AN ARTIFICIAL NETWORK FOR EMISSION TESTS IN THE FREQUENCY RANGE 2-9KHZ

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SUMMARY

Starting from general requirements for repeatable measurements and correct assessment of current emissions which originate from low-voltage (LV) apparatus in the range 2-9 kHz, this paper proposes an artificial network (AN), addresses its manufacturing criteria and reports test results gained with a first prototype. The AN is expected to be connected between the test voltage (230 V/50 Hz), e.g. the common LV supply system, and the equipment under test (EUT). It comprises only three resistors, three reactors and one capacitor in each phase and causes only small losses. Moreover, the damping of distortions in the range 2-9 kHz by the AN is high in both directions. Therefore, this circuitry both isolates the EUT from distortion of the power source and preserves the power quality of the supply system.

Low-cost elements served to build up a prototype validated up to 10 A rms. It has a reasonable size and weight to be perfectly portable. Test results remained within 5% of its target values and proved the performance of this simple AN for measurements of current emissions in the range 2-9 kHz.

INTRODUCTION

Physical background

Some types of low-voltage (LV) equipment, e.g. switched-mode power supplies or pulse converters, emit voltage or current components into the power-supply system in the frequency range beyond the harmonic range. Some types tend to act as “voltage source”, others as “current source”. In order to achieve repeatable results of emission-test measurements the test conditions need to be identical as far as possible particularly those of the power source.

The impedance of the voltage source beyond the harmonic range, i.e. >2 kHz, may strongly influence the voltage and current components emitted by the EUT in this frequency range. Moreover, the voltage distortion at the EUT terminals in the harmonic range may alter the EUT behaviour and hence the emissions it produces as well. Therefore, the source side impedance at the fundamental and harmonic frequency also needs to be well defined, and should correspond to realistic values normally found in common LV systems.

Requirements for an artificial network

A well defined artificial network (AN) connected in series to the power source renders possible the desired repeatable and meaningful measurements provided it complies with the following requirements:

1. The AN should present at its EUT side terminals an impedance in conformity with realistic LV network impedances.
2. The AN should be adaptable to slightly different internal impedances of the voltage source without changing the impedance seen by the EUT.

3. The AN should effectively attenuate distortions introduced by the voltage source at the EUT side (for frequencies >2 kHz).
4. The AN should effectively attenuate distortions introduced by the EUT at the voltage source side.
5. The AN should be as simple as possible.
6. The AN should allow direct measurements of voltages (\(U_{EUT}\)) and/or currents (\(i_{EUT}\)) at the EUT side, and these values should follow the simple equation \(U_{EUT} = Z_{AN} \cdot i_{EUT}\) in the range 2-9 kHz.
7. The losses of the AN due to the 50Hz-current of the EUT should be as low as possible.

Historical background

For testing single-phase equipment above 9 kHz CISPR16-1: 1993 published an AN which provides an impedance defined by ((50 µH + 5 Ω) || 50 Ω). In order to extend its applicability down to the frequency range 3-9 kHz an “adaptive network” was added to the original CISPR-network [1a,b]. This new AN consisted of 16 elements, but its impedance characteristic in this lower frequency range differed from the usual impedances in actual LV systems (230V / 50 Hz). At least the requirements 1, 5 and 6 were not well covered by this AN. Therefore, research work for a new AN was started.

LV-SYSTEM IMPEDANCES AT 2-9 kHz

In order to find the appropriate impedance characteristics according to requirement 1, the internal impedances and coupling impedances (“phase to neutral” and “phase to phase”) within public LV networks in the frequency range 2-9 kHz were measured in Germany during 1 year. The “invasive” method was used, i.e. the quotient \(U/I\) of the voltage response \(U\) to a controlled injected current \(I\) was evaluated. Measurements at 250 different nodes, lasting between a few hours and one week per node, gained roughly 6000 impedance curves corresponding to 1000-h total measuring time [2]. The measurement points included cable- and overhead-line systems in cities, residential and rural areas; busbars in transformer stations; meter points and outlet sockets in labs, shops and households.

The curves “impedance over frequency” displayed mostly at 5 and 6 were not well covered by this AN. Therefore, research work for a new AN was started.
by 90-95% of all cases, i.e. at all nodes and all times. It is approximated by equation 1 for the frequency range of 2-9 kHz with \( f \) as the frequency and \( Z_{\text{ideal}} \) as the target impedance at the EUT side of the new AN.

\[
Z_{\text{ideal}}(f) = \left( \frac{f}{1\,\text{kHz}} + 1 \right) \Omega \quad \text{(Eq. 1)}
\]

NEW ARTIFICIAL NETWORK FOR 2-9 kHz

Measurement setup

The artificial network (AN) should be connected between any normal LV-supply system within a test laboratory and the equipment under test (EUT) as shown in Fig. 1. The AN can be used for single-phase measurements and three-phase measurements. In this case, three identical artificial networks have to be combined. The figure proposes the measurement of currents depicted from shunts (not shown) but the measurement of voltages directly on the EUT terminals is also possible.

![Fig. 1: General single- and three-phase measurement setup](image)

Description of the artificial network

The basic structure of the AN – low-pass elements in the main path and high-pass elements in the shunt path – was taken as prerequisite. The number of elements was minimized and their values were optimized by computer simulation in order to find the best fit to (Eq. 1) and to fulfil as far as possible other requirements mentioned before. The optimisation resulted in an AN which consists of only three resistors, three reactors and one capacitor per phase as shown in Fig. 2. A shunt resistor of negligible size (0.02 Ω) for current measurement can be added on the EUT side of the AN.

![Fig. 2: Artificial network circuit for one phase.](image)

Impedance and transmission behaviour

To precisely assess the signal transmission, the network depicted in Fig. 3 is investigated. Besides the elements \( R_1, R_2, R_3, L_1, L_2, \) and \( L_3 \) the inductors parasitical resistances \( R_{L1}, R_{L2} \) and \( R_{L3} \) are taken into account.

\[
I_{\text{Source}} = I_{\text{EUT}} \cdot Z(f) \cdot H_0(f) / Z_{\text{Source}}(f) \quad \text{(2)}
\]

For \( f = 2 \) kHz and \( I_{\text{EUT}} = 0.1 \) A, for example, the current injected into the voltage source is only \( I_{\text{Source}} \approx 0.033 \) A.
PROTOTYPE REALISATION

The proposed circuitry of the AN comprises a few resistors and one capacitor, all available at low cost, but also wideband high-power inductances at possibly high cost. Obviously, high-quality inductances with low tolerance and low losses can be built by using multiple isolated stranded conductors to reduce the skin-effect and high-permeability magnetic material up to 9 kHz but at increased cost. Stray capacitances and remaining skin effects of conductors substantially change the inductance characteristics as the frequency increases. Hence, a sensitivity analysis on appropriate accuracy of elements helped to produce a low-cost prototype of the AN for testing in the range 2-9 kHz. Resulting from the sensitivity analysis, table 1 presents the admissible errors in the frequency bands 50-2000 Hz and 2-9 kHz respectively. These errors clearly indicate the appropriate choice of the target frequencies for the layout of the elements. Since the voltage-source impedance ($R_{source}$ and $L_{source}$) may largely fluctuate without affecting the AN output impedance in the 2-9 kHz range, the sensitivity analysis proves that requirement 2 is fulfilled. In fact, $R_{source}$ and $L_{source}$ may be excluded from the equivalent network (Fig 3) without affecting the emission test in the 2-9 kHz range. Except for $R_{source}$ which is by 62 m$\Omega$ lower than the target, measurements of each element at 50 Hz, 2 kHz and 9 kHz show values very close to the target well within the allowed error bands. Additional resistance resulting from welding and wiring adds serial resistance very close to this missing 62 m$\Omega$ for $R_{source}$.

The most inductances of the prototype consist of small toroidal ferrites with air gaps and round copper conductors of 5.25 mm², see Fig. 6. Depending on the number of turns, each inductor reaches an inductivity of up to 150 µH in the range 50 Hz to 9 kHz combined with a resistance of 0.025 $\Omega$ at 50 Hz to 0.75 $\Omega$ at 5 kHz. Only the inductance $L_3$ consists of a rectangular-window core with flat conductor which provides 700-µH inductivity at a low resistance close to 0.025 $\Omega$ (see [3, 4] for more information).

Fig. 5: Impedances of the artificial network

This analysis examined in steps of 10 Hz up to 9 kHz the changes of the EUT side impedance of the AN depending on element changes. The AN with perfect elements would provide the “ideal” impedance. Detuning one element at the time, the maximum error for that element is defined by the point where one frequency component of the AN impedance deviates by more than 5% from its ideal value. The analysis was performed in 2 frequency ranges. This helped to find the appropriate target frequency for the design of each element.

Table 1: Maximum error allowed for keeping output impedance within ±5%, and measured values

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Target values</th>
<th>Max. error in frequency range</th>
<th>Target frequency</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{source}$</td>
<td>318.3 µH</td>
<td>-10%, +9.6%, -100%, +68%</td>
<td>50 Hz</td>
<td>319 µH</td>
</tr>
<tr>
<td>$R_{source}$</td>
<td>0.2 $\Omega$</td>
<td>-25%, +23%, -100%, +1470%</td>
<td>50 Hz</td>
<td>0.138 $\Omega$</td>
</tr>
<tr>
<td>$L_1$</td>
<td>500 µH</td>
<td>-11%, +12%, -72%, + + $\infty$</td>
<td>50 Hz</td>
<td>504 µH</td>
</tr>
<tr>
<td>$R_{L1}$</td>
<td>0.1 $\Omega$</td>
<td>-60%, +55%, -100%, + $\infty$</td>
<td>50 Hz</td>
<td>0.06 $\Omega$</td>
</tr>
<tr>
<td>$R_1$</td>
<td>4 $\Omega$</td>
<td>-8%, +14%, -43%, +160%</td>
<td>50 Hz</td>
<td>4.0 $\Omega$</td>
</tr>
<tr>
<td>$L_2$</td>
<td>225 µH</td>
<td>-27%, +36%, -7.4%, +7.6%</td>
<td>5 kHz</td>
<td>227 $\mu$H</td>
</tr>
<tr>
<td>$R_{L2-R2}$</td>
<td>3.4 $\Omega$</td>
<td>-10%, +10%, -10, +10%</td>
<td>5 kHz</td>
<td>3.247 $\Omega$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>1 $\Omega$</td>
<td>-19%, +15%, -14.4%, +15%</td>
<td>1 kHz</td>
<td>1.0 $\Omega$</td>
</tr>
<tr>
<td>$C$</td>
<td>50 $\mu$F</td>
<td>-4%, +4.5%, -20.7%, +7.4%</td>
<td>1 kHz</td>
<td>50 $\mu$F</td>
</tr>
<tr>
<td>$L_3$</td>
<td>700 µH</td>
<td>-12%, +12%, -14%, +17.3%</td>
<td>2 kHz</td>
<td>750 $\mu$H</td>
</tr>
<tr>
<td>$R_{L3}$</td>
<td>0.025 $\Omega$</td>
<td>-100%, +225%, -100%, +1650%</td>
<td>2 kHz</td>
<td>0.032 $\Omega$</td>
</tr>
<tr>
<td>$R_{Shunt}$</td>
<td>0.02 $\Omega$</td>
<td>-100%, +225%</td>
<td>50 Hz</td>
<td>0.4 $\Omega$</td>
</tr>
</tbody>
</table>

Fig. 5: Impedances of the artificial network

Fig. 6: Typical inductance

Fig. 7: Prototype exterior

Fig. 8: Impedances

Table 5: Impedances of the artificial network
A wooden box of only 9 kg weight and only 20 x 21 x 57.3 cm size houses the AN, Fig 7, so that it is perfectly portable. A cover protects the electrical terminals during travelling. An angle of 90° in magnetic field direction between each inductance reduces the field interaction although the toroidal cores control already the major proportion of the magnetic field.

TEST RESULTS

Laboratory tests performed by Hydro-Québec (IREQ) in Canada confirmed that the impedance of the artificial network prototype remains within ±1.5% of the target value in the range of 2-9 kHz, Fig. 8.

Since IEC considers this artificial network in the international standard IEC 61000-4-7 [5], this prototype is circulating in several countries for extensive validation. Up to now, manufacturers of different products in Belgium, Germany and the Netherlands observed very good performance of the prototype during emission tests. The electrical behaviour of the equipment was not changed due to the insertion of the artificial network between the voltage source and the EUT. Similar results of tests which, on the one hand, used directly the outlet socket in a lab as voltage source without the AN and, on the other hand, included the AN in series between the outlet socket and the EUT, confirmed that the AN reproduces correctly the usual system impedance characteristic in the range 2-9 kHz.

CONCLUSIONS

A new artificial network which allows repeatable emission measurements of low-voltage equipment in the frequency range 2-9 kHz is presented. It was developed by computer simulation at the university Erlangen-Nuremberg in Germany. A first prototype based on the results of the simulation was built up and tested at Hydro-Québec in Canada. Further tests with the prototype network are going on in other countries.

The new circuit complies well with the basic requirements: It presents a power source with appropriate and stable impedance characteristic to the tested equipment, isolates it from distorting effects of the voltage source and – vice versa – protects the source from distortions of the tested equipment; it consists of only a few low-cost elements and causes only low losses during operation.

The first tests with the new artificial network are very promising. The measurement results are repeatable, and the electrical behaviour of the tested equipment is not altered by the network. If – as it is expected – the tests running at time confirm the good experiences gained up to now, the new artificial network should be standardised by IEC.

REFERENCES

[1a] EN 50065-1, 1997, “Specification for Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz. Part 1: General requirements, frequency bands and electromagnetic disturbances”.


