SURVEY OF NETWORK IMPEDANCE IN THE FREQUENCY RANGE 2-9 KHZ IN PUBLIC LOW VOLTAGE NETWORKS IN AT/CH/CZ/GE

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ABSTRACT

Setting realistic emission limits for distorting customer installations is a crucial requirement for a reliable and disturbance-free operation of public distribution networks. Therefore only an adequate share of the total allowable voltage distortion (compatibility level) has to be allocated to each customer installation. This allowable contribution of a single customer installation is usually small and difficult to assess. Hence, nowadays most standards and guidelines translate the allocated voltage distortion in a respective current distortion by using the network impedance at the considered frequency. As frequency-dependent network impedance is usually not known during the planning process, assumptions are required, which have to be realistic and not too conservative. This applies in particular to frequencies above 2 kHz, where the usually used extrapolation based on short circuit impedance can be very conservative due to the increasing impact of connected customer equipment on the network impedance. Based on a comprehensive measurement campaign in four different countries this paper identifies typical ranges of the frequency-dependent network impedance in the frequency range 2-9 kHz. It analyses the impact of short circuit power and proposes a simplified impedance estimation, which can be used to calculate realistic current emission limits in the planning stage.

INTRODUCTION

Distortion is commonly divided into subharmonics, harmonics, interharmonics and the frequency range above 2 kHz, which is also frequently referred to as supraharmonics. Emission limits for a new customer installation are determined in the planning stage. In most cases no detailed information about the frequency dependent network impedance is available and consequently simplifying assumptions must be applied. In low voltage (LV) networks usually the "impedance line" is used, which simply corresponds to the linear extrapolation of the short circuit impedance by multiplying it with the harmonic order. Several studies have shown that with increasing frequency this assumption gets less realistic, especially in the frequency range above 2 kHz ([1], [2]). Consequently, the calculated emission limits might be too restrictive, resulting in a less effective utilization of networks with regard to emission in the frequency range 2-9 kHz and/or unnecessary investments in filter equipment.

This issue is already taken into account in IEC 61000-4-7 [3]. It proposes in an informative annex a reference impedance for testing the compliance of appliances with emission limits in the frequency range 2-9 kHz, which are currently under development at IEC SC77A WG1.

The reference impedance in IEC 61000-4-7 is based on the reference short circuit power according to IEC/TR 60725 [4]. This value is rather conservative in order to ensure that more than 90 % of the connection points in public low voltage (LV) networks have a higher short circuit power.

The 3rd edition of the AT/CH/CZ/GE (Austria/Switzerland/Czech Republic/Germany) rules for assessment of network disturbances for customer installations is currently under development and shall be extended to the frequency range 2-9 kHz. Therefore, a realistic, reliable and widely accepted assumption for the network impedance in this frequency range is required. As larger customer installations are usually connected at points with a higher short circuit power than specified in IEC 60725, the reference impedance provided in IEC 61000-4-7 for the frequency range 2-9 kHz might still be too conservative. Especially for high short circuit powers even the "impedance line" can be significantly lower than the reference impedance according to IEC 61000-4-7 as it is illustrated in Fig. 1.

Consequently also the dependency of the frequency dependent network impedance in the frequency range 2-9 kHz on the short circuit power has to be considered when developing a realistic approach for the calculation of current emission limits for larger customer installations. At frequencies above 2 kHz the frequency-

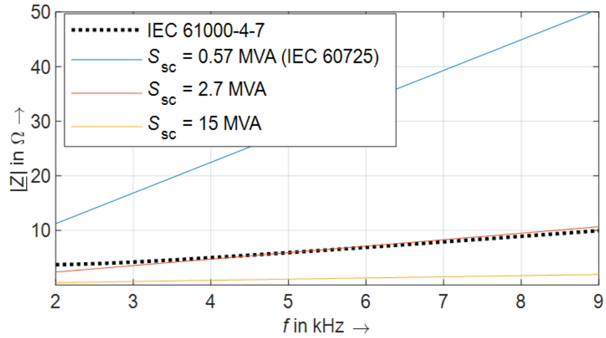

Fig. 1: IEC 61000-4-7 compared to impedance lines for different short-circuit power.

dependent network impedance is getting more influenced by the input impedance of connected devices, while the impact of the network elements decreases. Up to now no comprehensive knowledge about the level of influence of the short circuit power on the frequency-dependent network impedance is available.

In order to get a representative overview about typical ranges of the network impedance in the frequency range 2-9 kHz and its dependence on the short circuit power, a comprehensive measurement campaign has been conducted with the help of DSOs in the four countries AT/CH/CZ/GE. This paper presents the results of this measurement campaign, analyses the relation between short circuit power and frequency-dependent network impedance and develops a simplified approach for estimating the impedance for the calculation of current emission limits in the frequency range 2-9 kHz for customer installations connected to LV networks.

The first part of the paper describes the measurement campaign, the used measurement equipment and characterises the measured sites. The second part provides the measurement results and evaluates the impact of the short circuit power on the network impedance characteristic. Finally, a novel approach for the simplified estimation of the network impedance in the frequency range 2-9 kHz is presented. The paper closes with some conclusions and needs for future work.

MEASUREMENT CAMPAIGN

Measurement sites

With the help of twelve DSOs in the four countries AT/CH/CZ/GE impedance measurements were conducted at 81 measurement sites. Each DSO selected at least two typical public LV networks, one representing a stronger, urban network and one a weaker, rural network. In each network, at least two sites were selected for impedance measurement: one site directly at the LV busbar of the MV/LV substation (SS) (highest short circuit power) and one site at the furthest accessible point in the network (usually a junction box (JB)), where the lowest short circuit power in the particular network is expected.

For 76 measurement sites the DSO's provided also the short circuit power, which has been obtained from their network calculation software. In total 198 (out of 228 theoretical possible) single loop impedance measurements were obtained. Not at every site the loop impedance of all three phases could be measured.

Table 1 presents the number of measurement sites and measured loop impedances for each country distinguishing measurements at substations (SS) and at junction boxes (JB). About 75 % of all measurements have been performed at junction boxes significantly distant from the LV busbar.

Table 1: Overview of measurements

		AT	CH	CZ	GE	∑
Sites	SS	4	9	2	7	22
	JB	12	11	5	26	54
	∑	16	20	7	33	76
Single loop impedances	SS	12 (26 %)	11 (28 %)	6 (30 %)	21 (23 %)	50 (25 %)
	JB	35	29	14	70	148
	∑	47	40	20	91	198

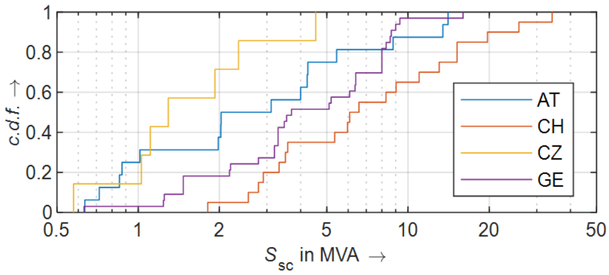

Fig. 2: Short circuit power of measurement sites by country.

Fig. 2 shows the cumulative distribution function (CDF) of the short circuit power of the measurement sites for each country. The short circuit power of the countries is distributed over a similar range. In Switzerland the short circuit power tends to be higher, this is most likely caused by the site selection, as in Switzerland only DSOs in more urbanized regions participated in the survey.

Measurement system

The measurement system is a joint development of the University of Technology in Dresden and an industrial partner. The measurement principle is based on an earlier developed setup, which is described in [5].

The layout of the measurement system is shown in Fig. 3, a photo of its field application in Fig. 4. The system consists of a linear amplifier operated as current source for network excitation and a unit for voltage and current measurement. The measurement system is controlled by a laptop. The measurement is performed as a stepwise discrete sweep. A current with a given frequency is injected in the network and the resulting voltage is measured. Based on both values the impedance of the

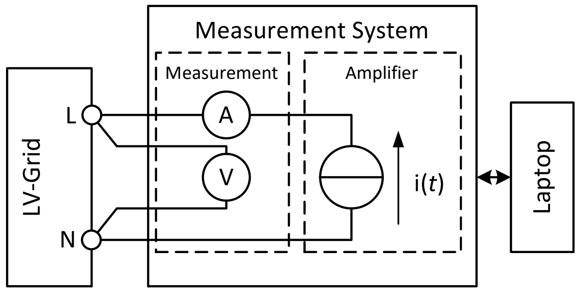

Fig. 3: Scheme of the measurement system.

Fig. 4: Measurement system while measuring at a junction box.

network at the given frequency is calculated.
The output current is measured internally, while the voltage of the network is measured at the connection point, so that the impedance of the measurement cables does not influence the measurement results. Both voltage and current signals are sampled with a rate of 10 MS/s and a vertical resolution of 16 Bit.
The magnitude of the injected current is automatically adapted to the situation at the connection point, in order to ensure an as small as possible excitation of the network by not exceeding 1 V. In this way the method is less invasive and damage of connected equipment as well as an unwanted influence of the measured impedance itself is avoided. For the last reason also the power supply of the system is disconnected during the measurement process.
The system is able to measure the frequency-dependent network impedance in the range between 0.1 kHz and 150 kHz with an uncertainty of better than 5 %.

MEASUREMENT RESULTS

Fig. 5 presents an overview of all measurements together with selected percentile curves for the whole measured frequency range. It also contains the IEC 61000-4-7 reference impedance, which only applies in the frequency range 2-9 kHz (solid part of the line). As this paper focuses on the frequency range 2-9 kHz, only this frequency range is presented and discussed further on in the text.
Almost all measured impedances are below the reference impedance, which proofs its feasibility. It should be noted that the reference impedance is based on a (three-phase) short circuit power of 0.57 MVA (cf. IEC 60725), but the lowest short circuit power of the measured sites is still higher than this (cf. Fig. 2). However, three measurements (1.5 %) are still partly higher than the reference impedance.
Fig. 6 presents all measured loop impedance separate for each country. The countries are rather similar, except in Switzerland the impedances are lower by almost one decade. The most likely reason for this is the already mentioned higher short circuit power at the Swiss sites. The low difference between substation and junction box measurements suggests that the networks are rather short and the distance between substation busbars and junction boxes are rather low. The variation in the impedance plots suggests that in the frequency range above 2 kHz the short circuit power seem to have still a significant influence on the impedance. Some of the impedances measured at the junction boxes have additional resonances at higher frequencies, which can result in

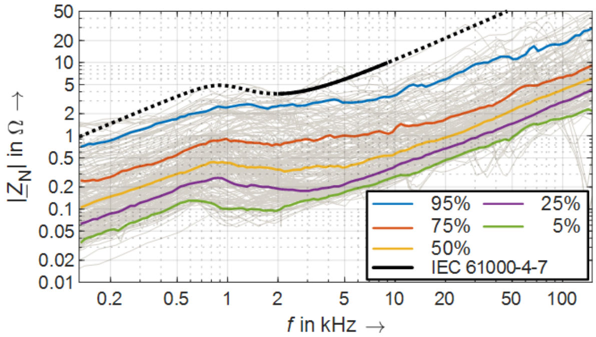

Fig. 5: All measured loop impedances in comparison with IEC 61000-4-7 reference impedance including selected percentile curves.

impedances at the junction box being smaller than at the respective substation. This confirms the known fact that at frequencies higher than 2 kHz the impact of connected customer appliances is not negligible anymore.
In order to study the impact of short circuit power on the impedance in the frequency range 2-9 kHz for each measured impedance the ratio between reference impedance ($Z_{4\text{-}7}$) and measured impedance (Z_m) is calculated and the median of all ratios for each measured loop impedance is determined. The results are presented in Fig. 7 and show an expected dependency, which however gets saturated with increasing short circuit power. The high variation for individual short circuit power values indicates the impact of the impedance of connected customer appliances, which reduces with increasing short circuit power. This is a simple consequence of the reduced grid-side impedance, which in turn increases its impact on the measured impedance in relation to the impedance of the connected appliances.

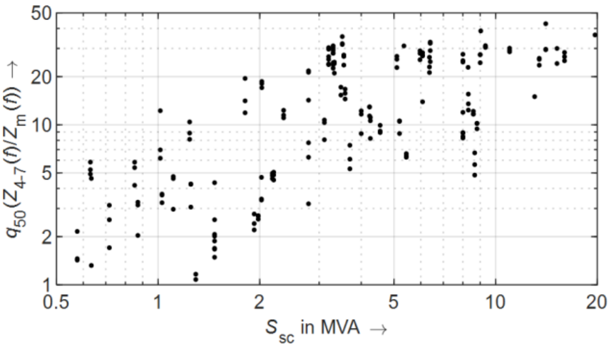

Fig. 7: 50-%-percentile of ratio between reference impedance according to IEC 61000-4-7 and measured impedance in the range 2-9 kHz depending on short-circuit power.

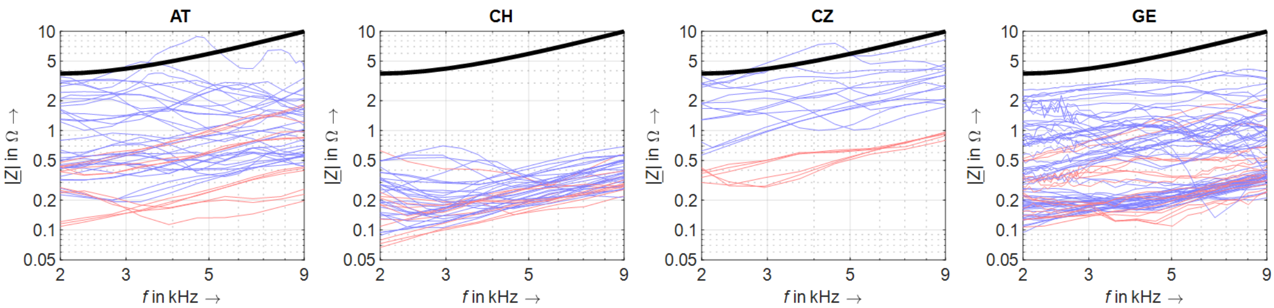

Fig. 6: Measured loop impedances per country (red: substation, blue: junction box, black: reference impedance acc. to IEC 61000-4-7)

PROPOSED IMPEDANCE APPROACH

As shown in Fig. 7, the measured loop impedance can vary about two decades and can be up to factor 100 smaller than the IEC 61000-4-7 reference impedance. Consequently, the assumption of a constant reference impedance seems not applicable for larger customer installations, which are usually connected to points with higher short circuit power than the reference short circuit power. A certain dependency of the impedance on the short circuit power is therefore also justified at frequencies above 2 kHz.
Comprehensive analyses of possible dependencies between short circuit power and characteristic parameters of the measured impedances could not identify any clear relation. Therefore the proposed impedance approach is based on an appropriate scaling of the IEC 61000-4-7 reference impedance by the short circuit power at the connection point of a customer installation.

Linearization of reference impedance

In order to keep the approach simple the reference impedance Z_{ref} for the frequency f is linearized in the considered frequency range 2-9 kHz according to (1).

$$Z_{\mathrm{ref}}(f) = \frac{Z_{9\,\mathrm{kHz}} - Z_{2\,\mathrm{kHz}}}{9\ \mathrm{kHz} - 2\ \mathrm{kHz}} \cdot (f - 9\ \mathrm{kHz}) + Z_{9\,\mathrm{kHz}} \quad (1)$$

Using $Z_{2\,\mathrm{kHz}}$ =3.25 Ω and $Z_{9\,\mathrm{kHz}}$ =10.25 Ω results in

$$Z_{\mathrm{ref}}(f) = \left(\frac{f}{\mathrm{kHz}} + 1.25\right)\Omega \quad (2)$$

The error ε with regard to the true reference impedance characteristic is in the range of -15 % to +5 %, which results in an average in the considered frequency range of about zero (Fig. 8).

Scaling methodology

To include the dependency on the short circuit power, the linearized reference impedance is scaled with the ratio of reference short circuit power ($S_{sc\ ref}$) and the real short circuit power at the connection point (S_{sc}). In order to keep the level of dependency flexible, a reduction factor r is introduced. The final equation for the calculation of the impedance at the connection point Z_{est} is given by

$$Z_{\mathrm{est}}(f) = Z_{\mathrm{ref}}(f) \cdot \left(r + (1 - r) \cdot \frac{S_{\mathrm{sc\,ref}}}{S_{\mathrm{sc}}}\right) \quad (3)$$

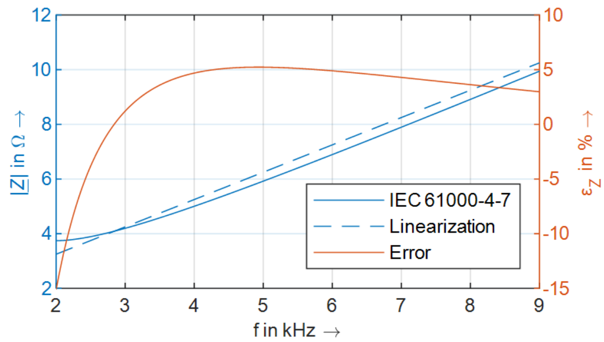

Fig. 8: Reference impedance linearization and linearization error

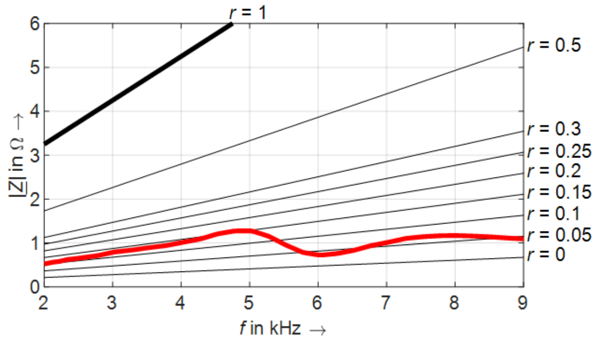

Fig. 9: Impedance lines for different reduction factors (black) compared with measurement at S_{sc} = 8.8 MVA (red)

A reduction factor of $r = 0$ means, that the short circuit ratio has the highest impact on the impedance. An increasing reduction factor r means a decreasing influence of the short circuit power. In case of $r = 1$, the impedance is independent of the short circuit power and equals the reference impedance. This corresponds to the method of compliance assessment for single appliances.
Fig. 9 illustrates the impact of the reduction factor using a real measured impedance at a short circuit power of S_{sc} = 8.8 MVA. The example shows that a reduction factor of $r = 0$ significantly underestimates the measured impedance, while using the reference impedance ($r = 1$) results in a far too conservative estimate. For the example in Fig. 9 a reduction factor of $r \geq 0.15$ leads to an estimated impedance Z_{est}, which is never below the measured impedance.

Determination of reduction factor

For each impedance measurement the reduction factor r is determined iteratively so that the estimated impedance $Z_{est}(f)$ is just not exceeded by the measured impedance for all frequency (cf. to $r = 0.15$ in Fig. 9).
Fig. 10 presents the cumulative distribution function (*c.d.f.*) of the calculated reduction factors. A reduction factor of zero is obtained for about 60 % of the measurements, which means that even at highest sensitivity ($r = 0$) the estimated impedance is still above the measured impedance. Analysing the maximum ratio between estimated and measured impedance has shown that it is less than 2.5 for about 80 % of the respective cases. Compared to the original approach just using the extrapolated short circuit impedance the new approach is still about 5 to 20 times better and therefore an acceptable trade-off.

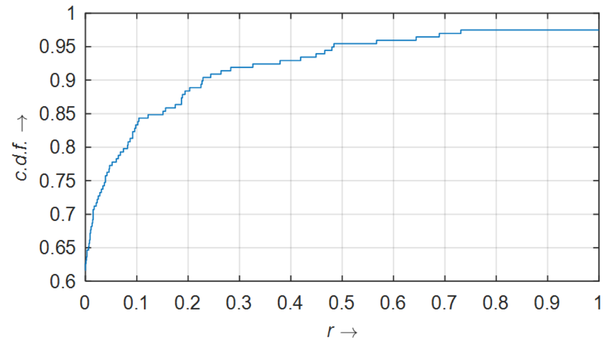

Fig. 10: Calculated impact reduction factor for all measurements

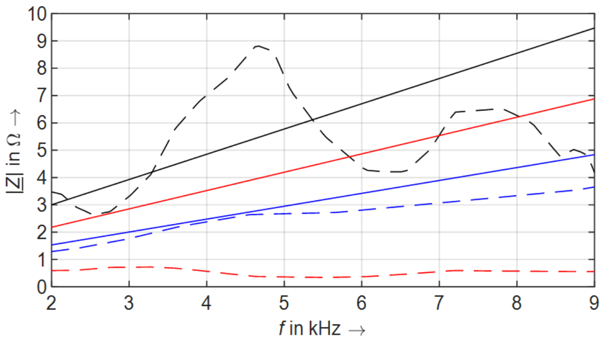

Fig. 11: Comparison of measured impedance (dashed) and estimated impedance (solid) for three different short-circuit powers: black: 0.64 MVA; red: 1.01 MVA; blue: 1.92 MVA

On the other hand, Fig. 10 shows that for about 40 % the influence of the short circuit power has to be reduced in order to ensure that the estimated impedance is not exceeded by the measured ones. For a small number of cases even a factor of $r = 1$ (no influence of short circuit power) is not sufficient, which means that the reference impedance of IEC 61000-4-7 is still exceeded by the measured impedances. However, these few cases are caused by specific resonances, which has to be treated individually and should not be considered for the development of a general value for the reduction factor r.

Following a similar probabilistic approach as for the determination of the reference impedance in IEC 60725, a reduction factor of $r = 0.25$ is proposed. For this value about 90 % of the measured impedances are below the respective estimated impedance (cf. Fig. 10).

Fig. 11 presents the application of the impedance approach for three different cases. For the first case (black) due to a pronounced resonance the estimated impedance is exceeded by the measured impedance. For the second example (blue) the estimated impedance matches the measured impedance very good, while for the third example (red) the estimated impedance is still significantly higher than the measured one. The last two example cases underline the weak link between short circuit power and network impedance at frequencies above 2 kHz. Since both cases do not show resonances, the better match between estimated and measured impedance is obtained for the site with twice as high short circuit-power.

CONCLUSIONS

This paper presents a new approach to estimate the network impedance in the frequency range 2 – 9 kHz for the determination of current emission limits during the planning of customer installations. The proposal is still simple, but represents a significantly better estimation compared to the current practice of using the impedance line extrapolated based on the short circuit impedance. The approach has been developed based on a comprehensive set of impedance measurements in public LV networks.

The analysis of the impedance measurements has confirmed that the link between network impedance and short circuit power at frequencies above 2 kHz becomes more and more weak, while the influence of the input impedance of close-by connected equipment increases. Therefore the proposed approach can still provide rather conservative results under specific circumstances.

Consequently, more research is needed to improve understanding and knowledge about the network impedance at frequencies above 2 kHz in order to improve the impedance estimation approach presented in this paper. This includes also frequencies above 9 kHz, for which compatibility levels have been established just now and suitable methods for emission limit determination have to be developed for future editions of the respective rules and guidelines for network disturbance assessment.

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