Estudio realizado por radioaficionados holandeses, que efectuaron una serie de medidas, comparándolas con los límites de radiación propuestos en varios países de la CEPT.

EMC Committee

The radio amateur and the effects of the use of the 230 Volt power line for broadband data communication (PLC).

Summary.

At the turn of the year 2002 a series of measurements was conducted to evaluate the risks of interference by PLC for the amateur station PA0KDF.

Both in-house and outside field strength measurements were taken and compared with the CEPT proposed radiation limits (NB 30, Norwegian Limit and BBC limit). In addition the coupling between the mains wiring and the antennas of the amateur station was determined.

In an audio test, where use was made of amateur antennas and receiver, the level of interference in the HF amateur bands was evaluated. Only in the case of the strictest limit, the BBC limit, adequate protection was provided against mains injected interference signals.

In addition measurements were performed to find the “normal” interference levels on the mains wiring. Firstly it became apparent that the present interference levels in a quiet rural area are far below the CISPR 22 limits and secondly, injection of interference signals with a level equal to the CISPR 22 limit level causes harmful interference to the reception of signals in the amateur bands.

Rietmolen, March 2002
Koos Fockens.
PAØKDF

Correspondence:
VERON EMC Comittee, P.O. Box 1166, NL6801BD Arnhem, The Netherlands.
Email: J_M_Janssen@hetnet.nl

Table of Contents

1. Introduction

In 2001 I became involved in the discussion about the application of Power Line Communication (PLC) and in the processes for the development of applicable interference limits. Not only professionally within CEPT and in a working group of the Dutch Radiocommunications Agency (IVW-T), but also as a radio amateur member of the VERON EMC committee.

In the discussions on the interference limits for PLC and other cable communication applications a few aspects appear to be of fundamental importance:

- What is the relation between the injected HF voltage on the 230 Volt mains and the resulting noise field strength in and outside the house.
- How are these generated noise field strengths related to the proposed field strength limits for PLC, if the interference voltage on the mains equals the limits as set forth in the EMC Standards (CISPR 22)?
- And finally how high are the already present noise voltages on the 230 V mains circuit.

All these points have been the subject of numerous discussions and studies by the supporters and opponents of PLC. In particular the first point has been extensively studied by theoretical analysis, simulations and measurements. A general applicable formula is still desirable.

The relationship in the second point is even more difficult to establish. Some supporters of PLC claim that the permitted noise level under the CISPR 22 limit is even higher is than NB 30 limit, which is seen by some already as the European standard..

In addition many supporters of PLC claim that the existing noise on the mains wiring is already equal to the CISPR 22 limit, and therefore that PLC signals can be made equal to this limit. A statement, which seems hardly called into question by EMC specialists.

So enough reasons to start a series of measurements to be made at home, not with the pretension of acquiring scientific evidence, but to find out the local effects and to get a personal impression in general. This knowledge should give me something to hold to during further discussions, in parallel to the theoretical knowledge.

These measurements at my home were relatively easy to carry out. An ESH2 measurement receiver with an ESH2 loop antenna was available from the QRL. I already have an HP 606B generator in my possession. A mains coupling device, necessary to inject a signal into the 230 Volt mains was easily constructed. The Christmas holidays gave me the time the time to carry out these measurements!

2. The environment.

Our house is located just outside the village. There are no busy main roads, nor we are in the neighbourhood of overhead high tension lines. We share a low voltage transformer with 16 families including 2 farms.

3. The measurement points.

Figure 1 provides the for this study relevant data on the lay-out of our house. Because of the location directly behind the electricity meter and house access point, a mains grounded wall outlet in the kitchen was used to couple the generator or the measurement receiver to the mains. The distance to the outlet is approximately 2 meters.

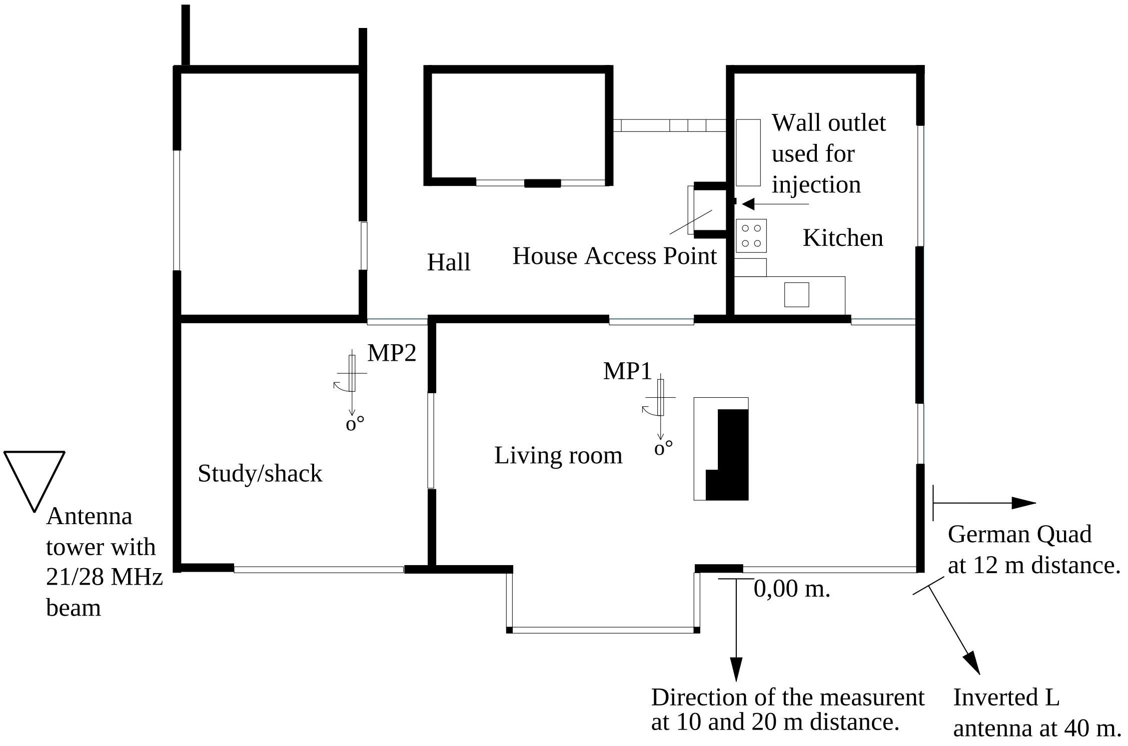


Figure 1. Lay-out.

In-house field strength measurements were performed at two positions. Measurement point 1 in the living (MP1) en measurement point 2 in the study annex shack (MP2).

The position of MP1 was selected for a local maximum in the field strength at 3.5 MHz, and is located approximately 0,5 m in front of the open fireplace on the prolonged side. Apparently there is a mains wiring located overhead, running from the window in the direction of the electricity meter. The distance to the centre of the measurement antenna is approx. 1.25 m. The loop antenna was turned around its vertical axis until a maximum signal was detected. The angle of rotation was noted where 0 degrees was in the direction of the mains wiring. The 0 degree reference is depicted in figure 1.

MP2 was also chosen at a location with a local field strength maximum under a mains wiring. Distance to rear wall: 0.7 m, middle wall: 1.3 m, distance to the centre of the measurement antenna is also approx. 1.25 m. Orientation is the same as for MP1.

In the garden are the two positions for field strength measurements, 10 m, respectively 20 m, from the outside wall, as indicated.

On the right side of the house is a German Quad antenna. This is a horizontal loop antenna with a height of 10 meters and sides of 20 m each. The nearest side of the loop is at a distance of 12 m from the wall of the house. This antenna covers the 160 - 20 m bands.

In figure 1, (right-hand corner), at a distance of 40 metres from the house, is an inverted L-antenna. The length of the vertical part is 10 m, the horizontal part is 30 m. Coupling is achieved via a home-made broadband transformer and a coaxial cable. The frequency range of the antenna is 9 kHz – 15 MHz.

On the left side of the house at a distance of 2 m is a variable length tower(max. 21 m) with a 2 x 4 element dual beam for 21/28 MHz.

4. The measurements.

The following measurements has been performed:

- Measurement of the impedances of the mains wiring at the injection point. As well as between Neutral – Earth port, as between Phase - Earth port, and as between Neutral – Phase.
- Measurement of the injected HF power at a constant available power setting of the generator.
- Field strength measurements inside the house.
- Field strength measurements outside the house.
- Measurements of the interference signal levels on the HF receiving antennas, determining of the antenna coupling factors and evaluation of the reception with an amateur receiver.
- Measurement of the effects of the height and direction of the HF beam.
- Measurement of the HF voltage at the 230 Volt injection point as a result of the radiation by the outside amateur antennas.
- Measurement of the actual mains interference voltages at the injection point in comparison with the CISPR 22 limit values.

5. Impedance measurement and measurement of the injected power.

Figure 2 shows the measurement set-up for all measurements where a HF signal is injected in the 230 Volt mains. Signal source is a HP606B signal generator from Hewlett Packard, adjusted to an available output power of 0 dBm. The injection into the 230 Volt mains is through a Mains Connector Device (MCD). For a description see Annex 1.

To get an impression of the impedance of the 230 Volts mains a measurement has been made at the injection point. For reasons of simplification it was assumed that the impedance of the mains is real. Also the impedance of the separation capacitor C is assumed to be zero Ohm. For the frequency range under consideration 1,6 – 30 MHz(21 Ohm at 1,6 MHz) this is acceptable.

The advantages for this approach are that simple measurement devices like an oscilloscope can be used and that computations also remain relatively simple.

Figure 3 gives the equivalent schematic for the measurement set-up.

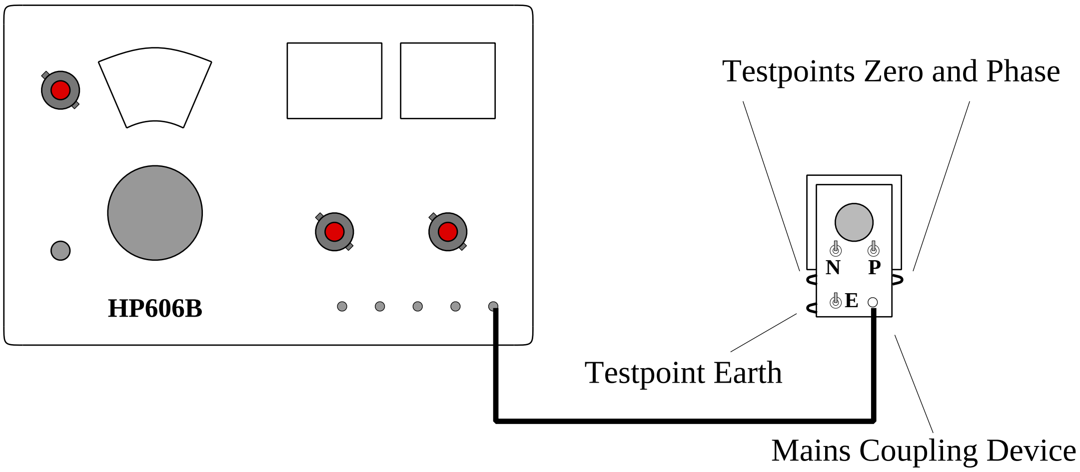


Figure 2. Set-up for injection measurements.

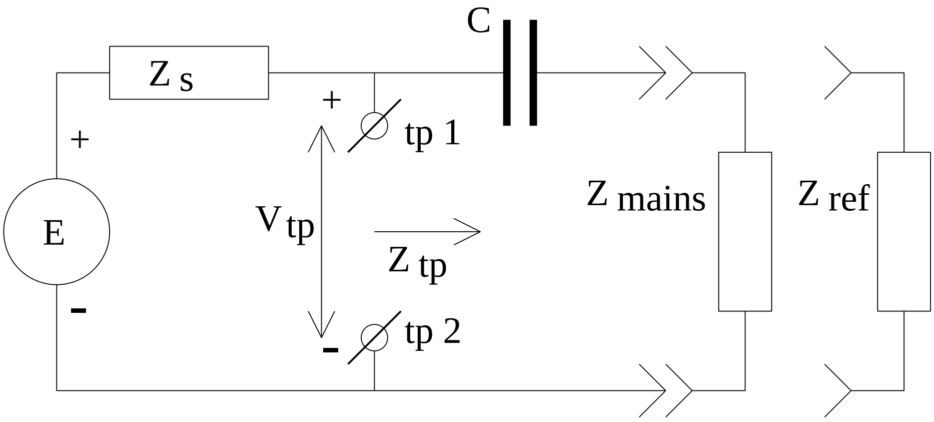


Figure 3. Equivalent schematic.

A comparative measurement has been performed, wherein the MCD first is plugged into a reference wall outlet containing two reference resistors of 50 Ohm each, see Annex 1. In figure 3 these reference resistors are marked as Z_{ref}. The voltage across the test points, V_{tp}, is measured and represented by V_{ref}.

Next the MCD is plugged into the 230 Volt wall outlet and the voltage across the test points is measured as now representing V_{mains}.

There are three possible combinations:

Measurement modes and measurement points, switch positions and impedance references.			
Measurement mode:	Neutral (N)	Phase (P)	Symmetric (S)
tp1	TP Neutral	TP Phase	TP Neutral
tp2	TP Ground	TP Ground	TP Phase
S1	open	closed	closed
S2	closed	open	closed
Sw E	closed	closed	open
Z_{ref} [Ω]	50	50	100

Table 1.

Floating voltage measurements were made possible by using a battery powered oscilloscope. The signal generator was powered from an wall outlet in the opposite wall via a 10 m long extension cable , thereby minimising the influence on the impedance to be measured. In addition the earth connection of the signal generator is connected to the earth connection of the wall outlet to be measured separately.

The voltages are read as top-top values and recorded as such.

The conversion to the impedance values is as follows. For the reference measurement is true:

$$\frac{V_{ref}}{E} = \frac{Z_{ref}}{Z_s + Z_{ref}} \tag{1}$$

For the measurement connected to the mains:

$$\frac{V_{mains}}{E} = \frac{Z_{mains}}{Z_s + Z_{mains}} \tag{2}$$

Dividing (2) by (1) gives:

$$\begin{aligned} \frac{V_{mains}}{V_{ref}} &= \frac{Z_{mains}}{Z_s + Z_{mains}} \Bigg/ \frac{Z_{ref}}{Z_s + Z_{ref}} \\ &= \frac{Z_{mains} \cdot Z_s + Z_{mains} \cdot Z_{ref}}{Z_{ref} \cdot Z_s + Z_{ref} \cdot Z_{mains}} \end{aligned} \tag{3}$$

After some ciphering follows:

$$Z_{mains} = \frac{Z_{ref} \cdot Z_s \cdot V_{mains}}{(Z_s + Z_{ref}) \cdot V_{ref} - V_{mains} \cdot Z_{ref}} \tag{4}$$

Z_s is the source impedance resulting from the combination of the MCD and the signal generator, and can be frequency dependant. Therefore the values used for Z_s are those computed with the use from data from Annex 1.

Although not indicated in the formulas all values for the impedance are absolute values without phase information. As the complex values for the impedance are not taken into account for the derivation, the calculated values for Z_{mains} are not to be taken as exact values but approximations. The values found are also in agreement with the measurements found in practice and recorded in [1] para. 3.2 and in Abbildung 24.

Table 2 gives the results:

Measurements of injected voltages and determination of mains impedances												
Frequency	Z_{source} [Ohm]			$V_{nominal}$ [mVpp]			V_{mains} [mVpp]			Z_{mains} [Ohm]		
[MHz]	N	P	S	N	P	S	N	P	S	N	P	S
1.84	52.85	52.85	224.9	640	640	880	460	460	320	28	28	28
3.58	51.03	51.03	223.2	620	620	840	475	475	110	31	31	9
7.03	51.88	51.88	223.1	600	600	780	410	420	720	26	27	89
10.12	53.81	53.81	223.5	600	600	780	870	870	1000	125	125	147
14.06	57.23	57.23	224.3	600	600	780	760	720	1040	83	73	157
18.1	61.64	61.64	225.4	620	620	790	1000	1000	1700	160	160	440
21.1	65.38	65.38	226.5	670	660	830	1120	1220	1750	172	263	413
24.9	70.58	70.58	228.0	700	680	840	740	700	660	55	53	72
28.4	75.58	75.58	229.6	710	700	840	620	700	460	40	50	46

Table 2. Measurement of the injected voltage and determining of the mains impedances.

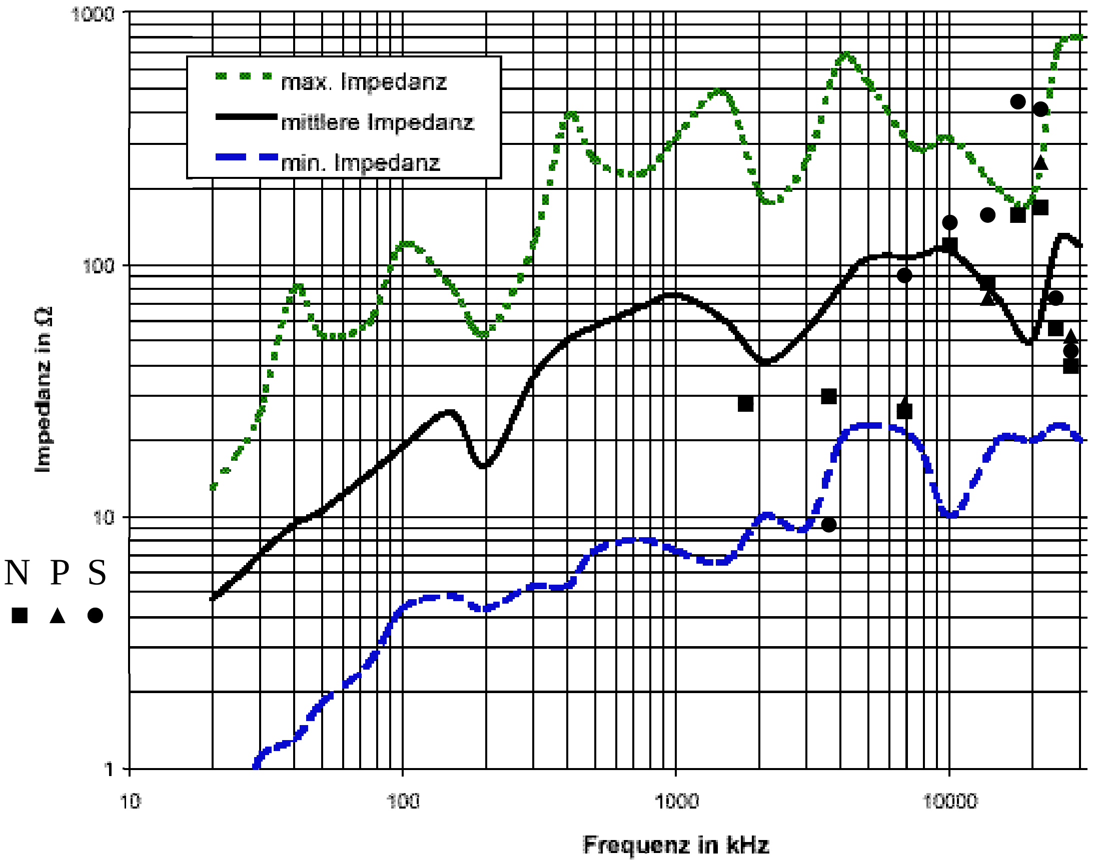


Figure 4. Abbildung 5 from [1] with the here measured values inserted.

In [1], para 3.2, a diagram represents the minimal, average and maximum expected values for the HF impedance's of the mains circuit. Figure 4 is a copy of this diagram but now with the values for the amateur bands from table 2 inserted. We can conclude that the measured values are in agreement with the values found in other sources.

From the results in table 2 estimations can be made of the injected HF power. First we have to convert the measured voltages Vmains into rms values by:

$$V_{mains\_rms} = V_{mains} / 2\sqrt{2}$$

The injected power is than:

$$P = V^2_{mains\_rms} \cdot Z_{mains}$$

In dBm:

$$P[\text{dBm}] = 10\text{LOG}\,(P * 1000)$$

Table 3 gives the results:

Injected power										
Frequency	Generator available output power: 0 dBm									
[MHz]	Mains RFI voltage [dBµV]			CISPR 22 QP	Over CISPR 22 [dB]			Mains injected RFI power [dBm]		
	N	P	S	[dBµV]	N	P	S	N	P	S
1.84	104.2	104.2	101.1	56	48.2	48.2	45.1	-0.31	-0.31	-3.5
3.58	104.5	104.5	91.8	56	48.5	48.5	35.8	-0.43	-0.43	-7.9
7.03	103.2	103.4	108.1	60	43.2	43.4	48.1	-0.95	-0.90	-1.4
10.12	109.8	109.8	111.0	60	49.8	49.8	51.0	-1.2	-1.2	-0.70
14.06	108.6	108.1	111.3	60	48.6	48.1	51.3	-0.58	-0.50	-0.64
18.1	111.0	111.0	115.6	60	51.0	51.0	55.6	-1.1	-1.1	-0.86
21.1	112.0	112.7	115.8	60	52.0	52.7	55.8	-0.40	-1.5	-0.33
24.9	108.4	107.9	107.4	60	48.4	47.9	47.4	0.94	0.66	-1.2
28.4	106.8	107.9	104.2	60	46.8	47.9	44.2	0.77	0.88	-2.4

Table 3. Results of the calculation of the injected power.

In the table the measured voltages are in dBµV's to facilitate a quick comparison with the CISPR 22-B noise limit. The difference with these limit values is also shown.

There is no great difference between the calculated values for the injected power and the available generator power (0 dBm). Some values are even somewhat higher. This is mainly explained by the limited accuracy of the measurements and the simplifications in the calculations. Also has to be taken in consideration that a part of this power could be reactive power as the impedance is not pure resistive.

6. In-house field strength measurements.

At two in-house positions field strength measurements were executed with the Rhode & Schwarz ESH2 measurement receiver in combination with the HFH2-Z2 magnetic loop antenna. These positions were already defined in para. 3. Table 4 shows the results for MP1 in the living room.

As customary for these kind of measurements is the, via the far-field impedance of 377 Ohm converted, electrical field strength *E* displayed. Also is shown the rotation *Angle* of the loop antenna in respect to the reference direction for the maximum signal strength. Then these measured values were normalized for the standard distance of 3 meter, assuming a linear decay of the field strength with distance. This procedure is in accordance with the guidelines of NB30. Finally, for comparison, the limit values of NB 30 are mentioned. For a description of NB 30 see Annex 3.

Indoor field strength measurements, MP 1 (Living room)										
	E, measured at distance 1.25 m [dBµV/m]						E, Normalized to 3 m			NB30
Frequency	N		P		S		N	P	S	E
[MHz]	E	Angle	E	Angle	E	Angle	E [dBµV/m]			[dBµV/m]
1.84	81	-60°	81	-60°	58	0°	73.4	73.4	50.4	37.7
3.58	87	10°	87	10°	56	0°	79.4	79.4	48.4	35.1
7.03	85	0°	85	0°	60	0°	77.4	77.4	52.4	32.5
10.12	79	-10°	80	-10°	74	0°	71.4	72.4	66.4	31.2
14.06	77	80°	77	80°	63	10°	69.4	69.4	55.4	29.9
18.1	76	-10°	75	-10°	66	-10°	68.4	67.4	58.4	28.9
21.1	71	90°	72	80°	69	40°	63.4	64.4	61.4	28.3
24.9	74	-10°	75	-45°	66	-70°	66.4	67.4	58.4	27.7
28.4	74	20°	68	40°	65	0°	66.4	60.4	57.4	27.2

Table 4.

Evaluation indoor field strength measurements													
MP 1	Generator available output power: 0 dBm.									CISPR 22 QP			
Frequency	Mains RFI voltage [dBµV]			E_{3m} [dBµV/m]			K_1 [dB/m]			$V_{CISPR\ 22}$	$E_{CISPR\ 22}$ [dBµV/m]		
[MHz]	N	P	S	N	P	S	N	P	S	[dBµV]	N	P	S
1.84	104.2	104.2	101.1	73.4	73.4	50.4	-30.8	-30.6	-50.6	56	25.2	25.4	5.4
3.58	104.5	104.5	91.8	79.4	79.4	48.4	-25.1	-25.6	-43.4	56	30.9	30.4	12.6
7.03	103.2	103.4	108.1	77.4	77.4	52.4	-25.8	-25.6	-55.6	60	34.2	34.4	4.4
10.12	109.8	109.8	111.0	71.4	72.4	66.4	-38.4	-37.6	-44.6	60	21.6	22.4	15.4
14.06	108.6	108.1	111.3	69.4	69.4	55.4	-39.2	-38.6	-55.6	60	20.8	21.4	4.4
18.1	111.0	111.0	115.6	68.4	67.4	58.4	-42.6	-43.6	-57.6	60	17.4	16.4	2.4
21.1	112.0	112.7	115.8	63.4	64.4	61.4	-48.6	-48.6	-54.6	60	11.4	11.4	5.4
24.9	108.4	107.9	107.4	66.4	67.4	58.4	-42.0	-40.6	-48.6	60	18.0	19.4	11.4
28.4	106.8	107.9	104.2	66.4	60.4	57.4	-40.4	-47.6	-46.6	60	19.6	12.4	13.4

Table 5.

Now with the HF voltages at the injection point are known, together with the measured field strengths, the relation can be defined in a coupling factor *K* [dB/m]. Table 5 shows these for

MP1. Note: *The resulting values for the coupling factor are only valid for this specific location.*

The resulting coupling factor *K* is then applied on the power line noise limit of CISPR 22 QP, also reflected in table 5, resulting in an equivalent noise field strength $E_{CISPR22}$ for this measurement point. The tables 6 and 7 show the results for MP2 in the study.

The six measured values for the coupling factors are together shown in figure 5, this in relation with the average K-factors for asymmetric and symmetric injection.

The results for *K* are comparable with the *K*-values found in literature. In [2], para. 5.11.1 a general value of – 60 dB/m at a distance of 15 m is stated. Measurements lead to values for the coupling factor *K* from -53dB/m to – 75 dB/m for a distance of 3 meter. Only symmetrical injection was used!

Indoor field strength measurements, MP 2 (Study/Shack)										
	E, measured at distance 1.25 m [dBµV/m]						E, Normalized to 3 m			NB30
Frequency	N		P		S		N	P	S	E
[MHz]	E	Angle	E	Angle	E	Angle	E [dBµV/m]			[dBµV/m]
1.84	94	0°	94	0°	58	0°	86.4	86.4	50.4	37.7
3.58	86	75°	86	75°	59	-45°	78.4	78.4	51.4	35.1
7.03	79	80°	80	80°	60	90°	71.4	72.4	52.4	32.5
10.12	72	5°	78	10°	76	15°	64.4	70.4	68.4	31.2
14.06	75	-40°	74	-40°	61	0°	67.4	66.4	53.4	29.9
18.1	66	90°	65	80°	57	15°	58.4	57.4	49.4	28.9
21.1	64	65°	65	80°	71	90°	56.4	57.4	63.4	28.3
24.9	64	55°	62	-20°	64	35°	56.4	54.4	56.4	27.7
28.4	71	-55°	66	-50°	60	-70°	63.4	58.4	52.4	27.2

Table 6.

Evaluation indoor field strength measurements													
MP 2	Generator nominal output power: 0 dBm.									CISPR 22 QP			
Frequency	Mains RFI voltage [dBµV]			E_{3m} [dBµV/m]			K_2 [dB/m]			$V_{CISPR\ 22\ QP}$	$E_{CISPR\ 22}$ [dBµV/m]		
[MHz]	N	P	S	N	P	S	N	P	S	[dBµV]	N	P	S
1.84	104.2	104.2	101.1	86.4	86.4	50.4	-17.8	-17.6	-50.6	56	38.2	38.4	5.4
3.58	104.5	104.5	91.8	78.4	78.4	51.4	-26.1	-26.6	-40.4	56	29.9	29.4	15.6
7.03	103.2	103.4	108.1	71.4	72.4	52.4	-31.8	-30.6	-55.6	60	28.2	29.4	4.4
10.12	109.8	109.8	111.0	64.4	70.4	68.4	-45.4	-39.6	-42.6	60	14.6	20.4	17.4
14.06	108.6	108.1	111.3	67.4	66.4	53.4	-41.2	-41.6	-57.6	60	18.8	18.4	2.4
18.1	111.0	111.0	115.6	58.4	57.4	49.4	-52.6	-53.6	-66.6	60	7.4	6.4	-6.6
21.1	112.0	112.7	115.8	56.4	57.4	63.4	-55.6	-55.6	-52.6	60	4.4	4.4	7.4
24.9	108.4	107.9	107.4	56.4	54.4	56.4	-52.0	-53.6	-50.6	60	8.0	6.4	9.4
28.4	106.8	107.9	104.2	63.4	58.4	52.4	-43.4	-49.6	-51.6	60	16.6	10.4	8.4

Table 7.

The coupling factor *K* is dependant on the measurement set-up and will be different for each house and location caused by the difference in power line wiring. Given the fact that *K* is also frequency dependant means: *a well defined definition of the measurement procedures in a limit is of decisive importance to determine if an interference level is too high in case of complaints.*

Figure 5. Coupling factor.

7. Relation of CISPR field strength limits against NB 30.

The data from the tables 5 and 7 for the field strength are further modified by levelling out the values of both measurement points and then plotted in fig 6. For comparison the NB 30 limit was also plotted in. Now we have the resulting electrical field strength generated in a home by a test signal, injected at a CISPR 22 B (Quasi Peak) limit level.

The conclusions are easy to draw:

- All field strength values are below the NB 30 limit.
- Despite the spread as result of the unpredictable standing wave behaviour on the

230Volts in-home network, and even the fact that the CISPR 22 limits in the frequency range above 5 MHz are higher, clearly is shown that the generated field strength decays with frequency, this as a result of the decreasing K- factor.

- Symmetrical coupling results generally in substantial lower field strength levels. However, in the higher frequency region were the symmetrical behaviour of the wiring decreases, the field strength increase as a result of the symmetrical injection.

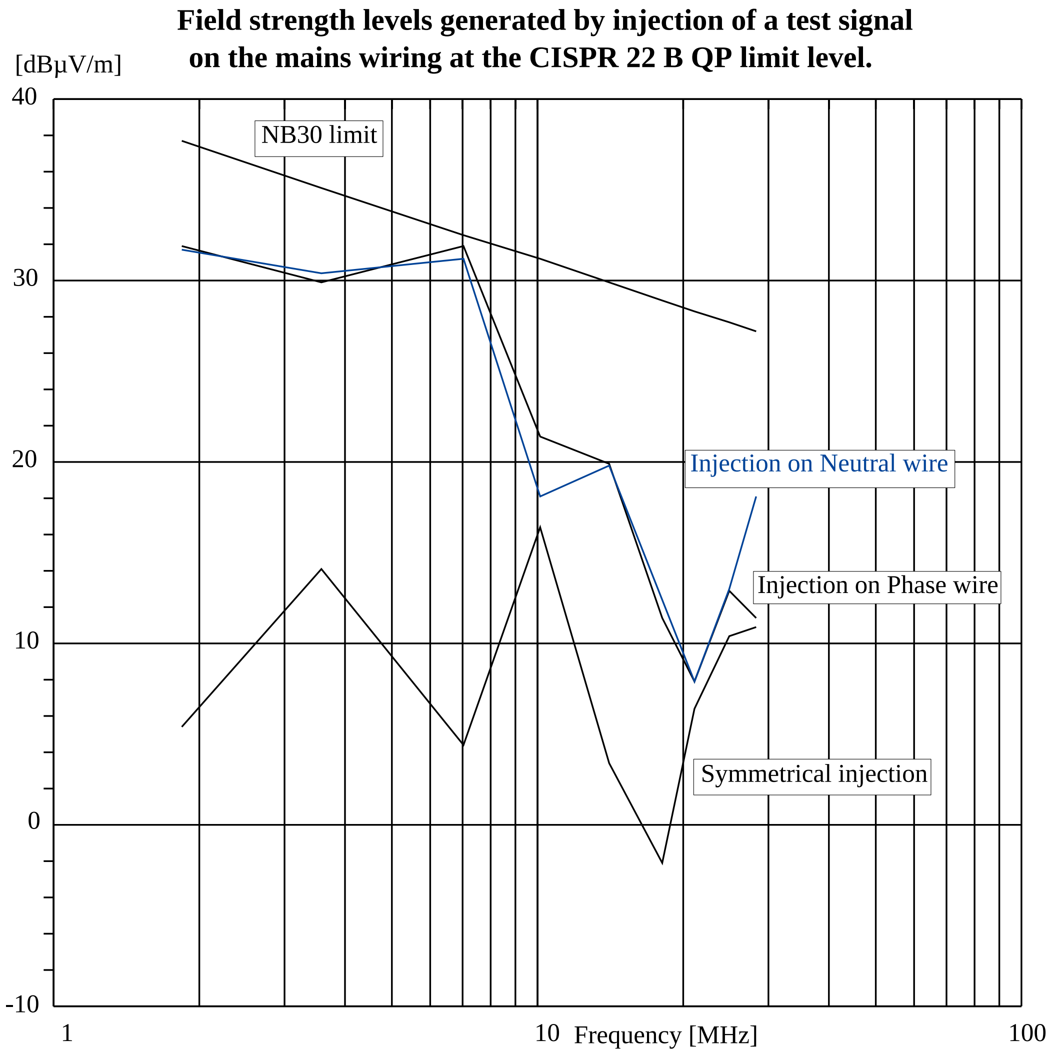


Figure 6. Field strength levels related to the CISPR 22 B QP limit.

8. Outside field strength measurements.

To acquire an impression of the decay of the radiating field with distance in two spots in the garden was measured. One at 10 m and another at 20 m from the house wall (not from the extension). Signal injection only in the Neutral. Field strength measurements again with the R&S ESH2 in combination with the HFH2-Z2 magnetic loop antenna.

Table 8 shows the results, where for a distance of 3m the averages of the in-house measured

Outdoor field strength measurements									
Frequency [MHz]	1.84	3.58	7.04	10.12	14.06	18.100	21.100	24.900	28.400
Distance [m]	E [dBµV/m]								
3	79.9	78.9	74.4	67.9	68.4	63.4	59.9	61.4	64.9
10	57	57	60	56	57	46	51	49	59
20	49	50	55	50	54	39	45	43	55
Mean roll-off [dB/dec]	37.5	35.0	23.5	21.7	17.5	29.6	18.1	22.3	12.0

Table 8.

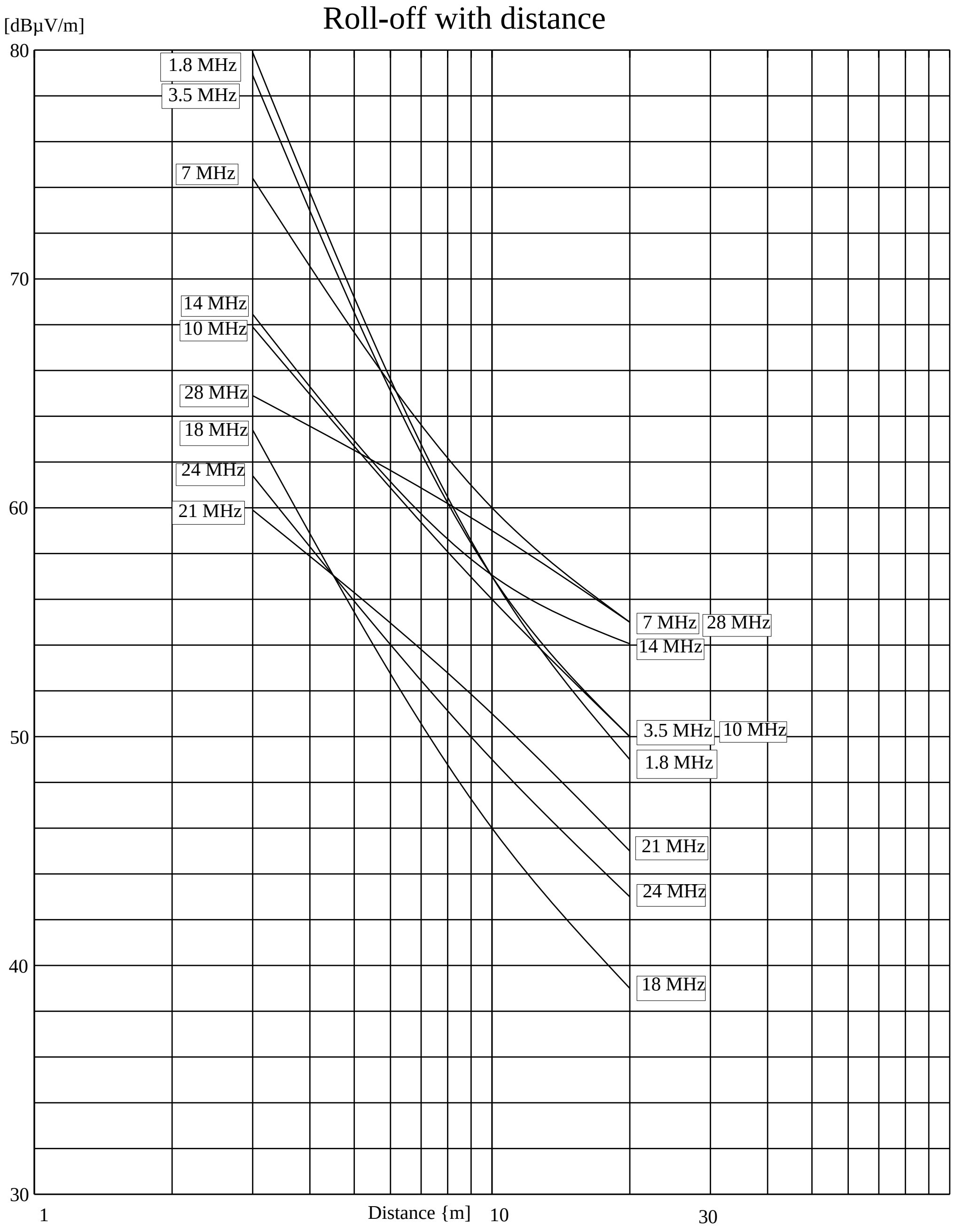


Figure 7.

field strengths are used.

Much indistinctness exists about the course of the field strength in the near- and in the changeover to the far-field region. The results of the measurements were therefore plotted in figure 7, and the average decay in dB's per decade in table 8.

Field strength values normalized for NB 30 field strength at 3m are depicted in figure 8.

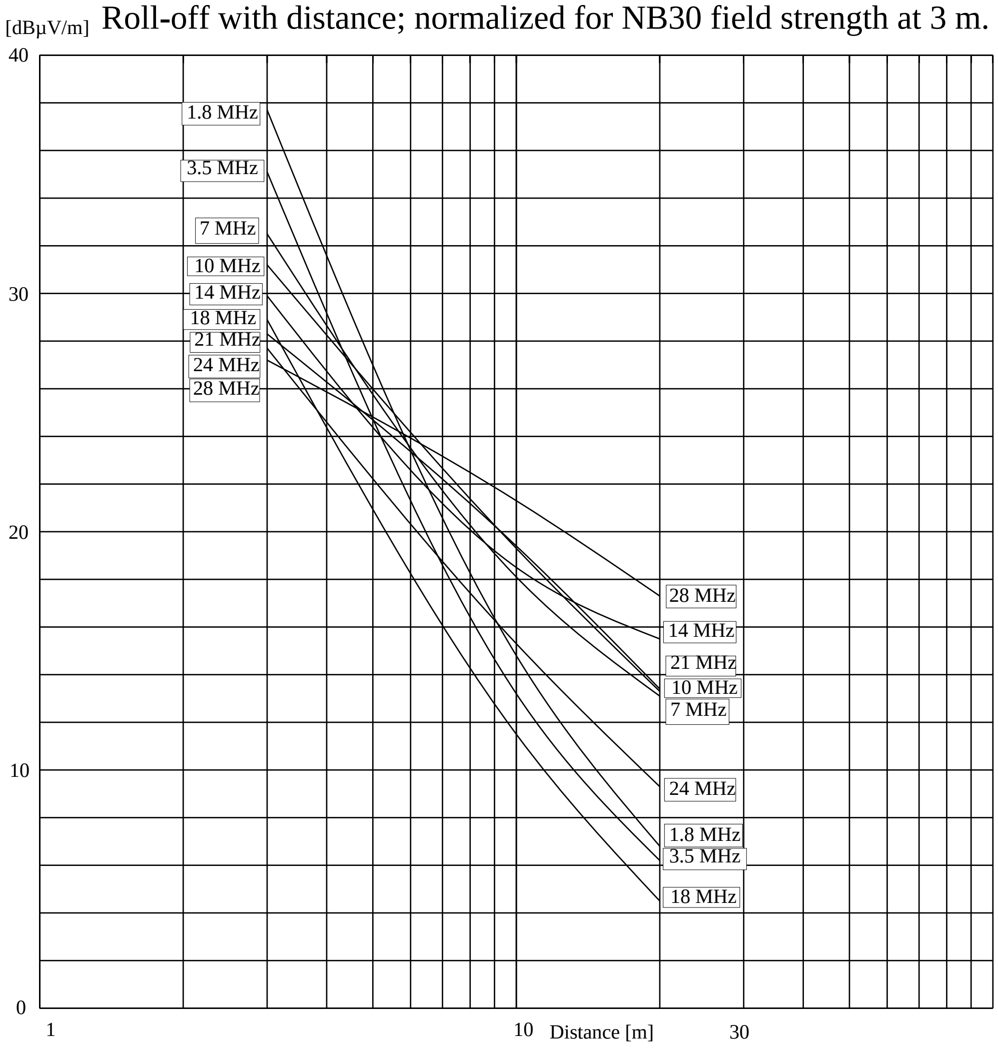


Figure 8.

From figures 7 and 8 we can conclude that the general assumption, that for all frequencies in this situation there is a linear decay, is only true for the statistical average over the 7 higher bands. At 1.8 and 3.5 MHz there is a faster decay.

Note: The assumption, that the field strength roll-off with distance linearly in the near- as well as in the far-field, is only true in one theoretical situation: for a half wave dipole and only if measured magnetically.
Moreover one has to consider these results with great care because of many accidental factors

like the flow of the currents in the wiring system of the house or ground reflections, all have impact on the results.

9. Effects of height and direction of the antenna.

A very interesting question is if we can escape from the interference by PLC systems by the use of higher antennas. In my situation I could check this by varying the height of the 21/28 MHz beam. During these measurements the directive sensitivity could also be checked for the interference. Measurements were conducted in all three injection modes. For the results see table 9.

Coupling measurements using rotary HF beam																		
21.1 MHz	Output generator: 0 dBm. Beam heading: Antenna output voltages in dBµV																	
	0° V_{ant} [dBµV]			90° V_{ant} [dBµV]			180° V_{ant} [dBµV]			270° V_{ant} [dBµV]			Reception at beam heading of maximum signal					
Height [m]	N	P	S	N	P	S	N	P	S	N	P	S	N		P		S	
9	51	47	50	61	61	63	53	51	55	32	32	32	110°	64	90°	61	120°	64
15	46	46	36	59	60	62	45	43	50	38	42	43	110°	60	90°	60	110°	63
21	41	46	43	55	57	61	44	37	47	32	39	41	120°	57	90°	57	90°	61
28.4 MHz																		
9	42	43	44	55	50	50	52	54	50	48	43	44	85°	55	160°	55	180°	52
15	42	42	41	56	54	43	47	53	52	46	52	40	90°	56	135°	55	180°	52
21	44	46	37	54	54	41	47	52	50	49	43	39	100°	55	135°	55	190°	50

Table 9.

The results of table 9 are next normalized to the NB 30 limit. This was done by averaging of the on MP1 and MP2 measured field strengths (tables 4 and 6) for each injection method (N,P,S) and frequency f:

$$E_{mean,M}(f) = \frac{E_{mp1,M}(f) + E_{mp2,M}(f)}{2} \qquad M = N,\ P,\ of\ S$$

and subtracting from those averages the field strength values for those frequencies NB 30 $E_{NB30}(f)$, and subsequently to subtract the remaining values from V_{ant} in table 9: The results are plotted in figure 9.

$$V_{ant,NB30,M}(f) = V_{ant,M}(f) - (E_{mean,M}(f) - E_{NB30}(f))$$

We can see, that from the results of the measurements, the height of the beam has in average only a very limited effect on the amplitude of the interference signal. In the most favourable position only 7 dB for a difference in height between 9 and 21 meters. Considering that the interference signals approach the beam from underneath and not in the main direction, then reflections and accompanying standing wave effects have to be the reason for this irregular and unpredictable behaviour.

The maximum interference is approximately received when the beam is pointing in parallel with the longitudinal axis of the house.

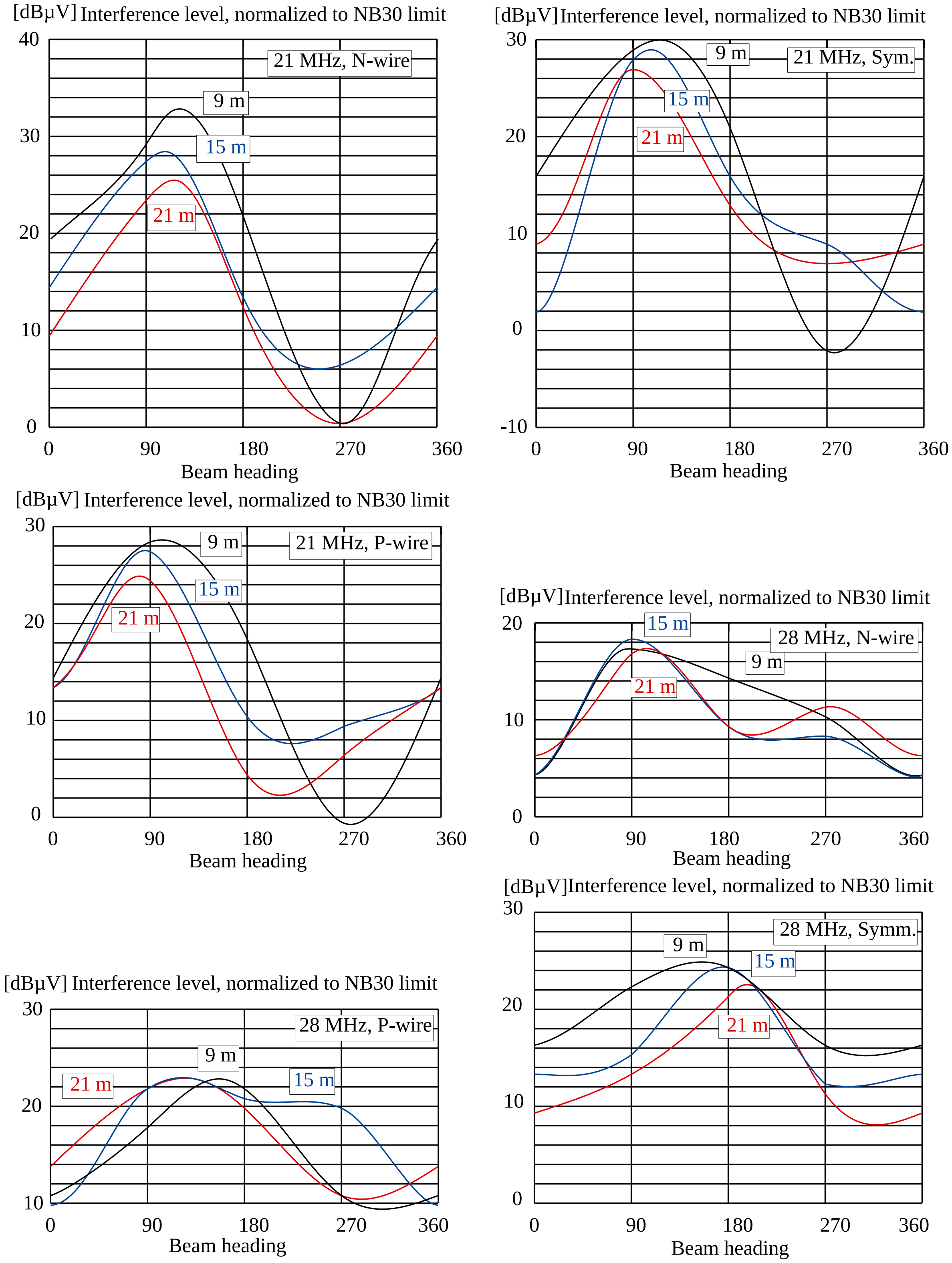


Figure 9. Antenna voltages $V_{ant,NB30,M}(f)$.

10. The interference voltage on the mains wiring.

Within the PLC community is often stated that the CISPR 22 limits already represent the normal background noise level. The purpose of this measurement is to establish the actual level of the background noise level on the 230V in-house grid and to research if the last statement is valid in my particular situation.

The ESH2 measurement receiver is for this measurement connected through the MCD to the grounded wall outlet, approximately in 2m distance from the electricity meter. All noted measurements were taken from the Neutral. The voltages on the Phase are nearly equal to those on the Neutral and the symmetrical voltages between Neutral and Phase are much lower, except for the highest frequency range from 20 – 30 MHz, where grid shows a less symmetrical behaviour. All measured values have been corrected for the transfer function of the MCD.

In order to achieve a representative situation, a number of common and potential internal sources of interference were switched on. The TV set in the living room, the PC in the study and also two electronic energy saving lamps.

10.1 The results.

The figure 10 (Average mode) and 11 (Quasi-Peak mode) show the mains interference voltages on the MF and HF bands. The measuring bandwidth is here 9 kHz, although in the case of the broadband interference for the average measurement often an actual bandwidth of 200 Hz has been used with a correction of + 16.5 dB towards a normalized bandwidth of 9 kHz.
In the figures 7 and 8 a differentiation is made between more or less broadband, rattle-like, hum modulated (background) signals, and well outstanding small-band signals. The first ones are shown as a curve, the latter as single points. Not all the detectable signals are shown, only a selection, giving a good representation of frequencies and levels.

In the figures 10 and 11 also the CISPR 22 limits (class B equipment = equipment for use in domestic environment, for limits see Annex 3) have been drawn, as well as the equipment measurement sensitivity limits.

10.2 Discussion.

Outside the (used) broadcast frequencies on long and medium wave and below 2 MHz it was well possible to measure the broadband noise on the mains wiring. Above the 2 MHz
the real broadband noise vanishes rapidly, although hum modulated noise lumps reappear there and here. Remarkable are the harmonics of the line deflection from the TV set, which become audible above 1.6 MHz, and show their maximum in the neighbourhood of the 80 m band. In the higher frequency band, above 20 MHz, a number of carriers show off, probably clock signals, some hum modulated. These carriers were positively identified as generated in-house and not coming from outside.

In the frequency range from 5 -15 MHz the measurements were hampered by the strong reception of radio signals. In fact the mains wiring appears to be a real effective receiving antenna!

The TV line deflection harmonics, which are a very common source of interference as experienced by radio amateurs on the 1.8 and 3.6 MHz bands, disappear when the TV outside antenna was disconnected. Probably the mains wiring together with the lightning ground of the TV antenna form a closed loop.

10.3 Conclusion for the interference voltage measurements.

- Although on LF and MF up to 1 MHz the measured interference voltages more or less approach the CISPR 22 limits, above 1.6 MHz they stay far below these limits. For frequencies above 5 MHz the broadband interference is more than 40 dB below the CISPR limits. Only some narrow band interference signals were up to 30 dB below CISPR 22.
- TV line oscillator harmonics approach the CISPR limits up to 20 dB for frequencies 1.6 – 5 MHz. In practice these harmonics are very often experienced as harmful interference.
- Although the outcome of these measurements does not need to be representative for all residences, they do indicate that the CISPR 22 limits cannot be regarded as the general level of existing background interference/noise on the 230 V mains grid. This is not unexpected as the CISPR 22 limits only apply to the mains connector of an *apparatus*, and not to a (mains) network.
- When such a piece of equipment actually is connected to the mains network, the available interference power is spread out over the two or three dimensional network. Partly this power is also dissipated in the high frequency losses (PVC isolated wires!), and even radiated increasingly with frequency, which is inherent to such a network which is not intended to be used as a conductor for RF energy. This makes clear that from the point of energy balance it is very unlikely to measure a level of interference voltage equal to the CISPR 22 limits at a random point of a mains network.

However, the most important conclusion of this measurement is that the conducted measured noise level at a random chosen point on the mains grid is much lower than what is expected in accordance with the CISPR 22 Standard.

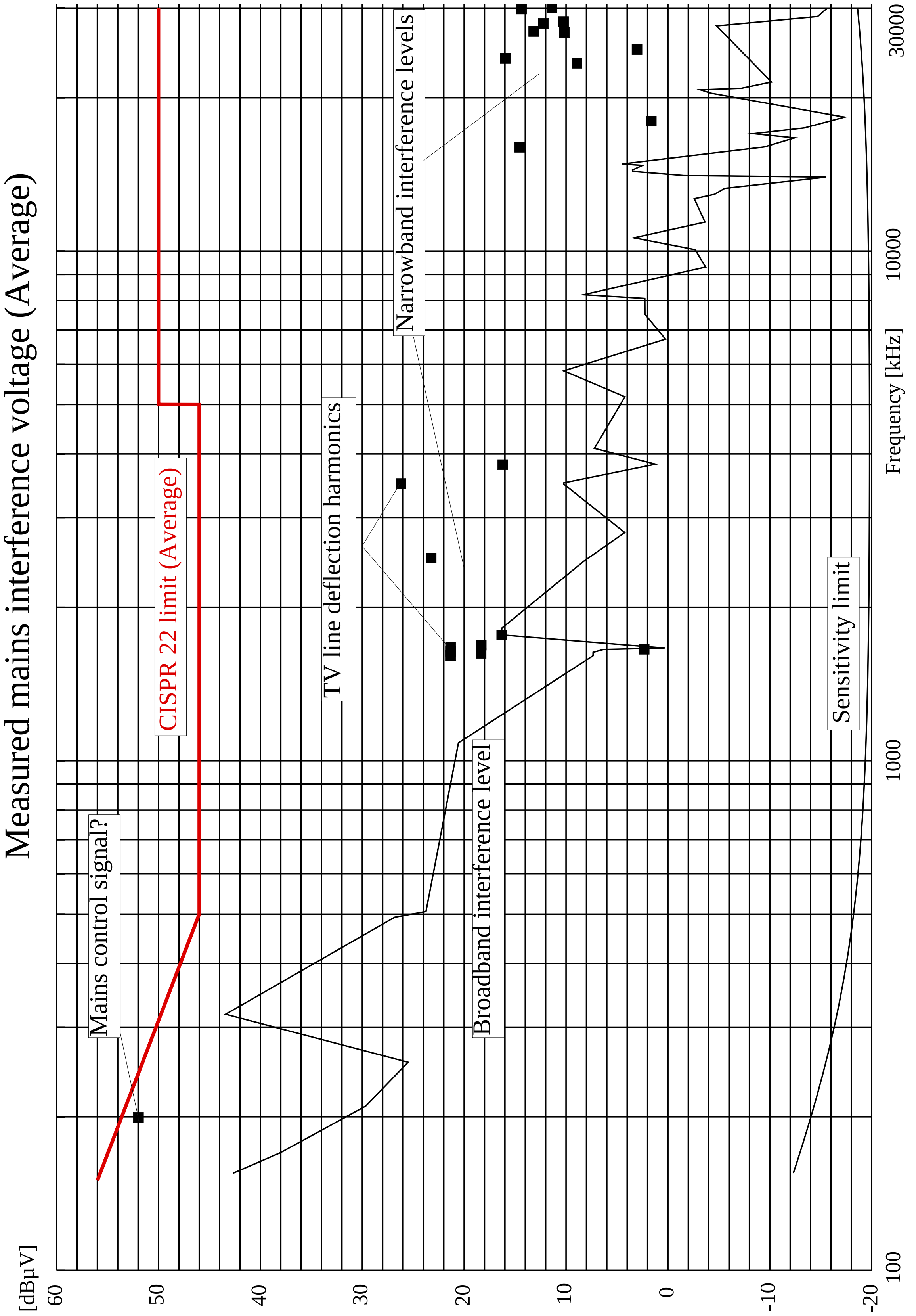


Figure 10. MF and HF, 150 kHz - 30 MHz, Average.

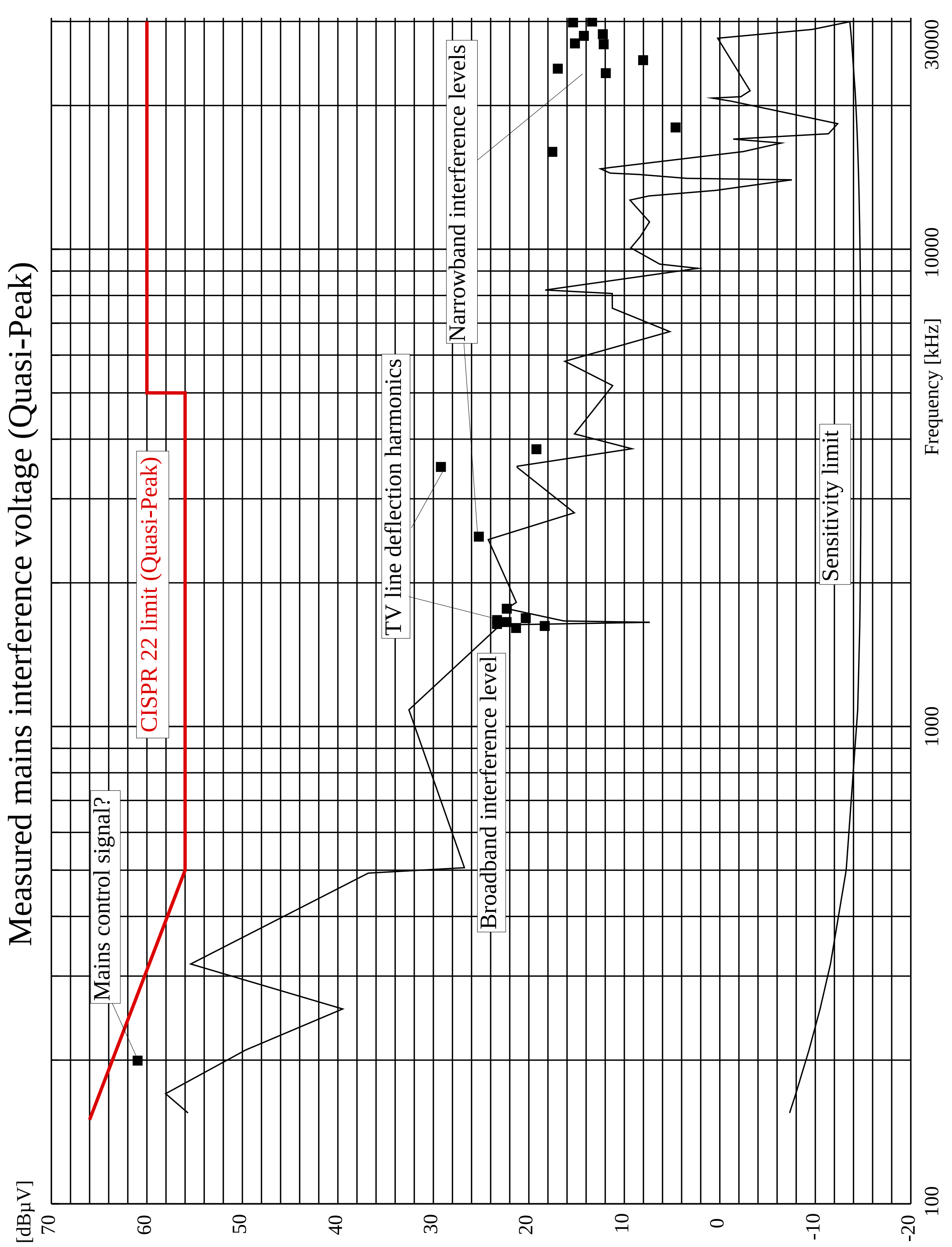


Figure 11. MF and HF, 150 kHz - 30 MHz, Quasi-Peak.

11. Disturbance by the emission of an interference voltage on the mains.

The question is, after we have found the noise level on the mains via conducted measurement, what are the resulting EM fields in home?

With the aid of the measured K- factor, see tables 5 and 7, and the averages of K_1 en K_2 in figure 5, we can compute the interference field strength on the amateur bands. For that reason an estimation of the broadband noise on the HF bands was made with the Quasi Peak measured values from figure 8, and imported in table 10.

The relevant small band noise signals are also incorporated in the second column of this table. Using $K_{asymmetrical}$ these values were converted into field strength values, and consequently plotted in figure 12, together with the three previous mentioned limits. These field strength values are valid for a measurement distance of 3 meter.

Interference field strength, caused by Mains Interference Voltage, calculated with measured K-factor.

Frequency	$V_{interference}$ Broadband QP, [dBµV]	$V_{interference}$ Narrowband, [dBµV]	$K_{asymmetrical}$ [dB/m]	$E_{interference}$ Broadband [dBµV/m]	$E_{interference}$ Narrowband [dBµV/m]
1.84	23	23	-24.2	-1.2	-1.2
3.58	21	30	-25.9	-4.9	4.1
7.03	15		-28.5	-13.5	
10.12	12		-40.2	-28.2	
14.06	9		-40.2	-31.2	
18.1	6	18	-48.1	-42.1	-30.1
21.1	5	17	-52.1	-47.1	-35.1
24.9	3	16	-47.0	-44.0	-31.0
28.4	2	15	-45.2	-43.2	-30.2

Table 10.

From figure 12 we can remark several points:

- All measured interference signals have a field strength below all limits including the BBC limit values.
- A number of small band noise signals in the range from 20 -30 MHz were positively observed with the station receiver and HF beam, although weak. This supposes though a much higher field strength that computed. A good explanation for this effect could be that the source for these signals, the PC with peripheral equipment which are fed via an extra mains rfi filter, is located in the shack. For this reason the coupling with the antenna for the PC-noise is stronger than what would be expected from the conducted measured PC-noise signal level at the wall outlet in the kitchen. Also the signal attenuation of the signal between the study/shack and the kitchen wall outlet plays a role here.
- The coax cable to the TV antenna is probably the cause for the contribution of the radiation of the line deflection harmonics from the TV.

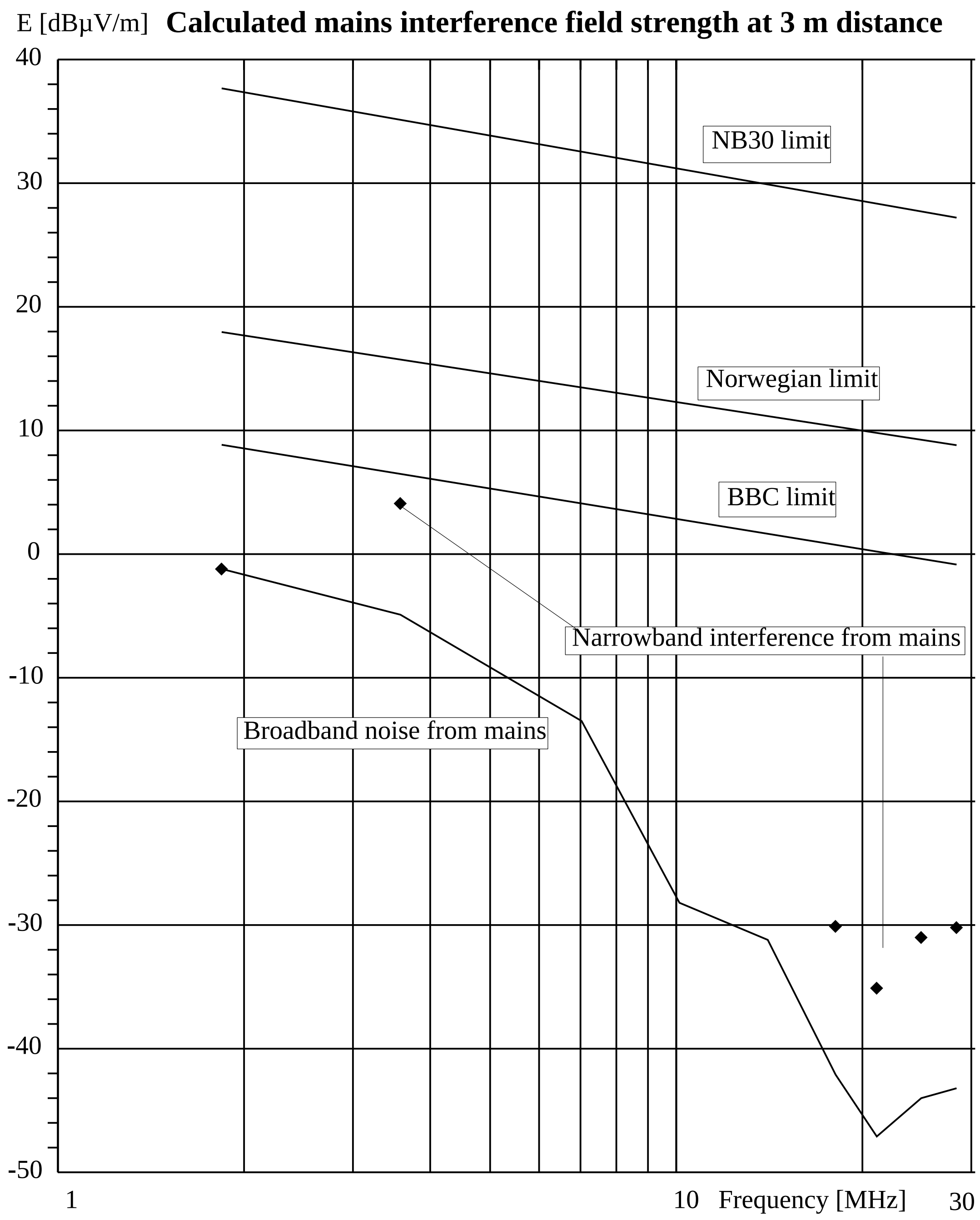


Figure 12.

12. Relationship between received interference in a amateur receiver and the various limits.

The perception of the noise from his receiver is finally what counts for the radio amateur. For that not only the absolute signal strength in dBuV's is important, but also the background noise. This composite noise, from several sources, like man made noise, atmospheric noise and galactic noise is received by the station antennas).

For this experiment alternately the measurement receiver and the NRD 525 station receiver were connected to one of the three antennas and was listened to the received injected interference signal. The signal generator was set to different output levels.

These levels are equal to:

1. 0 dBm, available output power of the generator.
2. So much output power that the average of the measured field strength at the measurement points 1 and 2 is equal to the NB30 limit value for that frequency.
3. So much output power that the average of the measured field strength at the measurement points 1 and 2 corresponds with the field strength which is related to a mains interference voltage in accordance with the CISPR 22 limit value for that frequency.
4. So much output power that the average of the measured field strength at the measurement points 1 and 2 is equal to the limit value of the Norwegian proposal for that frequency.
5. So much output power that the average of the measured field strength at the measurement points 1 and 2 is equal to the limit value of the BBC proposal for that frequency.

In case of experiment number one where power was injected in the Neutral line, the averages of the field strength computed from tables 6 and 8 for MP1 and MP2, respective $E_{3m,0dBm,MP1}$ and $E_{3m,0dBm,MP2}$ and are displayed in table 11 as $E_{3m,0dBm}$. Additionally the limit values were computed for the NB30, the Norwegian, and the BBC limit (see Annex 3 for details), and reflected in table 11 as respective $E_{3m,NB30}$, $E_{3m,Norway}$, $E_{3m,BBC}$.

Also field strength $E_{3m,CISPR}$ was defined, which is equal to the average of the field strengths measured at MP1 and MP2 (see tables 5 and 7), where the at the Neutral injected voltage at the injection point is equal to the CISPR 22 QP limit.

The corresponding injected power levels for these limits, IP_{NB30}, IP_{CISPR}, IP_{Norway}, IP_{BBC}, were determined from:

$$IP_{limit} = E_{limit} - E_{0dBm}$$

Calculation of injected power levels in experiments 2 - 5											
Frequency [MHz]	$E_{3m,0dBm,MP1}$ [dBµV/m]	$E_{3m,0dBm,MP2}$ [dBµV/m]	$E_{3m,0dBm}$ [dBµV/m]	$E_{3m,NB30}$ [dBµV/m]	$E_{3m,CISPR}$ [dBµV/m]	$E_{3m,Norway}$ [dBµV/m]	$E_{3m,BBC}$ [dBµV/m]	IP_{NB30} [dBm]	IP_{CISPR} [dBm]	IP_{Norway} [dBm]	IP_{BBC} [dBm]
1.84	73.4	86.4	79.9	37.7	31.7	18.0	9.3	-42.2	-48.2	-61.9	-70.6
3.58	79.4	78.4	78.9	35.1	30.4	15.7	6.9	-43.8	-48.5	-63.2	-72.0
7.03	77.4	71.4	74.4	32.5	31.2	13.5	4.6	-41.9	-43.2	-60.9	-69.8
10.12	71.4	64.4	67.9	31.2	18.1	12.3	3.3	-36.7	-49.8	-55.6	-64.6
14.06	69.4	67.4	68.4	29.9	19.8	11.2	2.1	-38.5	-48.6	-57.2	-66.3
18.1	68.4	58.4	63.4	28.9	12.4	10.3	1.2	-34.5	-51.0	-53.1	-62.2
21.1	63.4	56.4	59.9	28.3	7.9	9.8	0.7	-31.6	-52.0	-50.1	-59.2
24.9	66.4	56.4	61.4	27.7	13.0	9.2	0.1	-33.7	-48.4	-52.2	-61.3
28.4	66.4	63.4	64.9	27.2	18.1	8.8	-0.4	-37.7	-46.8	-56.1	-65.3

Table 11.

The results as shown in table 11 are used to set the output level of the generator for the measurements.

The antenna voltage was measured with the measurement receiver. Then was listened with the NRD 525 and the reception of the injected “interference” assessed against the IARU defined S-units. For a strong received interference signal the S-meter read out (the NRD 525 meets the IARU specification fairly well) was translated to the IARU description. For a weak signal the level was determined in relation to the background noise.

From the in this way found values for the interference we can clearly see what the effects are for the Amateur service when these limits are enforced. The results are shown in table 12.

Evaluation table of Amateur radio reception, interfered by powerline communication								
Receive antenna:		German Quad: a square loop of 20 by 20 m, 10 m high. The smallest distance to the house is **12 m**. Connected via balun trafo and matching circuit. Full matching only on 3.5 and 14 MHz band. [ ]: Inverted L receive_only antenna, 30m horizontal, 10 m height, **40 m** distance to house. Connected via broadband trafo.				Duo bander, 2 x 4 elements beam. Positioned at mast **2 m** from house, **21 m** above ground.		
Experiment:	Frequency:	1.84	3.575	7.03	14.09	21.1	28.4	MHz
1. $E=E_o$	**Injected power:**	**0**	**0**	**0**	**0**	**0**	**0**	dBm
	E@3m:	79.9	78.9	74.4	68.4	59.9	64.9	dBµV/m
	$V_{antenna}$:	49 [39]	62 [43]	55 [55]	49 [35]	56	56	dBµV
	Experience of interference: (on rx: NRD525)	Very strong [very strong]	Very strong [very strong]	Very strong [very strong]	Very strong [very strong]	Very strong	Very strong	
2. $E=E_{NB30}$	**Injected power:**	-42.2	-43.8	-41.9	-38.5	-31.6	-37.7	dBm
	E@3m:	37.7	35.1	32.5	29.9	28.3	27.2	dBµV
	$V_{antenna}$:	8 [0]	19 [0]	14 [14]	10 [-4]	23	19	dBµV
	Interference:	Reasonable [weak]	Rather strong [reasonable]	Well [well]	Reasonable [very weak]	Rather strong	Rather strong	
3. $E=E_{CISPR22}$	**Injected power:**	-48.2	-48.5	-43.2	-48.6	-52.0	-46.8	dBm
	E@3m:	31.7	30.4	31.2	19.8	7.9	18.1	dBµV/m
	$V_{antenna}$:	1 [-6]	13 [-]	12 [12]	1 [-14]	3	9	dBµV
	Interference:	Weak [very weak]	Reasonable well [hardly perceptible]	Well [well]	Hardly perceptible [no]	Reasonable	Rather strong	
4. $E=E_{Norway}$	**Injected power:**	-61.9	-63.2	-60.9	-57.2	-50.1	-56.1	dBm
	E@3m	18.0	15.7	13.5	11.2	9.8	8.8	dBµV/m
	$V_{antenna}$:	-13 [-]	-1 [-]	- [-]	-7 [-]	6	0	dBµV
	Interference:	Hardly perceptible [no]	Hardly perceptible [no]	No	No	Reasonable	Weak	
5. $E=E_{BBC}$	**Injected power:**	-70.6	-72.0	-69.8	-66.3	-59.2	-65.3	dBm
	E@3m:	9.3	6.9	4.6	2.1	0.7	-0.4	dBµV/m
	$V_{antenna}$:	- [-]	- [-]	- [-]	- [-]	-3	-7	dBµV
	Interference:	No	No	No	No	Very weak	Very weak	
6. Amb. noise	B = 500 Hz:	-12 [-6]	3 [-4]	3 [1]	-4 [-9]	-20	-21	dBµV
	B = 2.7 kHz:	-3 [1]	10 [3]	10 [8]	3 [-2]	-13	-14	dBµV
	Antenna factor:	Unknown	Unknown	Unknown	Unknown	-11.2	-8.7	dB/m
	Noise field strength:					-24.2	-22.7	dBµV/m

Table 12.

12.1 Background noise.

Background noise was also measured. For this purpose the measurement receiver was set to “ Average” and further averaging was done on the face of the reading. The values were then normalized to a band width of 2.7 kHz for purpose of comparison with the values in ERC Report 69 [3].

However, only for 21/28 MHz an antenna factor k could be determined, using an antenna gain of 8 dBi, with formula (7) in Annex 2. To define the noise field strength, the value of k is first converted in dB/m and than added to the noise voltage.

ERC Report 69 gives for the noise field strength at 21 MHz: -19 dBµV/m, and for 28 MHz: -20.0 dBµV/m in "Quiet Rural Area". This are values valid for a short monopole receiving antenna over a perfect conducting ground. For a half wave dipole in free space we must subtract 3.5 dB[1], so we arrive at -22.5 resp. -23.5 dBµVm. The measured values are about these same levels.

13. RF voltages induced in the mains because of the fields from an amateur radio transmitter.

PLC modems not only may be able to interfere the reception on the amateur bands, but inversely a PLC modem may be interfered by RF voltages that are induced in the mains wiring by an amateur transmitter via its antenna. In fact this is the reciprocal effect of the coupling, discussed in the foregoing paragraph.

The measurement was performed by transmitting an unmodulated carrier with transmitting power of 10 W via the for that frequency relevant antenna. At the wall outlet, earlier used as injection point, the RF-voltage of the carrier was measured using the MCD and the ESH2 measuring receiver.

The results are given in table 13. Also the received signal levels are converted in dBm's according:

$$
\begin{aligned}
P_{mains} &= \frac{V_{mains}^{2}}{R} \\
\log P_{mains} &= \log V_{mains}^{2} - \log R \\
10\log P_{mains} &= 10\log V_{mains}^{2} - 10\log R \\
10\log P_{mains} &= 20\log V_{mains} - 10\log R \\
P_{mains}[\text{dBW}] &= V_{mains}[\text{dBV}] - R[\text{dBohm}] \\
P_{mains}[\text{dBm-30}] &= V_{mains}[\text{dBµV-120}] - R[\text{dBohm}] \\
P_{mains}[\text{dBm}] &= V_{mains}[\text{dBµV}] - 107
\end{aligned}
$$

The difference with the transmitting level (40 dBm), indicates the coupling between transmitting antenna and the mains at the position of the injection point:

$$K_{tx} = P_{mains} - P_{tx} = P_{mains} - 40$$

---

[1] According Rec. ITU-R PI.372-6. The relationship between the noise field strength and the type of antenna is addressed in CCIR Report 670 and in the therein mentioned reference: LAUBER, W.R. [1977] Preliminary urban UHF/VHF radio noise measurements in Ottawa, Canada. Proceedings of 2nd Symposium on EMC, Montreux, Switzerland, June 28-30,357-362.

Induction of HF transmitter voltage into mains network										
Frequency	Antenna	RF voltage [dBµV]			P_{mains} [dBm]			K_{tx} [dB]		
[MHz]		N	P	S	N	P	S	N	P	S
3.58	German Quad	102	102	71	-5	-5	-36	-45	-45	-76
7.04	German Quad	95	97	82	-12	-10	-25	-52	-50	-65
14.06	German Quad	84	77	82	-23	-30	-25	-63	-70	-65
21.10	4 el. Beam, 21 m heigth	99	99	96	-8	-8	-11	-48	-48	-51
28.40	4 el. beam, 21 m heigth	89	92	88	-18	-15	-19	-58	-55	-59

Table 13. RF voltage induced in the 230 V network by the amateur radio transmitter.

14. General conclusions.

By injecting a test signal into the 230 V grid of the house a series of preliminary measurements were carried out for the EM radiation as result of the injected RF interference signal on the 230 V mains. For this specific situation the following conclusions can be drawn:

- If the RF voltage on the injection point has a level which is equal to the CISPR 22 Quasi Peak limit, then the resulting field strength has in average a level 2 – 10 dB below the NB 30 limit.
- That the level of the actual present mains interference voltage on the grid for frequencies above 1.6 MHz is several tens of dB's below the CISPR 22 limits. One can distinguish here between the relative sporadic appearing small band signals, the "clock signals" and the signals of a broad band type. These wide spectrum signals have a roll-off of 20 dB/decade and reach at 30 MHz a value of 55 to 60 dB below the CISPR 22 B limits.

More general conclusions are:

- In residential situations one cannot say that the NB30 limit forms a more stringent limitation on interference carried by the mains grid than the CISPR 22-B limit. The opposite seems to be true.
- For an antenna location as is common for most amateurs, close to or above the house, the reception of interference radiating from the mains is very serious for field strength levels equal to the NB 30 limit or equivalent field strength level of the CISPR 22 limit.
- Even the BBC limit is inadequate to avoid interference in the above mentioned situation, in particular on the higher amateur bands.
- For the residential situations and for frequencies above 1.6 MHz the CISPR 22 limits do not form a useful indication for the existing background noise levels on the mains wiring.

15. Literature.

[1] PLC Studie RegTp, door EMV- Beratungs-und Planungsbüro, Prof. Dr.-Ing. K.H. Gonschorek, Dr.-Ing. R. Vick. www.emc.experts.de.

[2] Powerline Communications, door Klaus Dostert. Prentice Hall, ISBN 0-13-029342-3.

[3] CEPT/ERC Report 69.

ANNEX 1.

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 A1-1 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:

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

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:

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

$$Z_p = \frac{R_L \cdot j\omega L_p}{R_L + j\omega L_p} \qquad (3)$$

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

$$Z = \frac{R_L + j\omega L_p + j\omega L_s \cdot j\omega C\,(R_L + j\omega L_p) + j\omega C \cdot R_L \cdot j\omega L_p}{j\omega C\left(R_L + j\omega L_p\right)} + R_s + R_{loss}$$

$$Z = \frac{\omega^2 L_s C R_L + \omega^2 L_p C R_L - R_L + j\omega^3 L_s C L_p - j\omega L_p}{\omega C\left(\omega^2 L_p^2 + R_L^2\right)} \cdot \left(\omega L_p + jR_L\right) + R_s + R_{loss}$$

$$Z = \frac{\omega^3 L_p^2 C R_L + j\left\{\omega^4 L_s L_p^2 C - \omega^2\left(L_p^2 - L_s C R_L^2 - L_p C R_L^2\right) - R_L^2\right\}}{\omega C\left(\omega^2 L_p^2 + R_L^2\right)} + R_s + R_{loss} \qquad (4)$$

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

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

$$= \frac{\omega^2 L_p^2 R_L}{\omega^2 L_p^2 + R_L^2} + R_s + R_{loss} \qquad (5)$$

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

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

Combining we get:

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

In the same way we derive for Z_p:

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

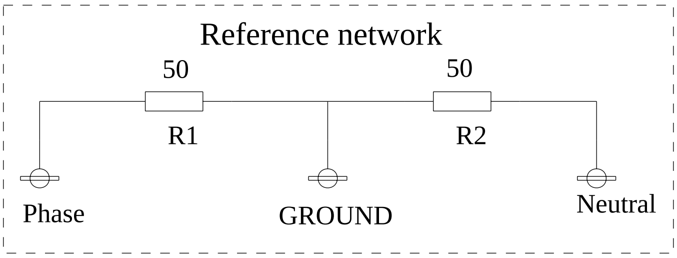
and

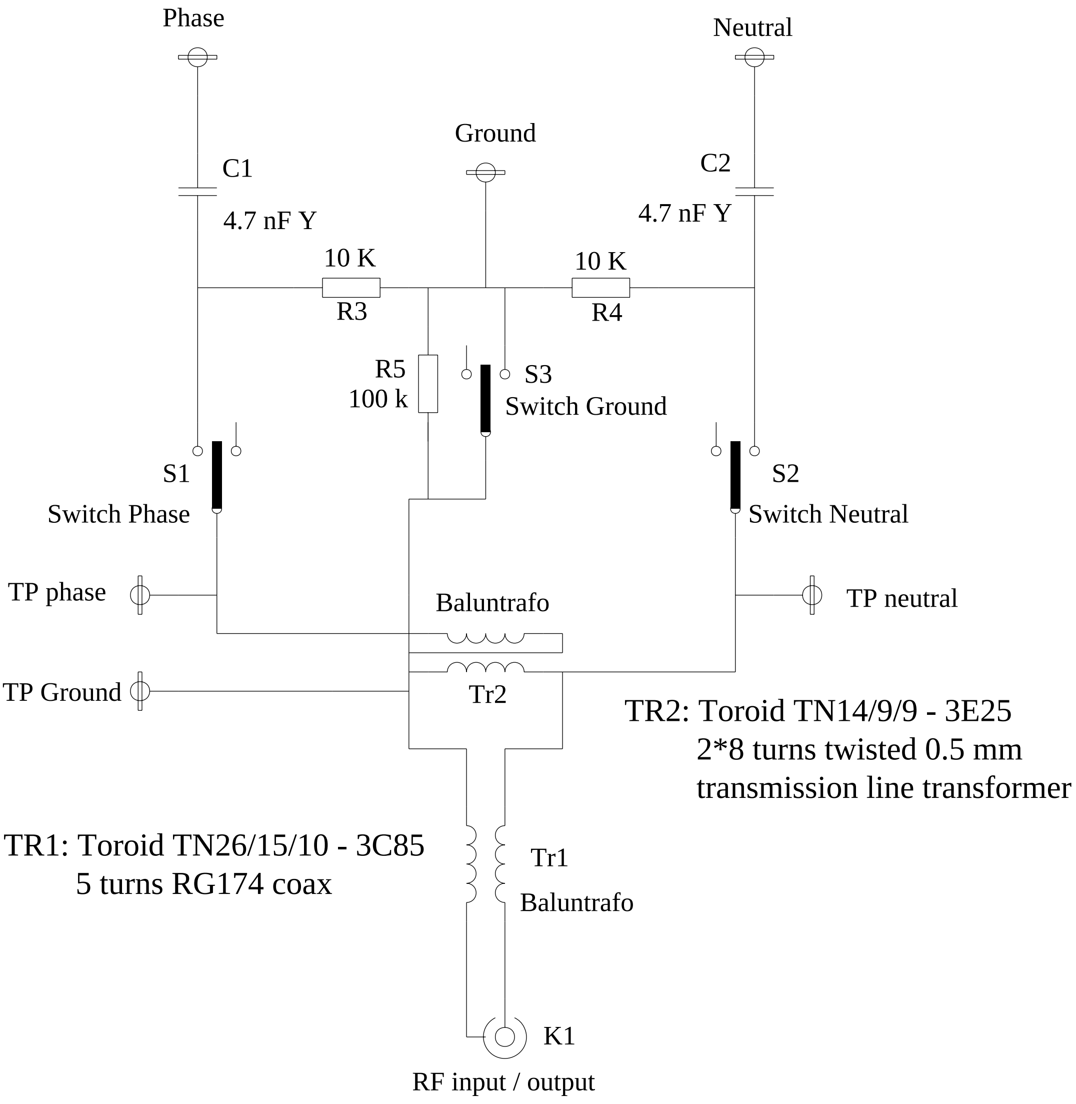
$$|Z_p\ | = \frac{1}{R_L^2 + \omega^2 L_p^2}\sqrt{\omega^4 L_p^4 R_L^2 + \omega^2 L_p^2 R_L^4} = \frac{\omega L_p R_L \sqrt{\omega^2 L_p^2 + R_L^2}}{R_L^2 + \omega^2 L_p^2} \qquad (8)$$

The formulas (1), (5), (6), (7), and (8) are being inputted in a math program[2] together with a list of frequencies and the component values. The result is displayed in figure A1-3 for asymmetrical coupling, and in figure A1-4 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.

[2] 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).





TR2: Toroid TN14/9/9 - 3E25
2*8 turns twisted 0.5 mm
transmission line transformer

TR1: Toroid TN26/15/10 - 3C85
5 turns RG174 coax

Figure A1-1. Circuit of the Mains Connector Device.

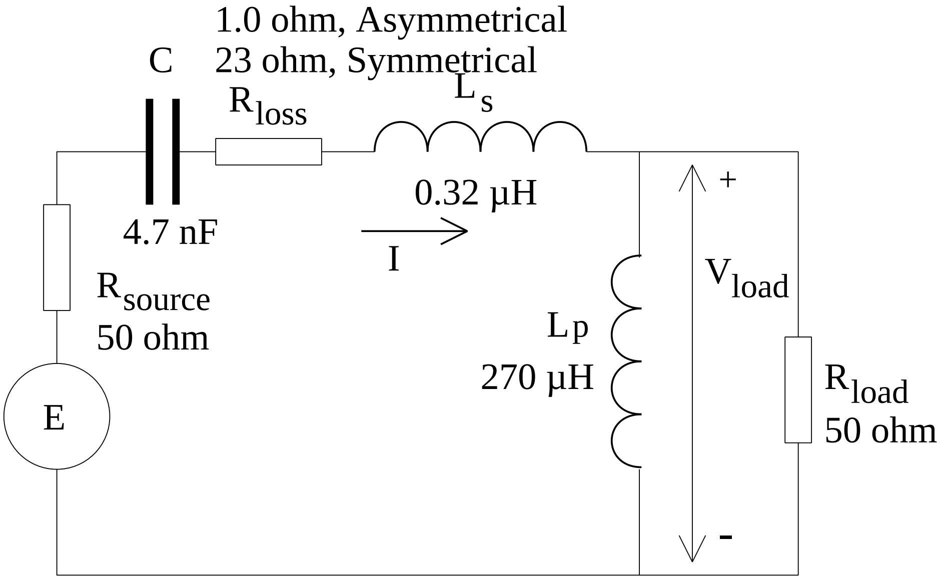


Figure A1-2. Principal schematic.

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.

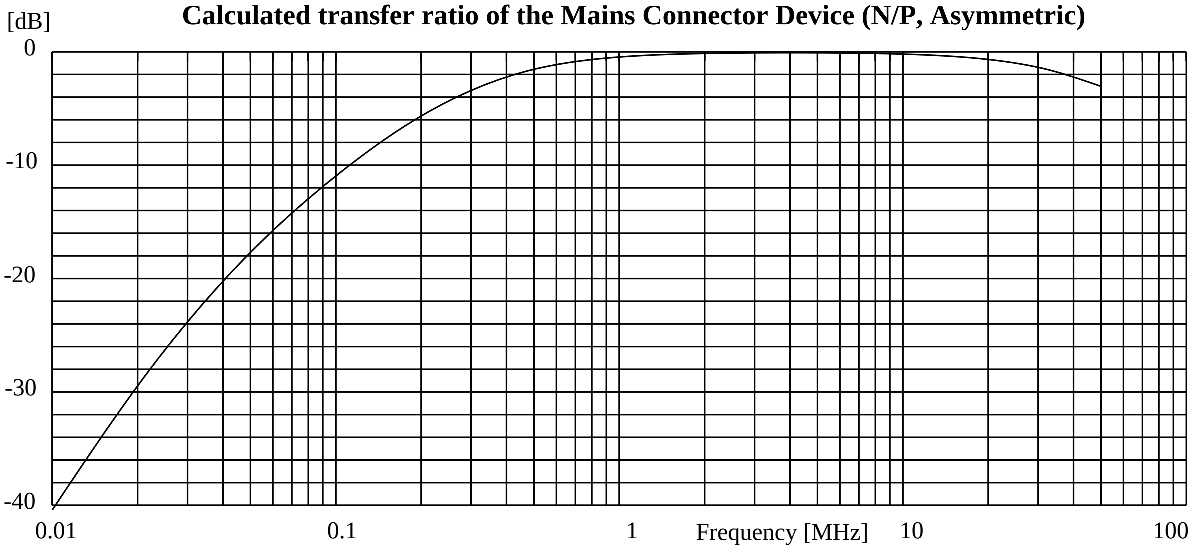


Figure A1-3. Transfer function for the case of asymmetric coupling.

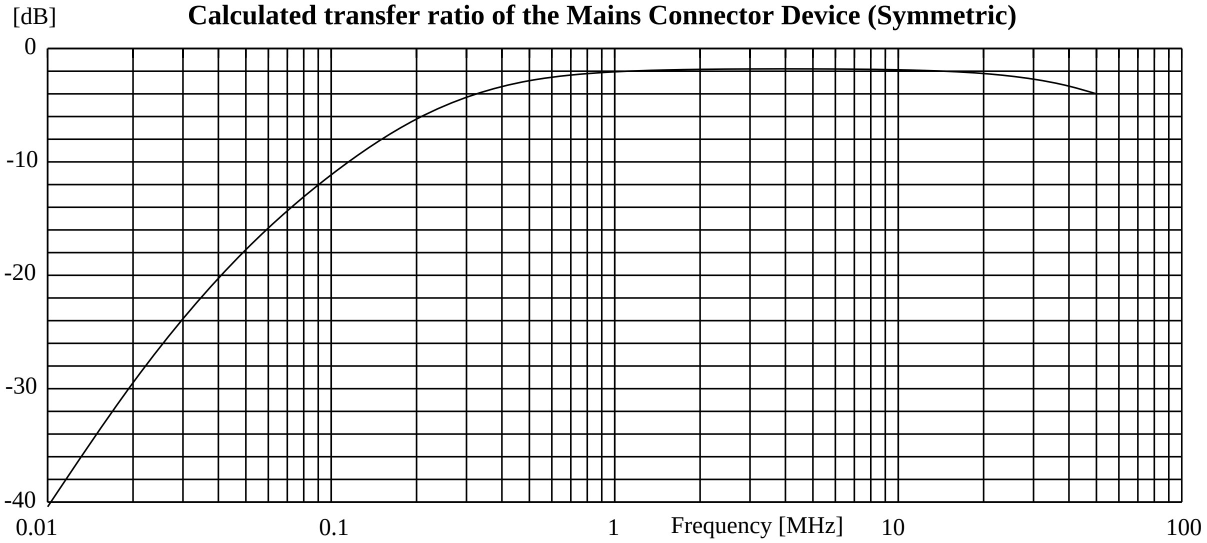


Figure A1-4. Transfer function for the case of symmetric coupling.

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 A1-2, see figure A1-5. The component values are based on the measurements of the transfer function in figure A1-2. 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.

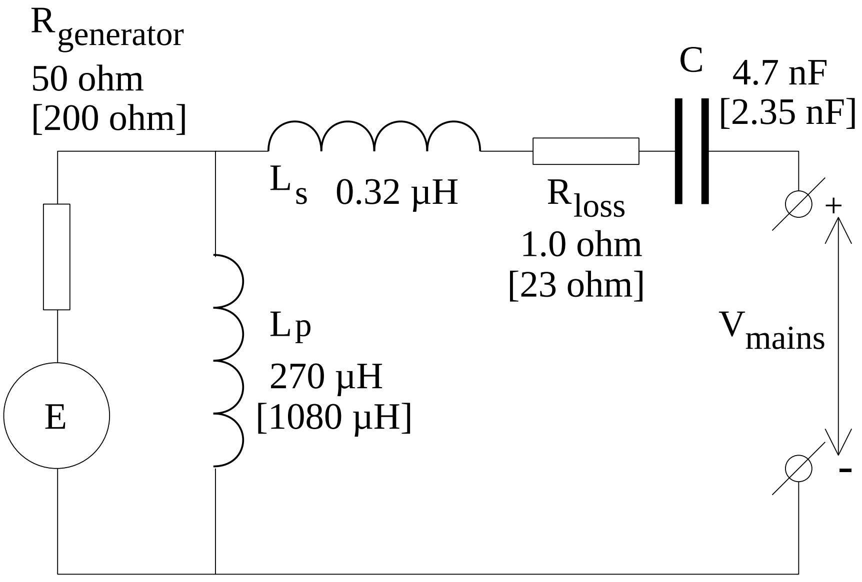


Figure A1-5. Principal schematic mains impedance measurement.

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

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

$$Z_{pp} = \frac{R_G \cdot j\omega L_p}{R_G + j\omega L_p} \tag{10}$$

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

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

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

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

Figure A1-6 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.

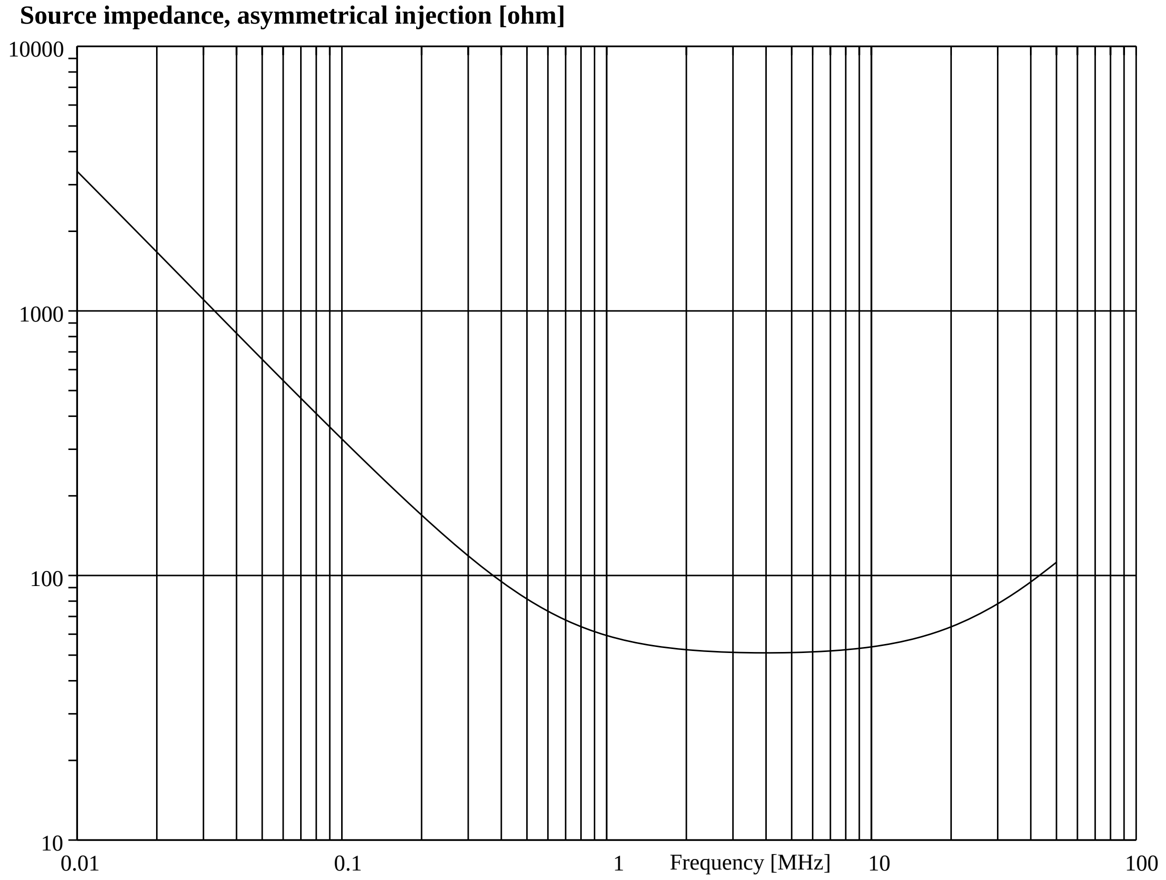


Figure A1-6. Source impedance for the case of asymmetric injection.

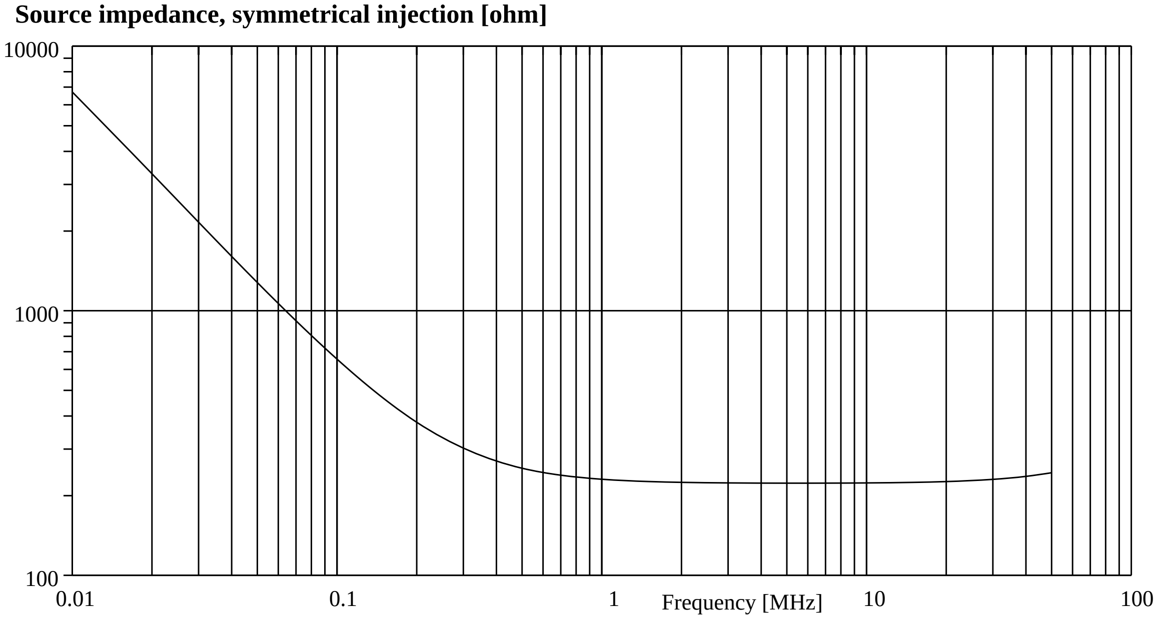


Figure A1-7. Source impedance for the case of symmetric injection.

ANNEX 2

Calculation of the antenna factor of a receiving antenna.

Introduction.

When the field strength, *E*, or the power density, *p*, of a radio signal is known we are able to calculate the voltage, that is induced in a conductor with a length small in relation to the wavelength directly from the field strength pro meter.

For a receiving antenna with dimensions that are not small compared with the wavelength, like a half wave dipole, we have to integrate the field strength over the length of the antenna.

We can avoid this calculation if we know the effective surface, aperture, of the antenna. For an electrical dipole is that (every dimension, but loss free!):

$$A_{eff} = \frac{3\lambda^2}{8\pi} \tag{1}$$

For a receiving antenna in general:

$$A_{eff} = \frac{g \cdot \lambda^2}{4\pi} \tag{2}$$

with *g* as the antenna gain.

The power density is:

$$p = \frac{E^2}{120\pi} \quad [W/m^2] \tag{3}$$

Then the received power is:

$$P_{rx} = A_{eff} \cdot p = \frac{g \cdot \lambda^2}{4\pi} \cdot \frac{E^2}{120\pi} = \frac{g \cdot \lambda^2}{480\pi^2} \cdot E^2 \tag{4}$$

But at the receiver input with input resistance, R_{rx}, is valid:

$$P_{rx} = \frac{V_{rx}^2}{R_{rx}} \tag{5}$$

with V_{rx} the voltage over the receiver input terminal, thus:

$$\frac{V_{rx}^2}{Z_{rx}} = \frac{g \cdot \lambda^2}{480\pi^2} \cdot E^2$$

$$V_{rx} = \frac{\lambda}{4\pi}\sqrt{\frac{g \cdot R_{rx}}{30}} \cdot E \tag{6}$$

This means for the antenna factor, *k*:

$$k \equiv \frac{E}{V_{rx}} = \frac{4\pi}{\lambda}\sqrt{\frac{30}{g \cdot R_{rx}}} \tag{7}$$

The antenna gain, *g*, is mostly given as, *G*, in dB's, so:

$$G = 10 * log(g) \tag{8}$$

or

$$g = 10^{G/10} \tag{9}$$

For a half wave dipole with a gain of 1.64 (2.14 dB) relative to an isotropic radiator and a receiver input impedance of 50 ohm (real) we get:

$$k = \frac{4\pi}{\lambda} \cdot 0.605 \tag{10}$$

Or in dB's:

$$K_{ant} = 20 * log(k) \tag{11}$$

For half wave dipoles on several amateur bands that results in:

Antenna factor									
Band	1,8	3.6	7.0	10.1	14	18	21	24	28 [MHz]
k	0.046	0.091	0.177	0.256	0.360	0.459	0.537	0.631	0.732 [1/m]
K_{ant}	-26.8	-20.8	-15.0	-11.8	-8.9	-6.8	-5.4	-4.0	-2.7 [dB/m]

ANNEX 3.

The currently proposed limits for PLC interference field strenghts.

1. NB30.

Frequency Range MHz	(Peak) Disturbance Field Strength Limit dB(µV/m)	Measurement Distance	Measurement Bandwidth
0.009-0.15	40-20*log f (MHz)	3 metres	200 Hz
0.15-1	40-20*log f (MHz)	3 metres	9 kHz
1-30	40-8.8*log f (MHz)	3 metres	9 kHz

2. Norwegian proposal.

Frequency Range MHz	(Peak) Disturbance Field Strength Limit dB(µV/m)	Measurement Distance	Measurement Bandwidth
0.15-1	20-20*log f (MHz)	3 metres	9 kHz
1-30	20-7.7*log f (MHz)	3 metres	9 kHz

3. BBC proposal.

Frequency Range MHz	(Peak) Disturbance Field Strength Limit dB(µV/m)	Measurement Distance	Measurement Bandwidth
0.15-30	21.8-8.15*log f (MHz)	1 metres	9 kHz

CISPR 22 B, limit for mains disturbance voltage, measured at the 230 V mains terminal of ITE apparatus classe B, intended for use in residential areas.

Frequency Range MHz	Quasi Peak Disturbance Voltage limit dB(µV)	Average Disturbance Voltage limit dB(µV)	Measurement Bandwidth
0.15 - 0.5	66 - 56	56 - 46	9 kHz
0.5 - 5	56	46	9 kHz
5 - 30	60	50	9 kHz