SYSTEM IMPEDANCES AND BACKGROUND NOISE IN THE FREQUENCY RANGE 2 TO 9 KHZ

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A one year research effort was launched to investigate the internal impedances and coupling impedances within German public low voltage networks in the frequency range from 2 kHz to 9 kHz. At 250 different nodes, roughly 6000 impedance measurements were carried out. In addition, the background voltage level in the same frequency range was investigated. The most important results of the measurements are summarized and presented in this paper.

1. INTRODUCTION

Power systems are increasingly subjected to non-sinusoidal currents from customer installations resulting in distorted voltages. For harmonic frequencies up to 2 kHz, current emission limits have been defined in EN 61000-3-2 [2]. Up to now, however, no limits exist for the frequency range above 2kHz, which is more and more used by modern electronic equipment, particularly switched mode power supplies.

For a possible future international standardization of current emission limits in the frequency range from 2 kHz to 9 kHz, detailed knowledge about the network impedance in this frequency range is indispensable. Previous studies [4,8-13] have mainly been confined to the frequency range below 2.5 kHz. Therefore, reliable data covering the higher frequency range still had to be collected.
Based on experiences from former research [3,4,6-8], a portable instrument for measuring internal impedances and coupling impedances in the frequency range 1...40 kHz was developed. It was used to measure

- the line impedance in the frequency range 1...20 kHz
- the corresponding 50Hz-impedance at the same terminals
- the voltage noise level in the range 2...10 kHz
- some coupling impedances (exemplary)

within public low voltage systems. The measuring points were selected to cover a widespread range of different network configurations and consumer types. Industrial networks and industrial zones were excluded, however.
Within the particular installations, measuring was performed at the service connections, if accessible, and at a couple of socket outlets within different distances from the service entrance. Some measurements were carried out directly at transformer or distribution systems bus bars.

2. MEASURING METHOD

In the considered frequency range, an invasive method, using an active current source, **fig.1**, is appropriate.

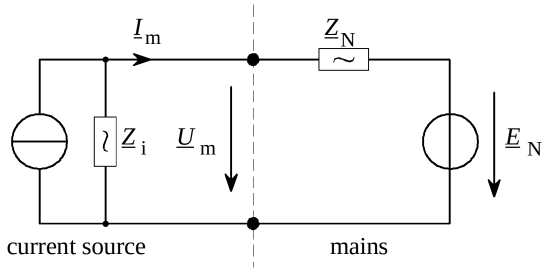

Fig. 1: Principle of line impedance measurement

To suppress noise originating in the line voltage $\underline{E}_N$, a differential measurement of both voltage $\underline{U}_m$ and current $\underline{I}_m$ is performed, with and without injecting an additional current of measuring frequency f_m. The line impedance $\underline{Z}_N$ can then be calculated as

$$\underline{Z}_N = \Delta \underline{U}_m / \Delta \underline{I}_m \ . \qquad (2)$$

The simplified structure of the measuring instrument is shown in **fig. 2**. Instead of a single measuring frequency, a multispectral signal, optimized for mimimum crest factor, is used. Thus, the total measuring time for the frequency range 1...20 kHz could be reduced to 5 seconds.

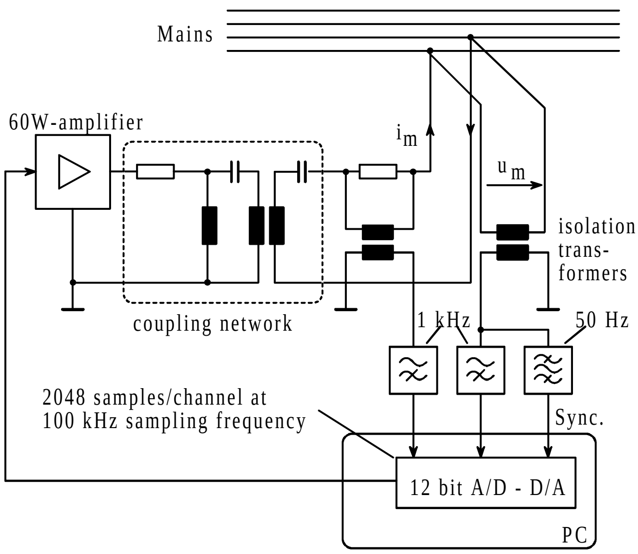

Fig. 2: Simplified structure of the impedance measuring instrument (Possible connections: L-L or L-N)

3. IMPEDANCES IN THE PUBLIC LV GRID

3.1. Internal impedances

Fig. 3 shows some of the measured phase-to-neutral impedances in comparison to the standard impedance of the CISPR16-1 network (in connection with the "adaptive network" for the range 3..148,5 kHz) [1].
It can be clearly seen that the impedances of overhead supply lines, curves F and G, exceed by far the tolerance band that can be given for cabled areas, so both systems will have to be considered separately. A closer examination reveals that, with respect to the magnitude of their impedances, even cable systems themselves have to be classified into two groups: rural and urban areas.

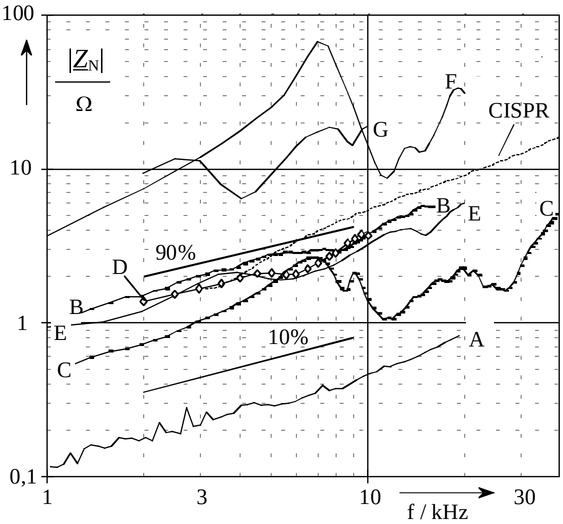

Fig. 3: Phase-to-neutral impedances of some selected measuring points, compared to the CISPR 16-1 standard impedance [1]. The tolerance band (10%...90% of all values) applies to cable systems only.

A:Busbar L1-N of a distribution transformer S_n=1MVA, u_k=6%.
B: block of flats, urban, 2nd floor
C: apartment house with high installed load (flow-type heaters), urban, 3rd floor
D: family house, city center, ground floor
E: university lab
F: rural hermitage, supplied by 100 kVA pole-type transformer and 300 m overhead line
G: family house, village, overhead line, 2nd floor

Since most of the impedance curves show resonances, their quality factors can be used as additional characteristics. These resonances can clearly be seen from the impedance curves in the complex plain; **fig. 4** gives a few examples.

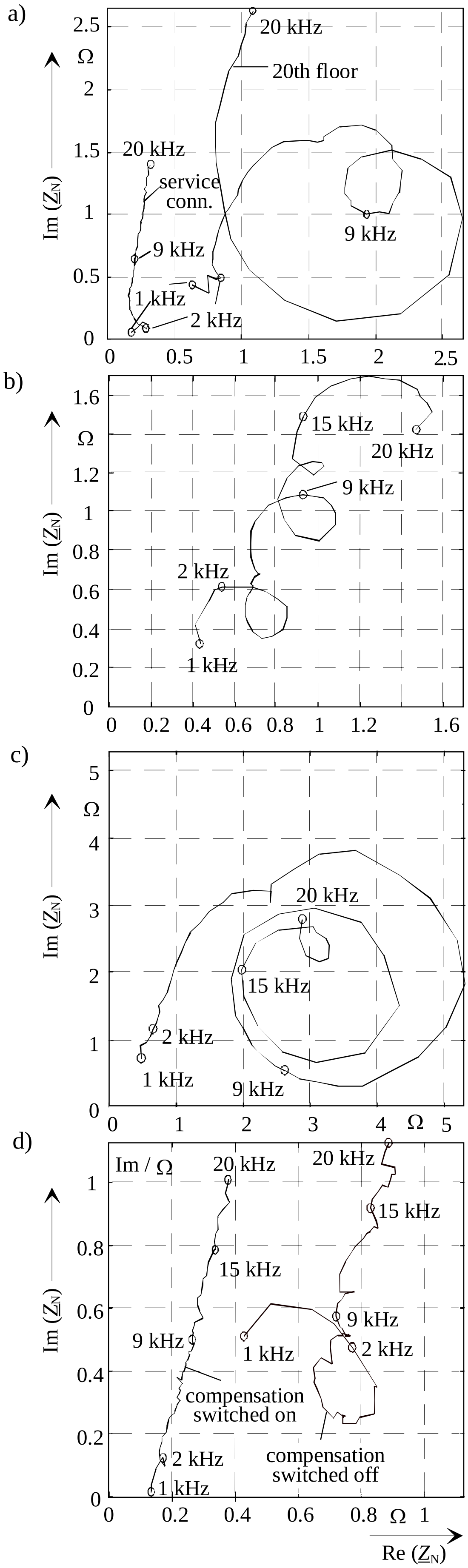

Fig. 4: Phase-to-neutral impedance loci in cable systems
a) Residential high-rise building
b) University lab
c) Students appartment
d) Distribution system of a university building with 200 kVar reactive compensation

In a lot of cases several resonances occur at the same location. Since they depend on the loads which are connected in the close vicinity, they are time-dependent, and the impedance curves may be quite different even between neighbouring nodes.

3.1.1. Cable systems (excluding industrial zones and industrial networks). In urban cable systems, resonances occur in about 70% of all cases. Quality factors are moderate (Q = 1..1.5...2.5), the distribution of resonance frequencies in the considered range 2...9 kHz is roughly uniform. The characteristics of impedance loci vary widely and are -except for non-resonant or low impedant nodes- likely to differ even within the three phases of the same node.

Rural (cabled) areas are characterized by a lower load density and a greater average cable length. As a result, significantly higher network impedances can be expected. Resonances are even more likely and the average quality factor is slightly higher than in urban areas (Q = 1.5..2..3).

The overall spread of the impedances in cable networks is relatively large, as can be seen from **fig. 5**.

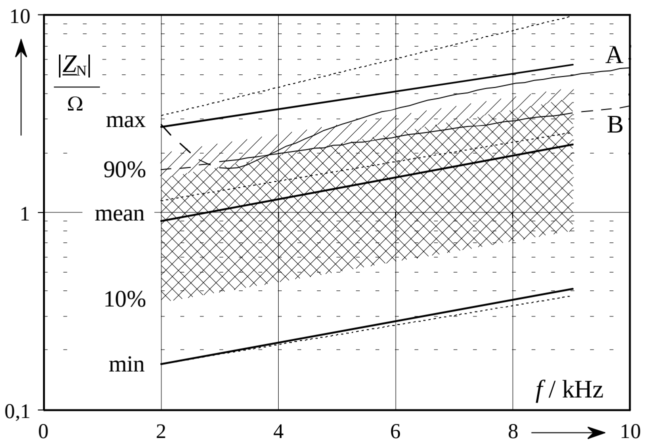

Fig. 5: Spread of the impedances in cable networks (phase to neutral)
single hatch / dashed line: all measuring points (≈250)
cross hatch / solid line: measuring points with low-Q or missing resonances only (≈90)
A: equiv. network according to CISPR 16-1 with adaptive network for the frequency range 3...148,5 kHz [1]
B: equiv. network (50Ω‖(1,6Ω + 50 μH)) [1]

To a certain degree, however, the impedances $|\underline{Z}|$ at high frequencies correspond to the impedance $|\underline{Z}_{50}|$ at line frequency, and the spread can be reduced by normalizing the impedances to their 50-Hz-values, **fig. 6**.

The spread of impedances in the subgroup of nodes with *missing or low-Q resonances* (cross-hatched area in fig. 6) is even smaller. For better clarity, the probability values of the normalized impedances in this group, at 2 kHz and 9kHz, respectively, are summarized in **tab. 1**.

To find a reasonable maximum of the impedance, which will probably not be exceeded in a specific case, it is recommended to use the 95%-value from tab. 1 and multiply it by the average quality factor. For example, a node in a rural cable system is considered whith a 50-Hz impedance equal to the CENELEC reference impedance, Z_{ref} = 0.47Ω. Assuming Q = 2, the maximum impedance to be expected at a frequency of 9 kHz will then be:

$$Z_{9k,\max} = Q \cdot Z_{9k} / Z_{50} \cdot Z_{ref} = 2 \cdot 10.5 \cdot 0.47\,\Omega \approx 10\,\Omega\,.$$

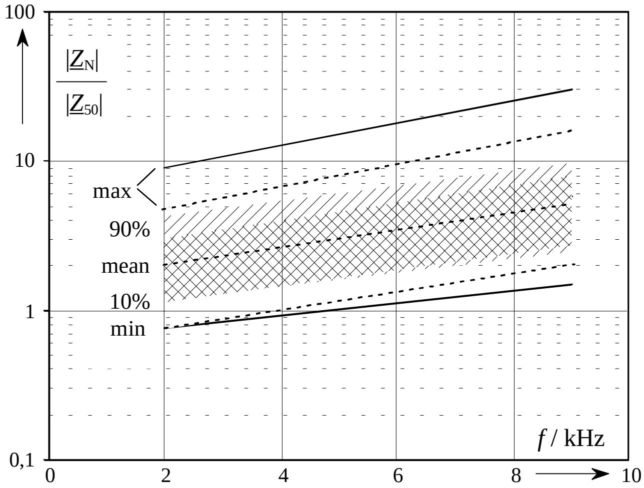

Fig. 6: Spread of the impedance ratios in cable systems;
single hatch (10..90%) / solid line: all measuring points
cross hatch (10..90%) / dashed line: measuring points with low-Q or missing resonances only

Tab. 1: Impedance ratios of *low-Q nodes* in cable networks, which will not be exceeded in 10% (90%, 95%, resp.) of all cases. (Indices: 2k: at 2 kHz; 9k: at 9 kHz)

	$\frac{R_{2k}}{R_{50}}$	$\frac{L_{2k}}{L_{50}}$	$\frac{Z_{2k}}{Z_{50}}$	$\frac{R_{9k}}{R_{50}}$	$\frac{L_{9k}}{L_{50}}$	$\frac{Z_{9k}}{Z_{50}}$
10%	1,0	0,12	**1,1**	1,3	0,1	**2,8**
50%	1,3	0,26	**1,8**	2,1	0,2	**4,6**
mean	1,55	0,27	**2,01**	2,55	0,21	**5,1**
90%	2,6	0,44	**3,2**	4,3	0,32	**8,0**
95%[1]	2,9	0,47	**3,9**	6,0	0,34	**10,5**

3.1.2. Overhead systems (rural areas only). Overhead systems are characterized by high-Q resonances (Q= 2..3...5). Impedances are by a factor of 3...5 higher than those of cable systems and are likely to vary within a wide range during the day. Distant from resonance frequencies, the average phase-to-neutral values are within a range of 3...10 Ω. Assuming an average quality factor of Q=3, the maximum values will normally not exceed 30Ω, however, in some cases even higher values can be possible, fig. 3. The maximum value, measured at a rural family house, was even above 90Ω, at a frequency of 7.5 kHz.

[1] Note that the number of measurements is too small to give a statistically justifiable 95%-value

3.1.3. General observations. Generalizing, further experience can be summarized as follows:

- Phase-to-phase impedances are by a factor of 1,5...2 higher than phase-to-neutral impedances. This difference diminishes within house installations and distributions, where all four wires are of the same kind.
- Symmetry is in general poor, except for low-impedant nodes, e.g. transformer bus bars or nodes with reactive-power compensation capacitors.
- Impedance may vary considerably during the day, especially at higher frequencies and in case of resonances. In some but not all cases the day-time characteristic of the impedance is periodical.
- There is neither a significant difference between summer and winter, nor between workdays and weekends.
- Correlation between impedance and consumer types is weak. The variance of the impedances at different nodes may differ with regard to consumer groups, but the average values do not show statistically significant deviations.

3.2. Coupling impedances

The internal impedance of a network node only gives information about the spectral voltage component, which is caused locally by the current component of a device connected to this node. The propagation of conducted interferences to other nodes within the network is governed by the coupling impedances, e.g. $\underline{z}_{12} = \underline{z}_{21}$ in **fig. 7**.

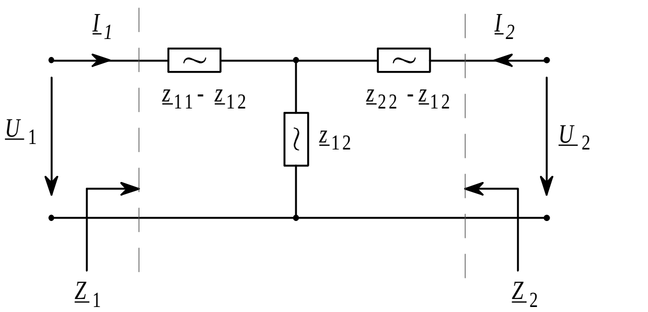

Fig. 7: T-equivalent diagram representing any part of the LV grid between nodes 1 and 2

In most cases, the coupling between any two nodes will be $|\underline{z}_{12}| \leq |\underline{Z}_x|$, where x denotes the point of lowest impedance on the line connection between the considered nodes. If this point can´t be measured, the assumption

$$|\underline{z}_{12}| \leq \min(|\underline{z}_1|, |\underline{z}_2|), \qquad (2)$$

will yield a reliable estimation for the maximum value of the coupling impedance.

An example of a residential cable distribution is shown in **fig. 8a**. The point of lowest impedance between the service connections A and B is the underground cable junction D, which of course is not accessible for measurements. Its impedance is roughly represented by the measured coupling between points A and B, **fig. 8b**. Similarly, the coupling between A and C represents the impedance of the junction E.

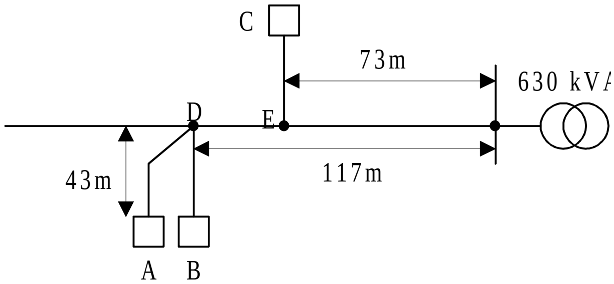

Fig. 8a: Detail of a cable distribution in an urban residential area

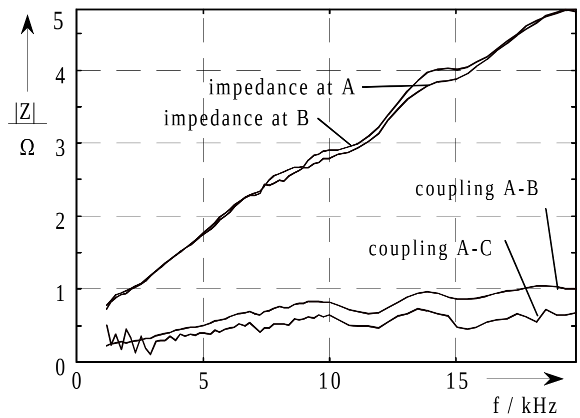

Fig. 8b: Impedances and coupling impedances in the network according to fig. 8a

In some cases, due to resonances between the network cabling and certain capacitive loads, the coupling may get larger than the estimation according to eqation (2), i.e. the harmonic level at some distant node may exceed the level at the "emission" node. An example of such a case, measured within an urban flat, is depicted in **fig. 9**.

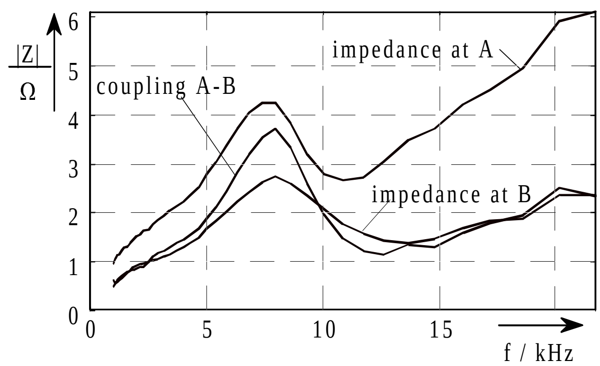

Fig. 9: Impedances and coupling impedance of different socket outlets in an urban flat. A spurious current with an amplitude of 0,1A and a frequency of $f \approx 7{,}5$ kHz fed into socket B will cause a voltage level of 0,27V at socket B and 0,38V at socket A. This corresponds to a signal amplification by a factor of 1,4.

However, in no case did the coupling exceed the impedance of the higher-impedant of both nodes:

$$|\underline{z}_{12}| < \max(|\underline{z}_1|, |\underline{z}_2|). \qquad (3)$$

Further experience can be summarized as follows:

- Noise "amplification" by resonances will occur occasionally, especially within house installations.
- The coupling between two nodes but different conductor loops, e.g. from L1-N at node 1 to L2-N at node 2, is significantly (roughly factor 2...4) smaller than the coupling within the same loop.
- The coupling between different branches in a meshed network is even smaller than the impedance of the nearest transformer.

4. PHASE-TO-NEUTRAL NOISE LEVELS IN THE FREQUENCY RANGE 2...10 KHZ

In order to get some information about the present noise level in the LV grid, the time functions of the line voltages were recorded together with the impedances at each measuring point. The following examples may illustrate some typical characteristics of the voltage noise spectra.

Fig. 10a) shows the envelope of the voltage levels (frequency range 2...10 kHz) at all 250 measuring points, which were recorded during a total measuring time of ca. 1000 hours. The frequency resolution is 50 Hz.
It should be pointed out that the average values are considerably lower. However, since the duration of measurement was different for each node, a reliable mean value cannot be given.

Furthermore, it can be stated:
- In general, the spectral energy concentrates on the frequency range between 2...5 kHz, fig. 10a). Maxima at higher frequencies are seldom and mostly wide-band. Single spectral lines are rare and of short duration.
- Noise levels are low at the bus bar of distribution transformers, **fig. 10b)** ,and are increasing with the distance from the transformer, **fig. 10d)**.
- Odd harmonics are represented with considerably higher amplitudes than even ones. Static converters can cause voltage harmonics ($\nu = 6n \pm 1$) even at high frequencies, **fig. 10c)**.
- The values vary considerably during the day, especially in overhead systems. In general, the highest levels are measured in the evening from 8 pm until 2 am, the lowest levels appear in the morning from 3 - 6 am.
- The voltage levels in rural overhead systems are mostly lower than those in urban cable networks, probably because there are comparatively less electrical appliances in use. On the other hand, the high network impedance will at times lead to the highest maximum values.

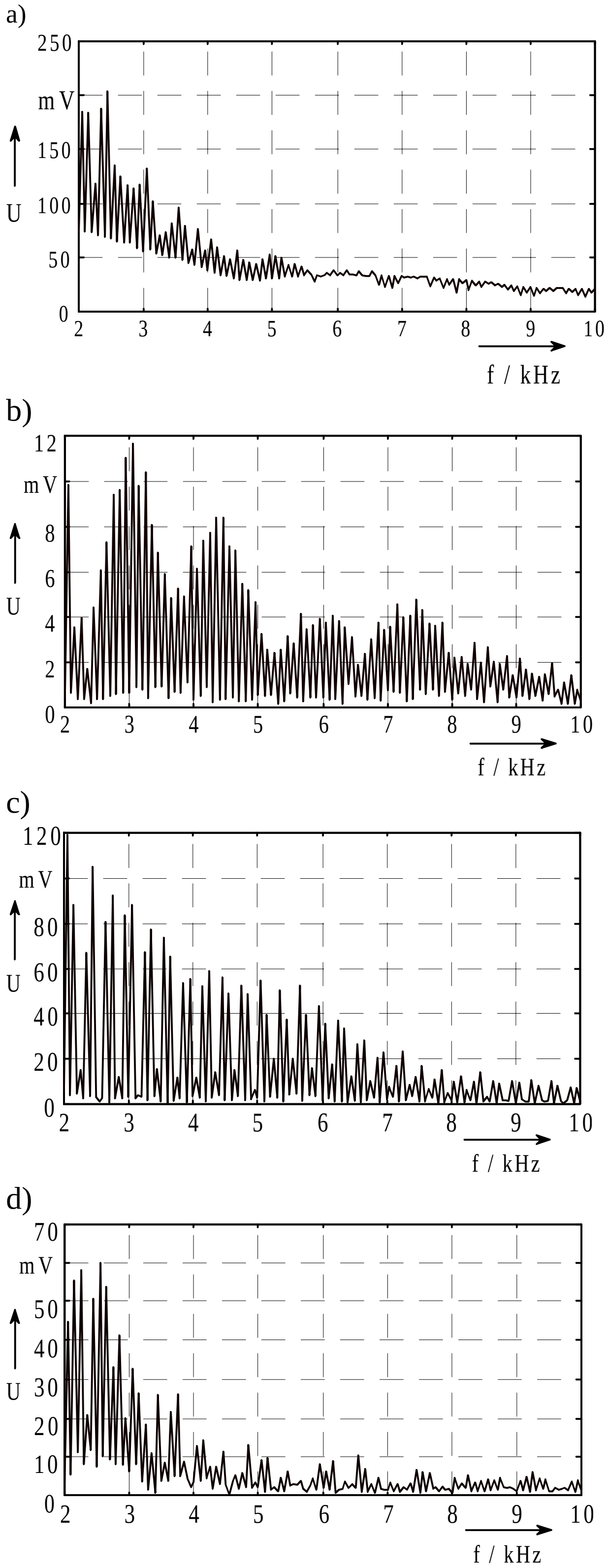

Fig 10: Phase-to-neutral voltage noise spectra in the range 2...10 kHz (rms, frequency resolution 50 Hz)
a) Envelope of all measured spectral lines
b) distribution transformer
c) university lab
d) Small-town family house

5. CONCLUSION

Extensive measurements on public LV networks were carried out to determine the line impedances in the frequency range 2..9 (40) kHz. Statistical evaluation of the data was performed, resulting in recommendations on the estimation of impedances in cable systems and overhead systems. Coupling impedances and the background voltage level in the same frequency range have been examined exemplary, yet some additional work would be desirable to establish statistically validated data. Reliable data are a valuable support of future standardization work in IEC on the frequency range 2...9 kHz.

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LIST OF SYMBOLS, SUBSCRIPTS AND ABBREVIATIONS

$\underline{E}_N$	vector of EMF voltage
f	frequency
i	time function of current
$\underline{I}$	vector of current
L	inductance
LV	low voltage
m	measurement, e.g. f_m, $\underline{I}_m$, $\underline{U}_m$
N	line, e.g. $\underline{U}_N$
Q	quality factor of a resonant circuit
R	resistance
u	time function of voltage
$\underline{U}$	vector of voltage
$\underline{Z}_N$	line impedance
$\underline{Z}_1$, $\underline{Z}_2$	line impedance at port 1, 2 resp.
$\underline{Z}_{50}$, $\underline{Z}_{2k}$, $\underline{Z}_{9k}$	line impedance at 50Hz, 2kHz, 9kHz, resp.
$\underline{z}_{11} \cdots \underline{z}_{22}$	elements of impedance matrix
Δ	variation, change

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