# Conducted mains test method in 2–150 kHz band

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***Abstract* - The frequency band from 2 to 150 kHz is used for most mains related power conversion applications, like uninterruptable power supplies (UPS), pulse width modulation (PWM) drives, active in-feed converters (AIC), switched mode power supplies (SMPS), solid state ballasts, LED drivers which are all polluting the domestic and industrial mains distribution networks. On the other hand, the same frequency band is used for power line communication (PLC) and distribution line carrier (DLC) communication systems as well as for most active capacitive, inductive and even resistive sensors. Most of these sensors have their carrier frequency within this band.**

**As such, conducted emission as well as conducted immunity requirements need to be established for single phase, symmetrical and three phase applications and for grounding structures by using coupling and decoupling networks with a defined source/load impedance. The coupling and decoupling network shall be mains distribution network type independent: TN-S, TN-C, TT, IT. Disturbances within this band can occur either in unsymmetric, asymmetric or differential mode and may affect systems like power meters, residual current detection devices (RCD), active sensors and many other telemetry systems.**

**Several International Standards (IS) have been published [3–15] but none of them offers (yet) an unambiguous solution for the coupling and decoupling network(s) required. In this paper, a coupling and decoupling network is presented which can be used in this frequency range for measuring the RF emission from as well as enable the injection of disturbance onto a dedicated mains port. A network has been implemented for 3-phase power applications, is transparent at the mains frequencies: 50/60 Hz, and capable to handle up to 150 Amp/phase.**

***Index Terms - coupling and decoupling network, single phase, symmetic and 3-phase mains distribution system, low frequency conducted emission, low frequency conducted immunity, power line impedance***

## I. Introduction

By lacking proper legislation, the frequency band 2-150 kHz has been used as the ‘garbage’ band for many power conversion designs. Posing EMC requirements now means that these power conversion systems might become more expensive, larger (due to the extra filtering required) or even obsolete as other conversion concepts or other switching frequencies need to be chosen.

Over the last few years, many reports have been published about the noise which appear to occur in the frequency band concerned [Bartak, SC205A]. Aside the noise on the mains distribution networks, also impedance resonances, due to the many mains filters connected to these mains distribution networks occur [21, 22]. Even worse, at the local low-voltage mains distribution centers, large power factor (PF) correction capacitors (which equal an RF short-circuit) are added in-between or across the mains phases to assure a PF i.e. cos (φ) equals ‘1’ at the mains frequency. This is done to minimize the so called ‘blind currents’ and as such optimize the power system efficiency beyond the local low-voltage mains distribution system.

Dependent upon the power cables used for distribution, the mains frequency power is dispersed to its loads. But even at these low frequencies: 2-150 kHz, circuit and cable length resonances occur in the mains distribution network for which no requirements apply. As such, even small disturbance voltages or currents injected onto such a distributed resonant network may show up somewhere as excessive voltages due to the impedance resonances occurring.

Neither of the International Standards [3–15] define impedances for the mains distribution network in such a way that these impedance requirements can be used to establish an ‘artificial’ impedance (similar to the AMN or V-network for the higher frequencies (9) 150 kHz onwards: 50 Ω // (50 µH + 5 Ω) from each of the phases to PE [IEC CISPR 16-1-2]).

## II. Requirements

From the introduction it is clear that we need a coupling and decoupling network, preferably suited for 3-phase mains distribution network systems which is transparent at the mains frequency: 50/60 Hz but which provides sufficient decoupling above 2 kHz. Only at the mains frequency: 50/60 Hz, the mains impedance is defined [4] and has an equivalent network impedance of 0,1 Ω (for domestic environments and even less for industrial environments) with 470 µH (representing the sum of the mains transformer’s stray inductances and some cabling inductance) in series.

To enable conducted emission measurements, the mains frequency signals must be suppressed sufficiently to enable measurement e.g. into a 50 Ω measurement system. The measurement system may be an EMI-receiver or an oscilloscope with the proper FFT capabilities. If a suppression factor for the fundamental mains frequency of 60 dB is taken as a requirement, at least a $3^{rd}$-order high-pass filter at 2 kHz shall be used. Typically, the amplitude of the mains harmonic signals decline with the harmonic numbers as required [3-6].

On the opposite, while performing conducted RF immunity tests, the mains frequency signal (and its harmonics) may not affect the output of the power amplifier providing the disturbance signal with an amplitude up to e.g. 30 Volts to be superimposed on the mains signal e.g. 230 $V_{AC}$ @ 50/60 Hz. Also here, the impedance of the disturbance source represented in series or parallel to the decoupled mains distribution network has to be defined and shall NOT affect the mains distribution network impedance at the fundamental frequencies.

Own measurements have revealed a rather low asymmetric mains impedance of 1 Ω: phase or neutral to PE, in the frequency range 2-150 kHz for industrial networks whereas a value of 8 to 10 Ω can be found for domestic environments. The latter finding combines fluently with the impedances used in the AMNs as defined in IEC CISPR 16-1-2 which should equal 50 Ω // (50 µH + 5 Ω) from 9 (for lighting applications) or 150 kHz onwards.

Due to the circuit impedance resonances occurring and the mains distribution cable lengths involved, the mains impedance scatter over a very broad range. Then, fully determined by the stack-up of mains filters connected, typically π-filters rather than T-filters, an RF-wise short-circuit or open-circuit will be represented by the 'filtered' load connected. Further statistical evidence needs to be gathered, similar as done to define the impedances used with an AMN or an AAN. Even the present AMN requirements might need revision as the latest large scale inventory was made in the mid 80-ties, then when only a limited number of equipment used mains filters and most of the cables used for mains distribution were non-shielded.

## III. Decoupling Network

For decoupling, no simple reactor network can be used as the voltage drop across the series inductances at low frequencies at high current would become intolerable. Using common-mode structures instead e.g. using a ring core/toroid has the advantage of less voltage drop, due to flux compensation, but with the disadvantage that the decoupling impedance only occurs in common-mode with too little stray inductance/leg.

To overcome this issue, a 4-leg common-mode choke has been developed based on I-core laminated thin-transformer steel layers which are magnetically coupled at all four corners forming a square. At low frequencies the magnetic flux induced by the four coils: 3 phases and neutral compensate each other resulting in 'zero' flux. However, at the higher frequencies, the relative permeability of the core drops and thus the coupling between the individual inductors reduce and above 10 kHz four fully independent reactors result.

While starting with core-based inductances of 1-10 mH each at 1 kHz or less, the effective inductance will turn into non-coupled near air-coils at about 0,4 MHz. At mains frequencies, the mutual coupling is ≥ 0,97 yielding a stray inductance of a few µH's which is neglect able compared to the 470 µH used in [4], see figure 4. When the phase inductance is 1 mH, the impedance reaches 12,5 Ohm at 2 kHz, Two 150 Amp 4-leg chokes as manufactured in different batches and measured have 5,6 and 8,5 mH/leg. Also 700 Amp 4-leg common-mode versions have been created successfully. When the industrial mains distribution network impedance has to represent 1 Ω asymmetrically, a decoupling of at least 20 dB @ 2 kHz is achieved. Due to the complex permeability decline of the laminated transformer steel no simple equivalent element can be derived to be used in an analogue circuit simulation environment like SPICE.

## IV. Coupling Network

The coupling network may look quite simple but from the fact that 30 Volts RMS may have to be injected onto the mains voltage as a 1 Ω equivalent network, the filtering needs to be robust and lossless. To ultimately drive 30 Volt onto a 1 Ω load, a 900 Watt signal LF source is needed, preferably with an output impedance of 1 Ω or 10 Ω.

Many high-power class D audio power amplifiers have an internal output filter which ensures a low output impedance below 20 kHz but then the output impedance increases substantially above 20 kHz. A few COTS amplifiers have been found which satisfy the impedance conditions required.

Equal to the output voltage of 30 Volt also the output current of 30 Amps needs to be achieved over the full range up to 150 kHz.

Worse-case, the bandwidth of the band-pass or high-pass filter, being a T-filter, has its -3 dB at these corner frequencies. As such, a (known) error is made of 30%, which from a metrology and a measurement uncertainty point of view is intolerable. The proposed 4$^{th}$-order Chebyshev F-filter used comprises two AC-capacitors and two wide copper-band foil inductors of 0,22 mH each, lined up similar as in figure 1.

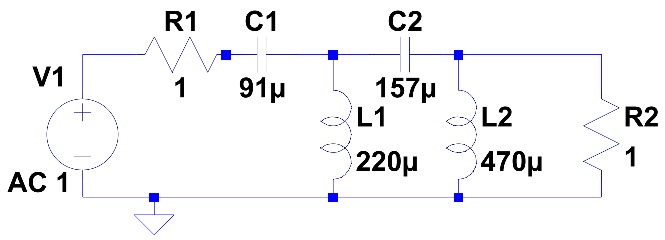


Figure 1 - High-pass coupling filter

By using a Chebyshev 5$^{th}$-order high-pass filter in a 1 Ω impedance environment, while deleting the last capacitor, a smooth transfer function can be achieved as given in figure 2. The horizontal scale is from 10 Hz to 1 MHz and the vertical scale ranks from 0 to -120 dB. At 2 kHz the insertion loss is 0,6 dB while the losses i.e. rejection at 50/60 Hz is already 90 dB.

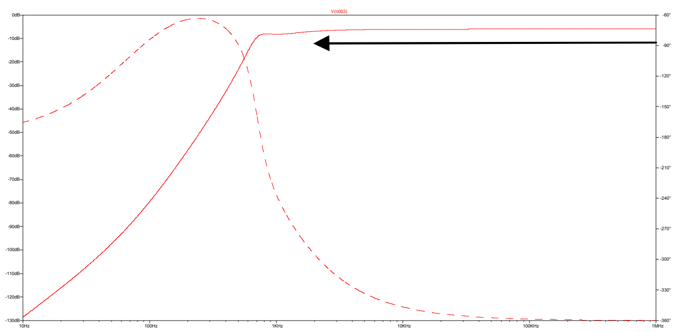

Figure 2 – Calculated transfer of the high-pass coupling filter

To create a true measurement port impedance of 1 Ω with the conducted emission measurements a 1,02 Ω shall be placed in parallel to a 50 Ω input port. COST probes are available for this function. By using a 1,0 Ω power resistor in parallel to a 50 Ω impedance, the total impedance becomes 0,98 Ω, resulting in an known error of 2 %. With the $4^{th}$-order F-filter as given in figure 1, the measurement port impedance becomes 1,2 Ω @ 2 kHz, see figure 3, when no mains decoupling circuit is taken into account e.g. when injecting into the grounding structures.

The full coupling network is needed once for injecting to or measuring from the groundings structures but is needed 4 times for all three phases including neutral. The protective earth (PE) terminal itself is considered continuous and left unaffected.

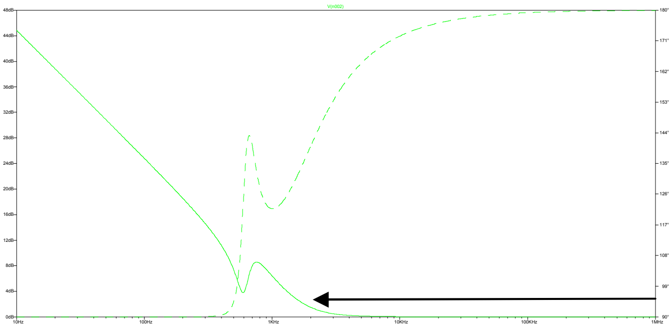

Figure 3 – Calculated input impedance of the high-pass coupling filter

With a 4-leg common-mode choke a series inductance of 1-10 mH can be achieved at 1 kHz/mains phase with a coupling factor of 0,97. The series inductance then reduces above 1 kHz by which also the mutual coupling between the phases degrades to 10% or less. As such a series impedance per mains phase of j·12,6 - 126 Ω can be achieved at 2 kHz leading to minor errors in the port impedances. At the higher frequencies, the series impedance increases though the effective permeability decreases: $|\mu_r| = |\mu_r' + \mu_r''|$.

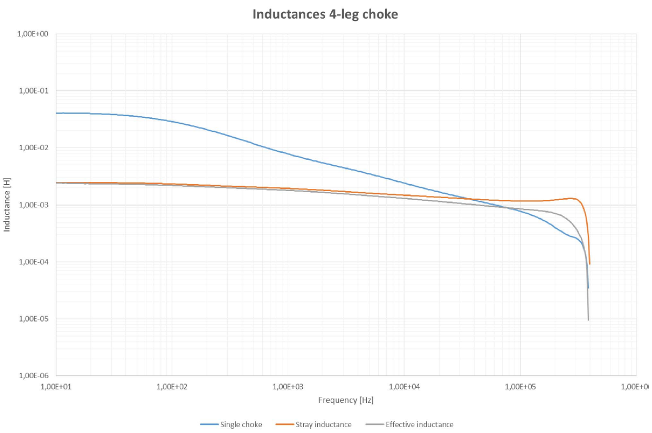


Figure 4 – Measured inductances from the 4-leg choke

## V. TOTAL CIRCUIT

The total 3-phase + neutral conducted mains measurement circuit, providing coupling and decoupling then becomes equal to the circuit given in figure 5. The mains distribution supply impedance is considered equal to the value of 0,1 Ω with 470 μH in series [4]. For the disturbance source output impedance (immunity) or the measurement equipment input (emission) an impedance value of 1 Ω is taken.

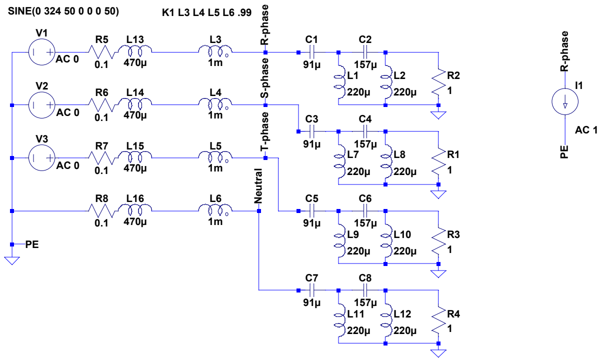


Figure 5 – 2 - 150 kHz coupling/decoupling circuit for a 4-line mains

The left hand side represents the 3-phase mains w/wo neutral. The center inductances represent the over-simplified 4-leg I-core with mutual coupling. The right hand side circuits show the high-pass filters and totally right the I/O port for measuring the emission from or injecting the disturbance to is given and represented by 1 Ω resistors.

By applying a current source at the terminals R-phase versus PE, the measurement port impedance is calculated, see figure 6. As can be seen, the measurement port impedance does become erratic below the intended measurement frequency of 2 kHz but is close to 1 Ω above 2 kHz.

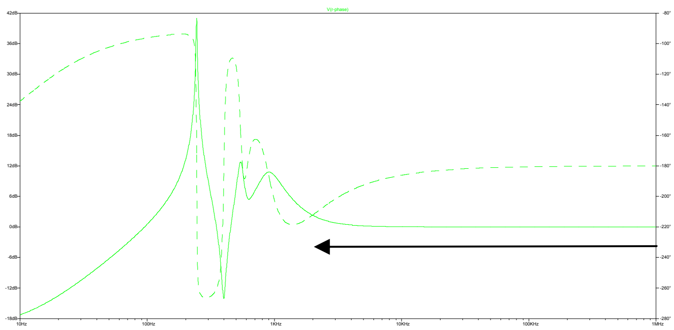

Figure 6 – Measurement port impedance between e.g. the R-phase and PE of the total 2 – 150 kHz coupling/decoupling circuit

Furthermore, the insertion losses between the measurement i.e. injection port and the measurement port is calculated and given in figure 7. The transfer is close to flat above 1 kHz but within 0,4 dB above 2 kHz

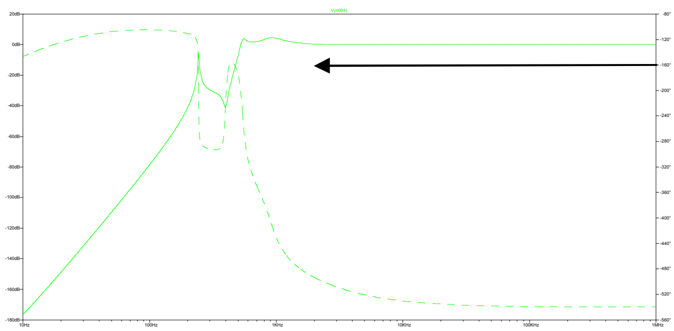

Figure 7 – Insertion loss from the R-phase to PE of the total 2 - 150 kHz coupling/decoupling circuit to the right hand side equipment port

The phase-to-phase impedance becomes slightly too high at the lowest frequencies but then becomes well-defined above 4 kHz and equal again to 1 Ω.

At present the total 2–150 kHz coupling/decoupling network is under construction and first tests have been done on the 4-leg common-mode choke w.r.t. the current carrying capabilities and saturation. The final results will be presented at the symposium.

## VI. Conclusions

The present standards and publications [3-15] do consider the issues in the frequency band 2-150 kHz, but no proper measurement network for measurement of or injection onto equipment ports had been defined.

No large-scale investigation has been carried out (yet) w.r.t. the actual impedances occurring on a broad range of mains distribution networks. Just a few empiric mains impedance measurements have been taken. Additional work should be carried out to underpin the mains impedance values as defined in this paper.

Adopting the presented 2-150 kHz coupling/decoupling circuit makes it possible to perform qualitative and quantitative conducted emission and immunity measurements for any type of mains supplied equipment without constraints up to a level of 150 Amp/phase. Similar 4-leg decoupling chokes have been manufactured up to 700 Amp/phase with short-circuit handling capabilities of 35 kA/phase. As such there are little engineering limitations for practical application.

Similar as in real installations as with other measurement networks, the measurement port impedance goes erratic below 2 kHz due to the $4^{th}$-order filtering applied.

It is quite unlikely that COTS high-power AC power sources, single, symmetric or three-phase, will become available to generate the disturbance signals required superimposed on the power mains frequency signal with the impedances and amplitudes over the frequency considered.

A similar coupling and decoupling technique can also be applied when common-mode disturbance signal injection is required into a single, symmetric or three-phase system.

## VII. Acknowledgment

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