‘Live’ mains impedance measurement and analysis

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'Live' Mains Impedance Measurement and Analysis

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***Abstract*— Since the 1980-ties, the asymmetric mains impedances have been defined by IEC CISPR 16-1-2 [1] and used in an artificial mains network (AMN) suited in the frequency range (10) 150 kHz to 30 MHz. The mains impedance has recently been extended by the definition of asymmetric or common-mode artificial networks (AAN) and coupling/ decoupling networks (CDN) which are defined to be used in the frequency range 150 kHz to 80 MHz.**

All power mains impedances defined with these networks represent mean values from statistical data gathered and these networks are formally used to demonstrate conducted mains RF emission (and RF immunity) compliance in a defined and reproducible manner.

However, other international EMC standards like IEC 61000-3-2 [4] and 61000-3-3 [5] consider mains frequency harmonic emission and flicker from the same mains wall outlet sockets with other impedances, this from the mains frequency upwards to 2 kHz. The mains impedance in the intermediate/overlapping frequency range from 2 kHz to 150 kHz is considerably less as defined by IEC 61000-4-19 [3] which is opposed to the mean values as given by IEC 61000-4-7 [2] where the mains impedances are much higher.

In this paper, two 'live' mains impedance measurement techniques are given to obtain a detailed impedance behavior in time and/or frequency domain. Knowing the 'real' mains impedances means that one is able to forecast resonances and derive the optimal way on how to apply mains filters effectively, while using their appropriate parameters. Mains distribution optimization can also be used inside a large system or installation.

Keywords*— *mains filter, mains impedance, 'live' mains

I. Introduction

Since the mid of the 1980-ties, the asymmetric mains impedance has been defined by IEC CISPR/A. This asymmetric mains impedance is defined by an artificial mains network (AMN) or V-network, suited in the frequency range (10) 150 kHz to 30 MHz, having an impedance: 50 Ω in parallel to (50 µH + 5 Ω) with tight phase tolerances. This mains impedance definition has recently been extended by an asymmetric artificial network (AAN) or coupling/decoupling network (CDN) in IEC CISPR/A/1023/FDIS being 150 Ω in the frequency range 150 kHz to 80 MHz. The latter network definition is close to similar to the ones described in IEC 61000-4-6.

All mains impedances defined represent mean values from statistical data gathered from various mains wall outlet sockets and are thereafter used to demonstrate conducted mains RF emission (and RF immunity) compliance in a defined and reproducible manner.

Other international EMC standards e.g. IEC 61000-3-2 and 61000-3-3 consider mains frequency harmonic emission and flicker from the same mains wall outlet sockets with other impedances up to 2 kHz but the mains impedance is just 0.1 + j0.15 Ω between phase and neutral at 50/60 Hz. This impedance equals 0.1 Ω + 470 µH at 50 Hz. The differential mains impedance (between neutral and one of the phases) in the intermediate/ overlapping frequency range from 2 kHz to 150 kHz is assumed to be 1 Ω by IEC 61000-4-19 whereas to the values given in IEC 61000-4-7 vary between 0.2 and 12 Ω in the same frequency band. An overview of the impedances throughout the frequency bands is given in figure 1.

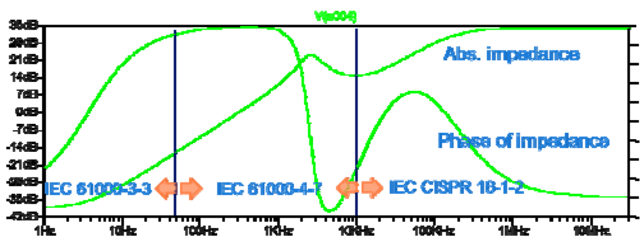

Figure 1 – Cascaded mains impedances from the various standards

On the left hand side of the vertical axis of figure 1, the absolute mains impedance is given in dB(Ω) as a function of frequency. On the right hand side vertical axis, the phase of the impedance is given, being resistive at 30 MHz. This varying mains impedance can be easily achieved by an equivalent lumped network.

When also mains transient phenomena are considered like surge and burst, again other impedances are considered from the same mains wall outlet sockets. ~2 Ω is used as differential impedance with the surge (1.2/50 µs) as where 12 Ω is used as an asymmetric mains impedance for the same phenomena. For electrical fast transient bursts (EFT), 50 Ω is considered the asymmetric mains impedance.

Various attempts have been taken to measure the 'live' mains impedance [7, 8, 9] but most of them are limited in frequency range.

II. WHAT HAS CHANGED ?

While being involved with these mains impedance measurements in the late 1980-ties, these impedances were mostly gathered in the frequency domain. In those days, hardly any legally enforced requirements were given for the conducted RF emission requirements, power quality and the mains frequency harmonics. The legal necessity to comply with EMC requirements in Europe started in 1992 with the publication of the 1st EMC Directive.

The mains impedance was dictated by the mid-to-low voltage mains transformer with some cabling in-between leading to the public mains wall outlet sockets considered. Statistically, it could even be proven that the asymmetric impedance as seen at the mains wall outlet sockets is dominated by the characteristic impedance of the mains distribution network cables and wiring used. The mains impedance becomes scattered by the various impedance transformations as a function of cable length, branching, loading and frequency, yielding every impedance between 1 Ω and 2.5 kΩ: $\mu \pm 3\sigma$, where $\mu \approx 50\ \Omega$ holds for the frequencies above 1 MHz. When these asymmetric mains impedance values are considered by their logarithmic impedance values, a normal distribution results where 50 Ω equals 34 dBΩ, which is just the average between 0 and 68 dBΩ.

In the past, the AC mains voltage was typically rectified by a bridge rectifier, followed by a huge buffer capacitance. Only during a short fraction at the voltage maxima of the mains period, the rectifying diodes became conductive and charging of the buffering capacitor took place, figure 2. In some cases, a mains filter was used at the mains entry but in those days filter usage was quite uncommon.

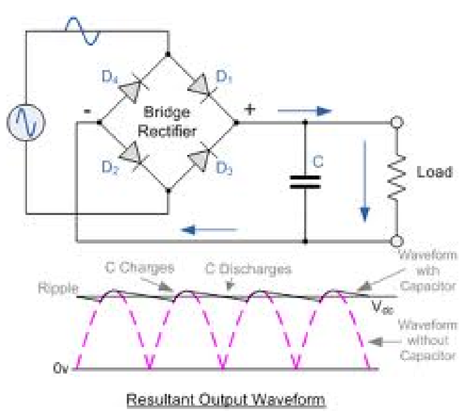

Figure 2 - Example of a diode bridge rectifier

In the meanwhile, power factor correction (PFC) circuits have been introduced on all electronic equipment using more than 75 VA and especially for lighting appliances already above 25 VA. These power factor and mains harmonic emission requirements are mostly not applicable for apparatus for professional use.

Mains filters and overvoltage limiters are now a commonality on all electronic equipment mains entries. This is not only done to achieve compliance with the conducted RF emission standards but more to be able to withstand all immunity threats too.

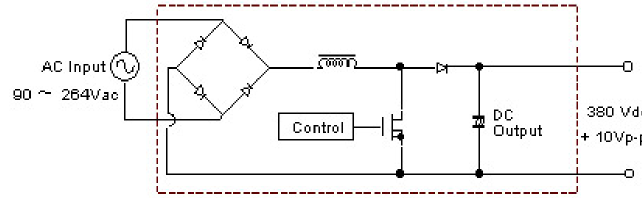

Figure 3 – Simplified example of a power factor correction circuit

As compliance to the mains harmonics and power factor requirements cannot be easily achieved by passive circuitry e.g. using huge series inductors to limit or blur out the di/dt, active circuits are used to align the 'load' current to the mains voltage wave shape, figure 4.

The mains voltage is rectified and then buffered with a small capacitor (omitted in figure 3). The instantaneous rectified mains voltage is used to store energy: $\frac{1}{2} \cdot L \cdot I^2$, into the series inductance, this to represent a near to resistive load to the mains. For PFC circuitry, switching frequencies are typically used between a few kHz: > 2 kHz (mains harmonics) up to slightly less than 150 kHz (EMC requirements).

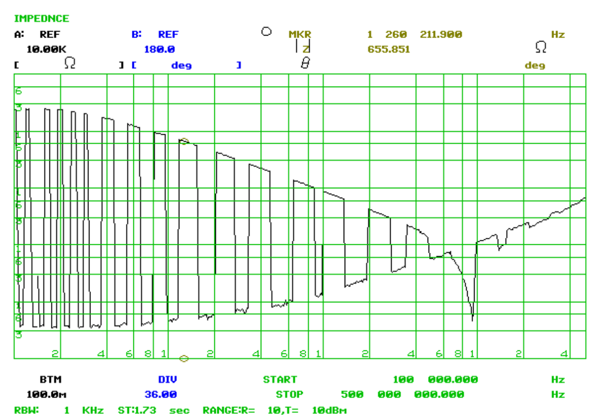

Figure 4 – Impedance behavior of a Schottky diode when biased by a 10 V_{pp}, 10 Hz square wave @ 15 dBm

Different from the 'old' applications, figure 2, the bridge diode rectifiers in figure 3 provide a near constant conductive path to the PFC circuitry used. The equipment's 'load' impedance is therefore more than 95% of the mains period connected to the mains (acting resistively) as whereas in 'old' applications this 'being connected' was typically less than 10% of the mains period, yielding a higher equivalent impedance. Those narrow current pulses were the root cause for a high level of mains harmonic emissions. Top voltage rectification is also the root cause for transformer saturation leading to a trapezium rather than sinusoidal mains voltage wave shape.

When a buffering capacitor of some mF is coupled onto the mains for a fraction of the mains period, what will be the equivalent impedance as seen by the mains? Opposite, for equipment producing interference, it will be connected to the mains for only a fraction of a mains period, compared to a near continuous 'connection' condition when a PFC is used. This conductivity issue also holds for RF immunity. As long as the rectifying diodes are blocking, no interference can pass other than through the stray capacitance of the diodes and the capacitors used in parallel with the rectifying diodes (to dim the dV/dt i.e. diode 'rattle'). With transient phenomena it is assumed that the applied impulse voltages are so high that the rectifying diodes will always become conductive, figure 4.

When measuring the mains impedance of an unloaded mains distribution network, the impedances, as defined in the 1980-ties [1], still hold. When considering a high number of electronic equipment used in parallel to a mains wall outlet, the mains impedance will be substantially less than presently defined for the AMN and AAN (CDN)

III. MEASURING 'LIVE' MAINS IMPEDANCES

The main problem, when one wants to measure the 'live' mains impedance, is the presence of the mains fundamental frequency signal (230 V_{AC} @ 50 Hz or 120 V_{AC} @ 60 Hz) and its harmonics. The second issue, as explained above, is the fact that the mains impedance, when measured near to active loads will vary throughout the mains period determined by the equipment connected, figure 4. In industrial installations, a 'live' mains voltage is used to control the magnet switches which supply the internal mains distribution network down to its load branches.

The interest in mains impedances covers the frequency range from less than the fundamental mains frequency (w.r.t. sub-mains frequency stability issues e.g. with smart grids) up to 30 MHz (= upper limit for conducted RF emission requirements).

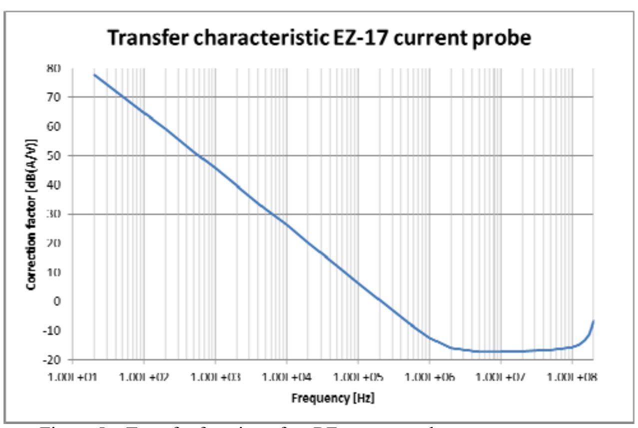

Figure 5 – Transfer function of an RF current probe

'Live' mains impedance measurements can be performed in time- and frequency domain. When performing the impedance measurements in the time-domain, the dynamic range for a high-end oscilloscope is practically limited to 8 or 12 bits with a record length of over 10 MS. Considering the amplitude of the mains fundamental voltage (and its harmonics) all higher frequency signals will vanish in the oscilloscope's quantization noise.

To overcome this dynamic signal constraint known high-pass filters must be added to bring the voltages and the currents to be measured in perspective. After data gathering, the measured raw data has to be corrected for the high-pass filtering applied, either by using convolution algorithms in the time domain or by applying complex inverse high-pass transfer functions in the frequency domain. The high-pass filtering characteristic for an RF current probe stems from the intrinsic low mutual coupling between the primary and secondary winding. With an R&S EZ-17-3 used, the output signal increases proportional with frequency in the band considered up to 1.5 MHz, figure 5.

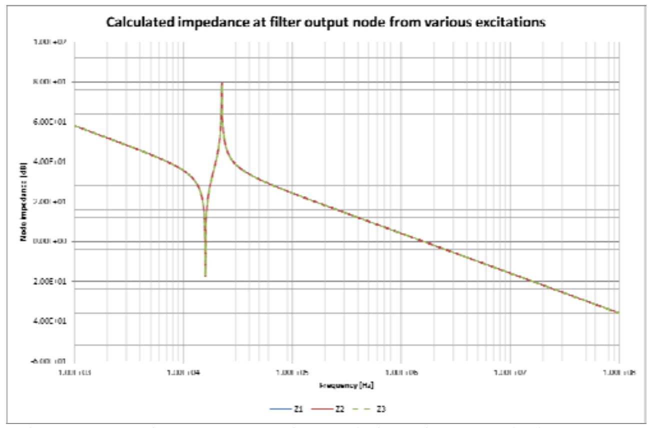

Figure 6 – Impedance as measured at V2, independent on excitation: I1, I2, I3

Using such RF current probes will reduce the accuracy of the current signals at low frequencies but improves the results above 10 kHz. For the voltage probe an AC-coupled 1st-order high-pass filter with a corner frequency of 1 kHz is taken.

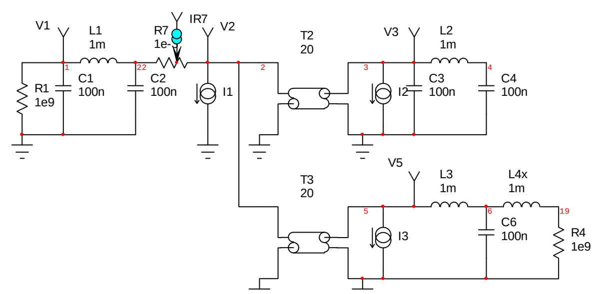

Figure 7 – Example circuit equivalent of a mains distribution network

When the RF current probe is placed somewhere in the power mains distribution network current path, only the current in that loop or mesh will be measured, while it remains unknown how the current loop will be closed i.e. how the total current distribution looks alike.

Also the voltage at that current measurement node shall be measured against an opposite conductor of that loop or mesh. Their ratio (V/I) will determine the node's equivalent impedance (Z_{node}), see figure 6 as a result of the circuit from figure 7.

In figure 7, a common π-filter (upper-left) is connected to two branches, one being terminated by another π-filter and the other branch being loaded by a T-filter. The voltage at V2 (against common) varies as a function of frequency and the excitation position of an internal current. While changing the excitation position of an internal current: I1, I2, I3 (applied sequentially), the accompanying current IR7 adapts too, such that the ratio V2/IR7 is independent from where the mains distribution network circuit is excited.

With time domain measurements the synchronously sampled raw voltage and current signals following the high-pass filters will be recorded over a 100 ms interval at 100 MS/s, thus 10 MS records are taken. These data records result, after FFT, in frequency spectrum plots from 10 Hz up to 50 MHz with spectral components at 10 Hz intervals when the whole record is observed at once. When one is interested in the change of mains impedance at a certain frequency as a function of time, the data record taken can be subdivided in 1000 sub-records of 100 μs each and the impedance change over a time interval e.g. an impedance component at 10 kHz can be obtained.

To perform impedance measurements on 'live' mains in the frequency domain with a VNA, two measures have to be taken:

- The mains fundamental signals have to be suppressed to less than 1 volt (to protect the VNA) and
- The (high-pass) filtering network has to be defined transparent from the lowest frequency onwards to e.g. 10 kHz.

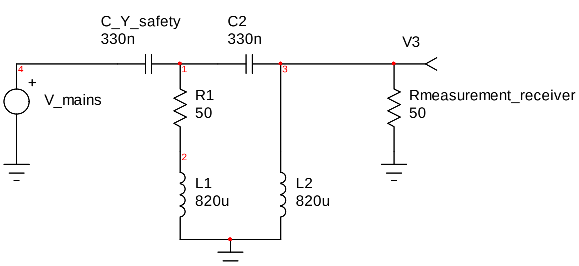

Figure 8 – 4th-order dissipative high-pass filter

For this purpose a 4th-order dissipative high-pass filter has been defined and tested, see figure 8. Different from standard high-pass filters, the RF input impedance remains critically damped, even in the rejection band. To ensure electrical safety, AC-coupling is provided by a safety class-Y capacitor followed by an LC network to protective earth (PE). Then a common 3rd-order high-pass Bessel-filter network is added.

Due to the Y-cap and the RL circuit following, the output signal has become intrinsic non-hazardous if the reference is properly grounded. Due to L2, the output is DC grounded to PE. The transfer function of this filter circuit results in a suppression of the mains voltage by more than 130 dB while being transparent above 10 kHz (-3 dB), see figure 9.

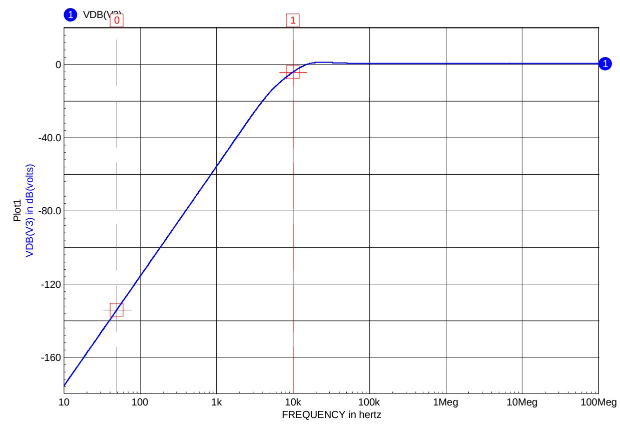

Figure 9 – Transfer function of a 4th-order dissipative high-pass filter

The VNA's impedance port can be connected to the 10 kHz high-pass filter under the condition that the output noise of the 10 kHz high-pass filter, when connected to the 'live' mains, is less than 1 volt (measured across 50 Ω using an oscilloscope with a bandwidth ≥ 50 MHz). As VNAs use synchronous demodulation in their impedance measurements, the VNA can withstand some non-correlated noise. Prior to measuring the 'live' mains impedance, the input port at the mains plug shall be calibrated as an impedance reference plane using an open, short and load condition. Thereafter, the 'live' mains impedance can be measured without further corrections. What this mains impedance means w.r.t. an altering mains impedance over mains periods, figure 4, is unclear and a comparison between time and frequency domain impedance measurements needs to be carried out. These findings will be presented at the symposium.

Impedance measurements in the frequency domain on a live mains circuits have been carried out succesfully without causing damage to the VNA, see figure 10. After calibration at the impedance plane, impedance measurements were taken at the output of an 150 kHz upwards AMN using a 0,3 meter mains cable in-between the impedance plane and the AMN EUT port.

At the frequencies below 150 kHz, the AMN EUT port impedance becomes undefined and is substantially higher than expected from the definition of IEC CISPR 16-1-2. At about 15 MHz, the mismatch effect of a short mains cable ($Z_0 \neq 50$ Ω), is already significant [6]. Other measurements on 'live' mains wall outlets have been performed and this data needs further statistical analysis.

IV. RESULTS

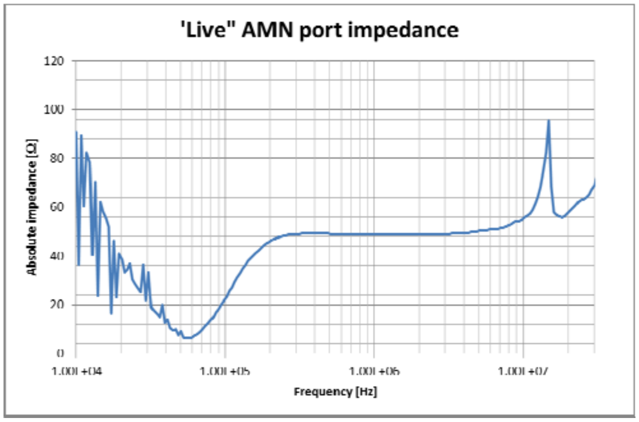

Figure 10 – 'Live' mains impedance measured at an AMN port

On the intra-system mains distribution network, just after a common mains filter, mains impedance measurements were taken in the time domain and thereafter corrected for the voltage and current probes used, figures 5 and 9. From these time domain records 100 ms sampled at 100 MS/s the frequency range from 10 Hz to 30 MHz can be derived, figure 11. In this figure, the whole data record is taken at once, without looking to the impedance variations as a function of time within a mains period. At low frequencies, the average mains impedance is in the milliohm range (as expected) whereas it increases to above 100 Ω at the end of the frequency range considered.

No change in the mains impedance values can be seen at the mains frequency and its harmonics, as expected as the impedance is not determined by the excitation of the mains distribution network. Slight resonances can be found around 2 kHz being an intra-filter resonance. With a common mains filter π-type, peaking occurs just before the filter starts to attenuate.

From these results, the 1 Ω mains impedance as defined in the frequency range 2 – 150 kHz [3] coincides fairly well with the results of this measurement. Measurements in the, frequency domain reveal close to equal results with the time domain measurements, figures 11 and 12. In figure 12 only the impedances are shown for frequencies above 10 kHz as where the time domain obtained results start at 10 Hz.

While taking the impedances in the frequency domain using a VNA the noise on the mains was above 1 volt at 20 kHz, measured with an oscilloscope at the same port where the VNA was thereafter connected to. As the VNA used uses synchronous demodulation for its measured signals, the integrity of the readout in that frequency range is affected.

Secondly, the way the VNA integrates its impedance data per frequency (bandwidth = 10 Hz at 401 frequency point) is different from the time domain data where 10 MS were taken.

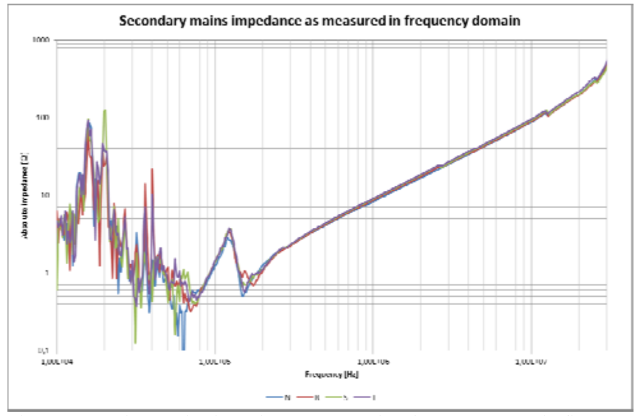

Figure 12 – 'Live' mains impedance measured at the same port as in figure 11 but acquired in the frequency domain.

As indicated, the measurement probes used with the time domain measurements are a current and voltage probe as where a single 10 kHz high-pass filter probe is used with the frequency domain measurements.

When impedance measurements are taken in the time domain over multiple periods, these enable analysis of the impedance variations over time e.g. at zero-crossing or at the maxima of the sine wave.

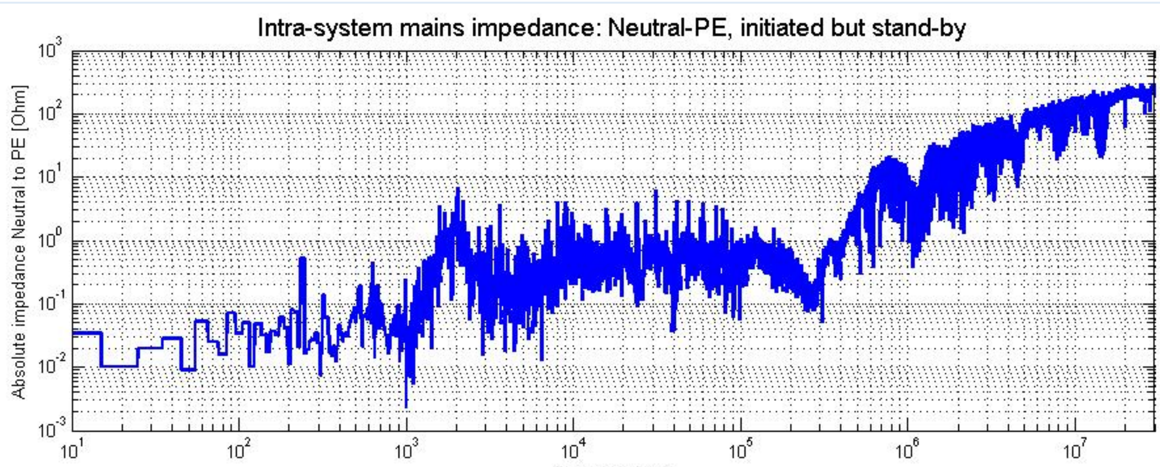

Figure 11 – Example of a 'Live' mains impedance measured in a system

V. CONCLUSIONS

The 'real' mains impedances have altered over the years due to the change of the equipment's supply circuitry used and the mains filters applied. Both PFC circuits as well as π-filters reduce the mains impedance by their loading well below the value as represented by the bare mains distribution network cabling.

The mains impedance will vary over a mains period quite different from the past. This has its impact at the lower frequencies where an input mains filter isn't dominant but due to the PFCs, the loading has become more constant.

The differences between frequency-domain and time domain impedance measurements needs further analysis, in particular at the lower frequencies where impedance is of dominant importance during conductivity of the rectifying diodes.

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