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Investigation Results on Electromagnetic Interference in the Frequency Range below 150 kHz

National foreword

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English Version

Investigation Results on Electromagnetic Interference in the Frequency Range below 150 kHz

Résultats des études réalisées sur le brouillage
électromagnétique dans la plage des fréquences inférieures
à 150 kHz

Untersuchungsergebnisse zu elektromagnetischen
Interferenzen im Frequenzbereich unter 150 kHz

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European foreword

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Introduction

In April 2010, SC 205A¹⁾ published its first Study Report on “Electromagnetic Interference between Electrical Equipment in the Frequency Range 2 to 150 kHz” [1], providing first results of investigations on electromagnetic interference (EMI) in this frequency range, due to Touch-dimmer lamps (TDLs) as an EMI victim, an inverter as an EMI source, and automated meter reading systems using powerline communication (AMR-PLC) figuring as EMI victims as well as sources.

With a second edition of this Study Report, in 2013 [2], the specific situation in the frequency range 2 kHz - 150 kHz and the broad relevance of recognised EMI for safeguarding electromagnetic compatibility (EMC) also in this frequency range was highlighted; that also with provision of results of measurements on the existing situation of emissions in the grid as well as with an overview of results of investigations on proven EMI cases. This 2nd edition of the Study Report has been published as CLC/TR 50627:2015 [3].

Based on a third edition of this Study Report [4], CLC/TR 50669 covers the same scope as CLC/TR 50627 but provides a comprehensive set of additional measurement results on electromagnetic interference in this frequency range.

It documents the existing disturbances on the electricity supply network, including customer premises. It covers both products acting as emission sources and those which are susceptible to such, including cumulative effects and the effect of ageing of components that are intended to suppress emissions. It also provides information on interference mechanisms and on the current situation with regard to standardisation. The TR is based on investigation results (measurement results, reported EMI cases) from twelve countries involving network operators, manufacturers, universities, accredited test houses and consultants.

¹⁾ CENELEC SC 205A "Mains communicating system"

1 Scope

Following to [1, 2, 3] having proceeded with the collection of related information, with this Technical Report, further extended information is provided including:

- the given EMC problems in the frequency range 2 kHz - 150 kHz, concerning EMC between electrical equipment in general as well as EMC between non-mains communicating equipment / systems (NCE) and mains communicating systems (MCS) as a particular issue
- the given situation of related emissions in the grid, with other measurement results
- EMI cases and related investigation results
- new findings on parameters to be considered when dealing with EMC in this frequency range, in particular related to
 - the impact of the network impedance and its variation over time on the more or less disturbing effect of emissions in this frequency range
 - the behaviour of emissions in this frequency range over time and the increasing need for performing also time domain measurements for comprehensively evaluating emissions and their disturbance potential
- the actual standardisation situation
- needs for the future, concerning
 - measurement of related emissions
 - investigation on the impedance of the grid / in installations over time
 - closing gaps in standardisation
 - installation guidelines and possibly regulatory measures related to the ageing effect.

In light of different positions on and in evaluating related EMC problems, with additional measurement results concerning emission levels in the supply network and results from investigations of additional proven EMI cases, the given problems are highlighted in more detail and recommendations for what to do in the future are provided.

2 General

As the results of investigations having been made for the Study Reports [1, 2, 3] show, utilisation of the frequency range 2 kHz – 150 kHz by electrical equipment shows several effects, which, compared with other frequency ranges, needs to be considered as a somehow specific situation; that resulting in the need for consideration of these effects when considering related EMC issues.

In the following, extended information about this specific situation and measurement and investigation results on related emissions and EMI cases are provided.

3 Specific situation in the frequency range 2 kHz – 150 kHz

Concerning the origin of disturbing interactions between electrical equipment using frequencies in the range 2 kHz – 150 kHz, there are to be considered

- Non-intentional emissions (NIE), being inherent to the operation of (power) electronic equipment / systems, increasingly being applied – from large inverters and uninterruptible power supplies (UPS) down to small voltage converters
- Signals from MCS, being the intended means for transmission of information over the mains in general. In Europe, MCS technology is chosen for automated meter reading systems (AMR-PLC) to a large extent.

Both types of emissions contribute to potential for causing disturbing effects to several types of electrical equipment. With regard to the increasing application of equipment using related technologies, increasing weight of the problem can be expected.

Sometimes, such emissions are also called “Supraharmonics”, this term obviously being intended to describe emissions on frequencies higher than those assigned to harmonics, i.e. multiples of the fundamental, usually defined up to 2 kHz or 2,5 kHz. While the term “harmonics” is connected with the fundamental of the supply voltage, for Europe 50 Hz, emissions in the frequency range 2 kHz – 150 kHz, as being considered in this TR, may have any frequency, without any relation to the fundamental.

From the disturbing effects’ point of view, the following types of equipment appearing as being susceptible to such EMI and having been involved in related EMI cases have been recognised

- NCE including solid-state meters (without communication)
- MCS, also for AMR-PLC systems.

Generally, when viewing at EMI in the frequency range 2 kHz – 150 kHz, the following combinations of equipment / systems need to be considered.

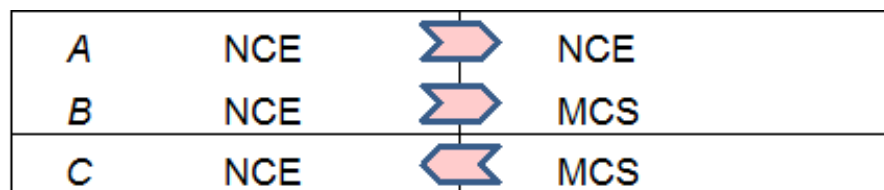


Figure 1 — Combinations of groups of equipment / systems to be considered related to EMI in the frequency range 2 kHz - 150 kHz

- | | |
|------------|---|
| NCE | General, non-mains communicating equipment / systems,
e.g. power supplies, inverters as an EMI source
telecom equipment, measuring part including power supply of a solid-state meters, TDLs as an EMI victim |
| MCS | Mains communicating systems
as applied e.g. for distribution system operators’ (DSO) AMR-PLC systems, home automation / domotic |

While case A relates to disturbing interactions between NCE (see e.g. 9.3.1.4), EMC problems in cases B and C are based on the parallel utilisation of the supply network by NCE on the one side and by MCS on the other side, around the same frequencies, i.e.

- NCE switching frequencies (and its multiples) and
- MCS signal frequencies (out of the standardised CENELEC band A).

It appears being necessary to get awareness of the need for a new, more complex view on phenomena in the supply voltage, concerning 2 kHz – 150 kHz, linked with

- NIE: Periodic occurrence of currents/voltages with spike shape at a certain switching frequency or at variable ones and its multiples,
 - stemming from NCE,
 - on frequencies between 2 kHz and some tens of kHz, not linked to the power frequency,
 its EMI effect being mainly dependent on the emission source and the impedance situation (source, grid).
- Signals from MCS: Discontinuous currents/voltages at information-dependent frequencies not being linked to the power frequency, in the frequency range 3 kHz - 95 kHz (148,5 kHz), with different signal durations – the EMI effect to other equipment being dependent on the time behaviour of emissions.
- Mixture of NIE and MCS signals: Parallel operation of NIE and MCS in supply areas where MCS are applied, with possible EMI between the both groups of equipment. The understanding of EMI requires to analyse signals in the frequency domain as well as in the time domain, what is not considered in measurement methods being standardised today (see Clause 7, Annexes B, C).

Starting with emission levels and immunity performance, EMC is always a result of coincidence of several technical factors. These factors appear as being wider spread for the frequency range 2 kHz – 150 kHz. Table 1 gives an exemplary overview of the different impact factors on EMC in this frequency range and its primary influence on the aforementioned groups of electrical equipment.

Table 1 — EMC factors and its relevance for EMI in the frequency range 2 kHz - 150 kHz

		EMC relevance for		EMI relevance for	
		NCE	MCS	NCE	MCS
		as a source		as a victim	
Equipment design	Emission				
	Level				
	frequency / frequencies				
	frequency volatility				
	time behaviour				
	Immunity				
	level in general				
	level due to specific characteristics of victim				
	Load impedances				
	Rated value				
	Volatility in equipment application				
Mains design	Network / installation impedance				

As the table shows, impedances represent a major impact factor on EMC in the considered frequency range – on equipment side as well as on supply network side, thus influencing the effect of emissions in the range 2 kHz - 150 kHz in terms of

- attenuation of emissions
- frequency-dependent effect of the impedance of the grid / the installation and individual devices.

(see also Clause 5, item 6.3).

It is recommended to further investigate this effect, in particular

- the process leading to a remarkable reduction of the impedance
- the effect of mitigation measures for reducing emission levels' effects on the impedance
- related to the appropriateness of avoiding measures resulting in an inappropriate reduction of the impedance, what should give rise to consider the definition of a related mask.

The above-mentioned relevance of the recognised EMC problem for several types of electrical equipment as well as the increase EMI origins in the frequency range below 150 kHz gives rise to considering the issue as being of broader importance, featuring with effects like

- degradation of performance / malfunction, including the display of wrong meter register values in case of solid-state meters
- loss of function
- hidden effects like ageing of electronic components and reduction of lifetime of equipment

see also Table 1.

4 Dimension of the EMC problem & Environment

As shown in Figure 1, one part of the problem relates to EMI between NCE, thus without any involvement of MCS and representing a problem, which relates to electrical equipment worldwide. On the other side, EMI between NCE and MCS are to be considered, whose occurrence can be seen as limited to areas, where MCS operating in the frequency range 3 kHz – 148,5 kHz (CENELEC bands A – D) are applied, what is the case for Europe, but not only.

Therefore, measures to ensure EMC in the frequency range 2 kHz – 150 kHz need to be taken

- a) for the general case A: to consider an appropriately limited emission from as well as an appropriately high immunity of NCE,
- b) for the regionally limited cases B and C, a solution which ensures co-existence between NCE and MCS

For the specific case b), with the previous editions of this Study Report, some overview of

- frequency utilisation by MCS
- applications and tasks for MCS
- deployment of MCS, where, in Europe, in the huge majority of cases, for the communication between meter and data concentrator an MCS is chosen.

has already been given, in particular related to AMR-PLC for the smart grid for electricity supply [1]²⁾, [2]³⁾. The EU set out energy and environmental policies to improve the energy efficiency by 2020: the Third Energy Package targets at 80 % of smart meter penetration by 2020 (see also item 10.2).

Many Member States established complementary national regulation and are paying close attention to the required deployment of smart metering systems (see e.g. [5]).

Figure 2 shows the typical architecture for smart metering systems [6].

²⁾ Study Report I, item 2.2.2

³⁾ Study Report II, items 2.2, 6.1.3

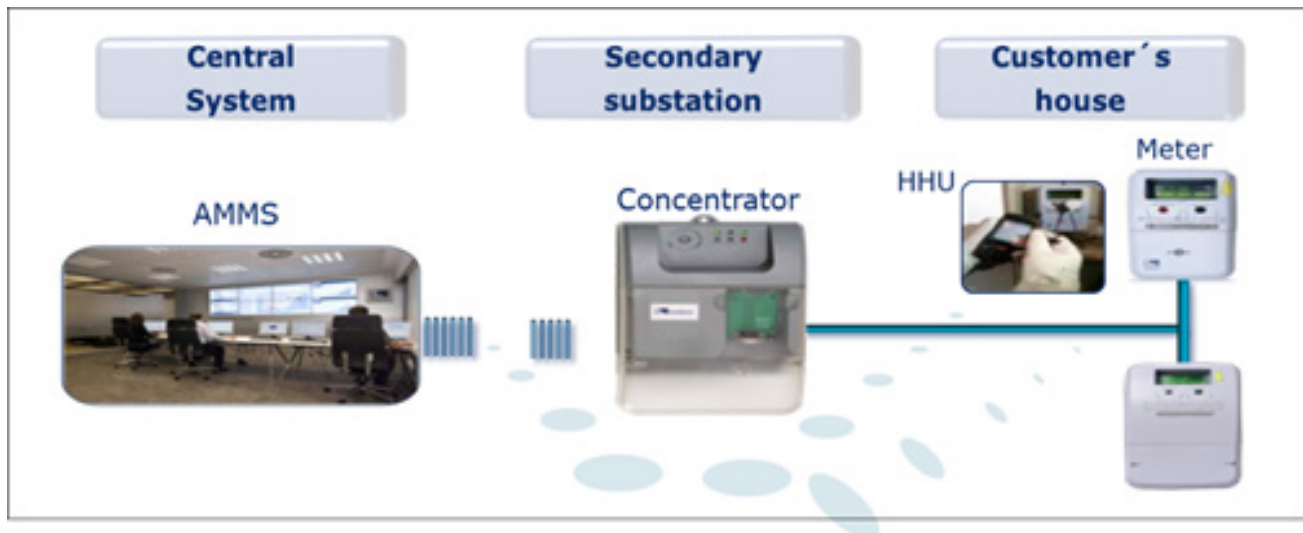


Figure 2 — Typical smart metering architecture

AMMS Automated Maintenance Management System

HHU Hand-held Unit

Further, multi-utility applications of powerline communication (PLC) technology are being pursued in Norway [7] and The Netherlands [8]. After having transferred the water and gas meter data via short range wireless communication from the related meters to the electricity meter, such systems would route the smart (electricity) meter's PLC to transmit all meter data to the head-end system, from which the data would be forwarded to the designated parties. That together with integrating signalling for home automating functions in the course of services offered by the one or the another utility to network users (Figure 3 [9]).

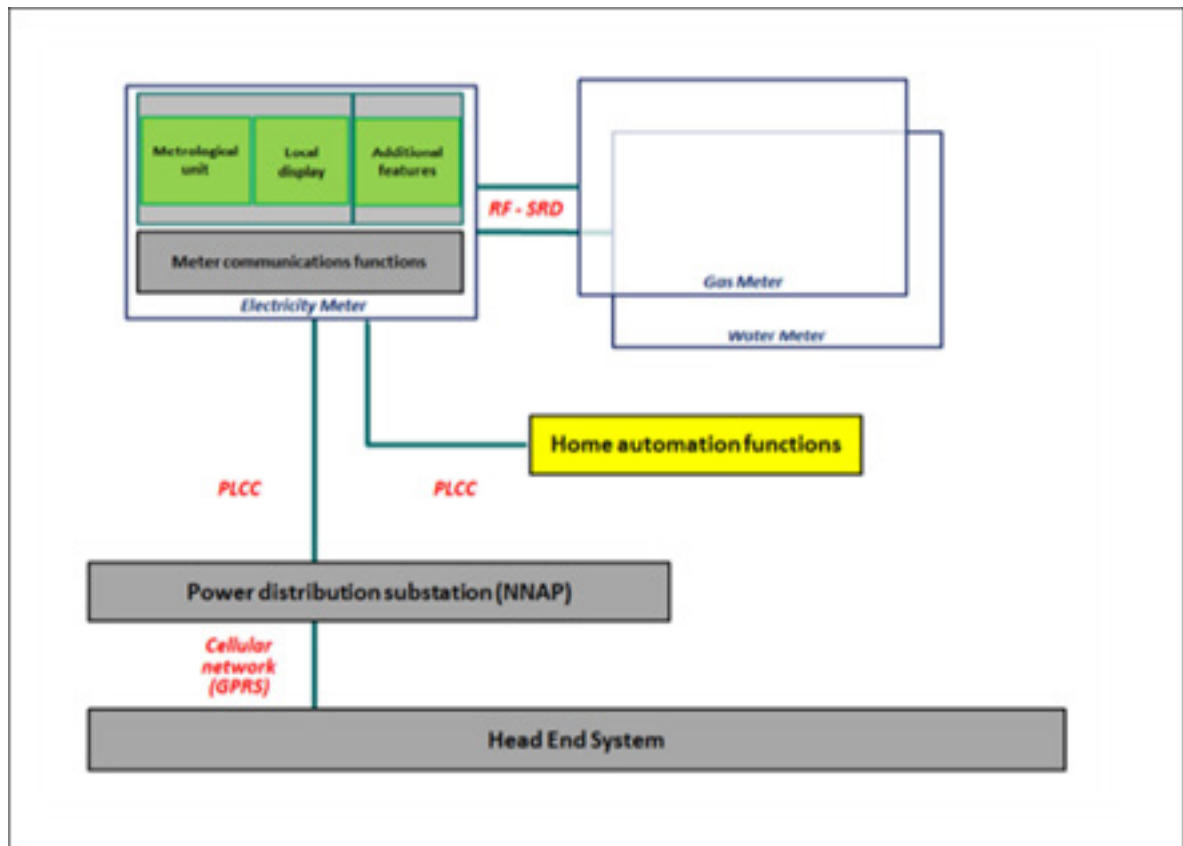


Figure 3 — Multi-utility application of PLC technology

Figure 4 gives an overview of the status of smart meter projects in Europe in 2014 [6, 10], where more than 50 M smart meters were already installed, in the huge majority of cases, an MCS being chosen for the communication between meter and data concentrator, that solution being even presented as the preferred communication technology by national regulators.

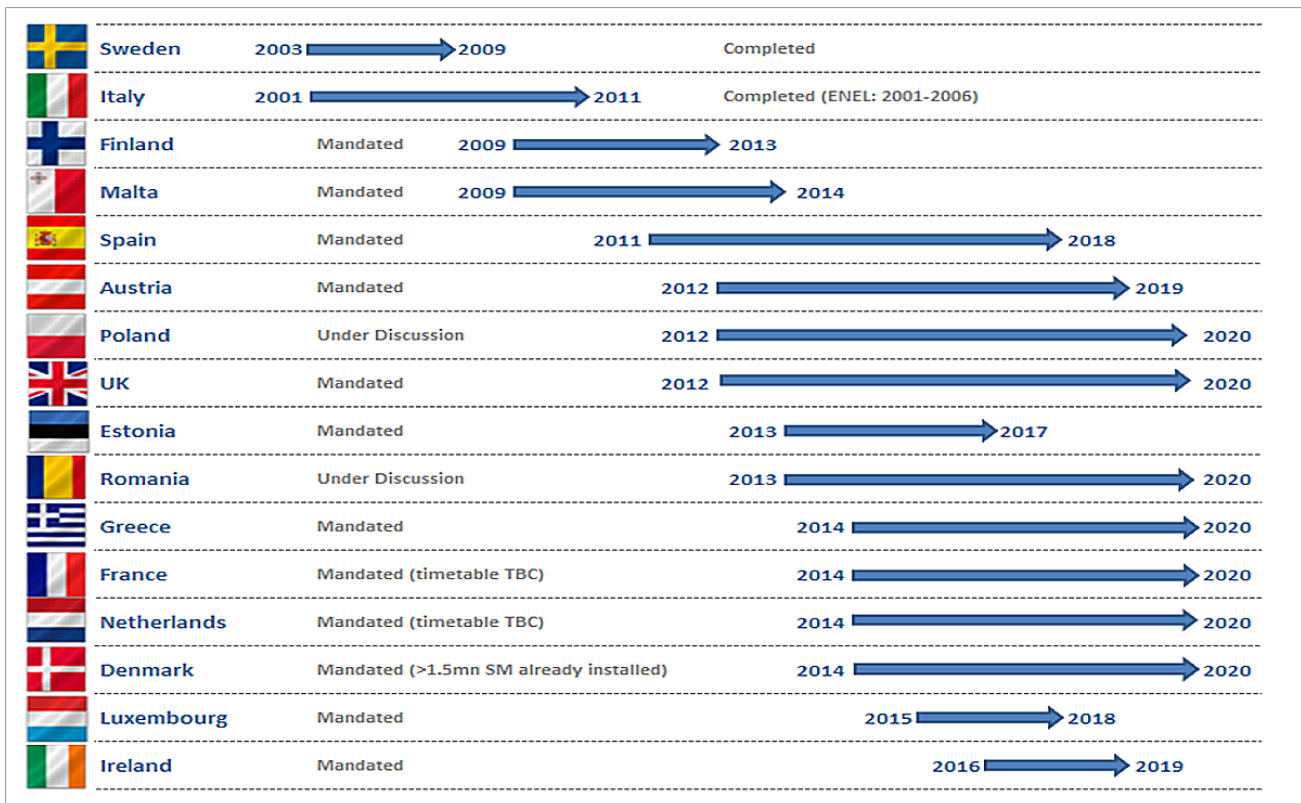


Figure 4 — Smart Meter rollout status in Europe [6, 10]

(Source: European Commission, DG ENER, 2014)

In two countries, Italy and Sweden, the rollout is completed, with ~ 0,6 M smart meters installed in Sweden and more than 35 M smart meters installed in Italy.

Altogether, with roll-outs in 19 Member States, smart meters are expected to be provided to around 72 % of European electricity consumers by 2020.

A report from the European Commission, released in June 2014 [11],

- measures progress on the deployment of smart meters across the EU, showing that Member States have committed to rolling out close to 200 M smart meters for electricity and 45 million for gas by 2020 at a total potential investment of € 45 billion. By 2020, it is expected that almost 72 % of European consumers will have a smart meter for electricity while 40 % will have one for gas.
- provides an overview of the results of cost-benefit analyses (CBA) concerning smart metering systems for electricity and gas in the EU.

An overview of the legal and regulatory framework for metering services and the smart metering landscape in Europe, which is strongly fostered by European policy makers, can be taken from [12].

Beyond that, as already mentioned in Study Report I [1], a number of related bigger AMR system rollouts have been started or are under way in Russia, North America, South Africa, Australia and Asia.

Table 2 provides information about major ongoing mass-roll-out projects of smart metering in Europe [6]:

Table 2 — Mass-roll-outs of smart metering in Europe (November 2014)

Country	DSO	Meters to be installed	Project scale	Meters installed
France	ERDF ⁴⁾	35 M	Pilot test and rollout	300.000
Italy	ENEL D. Muntenia	--	Pilot test	864
Italy	ENEL	32 M	Rollout completed	32.000.000
Portugal	EDP	0,1 M	Demo	30.000
Spain	Gas Natural Fenosa	4 M	Rollout	500.000
Spain	Hidrocantabrico	0,73 M	Rollout	150.000
Spain	Endesa	13 M	Rollout	3.500.000
Spain	Iberdrola	10 M	Rollout	3.800.000

When looking at disturbed equipment, in cases of EMI, careful consideration is advisable when talking about the (more or less) limited number of affected equipment; here, the sole consideration of percentages of the overall number of equipment being installed over a country, one continent or even worldwide may result into misleading, biased conclusions. That may be explained as follows:

EMI cases have been identified with different types of electrical equipment (NCE as well as MCS; see Tables 4, 5). Reports about lower numbers of such EMI cases may lead to considerations for the taking of general (standardisation) measures not being justified and for taking case-by-case solutions appearing as the preferable solution.

Apart from the solid-state meter case, which is sensible in terms of tarification, it is not the more or less limited number of reported EMI cases, in particular in terms of percentages of the overall installed numbers of equipment, which needs to be solely considered for evaluating the dimension of the problem, but the aspects of

- diversity of types of equipment, showing a broader spectrum of affected types
- the number of customers suffering from one of the aforementioned EMI effects – and possibly complaining; a quite higher number of EMI cases, not being recognised by network users as such but resulting in a quality loss in operating electrical equipment – at the time of interaction or, with some delay, in a reduction of lifetime, through ageing effects
- the efforts of DSOs, who are in most cases the primary instance for receiving related complaints, to analyse the related EMI cases and to find the underlying causes respectively the disturbance source
- taking measures for solving the single problem, e.g. replacing one element of equipment being involved in the EMI or a punctual mitigation measure, with consent by the affected customer and with an accepted solution concerning the bearing of related costs
- publicity effects when customers publicise related EMI problems they are suffering, referring to their purchase of good quality equipment (in Europe: with reference to the CE mark – not related to quality but to conformity with essential requirements of Directives),
- requirements on PLC for the considered smart metering application, in particular the required data exchange cycle time.

A specific case relates to EMI between NCE and MCS. Beyond cases of EMI caused by MCS to NCE (case B of Figure 1), which have been verified as being quite lower in number than vice versa,

⁴⁾ Used throughout the document according to the time of occurrence.
Enterprise renamed on from 31 May 2016 to „Enedis“

- values of 1 % (estimated rate of 1 % of the installed meters relevant for mitigation, from the Netherlands) to ~1 % to ~26 % (disturbed meter communication, numbers stemming from a survey covering the experiences from several Finnish distribution system operators (DSOs, [13]) have been reported [1, 14].
- values of some tens of percent up to 100 % of the smart meters of an AMR-PLC system assigned to a certain data concentrator have been reported from several countries to have lost communication with the system, thus being unreachable and therefore unreadable for the DSO for the duration of a disturbance [2, 3].

In the first case, the percentage numbers may be considered as quite small, but the effect to the DSO, whose operational means are affected in the order of magnitude of some 10.000 devices, may better highlight the dimension of the problem – economically as well as related to the effect opposite to the customers.

In the second case, the loss of functionality of significant parts of an AMR-PLC system may highlight the severe deterioration of the operation of such operational means for DSOs.

5 Situation of emission levels and EMI

As related investigations have shown, at present, NIE are occurring on the mains with levels of up to 160 dB μ V (~141 V) and even more, thus reaching and even significantly exceeding the standardised signal injection limits for MCS, 134 dB μ V (5 V) (see also [15, 16]).

As having been found when analysing different EMI cases as well as in laboratory investigations,

- generally, EMC is not ensured when high emission levels, of whatever type, are affecting insufficiently immune electrical equipment
- concerning the parallel operation of power electronics equipment, with its (switching) frequencies (and its multiples) and signal frequencies (out of the standardised CENELEC band A), with contemporaneous operation of power electronics and MCS around the same frequencies, proper function of MCS cannot economically be ensured.

Whilst, referring to Figure 1,

- for case A, beyond more or less economic solutions with case-by-case mitigation, the problem might be solved by setting
 - appropriately low limits for NIE from NCE figuring as a potential EMI source;
 - appropriately high immunity requirements, which consider also – beyond levels – the specific EMI interaction mechanisms in the frequency range 2 kHz - 150 kHz,
- for case C sufficient consideration of standardised signal level limits for MCS at design of NCE is needed,
- case B appears as not being solvable by the sole setting of levels; that with regard to the recognised need for a remarkable SNR between MCS signals and NIE. For the related test conditions, lab investigations at ERDF, on the performance of two particular implementations (G3-PLC technology – see ITU-T G.9903 [17] and ITU-T G.9901 [18] – and ERDF's S-FSK PLC technology – based on EN 61334-5-1 [19]) resulted in the recognition, that for proper MCS function a margin of
 - (at least) 45 dB to 50 dB for the frequency range 9 kHz – 95 kHz respectively
 - (at least) 52 dB to 56 dB for the frequency range 95 kHz – 148,5 kHz

seems to be required (Figure 5), that in particular when considering the attenuation of signals along the mains. Safeguarding such a margin is to be seen also together with economic constraints and for equipment design and manufacturing.

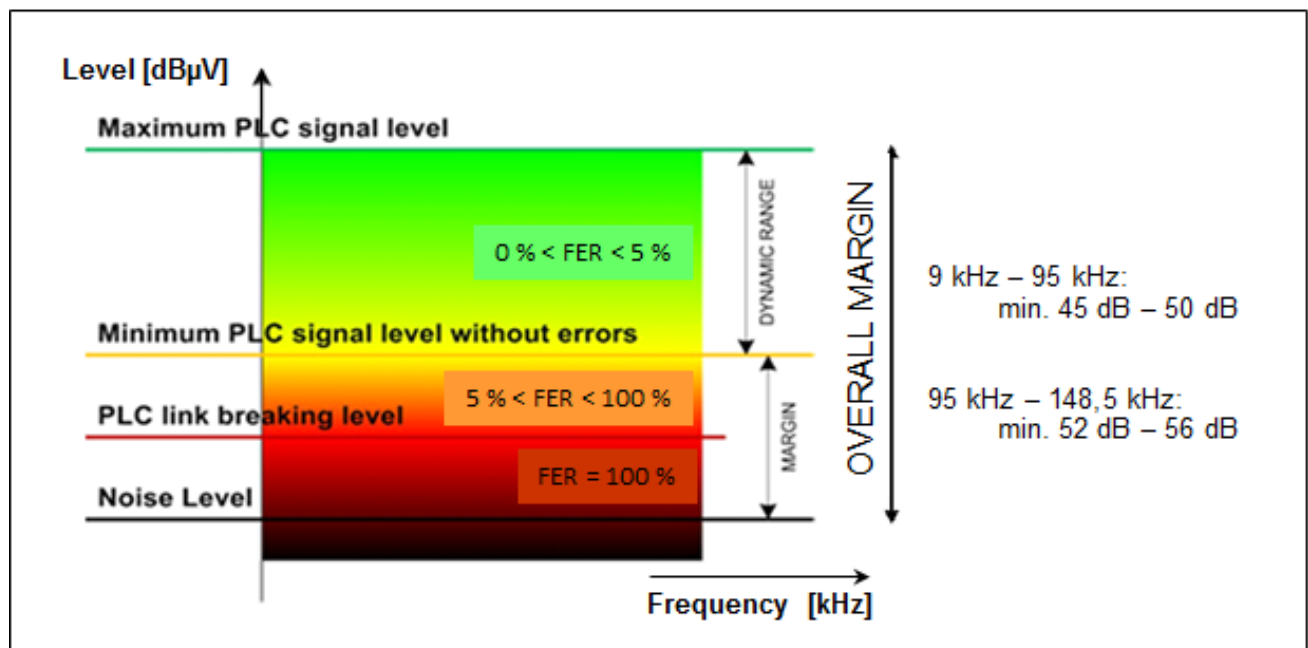


Figure 5 — MCS signal levels vs. NIE levels: Margin requirements for proper MCS function
with

“Maximum PLC signal level”: corresponding to the maximum output level of the transmitter.

“Minimum PLC signal level without errors”: corresponding to the minimum level required by the receiver such as no communication errors occur ($0\% < \text{FER} < 5\%$) for a given noise level.

“PLC link breaking level”: corresponding to the signal level at the receiver below which no PLC communication is possible ($\text{FER} = 100\%$) for a given noise level.

“Noise level”: corresponds to the measured noise level at the receiver

Furthermore, from the point of view of correct MCS operation, possible near-far-problems are to be considered, where a modem of an MCS is facing two components in the supply voltage

- a signal from its MCS, having been quite attenuated along the mains, i.e. with a level of e.g. $90 \text{ dB}\mu\text{V} - 30 \text{ dB}\mu\text{V}$
- an NIE from a nearby situated NCE, therefore having experienced quite low(er) attenuation along the mains

Beyond the issue of signal and disturbance levels and a related margin in between, when dealing with case B (Figure 1) problems, also the quite important impact of the impedances of connected equipment needs to be considered; that relating to

- the ever changing overall impedance value of all equipment/systems connected to a certain supply area/installation and its effect to MCS, that including,
- the impedance behaviour of possible measures for mitigating disturbances to signals from MCS
- the attenuation of MCS signals along the mains, through the resulting network impedance, is to be estimated between 40 dB and 100 dB – typically 60 dB –, thus resulting in accordingly lower signal levels at a certain point in the supply network compared with the signal injection level, which is limited by IEC 61000-3-8 [20] / 61334-3-1 [21] and CENELEC EN 50065-1 [22] over the frequencies in $2 \text{ kHz} - 150 \text{ kHz}$ respectively at signal frequencies of MCS in particular.

Finally, as new investigations with analysing emissions in time domain show, dependent on the characteristic of an NIE respectively a signal, as well as dependent on the parameters of the signal analysis, deviations from the measurement result in frequency domain with an order of magnitude of some tens of dB may be recognisable, thus indicating a higher disturbing effect of the analysed emissions than having been recognised from frequency domain measurement only.

Already in Study Report II [2] some overview has been given on main groups of EMI effects and examples for equipment figuring as EMI sources or victims as well as for effects of EMI to equipment in the frequency range 2 kHz – 150 kHz.

Considering additional information having been obtained during work on the 3rd Study Report [4], the related tables are completed as follows:

Table 3 — Main groups of EMI effects

(Non-intentional) Emissions from network users' equipment at or close to frequencies used for MCS interfere with intentional MCS signals, leading to disturbance or loss of MCS communication
Multiples of (non-intentional) emissions from network users' equipment, being close to frequencies applied for MCS may cause interference with the MCS resulting in failed communication
Distortion of the supply voltage due to discontinuous (non-intentional) currents/ voltages from network users' equipment or signal voltages from MCS may lead to degraded performance or maloperation of network users' equipment
Network users' equipment representing a low-impedance path at frequencies used for MCS lead to an attenuation of the intentional MCS signal which might disturb or interrupt communication ("shunting effect")
(Non-intentional) emissions from network users' equipment or (intentional) MCS signal voltages may result in somehow higher currents, leading to overheating and accelerated ageing of components in network users' equipment

Table 4 — Equipment figuring as a source of EMI, Examples

Inverters (e.g. photovoltaic infeed inverters, rectifiers) and variable speed drives (VSD) (e.g. in elevator drives, ski lift drives, heating system circulation pumps, air ventilation systems, household equipment)
Switched-mode power supplies, e.g. • PCs, faulty external power supplies of PCs • consumer electronic / home entertainment equipment (e.g. TVs, DVD players) • power supplies of TV antenna amplifiers, lighting devices with light emitting diodes (LED), • commercial equipment like punch-in clock, camera surveillance systems, • ICT equipment (e.g. fibre switches with built-in power supply, WLAN switches, 3G/4G base stations), • uninterruptible power supplies (UPS)), • charging devices (e.g. for electric vehicles (EV))
Lighting equipment (e.g. fluorescent lamps, compact lamps, LED lighting equipment)
Household equipment (e.g. induction cookers, washing machines, electric shavers)
Active filters
Portable mains operated tools
AMR-PLC

Table 5 — Equipment figuring as an EMI victim, Examples

AMR-PLC
Solid state meters
Electronic control, e.g. • touch-controlled equipment like Touch dimmer lamps (TDL), • alarm systems, • traffic control systems, • studio recording control units and mixing desks, • traffic lights, • in heating systems, • for street lighting, • in urinals, • for doors, • in kitchen appliances (e.g. steam irons, coffee machines, ceramic hobs)
Communication systems, e. g. • PABX, • Ethernet-systems, • ISDN-, ADSL-modems, • IP network branch exchange, • Routers, • LAN, • Home telephones
Telephone systems including inductive train radio systems
Earth leakage circuit breakers (ELB)
Contactless magnetic card readers, credit card terminals
Keyless entry systems
Notebooks (cursor position)
Broadcast standard time-signal systems (e.g. DCF77, Japanese system)
Road vehicle smart keys
TV and radio receivers
Mobile radio
Radio systems (Amateur radio, for railway control)

Table 6 provides information about different effects of EMI to certain equipment in the considered frequency range.

Table 6 — Effects of EMI to equipment in the frequency range 2 kHz - 150 kHz, Examples

TDLs	Unintentional switching (between light steps, OFF, also ON)
Street lighting	Unintentional switch-on and –off
Traffic lights	Malfunction
Traffic control system for public transportation buses	Malfunction
Solid state meters	Displaying wrong meter register values
MCS	Temporary or quasi-permanent loss of communication
Heat control with time basis through DCF77 signal	Malfunction
Radio system for railway control	Malfunction
Contactless magnetic card reader	Malfunction of reading function
Home telephone	Malfunction of ringing
Heating systems	Incorrect alarms due to sensor faults
ADSL modem	Loss of link, CRC error
Routers	Loss of synchronisation (40, 50 and 70 kHz) to the network
Notebooks	Disturbed cursor position (37 kHz)
Ceramic hobs	Incorrect relay switching
Coffee cooker	Incorrect control lamp function and malfunction
Professional hair-dryers	Switching ON/OFF spontaneously
Steam irons	Insufficient heat, water loss, incorrect control lamp blinking
Washing machines	Self-restart (some hours) after end of operation phase
Electronic ballasts	Audible noise
Induction cookers	Audible noise
PCs and Lamps	Audible noise
PABX	Audible noise
Telephone (analogue)	Audible noise
TV and radio receiver	Audible noise (up to 20 kHz)
Video telecom circuits	Audible noise
Inductive Train Radio System	Audible noise
Keyless entry systems	Malfunction
DC link capacitors in rectifier circuits	Thermal stress, Ageing, Lifetime reduction through larger HF currents
Increased emissions through dry-out electrolytic capacitors	Ageing, Lifetime reduction of other equipment
Automatic urinal water control	Switching to permanent operation
Broadcast standard time-signal systems	Electronic clocks: being fast (gaining up to 15 mins per day), Malfunction of control circuits fed by the time-signal
Amateur radio	Disturbed reception of distant transmitters

Tables 4 - 6 may need further amendments in future, following further investigations.

6 Specific EMC issues

6.1 General

EMC problems in the frequency range 2 kHz – 150 kHz have been and still are an item for extensive discussion in standardisation committees like IEC SC 77A WG8. This discussion can be divided into two basic options

- To strive for standardised emission limitation and immunity requirements, which together may ensure disturbance-free operation of electrical equipment.

As discussions show, setting of limits and requirements that way may cause high costs for equipment in general,

- possibly without being justified by the number of occurring EMI cases
- in the case of MCS being involved in related EMI connected with the question of relevance of the problem for areas with MCS application only.
- To agree upon less stringent emission limits and immunity requirements, leaving the solution of occurring EMI cases up to related mitigation measures to be taken.

This option leaves open questions concerning

- the appropriate choice of mitigation measures
- who would need to bear the costs for such measures

Of course, different parties, like manufacturers and appliers of different types of equipment which may interfere with each other, have different positions in terms of preference. It appears as quite difficult to evaluate the questions which of the two options would be the more appropriate in an objective manner. In any case it is appropriate to distinguish in related discussions between

- the general EMC matter, related to EMC between NCE
- the specific EMC matter, related to EMC between NCE and MCS

Concerning the latter, as also said in reports from TU Dresden (TUD) [23], it should be guaranteed, that NIE – as an example Battery electric vehicles (BEV) chargers are mentioned as originators – are lower than the intentional emissions from MCS in order to ensure its proper functionality. Analyses made by ERDF indicate an overall margin of around 50 dB between maximum PLC signal level and noise level to ensure proper MCS functionality (see Clause 5, Figure 5).

6.2 MCS robustness

Different MCS design results in different EMC behaviour of MCS, also related to immunity to emissions from NCE, i.e. disturbances.

The robustness is the ability of a system to function in an acceptable way in the presence of hazards. It is also the degree to which a system can function.

After investigating different types of EMI in the frequency band 2 kHz - 150 kHz, an ERDF paper introduces different techniques and methods that could be implemented at the chipset, meter and network level to improve the system's robustness at network level against potential noise and interference [24]. This paper also covers the propagation channel which is the principal contributor to many problems and limitations related to PLC.

As main components of EMI to MCS are figuring

- high noise levels
- (low) impedance
- influence of network situation between TX and RX of MCS over time. Here, the time depend-ability is to be distinguished between
 - change of attenuation over time, due to switch-on and –off of loads
 - periodic change of cumulative load impedance behaviour over time, within the 50-Hz-cycle
 - peaks of noise depending on the phase relations of components at different frequencies (possible MCS input circuit saturation due to such peaks) (see also Clause 7).

Concerning noise:

A noise is a bundle of electromagnetic interference of any kind and from any source, that usually does not carry information, and that may overlap with the main signal at any point in the transmission channel.

The robustness against noise is defined by the Signal-to-Noise Ratio (SNR).

Concerning impedance:

Dependent on the total impedance situation (supply network, loads (see item 6.3)), which is frequency- and time-dependent, signals from MCS are more or less attenuated. The resulting signal level at a certain network point is to be considered in relation to the local noise level.

The attenuation or loss is the decrease of the amplitude of a signal during its transmission. It is defined by ratio of the output magnitude over the input.

The robustness against attenuations is defined by a minimum threshold of reception at the receiver side in the absence of noise.

Options for improving the robustness of MCS are given

- at chipset and meter level
 - more complex signal modulation / demodulation
- at modem/Analogue Front End transceiver module, by improving the receiver sensitivity and filtering unwanted out-of-band emissions
- adaptation of reflection factor to the network impedance
- application of digital low-pass filters as a part of the digital signal processor (DSP)
- reception optimisation at DSP level with adaptation to the given noise conditions by applying appropriate statistical models
- at mains level
 - application of analogue filters/chokes behind the smart meter
 - Such installation can raise several questions:
 - Which party needs to pay the power consumption (DSO or client)?
 - Which party needs to pay for the filter (purchase, installation, maintenance)?

- Has the DSO the right to install a filter behind the smart meter?
- Does the DSO need to protect the filter?

Furthermore, Annex A provides a set of principles for field proven effective PLC systems with regard to MCS robustness, operating in CENELEC bands. Concerning the mentioned value for attenuation of signals on the public supply network, attention may be drawn to up until now limited knowledge on related values and the impedance behaviour over time (see also item 6.3)

6.3 The impedance behaviour

6.3.1 General

As highlighted in Clause 4 and item 6.3 (see also [25]), the impedance of the grid / the installation with the connected loads represents a major factor for EMC in the frequency range 2 kHz – 150 kHz.

The influence of impedances is well-known from the area around the fundamental frequency of the supply voltage; it is considered for setting of EMC requirements, that based on a probabilistic approach, with reference values for the network impedance at power frequency, in IEC/TR 60725 [26] and the proposed impedance for emission measurements between 2 kHz and 9 kHz, in the Informative Annex B to EN 61000-4-7:2002 [27].

For 2 kHz – 150 kHz, the impact of the impedance on the effect of emissions in this frequency range needs to be considered in a more detailed way, as it shows a quite more complex behaviour, based on a more systematic approach [25, 28]; that with regard to

- the higher frequencies and its effect to the impedances of the grid / installation as well as of the connected loads
- over the frequency range 2 kHz – 150 kHz
- over time
- the complex waveshapes being inherent from power electronics application as well as from MCS

and leading to the recognition of today, that for the considered frequency range, emissions' and their – possibly disturbing -- effect on electrical equipment increasingly needs, beyond frequency domain analysis, investigation in time domain.

6.3.2 Variable impedance characteristic and its possible effects

As an example, from an ongoing investigation, Figure 6 shows the network impedance in a certain public LV supply network during a period of the network frequency 50 Hz, in a spectrogram.

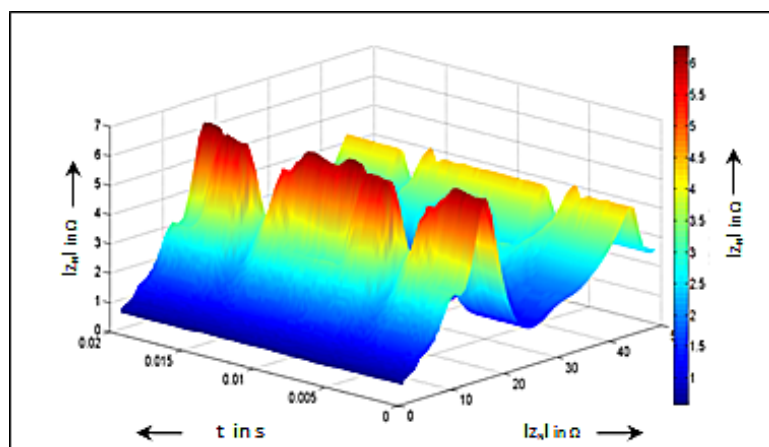


Figure 6 — Network impedance behaviour in 2 kHz – 150 kHz across one cycle of the 50 Hz-supply voltage

There can be recognised

- the change of impedance values during a cycle, at a certain frequency between 2 kHz and 150 kHz
- a somehow contrary tendency of the network impedance when proceeding in time when comparing higher and lower frequencies, i.e. that due to the lot of electronic equipment being connected to the network, the network impedance is at voltage maximum/minimum lower than around the zero crossings.

This behaviour of impedances in function of the frequency, in the supply network as well as in installations, represents an essential parameter for the propagation of emissions in the considered frequency range (see also [25, 29]) and its effects to electrical equipment, which will need to be considered at setting EMC requirements. In the light of —

- the increasing application of devices using inverters for their control, generating NIE in this frequency range,
- the effect of EMC filters applied for reduction of the levels of the aforementioned NIE and the contribution of these impedances, varying in function of the frequency, to the impedance of the supply network / installation
- the EMI potential of such devices including EMC filters to MCS with operating frequencies close to the switching frequency of a converter connected to the mains nearby, which may reach up to notching effects to the MCS communication
- the discussion of voltage distortion compatibility levels up to 150 kHz,

an improved knowledge and understanding of propagation mechanisms in the frequency range becomes more and more important. Unfortunately, related measurement results are limited up until now, so that more investigations appear as being needed.

6.3.3 Impedance values, measurement and calculation

Over all, the aforementioned need concerns

- a) the behaviour of impedance in the supply network as well as in installations as it may be expected, also for appropriately setting compatibility levels and, based on that, emission limits and immunity requirements; that together with appropriately chosen approaches for the loads connected to the mains, with consideration of the daytime aspect
- b) the measurement method for obtaining comparable results from related impedance measurements
- c) calculation methods for obtaining a quick overview of the impedance situation without measurement

From what is available up until now, as examples, the following investigation results may be mentioned:

Concerning: a) Grid/installation impedance values and EMI

appear to be a quite variable matter. Anticipating that it would be quite wrong to produce “THE” impedance or noise measurement of “THE” grid at 2 kHz - 150 kHz, that appears to require a statistical summary as being practiced for the 50-Hz reference impedance.

Nevertheless, as improved knowledge and understanding of propagation mechanisms in the frequency range 2 kHz – 150 kHz become increasingly important, it would be beneficial to collect; information about network/installation impedances referring to specific configurations and topologies (grid components, loads) and times.

Measurement values between 0,5 Ω and 50 Ω are known. It may be safe to expect the grid impedance amounting to values between 1 Ω and 30 Ω .

Compared with this range of impedance values, providing an example artificial network for measurements in the frequency ranges 9 kHz – 95 kHz and 95 kHz – 148,5 kHz, EN 50065-1 [22], referring to EN 55016-2-1 [30],

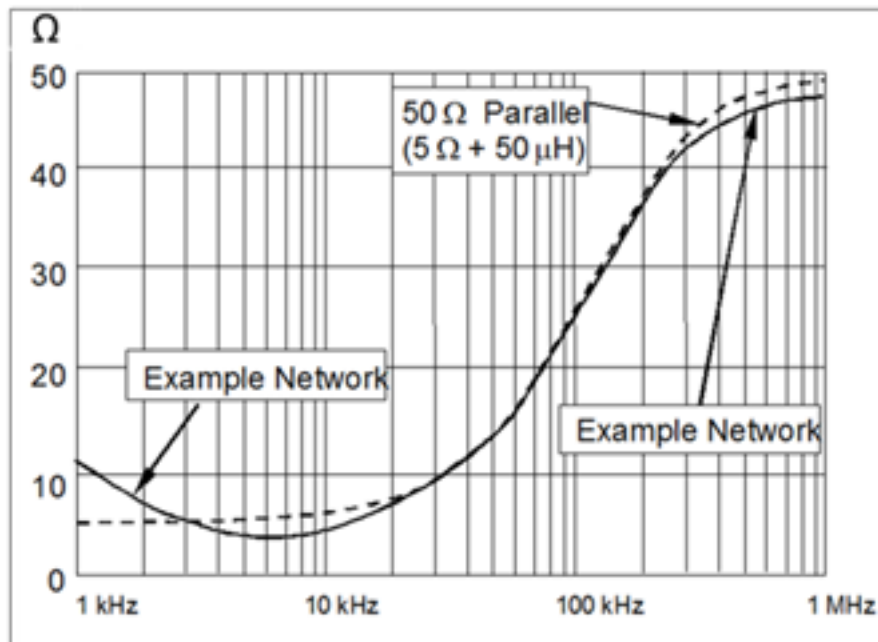


Figure 7 — Example of artificial network 9 kHz - 95 kHz and 95 kHz – 148,5 kHz (EN 50065-1, EN 55016-2-1)

indicates impedance values of $\sim 4 \Omega$ to $\sim 24 \Omega$ for the frequency range 9 kHz – 95 kHz and $\sim 24 \Omega$ to $\sim 34 \Omega$ for the frequency range 95 kHz – 148,5 kHz.

Irrespective of the recognised temporary variability of impedance values as mentioned above (see Figure 6), some measurement results have been provided e.g. with [31].

Figure 8 shows impedance values measured by Technical University of Dresden (TUD) in the LV network of the university, to be seen as a strong urban business area; in other networks, e.g. in the rural area, considerably higher impedances may occur.

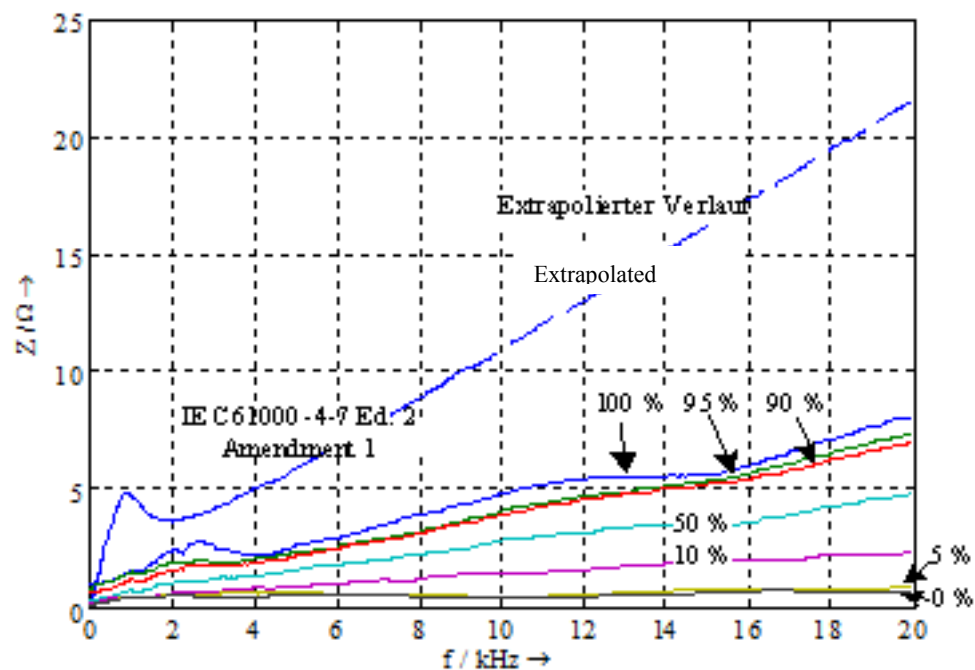


Figure 8 — Impedance values measured in the LV network of TUD

Furthermore, Figure 9 shows preliminary results of measurements of the impedance, performed with a network analyser, at concentrator level in two ERDF networks.

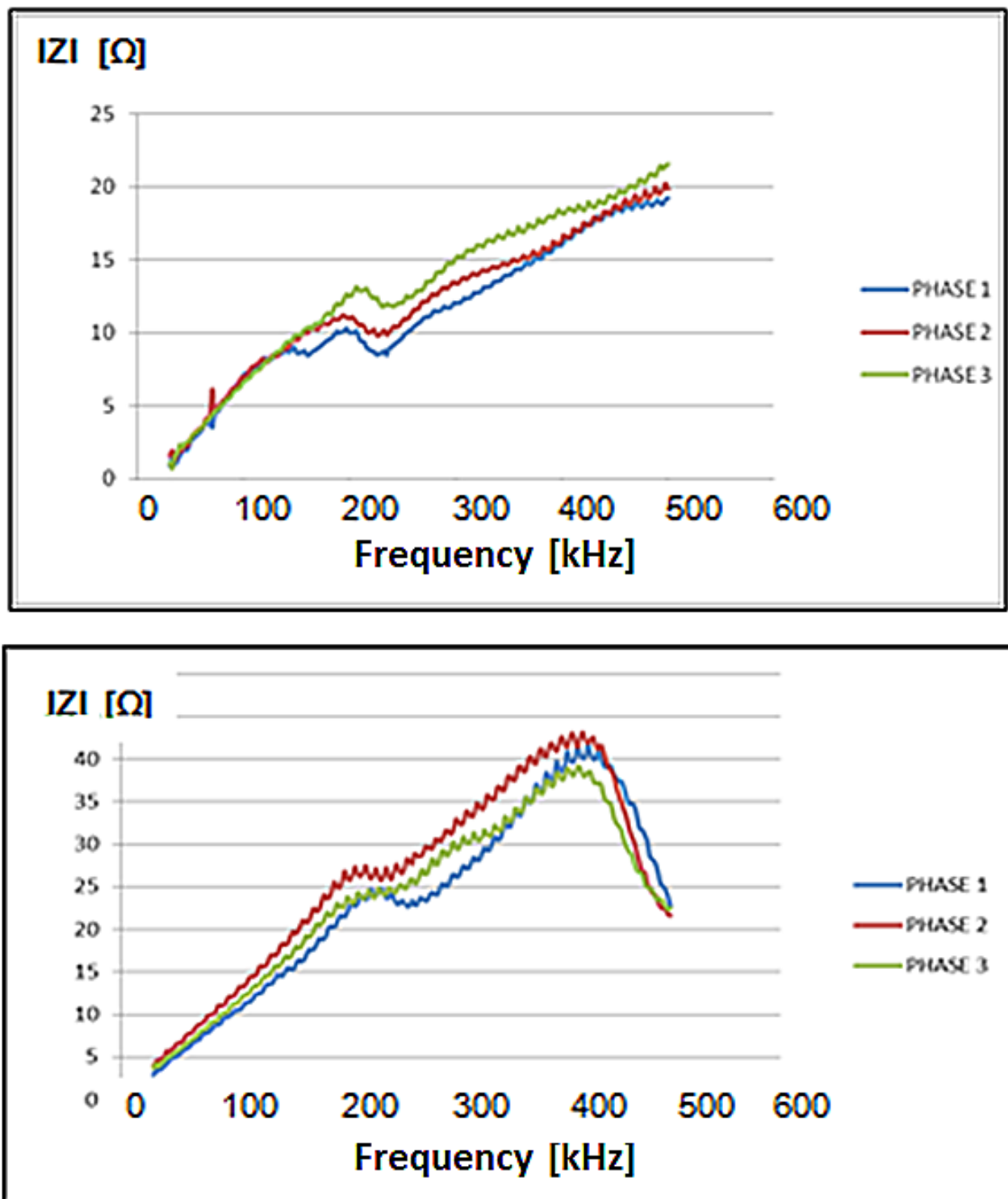


Figure 9 — Impedance values in ERDF LV networks
Preliminary measurement results

For the frequency range 30 kHz - 150 kHz these measurement results show

- typical impedance values from 1 Ω to 10 Ω (Figure 9, upper chart), but also values up to 40 Ω are observed (Figure 9, lower chart).

- a linear increase of the impedance with frequency
- almost the same impedance values on each phase

For these preliminary measurements, similar results are observed at meter level.

Maybe re-consideration of the impedance values for related measurement equipment towards possibly lower impedance values, for better mirroring the reality in supply networks / installations will be recommendable.

Concerning: b) Grid/Load impedance measurement

Beyond an overview of the PLC measurement procedure being practiced at Laborelec, providing information about different hard- and software aspects of such measurements together with related safety measures, a paper from Laborelec [32], having been provided to SC 205A for the purpose of this Technical Report provides also information about advanced calculations to visualise the characteristics of a grid or a load.

Clause 4 of this paper deals with

- measurements of the impedance of loads, based on the injection of a signal into the EUT and further calculation of the relation between voltage and current in function of the signal frequency
- the effect of the grid on different frequencies between 20 kHz and 120 kHz, based on the generation of a related frequency sweep and afterward calculation of the impedance using the injected current and the measured voltage, thus providing an impedance value

$$Z_x(f, t) = \frac{U_x(f, t)}{I_x(f, t)}$$

being valid for certain frequency values each and a certain location. In the calculation for the Impedance a division is made between the FFT of the voltage U_x and the current I_x .

This technique can also be used on loads like home appliances, resistances.

Sub-clauses 4.5.1 and 2 of this paper provide more information about treatment of the impedance measurements on

- high frequency resolution / low time resolution (Stationary Impedance) and
- low frequency resolution / high time resolution (Periodic Impedance)

With regard to

- “new power quality issues” as well as EMI between converters⁵⁾ and control signals transmitted over the supply lines (PLC) which we are facing due to increasing application of Active Infeed Converters (AIC), thus using the advantages in terms of cost, flexibility and efficiency,
- the dependence of the emission voltage at an In-plant Point of Coupling (IPC) at the frequency of the emission voltage,
- the complexity of the low-voltage distribution grid and in most cases the complete lack of knowledge of the line layout and of devices connected, regarding that expressing some reluctance in an appropriate calculation of the spectral impedance of a distribution grid section,
- the new dimension of complexity of EMC due to the increase of frequency ranges and of the density of electronic equipment connected to the same grid, leading to the need for a more systematic approach,

⁵⁾ The term “converter” here being used as an umbrella term for converters and inverters

- the recognition that none of the solutions for the measurement of the grid / installation impedance, having been proposed in the literature up until now [33 - 36] was covering the whole frequency range between 2 kHz and 150 kHz.

a Swiss paper [37] presents

- an “on-line” grid impedance meter designed for accurate and fast on-line measurement of the spectral impedance of low voltage distribution grids over the frequency range between 2 kHz and 150 kHz, having been developed within the IGOR project (Interferences Generated by Inverters On the Grid)
- as a useful application of grid impedance measurement over the considered frequency range, the analysis of interference between two photovoltaic (PV) inverters.

Concerning: b) & c) Measurement and calculation

Effects of power electronic devices including related EMC filters can be analysed based on the measured or calculated impedance situation in a certain grid area / installation.

In the following, as an example for results of related measurement on the one side and simulation on the other side, results of investigations [38] on the propagation of the sidebands of the operating frequency of a PV inverter at 16 kHz across a rural LV network, are provided.

In a first step, voltage distortion was measured at 4 different points in the network (MP 1 – 4, see Figure 10),



Figure 10 — Measurement of effects of a PV inverter

starting from the terminals of the inverter (MP1) up to the terminals of the incoming transformer (MP4), showing, that the max. voltage of the 16-kHz-sidebands of the PV inverter in percent of the inverter terminal voltage attenuated significantly over a distance of a few hundred meters (see Table 7, line 1).

Following simulation with a computer program with consideration of the frequency-dependent line parameters of the LV distribution network resulted in quite different values (see Table 7, line 2). Obviously, the network model used is not suitable for achieving reasonable results in this frequency range for the type of network considered. In order to improve the results, RFI (“Radio-Frequency Interference”) capacitors as being used in all electronic LV devices in order to fulfil radio-frequency emission standards and are typically connected line-to-neutral directly at the incoming point of the power supply, were introduced in a formal way into the network

model: For each household, at the connection point with the public network, one RFI capacitor of 1 μF was introduced per phase connected via a 5 m line, that representing around three electronic devices plugged in.

NOTE All capacitors were connected between line and neutral; on real products both neutral to ground and phase to ground ($\sim 22 \text{ nF}$) will also be found.

Further investigation showed, that introduction of two RFI capacitors per household resulted in simulation results with levels lower than what was measured in the field.

With this simple improvement in the model, the results according to line 4 of Table 7 were obtained:

Table 7 — Max. voltage of the 16-kHz-sidebands of a PV inverter in percent of the inverter terminal voltage — Results of measurement and of calculation

	MP 1	MP2	MP3	MP4
measurement	100%	19%	8%	6%
Simulation – distribution network	100%	91.8%	311%	306%
Simulation – with 1 RFI cap per phase	100%	24.8%	10.2%	9.0%
Simulation – with 2 RFI cap per phase	100%	15.1%	1.0%	1.1%

As can be seen,

- even without any detailed knowledge of the individual customers' loads, reasonable simulation results, in comparison with the measured values, were obtained
- the PV noise having been measured in a distance of 250 m of public network mixing overhead line and underground cable was measured with a highly attenuated value of 6 % of the initial injected signal
- unsatisfying results of a first network simulation, with regard to the real behaviour of the supply network, thus leading to some resonances when looking at the impedance characteristics, in theory could be changed to satisfying results when using a model with introduction of an RFI capacitor of 1 μF per phase connected via a 5 m line and household

Over all it can be recognised, that RFI capacitors (or maybe also the DC link capacitance of electronic devices without power factor correction (PFC)) have a significant impact on the propagation of emissions in the frequency range above 2 kHz; it may be noted that due to the application of different electronic equipment in every household the consideration of such capacitances seems to be justified for simulation purposes.

6.3.4 Summary

Up until now, the impedance characteristic of the supply network / installations together with the connected loads was not considered to a larger extent.

According to today's recognitions related to the frequency range 2 kHz – 150 kHz, there may be summarised:

- The impact of the impedance
 - in function of the frequency,
 - in the supply network as well as in installations,

represents an essential parameter for the propagation of emissions and, therefore, for their possibly disturbing effect to other electrical equipment

- Emissions and their – possibly disturbing -- effect on electrical equipment need to be considered in a more detailed way, as it shows a quite more complex behaviour, based on a more systematic approach. Amongst others, beyond frequency domain analysis, there appears to be an increasing need for investigations in time domain
- Several existing proposals for measurement of the impedance in the grid / installation do not cover the whole frequency range 2 kHz – 150 kHz.

Further investigations are needed concerning appropriate methods for finding information about the impedance reality in supply networks and installations as well as for defining measurement and calculation methods

- considering the specific situation in the frequency range 2 kHz – 150 kHz
- providing results being comparable with each other in general as well as between measurement in the lab and in situ
- Based on further investigations on the real impedance behaviour in 2 kHz – 150 kHz in the supply network / installations, a check of existing specifications for measurement equipment impedance towards possibly lower impedance values, for better mirroring the reality in supply networks / installations, may become recommendable.
- Results of further investigations will need to be considered at setting of EMC requirements respectively at maybe reviewing already standardised ones as far as available.

6.4 Long-term effects of EMI

6.4.1 General

In Study Report II ([2], item 4.3.2.3.10) a possible longer-term effect of emissions in the frequency range 2 kHz – 150 kHz when impacting electronic equipment was already highlighted.

There are two different types of problems to be considered

- Higher emissions in the frequency range 2 kHz – 150 kHz causing thermal stress to and following reduced lifetime of electronic equipment
- Occurrence of increased emission levels due to ageing of electronic components

the first problem having potential to affect in the way of the second-mentioned problem (see Figure 11).

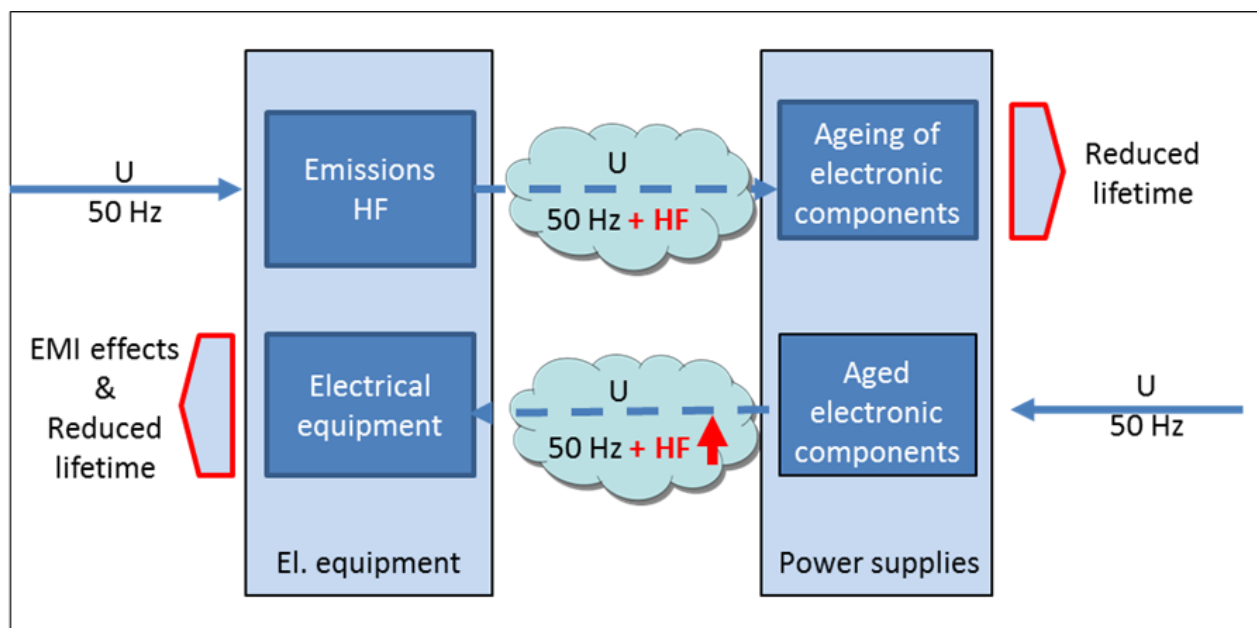


Figure 11 — Long-term EMI effects of EMI in 2 kHz - 150 kHz

6.4.2 Thermal impact on electronic components

TUD has carried out research on the systematic analysis of the impact of emissions in the frequency range 2 kHz – 150 kHz, in particular on the additional thermal stress on electronic mass-market equipment [39]. One central part of all commonly used rectifier circuits is the DC-link capacitor that provides the smoothed DC voltage to the internal circuit. In order to supply the DC-link, a rectifier circuit is used. Circuits without PFC and circuits based on capacitive voltage dividers represent the simplest and most sensitive designs. For both designs capacitors are directly connected to the grid during the recharging interval. Due to the low impedance at higher frequencies, already small HF voltages can cause significant additional currents flowing through the capacitor. As an example, Figure 12 presents a rectifier circuit without PFC, which is commonly used in compact fluorescent lamps (CFL) with rated power below 25 W. Comparing Figures 13 and 14, the additional HF component in the current flowing through the capacitor can be clearly seen in Figure 14.

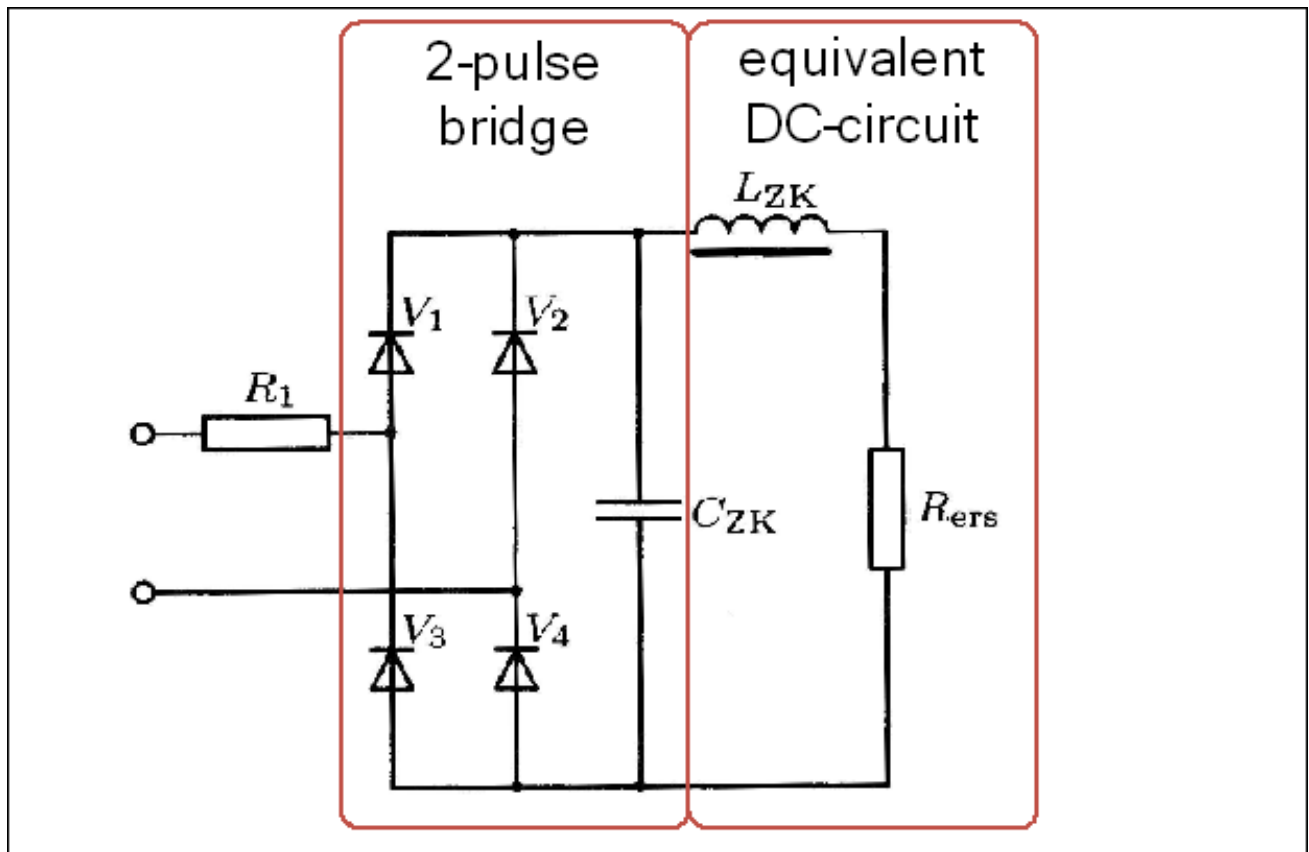


Figure 12 — Simplified schematic diagram of a CFL (11W) without PFC

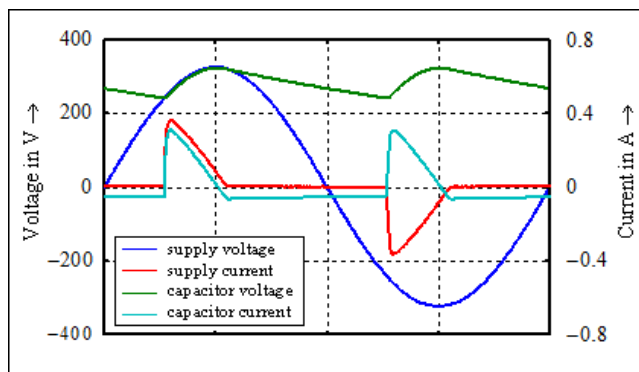


Figure 13 — Voltage and current measurement at 230 V (50 Hz)

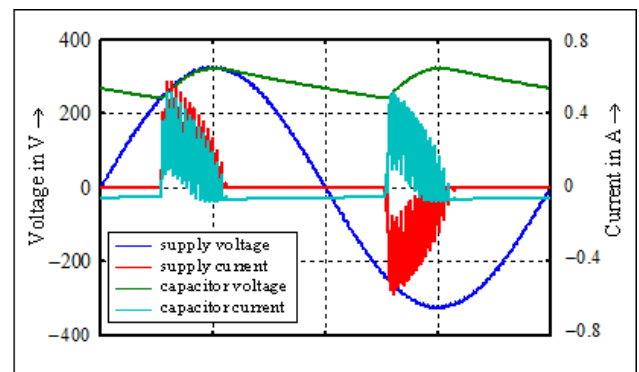


Figure 14 — Voltage and current measurement at 230 V (50 Hz) + 2,3V (5 kHz)

The analysis is based on measurements using different lamps with integrated electronic ballast as example (see also item 8.2.3). Two different types of CFL (one without PFC, one with active power factor (PF)) and one LED lamp were selected for a detailed study of the temperature behaviour inside the lamps. As an initial step a purely sinusoidal voltage with 230 V was applied and, after stabilisation, the temperature values were logged. In a second step a two-frequent voltage that consists of a fundamental component with 230 V and a HF component with variable magnitude up to 10 % of the fundamental voltage were applied.

As results, HF voltages can have a significant impact on the thermal stress and subsequently on the lifetime of electronic equipment, which contains rectifiers with electrolytic capacitors as DC link. The temperature increase at the DC-link capacitors of the equipment under tests (EUTs) amounts up to 1 Kelvin per percent HF component compared to the measurements with sinusoidal voltage, thus leading to temperatures measured at different points of the EUTs (CFL, LED) amounting up to ~ 74° C.

Due to the different mounting conditions and air streams at the ceiling, the temperature increase may be even higher under real conditions. Besides the additional heating, especially audible noise was observed for a lot of the analysed equipment. This can occur already at HF voltage levels of about 1 %.

The investigations were mainly, but not exclusively focused on the DC-link capacitor. In most cases not only the temperature of the DC link capacitor additionally increases due to the increased input current, but also other elements, like the rectifier diodes are affected.

It is most likely that this additional thermal stress increases the ageing and finally reduces the lifetime of electronic equipment. Many manufacturers are not yet aware of this problem, which would become more evident, if HF emission levels in the grid would increase in the future. Further studies are carried out to quantify this impact.

6.4.3 Increase of emissions due to ageing

On the other side, as pointed out in CLC/TR 50627 [3], ageing of electronic components in electric equipment can cause increased emissions in general and, following to that, result in EMI to other devices; that resulting in a status of electrical equipment not further meeting the essential requirements (ERs) of the EMC-Directive (EMCD), although having been so at the time of being placed on the market.

6.4.4 Summary

In related discussions some experts express the opinion, that these ageing problems were not an issue related to the EMCD [40].

In any case measures seem to be necessary for ensuring EMC and therefore conformity with the ERs of the EMCD also some time after being placed on the market.

Beyond the technical part of such measures, i.e. the application of technical mitigation measures, national legislation measures appear as a solution for easing to take enforcement action on interference from products after the action of 'placing on the market' and 'putting into service'. Related legislative measures to address situations outside the EMCD [40] and the Radio and Telecommunications Terminal Equipment (RTTE) Directive ([41]) are e.g. planned to be taken in the UK [43].

7 Measurement issues

7.1 General

An essential question for gaining measurement results on emissions in the frequency range 2 kHz – 150 kHz and evaluating /comparing the measured values is that one of the applied measurement method.

In general phenomena in the frequency range 2 kHz to 150 kHz can be analysed

- either in time domain (high-pass filtered momentary waveform)
- or in frequency domain (spectrum).

Both methods have their advantages and disadvantages. The choice of one of these methods as the one to be applied depends on the characteristic of the higher frequency content of the analysed signal; in many cases a combination of both analyses is beneficial.

As an example for time domain consideration, reference to the recognitions reported in Study Report I [1] related to EMI with TDLs may be made. In that case, from the spectrum the interference mechanism cannot be explained.

Graphical presentation in time-domain is usually a plot of the high-pass filtered momentary waveform of the signal (Figure 15a). For frequency domain most commonly a spectrum (Figure 15b) is used for graphical visualisation of a particular time instant. If in addition to frequency also the characteristic over time shall be included, a spectrogram (Figure 15c) is used.

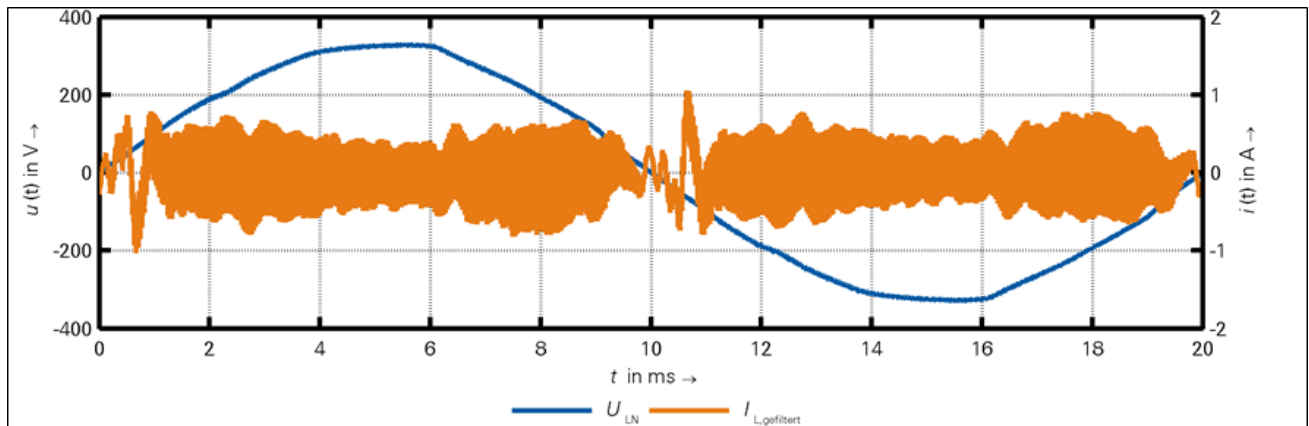


Figure 15a — Oscillogram of the filtered current

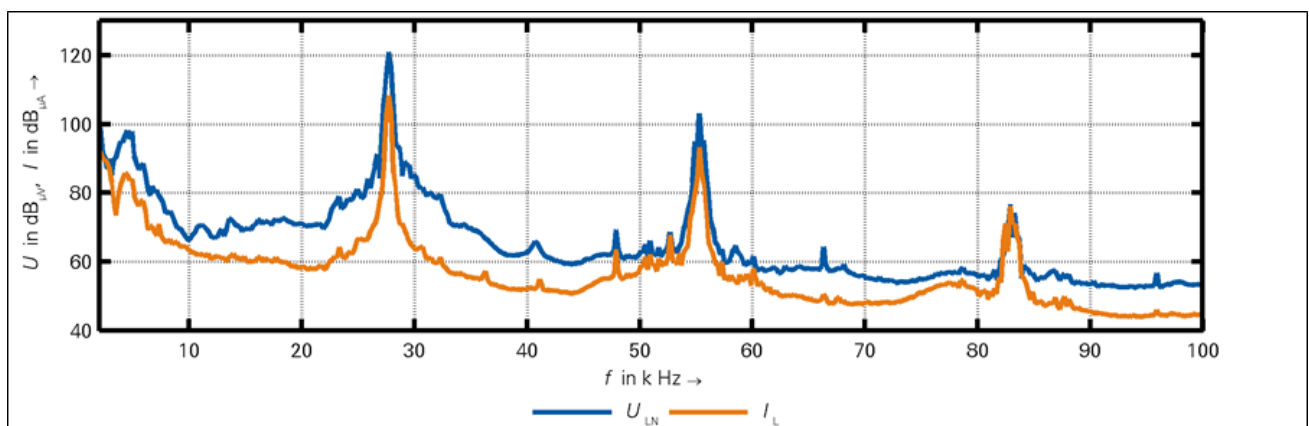


Figure 15b — Voltage and current spectrum

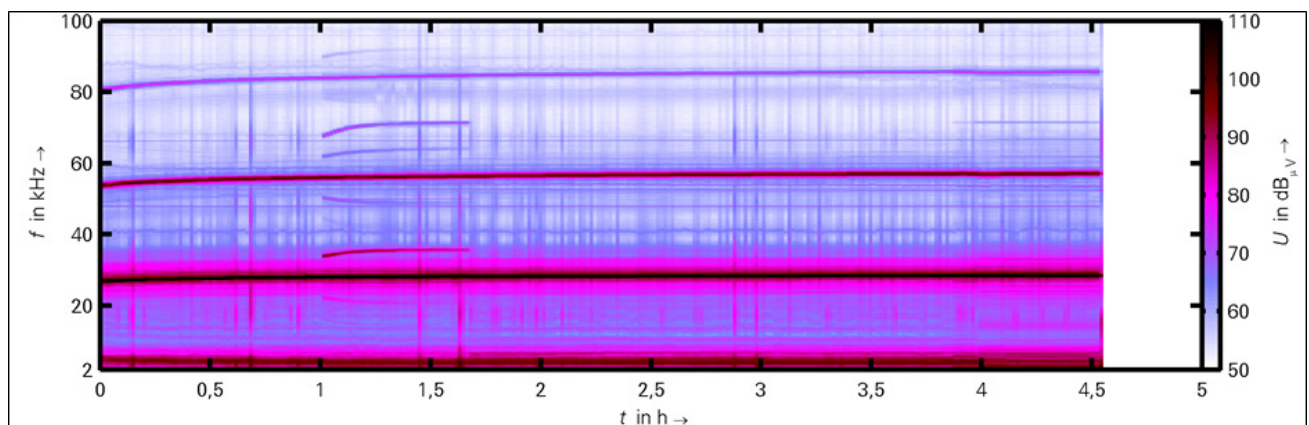


Figure 15c — Spectrogram of the voltage

Figure 15 — Different types of graphical presentation in time- and frequency domain (Example: EV charger)

For visualising the frequency characteristic within one fundamental cycle, the time resolution of the spectrogram needs to be increased (see Figure 31, item 8.2.3.2.2). Further details can be found in [44].

7.2 Status of standardisation

Up until now, discussions on EMI investigations as well as on the setting of compatibility levels in the frequency range 2 kHz – 150 kHz have mainly focused on frequency domain.

When looking at what is available as standardised measurement methods being applicable for – at least a part of -- the considered frequency range, there can be found EN 55016-2-1 [30], EN 61000-4-7 [27], EN 61000 4-30 Ed.3 [45] and EN 50065-1 [22].

EN 61000-4-19 [46] also covers the higher frequency range. However, it only specifies techniques of test equipment immunity to certain types of distortion. It does not require the user to perform measurements alongside the immunity tests and therefore does not contain or refer to any measurement methods.

Table 8 shows a list of standards recently available concerning measurement in the frequency range from 2 kHz to 150 kHz.

Table 8 — Comparison of today's standards regarding the frequency range from 2 kHz to 150 kHz

Standard	EN 61000-4-7:2002 (Annex B)	EN 61000-4-30:2015 (Annex C)	EN 55016-2-1	EN 50065-1
Purpose	Emission levels from equipment, in the grid	Levels in grid	Levels in grid and emission from equipment	Emission from equipment
Method	Discrete Fourier transform (DFT), 200-ms-interval, aggregation into 200-Hz-bands per 200 ms	DFT, 0.5-ms-intervals, aggregation into avg and max spectra per 10/12 cycles	Spectrum analyser with tunable filter and detector (peak/ quasipeak/ rms)	Spectrum analyser with tunable filter and detector
Frequency range in kHz	2 - 9	9 - 150	9 – 30000	3 – 148,5
Application	Emission levels in the grid, Emission levels of equipment	Emission levels in the grid		
Bandwidth	200 Hz	2 kHz	200 Hz ± 100 Hz (-6 dB)	100 Hz (sloped)
Scan times	200 ms	10/12 cycles of fundamental	14,1 s or 47 min	
Parameter	RMS values	RMS values (Max and average)		Peak values
Status	Informative annex	Informative annex	Normative	Normative

For power quality (PQ) purposes, in an Informative Annex C of EN 61000-4-30 [45], three options for measurement methods are provided.

Following to that, concerning related CISPR standardisation, EN 61000-4-30 indicates

“CISPR 16-1-2 emphasizes immunity and emission measurements for equipment under test (EUT), and may not be optimized for in-situ power quality measurements. For the purpose of in-situ power quality investigations and surveys, the measurement methods in CISPR 16 may be complex or expensive to implement, due to their gapless measurements and accuracy requirements. The measurement methods of CISPR 16 may provide a large amount of data in an in-situ power quality context. However, the amount of data for in-situ measurements specified by CISPR 16 may be required for coordination with levels defined by various IEC standards.”

Some specific attention appears advisable to be paid to measurement parameters for smart meter immunity testing. As has been highlighted with investigations at TU Hamburg [47], the appropriate choice of frequency steps for such tests may be crucial for results providing serious information about the immunity of the EUT. As shown, the susceptibility of actual smart meter devices to emissions in the frequency range 2 kHz – 150 kHz can be narrowband to an extent which makes it necessary to use a much finer frequency stepping than recently being considered [45]; with regard to the resulting increase of testing time, as an alternative,

application of broadband test signals are proposed, already having been used in the standards IEC 61000-4-4 [48] and IEC 61000-4-12 [49], which are prescribed for smart meter devices.

7.3 Characteristics of measurement quantities and requirements

7.3.1 Classification of higher frequency phenomena

The characteristic of measurement quantities of different types of phenomena in the frequency range 2 kHz to 150 kHz can be classified according to their behaviour on

- short time scale
(within a single fundamental cycle) and
- long time scale
(occurrence over longer time periods, like hours or days).

Regarding the short-time behaviour it has to be distinguished between

- Constant emission:
(emission does not significantly change in magnitude and/or frequency within one fundamental cycle)
(very rare)
- Varying emission level:
The emission changes noticeable within one fundamental cycle.
(e.g. PV inverters, PV chargers, many other types of electronic equipment)
- Transients:
The emission occurs only during a very short time of the fundamental period, like the spikes generated by a zero-crossing oscillation
(e.g. EV chargers, CFLs)

Transients can occur in combination with varying and constant emission levels. While time-domain analysis should be selected for transient phenomena, frequency-domain analysis is usually preferred for constant emission levels in order to assess the severity of their effects adequately.

On long-time scale it has to be distinguished between

- (Quasi-) continuous occurrence
The higher frequency emission appears over longer time intervals (multiple hours)
- Discontinuous occurrence
The higher frequency emission appears over shorter time intervals (few milliseconds)

Discontinuous phenomena may require sophisticated trigger options to be captured. This is usually not necessary for phenomena which appear for longer times. Here the pre-processing and storage capabilities of the measurement instrument are of higher importance.

This classification is also supported by CISPR. Regarding discontinuous emissions, CISPR-16-2-1 (EN 55016-2-1) [30] defines “discontinuous disturbance” as “for counted clicks, disturbance with duration of less than 200 ms at the intermediate-frequency- (IF-) port of a measuring receiver, which causes a transient deflection on the meter of a measuring receiver in quasi-peak detection mode”. When saying in item 7.2

“Continuous radio-frequency disturbances are predominantly measured in terms of frequency domain parameters. Discontinuous disturbances are also measured in terms of frequency domain parameters but may need additional time domain measurements.”, for emissions in the frequency range below 150 kHz, there may be anticipated, that with regard to the disturbing effects having been recognised with emissions in this frequency range, discontinuous emissions appear to need consideration with lower durations.

7.3.2 Types of application

The choice of an adequate measurement method also depends on the purpose of the measurement. In terms of EMC three major types of application are distinguished:

1) Measuring emission levels in the grid:

The main purpose of such measurements is e.g. the assessment of the present levels in the frequency range 2 kHz to 150 kHz or the investigation of interference cases.

2) Measuring individual equipment emission:

These measurements are carried out to test compliance of devices with existing emission limits. This is already mandatory e.g. for lighting equipment.

3) Verification of equipment immunity:

Immunity tests are performed to ensure that a device complies with existing immunity standards like EN 61000-4-19 [46]. Even if the additional verification of the test level is normally not required by the standard, such measurements can ensure that the designated test levels are really applied to the EUT.

Depending on the objective different requirements apply to the different aspects of the measurements. In order to ensure the comparability of results, at least within each of the above mentioned groups a comparable measurement method should be applied.

With regard to the spectrum of measurement conditions being applied for measuring emission levels with and without EMI background, as reported in Study Reports I [1] and II [2] / CLC/TR 50627 [3] as well as in Clauses 8 and 9 of this report, the results cannot be taken as exactly comparable but may fulfil the task of providing an overview of the existing situation.

7.3.3 General requirements

For each of the applications a few general requirements need to be considered.

Reproducibility / Comparability

One major requirement is the comparability of measurement results. Measuring a certain measuring quantity should provide comparable measurement results or a clear and reproducible way of conversion needs to be specified.

Accuracy

The term “accuracy” is quite complex when it comes to the evaluation of spectra and is influenced by systematic and random errors.

First, there is the accuracy of the measurement hardware, which includes all systematic errors. These are the constant and relative errors of an analog-digital converter, as well as the effect that the measurement hardware may have on the system it is connected to.

Second, the signal is affected by noise, which includes all random errors. It is determined by the quality of the signal conditioning hardware, the used measurement range, the analysed frequency range, the resolution of the analog-digital converter as well as the length of the measurement window that is used for the Discrete Fourier Transform (DFT) if applicable.

Signal filtering

Since all measurements are limited in bandwidth, the signal shall be bandwidth limited as well. Therefore, any measurement device shall be equipped with a suitable anti-aliasing low-pass filter. This applies to any measurement method. Depending on the method, the use of other signal filters is advisable or required.

7.4 Summary

It appears as advisable to establish a new consistent framework for measurement and assessment of voltages and currents in the frequency range 2 kHz - 150 kHz, thus providing a unification of the relevant measurement parameters

- for ensuring comparability and appropriate accuracy of measurement and evaluation results without requiring extensive processing performance.
- for the appropriate setting of emission limits, compatibility levels and immunity requirements

For establishing such, it appears to be recommendable (see also [50])

- to consider different types of application of measurements like
 - measurement of emission levels in the lab as well as in situ
 - analysis of electromagnetic (EM) interaction of equipment / EMI cases
 - immunity testing
- to define the types of data needed to be considered
- to analyse the impact of measurement parameters on related results
- to make the application of a high-pass filter, either digital or analog, mandatory for sufficient suppression of the fundamental component and to avoid leakage, thus ensuring an adequate accuracy across the full frequency range
- to ensure application of a common bandwidth, where a value higher than 200 Hz could be beneficial
 - Higher frequency resolution provides more details on magnitudes
 - Maximum values should be used in case of time-varying emissions (PLC)
- to ensure
 - gapless measurement (should be used, if very short emission is expected) or
 - measurement with gaps not being synchronised to power frequency, for achieving a reliable representation of the signal characteristics
- to consider possible problems with spectra with sharp boundaries between individual bands
- to apply quadratic averaging (RMS values) for aggregation of several spectra over a longer time period

The appropriate choice of a measurement method appears as highly dependent on the kind of higher frequency distortion that shall be measured and evaluated. This may mean that, finally, different measurement and/or evaluation methods could be appropriate to be defined for different types of disturbance issues in the grid.

More detailed information is provided in Annexes B and C.

Investigations on the specification of a measurement method for the frequency range 2 kHz – 150 kHz having been already made on research level [23, 47, 51, 52, 53, 54] may provide support in finding an appropriate standardised solution.

8 Emissions - Measurement and test results

8.1 General

Extending related information having been provided with [1, 2, 3], this clause provides additional results of measurements on different types of electrical devices without having been involved in EMI cases before.

Related information and measurement results have been provided from Austria, France, Germany, Sweden, Switzerland and EMC ADCO⁶⁾.

8.2 Measurement and test results

8.2.1 Large photovoltaic inverter installations

8.2.1.1 Solar campus

Extensive measurements were carried out by experts from Austria, Germany and Italy at a 1 MW photovoltaic (PV) installation [54, 55] with focus on the analysis of harmonic emission both for classical harmonics below 2,5 kHz and higher frequency emission in the range of 2 kHz - 150 kHz.

The installation of this “solar campus” consists of nine large inverters with rated power of 100 kVA and eleven small inverters with rated power in the range between 1 kVA and 10 kVA (total output of nearly 50 kVA), connected via a dedicated 1,25-MVA-transformer to the MV network. All large inverters are three phase while all small inverters are single phase. For R&D purposes, an MCS is installed.

Figure 16 shows the behaviour of the solar campus over 16 h, overnight.

⁶⁾ EMC Administrative Co-operation Group

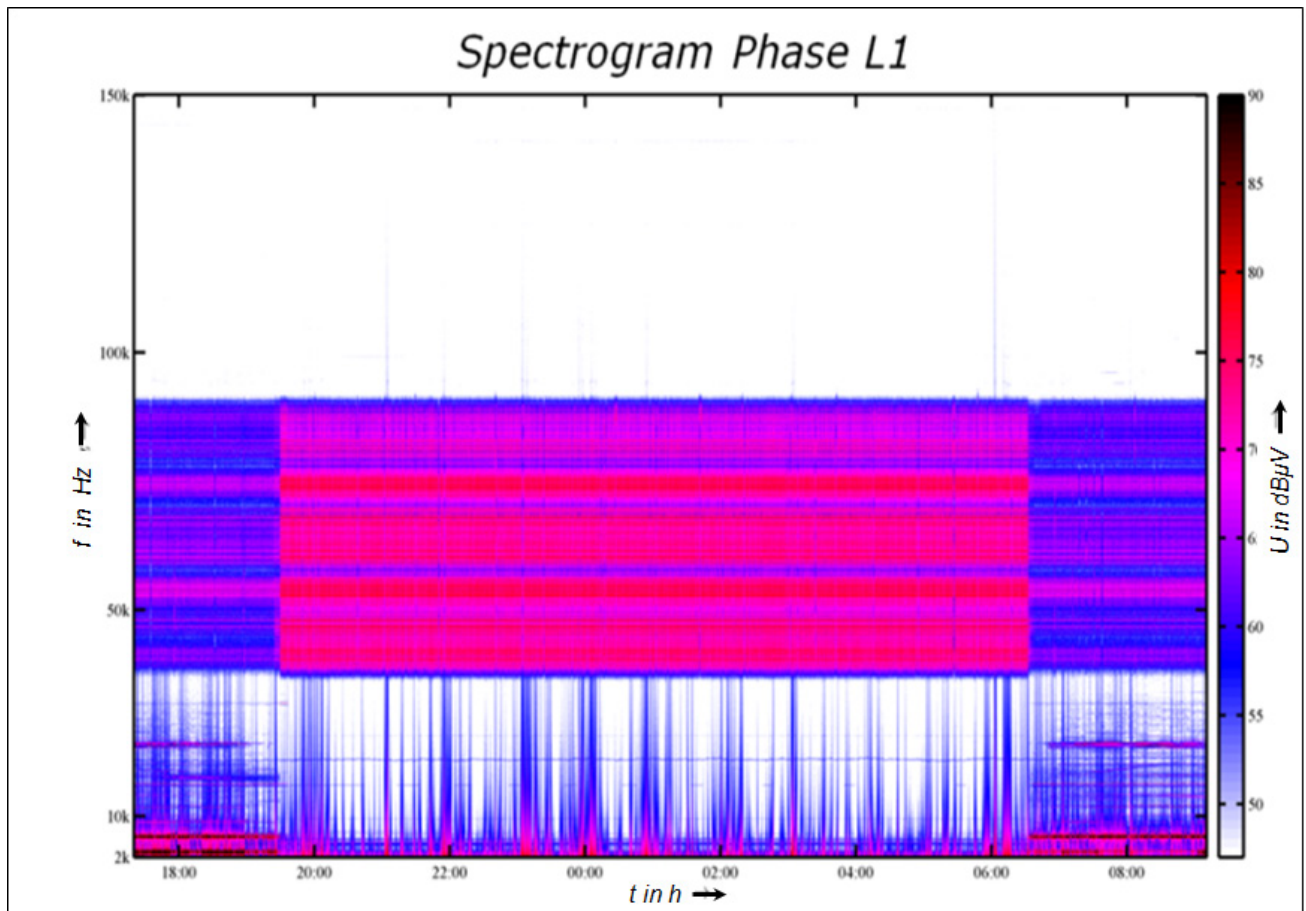


Figure 16 — Time variation of emissions and signal attenuation in a Solar Campus, measured at the busbar

There can be recognised

- the signalling situation of the MCS (40 kHz – 90 kHz), showing higher, almost unattenuated levels during night, while inverters and their filters are out of operation
- the emissions from inverters, in particular in the lowest part of the chart, at daylight and no emissions during night; the residual emissions being visible in this chart are stemming from other loads.

Beyond the measurement of total emission of all inverters, in one part of the measurement the inverters were switched off and on stepwise following a predefined schedule. This provides a comprehensive basis for a detailed characterisation of the interactions between the inverters in terms of harmonic emission.

Table 9 provides the times of switch-off of inverters.

Table 9 — Switch-off sequence of inverters

Time (mm:ss)	Inverter	Setting	Time (mm:ss)	Inverter	Setting
0:00	<i>Measurement Begin</i>		5:30	Inv 4	II
0:30	<i>PLC system OFF</i>		5:55	Inv 3	I
0:55-3:20	7 Small Inverters		6:20	Inv 2	I
3:50	Inv 8	I	6:45	Inv 1	I
4:15	Inv 7	I	7:10	Inv 9	I
4:40	Inv 6	II	7:35-8:50	4 small inverters	
5:05	Inv 5	II	9:00	<i>Measurement End</i>	

Figure 17 shows the response in terms of emissions measured from the systems (inverters, MCS) remaining in operation.

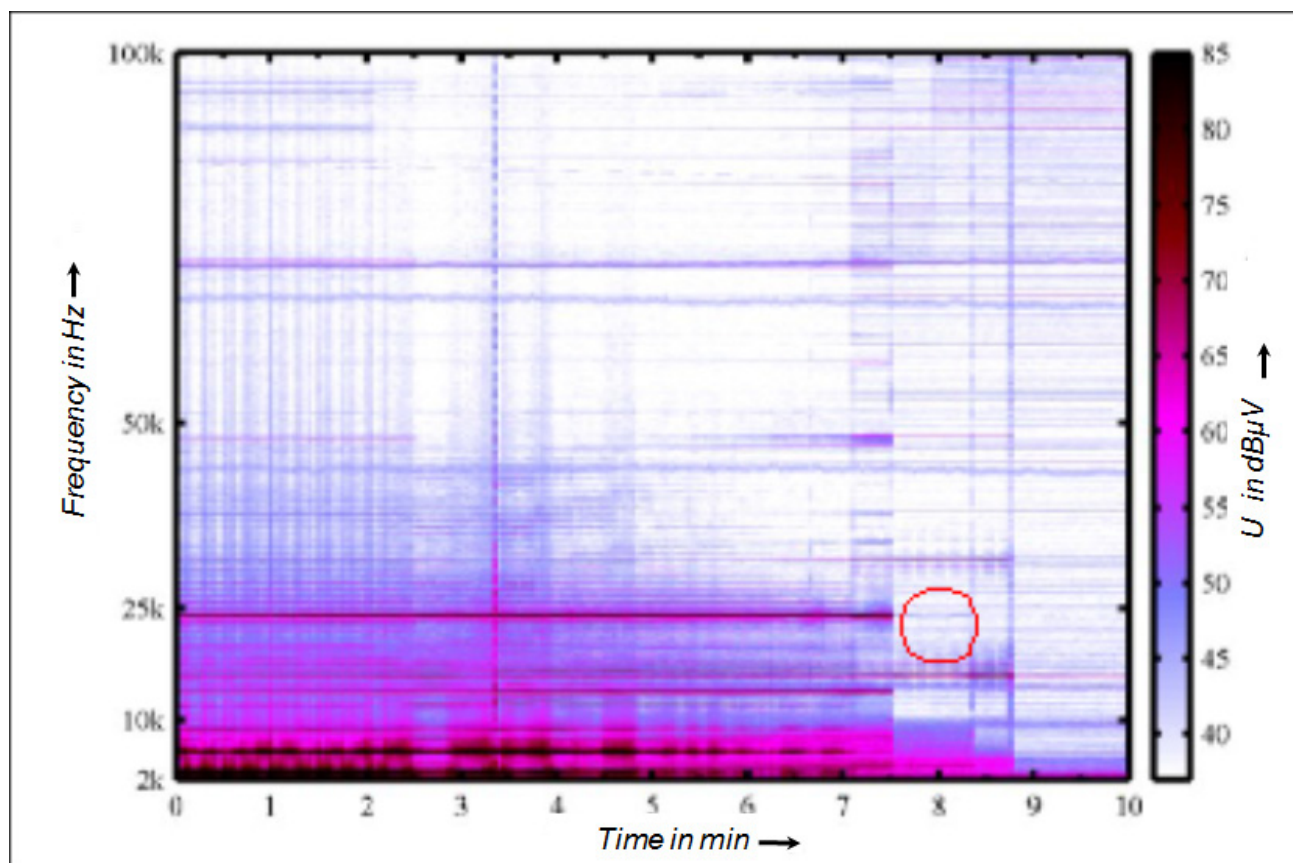


Figure 17 — Spectrogram of emissions from a set of inverters switched off step by step

Amongst others, it can be recognised, that the switch-off of small inverters at the end of the measurement results in some increase of emissions (see red circle), obviously due to reduced attenuation effects by filters built-in in the inverters.