the transformer and the low-pass filter. TVS diodes have to be carefully selected, since the junction capacitance of the TVS, which depends on its power rating, might attenuate the amplitude of the signals for the upper part of the frequency band under study.

As it can be observed, the components of the probe proposed in this work are simple and easy-to-obtain, resulting in a low-priced voltage probe. In comparison, the cost of the proposed probe is estimated to be similar to, or even lower than, probes P1, P2 and P3.

B. Characterization of the input impedance

Fig. 11 shows the measured frequency-dependent input impedance of the designed probe TSR. It shows a very stable pattern with frequency around the nominal value of 50 Ω for frequencies above 20 kHz.

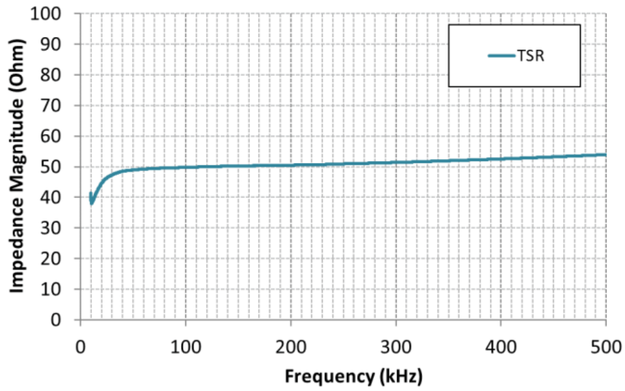

Fig. 11. Measured frequency-dependent input impedance of the designed probe TSR.

C. Characterization of the frequency-dependent response

The performance of this probe was characterized by following the measurement setup and methodology used for the rest of the analysed probes, already described in Section III. The accuracy of the designed probe for the frequency range 10 kHz - 500 kHz is shown in Fig. 12. In this case, the frequency band of operation for ±3 dB accuracy covers from 11 kHz to 500 kHz. Within this frequency band of operation, the mean absolute error of the new probe is 0.34 dB and the standard deviation of the error 0.59 dB.

Although the measuring device is a high impedance oscilloscope, the input impedance of the designed probe does not affect the accuracy of the measured voltage, as shown by the results (Fig. 12).

These results clearly show that the designed voltage adapter outperforms the commercial probes for the frequency band of interest. The frequency-dependent response of the adapter is flat for the whole range of the expected values of the grid access impedance, which guarantees accuracy in the measurements

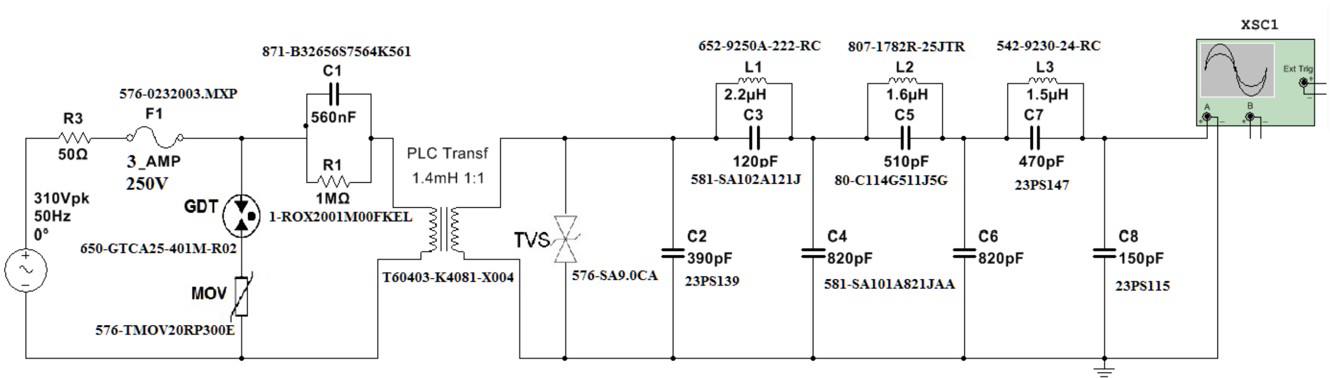

Fig. 10. Complete proposed model for receiver coupling circuit with protection components

regardless of the conditions of the LV network in a certain moment of time.

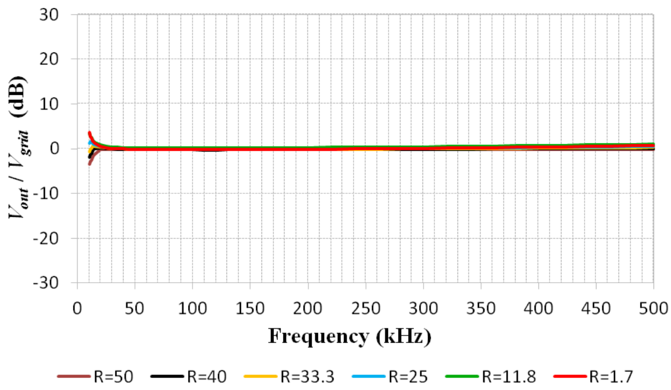

Fig. 12. Accuracy obtained in the measurements carried out with the new probe, for six different grid impedance values (R_{grid}).

VI. Conclusions

Power quality and electromagnetic compatibility issues, which have been traditionally limited to the frequency band below 2 kHz, are widening their scope to higher frequencies due to several reasons, including the presence of NB-PLC and emissions in the higher frequency bands due to power electronics converters.

One of the limitations of the voltage measurements in this frequency band is the lack of normative standards to certify voltage probes, which should be carefully characterised up to this frequency range in order to take into account systematic errors encountered during field measurements.

The characterization of four commercial probes has shown that the accuracy depends on the impedance mismatch conditions that are present in real LV networks. Considering that the access impedance of the grid at this frequency band is a priori unknown, these accuracy errors cannot be diminished even if the frequency characterization of the measuring devices is performed.

To solve these limitations, this paper presents a voltage probe that has a flat response for the whole frequency band of interest and for the whole range of expected LV access impedance values.

Acknowledgment

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