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Broadband Power Line Communication in Smart Grids

Realisations in UGent Campus Kortrijk

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Contributors to report

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1. The smart grid

In Ghent University a microgrid is available. The grid (Fig. 1) consists of 18 houses (cabinets) interconnected with the standard cable (700 m) used in Flanders. It represents in this way a street. The grid is configurable (TT, TN-C, TN-C-S). The houses can be connected to different phases (f.i. house to phase L1, house 5 to phase L3, house 8 to three phases). All houses have several sockets to connect consumers. The PV on the roof can be connected to different houses. As main source the public grid can be used, or a programmable power source.

Fig. 1. Microgrid

As addition two internal electricity grids of houses were constructed. The houses consist of the precabled electrical cabinet of the house (Fig. 2). Several devices (lighting, washing machines, dryer, …) can be connected.

Fig. 2. Connection box house

2. BB-PLC

For BB-PLC new boxes were developed. The system consist of 4 boxes in total. Three boxes have BB-PLC modules and an energy meter. The fourth box communicates with the three boxes and visualizes the data. It means, the three boxes are energy meters, the fourth box is the data collector. The energy meters communicate with the PLC module I2SE over RS485. The communication towards the energy meters is done by the ModBus RTU protocol. The touchscreen acts as master. Fig.s 3 to 5 show the different boxes, each time with the result on the datacollector.

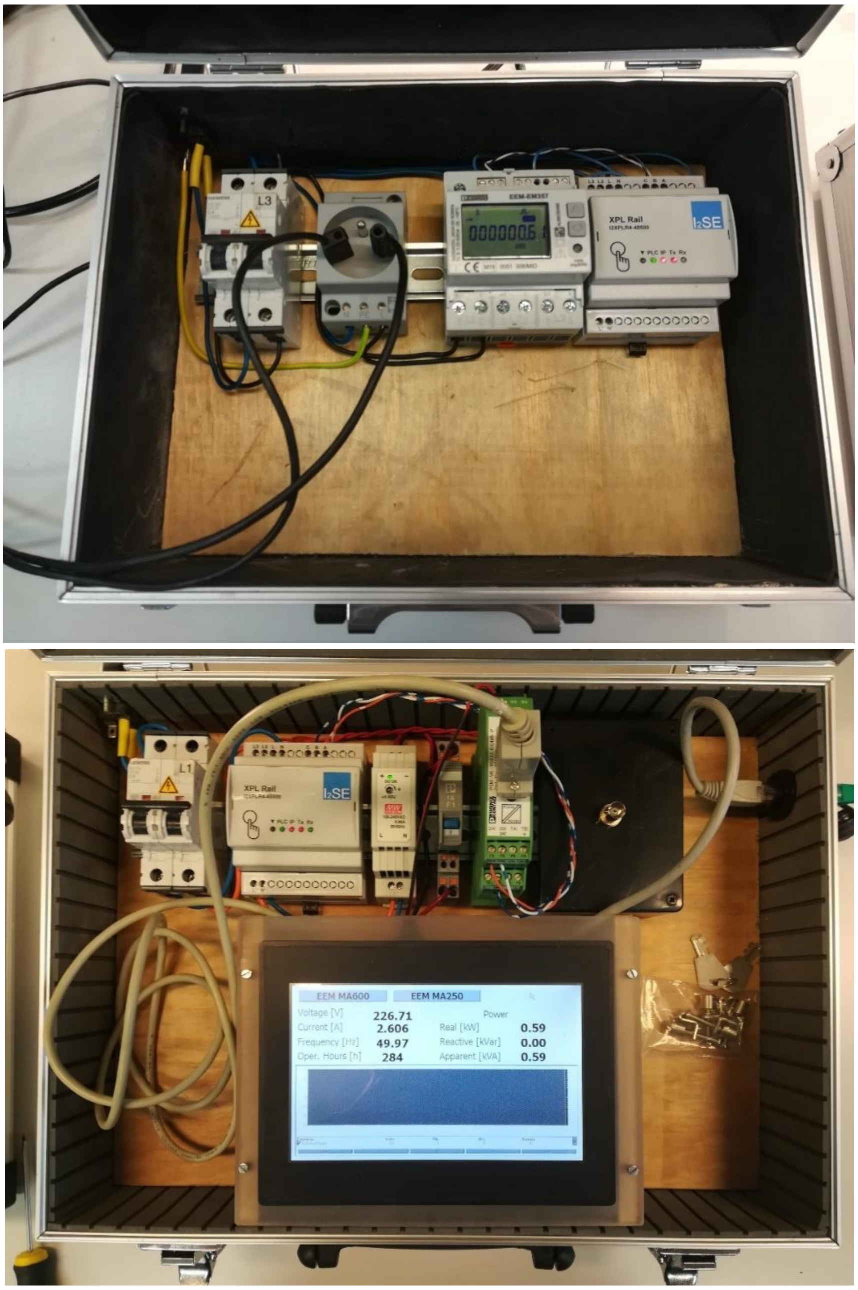
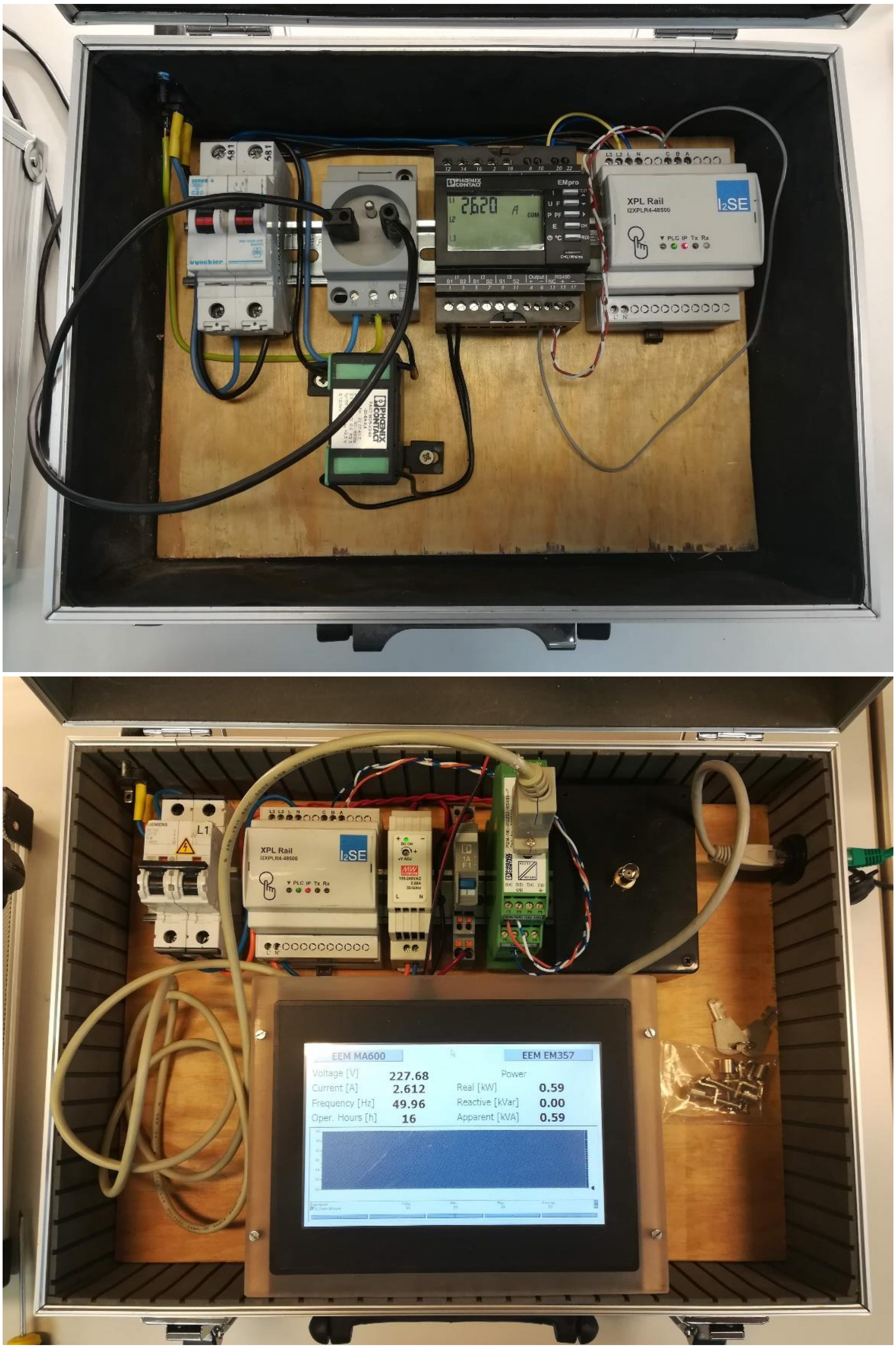


Fig. 3



XPL Rail
I2SE
PHOENIX CONTACT
EMpro
EEM MA600
EEM EM357
Voltage [V]
227.68
Current [A]
2.612
Frequency [Hz]
49.96
Oper. Hours [h]
16
Power
Real [kW]
0.59
Reactive [kVar]
0.00
Apparent [kVA]
0.59

Fig. 4

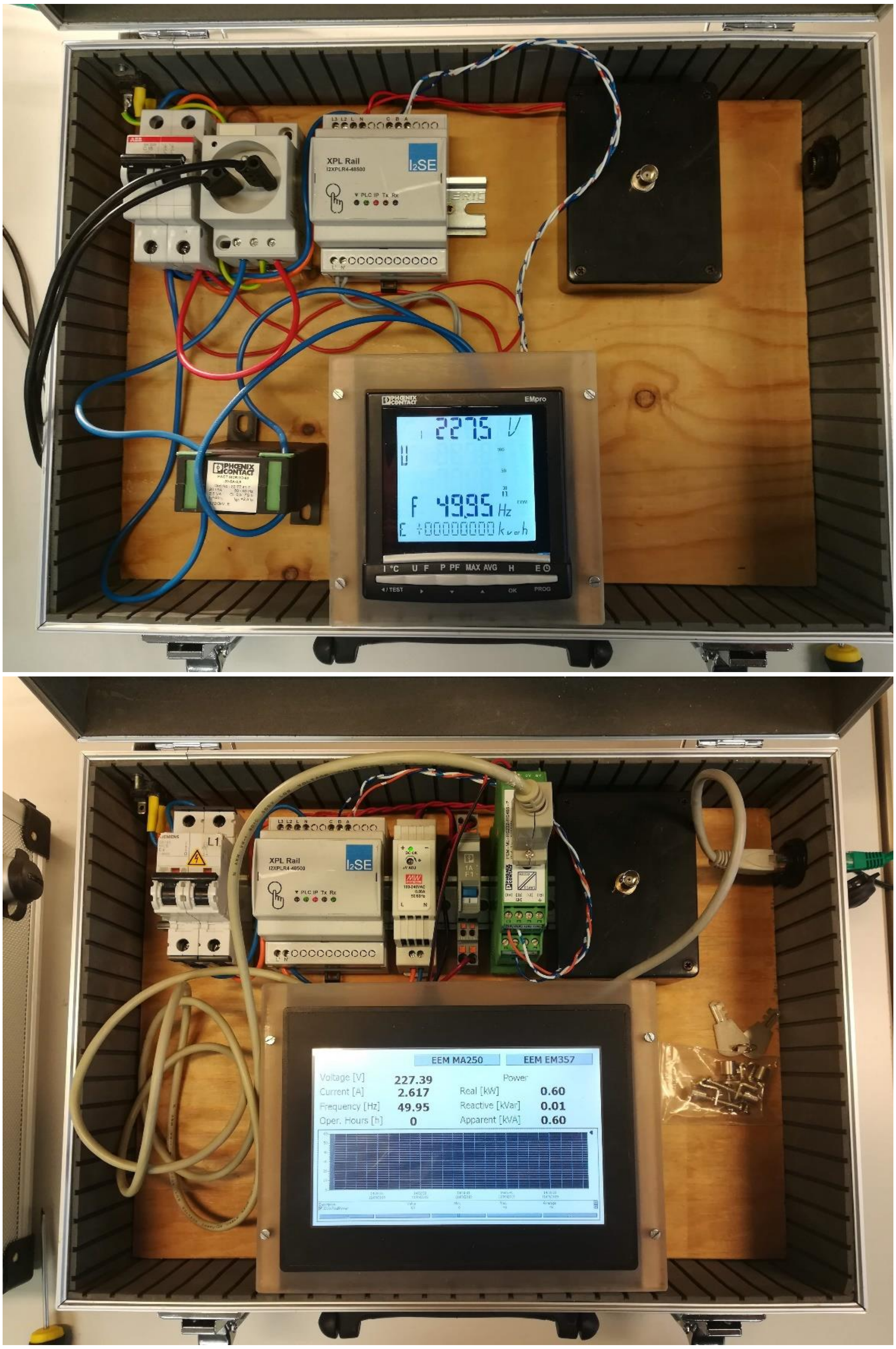

XPL Rail
I2SE
PHOENIX CONTACT
EMpro
227.5 V
F 49.95 Hz
EEM MA250
EEM EM357
Voltage [V] 227.39
Current [A] 2.617
Frequency [Hz] 49.95
Oper. Hours [h] 0
Power
Real [kW] 0.60
Reactive [kVar] 0.01
Apparent [kVA] 0.60

Fig. 5

3. Signal propagation in the grid between 10 kHz and 10 MHz

3.1. Introduction

The aim of this section is to characterize the attenuation for the frequency range 10 kHz to 10 MHz. The measurements are carried out on both short and long cables, but also on the same and different phases. The measurements are carried out on 'houses' in the Lemcko smart grid. A signal will be injected into a house and then a signal will be measured on another house in that district. Both the form of the signals and the differences between the input and the output will be explained on the basis of known theoretical concepts. Both the influence of the distance and the coupling between the different phases will be investigated. There are 4 chapters in which certain conclusions will be drawn, namely transmission line theory, net impedance, Cross Talk and Power Line Communication.

3.2. Measurement setup

Fig. 6 and Fig. 7 show an overview of the measuring setup. It consists of several elements that will be highlighted one by one.

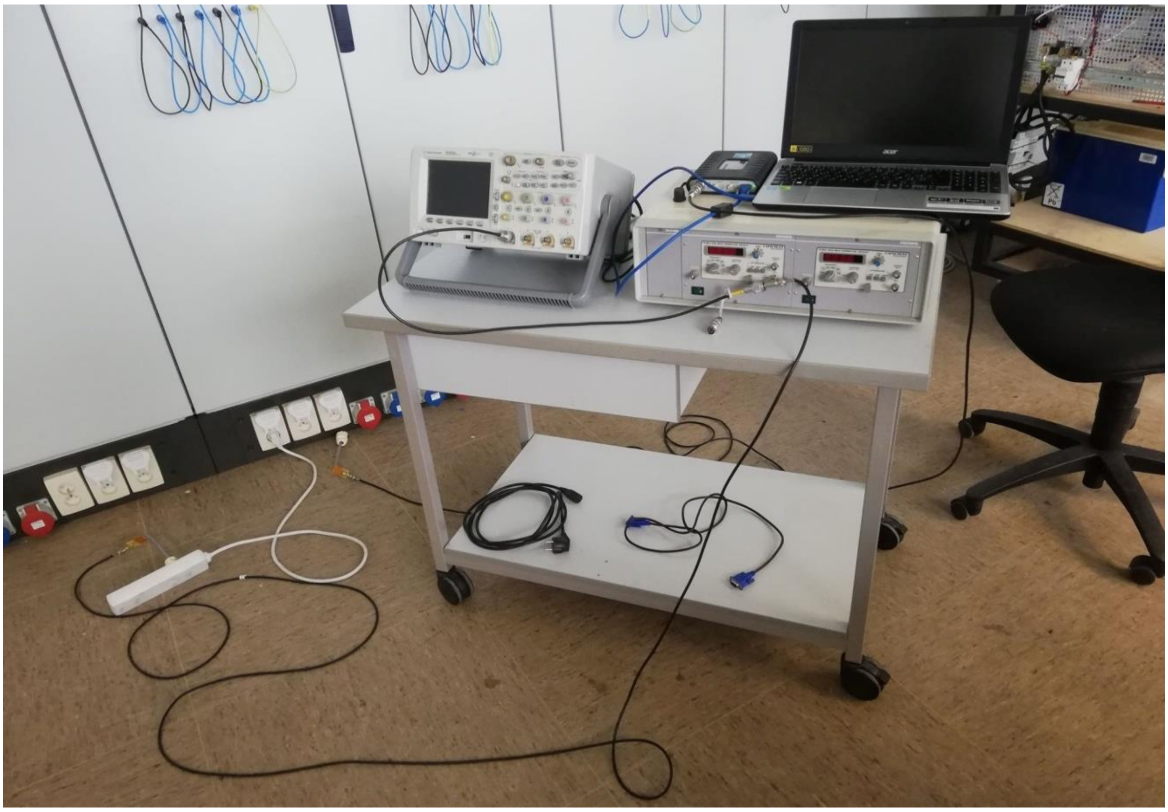


Fig. 6 Setup

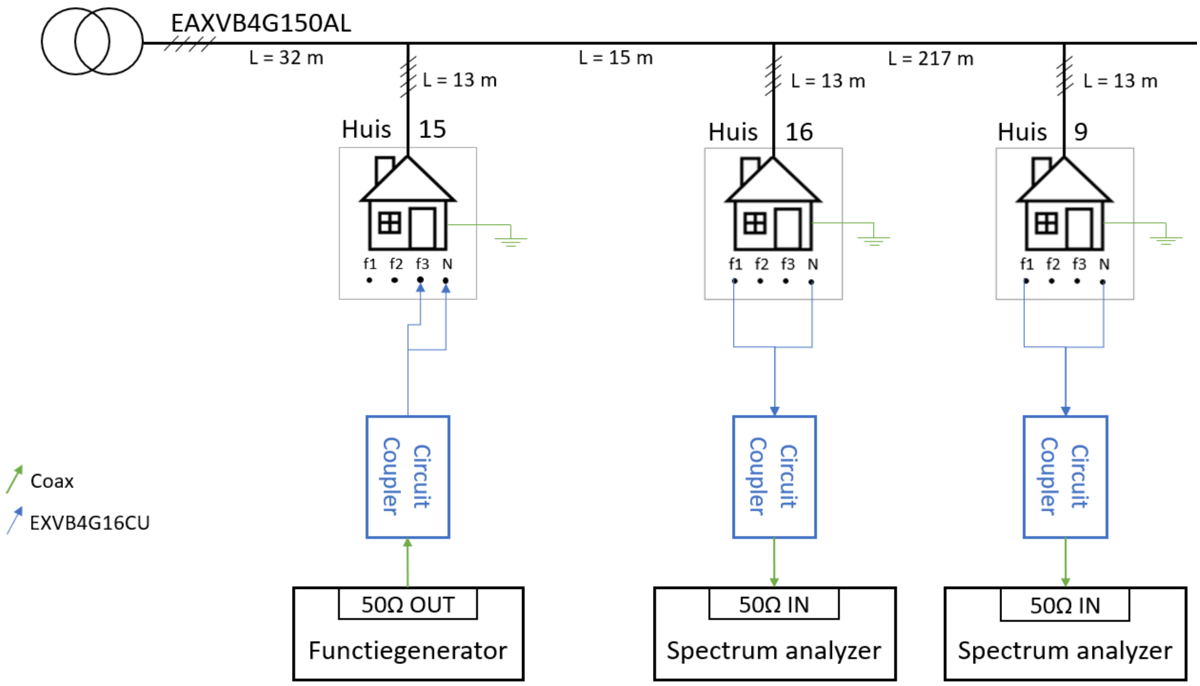


Fig 7. Schematic overview measuring setup

3.3. Used devices:

- **Spectrum Analyzer: Tektronix -** RSA306 Real Time Spectrum Analyzer (Fig. 8).

  This device makes it possible to visualize the measured signal. It measures the amplitude and corresponding frequency of an input signal and communicates this via a USB connection to the software on a PC.

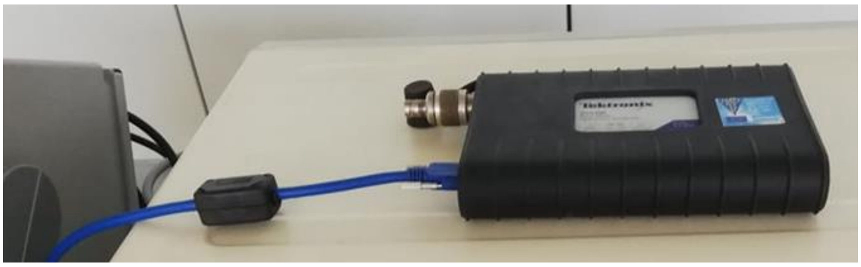


Fig. 8 Spectrum analyzer

- **Function generator: HAMEG - 20 MHz Sine Wave Generator - HM 8032 (Fig. 9).**

  This creates the desired signals. The most important parameter to set is the frequency. In this report it goes from 10kHz to 10MHz. The signal is sinusoidal.

Fig. 9 : Function generator

- **Circuit Coupler: A circuit board constructed by the EMC research group (Fig. 10).**
  This circuit board provides a galvanic separation between the inputs of the devices and the distribution network. The signal inputs of the used devices are not designed for voltages up to 230V. The galvanic isolation protects the devices. There are two such PCB available, each with a slightly different construction. One must be used for injecting the signals while the other is needed for reading them. The coupler circuit is therefore necessary to guarantee the safety of the used devices.

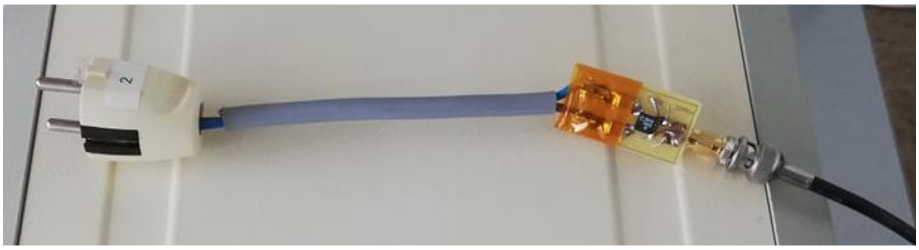


Fig. 10: Circuit Coupler

3.4. Measurement procedure

The function generator generates a sinusoidal signal which will be injected on a certain phase of a house. In this case, 23 signals were generated between 10kHz and 10MHz. Two other houses were chosen to check what the signal looks like at the output. In this case, house 9 and house 16 were used to measure this output, which have a long and a short cable distance respectively. In each case, the 3 phases of both dwellings are measured.

With a spectrum analyzer, the signal strengths can be measured. It is important to note that measurements were only taken at the frequency that was injected at a specific moment in time. For example: a signal is injected with a frequency of 150kHz. On the spectrum analyzer, only the value that is on a frequency of 150kHz will be viewed. The other values were not taken into account. In other words, only the amplitude of the ground wave will be measured.

3.5. Imperfections of the measurement

Some shortcomings of the measurement are:

- The measurements were not performed synchronously. This means that the input signal (injected signal) was not measured at the same time as the signal at the output (via spectrum analyzer). First, each frequency was injected and measured on house 15 - phase 3, and this was used as an input signal. The different measurements will therefore take place at a different time.
- The background noise was not measured beforehand, so there is no knowledge of which signals are already on the net. Not all peaks and troughs of the signal can therefore be explained with certainty. With hindsight, this could have offered added value.
- We worked with a fixed termination impedance of 50 ohms. The impedance of the line varies in function of the frequency. In an ideal case, per frequency should be calculated what the impedance of the line is. On the basis of this result a suitable termination impedance can be found per frequency. This is to limit the reflections as much as possible.
- The measurement is time-dependent. The values vary continuously in function of the time. If you wait a few seconds longer or less to read the number on the spectrum analyzer, then the result may differ slightly. It could be determined that the longer the measurement was made, the amplitude of the ground wave decreased slightly.

3.6. Results

Two situations were measured during this assignment:

1. Injection on phase 3 of house 15 and the measured output on house 16 was on both phases 1, 2 and 3. In this situation the cables between the injection and the output can be seen as 'short'. The cable length here is 41 m.
2. Injection on phase 3 of house 15 and the measured output on house 9 was on both phases 1, 2 and 3. In this situation the cables between the injection and the output can be seen as 'long'. The total cable length is 248 metres.

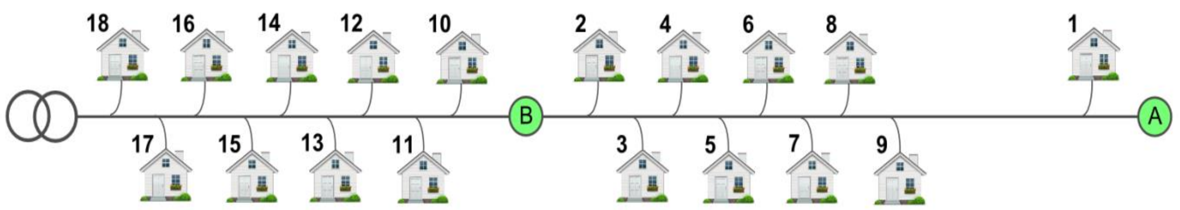


Fig. 11: Configuration of the houses

The CBA configuration of the smart grid is shown in Fig. 11. A number of symbols will also be used in the graphs, the meaning of which is given below:15_3: house 15, fase 3

- 16_1: house 16, phase 1

- 16_2: house 16, phase 2
- 16_3: house 16, phase 3
- 9_1: house 9, phase 1
- 9_2: house 9, phase 2
- 9_3: house 9, phase 3

On the Y axis of fig. 12 and 13, the signal strength is expressed in dB microvolts. This unit can be converted to µV. So the signal actually represents the measured voltage. The Tektronix equipment measures the full spectrum each time, but only the amplitude of the ground wave is used in the Excel calculations. The signal strength in the graphs is about the amplitude of the ground wave.

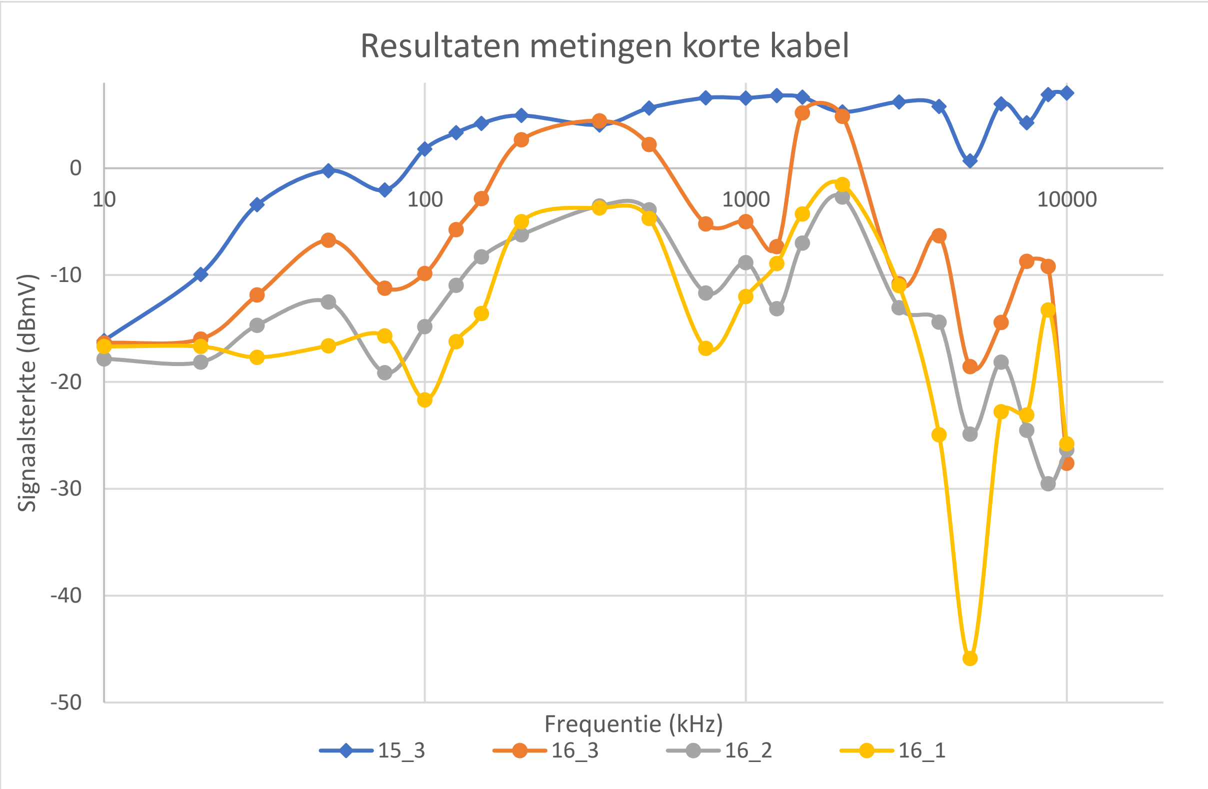


Fig. 12. Attenuation short cable

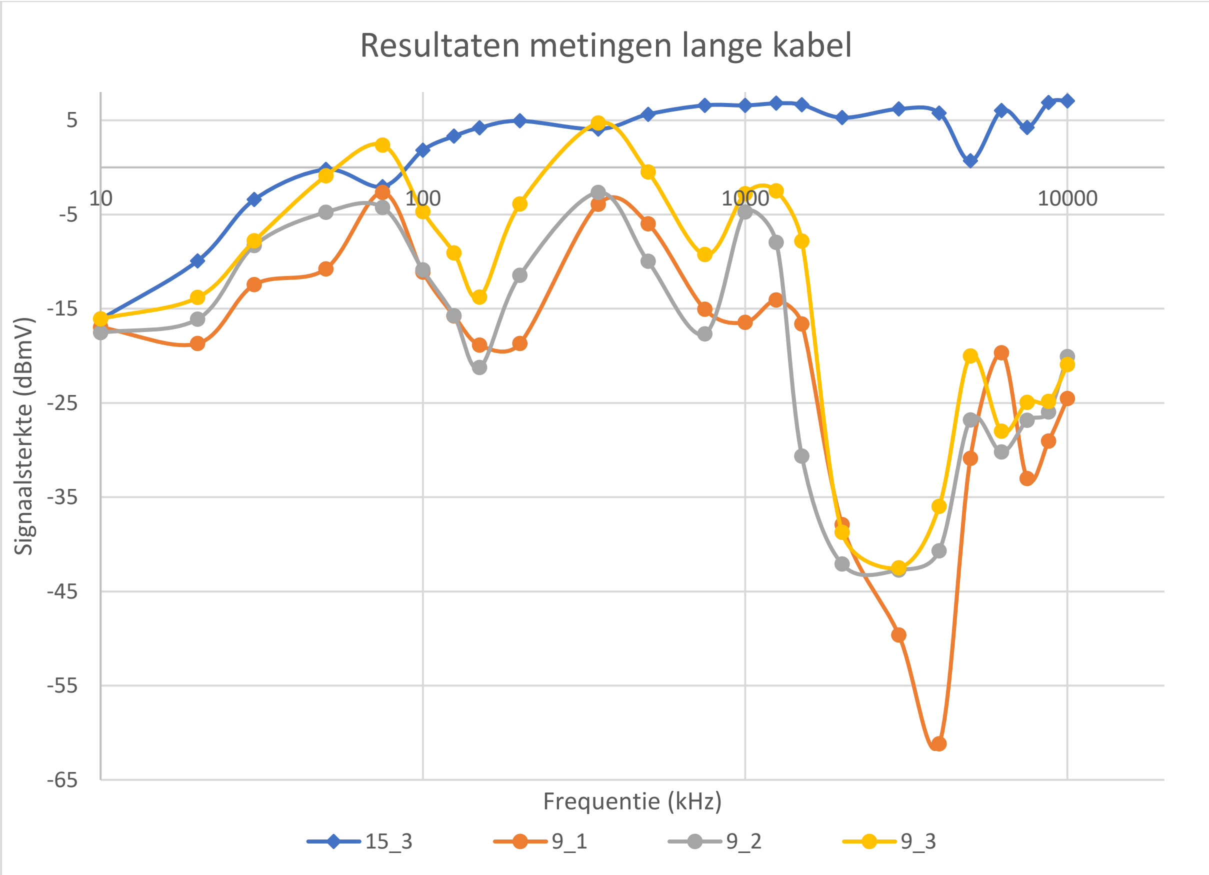


Fig. 13 Attenuation long cable

A first observation is that in the case of both the long cable and short cable housing, the measurement on phase 3 has the highest values. This is the same phase as where the signal was injected. Later it will become clear why these values are larger. In addition, it can also be seen that in the 1500-6000 kHz area, the dips are much deeper with a long cable. It seems that this frequency band behaves like a barrier filter with a long cable sight. With a short cable you can also see a dip, but less deep and less wide. Another observation is in the frequency domain 10-100 kHz. There the values of the long cable are higher than the short cable. Reflections can be the cause.

In this report, the y-axes of the graphs will sometimes have a different unit. Fig. 12 and 13 have dBµV for the signal strength as a unit. These may also be expressed in µV. How this can be achieved is shown below. dBµV is a unit of amplification or attenuation that represents the signal, but it is also necessary to know the actual voltage values.

$$U = 10^{\frac{[dBmV]}{20}} = [mV]$$

3.7. Transmission Line Theory

Introduction

The electrical diagram of a transmission line is shown in Fig. 14. In the picture, the lines are presented as 'ideal'. However, this representation is not entirely correct and will therefore not suffice for very specific applications. The imperfections of the connections (AB and A'B'), which are frequency-dependent, are not taken into account.

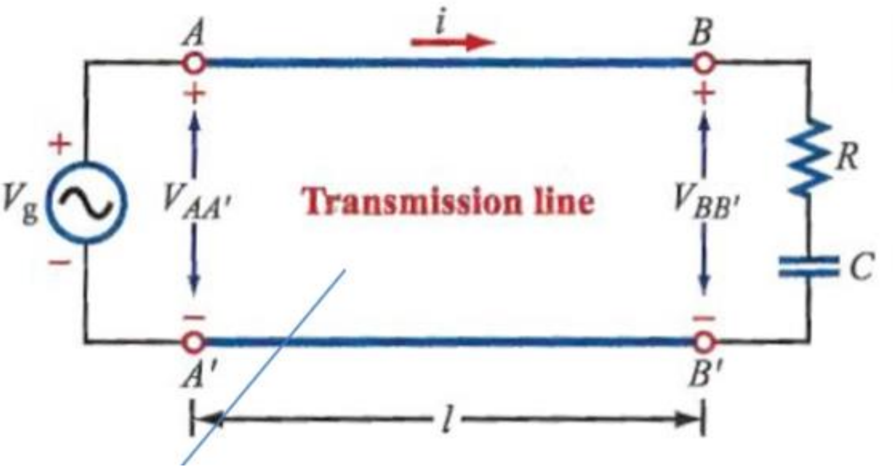


Fig. 14. Electrical diagram

The 2 deficits in the electrical diagram:

1. First of all, no losses, voltage drops, etc. are displayed in the performance.
   - A solution for this is to use the lumped-elements model.
   - The lumped elements are:
     - R: the resistance of both conductors per unit length [Ω/m].
     - L: The inductivity of both conductors per unit length [H/m].
     - C: the capacity of both conductors per unit length [F/m].
     - G: The conductivity of the insulation between the two conductors [S/m].
   - The graphical representation is shown in Fig. 15.

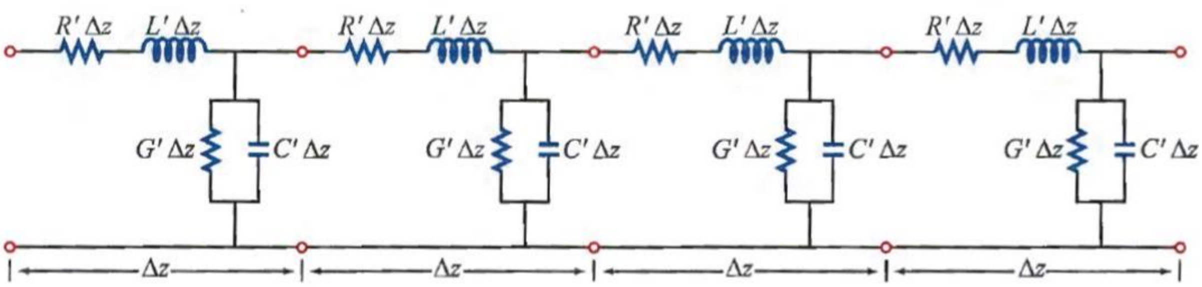


Fig. 15: Lumped-elements-model

2. A second deficiency in the representation is that it will not take into account the finite propagation speed of the signal.
    - This can only be solved by using the transmission line theory.

If the length of the line becomes too great in relation to the wavelength (λ) of the signal, the transmission line effects, such as reflections, must be taken into account. It is generally assumed that cable lengths greater than λ/100 transmission line phenomena may occur. In practice, however, the factor λ/10 is a commonly used limit value. In this laboratory assignment, the factor λ/20 is also used, since from then on the transmission line phenomena can become clear. The formula used is shown below.

$$l_{kabel} > \frac{\lambda}{20}$$

Determination Lumped Elements

The general data is presented in Table 1. The cable used is a 4 conductor XLPE-Aluminium cable with a diameter of 150 mm². The specific properties such as permittivity, conductivity, permeability... were searched for. To determine the Lumped Elements, the formulas present in Fig. 16: Lumped Elements formulas were used. A two-wire cable was used. This is not completely correct, as the cable used has 4 conductors, so this is more of an approximation. The values used here come from different internet sources and courses.

Table 1: General data Lumped Elements [2] [7] [8]

Parameter	Value	Unit
Long cable	258	m
Short cable	41	m
Cable cross section	150	mm²
Cable diameter	13,8	mm
Distance between conductors	14,8	mm

Specific resistance Al	2,65E-08	Ωm
Specific conductivity Al	3,77E+07	1/(Ωm)
Absolute Permeability	1,26E-06	N/A²
Absolute permittivity	8,84E-12	F/m
Rel. permittivity XLPE	4,5	-
Conductivity XLPE	1E-14	S/m

Parameter	Coaxial	Two-Wire	Parallel-Plate	Unit
R'	$\frac{R_s}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)$	$\frac{2R_s}{\pi d}$	$\frac{2R_s}{w}$	Ω/m
L'	$\frac{\mu}{2\pi}\ln(b/a)$	$\frac{\mu}{\pi}\ln\left[(D/d)+\sqrt{(D/d)^2-1}\right]$	$\frac{\mu h}{w}$	H/m
G'	$\frac{2\pi\sigma}{\ln(b/a)}$	$\frac{\pi\sigma}{\ln\left[(D/d)+\sqrt{(D/d)^2-1}\right]}$	$\frac{\sigma w}{h}$	S/m
C'	$\frac{2\pi\varepsilon}{\ln(b/a)}$	$\frac{\pi\varepsilon}{\ln\left[(D/d)+\sqrt{(D/d)^2-1}\right]}$	$\frac{\varepsilon w}{h}$	F/m

Notes: (1) Refer to Fig. 2-4 for definitions of dimensions. (2) μ, ε, and σ pertain to the insulating material between the conductors. (3) $R_s = \sqrt{\pi f \mu_c / \sigma_c}$. (4) μ_c and σ_c pertain to the conductors. (5) If $(D/d)^2 \gg 1$, then $\ln\left[(D/d)+\sqrt{(D/d)^2-1}\right] \simeq \ln(2D/d)$.

Fig. 16: Formules Lumped Elements

The resistance value is frequency-dependent (due to skin effect), the inductance, capacitance and conductance are not. The results of these values can be found in Table 2 below: Determination of Lumped Elements. These Lumped Elements can be used to determine the reflection coefficient, which is also frequency-dependent.

Table 2: Determination Lumped Elements

Parameter	Value	Unit
L'	1,51E-07	H/m
C'	3,31E-10	F/m
G'	8,31E-14	S/m

f (kHZ)	Rs (Ω/m)	R' (Ω/m)
10	3,23E-05	1,49E-03
20	4,57E-05	2,11E-03
30	5,60E-05	2,58E-03
50	7,23E-05	3,33E-03
75	8,86E-05	4,08E-03
100	1,02E-04	4,71E-03
125	1,14E-04	5,27E-03
150	1,25E-04	5,77E-03
200	1,45E-04	6,66E-03
350	1,91E-04	8,81E-03
500	2,29E-04	1,05E-02
750	2,80E-04	1,29E-02
1000	3,23E-04	1,49E-02
1250	3,62E-04	1,67E-02
1500	3,96E-04	1,82E-02

2000	4,57E-04	2,11E-02
3000	5,60E-04	2,58E-02
4000	6,47E-04	2,98E-02
5000	7,23E-04	3,33E-02
6250	8,09E-04	3,72E-02
7500	8,86E-04	4,08E-02
8750	9,57E-04	4,41E-02
10000	1,02E-03	4,71E-02

Table 3: Reflection Coefficient determination shows the reflection coefficient and phase shift per frequency. The formulas used can be found in Fig. 17 below.

$$\Gamma = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{Z_L/Z_0 - 1}{Z_L/Z_0 + 1} = \frac{z_L - 1}{z_L + 1} \quad \text{(dimensionless)}, \quad (2.59)$$

$$Z_0 = \frac{R' + j\omega L'}{\gamma} = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \quad (\Omega), \quad (2.29)$$

Fig. 17: Formula Reflection Coefficient

Table 3: Reflection Coefficient determination

f (kHZ)	Z0 (Ω)	ZL (Ω)	RC	theta_r (°)
10	457,625075183538-71,741799242395i	50	80,73%	-119,6
20	457,625074998029-50,7291131179304i	50	80,52%	-167,1
30	457,625074951797-41,420147551418i	50	80,45%	-203,9
50	457,625074922238-32,0839084393522i	50	80,39%	-262,4
75	457,625074910542-26,196401598382i	50	80,36%	-320,8
100	457,625074905645-22,6867493002561i	50	80,34%	-370,1
125	457,625074903065-20,2916454668322i	50	80,34%	-413,6
150	457,625074901509-18,5236532634499i	50	80,33%	-453,0
200	457,625074899779-16,0419543112011i	50	80,32%	-522,8
350	457,625074897956-12,1265776314289i	50	80,31%	-691,3

500	457,625074897382-10,1458227700262i	50	80,31%	-826,0
750	457,625074897012-8,28402960791028i	50	80,31%	-1011,5
1000	457,625074896858-7,17418008898453i	50	80,30%	-1167,9
1250	457,625074896777-6,41678174644645i	50	80,30%	-1305,7
1500	457,625074896725-5,85769351635827i	50	80,30%	-1430,3
2000	457,625074896672-5,07291139416555i	50	80,30%	-1651,5
3000	457,625074896626-4,14201481005681i	50	80,30%	-2022,6
4000	457,625074896606-3,58709004906851i	50	80,30%	-2335,4
5000	457,625074896596-3,20839087688423i	50	80,30%	-2611,0
6250	457,625074896588-2,86967203998701i	50	80,30%	-2919,2
7500	457,625074896584-2,61964018180421i	50	80,30%	-3197,8
8750	457,625074896581-2,42531553465378i	50	80,30%	-3454,0
10000	457,62507489658-2,26867494650011i	50	80,30%	-3692,5

The reflection coefficient is similar in amplitude for the different frequencies. The phase shift becomes larger as the frequency rises. The reflection coefficient and Lumped Elements were calculated, but nothing else was done with it. They are included in the report for completeness.

Results

In the area smaller than λ/20, there are no transmission line effects yet. Therefore we must look for another reason why the measured signal deviates from the injected signal. It is expected that the resistance of the cable will increase as the frequency increases. This phenomenon is called the skin effect (Fig. 11). In this frequency range, the skin effect is the dominant factor. Due to the increasing resistance of the cable, the losses over the cable will increase. Due to these increasing losses, it can be expected that the attenuation will increase.

The following formulas apply:

- $\Delta P = i^2 * R\ (cable\ losses)$
- $R \sim \sqrt{f}$ (pag. 42 course EMC)
- $U = i * R$

- i *is considered to be constant*
- $U \sim \sqrt{f}$

From the above formulas it can be deduced that the difference between the injection and the measured voltage will increase proportionally with √f for a cable length smaller than λ/20. From then on, transmission line phenomena start to play up, so that the skin effect is no longer the (only) dominant influence factor. The greater the extra losses (the greater the frequency), the greater the voltage drop across the cable and the greater the deviation will become.

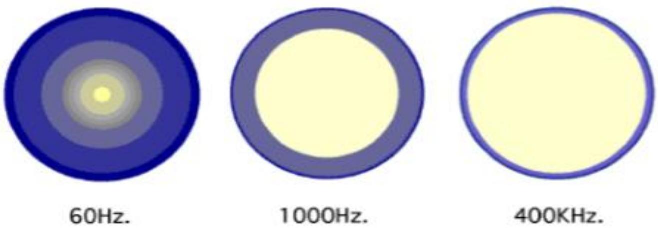


Fig. 2: Skin- effect

The wavelengths are calculated for the different frequencies using the formula below. The speed v is taken as 180,000 km/s, as this is the speed of the electrons through the cable. The wavelength can then be obtained by dividing that speed by the frequency of the sine wave with the function generator.

The wavelengths of the different frequencies are shown in Table 4.$\lambda = \frac{v}{f}$

Table 4: λ-values

f (kHZ)	λ (m)	λ/100 (m)	λ/20 (m)	λ/10 (m)
10	30000	300	1500	3000
20	15000	150	750	1500
30	10000	100	500	1000
50	6000	60	300	600
75	4000	40	200	400
100	3000	30	150	300
125	2400	24	120	240
150	2000	20	100	200
200	1500	15	75	150
350	857,1	8,6	43	86
500	600	6,0	30	60
750	400	4,0	20	40
1000	300	3,0	15	30
1250	240	2,4	12	24
1500	200	2,0	10	20
2000	150	1,5	7,5	15
3000	100	1,0	5,0	10

lange kabel

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4000	75	0,8	3,8	7,5
5000	60	0,6	3,0	6,0
6250	48	0,5	2,4	4,8
7500	40	0,4	2,0	4,0
8750	34	0,3	1,7	3,4
10000	30	0,3	1,5	3,0

The cable lengths are shown in Table 5 below. The shaded fields in the table above are the limit values from which transmission line phenomena may occur. It is true that a limit is difficult to determine, which is why several limit values are indicated per cable. In practice, λ/10 is often used, but from λ/100 and λ/20, phenomena can also appear.

Table 5: Cable lengths

Kabel	Afstand (m)
Long cable	258
Short cable	41

Results short cable

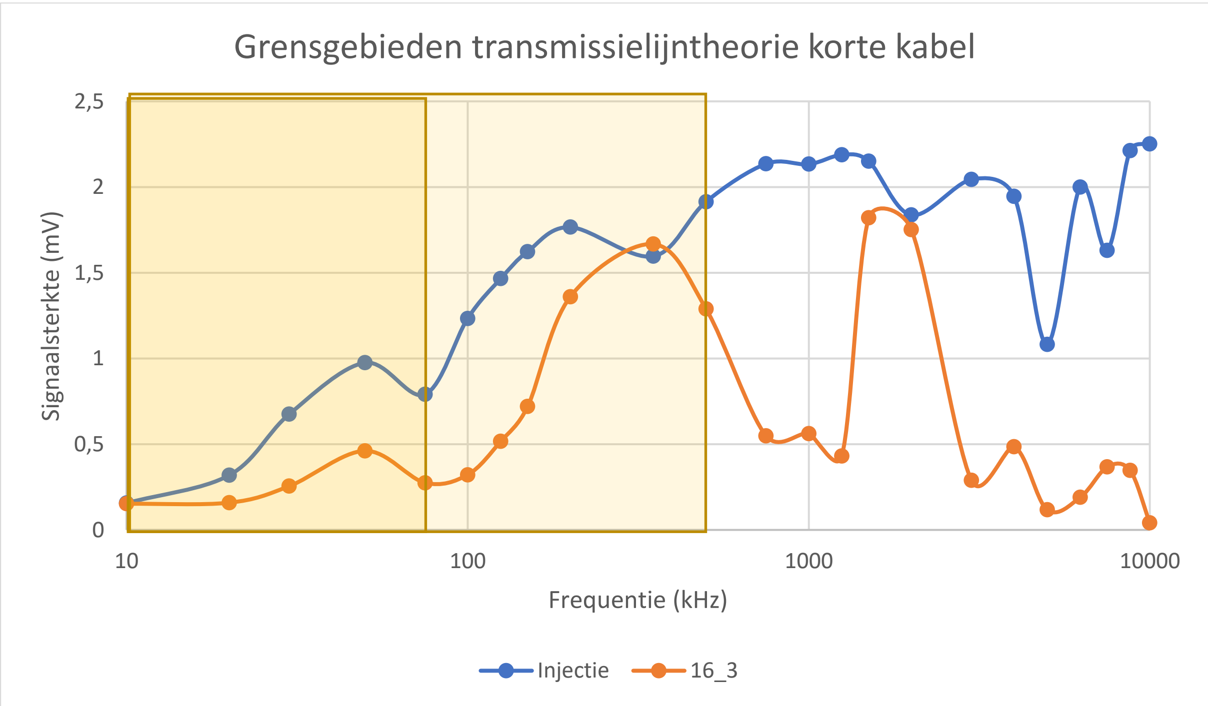

Fig. 18: Short cable

The darkest shaded area in Fig. 18 is for a cable length smaller than λ/100, the least shaded area is that of λ/20. The measured signal on the housing with a short cable distance deviates significantly from the injected signal when λ/20 is exceeded. The transmission line effects are clearly visible. In the least shaded area, however, it can be seen that at 350 Hz the measured signal is larger than the injected signal. This is only possible through reflections. From λ/100 phenomena start to occur, but they are strongly perceptible if the cable length is greater than λ/20.

It can be determined that there is a good correlation between what is injected and what is measured in the frequency band 10-200 kHz. The injection in house 15 and the measurement in house 16 have the same shape up to 200 kHz. This is the limit where the transmission line theory has to be taken into account. At that point the cable length relative to the wavelength becomes too large. It is clear to see that after this limit, in the frequency domain 200-10000 kHz, there is still little correlation.

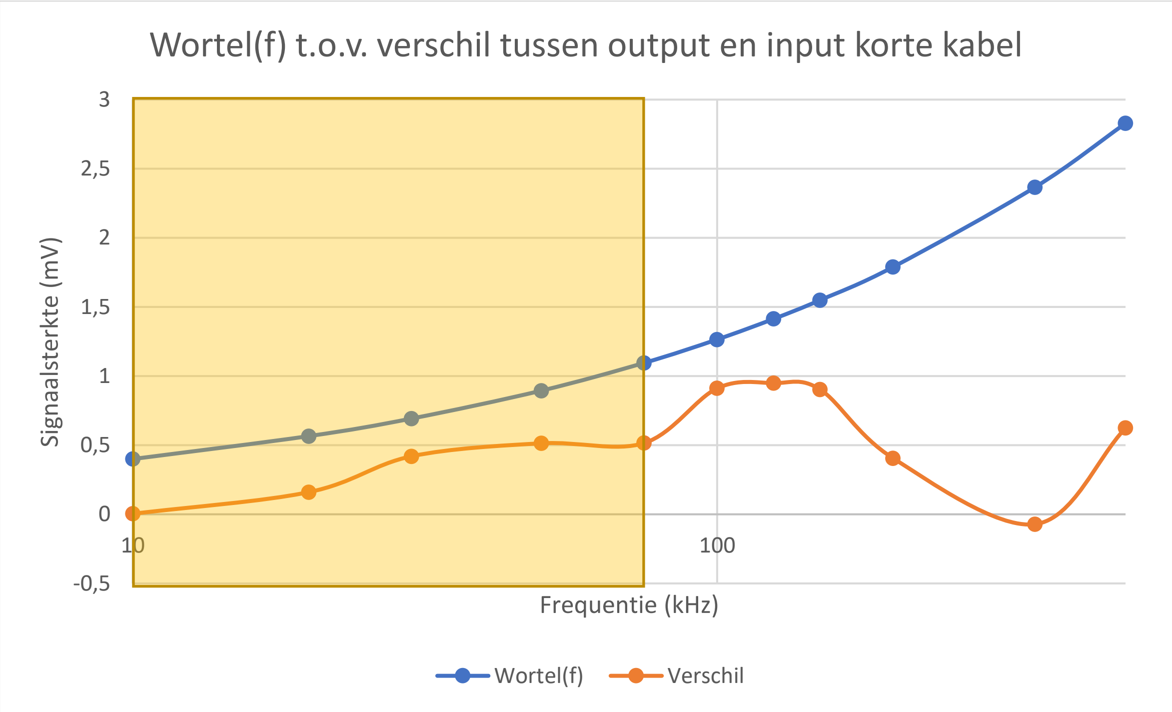

Fig. 19 Expected curve short cable

The orange curve in Fig. 19 is the difference between what is injected and what is measured. The shaded area is λ/100 and the maximum limit of the graph is 350 kHz, which is the λ/20 limit. In the area smaller than λ/100 you can see that the curve follows the √f curve. But from 150 kHz it starts to deviate strongly from the √f-curve. The skin effect is the dominant influence factor up to 150 kHz, from then on there are other phenomena that have to be taken into account. The skin effect is then no longer dominant.

Results long cable

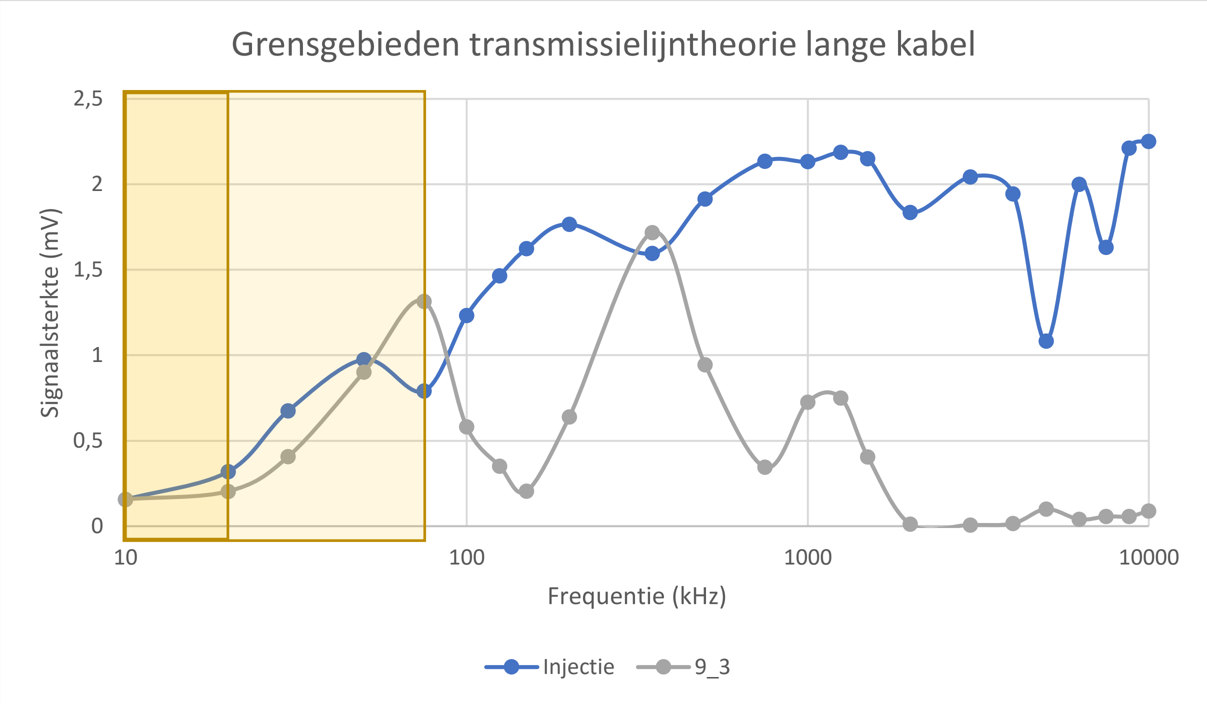

Fig 20. Results long cable

The darkest shaded area here is also the λ/100 area and the lightest area is the λ/20 area (Fig. 20). It is clear that the curves differ greatly from each other outside these 2 areas. At 75 kHz, the limit of the λ/20 range, there is even a large peak of the measured signal that is larger than the injected signal. So this is a strong reflection, just like at 350 kHz. This is also the case with the short cable at 350 kHz. With the long cable there is a strong correlation between the injected and measured signal up to 50 kHz, from then on other phenomena start to occur, in which transmission line effects play a role.

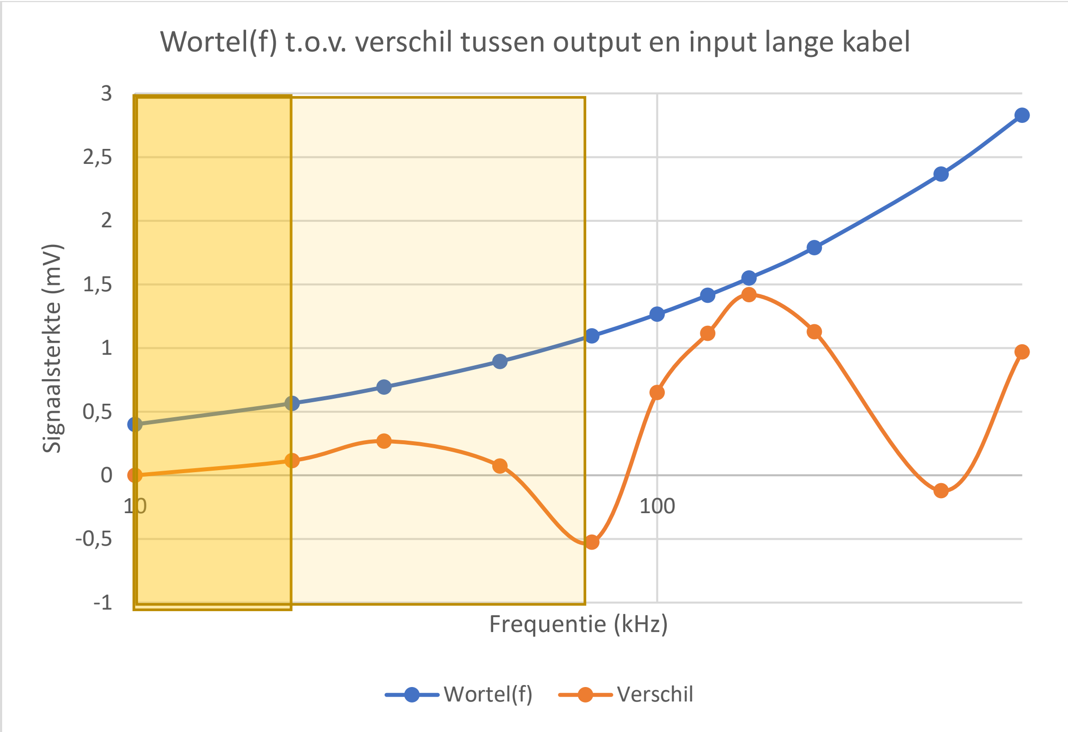

Fig. 21: Expected curve long cable

In the darkest shaded area (λ/100 area), the difference curve follows the expected √f curve (Fig. 21). However, in the λ/20 area this curve is starting to deviate significantly. But from 75 kHz on it rises to 150 kHz. In the first area, the skin effect is dominant, but beyond that, the skin effect is not the only dominant factor anymore. On the graph of the short cable from 150 kHz there is also a strong decrease with a drop at 350 kHz. So there is another dominant factor that occurs at both cable lengths.

Greater than λ /20

If the cable length is greater than λ /20, the expected transmission line phenomena can occur. Reference is made to Fig. 12 and 13. From the moment the cable length exceeds λ/20, reflections can make a non-negligible contribution. In the case of a house with short cable, the observable limit is from 350 kHz; in the case of a house with short cable, the observable limit is from 50 kHz. With a long cable, the transmission line effects will be observed more quickly, which was first expected.

Extra

The formula for the skin effect can be found below. It has been assumed that for cable lengths smaller than λ/100 (or λ/20), the skin effect is the dominant factor. It was assumed that the voltage drop is proportional to √f, which is only correct at frequencies much smaller than 1/(ρε). The formula shows that there are also other factors that determine the skin effect. If f is no longer much smaller than 1/(ρε), then the skin effect also depends on the second term (see formula). In addition, it is also stated that permittivity is also frequency dependent. In the calculations this was considered to be constant, but this is not always the case. The value of

1/(ρε) was calculated. A value of 3*1013 was obtained. This means that the part of the formula below the root, at the frequencies measured in this case, will be of less importance.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} * \sqrt{\sqrt{1 + (\rho\omega\varepsilon)^2} + \rho\omega\varepsilon}$$

3.3. Grid impedance

The results show that the measured signals have a capricious course (Fig. 12 and 13). Various peaks and dips can be recognized, especially after a cable length of λ/20. It can be seen that the measured signal differs from the injected signal at all phases. One reason for this may be that the impedance of the grid is not constant. The grid impedance will cause voltage drops so that the signal that arrives at house 16 and 9 at phase 3 will deviate from the signal that was sent at house 15 at phase 3. The measured signal on the other houses, are the output signals. Because of the variable grid impedance, the course of the signals on the houses 16 and 9 will also deviate from those on house 15.

Fig. 22 shows a impedance measurement of a network that was carried out on a residential distribution network. This is not the network that was used for the measurement itself. However, the values themselves are of secondary importance to the course. This Fig. was mainly used to show that the grid impedance is frequency dependent and can vary greatly at different frequencies. So there is no such thing as 'the net impedance'. As already mentioned, it can be expected that the measurement of the signals on houses 16 and 9 will differ in form from the injected signal on house 15 due to this variable mains impedance.

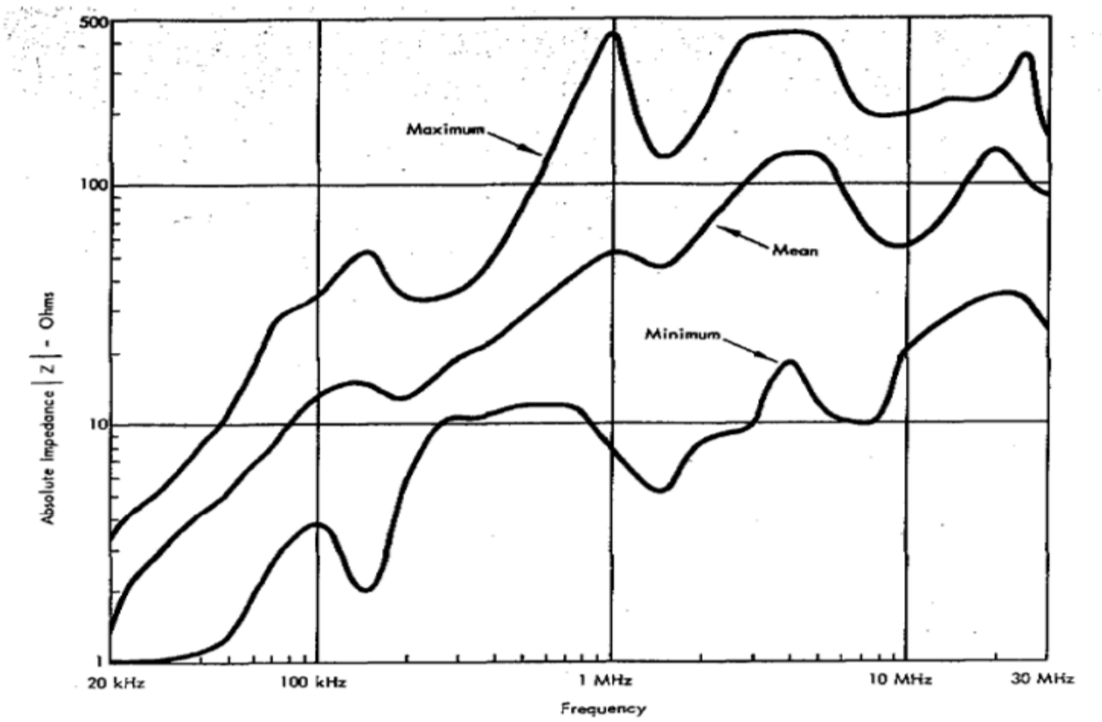

Fig. 22: Measurement grid impedance. [5]

3.4. Crosstalk

Introduction

Crosstalk can be described as the phenomenon that a cable can generate noise on a nearby cable, due to the capacity and inductivity between the two cables. There are two types of crosstalk: near-end and far-end crosstalk. Graphically this can be represented by Fig. 23. At the top left, a signal is injected into the so-called "Aggressor" line. The "Victim" line (lower cable) can therefore send a noise signal through the capacitive and inductive coupling between both lines.

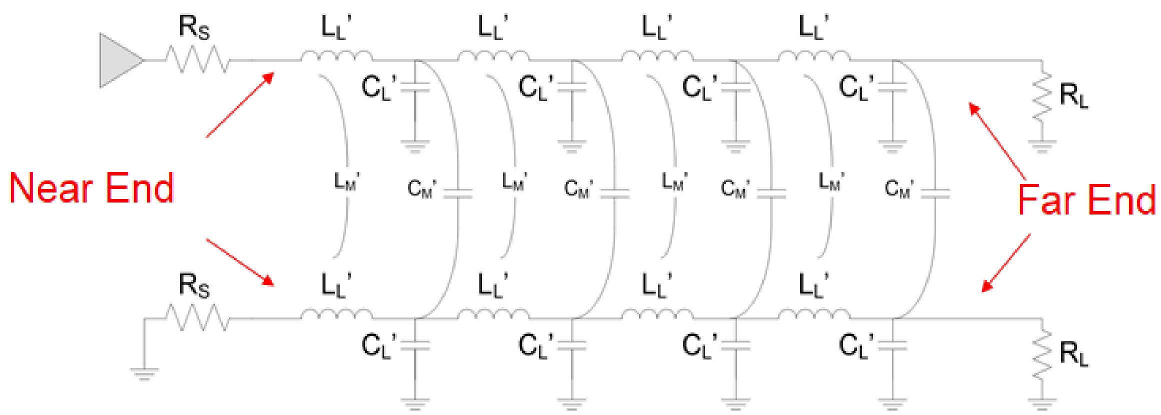

Fig. 23: Near- and Far-end crosstalk [6]

Near-end crosstalk is not an issue in this assignment. For this set-up, this would mean that a measurement would have to be made on phase 1 and/or 2 of house 15. In this assignment, this was not carried out, so this will not be discussed further. This could be an extension for the future. Far-end crosstalk is the issue here, as it concerns the other phases on another house. The crosstalk will be split into 2 parts, namely the capacitive crosstalk and the inductive crosstalk. Eventually they form 1 whole, where a connection can be found between the signal and the formed signal by Cross Talk.

Capacitiv far-end crosstalk

The voltage at the end of the line will be a measure of the current flowing through the Victim line. So it will be important to know which current will flow through the mutual capacity (Cm). The current flowing through Cm will increase proportionally as the cables are connected over a greater distance. The current through Cm can be written as (Fig. 3):

- $I_{C_{tot}} = C_M * lenght * (\frac{0{,}8*V_A}{t_{rise}})$

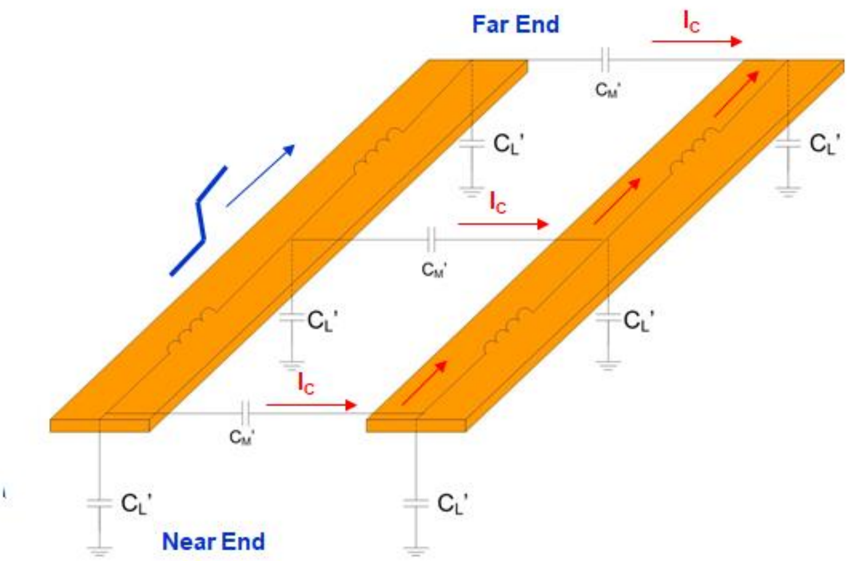

Fig. 3: Capacitive crosstalk [6]

The total current that will be injected into the Victim must be equal to the total current that will be injected into the last element of the Victim cable (see Fig. 25). The total current through the last element can be written as:

- $I_{C_L} = C_L * speed * t_{rise} * (\frac{0{,}8*V_B}{t_{rise}})$

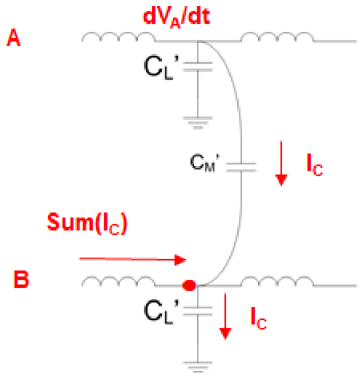

Fig. 4: Capacitive crosstalk last element [6]

In this way, the final formula for capacitive crosstalk can be arrived at.

- $C_L * speed * t_{rise} * \left(\frac{0{,}8 * V_B}{t_{rise}}\right) = C_M * length * \left(\frac{0{,}8 * V_A}{t_{rise}}\right)$
- $\left(\frac{V_B}{V_A}\right) = \left(\frac{length}{speed * t_{rise}}\right) * \left(\frac{C_M}{C_L}\right)$
- Since the current flows in both directions (continuous and backward), the following formula must still be multiplied by ½.
- $\left(\frac{V_B}{V_A}\right) = \frac{1}{2} * \left(\frac{length}{speed * t_{rise}}\right) * \left(\frac{C_M}{C_L}\right)$

Inductive far-end crosstalk

For the inductive far end crosstalk, exactly the same lead can be used. The only difference is that it will now be determined how much current flows through the inductive activities and not through the capacities. The current now flows in the other direction so that the influence of the inductive far-end crosstalk will have a negative effect on the capacitive far-end crosstalk. The following formula can now be obtained:

- $\left(\frac{V_B}{V_A}\right) = -\frac{1}{2} * \left(\frac{length}{speed * t_{rise}}\right) * \left(\frac{L_M}{L_L}\right)$

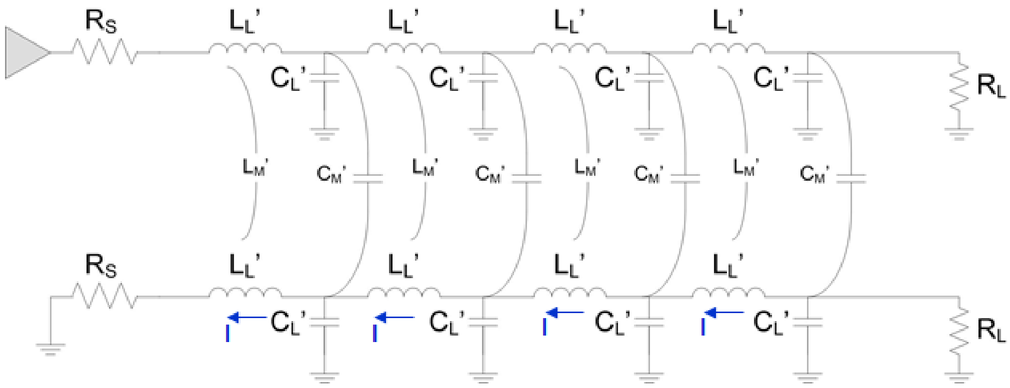

Fig. 5: inductive crosstalk [6]

Far End Crosstalk Coefficient (FEXT)

The FEXT can be seen as the total influence of both capacitive and inductive coupling between the two lines. The formula to calculate this can be found by simply adding up the above formulas. The formula shows a relation between the injected signal (VA) and the signal induced with crosstalk (VB).

- $\left(\frac{V_B}{V_A}\right) = \frac{1}{2} * \left(\frac{length}{speed * t_{rise}}\right) * \left(\frac{C_M}{C_L} - \frac{L_M}{L_L}\right) = FEXT$

Results

The data used can be found in Table 6. A datasheet of a similar cable was searched for to obtain the mutual capacity and inductance (CM and LM). The capacity and inductance of the cable, was already calculated when determining the Lumped Elements (CL and LL). The values for the different quantities come from different sources on the internet and can be seen as average values of the results found.

Table 6: Data [2] [7] [8]

Parameter	Value	Unit
C_M	$4{,}61*10^{-7}$	µF/km
C_L	$3{,}3*10^{-10}$	F/m
L_M	$1{,}7*10^{-4}$	H/km
L_L	$1{,}5*10^{-7}$	H/m
Snelheid	$180*10^{6}$	m/s
Lengte korte kabel	41	m
Lengte lange kabel	258	m

It is expected that the course of the voltage on the Victim lines (phase 2 and phase 1) is somewhat similar to the course of the voltage on the Agressor line (cross-talk curve). Crosstalk will be the main influence factor. The longer the cables, the higher the influence of the crosstalk will be. In other words, the measurements of phase 2 and phase 1 on house 9 will correspond better with the Cross-talk curve than with the measurement on house 9.

Fig. 27 an 28 show that the expectations that were set in advance correspond well with the results that were obtained. With the long cable you can clearly see that the crosstalk has a big influence. The coupling between the two lines is very strong here. The difference between the influence of the short cable and the long cable can be seen in Fig. 29.

The graph refers to the CT-factor. The CT factor is obtained by dividing the calculated Cross Talk curve by the measured signal at phase 1. In this way, the influence of crosstalk can be observed. With a long cable it can be seen that crosstalk has a much greater influence, which is not illogical. The longer the cable, the bigger the crosstalk phenomena will be.

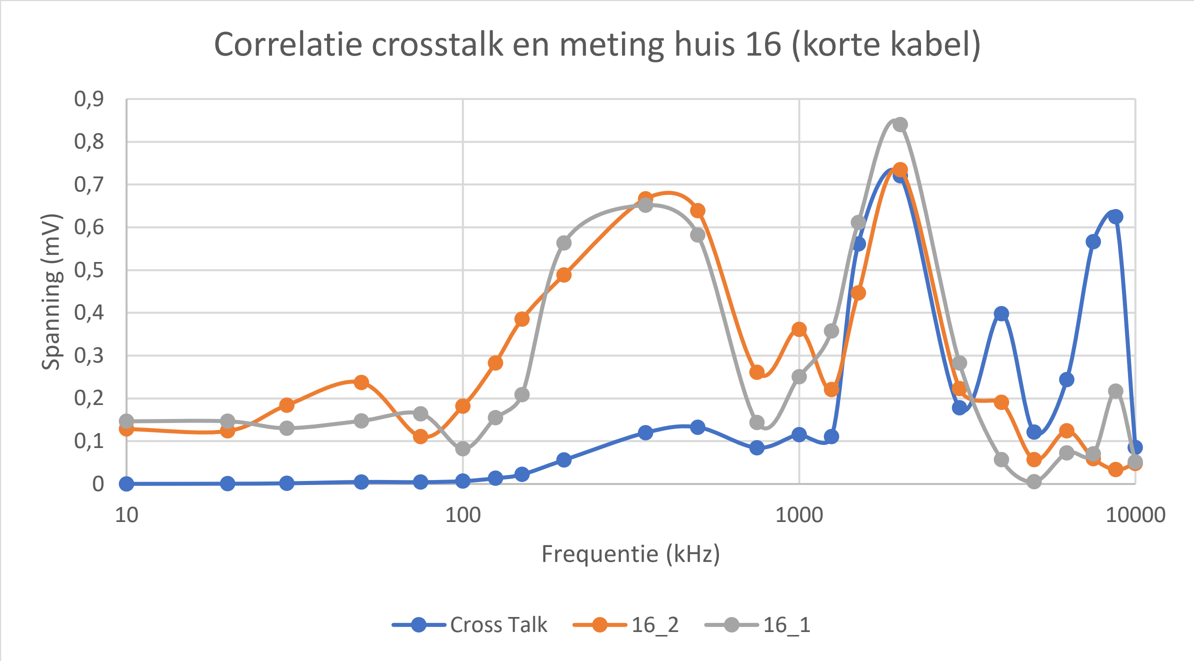

Fig. 21:Crosstalk – Short cable (house 15)

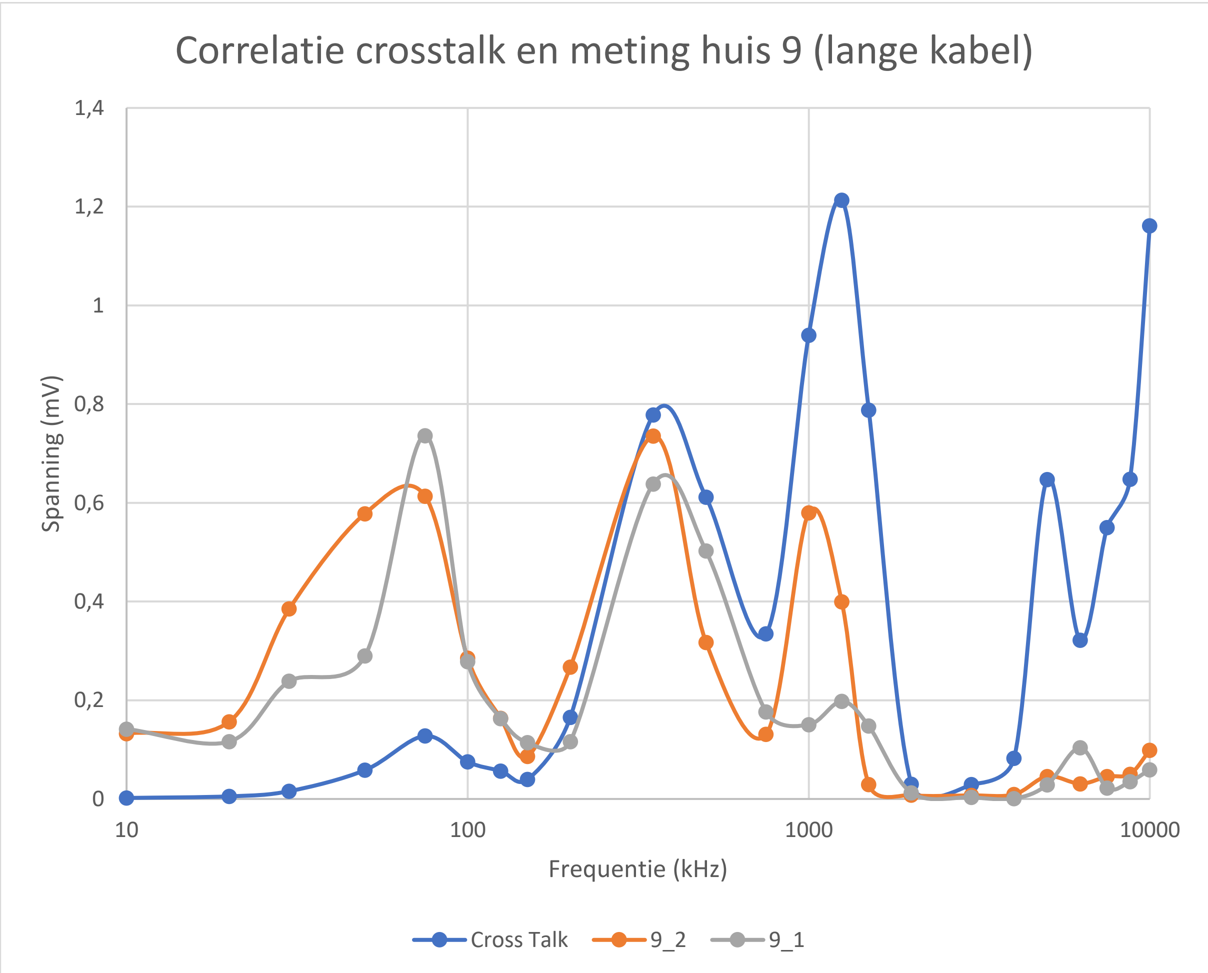

Fig. 22: Crosstalk – Long cable (house 9)

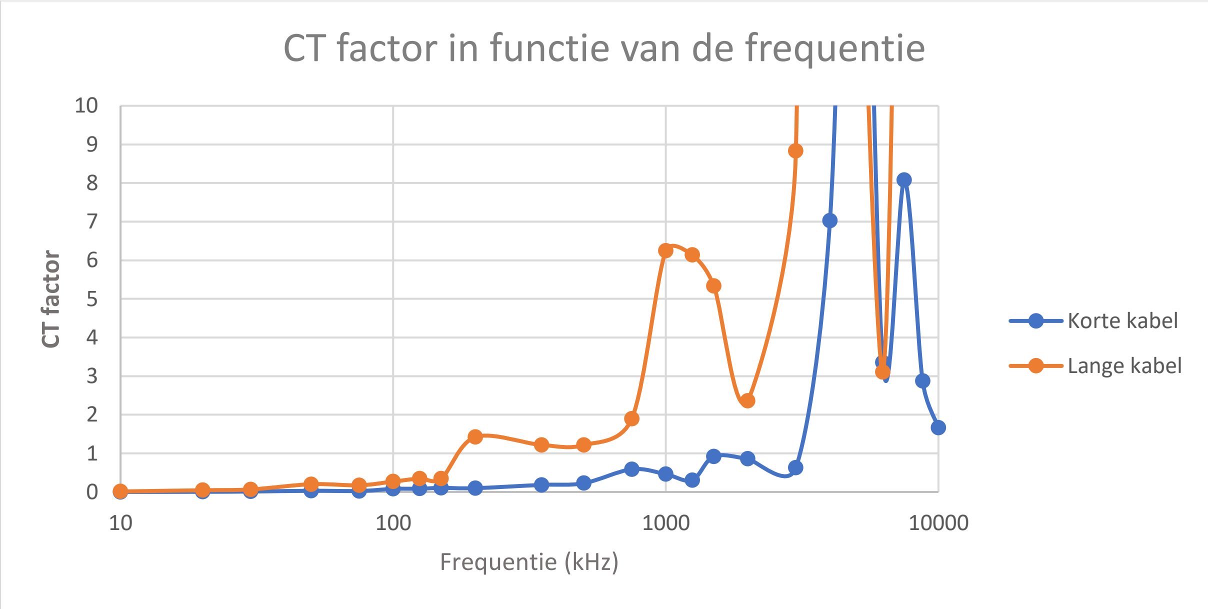

Fig. 23: CT-factor

There is a difference in form between the crosstalk at phases 1 and 2 on Fig. 27 and 28. There are two reasons for this.

- The cable of phase 2 can be a bit further or a bit closer to phase 3 (phase that is being injected) than phase 1.
- There may be small imperfections in the insulation of the wires of the cables so that the coupling between the phases may be slightly different.

These 2 reasons will ensure that the capacity between the cables will not be the same. This means that the C_M between the cables will be slightly different for the different phases, so that the injected current for the Victim will also be slightly different. The FEXT will be different for the 2 phases, so the crosstalk will be different.

3.5. Power Line Communication

Power line communication can be divided into different categories. In this report, the measurements were carried out with signals with a frequency of 10kHz up to and including 10MHz.

The quality of the PLC depends on 3 factors:

- The variations of the grid impedance: as already discussed, the grid impedance varies at different frequency. Because the impedance is unprecedented at a given time, it is impossible to perfectly estimate what the voltage drops, deformations, etc. will be. So it is possible that in some situations the signal is so distorted that it will no longer have the desired effect.
- Attenuation on the communication channel: Long cables cause higher voltage drops. If a cable becomes too long, it can happen that the signal is weakened too much by the large voltage drops. In this case, the receiver will no longer receive a clear signal, which may cause the functionality of the signal to be lost.
- Noise generated by nearby cables from the distribution network: the cables used in the distribution network are unshielded cables. Because these cables are not shielded, the cable can act as an antenna in case of high frequency signals. This antenna effect can cause signals to be generated on a nearby cable that are undesirable.

3.6. Conclusion

First of all, there are a few remarks about the measurement setup. The measurement of the input and output signals did not take place at the same time. In addition, the background noise should also be measured first, in such a way that already some dips and peaks can be explained.

In the transmission line theory it became clear that with a cable length smaller than λ/100, the skin effect is the dominant factor. In the area between the λ/100 and λ/20 areas, the skin effect still plays a decisive role. In this area, transmission line phenomena are beginning to occur more and more. In the area above λ/20 there is no longer a (strong) correlation between input and output. This is partly due to the transmission line phenomena. With a long cable, the effects can already be observed at lower frequencies.

The capricious shape of the measured signal can also be explained by the mains impedance. Some peaks and dips can be explained by the variation of the mains impedance. The mains impedance varies in function of the frequency and also in function of the time.

In this report, only far-end crosstalk was discussed. Crosstalk can be described as the phenomenon that a cable can generate noise on a nearby cable, due to the capacity and inductivity between the two cables. Crosstalk therefore only describes the phenomena on the other phases than the phase on which the injection is made. Depending on the length of the cable and the frequency of the signal, the coupling between the different phases will vary. At crosstalk the FEXT was calculated. The FEXT is a factor that represents the relationship between the induced signal and the original signal. Especially at high frequencies and long cables, the coupling between different phases is better, so there is more crosstalk.

The quality of Power Line Communication depends on 3 factors. First of all, the varying mains impedance. Because of this variation, the mains impedance cannot be determined exactly at all times. As a result, the PLC signal can sometimes arrive at the receiver differently than desired. Secondly, in the case of very long cables or cables with high resistance, the voltage drops can become so high that the receiver can no longer perceive the PLC signal correctly. Attenuation or attenuation occurs. Finally, there is also noise generated by the nearby cables, which can cause a distortion of the injected PLC signal.

Sources

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[8] /, „Fundamentels of applied Electromagnetics - Chapter 2”.