Attachment (1): measurement report by K Fockens, PA0KDF

Measurements concerning the disturbance potential of Homeplug vs 2 modems.

Differential mode measurements on main plug of the PLC modem.
In these measurements one of the PLC modems is connected to a mains outlet box, while a MCD (Mains Connector Device) is plugged directly next to the plug of the modem. De MCD has been described in annex to this report

The MCD has been set in the differential mode and the protecting earth is not connected. The MCD is connected on the side with a spectrum analyzer of the type Rohde & Schwarz FSP 3.

The measurements.
Figure 1 shows the spectrum of the modem signal in the frequency range 0 - 200 MHz. Next to the intended signal spectrum of 2 - 32 MHz spurious signals up to 130 MHz are visible.

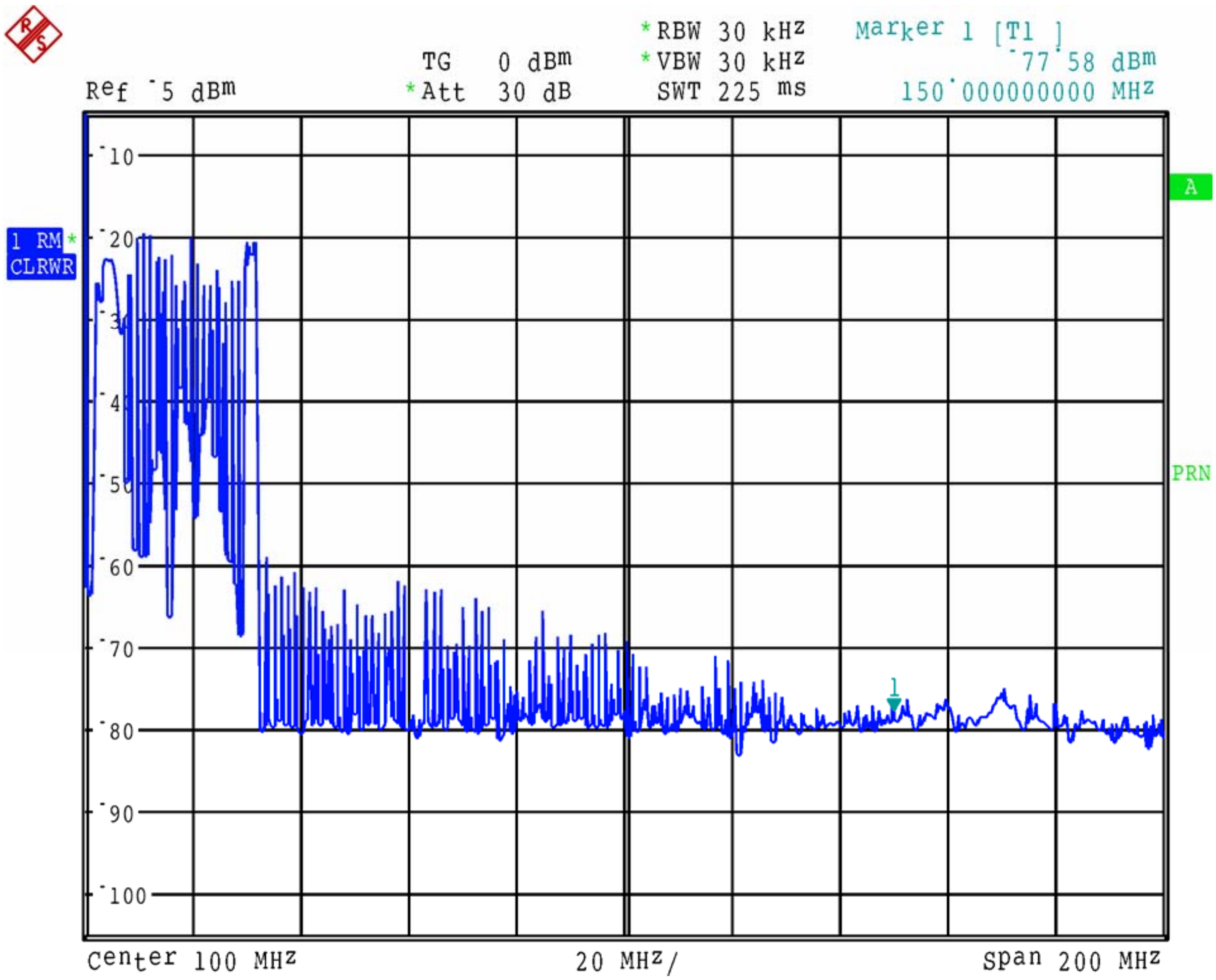

Figure 1

Figure 2 shows the same signal in the frequency range 0 - 40 MHz, while using the the max-hold function. From here the available source power of the modem can be calculated.

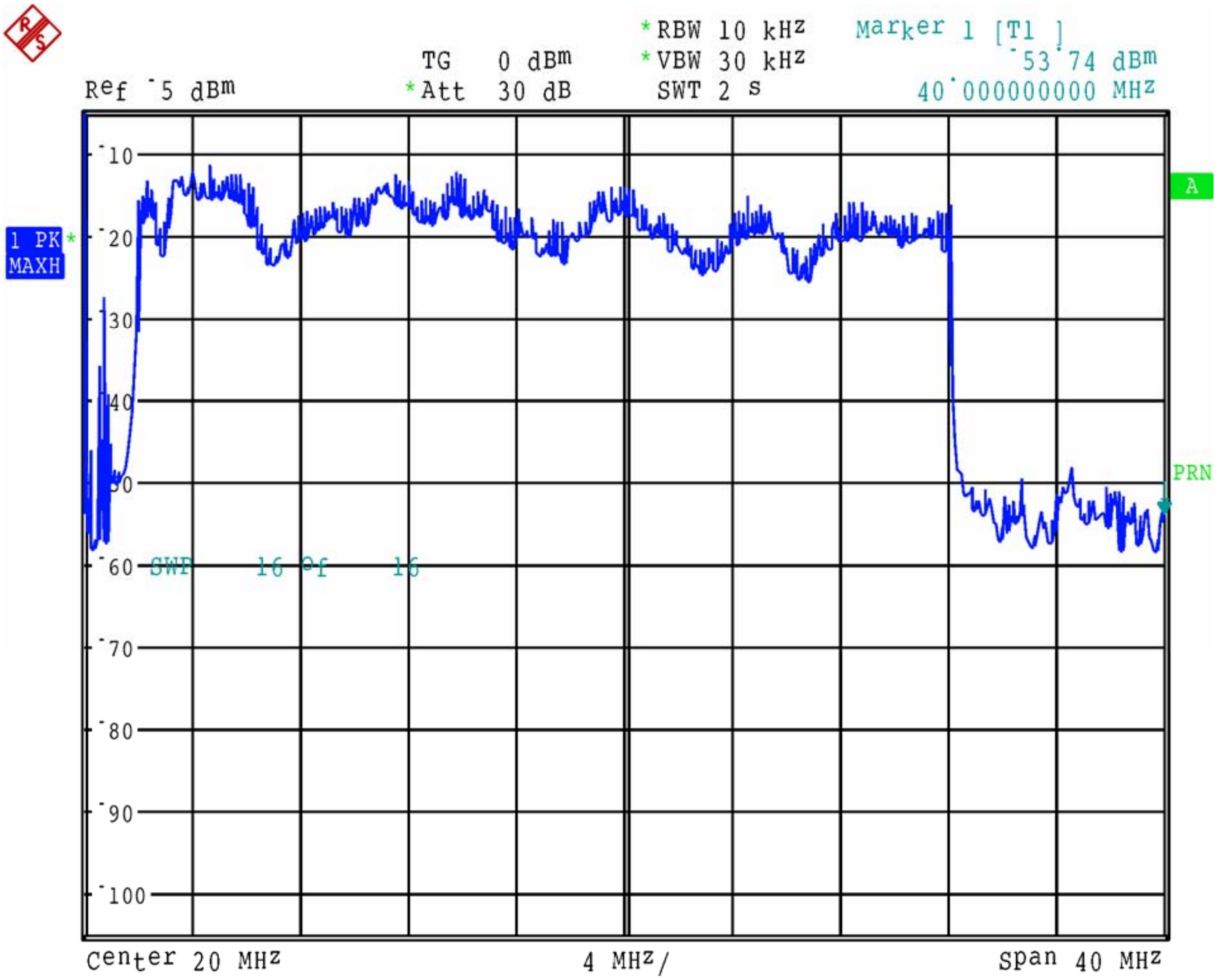

Figure 2

The MCD is connected in parallel with the modem power plug. Doing so the (differential) current is divided over the input impedance of the MCD and over the impedance formed by the low voltage network at that position.

The MCD contains a 4 ÷ 1 balun transformer, that the 50 ohm input impedance of the spectrum analyzer transforms to 200 ohm at the input of the MCD. See also the annex with the description of the MCD.

We only have a median value for the impedance of the mains network, being app. 50 ohm in the frequency range 2 - 30 MHz. The actual impedance is frequency dependant and dependant on the topology of the network, It can vary between 10 and 500 ohm.

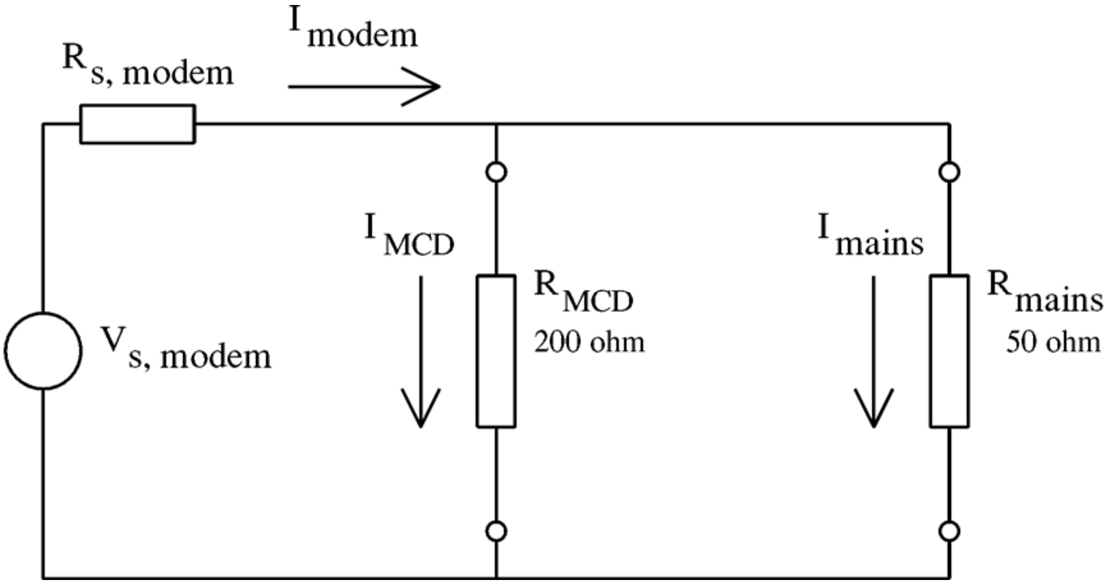

Figure 3.

Figure 3 shows the circuit. Given the impedance values I_{MCD} is smaller than I_{mains} by a factor 4, and so a factor 5 smaller than the current, I_{modem}, delivered by the modem. From this it can be expected that the power, delivered by the modem, is 7 dB higher than indicated by the spectrum analyzer.

The measuring bandwidth during the power density measurement was 10 kHz**.** So the maximal available power density equals the indicated power minus 40 dB.
In combination with the method of injection by the MCD the estimation of the available power density of the modem equals the power indication of the spectrum analyser plus -40 + 7 = -33 dB.

From the measuring result of figure 2 an estimation can be made of the available source power of the modem, that appears to be in the range from -14 -33 = -47 dBm/Hz down to -24 -33 = -57 dBm/Hz, so on average app. **-50 dBm/Hz.**

IT equipment that complies with CISPR 22B may maximally deliver on the mains port a disturbance power density of -94.5 dBm/Hz in the band 0.5 - 5 MHz, and -90.5 dBm/Hz in the band 5 - 30 MHz. This includes that the signals on the Live and the Neutral wire are thought to be in counter phase and synchronous (symmetrical injection).

It is my conclusion that the available source power of these modems is app. 40 dB higher than what is allowed in CISPR 22B using the V-network. According this high source power level the interference potential will be 40 dB higher in relation to the existing EMI practice.

Figure 4 shows the same signal spectrum as in figure 2, but now which notches switched on. Figure 5 shows the notch at 14 MHz enlarged.
In figure 5 it is remarkable that the notch does not show a rectangle shape, as can be expected in an OFDM system wherein an group of carriers can be switched off, but that the slopes are oblique.

This may be caused by intermodulation effects. Maybe the ferrite transformer in the MCD could tribute to this. The total power that passes the MCD, and doing so passing the transformer, equals about 100 mW. A quick test using a single carrier with a power of 100 mW, inputted in the MCD, show a mere harmonic distortion of -70 and -80 dB for the 2nd respectively. 3rd harmonic.

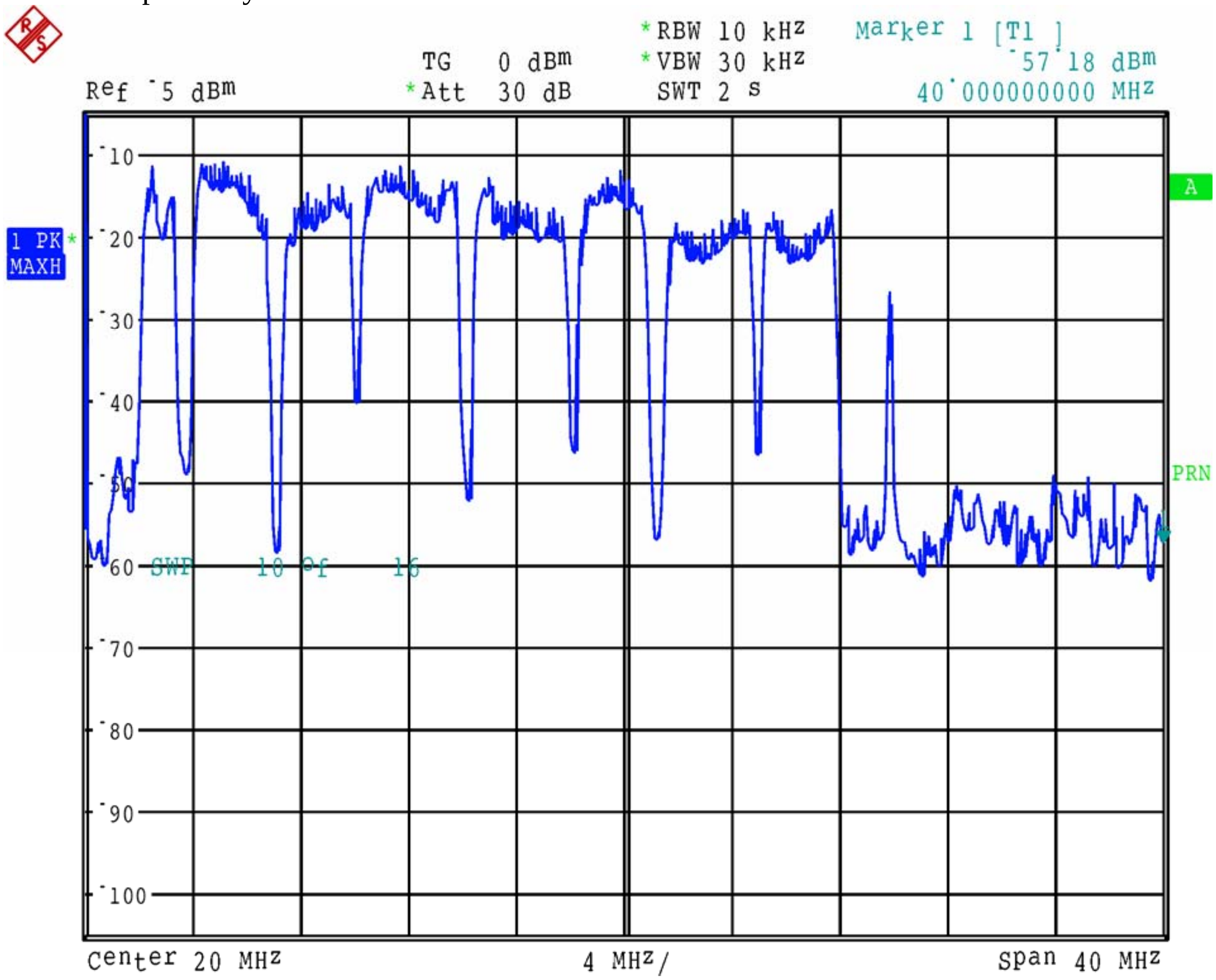

Figure 4

While I do not have the conversion formulas for calculating the results of the single tone measurements into the intermodulation measurements using broadband noise (well known from the late carrier telephony), I still have the impression that the contribution from the MCD to intermodulation products is negligible.

This shows the vulnerability of notches as migitation method. Only a small number of non-linearity effects needs to be there, like bad junctions, rectifier diodes, etc., to cause the generation of intermodulation signal products inside the notches to degrade them. This effect can also cause the generation of higher order harmonics above 30 MHz in the network.

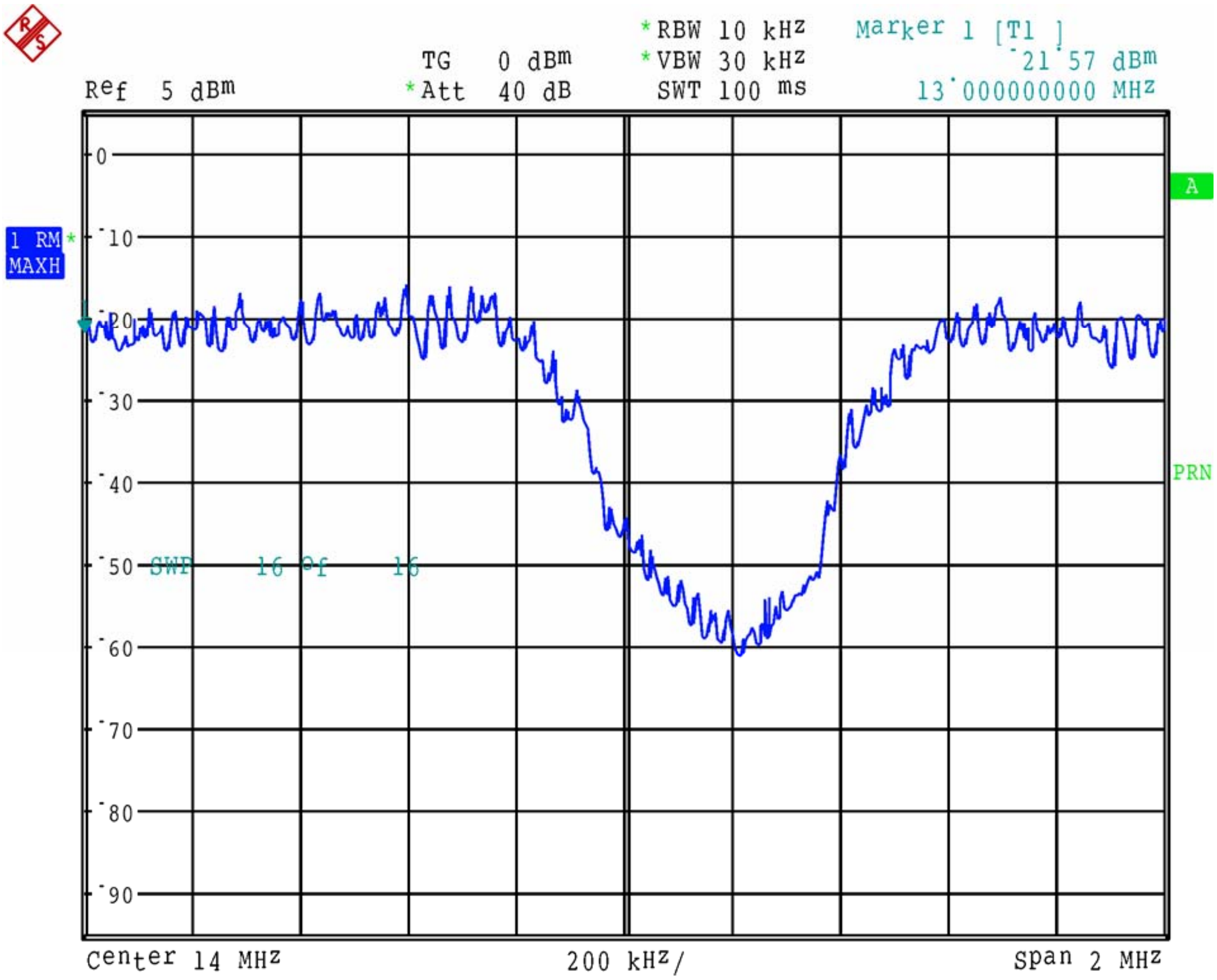

Figure 5

Common mode current measurement.
In the current version of the draft EMC standard for networks limit values for the common mode currents are set in table 1. In the frequency range from 0.5 until 30 MHz this limit is 30 dBµA QP and 20 dBµA Average measured in a 9 kHz bandwidth.

The assumption is that by measuring at many positions in the network the maximal value can be found. The common mode current will certainly not be maximal at the point of injection, because the modem has been designed to inject symmetrically.

But during the measurements it became clear that meaningful common mode current measurements were not possible, because in that house all the mains wiring were buried inside the walls, *like in almost other houses*.

To perform some CMC measurement still, another extension cord with a length of app. 20 m was inserted in the power cord to the spectrum analyzer, and connected to a distant wall outlet. The current probe, type R&S EZ17, was placed on the extension cable halfway. Figure 6 shows the result. The transfer impedance of the EZ17 was 3.16 ohm, resulting in a k-factor of -10 dB.

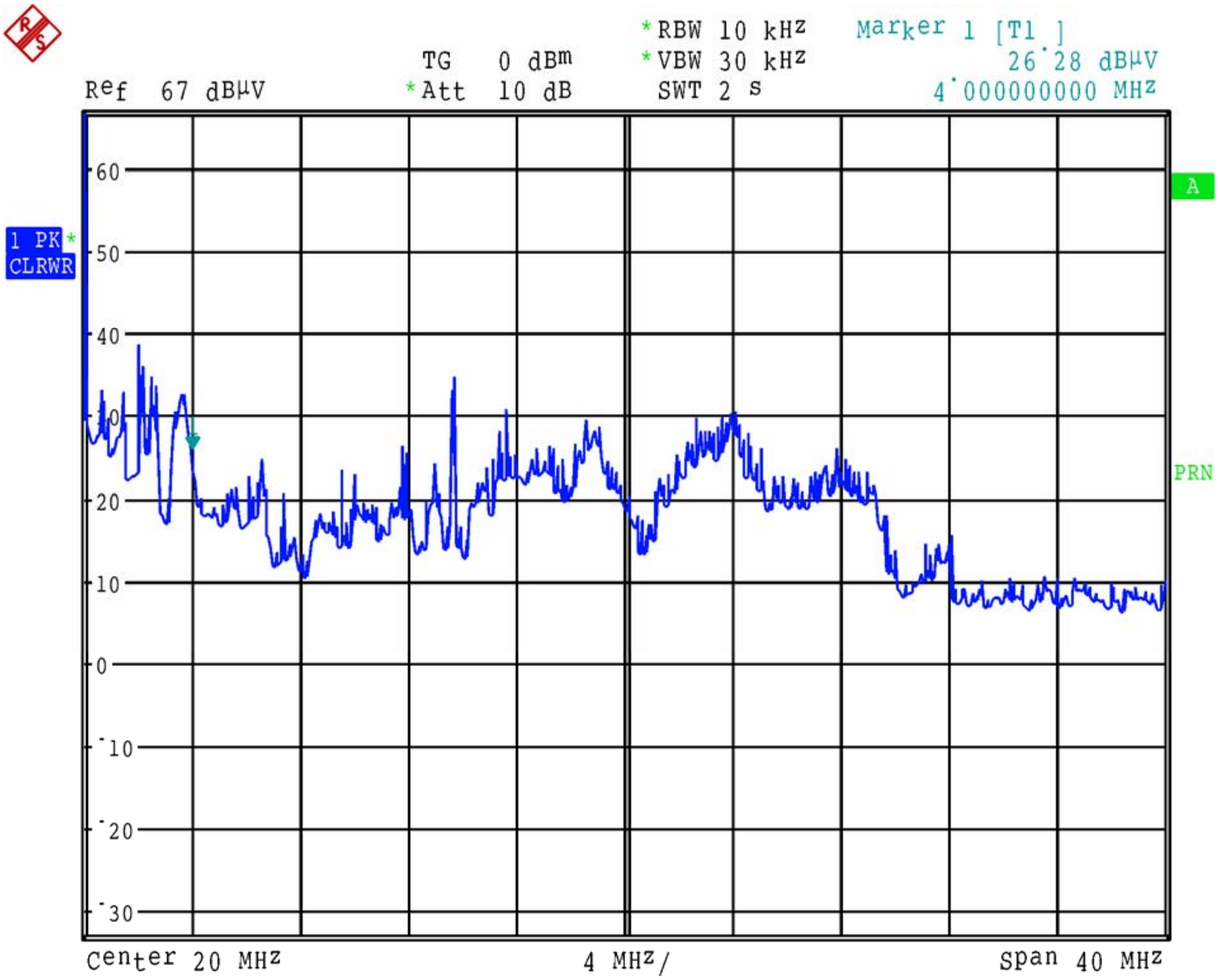

Figure 6. Common mode current measurement.

So we calculate a maximum common mode current of app. 20 dBµA. As the peak detector has been used here, this result should be compared with the quasi-peak limit 30 dBµA in table 1 of the draft standard.

Although from this single common mode current measurement no comprehensive conclusions can be drawn, it strikes that resonance effects are visible, and that despite the fact that the cable of concern comes to a dead end, still a notable amount of common mode current is flowing.

Field strength measurements.
There are some field strength measurements performed by means of the R&S Miniport receiver and the HE200 active antenna set. The receiver was operated using peak level indication, what fits with the NB30 limit.
In house only a few measurements were done, resulting in field strength values of app. 50 dBµV/m at a frequency of 14 MHz (notches off). That is app. 20 dB over the NB30 limit.

Measurements outdoor: at app. 3 m from the external wall field strength values were found of app. 40 dBµV/m@14 MHz, 10 dB above NB30. It should be noted that this measurement distance, 3 m outside the external wall, although prescribed in the draft standard, is not in compliance with NB30, as the physical distance to the radiating cable(s) is more than 3 m.

Measurements on antenna towers and lantern posts: all vertical conductors in the vicinity of the house appear to carry currents, that are induced by the PLC signal. Two propagation paths are possible, namely at first by conducting via the cables of the masts to the house, and secondly by induction from the disturbance field. These currents has been demonstrated by keeping the measurement antenna (an inductive loop) in one plane nearby the masts. The following field strength values were read:

Antenna tower 1, ca. 20 m from the external wall of the house: 35 dBµV/m@14 MHz,
Antenna tower 2, ca. 50 m from the external wall of the house: 27 dBµV/m@14 MHz.
Antenna tower 2, ca. 50 m from the external wall of the house: 35 dBµV/m@28 MHz.

Lantern posts along the street: demonstrable up to 100 m from the house: 35 - 27 dBµV@28 MHz.

The lower receiver sensitivity limit in combination with the used antenna is app. 27 dBµV/m.

This induction of currents in antenna towers is a serious effect: it makes that antennas, that are positioned relative far from the house, and thought to be reasonably well screened from the disturbance field inside the house, are still able to pick up and reradiate interfering signals.

The conclusion is that the positioning of antennas higher or further away from the house, is not an effective mitigation method to solve PLC interference problems.

ANNEX (1) by **K Fockens, PA0KDF**

Mains Connector Device (MCD)

Purpose.
A dedicated device was made for injecting RF power into a mains network and measure RF voltages on that network. This document describes this device and gives calibration information.

Objective.
The objective of the device is to inject RF power into a mains network in a asymmetrical way, using the Neutral - Earth port or the Phase - Earth port, or in a symmetrical way using Neutral - Phase connection. In the latter case a choice can be made between a forced symmetry by connecting the Earth as a reference, or a floating symmetry. In practice it appeared that the effect of this is small. *The registered symmetrical measurements are all performed with S3 open.*

The original intended frequency range was 1.6 to 30 MHz, but using the transfer function, described below, measurements can be performed from 10 kHz to 50 MHz.

Description.

Figure A1 gives the circuit diagram. For injecting in the Phase line (P) switches S1 and S3 are closed, for Neutral line (N) S2 and S3, and for symmetrical injection S1 and S2, while S3 left open. By closing S3 in the last case the symmetry of the voltages on the Neutral and Phase wire can be forced. However in practice it appeared that the effect is little. *For the symmetrical measurements only those measuring values for S3 is open are registered.*

Figure A2 gives the principal circuit. The $transfer\ ratio$ is defined as:

$$transfer\ ratio = \frac{V_{load}}{E/2} = \frac{I \cdot |Z_p|}{E/2} = \frac{E/|Z| \cdot |Z_p|}{E/2} = 2 \cdot \frac{|Z_p|}{|Z|} \tag{1}$$

with $|Z_p|$ the absolute value of the impedance of the parallel connection of L_p, the parallel selfinductance of balun transformer Tr2, and the (resistive) load on the output (= input impedance of the measuring receiver, 50 ohm).

$|Z|$ is the absolute value of the total loop impedance, in which the current I runs. The values of $C,\ R_{source},$ and R_{load} are set by design, the values of L and R_{loss} are determined from a transmission measurement using a spectrum analyser with a tracking generator as network analyser.

The calculation of the loop impedance Z:

$$Z = \frac{1}{j\omega C} + j\omega L_s + Z_p + R_s + R_{loss} \tag{2}$$

$$Z_p = \frac{R_L \cdot j\omega L_p}{R_L + j\omega L_p} \tag{3}$$

$$Z = \frac{1}{j\omega C} + j\omega L_s + \frac{R_L \cdot j\omega L_p}{R_L + j\omega L_p} + R_s + R_{loss}$$

$$\begin{aligned} Z &= \frac{R_L + j\omega L_p + j\omega L_s \cdot j\omega C\,(R_L + j\omega L_p) + j\omega C \cdot R_L \cdot j\omega L_p}{j\omega C\left(R_L + j\omega L_p\right)} + R_s + R_{loss} \\ &= \frac{\omega^2 L_s C R_L + \omega^2 L_p C R_L - R_L + j\omega^3 L_s C L_p - j\omega L_p}{\omega C\left(\omega^2 L_p^2 + R_L^2\right)} \cdot \left(\omega L_p + jR_L\right) + R_s + R_{loss} \\ &= \frac{\omega^3 L_p^2 C R_L + j\left\{\omega^4 L_s L_p^2 C - \omega^2\left(L_p^2 - L_s C R_L^2 - L_p C R_L^2\right) - R_L^2\right\}}{\omega C\left(\omega^2 L_p^2 + R_L^2\right)} + R_s + R_{loss} \end{aligned} \tag{4}$$

To determine the absolute value of Z we divide Z in a real part $Re\,(Z)$ and in a complex part $Im\,(Z)$:

$$Re\,(Z) = \frac{\omega^3 L_p^2 C R_L}{\omega C\left(\omega^2 L_p^2 + R_L^2\right)} + R_s + R_{loss}$$

(5)

$$= \frac{\omega^2 L_p^2 R_L}{\omega^2 L_p^2 + R_L^2} + R_s + R_{loss}$$

$$Im(Z = \frac{\omega^4 L_s L_p^2 C - \omega^2 \left(L_p^2 - L_s C R_L^2 - L_p C R_L^2\right) - R_L^2}{\omega C \left(\omega^2 L_p^2 + R_L^2\right)}$$

$$= \frac{\omega^4 L_s L_p^2 C - \omega^2 \left(L_p^2 - (L_s + L_p) C R_L^2\right) - R_L^2}{\omega C \left(\omega^2 L_p^2 + R_L^2\right)} \tag{6}$$

Combining we get:

$$\left|Z\right| = \sqrt{(Re(Z))^2 + (Im(Z))^2} \tag{7}$$

In the same way we derive for Z_p:

$$Z_p = \frac{R_L \cdot j\omega L_p}{R_L + j\omega L_p} = \frac{j\omega L_p R_L (R_L - j\omega L_p)}{R_L^2 + \omega^2 L_p^2} = \frac{\omega^2 L_p^2 R_L + j\omega L_p R_L^2}{R_L^2 + \omega^2 L_p^2}$$

and

$$|Z_p| = \frac{1}{R_L^2 + \omega^2 L_p^2} \sqrt{\omega^4 L_p^4 R_L^2 + \omega^2 L_p^2 R_L^4} = \frac{\omega L_p R_L \sqrt{\omega^2 L_p^2 + R_L^2}}{R_L^2 + \omega^2 L_p^2} \tag{8}$$

The formulas (1), (5), (6), (7), and (8) are being inputted in a math program[1] together with a list of frequencies and the component values. The result is displayed in figure A1-3 for asymmetrical coupling, and in figure A4 for symmetrical coupling.

The outcome has been compared with the measured transfer function, and in this way the values of L_s, L_p, en R_{loss} has been iterated to the indicated values. The resulting calculated curve is deviating less than 0,5 dB from the measured curve.

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[1] In my case *Praktikum* from Felder&Braun Software GdbR, running under the *RiscOS* operating system (from the former Acorn, now owned by RiscOS Ltd/Pace Ltd).

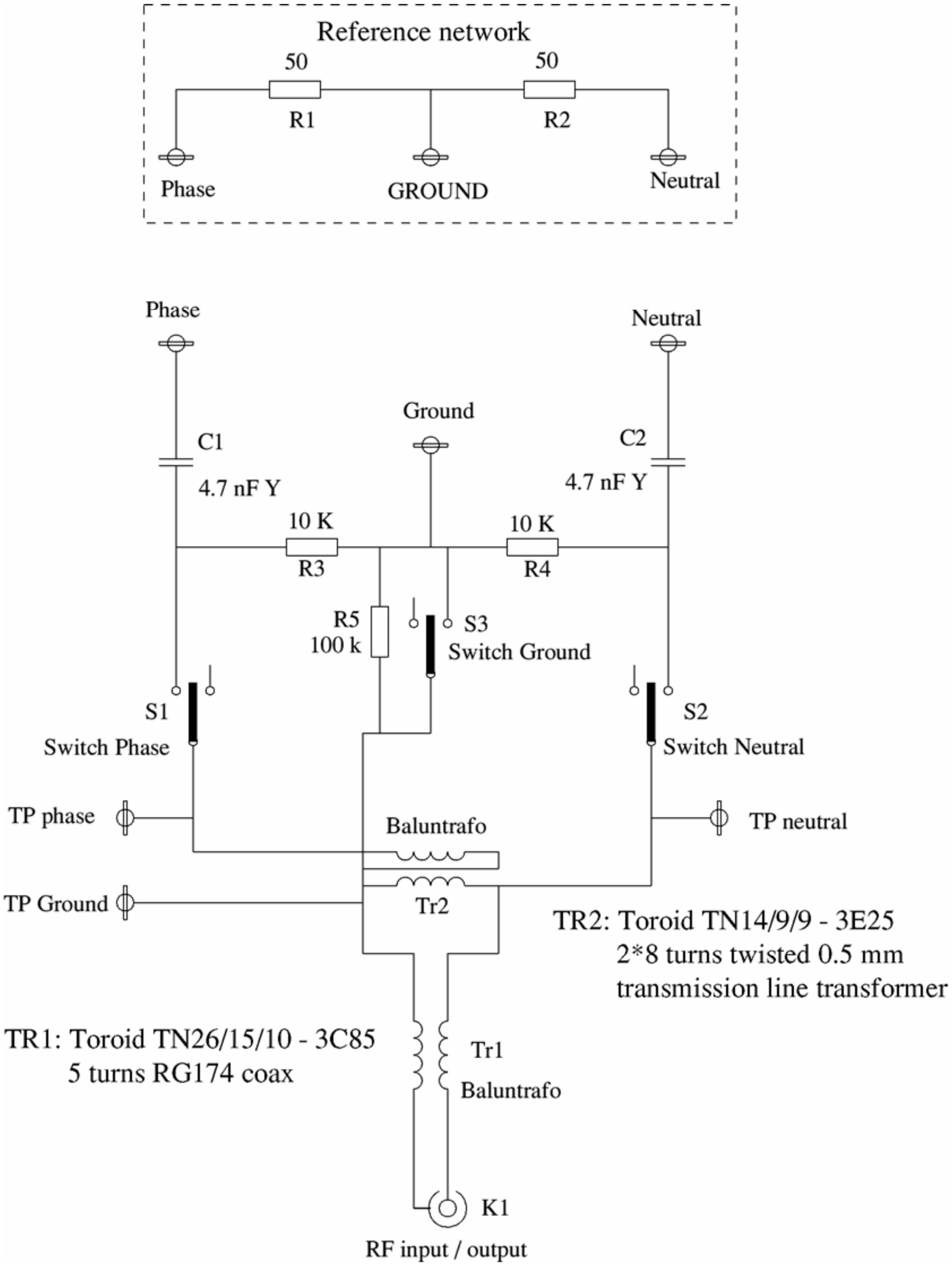

Figure A1. Circuit of the Mains Connector Device.

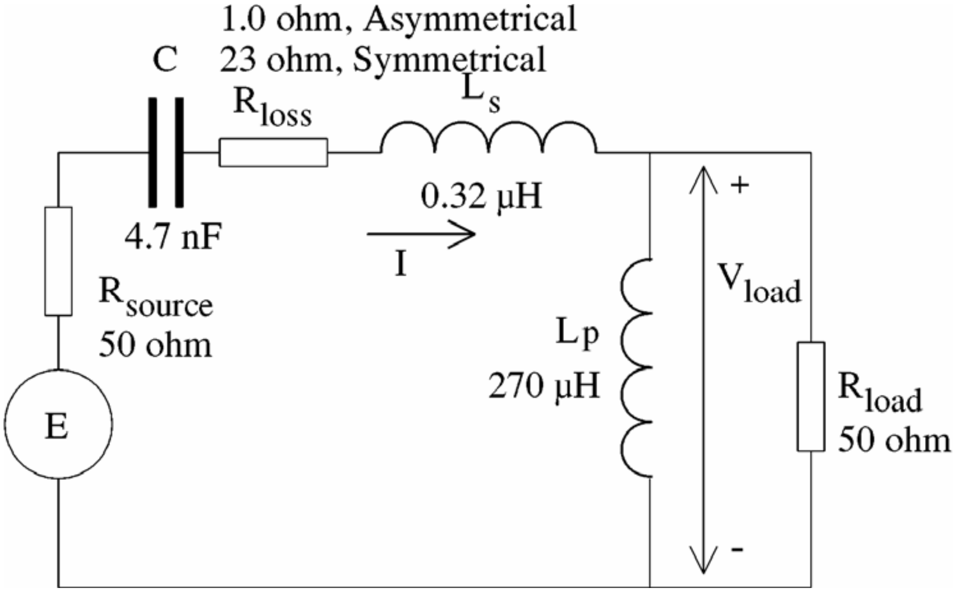

Figure A2. Principal schematic.

Now the transfer function is available in the form of a formula, the by the measuring receiver measured interference voltages at the connector of the MCD can be calculated back into mains disturbance voltages at the wall outlet where the MCD was inserted by software means.

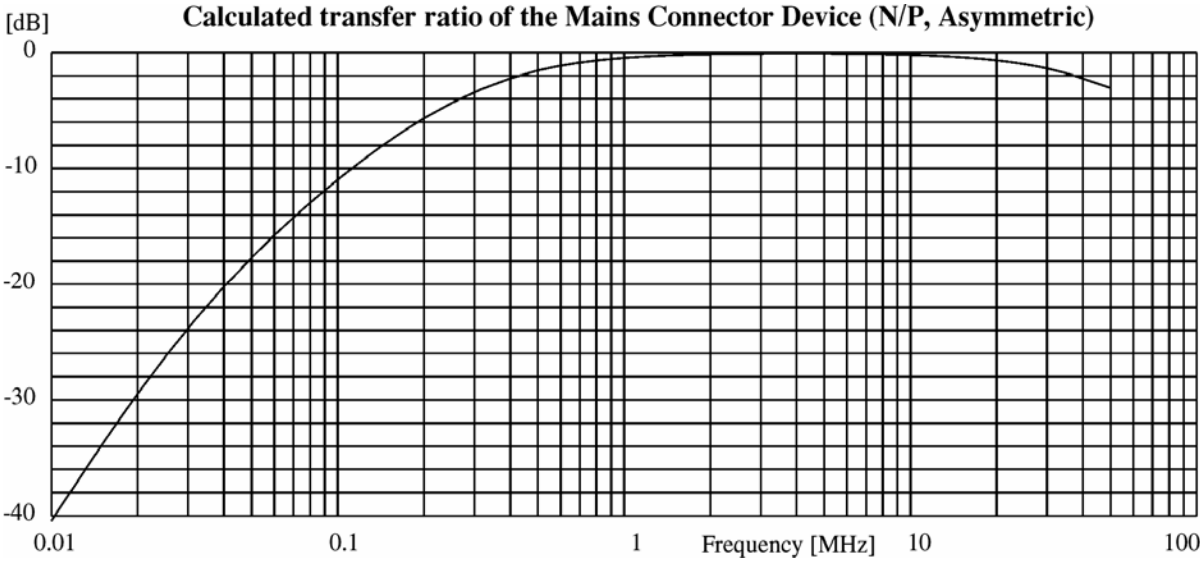

Figure A3. Transfer function for the case of asymmetric coupling.

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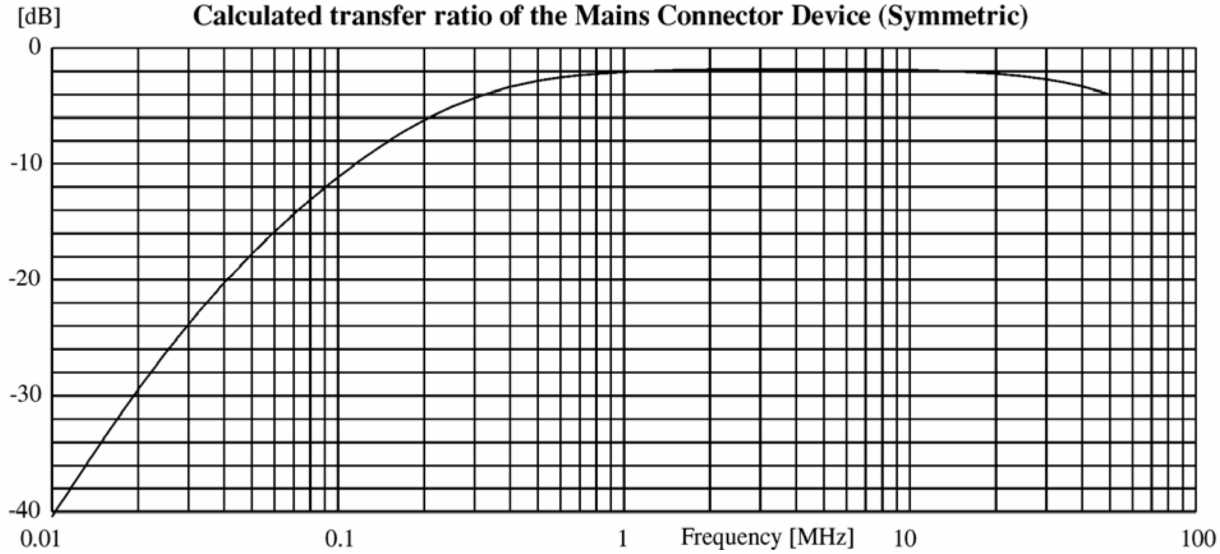

Figure A4. Transfer function for the case of symmetric coupling.

Source impedance.
For the benefit of measurement of the impedance that the 230 V grid forms at the place where a signal is to be injected, and also for an assessment of the injected power, we need the magnitude of the source impedance of the combination of generator and MCD. Therefor we reverse the principal schematic of figure A2, see figure A5. The component values are based on the measurements of the transfer function in figure A2. For the symmetrical injection the effect of the balun transformer is taken care of by quadruple the impedance of the generator. Also the other component values are modified for the symmetrical injection, and mentioned between square brackets.

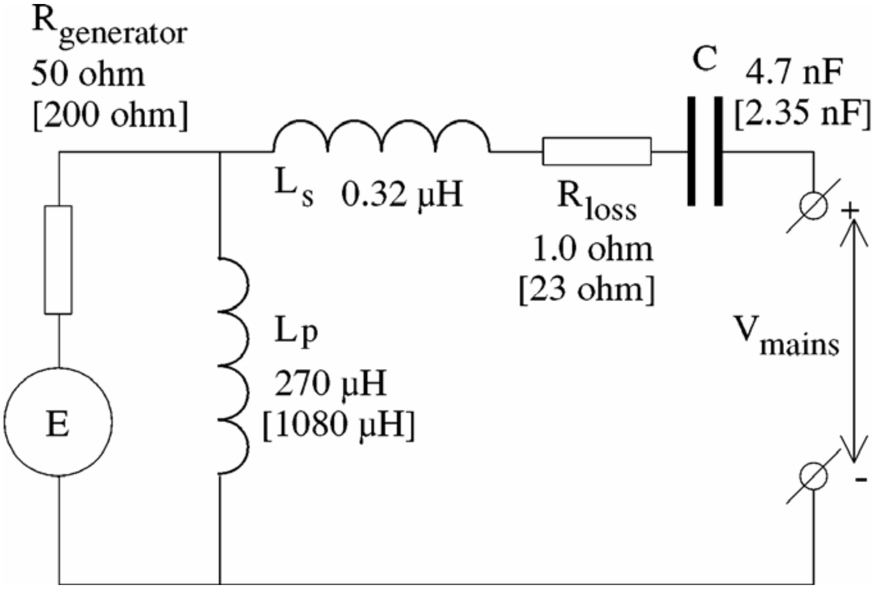

Figure A5. Principal schematic mains impedance measurement.

The source impedance follows from the modified formulas (2) en (3):

$$Z = \frac{1}{j\omega C} + j\omega L_s + Z_{pp} + R_{loss} \quad (9)$$

$$Z_{pp} = \frac{R_G \cdot j\omega L_p}{R_G + j\omega L_p} \quad (10)$$

According the same derivation we arrive at the magnitude of the soruce impedance Z_{ss}:

$$Re(Z_{ss}) = \frac{\omega^2 L_p^2 R_G}{\omega^2 L_p^2 + R_G^2} + R_{loss} \quad (11)$$

$$Im(Z_{ss}) = \frac{\omega^4 L_s L_p^2 C - \omega^2 \left(L_p^2 - (L_s + L_p) C R_G^2\right) - R_G^2}{\omega C \left(\omega^2 L_p^2 + R_G^2\right)} \quad (12)$$

$$\left|Z_{ss}\right| = \sqrt{(Re(Z_{ss}))^2 + (Im(Z_{ss}))^2} \quad (13)$$

Figure A6 gives the result of the calculation for the asymmetric injection, as well as in the neutral, as in the phase wire, and figure A1-7 shows the results for the symmetric injection.

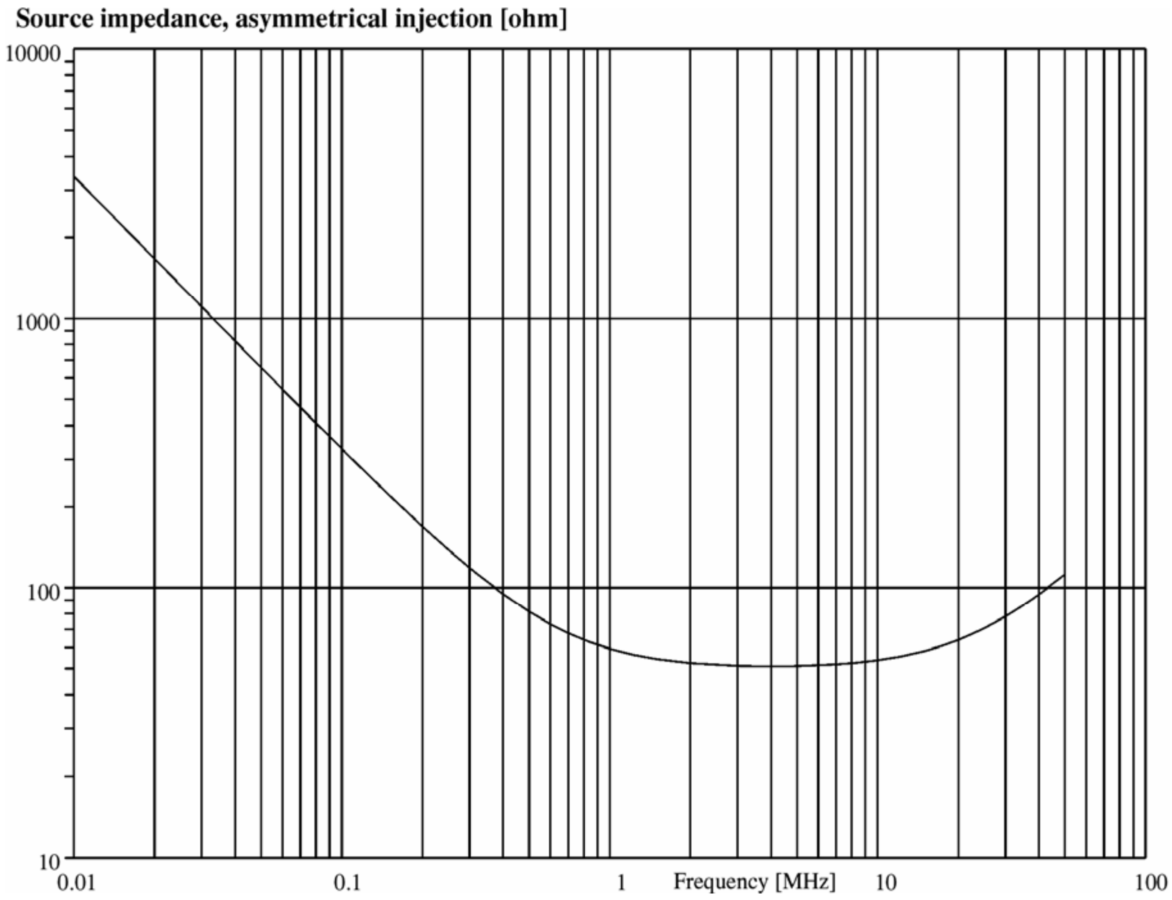

Figure A6. Source impedance for the case of asymmetric injection.

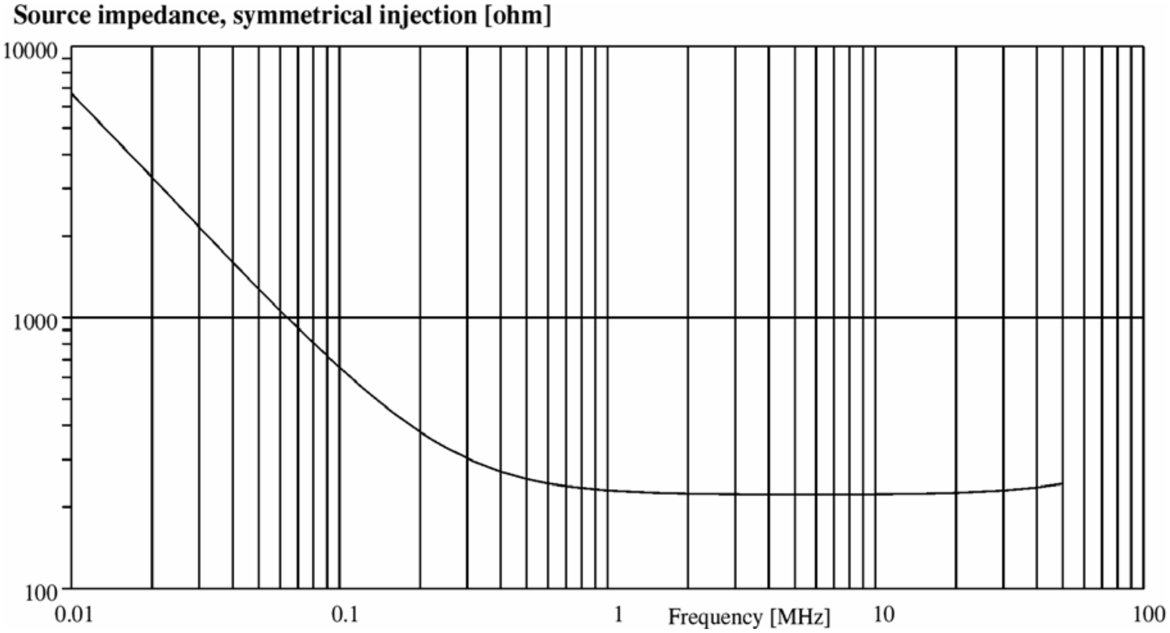

Figure A7. Source impedance for the case of symmetric injection.