Interreg
EUROPEAN UNION
2 Seas Mers Zeeën
INCASE
European Regional Development Fund

Narrowband Power Line Communication

&

High-Frequency Power Quality

A short overview of technology and problems

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Contents

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The INCASE project

Industry 4.0 (I4.0) is the next industrial revolution. Manufacturers are focussing on client-specific production and added-value products. In Germany 84% of the companies feel the pressure to digitize and 57% will significantly change their business model due to the digital revolution. Germany is world leader in this revolution. The project main objective is to ***close the gap between the 2 Seas region and Germany & other leading countries***, by developing and demonstrating the necessary key technologies towards companies, in this way facilitating the conversion towards I4.0.

INCASE develops knowledge, innovative applications and pilots on key enabling automation technologies for the future I4.0. INCASE will deliver ***10 thematic demonstration trajectories*** on those key enabling automation technologies for smart factories and green technologies for smart homes and factories. The demonstration actions will inspire practicing engineers towards new products and new production methodologies. The intermediary organizations will actively create awareness on the future I4.0.

The project contains ***three main workpackages***. ***WP1*** develops pilots on key enabling automation technologies for Industry 4.0, to achieve an early market uptake by and increased awareness of the manufacturing industries. Involved technologies are Industrial Communication (Profinet, Power Line Communication, ProfiCloud, Networked Control) and Integrated Design (Mobile robotics, Industrial Hardware Targets, Cosimulation). ***WP2*** develops pilots to reduce energy consumption in both home automation and industrial automation, and increase the awareness & knowledge for the automation and manufacturing industries. Involved technologies are Communication and HMI technologies for smart factories and smart houses (ProfiEnergy, Power Line Communication for smartgrids, Control & HMI for Smart Houses, energy monitoring devices connected to the Internet of Things). ***WP3*** develops demonstration tools, based on the pilots, to perform numerous demonstration actions for practicing engineers in industry. In this way the knowledge on new technologies is increased and an early market uptake of Industry 4.0's new automation technologies is achieved in the 2 Seas region.

The ***main objective*** of INCASE is preparing the industry (automation & manufacturing industry) for the future "Industry 4.0" (I4.0) and "Industrial Internet of Things" (IIoT). This is done by:

- Creating awareness of technical management and decision makers of companies on the possibilities of the new technologies.
- Preparing practicing engineers by demonstrating new technologies for the future smart interconnected factories, smart buildings and sustainable engineering.

The project ***specific objectives*** are:

- Pilots on ProfiCloud
- Pilots on Stress-testing on Profinet
- Feasibility study on PLC
- Pilots on Networked Control
- Pilots on Integrated Design
- Pilots for ProfiEnergy
- Pilots for smartgrids using PLC
- Pilots for Control&HMI for Smart homes
- Pilots for energy monitoring devices connected to IOT, IIOT and industrial networks
- Demonstration tools & actions

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1. The demand for communication

For more than 100 years, the electrical power grid has been used to transport electrical energy from the source to the load, or from the provider to the user. Due to the increasing integration of local sources of energy, as photovoltaics and wind turbines, the hierarchical structure and centrally controlled grid is not suitable for these new technologies. Current state-of-the-art asks for integration of storage, increasing complexity and the demand for control and communication. The key factor in this story is communication (Fig. 1**Error! Reference source not found.**). Sources and loads have to communicate, meaning that a bidirectional communication is necessary. The smart grid can be visualized by the electric grid with sources and loads and on top of that an "internet-like" communication grid. But there is one main difference between the Internet and communication in smart grids. The Internet is a "best effort of service delivery". It means that a slow communication (f.i. due to disturbances causing several retries) or the full unavailability for some minutes is publically accepted. Availability of electric power on the other hand is nowadays so essential, that the "quality of service (QoS)" is a top priority. Given the fact that smart grids rely on communication technologies, the used technologies have to be 99.999 % reliable.

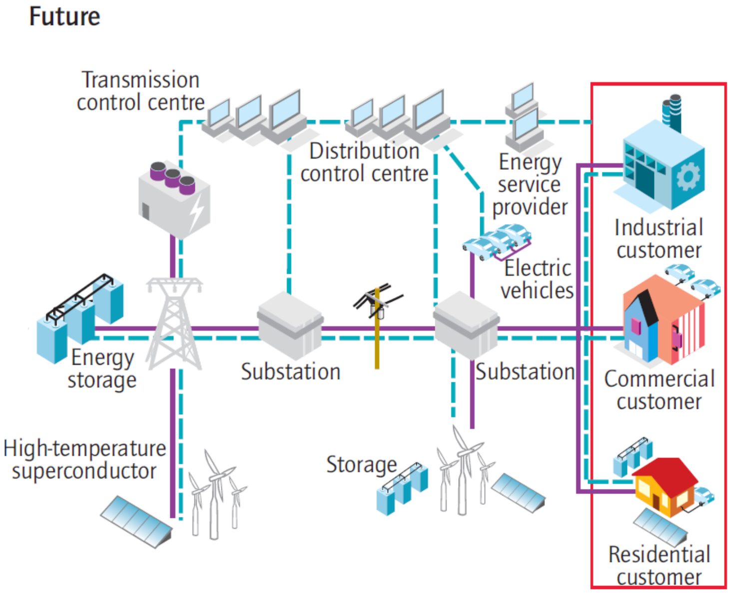

Fig. 1. Evolution to a smarter grid

A second increasing demand of communication is due to smart devices. The master from the home automation system communicates with several devices, f.i. the refrigerator or washing machine in order to control the use of energy. The revolution that the internet of things is bringing asks for communication channels, with mobile devices (tablet, smartphone) as the master in the system.

The basics of industrial automation is also communication between devices. Several protocols are worldwide used, both wired and wireless. The industrial environment is much harsher than the domestic environment, asking for more robust communication systems. This stimulates the evolution to more robust and safe communication systems.

The demand for communication channels is increasing as everything will communicate in the future. The increasing demand of bandwidth requires ever higher carrier frequencies. Due to the increasing use of mobile devices, wireless communication seems to become more important than wired communication. In the whole spectrum of solutions, power line communication (PLC) is one candidate. In this text, the feasibility and possibilities of PLC are investigated. What are the benefits and is PLC still useful? Will PLC be dead within 10 years or will it survive as valid or as niche communication method?

2. Power Line Communication

2.1. PLC basics

A. Scope of the report

Power line communication modems use the electrical wiring for communication purposes. PLC dates back to the beginning of the 20th century and was mainly used by utility companies to control loads and metering devices. In this way street lights were controlled and electricity meters were changed from day to night tariffing. These applications typically demand very low bandwidths, low carrier frequencies and only needs unidirectional communication. As it only superimposes a signal on the sinusoidal grid voltage, it is called ripple control (RC). Ripple control signals are injected at medium voltage level at frequencies below 2 kHz. Due to the low frequency, it can pass through transformers to control devices at the low voltage side. Real (bidirectional) communication below 2 kHz is called ultra-narrow band (UNB) PLC. These signals can reach up to 100 bps over 150 km. RC and UNB-PLC are not in the scope of this work.

PLC can be divided in narrow-band and broad-band PLC. Narrow-band power line communication (NB-PLC) has a carrier frequency typically between 2 and 500 kHz, broad-band power line communication (BB-PLC) contains a carrier frequency above 1 MHz. Due to the aforementioned reason of the transformer, both NB- and BB-PLC typically communicate in the low voltage grid.

NB-PLC is typically used for limited-bandwidth applications. Examples are control of devices for home automation systems and smart meters. BB-PLC is typically useful for demanding applications as audio, video and internet. NB-PLC will be discussed in this report. BB-PLC will be discussed in the second report.

NB-PLC is further divided in low data rate and high data rate PLC (LDR and HDR).

The low voltage (LV) grid is considered as a harsh environment for communication. The impedance is very time-dependent as consumers are switched on and off. Devices will also generate noise on the grid, drowning the communication signal. The medium voltage (MV) grid is in this way much cleaner and much more stable. Few devices are directly connected to the MV grid. The noise from the LV grid will be filtered by the transformer and will not contaminate the MV grid. On the other hand, for communication from the MV to the LV grid, repeaters will be necessary to handle with the transformer (Fig. 2). The scope of this report is on the LV-grid.

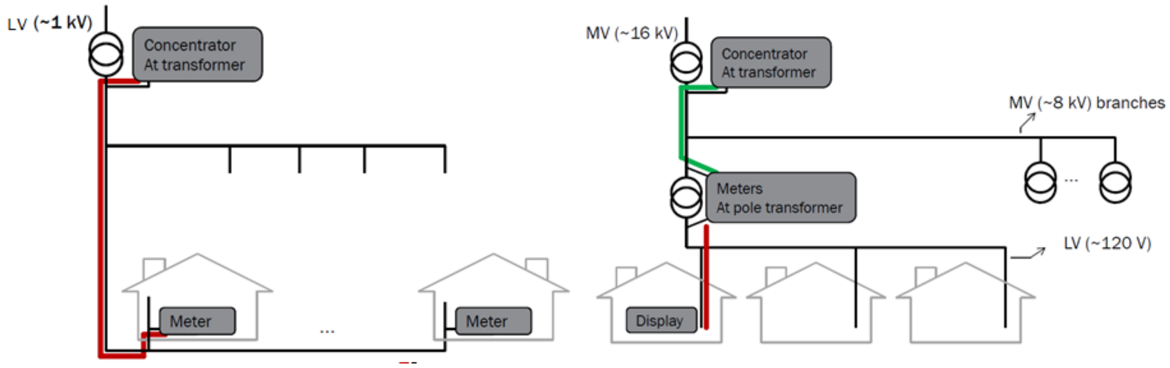

Fig. 2. Smart metering application in LV and MV grid

Communication can be divided in digital and analogue communication. As ripple control switches on/off devices, it can be considered as digital unidirectional communication. An example of analogue communication can be found in old baby alarms, using amplitude modulation (AM). Bidirectional digital communication for metering purposes started in the 70's. For this report, only digital communication is considered.

B. PLC at signal level

X10 is considered as the first PLC protocol. X10 uses a 120 kHz burst synchronized to the zero crossing of the 50 Hz voltage (Fig. 3). X10 reached 20 bit/s and was used to control lights and thermostats in domestic environments.

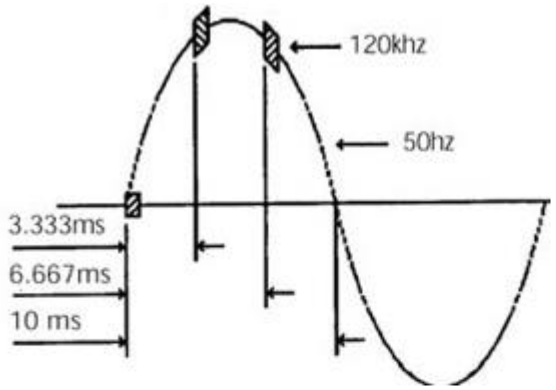

Fig. 3. X10 signal

To increase the robustness of the communication and to increase the communication speed, several modulation schemes were used. Nowadays, the most used schemes are:

- binary phase shift keying (B-PSK, Fig. 4)
- frequency shift keying (FSK, Fig. 5)

due to simplicity of the technology and limited cost. For NB-PLC, lower data rates are sufficient, which makes FSK a favorable method.

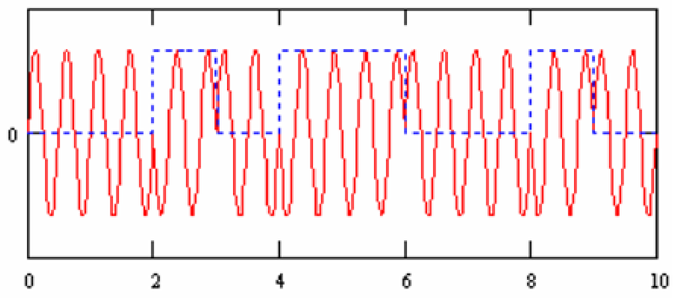

Fig. 4. B-PSK

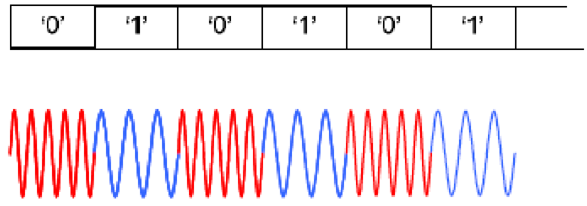

Fig. 5. FSK

By using multiplexing techniques, as orthogonal frequency division multiplexing (OFDM, Fig. 6), multiple channels can be used on the same wire. OFDM is typically used for BB-PLC, but has proven to be a useful solution against noisy environments as the optimal channel (frequency) can be chosen. OFDM is normally used in combination with the B-PSK scheme. A drawback of OFDM is that energy is spread in multiple channels. Given the limited output power in the standard, this results in lower signal-to-noise ratio's (SNR). Additional methods as spread spectrum techniques and frequency hopping are used to increase the security and the robustness of the channel.

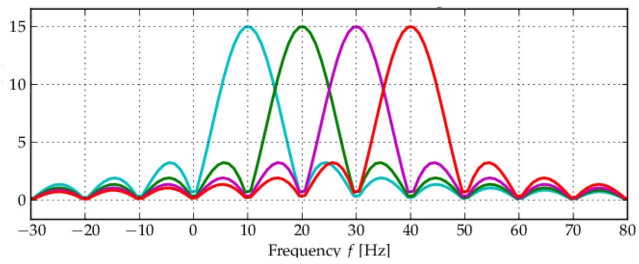

Fig. 6. OFDM

C. Coupling networks

For PLC, a high frequency signal of typically 1V must be superimposed on the 50 Hz 230 V voltage. The connection is made through a coupling network for both safety and filtering reasons.

Coupling networks are discussed in the standard EN50065-4 (Fig. 7). Both differential and common mode coupling is described, but common mode is only allowed under strict EMC conditions.

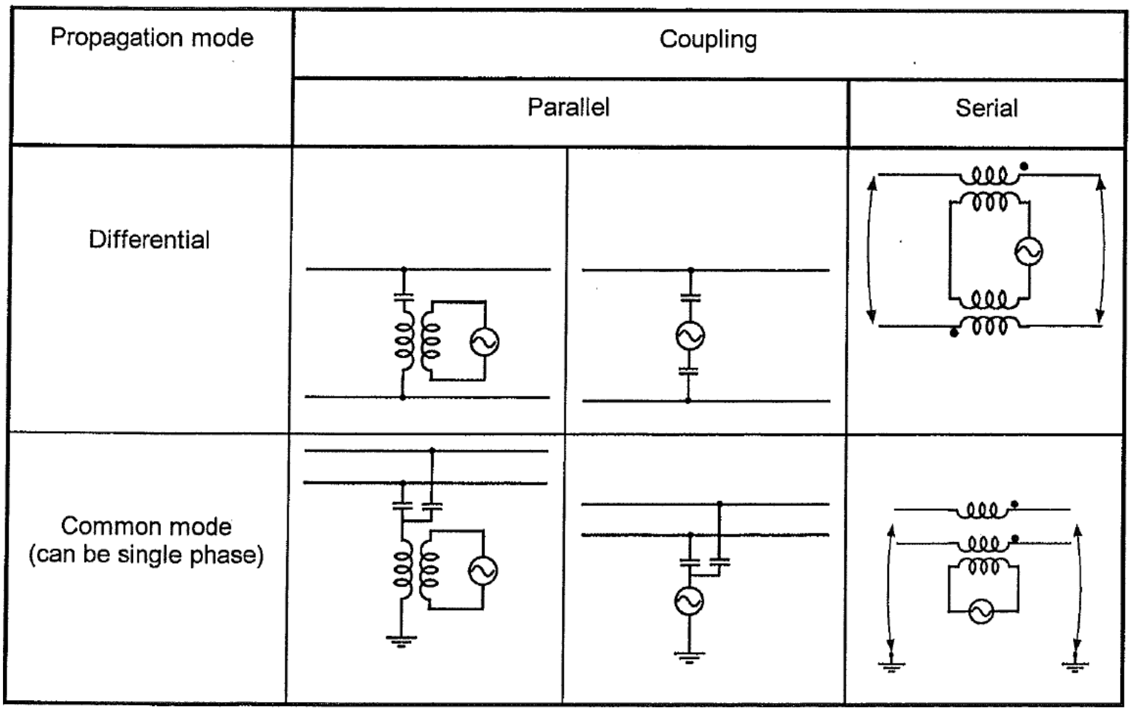

Fig. 7. Coupling methods (EN50065-4-1)

A typical PLC coupler is shown on Fig. 8. It is a passive circuit consisting of a 1:1 transformer T1 and decoupling capacitor C1. This circuit is used for differential coupling (signal exists between two active wires L1 and L2 or L1 and N).

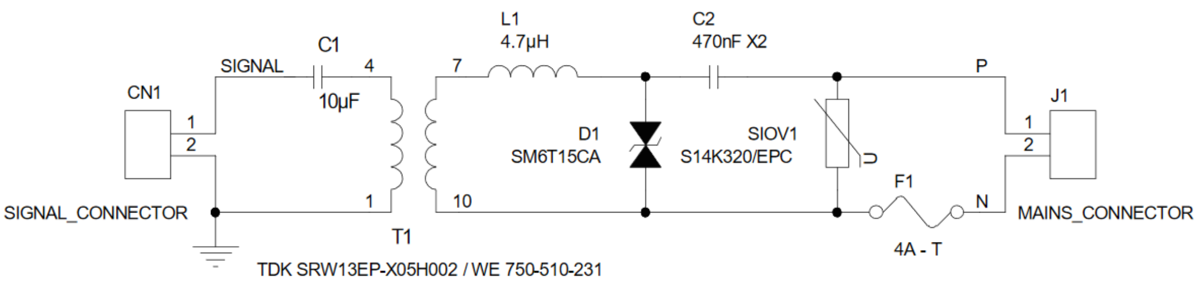

Fig. 8. PLC coupler STEVAL-XPLM01CP

2.2. Advantages and disadvantages

NB-PLC has to cope with several competing technologies. For limited data, f.i. smart meters, sensors and actuators, the bandwidth is sufficient.

Advantages

The largest advantage is that the low voltage grid is available in almost every room. No additional cables are necessary. This is a large benefit in comparison to cable networks (ADSL, Cable and Ethernet). On the other hand, wireless networks need no cables for the communication, except for power supply if batteries are insufficient as source.

In comparison to Wi-Fi, PLC has no problems with concrete walls. One or two floors is sufficient for Wi-Fi to lose the signal. PLC propagates even between houses and up to 1 km and more. The galvanic connection makes PLC more reliable.

In comparison to other cabled technologies, PLC is cheaper, mainly due to the presence of the voltage grid network.

Another advantage is for the grid operators. With PLC, both the communication/monitoring channel and the monitored system (the grid) are the same. It means that the grid operators are independent from telecom operators. For medium voltage grids, PLC can be considered as an optimal solution.

Disadvantages

The low voltage grid is known as a harsh environment for PLC. On the low voltage grid, there is an increasing number of power electronic devices connected, all switching in the range 2 – 150 kHz.

The grid impedance is never constant, due to the switching of devices. Signal attenuation depends mainly in grid impedance and on the impedance of the connected devices. Communication can be unpredictable. Modern devices all contain EMI filters. The capacitors in the filters will attenuate the signal.

The grid topology will have an influence on the communication. Neutral conductors (when present) are typically noisier than phase conductors.

NB-PLC itself causes an increasing number of problems with interference. Due to a lack of standards, devices are not always immune to PLC signals, which can cause malfunction of the device.

In house communication can have problems because sender and receiver are on different phases.

Security of the channel. Power line is an open access medium and does not stop at the building border.

2.3. Narrow Band Frequency allocations

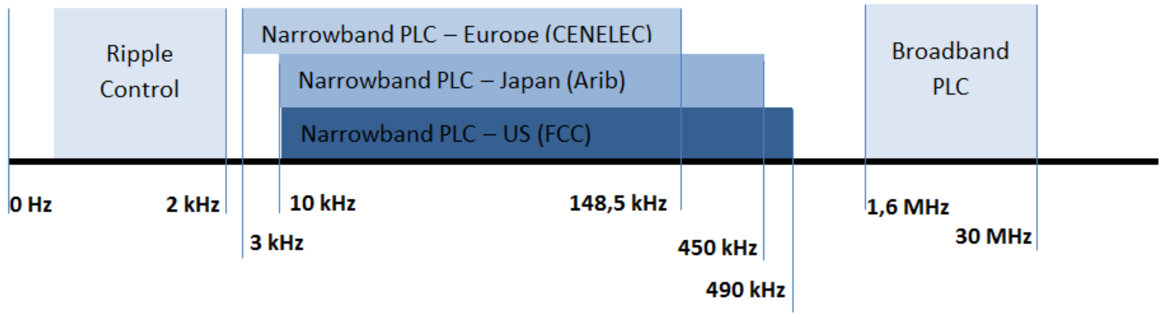

Fig. 9. Frequency allocations

Fig. 9 demonstrates the allowed frequency bands for PLC. As can be noticed, in Europe NB-PLC is limited to 148.5 kHz (further denoted as 150 kHz). In Japan, the US and China NB-PLC is allowed up to approximately 500 kHz. Due to the limitations of bandwidth, there is a demand from manufacturers to extend the range up to 500 kHz also in Europe. 500 kHz ± 10 kHz was in the past not allowed for any communication, as this was the international distress tone (SOS), but this is currently phased out.

3. PLC Narrow Band standards

3.1. Signalling on low voltage networks

The basic standard for devices communicating through the voltage grid is the IEC61000-3-8. This standard considers communication from 3 kHz up to 525 kHz. A difference is made between the different ITU regions, where ITU region 1 (Europe, Africa, former Soviet Union) is limited to 148,5 kHz. The limitation is due to the low frequency AM broadcasting (sometimes denoted as 'longwave radio'), which is only used in region 1. The standards focus on the measurement and allowed value of the output signal. The standard also defines limits for conducted and radiated emission, in conformity with the relevant CISPR standards (CISPR14 and CISPR22/32).

The European standard EN50065[1] can be considered as the fundamental standard for power line communication in Europe. The standard applies to electrical equipment using signals to transmit information on the low voltage electrical network. The first part EN50065-1 defines the frequency bands, voltage limits and disturbance limits. It also describes the basic measurement methods. The standard is summarized in Fig. 10. There are four frequency bands, commonly referred as the CENELEC A, B, C and D band.

[1] EN50065-1: Signalling on low-voltage electrical installations in the frequency range 3 kHz – 148,5 kHz

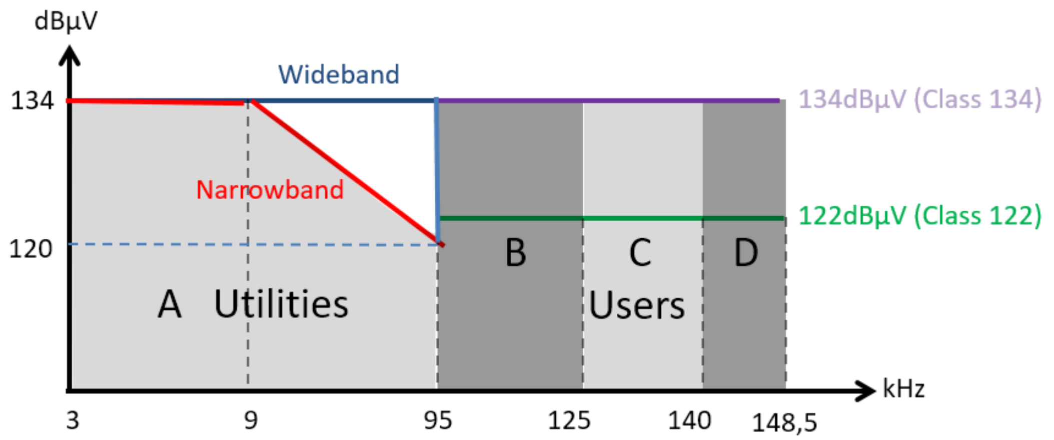

Fig. 10. EN50065 – frequency bands and output levels for single phase devices

The 3 kHz to 95 kHz band (CENELEC A) is only available for utilities. This includes monitoring, measuring and controlling the low-voltage distribution network and connected equipment. The 95 kHz tot 148.5 kHz band can only be used for analogue and digital applications within buildings (domestic, commercial and industrial applications) or for equipment installed on the low voltage network. Typical examples are streetlight control and electrical vehicle charging. Equipment working in subband C require the use of a carrier-sense multiple-access protocol (CSMA). This coexistence requirement is considered as the most important reason of the spreading of PLC, despite the lack of standards.

In the A-band, signals are divided in wideband and narrowband signals. The distinction between narrowband and wideband signals is made at 5 kHz bandwidth. In the other bands, equipment is divided in class 122 and class 134 equipment. Class 122 is suitable for general use, class 134 is only used for industrial environments.

The signal is typically in differential mode. Common mode signaling is only allowed in industrial environments and with clear safety instructions. Common mode signals can cause interference, especially because all electrical conductors in the low voltage grid will carry the signal. The maximum output levels are measured with an artificial mains network (AMN) between phase and ground. The maximum values for single phase devices can be found in Fig. 10. For three phase devices, the reader is referred to the standard.

Above 150 kHz, the EN50065 standard is similar to the CISPR standards class B (domestic applications).

3.2. Alliances and protocols

Many proprietary systems were developed [x][2] to standardize communication. Most protocols are available for different media and are not exclusive for PLC. A short overview is given here,

[2] Alberto Sendin, Ivan Peña, Pablo Angueira, Review Strategies for Power Line Communications Smart Metering Network Deployment. Energies 2014, 7, 2377-2420

without the intention of being complete. The main purpose is to have an idea of characteristics. A division can be made between consumer technology, used for home automation applications, and technology for utilities.

For consumer technologies, the predecessor is the X10 protocol, historically followed by UPB, CEBus and Lonworks:

UPB (pulse position modulation (PPM), 0.2 kbps, 4 – 40 kHz)
Universal Powerline Bus is a protocol for home automation systems. The protocol is typically used in low-cost, low-demanding systems.

Lonworks/LonTalk (BPSK, 3.6 – 5.4 kbps, 86 and 131 kHz)
This networking platform originating from Echelon Corporation, develops protocols for control applications, communicating over several media, including power lines. The protocol has been accepted as standard by ANSI. The mentioned frequency ranges and speed are only for the EN50065 compliant version. Other frequency ranges for use in the US are available.

CEBus (7.5 kbps, 100 – 400 kHz)
CEBus (Consumer Electronics Bus) is an open access protocol mainly for home automation applications.

KNX Powernet (FSK, 1.2 kbps, 95-125 kHz)
KNX association certifies products which are compliant with the KNX communication standard. Typical applications are home automation.

For utilities (mainly automated meter reading), the following standards and protocols are the most important ones:

IEC61334 (S-FSK, 2.4 kbps, 9 – 95 kHz)
This standard describes the basic S-FSK for LDR NB-PLC. The standard describes the physical layer, access layer and management layer. The physical layer has been used by other standards. Applications are typically automated meter reading and SCADA. OnSemi and STMicroelectronics, among others, have developed dedicated ICs.

IEEE P1901.2 (OFDM, < 500 kbps, 9 – 500 kHz)
This standard specifies HDR NB-PLC using transmission frequencies less than 500 kHz. Data rates will be scalable to 500 kbps depending on the application requirements. This standard addresses grid to utility meter, electric vehicle to charging station, and within home area networking communications scenarios. The standard addresses the necessary security

requirements that assure communication privacy and allow use for security sensitive services. This standard defines the physical layer and the medium access sub-layer.

Prime (OFDM, 21.4 – 128.6 kbps, 42 – 89 kHz)

Prime (PoweRline Intelligent Metering Evolution) is developed by the PRIME Alliance. It is standardized under ITU-T G.9904. The standard is mainly used for automated meter reading. PRIME specifies the use of OFDM in combination with PSK (BPSK, QPSK and 8PSK). Several mechanisms are added to increase robustness. In the latest version of the standard, frequencies up to 471 kHz are used.

G3-PLC (OFDM, 5.6 – 45 kbps, 36 – 90.6 kHz)

G3-PLC alliance is a combination of distribution network operators (ERDF), meter vendors and chip vendors. G3-PLC uses OFDM in the CENELEC A band. The technology is recognized as a standard by the ITU (ITU G.9903). G3-PLC is also available for the CENELEC B band (98,4 kHz – 121,9 kHz). Other frequency bands above the CENELEC bands are also used.

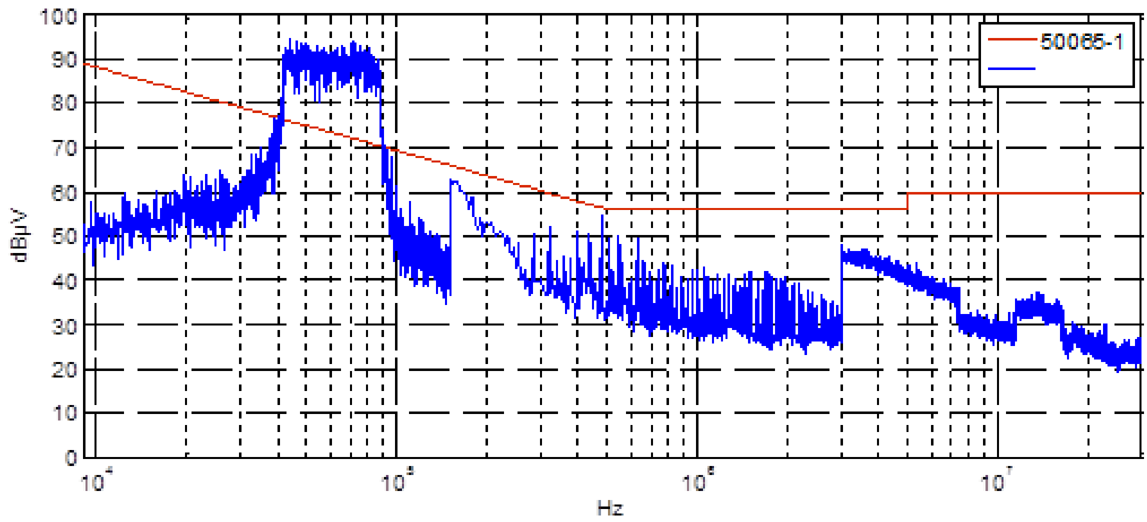

Fig. 11. Measured PLC signal (OFDM)

4. HFPQ

4.1. Sources

The term ‘High frequency power quality’ was first used by J. Desmet and J. Knockaert in 2015 [1]. It can be summarized as the problems in the electrical grid between 2 and 150 kHz. The same is sometimes denoted as low frequency EMC, superharmonics or supraharmonics. These harmonics cause problems as interference and overload (heating) of devices. In [2], all known problems in this range are summarized.

There are three main sources of harmonics in the range 2 to 150 kHz:
- Power line communication
- Power conversion harmonics
- Resonances

4.2. Power line communication

Power line communication can be disturbed by other harmonics, but power line communication itself is seen as one of the main contributors to grid problems. Several reports show that mass roll-out of smart meters [3] gave problems for devices. The reason for this is that other electronic devices are not tested for immunity against these phenomena. As previously mentioned, there was no immunity test standard until 2015 for differential mode problems in the range 2 to 150 kHz.

4.3. Power electronics

Power electronics can be found in all modern devices. This is mainly caused by the push towards smaller devices (the higher the switching frequency, the smaller the used inductors and capacitors) and energy efficiency.

Modern lighting as compact fluorescent lamps (CFL) and LED use power electronics to control the light power. CFL typically switch at 40 kHz. Fig. 12 and Fig. 13 give the typical current (in time domain and frequency domain) of a CFL. The switching frequency is not constant but has a bandwidth of approximately 5 kHz. Also the switching harmonic at double frequency can be seen. The amplitude of the current is highly dependent of the impedance of grid.

For LED, there is no standardisation. Several circuit topologies exist, with and without semiconductive switches. When switches are used, switching frequencies between 20 and 100 kHz can be found.

Besides lighting, almost all devices in houses work internally at DC. Think of all mobile devices with chargers, television, vacuum cleaner with power control, washing machine with speed control. All the devices have power electronics inside to convert the AC voltage from the grid to the appropriate DC-voltage. Switching frequencies range from several kHz up to MHz for mobile chargers.

Another large source in domestic environments are PV-inverters. Fig. 14 shows a voltage measurement on the grid between 2 and 150 kHz, during 6000 min (4 days). The largest emission in the grid is obviously due to the PV-inverters working during the days. The frequency is typically around 16 kHz and the levels are at 1V.

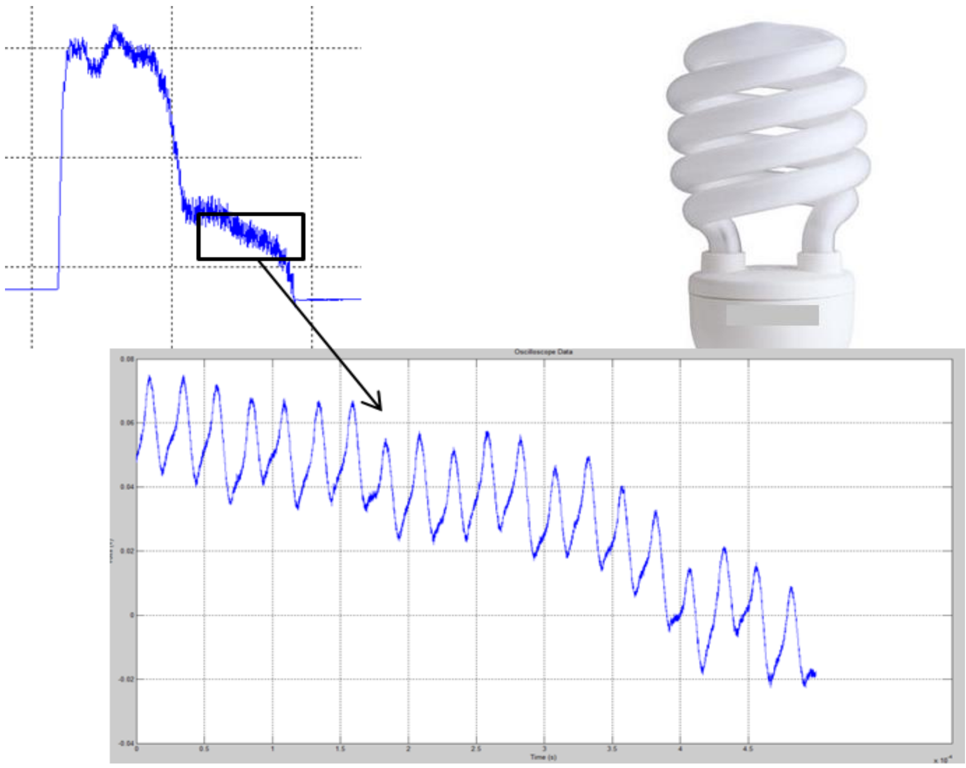

Fig. 12 CFL current measured in time domain

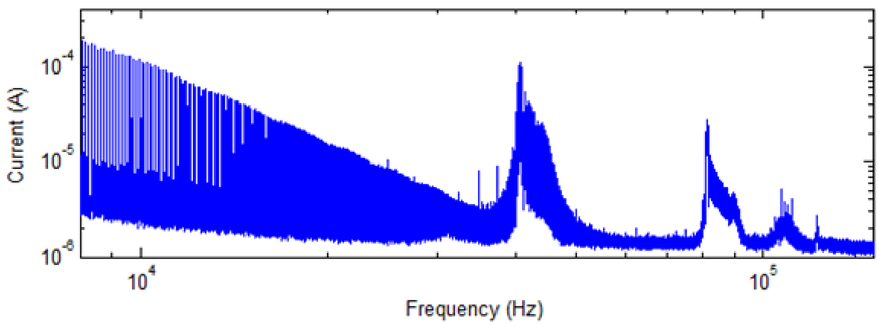

Fig. 13. CFL current measured in frequency domain

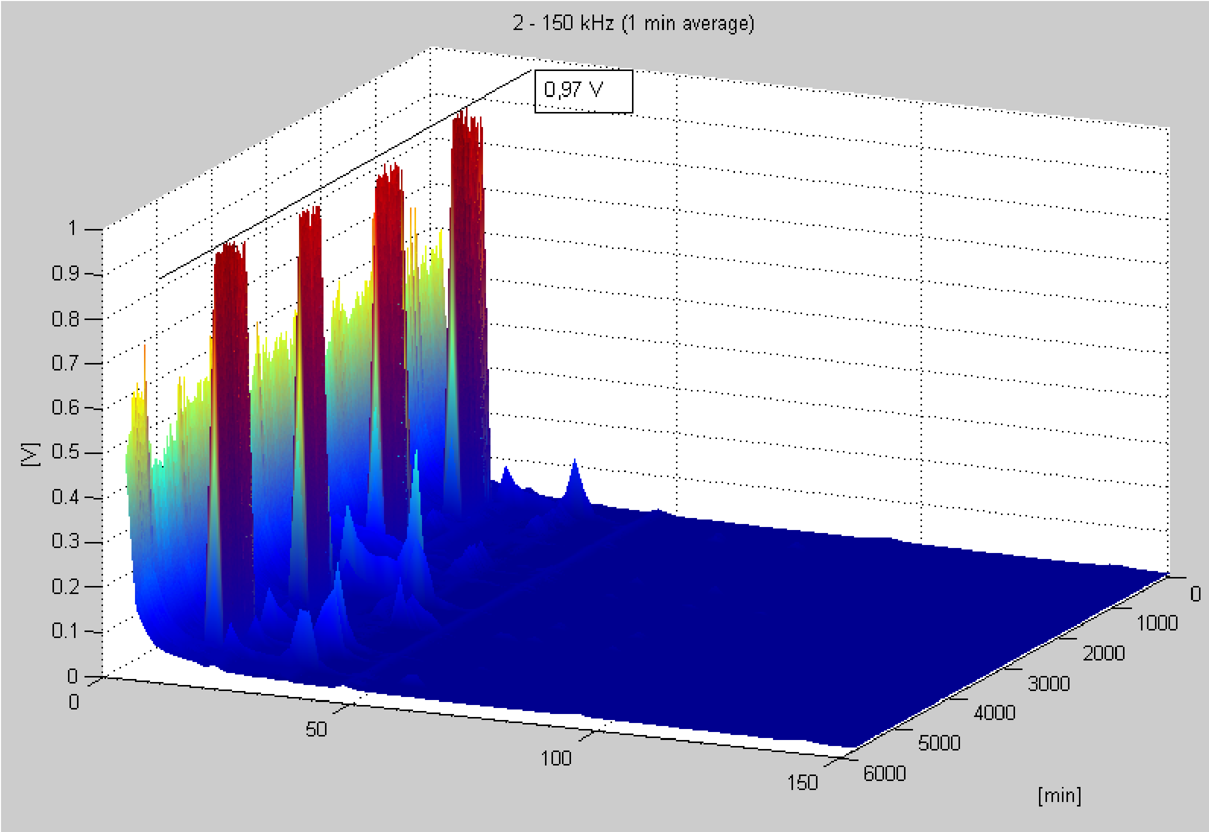

Fig. 14. Emission in domestic environment (2 – 150 kHz, measurement during 4 subsequent days)

An upcoming source creating large high frequency currents in the grid are the electrical vehicle chargers. As there is no standardization, switching frequencies between 2 and 30 kHz are used.

In commercial and industrial environments, the emission is similar in the higher frequencies. The lower frequencies show much more emission, due to motor drives (typically at 2 kHz and multiples). For commercial environments, power factor correction units (PFC) and uninterruptable power supplies (UPS) typically show high emission at some tens of kHz.

The switching harmonics can be measured in the grid at a certain distance of the switching device. It means that the switching device is a source (voltage or current source), injecting current in the grid. The question that can be asked is, what is the real driving source for the harmonic. Three sources can be identified:

- $L.\frac{di}{dt}$ (differential mode voltage, caused by current variation on parasitic and real inductive components)
- $C\frac{dv}{dt}$ (common mode current, caused by common mode voltage source)
- $i.R$ (differential mode voltage source caused by equivalent series resistance in capacitors (ESR)

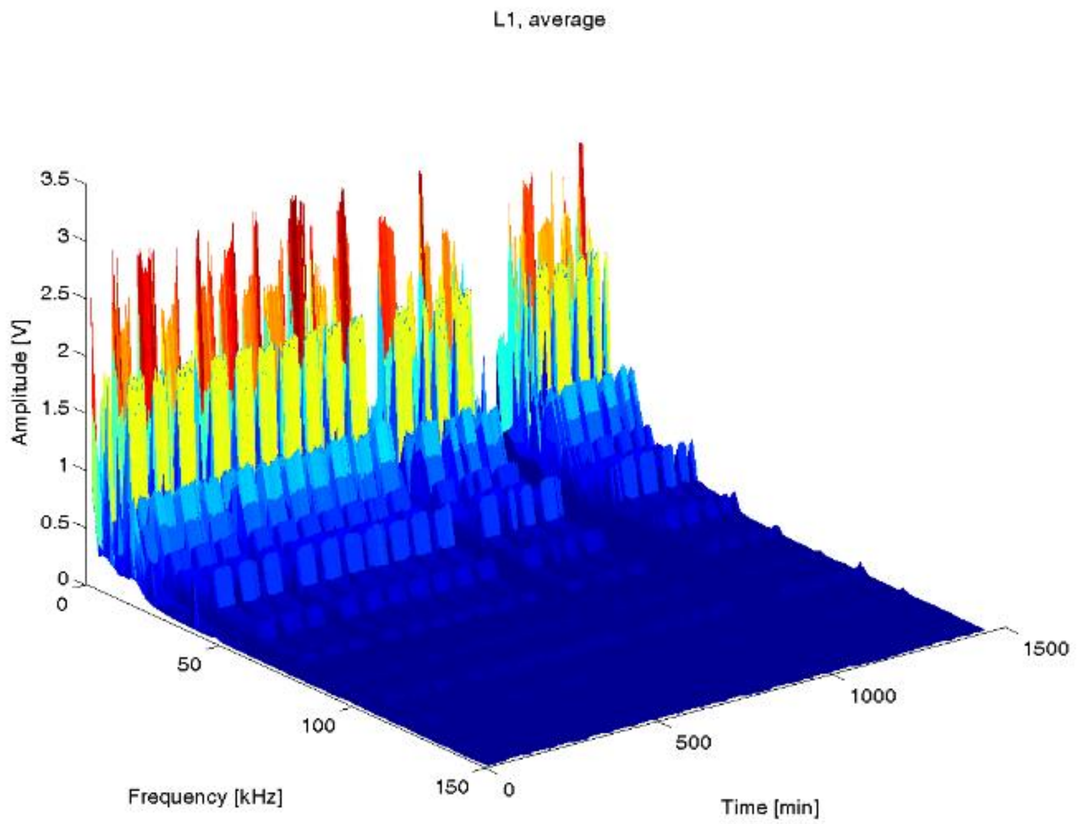

Fig. 15. Emission in industrial installation (2 - 150 kHz)

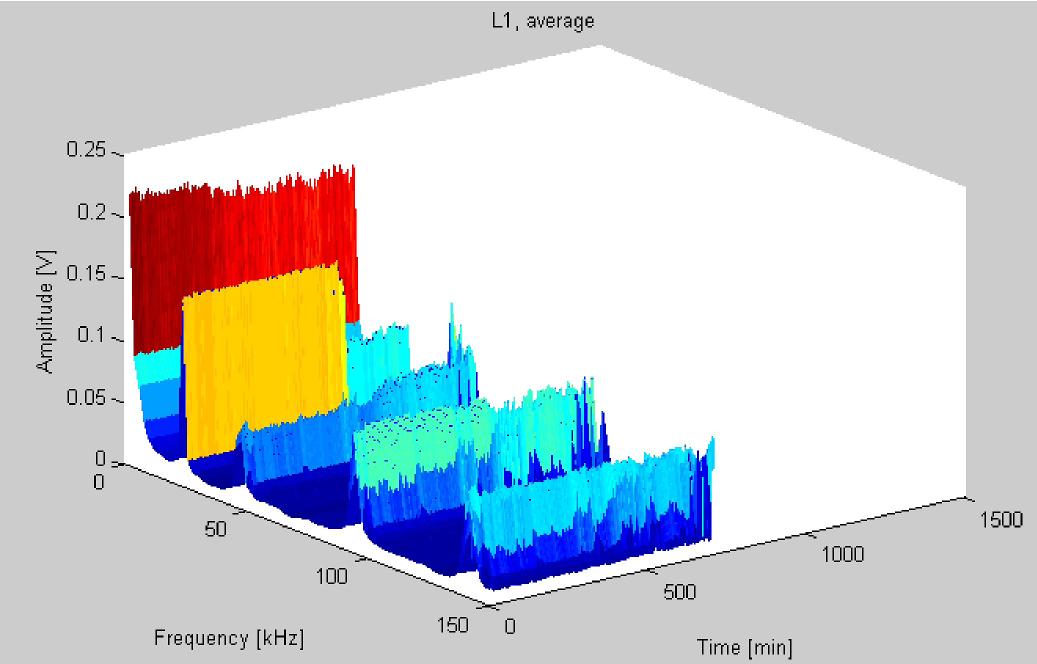

Fig. 16. Emission in commercial environment (2- 150 kHz)

4.4. Resonances

The last source of emission in the range 2 – 150 kHz is due to resonances in the grid. In practice, these are mainly seen between the grid components and PFC-capacitors or harmonic filters. Problematic resonances, creating high mechanical load and vibrations on cables, are typically below 10 kHz.

4.5. Measurement

Measuring high frequency harmonics has proven to be challenging. At current state, there is no adequate standard on how to measure these harmonics. The authors have proven during the INCASE project and published several papers [x] on the fact that several parameters highly influence the measurement.

5. Impedance and attenuation

5.1. Grid influence

TABLE 1.1

Power Line Impedances

Frequencies	Country	L-N in Ω	L-PE in Ω	N-PE in Ω	Source
50–500 kHz	JP	0.5–20 (6.5)	na	na	[50,51]
	Germany	1–60 (10)	na	na	Chapter 2
	Europe	na	1–200 (30)	na	[52]
	China	1–9 (5)	na	na	Chapter 3
	United States	na	1–150 (18)	na	[52,53]
1–30 MHz	JP	3–1 k (83)	na	na	[54]
	Germany	10–300 (30)	20–400 (60)	na	[27]
	Europe	(102)	9–400 (90)	na	[47,52]
	United States	na	6–400 (95)	na	[52,53]
1–100 MHz	Europe	10–190 (86)	10–190 (89)	10–190 (87)	Chapter 5

Power line communication (PLC) signals, which are useful, and power conversion harmonics (PCH), which are a disturbance, have very similar characteristics. Both propagate in the same way in the grid. This grid cause attenuation and distortion on the signal. For PCH it is better that the signals don’t propagate that well, for communication the less attenuation there is the better. Both signals have opposing requirements. In this chapter, the conclusions are valid for both PLC and PCH.

5.2. Grid impedance

The grid consists of connected devices, grid components and cables. In this part, the focus is on the cables. The grid impedance is not constant, but frequency- and time-dependent [4] (Fig. 17).

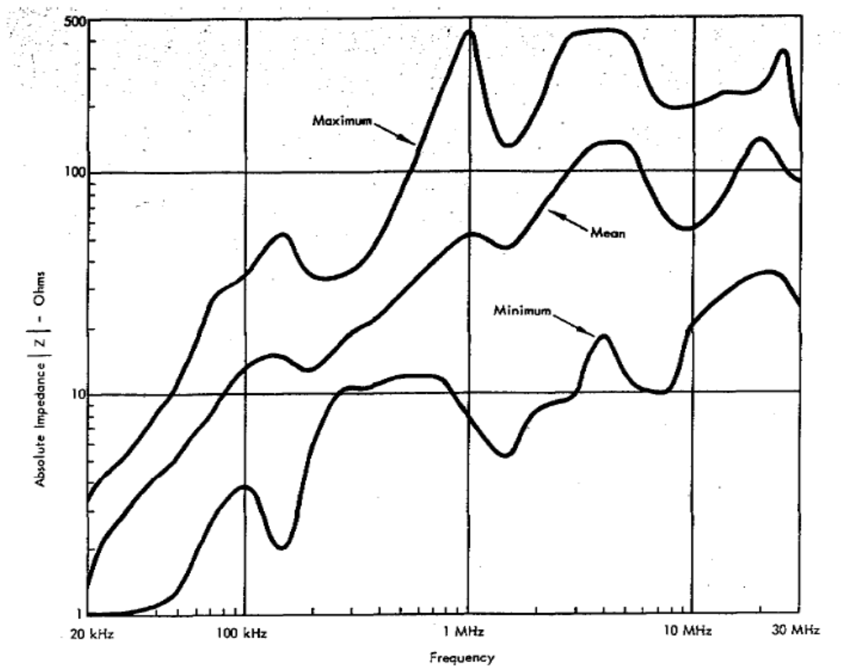

Fig. 17 Grid impedance measurement

Frequency dependency

Fig. 18 shows the frequency dependency of the grid. The impedance is typically increasing due to the resistive-inductive nature of the cables. The impedance is as low as 1 Ω or lower at low frequencies. This is impedance represents the transformer and cables. At higher frequencies, the impedance increases as the inductive impedance $Z = 2.\pi.f.L$ is frequency dependent.

At higher frequencies, the cable model consisting of a resistance and inductance is no longer valid. When measuring the impedance of a cable, resonance frequencies can be noticed.

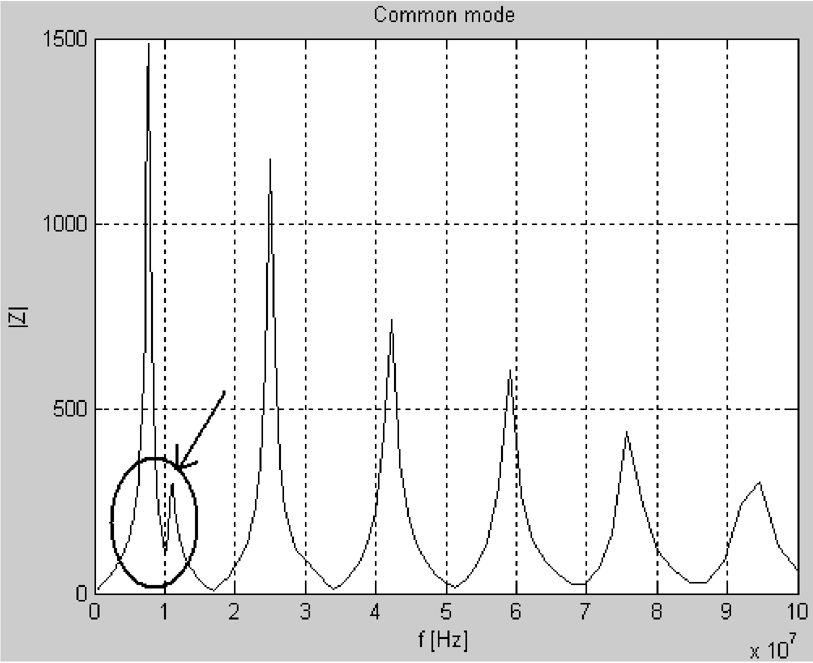

Fig. 18 Frequency dependency grid impedance

The frequency where the resonances occur depend on the length of the cable. It also means, that a signal at the beginning of the cable can see a very small or very large impedance.

EN50065-4-1 gives an indication for the grid impedances in the considered range. It is considered that the impedance is typical between 0,5 and 10 Ω. Extrema go to 0,1 and 20 Ω. Devices with a low impedance (typical due to capacitors) can highly attenuate the signal. To cope with this impedance filters are used, to increase impedance seen from the grid side. A minimum value of 10 Ω is proposed in the standard. EN50065-7 finally determines the minimum impedance for communication equipment itself.

5.3. Attenuation

UGent developed several measurement setups to measure the attenuation in the grid. The basic setup can be seen on Fig. 19. A signal is injected in one house and measured at another house.

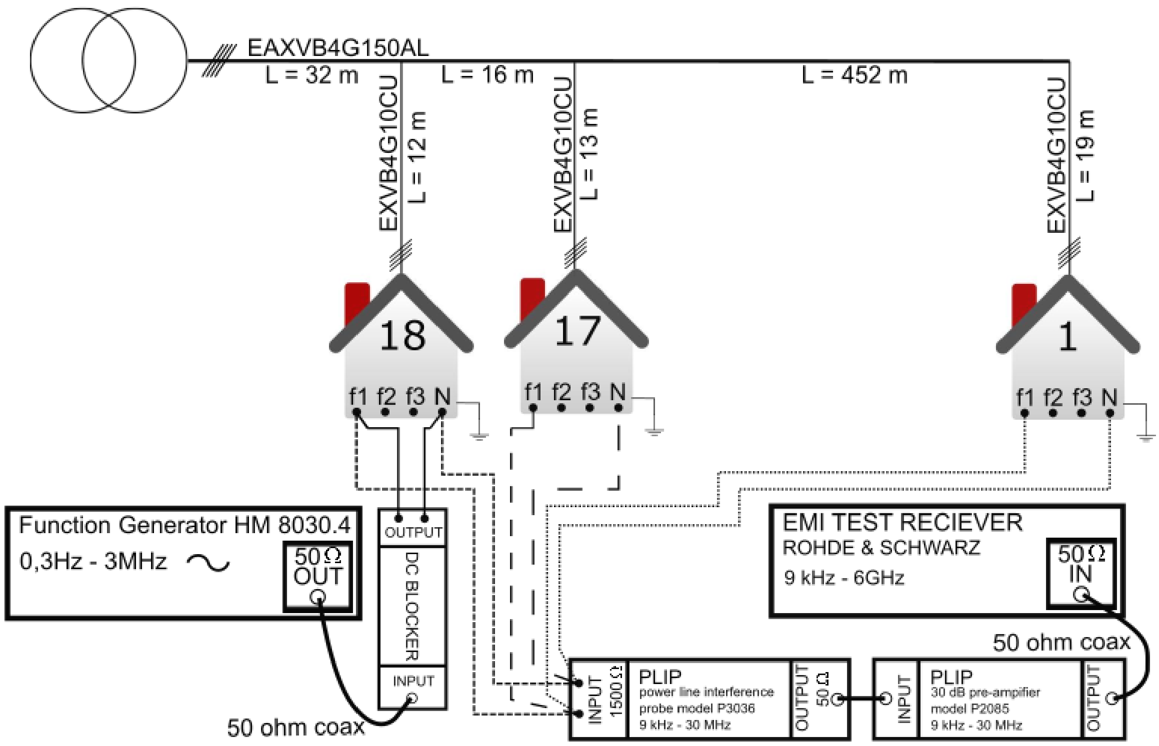

Fig. 19. Attenuation measurement setup

The measured attenuation is very dependent on the cables and connected devices. In one house, the attenuation is (typically some dB). Between separated phases, the attenuation is high (up to 60 dB). Between houses, the attenuation between phases decreases. This is due to the fact that the longer the line, the more crosstalk between phases is present, due to the increased cable capacitance.

5.4. Grid components

Fig. 18 (cable impedance) showed a large variation in impedance. Fig. 17 showed a much smaller variation. This is because devices are connected to the grid. The impedance of these devices will have its influence on the total impedance behavior. Due to this, in a normally used grid, the grid impedance has no excessive values and is typically some Ohms to tens of Ohms.

An evolution that is seen, is the decrease of impedance during time (long term). Nowadays, most devices contain power electronics. These will cause electromagnetic interference. To limit this interference, EMI-filters are placed. This means that almost every device contains filter capacitors. As a consequency, the impedance of the grid decreases with increasing frequency, as the capacitive impedance value is $Z = \frac{1}{2.\pi.f.C}$

5.5. Primary and secondary emission

Primary and secondary emission have been discussed in several papers [x]. Consider three devices A, B and C connected to grid (Fig. 20). The supplying current normally flows between the grid and the device. The high frequency disturbances flow from the device to the grid, as the source is located in the device. It means, the primary emission is in this case made by three devices A, B and C, giving the red, blue and green currents. The magnitude of the current depends on the impedance of the grid at the PCC (point of common coupling) and the cable impedances.

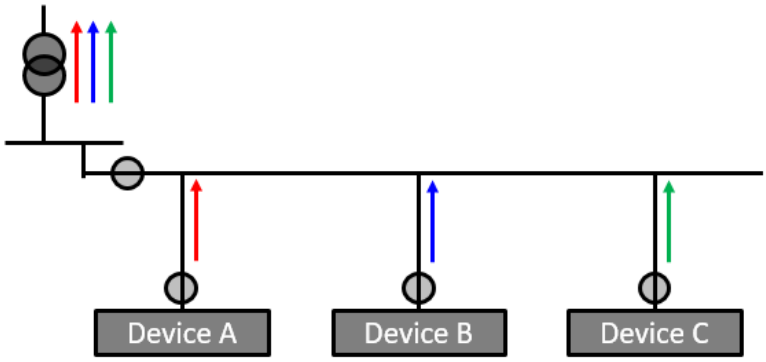

Fig. 20. Primary emission

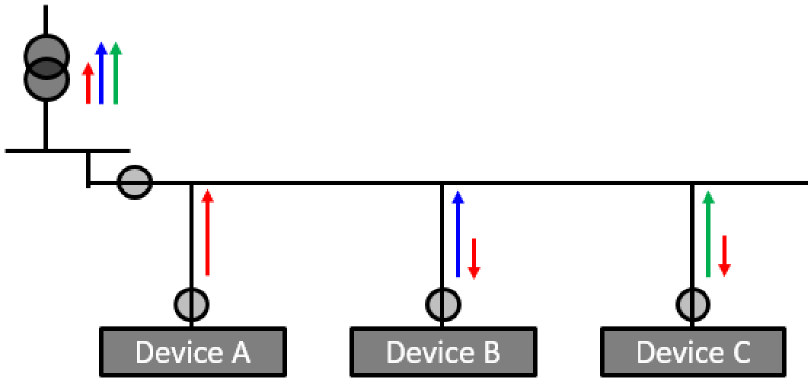

Fig. 21. Secondary emission

At higher frequencies, the impedance of the devices typically decrease due to the capacitive behavior. The impedance of the grid at the PCC increases due to the inductive behavior. It means that at higher frequencies, the lowest impedance path for the currents will be to other devices. The disturbing currents will now flow from device A to device B and C, and partially to the PCC. This is the secondary emission. An example is discussed in (Fig. 22).

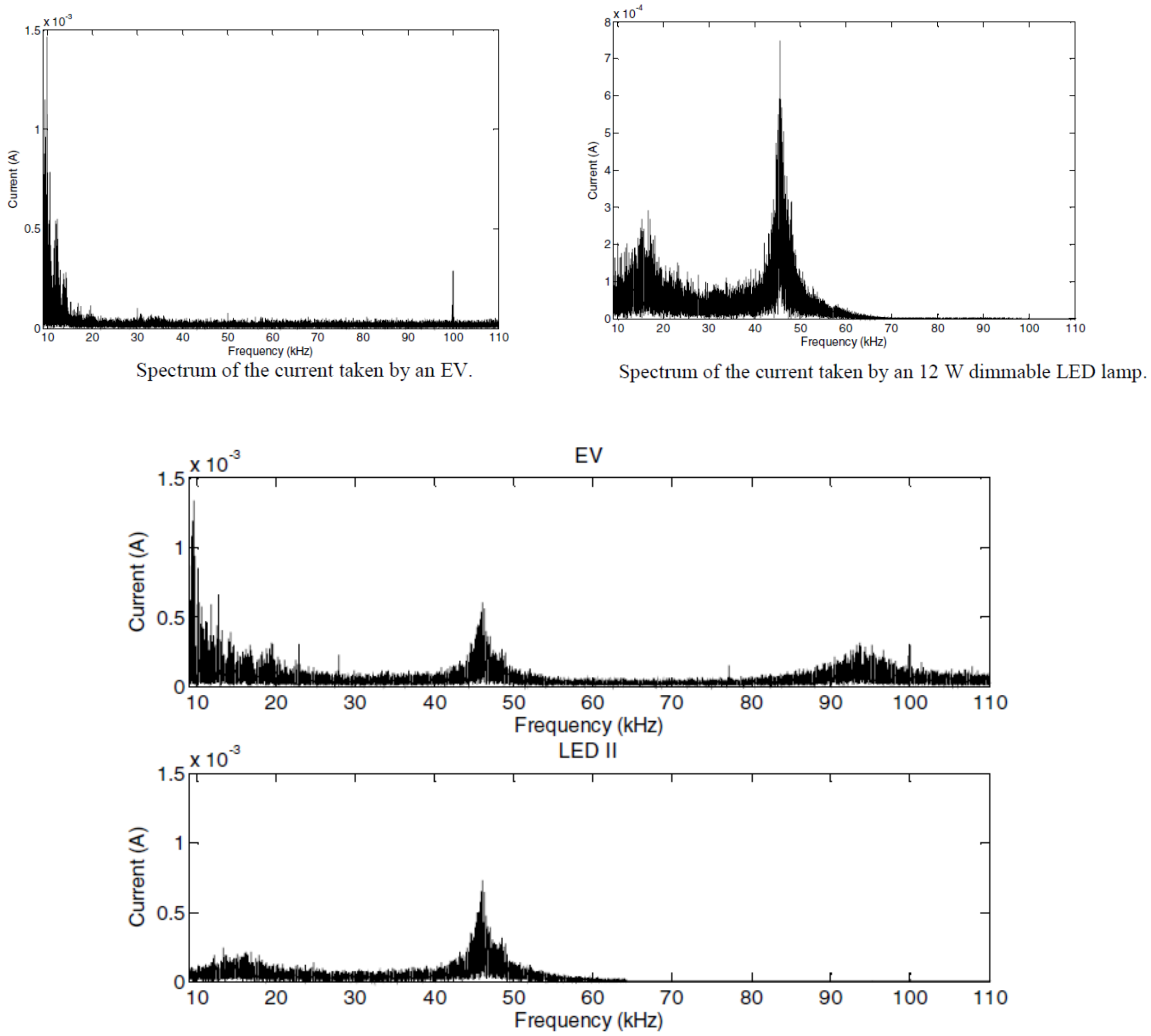

Fig. 22. Secondary emission [x]

The measurement shows the primary emission of an electrical vehicle (EV) (left) and a CFL (right). When both are connected, the emission from the CFL flows to the EV (at 48 kHz). The emission from the EV is not flowing to the CFL (at 93 kHz). All can be related to the impedance of the devices and the PCC.

5.6. Demonstrator by UGent

UGent developed several demonstrators on HFPQ. To have reproducible emission of high frequency switching harmonics, both an DCDC converter and an ACDC converter were built, controllable by Matlab/Simulink. With Simulink it is possible to change the switching frequency, but also to apply variable switching frequencies (spread spectrum techniques) to decrease the emission. Fig. 23 shows the DCDC converter.

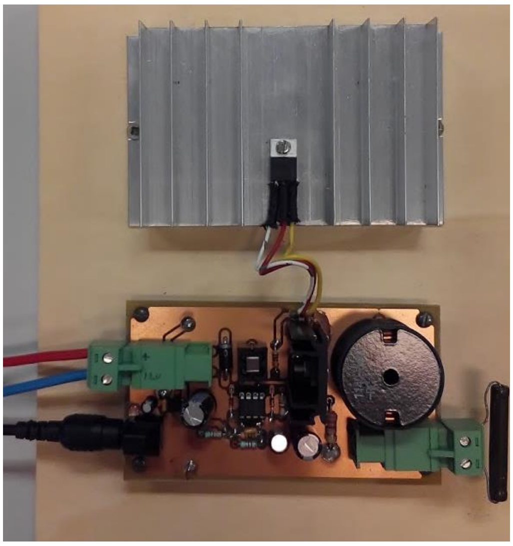

Fig. 23 DCDC converter

For the ACDC converter, a variable resistance in series with the DC capacitor was added. In this way the behaviour of the equivalent series resistance (ESR) can be simulated. An increased ESR gives an increased emission. Several measurements and conclusions are reported in the project.

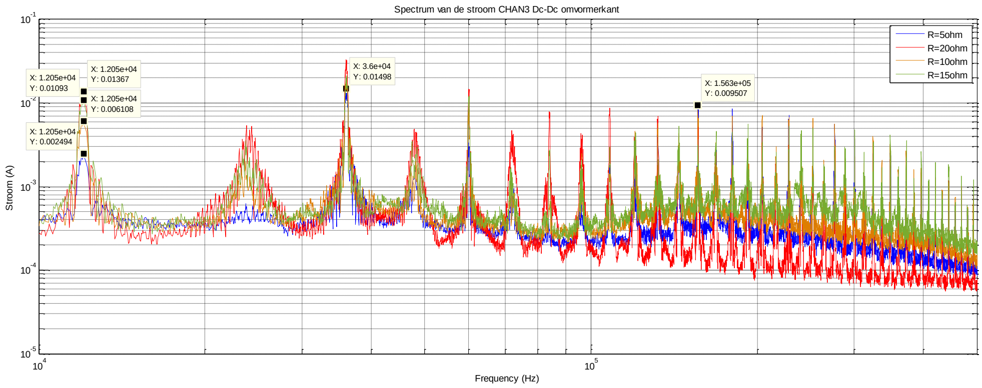

Fig. 24 Emission of ACDC converter with ESR as parameter

Other setups focused on the measurement of HFPQ and solving HFPQ by filters and active compensation. Finally, measurement setups for measuring the grid attenuation were developed.

6. Testboards

Ugent developed several demonstrators on narrowband PLC.

Fig. 25 Demonstrator kit 1 NB-PLC

To demonstrate the operation of power line communication, demonstrator kits were made (Fig. 25). The demonstrator consists of several parts (Fig. 26):

- a power supply
- potentiometers
- LED Dimming Modules
- LED lamps
- Arduino MEGA with a build-up shield
- PLC modem, the MAX79356
- RF transformer

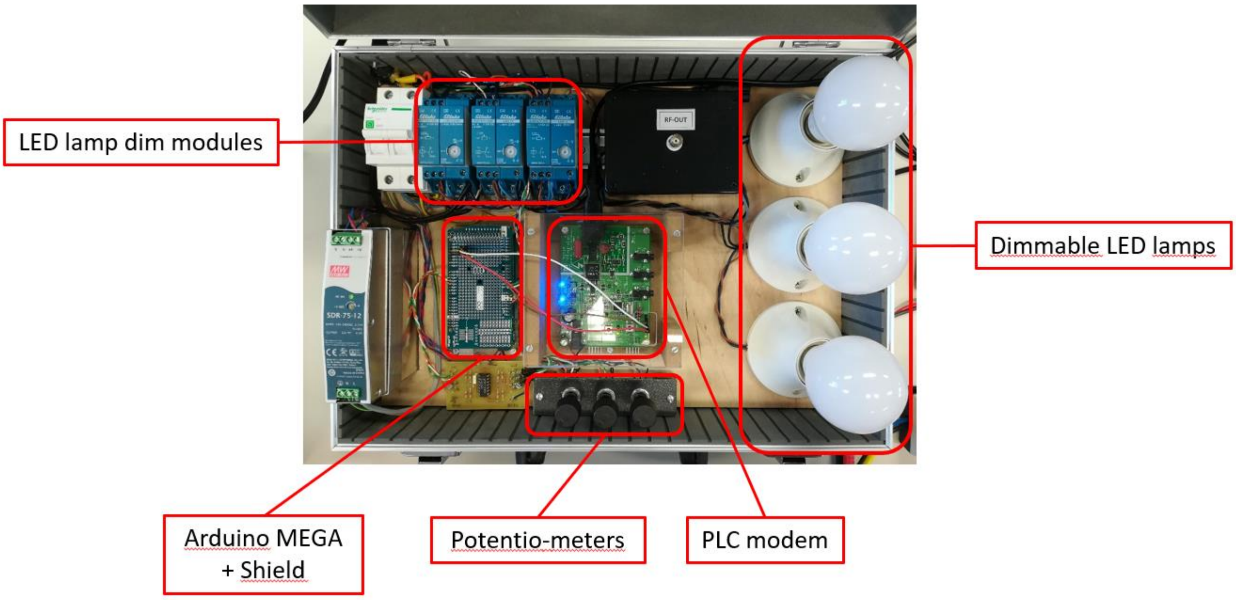

Fig. 26 Demonstrator kit 1 NB-PLC parts

A complete demonstrator consists of two cases. Each case is connected to the low-voltage grid, so communication is automatically established.
The PLC modems can also establish a connection with a cold wire[3] and when using DC voltage networks. The use of a cold wire is especially useful in debugging applications and when the communication signal needs to be visualized. When using a cold wire, the setup can be isolated so that influences present on a normal low voltage grid can be eliminated.

The 12VDC power supply powers the Arduino Mega and the PLC-modem. In this setup, the PLC-modem is not powered by the low voltage network as it would be in a normal application, but by a separate power supply. This way of working ensures that communication over a cold wire is possible. The developed case is equipped with two power cords, one to power all components and the other to communicate.

The RF transformer can be used to measure the communication signal on power cord at the output of the case. The RF transformer has an operating range between 10kHz to about 30MHz.

The block diagram of the setup is shown in Fig. 27.

[3] Cold wire: The electrical conductors are connected, but there is no voltage present on the conductors.

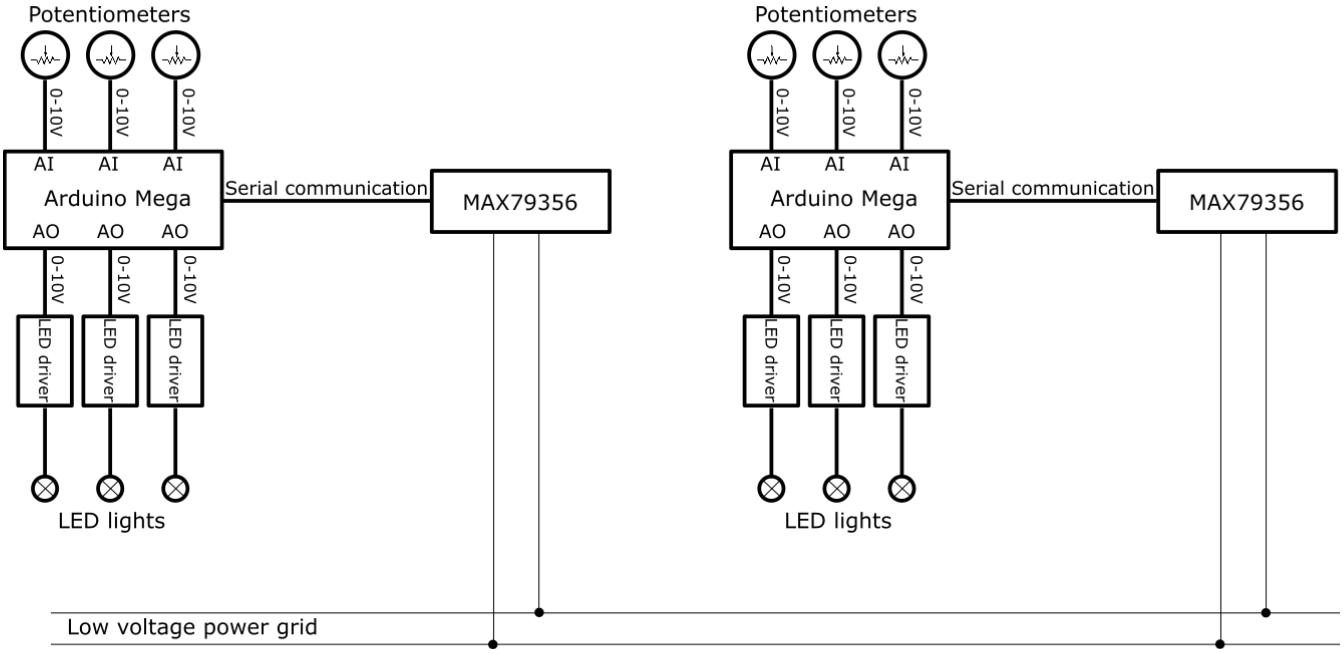

Fig. 27. Block diagram demonstrator

The operation of the demonstrator is as follows;

- with the potentiometers of case 1, the LED lights in case 2 can be dimmed
- the LED lights in case 1 are dimmed with the potentiometers in the 2 case

In case 1 the analog voltage value, which is proportional to the position of the potentiometer, is read into an analog input of the Arduino MEGA. This value is converted to the right message size so that it can be transmitted over the serial port of the Arduino MEGA. On the other side of the serial bus is the PLC-modem. The PLC-modem receives the analog value and will prepare it for transmission over the low voltage network.

The reverse data flow takes place in the second case. The PLC modem receives a message from the low-voltage grid. The message is decoded and the analog value is placed on the serial port of the PLC modem. The Arduino MEGA receives the analog value over the serial bus. The value is converted, after which the analog output is controlled. The voltage value is offered to the LED driver, which in turn controls the LED lamp.

The used PLC modems MAX79356 are assembled on evaluation boards.
Different firmware versions can be used in the PLC modems.

- G3 firmware with the possibility between full MAC support, simple MAC support and transparent UART
- PRIME firmware with simple MAC support

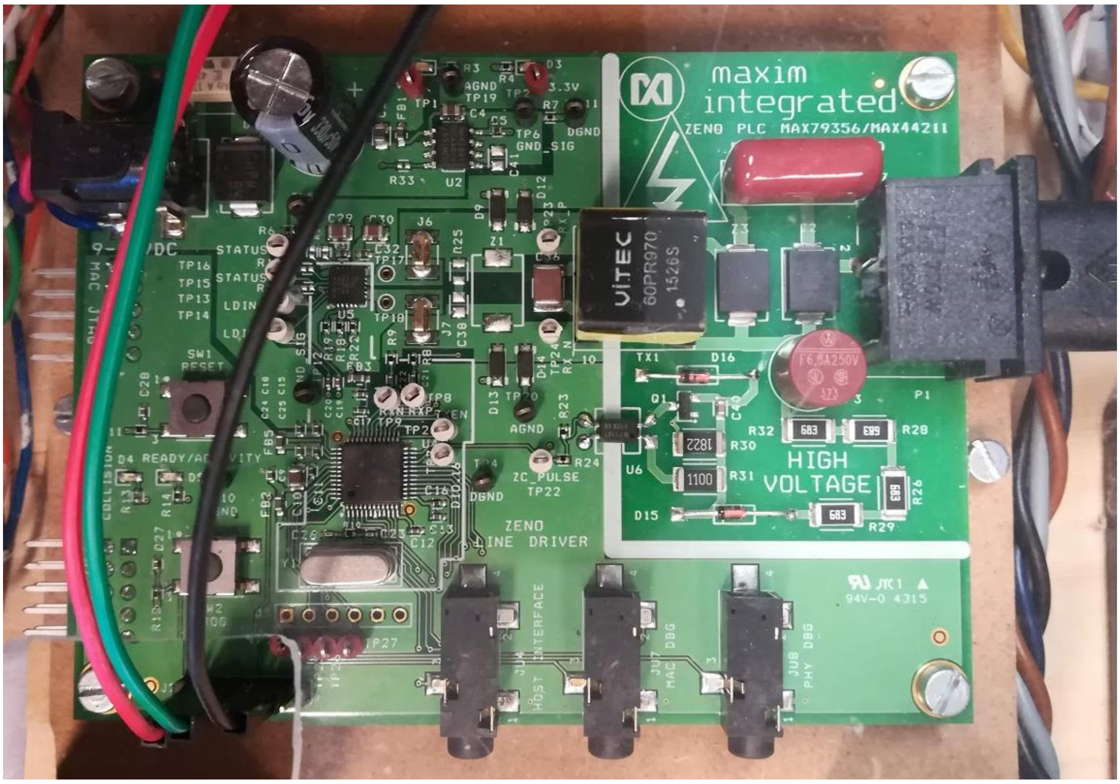

Fig. 28 MAX79356 Evaluation board

The transparent firmware consists of two firmware parts, one master firmware and one slave firmware. Both must be used to achieve a working setup. For this demonstrator this means that the PLC-modem in case 1 is equipped with the master firmware and the PLC-modem in case 2 with the slave firmware. This has the following consequences for our demonstrator;

- Main idea; The potentiometers in case 1 control the LED lights in case 2.
- the master can send messages to and receive messages from all the nodes on the low voltage network. Case 1 is equipped with the master firmware. In this case the potentiometers can be used to dim the LED lights in the second case.
- the slave can only send messages to the master node on the low voltage grid. Suitcase 2 is equipped with the slave firmware. Consequently, in this case only the LED lights will dim, if the potentiometers in case 1 are operated.

Specification of the transparent UART firmware;

Table 1: Specification UART firmware

UART baudrate	115 kbps with HW flowcontrol
Frequency band	320 – 487 kHz
Communication mode	Master send packets to all nodes Slaves send packets only to the master node
Modulation & Subbands	ROBO and all bands (Robust OFDM)
Security	AES-CCM encrypted

The Arduino MEGA, which is the microcontroller in the demonstrator, is programmed from Matlab Simulink. Two different simulink schemas were built. A program that controls the master PLC-modem (host master) and a program that controls the slave PLC-modem (host slave).

The block diagrams are shown in Fig. 29.

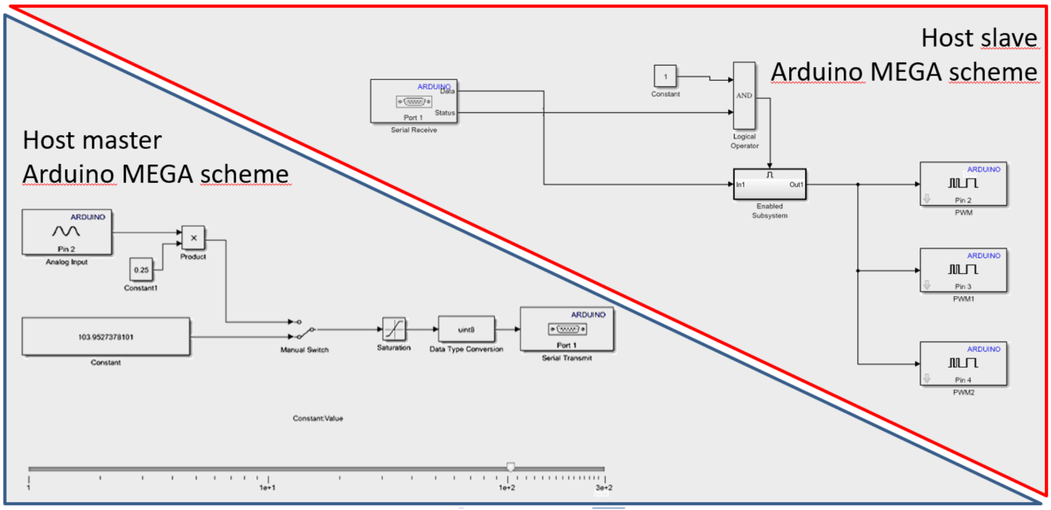

Fig. 29 Block diagrams - Simulink schemes

PLC modem: MAX79356

The MAX79356 is a programmable narrowband orthogonal frequency division multiplexing (OFDM)-based powerline communication (PLC) modem system-on-chip (SoC) device that provides standards compliant high performance and secured powerline communication. The two 32-bit RISC processors perform dedicated PHY signal processing functions and MAC layer functionality. Factory or infield firmware update feature allows adoption of changes and updates in PLC communication standards. The integrated high-speed AES-CCM[4] engine ensures standards compliant data communication security and integrity.

Measuring equipment

To make the electrical signal visible, different measuring equipment is used. The signal can be visualized in both time and frequency domain. The oscilloscope used to visualize the signal in the time domain is the Rohde&Schwarz RTE 1024. The measuring device for visualizing the signal in the frequency domain is the Tektronix real time spectrum analyzer RSA 306.

The probe used to measure the signal is a differential voltage probe from Pico-Technology. The signal is attenuated by a factor of 20 or 200 and then read on the oscilloscope or the real time spectrum analyzer.

Measuring results

In this section the measurement results are discussed. To get in touch with the PLC-modem the electrical signal is measured. A better understanding is obtained of the frequency bands, amplitudes, modulation techniques, etc....

[4] Cipher block chaining - message authentication code (CCM) mode is an authenticated encryption algorithm designed to provide both authentication and confidentiality during data transfer. The AES CCM supports three operations: key-stream generation, packet encryption, and packet decryption.

An oscilloscope image is shown below. On the horizontal axis, the time is displayed in seconds. A period of 4 seconds is displayed. The vertical axis shows the amplitude of the signal. The signal itself is displayed in yellow color.

The signal from the PLC modem is present every second. This is clearly shown in the figure. This is the result of the program in the Arduino MEGA. The program in the Arduino has a sample time of 1 second (Fig. 30). The consequence of this is that there is also only communication every second. The sample time can be adjusted depending on the needs of the application. This can vary between milliseconds, hours, days, weeks ...

When zooming in further, the above oscilloscope image is obtained. Here you can see that the communication is in two blocks. Further zooming in shows this even more clearly. This is shown in the oscilloscope image below.

It is clearly visible that the communication takes 30ms and consists of two blocks. The first block takes 20.1ms and the second 7.7ms. There is a pause of 2.2ms between block 1 and block 2.

The data handled in each block cannot be deciphered by the security applied.

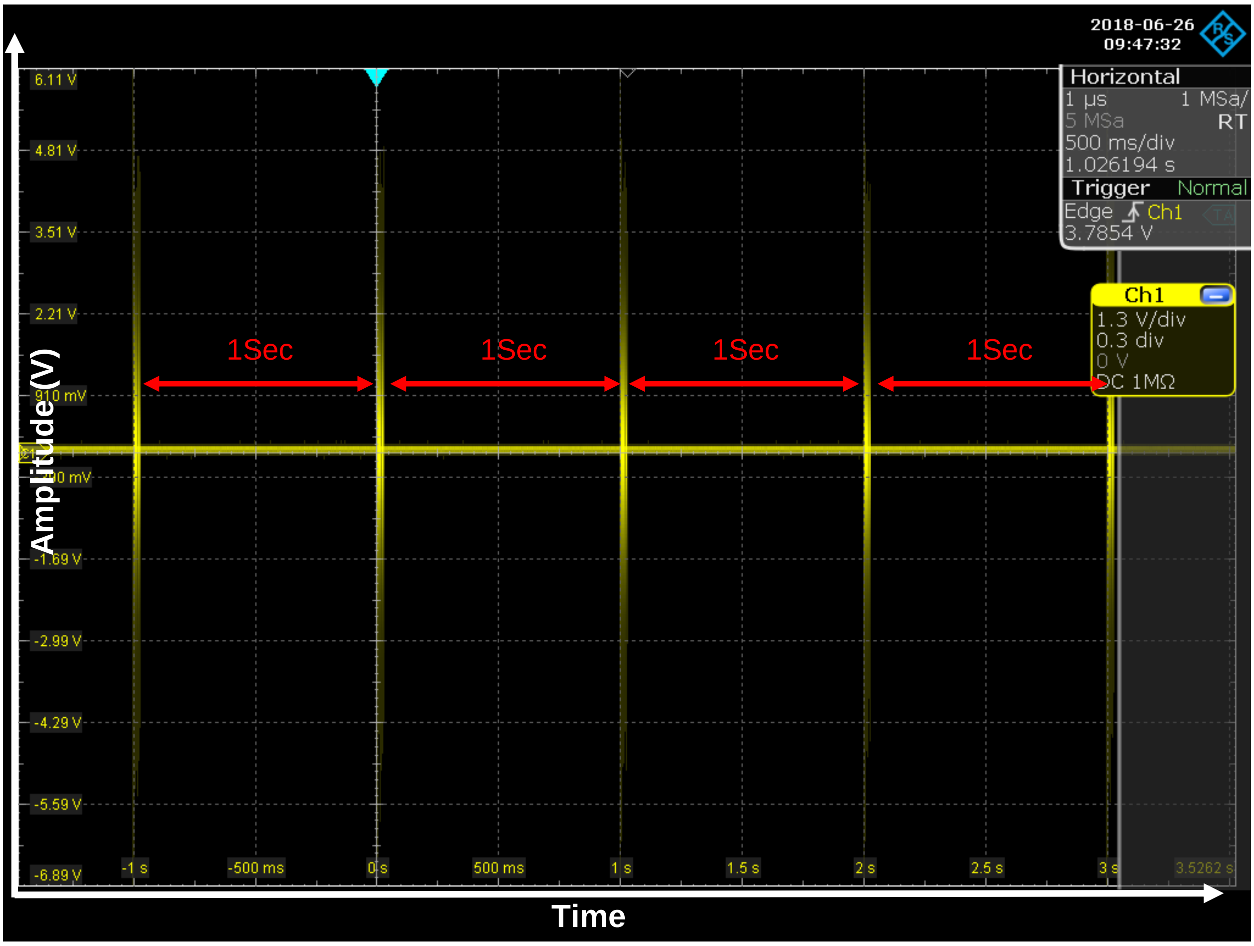

Fig. 30 PLC Communication per second

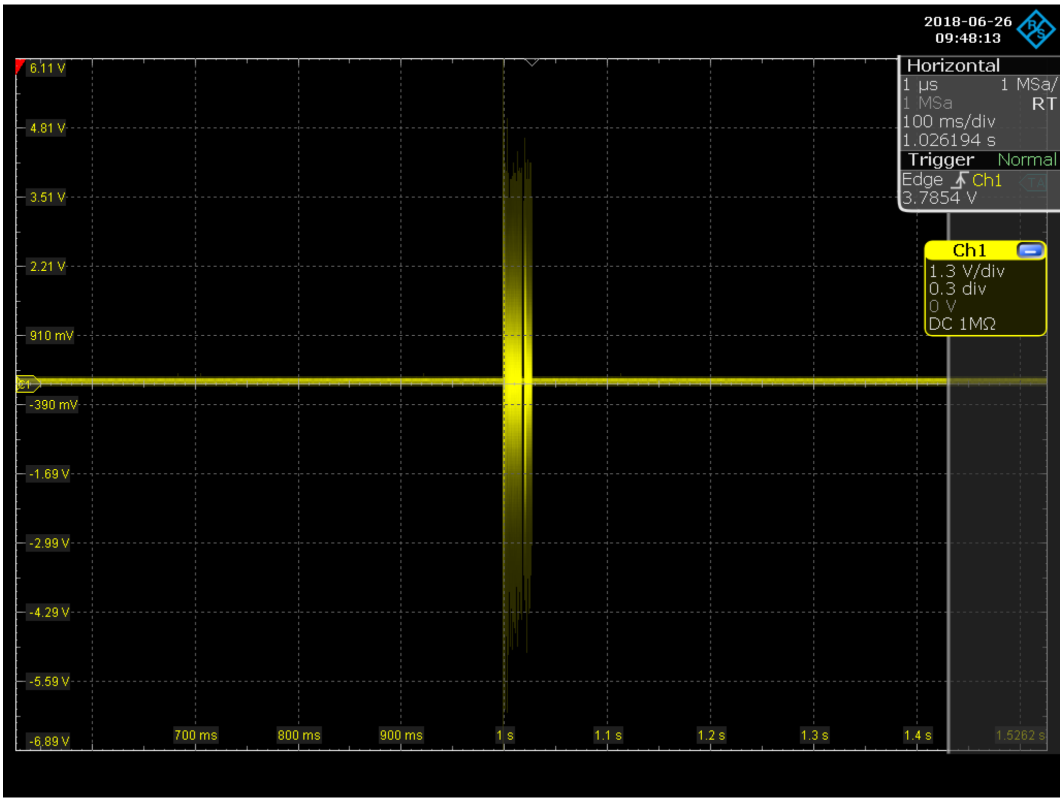

Fig. 31 Zoom on communication signal (2 sec)

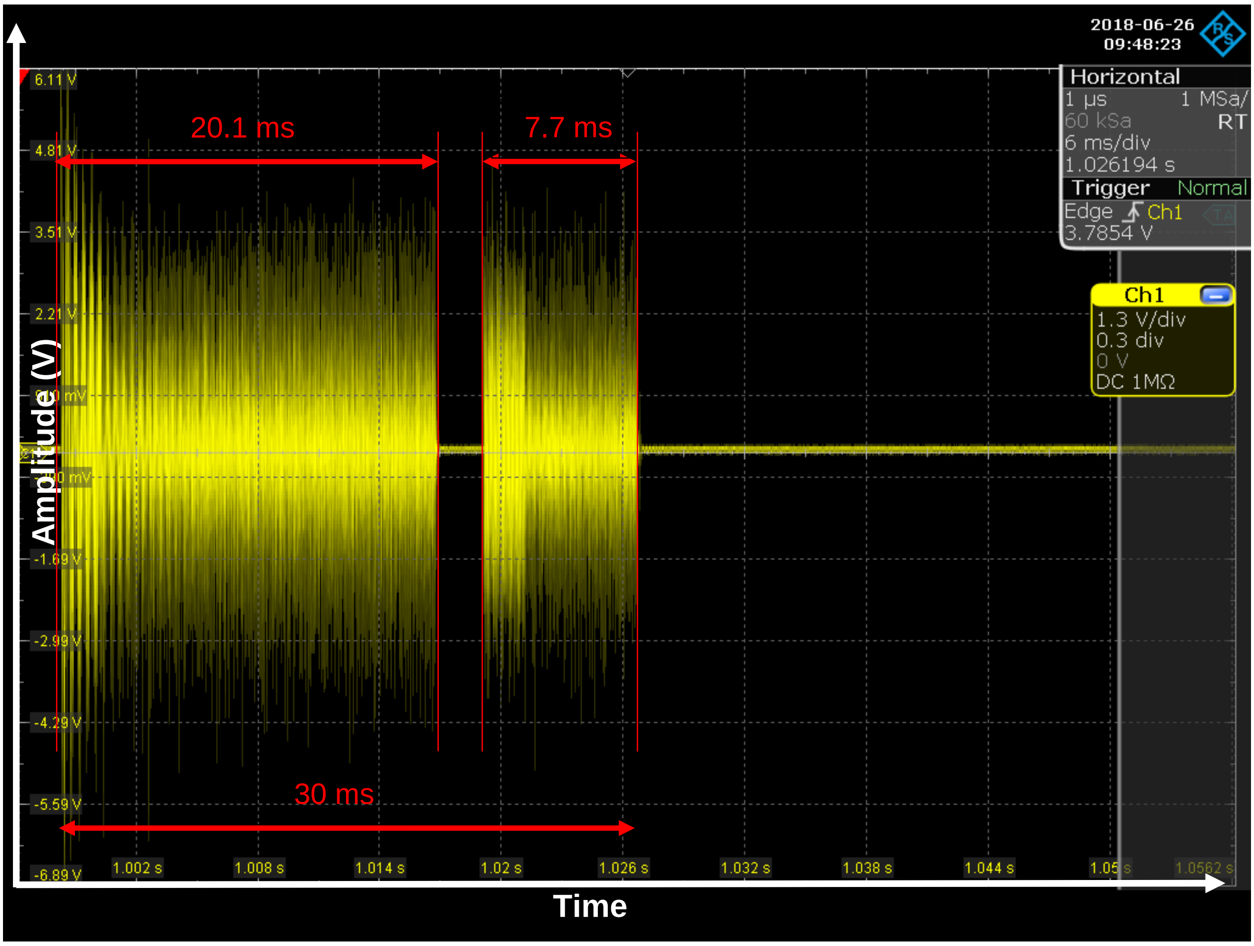

Fig. 32 Zoom on PLC communication (microseconds)

Then you can zoom in further to the area of microseconds (see Fig. 32). This makes it possible to look at the signal level. From the documentation it is known that phase shift keying is used as a modulation technique. This is also visible in the oscilloscope image, see Fig. 32**Error! Reference source not found.**. At some moments a phase shift of 180° is visible, resulting from a logical 0 to a logical 1 depending on the applied logic.

Fig. 34 **Error! Reference source not found.**is the measurement result of the RSA connected to the differential probe. The differential probe is electrically connected to the PLC modems. It is a cold wire setup. So there is no mains voltage present. The reason for this is to switch off external factors (present on the low-voltage grid).
A frequency band can clearly be found on the figures on which the PLC modems communicate. The frequency band ranges from 320 to 487 kHz with an amplitude of 80dBuV.

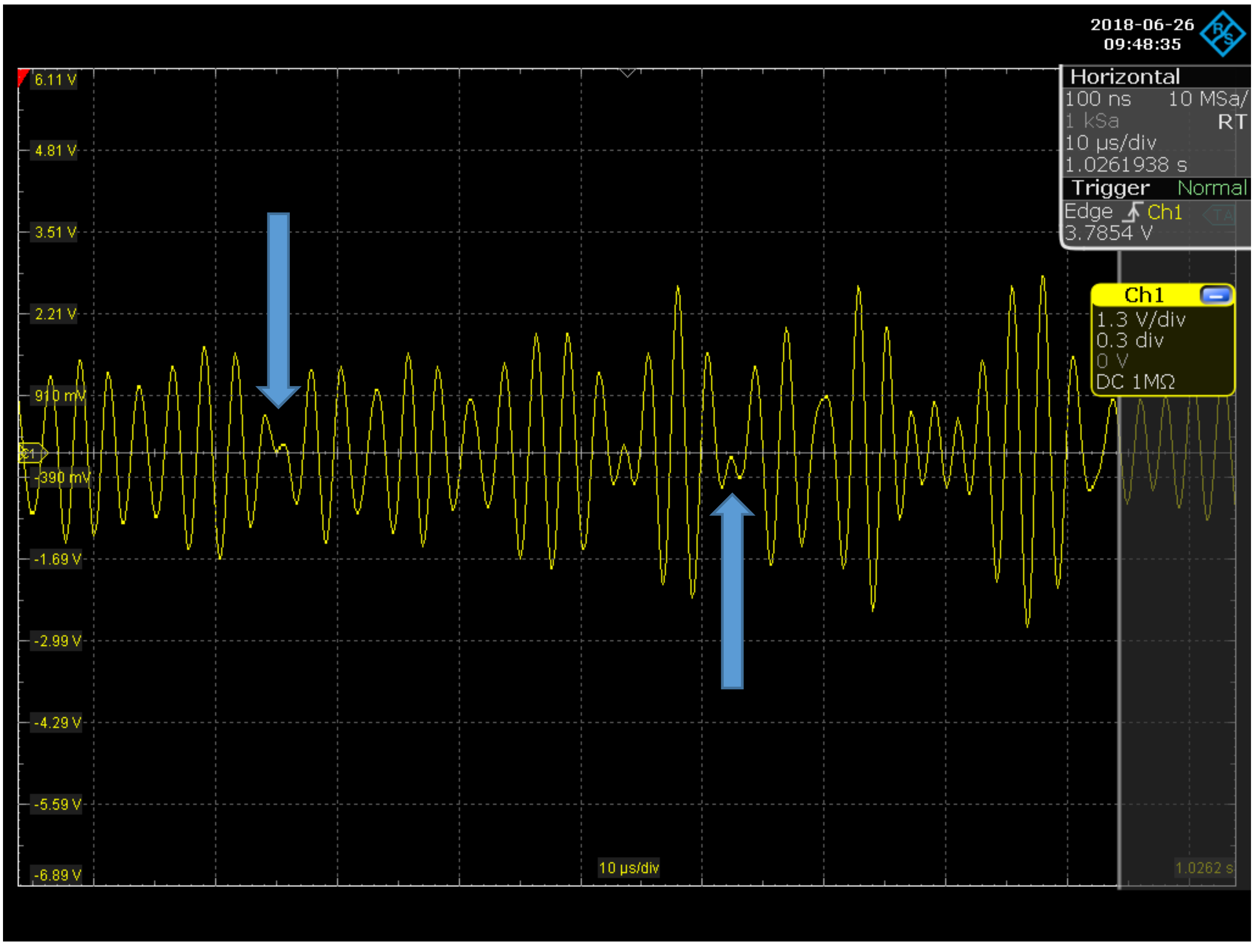

Fig. 33 Measured PSK

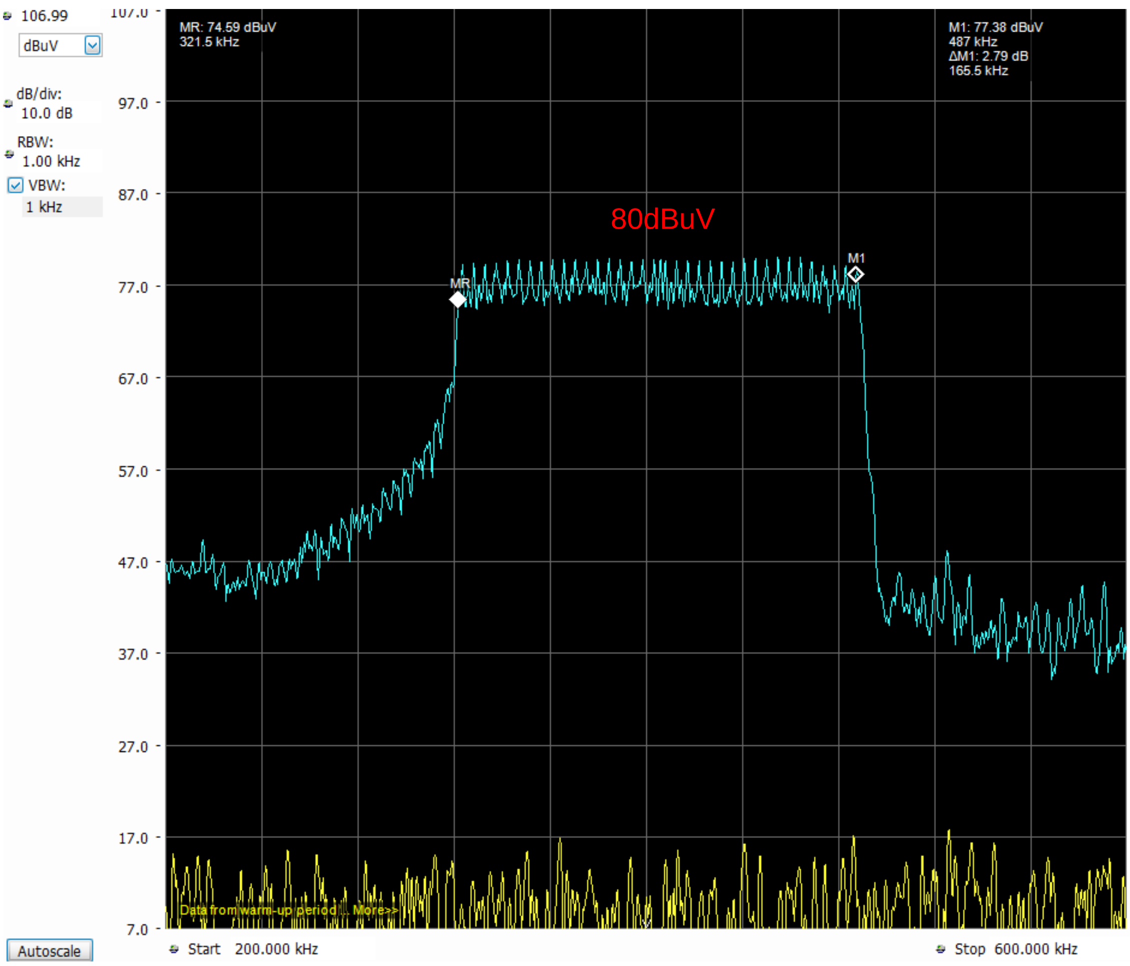

Fig. 34 Zoom on PLC communication (microseconds)

7. Solving problems

Solving HFPQ problems can be done in two ways. The first method is preventing emission. This is done by standardization. Emission standards in the range 2 – 150 kHz are still under construction. One of the main problems is to have accurate measurement methods.

The second method is curing the symptom by using filters or active compensation. For filters, few are currently available on the market, as there is currently no standard asking for limiting the emission. Another way is actively compensating the emission.

UGent developed a setup, where the harmonics are injected in counterphase. This is done by using two similar DCDC converters and switch them in counterphase.

The next figures show the current measurement of two DCDC converters connected to a battery. The peak current of each harmonic (10 kHz, 20 kHz, …) is measured at both DCDC converters and at the battery (last measurement). As can be seen, depending on the phase shift between the converters, the emission in the grid (battery) is heavily reduced. This shows the basic principle of active compensation.

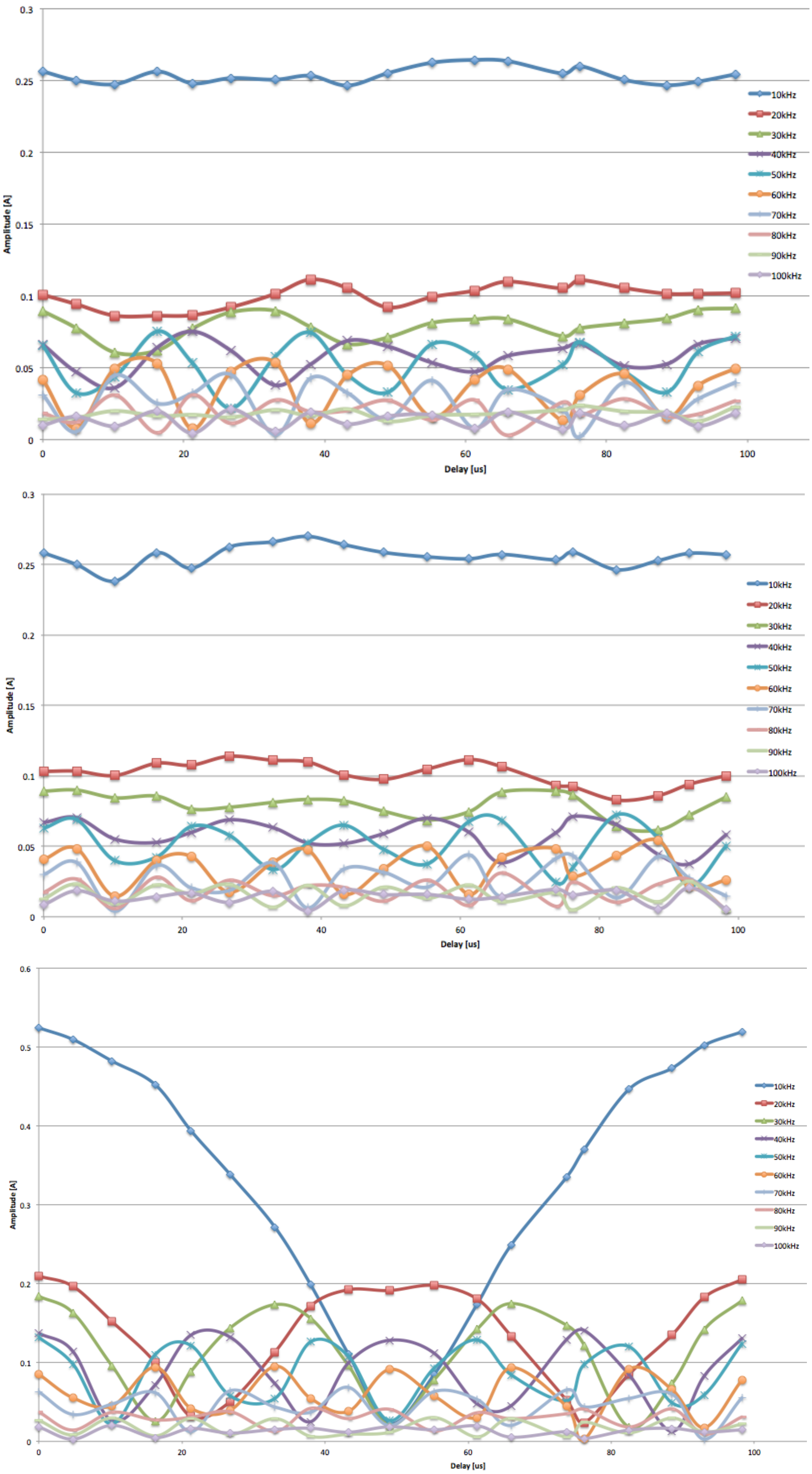

Fig. 35 Active compensation in DCDC converters

8. Feasibility and conclusion

Power line communication has evolved during the years. Where communication was difficult due to attenuation and disturbances, nowadays impedance matching and robust techniques for signal shaping are used. Nevertheless, also the environment evolved. Due to the increased use of power electronics and a lack of standards, power line communication still has difficulties to compete with other technologies.
In comparison to other technologies, PLC has its advantages, but a lot of disadvantages.

PLC can be used for several applications, but the question remains if it can compete with wireless technologies. The limited data rates, the hostile grid environment and the lack of standardization give problems. On the other hand, these are all technological limitations. An economical limitation is the price of the components. As conclusion it can be said that when wired solutions are used (ADSL, PLC, Ethernet), PLC has the benefit that the infrastructure is normally there without additional cost. In comparison to wireless solutions, PLC can be considered as more robust and secure once the system is working. However, practice shows that the latter is not always the case.