IEC TR 61000-1-8

Edition 1.0 2019-01

TECHNICAL REPORT

colour inside

Electromagnetic compatibility – Part 1-8: General – Phase angles of harmonic current emissions and voltages in the public supply networks – Future expectations

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FOREWORD

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IEC TR 61000-1-8, which is a Technical Report, has been prepared by subcommittee 77A: EMC – Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
77A/1002/DTR	77A/1012/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61000 series, published under the general title *Electromagnetic compability*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

0.1 Series overview

IEC 61000 is published in separate parts, according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: 61000-6-1).

0.2 Purpose of this document

This part of IEC 61000 documents measurements at a number of public supply networks in Germany, and explains the analysis of the obtained data. Data were acquired under certain conditions. These conditions include categories of different network structures, load structures and power generation structures, especially including a review of networks with varying degrees of renewable energy. The loads in various networks include mainly consumers, office buildings, and retail/shopping centres, and thus represent several categories of technologies in the input circuit of the electrical devices.

This document provides statistical evaluations aimed at quantifying the level of diversification of the prevailing harmonic current phase angles, and, where possible, to identify methods to reduce the overall emissions of dominant harmonics in the network.

For that purpose, the existing prevailing phase angle in the network at this time is analysed, and the type of prevailing phase angle expected in the future is evaluated. In particular, the potential changes in phase angle that can be expected, because of new technologies and/or network structures, are of interest. This would mean determining what harmonic compensation, if any, can be expected from various products. The goal is to determine or verify the existing phase angle (mainly of the 5th harmonic) and to assess the possible influences of future developments – such as changes in lighting types and other electronic equipment.

This document is exclusively applicable to public low-voltage electricity supply networks.

ELECTROMAGNETIC COMPATIBILITY –

Part 1-8: General – Phase angles of harmonic current emissions and voltages in the public supply networks – Future expectations

1 Scope

The objective of this part of IEC 61000 is to provide information about the current conditions, and project future developments, of prevailing phase angles, predominantly for the 3rd and 5th harmonic currents, on public supply networks. This objective is accomplished by monitoring a number of networks, and efforts to forecast the effects of changes in technologies.

This document presents information to guide the discussion about the effectiveness of potential mitigation techniques and the generalisation of effects of the prevailing angle positions of selected current harmonics.

This document mainly deals with the phase angles of the 3rd and 5th harmonic currents, but also contains information about other harmonics.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
phase angle of I_5 related to the fundamental phase-to-neutral voltage U_{p1}
phase angle of the 5th harmonic current determined as described in Figure 1

[SOURCE: IEC 61000-3-12:2011, 3.16, modified – the reference to Figure 2 has been removed.]

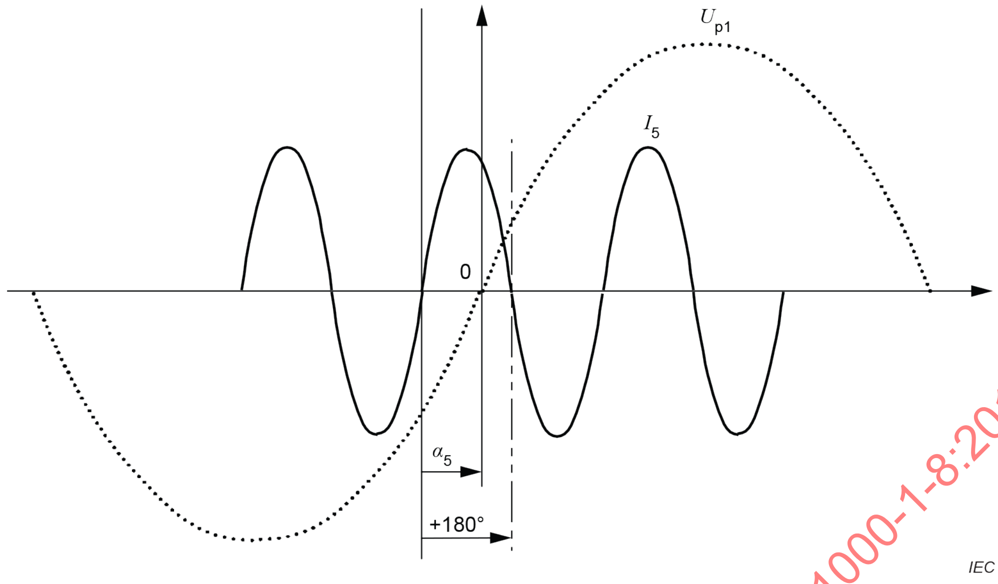

Figure 1 – Definition of the 5th harmonic current phase angle (I_5 leads U_{p1}, α_5 > 0)

3.2
prevailing vector

$$\underline{x}_{\mathrm{pv}} = x_{\mathrm{qm}} \cdot e^{jx_{\mathrm{vs\_ph}}} \tag{1}$$

where the quadratic mean of magnitudes is

$$x_{\mathrm{qm}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\left(\underline{x}_i\right)^2\right|} \tag{2}$$

with $\left|\left(\underline{x}_i\right)^2\right|$ as the magnitude (absolute value) of the complex value $\underline{x}$,

and where the phase of the vectoral sum is the phase of the prevailing vector:

$$x_{\mathrm{vs\_ph}} = \tan^{-1}\left(\frac{\sum_{i=1}^{n}\mathrm{Im}\left(\underline{x}_i\right)}{\sum_{i=1}^{n}\mathrm{Re}\left(\underline{x}_i\right)}\right) \tag{3}$$

Note 1 to entry: The phase of the vectoral sum is different from the definition of the vectoral mean: this is the arithmetic mean of the real-part and the arithmetic mean of the imaginary-part.

Note 2 to entry: See 6.2.3 for details.

3.3
in-phase factor

$$r_{\mathrm{in\_phase}} = \frac{x_{\mathrm{vs\_mg}}}{x_{\mathrm{as\_mg}}} \tag{4}$$

where the magnitude of the vectoral sum is:

$$x_{\text{vs\_mg}} = \sqrt{\left(\sum_{i=1}^{n} \text{Re}(x_i)\right)^2 + \left(\sum_{i=1}^{n} \text{Im}(x_i)b\right)^2} \quad (5)$$

and the arithmetic sum of magnitudes is:

$$x_{\text{as\_mg}} = \sum_{i=1}^{n} \left| \underline{x}_i \right| \quad (6)$$

Note 1 to entry: See 6.2.3 for details.

3.4
dispersion factor
deviation factor
subtraction of the in-phase factor from digit 1:

$$r_{\text{disp\_phase}} = 1 - \frac{x_{\text{vs\_mg}}}{x_{\text{as\_mg}}} \quad (7)$$

Note 1 to entry: See 6.2.3 for details.

3.5
total harmonic current
THC
total RMS value of the harmonic current components of orders 2 to 40:

$$THC = \sqrt{\sum_{h=2}^{40} I_h^2} \quad (8)$$

3.6
total harmonic distortion
THD
ratio of the RMS value of the sum of the harmonic components (in this context harmonic current components I_h of orders 2 to 40) to the RMS value of the fundamental component:

$$THD = \sqrt{\sum_{h=2}^{40} \left(\frac{I_h}{I_1}\right)^2} \quad (9)$$

4 Summary of field measurements and data analysis

4.1 Field measurement methods and concepts

All measurements reported in this document have originated from an initiative by Forum Netztechnik/Netzbetrieb (FNN) and within the scope of a research assignment financed by FNN and assigned to the University of Technology of Dresden. The network operating authority N-ERGIE (today MDN) was involved, along with several other network operating authorities in the realisation of the measuring campaign. Data have been handed over to the research partner, but the network authorities could carry out their own analyses as well. Apart from the task of the research partner, additional test sites have been examined by N-ERGIE and data analyses continue, with emphasis on correlation aspects.

This document is based primarily on the results of the N-ERGIE investigations which are consistent, nevertheless, with the results of the larger FNN studies. The data pool of FNN offers the big advantage of a large number of random tests (within Germany). The enormous amount of data necessitates substantial compression for a meaningful presentation, and admittedly leads to a less-detailed consideration of the results. More detailed analysis has also been carried out, however, particularly concerning correlation, and that analysis is presented as well.

Test sites were chosen according to criteria from [1][1] with regard to network structure, load structure and generator structure. These diverse test sites, representing various topologies and load types in the network area of the N-ERGIE are listed in Table 1.

Thus, eight residential area networks (e.g. “A1” and “A2” in the column “Category” of Table 1, see Table 9 for definitions) and four networks that include commercial offices, trade, and retail stores, were examined. Additionally, one of the last four networks was a repetition of M9 concerning the phase angle of the harmonic voltage instead of the phase angle of the harmonic current, listed as M17. At the test sites M1 to M8, measurements were made from the middle of December 2012 to the middle of January, 2013, with a duration of 35 days to 40 days. The measurements at the test sites M9 to M12 followed in May 2013. These were repeated at the same test sites in July 2013, listed as M13 to M16, with a modified interval time of measurement (60 s instead of 1 s) at M10 to M12, respectively M14 to M16. These test sites (M9 to M12) are listed as M13 to M16, mainly as a means of differentiation. With a choice of the measuring period, the opportunity was consciously taken to measure, on the one hand, during the winter months and summer months and to measure, on the other hand, in a time window with varying users' behaviour (work times and holidays about the turn of the year). The background is to identify network parameter dependencies, specifically the prevailing phase angle of harmonics, resulting from the users' behaviour and load structure.

As follows from Table 1, the 16 measurement sites are representative of a good cross section of the public supply, and as follows from the more detailed data review, the analysis includes a statistically meaningful sample set that can be extrapolated to the 220/230 V 50 Hz public supply networks in general. No attempt is made to extrapolate the findings to other network topologies, but given that the load structures are similar in 120 V 60 Hz networks, the findings of this document can apply to some extent to those other networks as well.

The field measurements included exclusively the public low-voltage network at the terminals of the local network transformers. Current and voltage were measured in each of the three phases, and included magnitude and phase. The measurement window was 200 ms with a sampling rate of 100 kS/s. The measurement repetition rate amounted to 1 min, except with M10 to M12 where data were acquired with 1 s intervals. The measuring instruments used by N-ERGIE recorded the harmonics up to the 50th order and the basic electrical parameters, including phase angle information for current and voltage. The harmonic currents phase angles are measured with reference to the zero crossing of the fundamental of the voltage according to 61000-3-12 [3] (positive zero crossing).

In 4.2, a brief summary of the measurement results is presented, along with a summary review of the potential future impact of technologies and societal developments. The data are then analysed in detail, and technology and economic factors are analysed in more detail, to further explain the summary findings.

[1] Numbers in square brackets refer to the Bibliography.

Table 1 – Structure of test (measurement) sites

Test site	Network	Load	Generation	Category[a]	Number of days
M1	Mid-sized network	SFH, small residential area	No renewables	N2 A1S E1	40
M2	Large-sized network	SFH, small residential area	Sporadic renewables	N3 A1S E2	40
M3	Large-sized network	SFH, Mid residential area	Sporadic renewables	N3 A1M E2	43
M4	Large-sized network	SFH, Mid residential area	A few renewables	N3 A1M E3	36
M5	Large-sized network	SFH, Large residential area	A few renewables	N3 A1L E3	36
M6	Large-sized network	MFH, Mid residential area	No renewables	N3 A2M E1	41
M7	Large-sized network	MFH, Large residential area	No renewables	N3 A2L E1	43
M8	Large-sized network	MFH, Large residential area	A few renewables	N3 A2L E3	41
M9	Mid-sized network	Office	No renewables	N2 A4 E1	10
M10	Small-sized network	Stores	No renewables	N1 A3 E1	1[b]
M11	Small-sized network	Stores	A lot of renewables	N1 A3 E4	1[b]
M12	Mid-sized network	Office	A lot of renewables	N2 A4 E4	1[b]
M13	Mid-sized network	Office	No renewables	N2 A4 E1	27
M14	Small-sized network	Stores	No renewables	N1 A3 E1	26
M15	Small-sized network	Stores	A lot of renewables	N1 A3 E4	27
M16	Mid-sized network	Office	A lot of renewables	N2 A4 E4	26
M17	Mid-sized network	Office	No renewables	N2 A4 E1	12

[a] The description of 'Category' is given in Table 8, Table 9 and Table 10.

[b] For these measurements, an aggregation time of 1 s was used instead of 60 s.

4.2 Summary of measurement results, analysis, and conclusions

Harmonic emission standards, such as [2] and [3], are based on past analysis by various experts and institutions. It was found, through a number of measurements and long-time monitoring on the networks, that the lower order harmonics H3 and H5 are dominant and represent the highest impact on voltage distortion. Consequently, network operators and authorities are mainly concerned with emission levels at H3 and H5, and to some extent H7.

During the last 10 years, several IEC working groups considered that it might be possible to “guide” developments in technology or network topology and structure, to achieve compensation of emissions, in the sense that the emissions of one product group or specific technology might compensate for the prevailing harmonics on the network. If, therefore, the prevailing phase angle on the network can reliably be established, and is sufficiently consistent, it might be possible to devise products or product technologies with power input topologies that – if any – generate harmonic emissions that oppose, i.e. compensate for, the distortion on the networks.

The results of the measurement campaign explained in 4.1 appear to dispel the possibility of “guided compensation” of prevailing distortion in the network. Figure 2, Figure 3 and Figure 4 with the measurement results from 3 of the 16 measurement sites, M1 – M7 – M16, are used to illustrate this initial observation.

Prior to the measurement campaign, it was assumed that harmonic emissions were such that the lower order harmonics (H3 and H5) had a relatively narrow distribution, such as shown for the test site M16 below (Figure 4). The measurements at other test sites, however, show a broad dispersion of emission phase angles and amplitudes. High dispersion for H3 and a moderate level of dispersion for H5 are observed at test site M1. A very wide distribution of emissions, both in amplitude and phase for the 5^{th} (and 7^{th}) harmonic is observed for test site M7. In addition, the prevailing phase angle for H5, with moderate dispersion at test site M1, opposes the prevailing phase angle with narrow dispersion at M7. Likewise, the main amplitudes of the highly dispersed H5 emissions at test site M7 oppose the narrow distribution of H5 at test site M16.

Similar conclusions can be drawn when comparing other test sites, such as M15 and M16 (see Annex A).

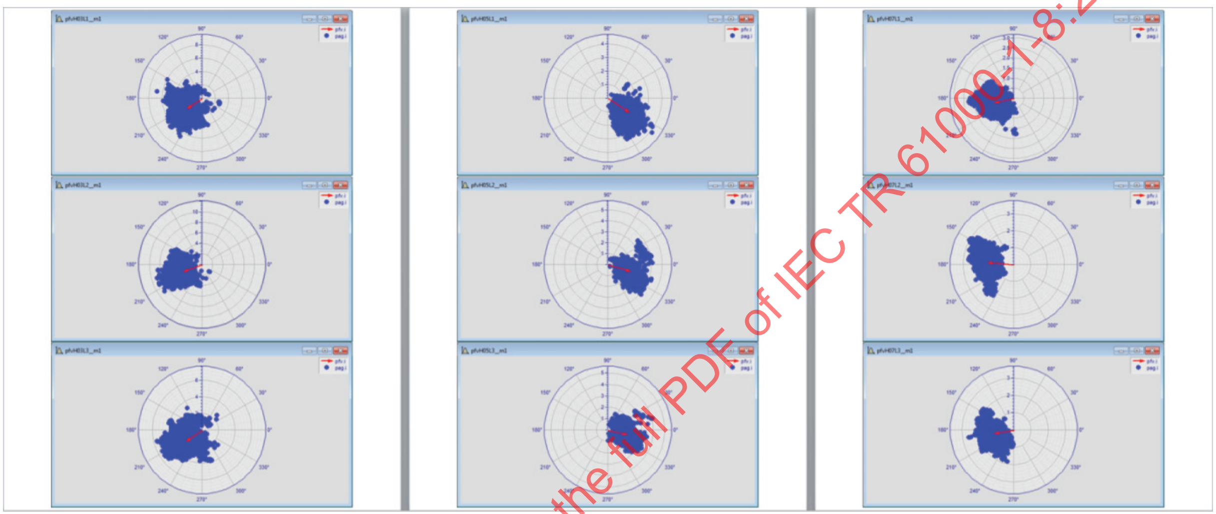

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Figure 2 – Polar diagrams with prevailing vector for each of the three phases of the 3^{rd}, 5^{th} and 7^{th} harmonic currents at test site M1

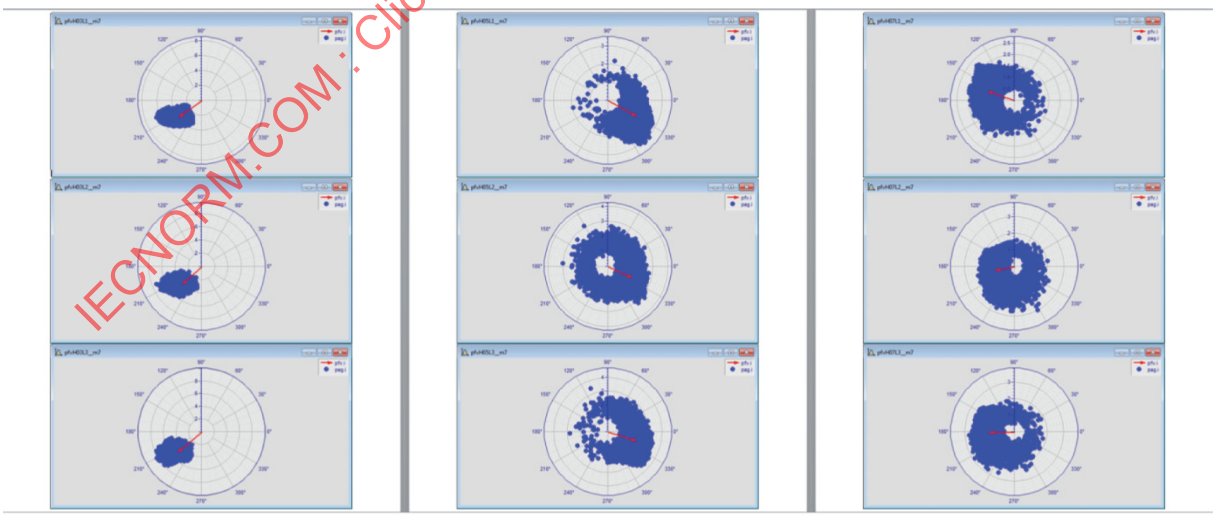

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Figure 3 – Polar diagrams with prevailing vector for each of the three phases of the 3^{rd}, 5^{th} and 7^{th} harmonic currents at test site M7

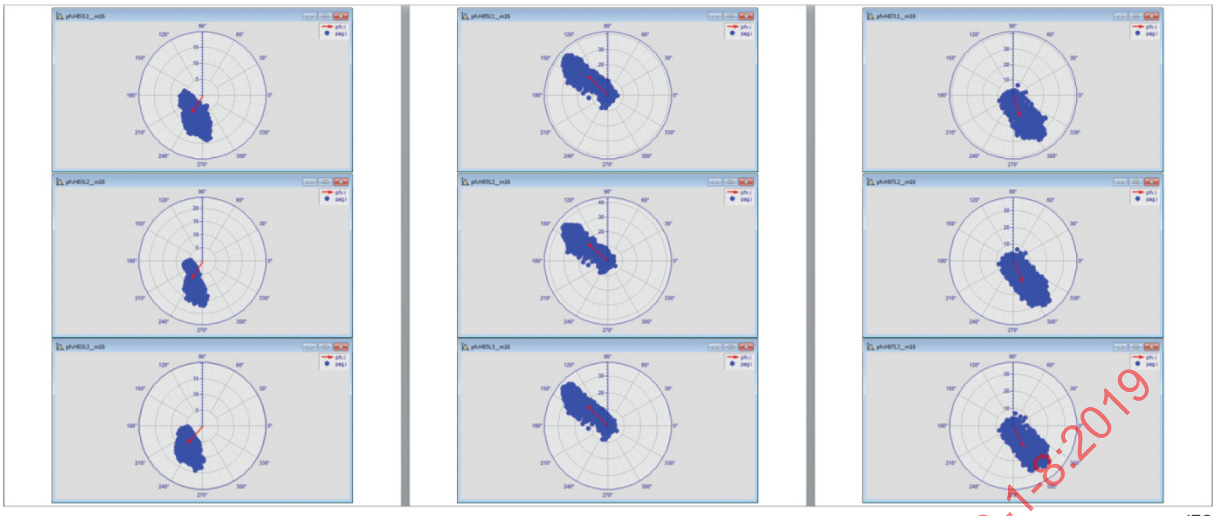


Figure 4 – Polar diagrams with prevailing vector for each of the three phases of the 3rd, 5th and 7th harmonic currents at test site M16

Whereas the harmonic current phase angles show a wide variety, the 3rd, 5th, and 7th harmonic voltage phase angles vary by measurement site as well. This is depicted in several forms in Figure 5 to Figure 9.

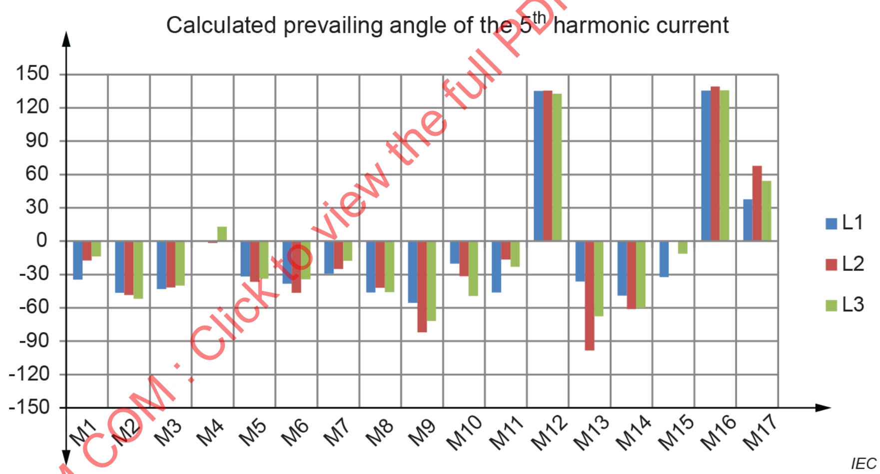
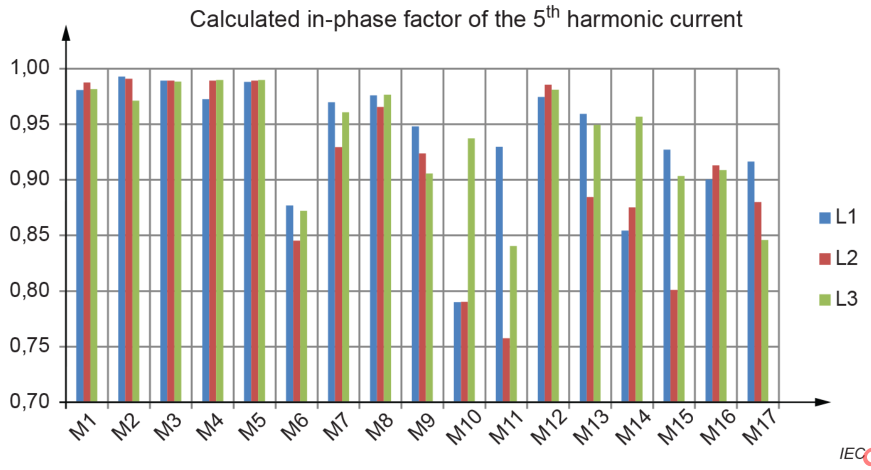


Figure 5 – Computed prevailing phase angle of the 5th harmonic current



Note 1 to entry: The term in-phase factor is defined in 3.3. The term prevailing ratio is not used in this document.

Figure 6 – Computed in-phase factor of the 5th harmonic current

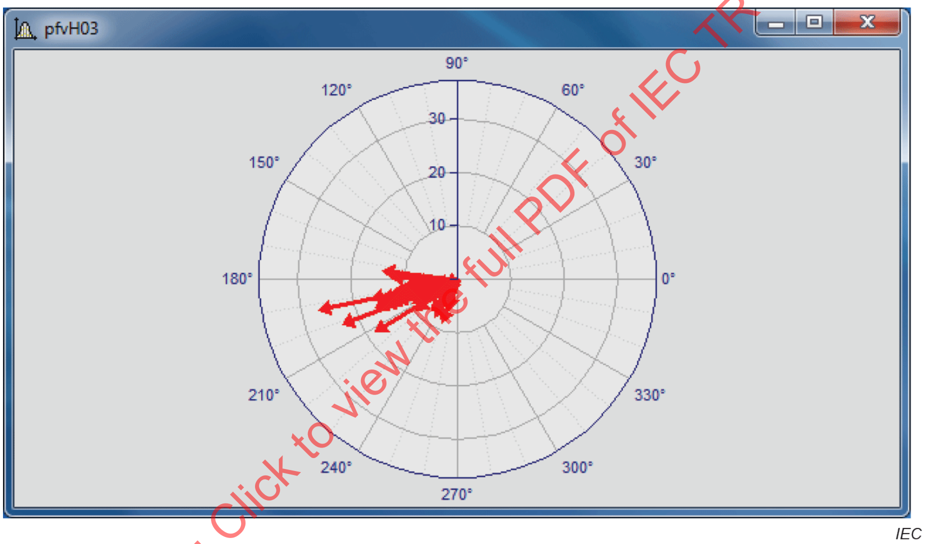


Figure 7 – Prevailing vectors of the 3rd harmonic current (three phases, all test sites)

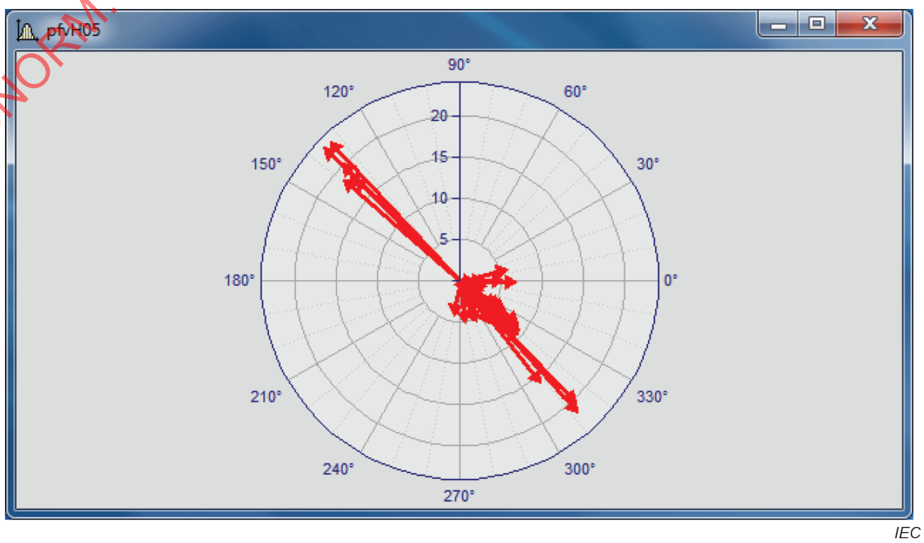


Figure 8 – Prevailing vectors of the 5th harmonic current (three phases, all test sites)

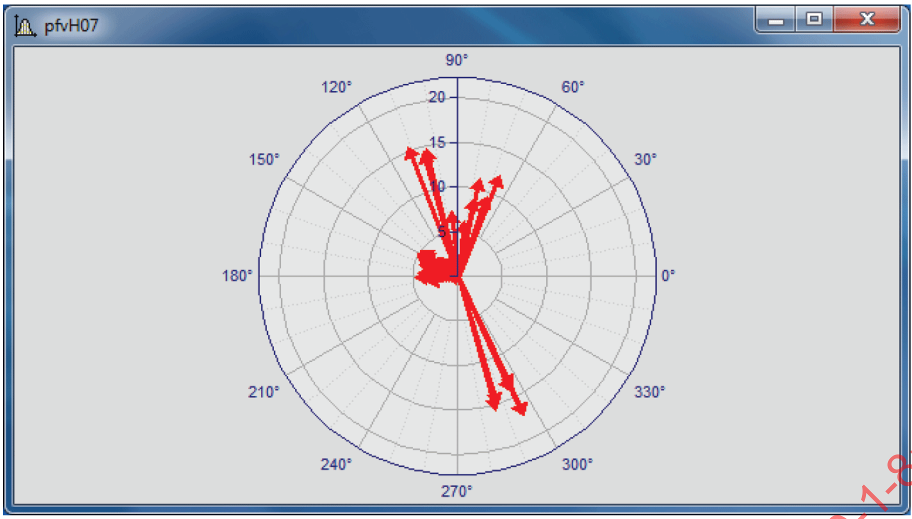


Figure 9 – Prevailing vectors of the 7th harmonic current (three phases, all test sites)

As is already evident from the foregoing figures, "guided compensation" in the form of recommending specific technologies, or network topologies, appears to be a very difficult –if not impossible – task. The voltage (and current) distortion at various measurement sites vary(ies) so much, that what "compensates' for one site, can exacerbate distortion at another site.

In other words, to achieve compensation of certain products for the emissions of others or compensation for global distortion levels in the network does not seem to be a possibility, except perhaps for very much localized situations.

To numerically quantify the measured data, that data are analysed in substantial detail, and evaluation of various calculated parameters is performed. The methodology and analysis techniques are explained in Clauses 6 and 7. Subsequently, somewhat more detailed conclusions are presented.

Before going into great detail on the technical and data analysis aspects of the survey, it is appropriate to evaluate economic and societal conditions and assess whether or not a major shift in electricity demand and/or type of loads is to be expected because of economic reasons, such as disrupting new technologies and/or widespread adoption of products that significantly alter power demand.

5 Critical appraisal of potential economic impact

5.1 General

Electricity consumption and demand is relatively stable in the developed nations. Even though new technologies, such as solid state lighting, can have some impact, lighting represents less than 10 % of the electricity consumption, and solid state lighting is just a part of that percentage. Similar considerations apply to renewable energy and the effect of energy efficient motor drives. Because each sector represents only a fraction of the total demand, and changes in each sector represent only a small part of the applicable sector, no significant shift in either consumption of electricity or emission patterns in developed countries is to be expected. A possible exception could be the widespread adoption of electrical vehicles, and associated battery chargers, but any such development will take at least 5 years to 10 years to even emerge. Even if such developments take place, industry plus household electricity consumption will still dominate, and thus no significant change in harmonic current emission patterns is anticipated.

While electricity consumption in the BRICS countries has increased rapidly in the last 20 years or so (see Figure 10), electrical products consumption patterns mimic those of the developed nations, and thus few differences in harmonic emissions are to be expected in those countries.

Economic impact factors will be reviewed in more detail later in this document.

5.2 Dependencies on electrical parameters

Thus far, economic factors have not been considered with respect to their potential impact on the phase angles of the harmonic current. For example, if economic factors lead to a major shift in power consumption, this could affect the phase angle of harmonic emissions also.

5.3 Dependencies on non-electrical influence quantities

5.3.1 General

It can be concluded that at the present time, there is no direct connection between the initial network structure and the electricity producer's structure regarding harmonic compensation effects for selected harmonics. Thus far, network topology and structure are mainly aimed at ensuring reliable power delivery to the consumer. There are power quality requirements in most developed nations, but "harmonic compensation" has not been a design criterion for network structure.

Changes in consumer behaviour, i.e. economic aspects, can have feedback effects on technologies and thus on diversity – or the lack thereof – in the vectoral overlapping of harmonic current of various products. These effects are considered in the detailed analysis, but any impact appears to be limited.

Finally, climate developments can also have an effect on technology developments, and in turn feed back into the power system.

Nevertheless, the main influence quantities, and the status quo, are economic drivers as is briefly indicated in 5.3.2 to 5.3.4.

5.3.2 Development of economic sectors and demand of energy

The worldwide electricity demand amounted in 1980 to 7 328 TWh and had increased in 2008 to 17 455 TWh. This corresponds to an annual growth rate of 3,15 %. The demand[2] split for electric energy between the regions[3,4] of the world is shown in Figure 10.

2 Source of data: U.S. IEA.

3 BRICS: Brazil, Russia, India, China, South Africa.

4 EU-27: BE, DE, FR, IT, LU, NL, DK, IE, UK, GR, PT, ES, FI, AT, SE, EE, LV, LT, MT, PL, SK, SI, CZ, HU, CY, BG, RO.

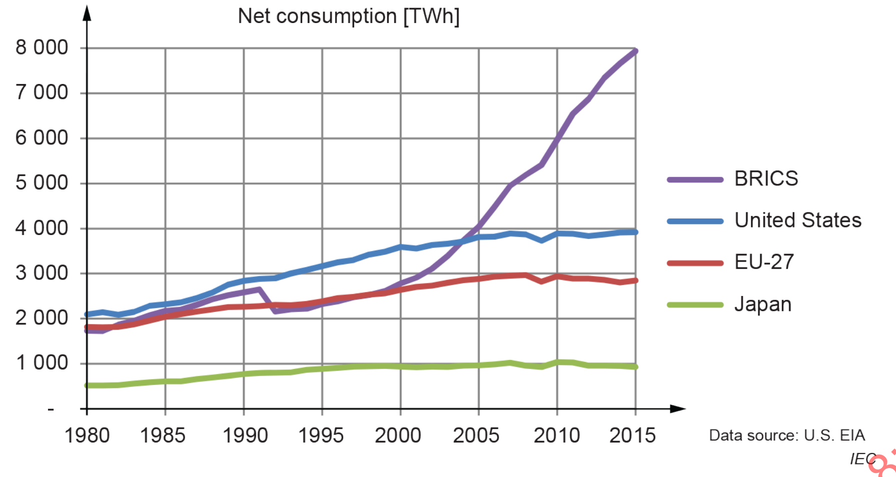


Figure 10 – Development of demand of energy

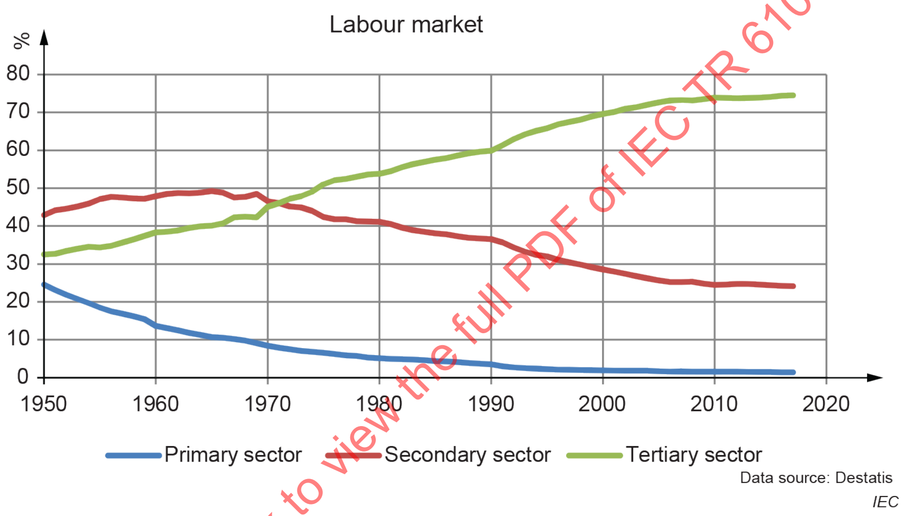


Figure 11 – Development of economic sectors in industrial countries

Industrial countries register a movement of the production between the sectors since decades. The primary sector (agriculture) lies stable with a relatively small share of 5 %. The secondary sector (industry) with a share of 15 % to 25 % is shrinking in favour of the growing tertiary sector (service) which is growing towards 80 % (Figure 11). The sub-sectors of the tertiary sector spread as follows:

- health and education (20 %), increasing,
- trade, hotel business, gastronomy, culture and recreation industry (20 % to 25 %),
- enterprise related services, consulting, accounting, design, IT, real estate, financial sector, insurance and logistics (20 %),
- national jurisdiction and security, general administration, judiciary, police and army (10 %).

In these sub-sectors, increasing numbers of electrical equipment are required, and new technologies to improve productivity are continuously introduced, in particular:

– lighting
– IT
– consumption electronics
– motor drives

– cooking machines
– white-goods household appliances (washing and kitchen machines)
– heating appliances/air-conditioners
– E-mobility

What trends are expected in the growth rate?

a) Lighting:
   – high innovation driven by competition in the industry (supply side)
   – inelastic demand by consumers, because it is an inferior/common good, income elasticity of demand: $\in (x, Y) < 1$
   – change, especially substitution, is going relatively slow
b) IT and consumer electronics:
   – high innovation driven by competition in the industry (supply side)
   – elastic demand by consumer, because it is a superior/novel good, income elasticity of demand: $\in (x, Y) > 1$
   – change, especially expansion, is going relatively fast

5.3.3 Consumer durables

Data for the equipment of customer durables (durable goods in the sense of economics) can be taken from the database GENESIS[5] [4].

The rates of growth of electrical and electronic products in the LV network are indicated, as an example, for the sector 'household', with the help of statistical evaluations in Germany. The power consumption (electrical energy) in the household sector in developed industrial states amounts to approximately one third of the whole electrical energy consumption.

The degree of product ownership (market penetration) is analysed on the basis of selected consumer products and is divided into the categories of household appliances (Table 2), information and telecommunication technology (Table 3) and entertainment electronics (Table 4).

These tables show, for each of the above-mentioned categories, in the upper part, the degree of product ownership of consumer products per household in percent. With regard to the unstated number of consumer products per 100 households, which is a measure of the multiple products in one household, the total number of consumer products was computed for all projected households. The total number of consumer products is shown, for each of the above-mentioned categories, in the lower part of Tables 2, 3 and 4 in millions of pieces.

On the basis of the development of the total number of consumer products, the calculation of the moving-average annual growth rates is applied to a base year, as a rule the year of the first statistical survey. These above-named methods are better suited for long term consideration than the illustration of the development of the annual growth rates of two sequential years.

Figure 12, Figure 13 and Figure 14 show, for each of the above-mentioned categories, the moving-averaged growth rates of the selected consumer products.

In the analysis, the saturation in the degree of product ownership in consumer products always shows at a certain level after newly-introduced technologies, which is demonstrated by sustained near-zero values of moving averaged growth rates.

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5 Statistics for German national economy.

The diagrams show exactly which new technologies are discontinued in terms of market penetration and which still continue. Further mathematical predictions can be estimated for the numbers of pieces of selected technologies, which permit again an evaluation of the influence on the development on the contributions to reactions of the network, particularly in terms of harmonics and their phase angles.

Table 2 – Product ownership of electrical household appliances

Electrical household appliances and others (EHA)	2000	2001	2002	2003	2004	2005	2006	2007	2008
Households projected (1 000)	34 390	34 777	35 009	35 192	35 375	35 528	35 555	35 887	36 175
Share of the households in percent (equipment rate)									
Refrigerator	99,2%	99,3%		98,8%		99,1%	98,9%	99,4%	98,6%
Freezer				66,0%	63,3%	60,6%	57,8%	55,1%	52,4%
Dishwasher	48,3%	51,3%	52,3%	56,6%	56,7%	59,1%	61,6%	62,4%	62,5%
Microwave oven	56,1%	58,2%	58,7%	62,7%	62,3%	67,0%	68,0%	68,7%	69,6%
Washing machine	94,1%	95,1%		93,5%	95,5%				
Dryer	31,8%	33,3%	33,3%	36,5%	36,8%	39,3%	34,5%	40,0%	38,5%
Hometrainer			21,6%	24,3%	26,6%	27,3%	28,4%	28,9%	27,5%
E-Bike									
Number of the goods in millions									
Refrigerator	39,5	40,5		40,6		41,0	41,6	42,4	43,4
Freezer				25,9	25,0	24,0	23,0	22,1	21,2
Dishwasher	16,8	18,0	18,5	20,1	20,3	21,2	22,2	22,7	22,9
Microwave oven	19,6	20,7	21,1	22,5	22,6	24,4	24,9	25,3	25,8
Washing machine	32,9	33,8		33,5	34,4				
Dryer	11,0	11,7	11,7	12,9	13,1	14,0	12,3	14,4	14,0
Hometrainer			8,5	9,8	10,4	11,0	11,6	12,0	11,9
E-Bike									
Electrical household appliances and others	2009	2010	2011	2012	2013	2014	2015	2016	2017
Households projected (1 000)	36 462	36 521	36 640	36 701	36 522	36 343	36 650	37 207	37 381
Share of the households in percent (equipment rate)									
Refrigerator	98,7%	97,8%	99,1%	99,4%	99,7%	99,8%	99,9%	100,0%	99,9%
Freezer	54,1%	54,0%	57,2%	57,2%	50,5%	50,8%	50,8%	50,3%	51,6%
Dishwasher	64,8%	65,7%	67,0%	68,3%	67,3%	68,3%	69,5%	69,8%	71,5%
Microwave oven	71,9%	72,9%	72,0%	72,4%	71,1%	72,9%	73,3%	73,3%	73,9%
Washing machine			95,0%	96,0%	94,5%	95,6%	93,9%	96,2%	96,4%
Dryer	38,6%	39,9%	39,7%	40,0%	39,1%	40,3%	39,5%	41,1%	42,2%
Hometrainer	30,1%	29,7%	30,3%	28,7%	24,6%	26,0%	26,3%	25,6%	25,3%
E-Bike						3,4%	4,2%	5,1%	6,1%
Number of the goods in millions									
Refrigerator	43,8	43,8	44,4	44,6	44,5	44,6	45,2	46,4	46,7
Freezer	22,0	22,1	23,4	23,7	20,5	20,7	20,9	21,1	21,7
Dishwasher	23,9	24,4	24,9	25,4	25,1	25,3	26,0	26,5	27,3
Microwave oven	26,9	27,5	27,2	27,3	26,8	27,5	27,8	28,2	28,6
Washing machine			35,5	36,0	35,5	35,8	35,4	36,9	37,2
Dryer	14,1	14,7	14,6	14,8	14,4	14,8	14,6	15,4	16,0
Hometrainer	13,1	13,1	13,4	12,8	10,3	10,9	11,1	11,0	10,9
E-Bike						1,6	2,0	2,5	3,1

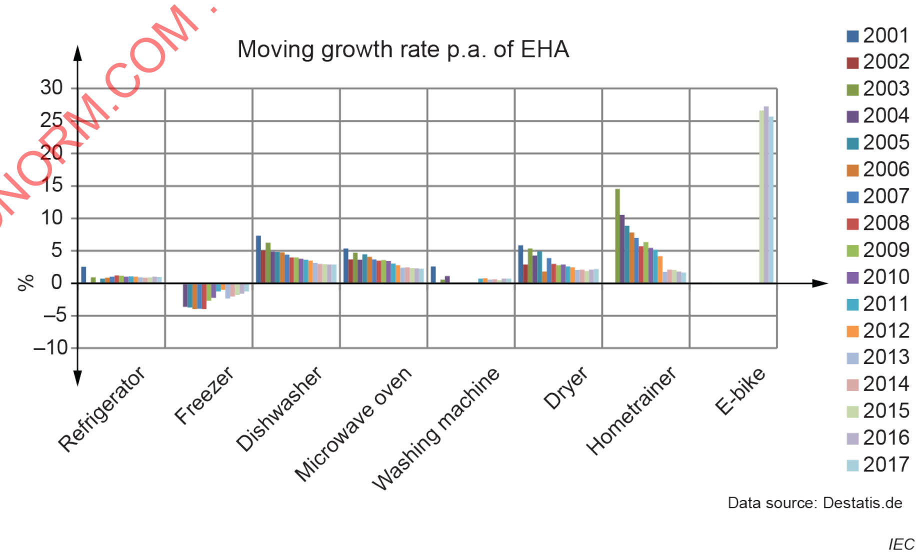


Figure 12 – Growth rates of product ownership of electrical household appliances

Table 3 – Product ownership of information and communication technology

Information and communication technology (ICT)	2000	2001	2002	2003	2004	2005	2006	2007	2008
Households projected (1 000)	34 390	34 777	35 009	35 192	35 375	35 528	35 555	35 887	36 175
Share of the households in percent (equipment rate)									
Telephone	98,2%	98,5%		98,7%	98,7%	99,3%	99,4%	99,4%	99,0%
Telephone, fixed	96,4%	96,4%		94,5%	95,1%	95,9%	95,2%	95,4%	89,7%
Telephone, mobile	29,8%	55,7%	69,8%	72,5%	72,1%	76,4%	80,6%	81,8%	86,3%
Fax machine	14,9%	16,0%	16,2%	20,7%	17,2%	18,7%	18,9%	18,6%	20,7%
Personal computer	47,3%	53,4%	57,2%	61,4%	63,6%	68,6%	71,6%	72,8%	75,4%
PC, fixed	45,6%	51,6%	54,1%	58,2%	58,7%	62,9%	64,5%	63,8%	62,1%
PC, mobile	5,5%	6,1%	7,9%	10,7%	13,3%	17,2%	21,3%	25,1%	34,7%
Internet access	16,4%	27,3%	36,0%	46,0%	47,1%	54,6%	57,9%	60,0%	64,4%
Car navigation						4,4%	7,7%	12,3%	20,7%
Number of the goods in millions									
Telephone	47,6	63,3		82,6	78,7	85,7	92,9	95,8	97,1
Telephone, fixed	35,4	35,4		42,4	38,1	40,8	44,1	45,2	41,4
Telephone, mobile	12,2	27,9	37,0	40,2	40,6	44,9	48,7	50,7	55,6
Fax machine	5,2	5,6	5,7	7,4	6,2	6,7	6,8	6,7	7,6
Personal computer	20,9	24,1	26,4	29,9	31,7	35,0	38,0	39,8	44,0
PC, fixed	18,8	21,8	23,4	25,8	26,5	28,2	29,4	29,6	29,0
PC, mobile	2,1	2,3	3,0	4,1	5,2	6,8	8,5	10,2	15,0
Internet access	6,2	10,2	13,2	16,9	17,5	20,3	21,4	22,5	25,0
Car navigation						1,6	2,8	4,6	8,1
Information and communication technology (ICT)	2009	2010	2011	2012	2013	2014	2015	2016	2017
Households projected (1 000)	36 462	36 521	36 640	36 701	36 522	36 343	36 650	37 207	37 381
Share of the households in percent (equipment rate)									
Telephone	99,5%	99,4%	99,6%	99,7%	99,8%	99,9%	99,9%	99,9%	100,0%
Telephone, fixed	91,5%	91,6%	92,7%	93,4%	90,5%	91,5%	91,5%	91,0%	90,9%
Telephone, mobile	86,7%	88,9%	90,0%	90,3%	92,7%	93,6%	93,5%	95,1%	95,5%
Fax machine	19,2%	20,1%	19,0%	18,8%	23,8%				
Personal computer	78,8%	80,8%	82,0%	83,5%	85,2%	87,0%	88,3%	88,6%	90,0%
PC, fixed	62,9%	63,1%	61,1%	59,6%	53,3%	54,0%	51,3%	49,4%	48,6%
PC, mobile	40,0%	45,5%	51,9%	57,5%	65,2%	68,3%	73,5%	75,4%	79,0%
Internet access	68,9%	72,9%	75,9%	79,4%	80,2%	78,8%	88,2%	89,3%	91,1%
Car navigation	27,0%	33,2%	38,9%	42,7%	46,3%	48,3%	49,7%	50,8%	50,6%
Number of the goods in millions									
Telephone	98,7	99,8	102,7	102,8	108,2	108,3	109,1	111,3	112,9
Telephone, fixed	41,5	41,0	42,0	42,0	45,5	44,8	45,3	45,7	45,9
Telephone, mobile	57,2	58,8	60,7	60,8	62,7	63,5	63,7	65,7	66,9
Fax machine	7,1	7,9	7,1	6,9	8,9				
Personal computer	47,1	50,6	53,2	56,8	60,2	62,8	71,9	76,1	80,3
PC, fixed	29,6	29,5	28,5	27,7	24,4	24,2	23,1	22,9	22,7
PC, mobile	17,4	21,1	24,7	29,1	35,8	38,6	48,8	53,2	57,6
Internet access	26,7	28,3	30,5	40,9					
Car navigation	10,6	13,3	15,9	17,6	19,8	20,1	20,9	22,1	22,2

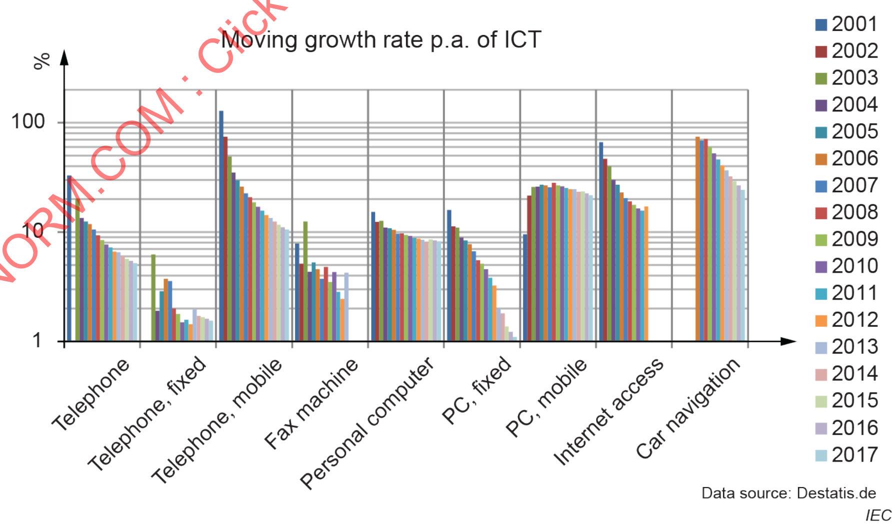
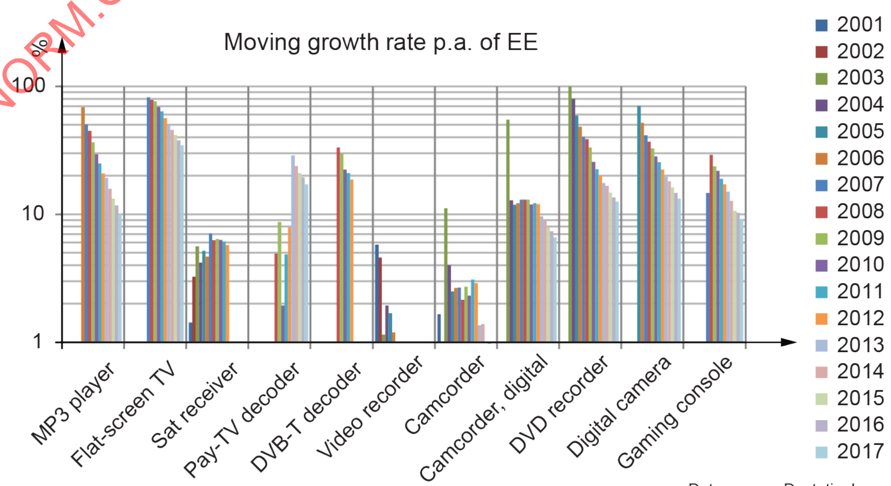


Figure 13 – Growth rates of product ownership of ICT

Table 4 – Product ownership of entertainment electronics

Entertainment electronics (EE)	2000	2001	2002	2003	2004	2005	2006	2007	2008
Households projected (1 000)	34 390	34 777	35 009	35 192	35 375	35 528	35 555	35 887	36 175
Share of the households in percent (equipment rate)									
MP3 player						14,7%	22,8%	29,0%	37,3%
Flat-screen TV							5,0%	9,3%	15,7%
Sat receiver	31,5%	31,7%	33,2%	36,8%	36,7%	39,0%	40,3%	39,1%	39,1%
Pay-TV decoder								4,4%	4,7%
DVB-T decoder								11,9%	16,2%
Video recorder	65,9%	68,6%	68,9%	67,8%	69,7%	70,1%	69,4%		
Camcorder	18,0%	18,2%		21,9%	19,8%	19,4%	19,7%	20,0%	19,5%
Camcorder, digital			4,7%	7,0%	6,1%	6,6%	7,5%	8,6%	9,7%
DVD recorder			14,1%	27,1%	36,4%	50,1%	59,3%	62,9%	69,1%
Digital camera					19,4%	31,9%	41,8%	48,7%	58,3%
Gaming console							14,4%	14,9%	19,4%
Number of the goods in millions									
MP3 player						6,6	11,1	14,9	20,0
Flat-screen TV							2,0	3,6	6,3
Sat receiver	11,6	11,8	12,4	13,7	13,7	15,0	15,3	18,7	18,9
Pay-TV decoder								1,8	1,8
DVB-T decoder								5,1	6,8
Video recorder	27,7	29,3	30,3	28,6	29,9	30,1	29,7		
Camcorder	6,5	6,6		9,0	7,6	7,4	7,6	7,9	7,7
Camcorder, digital			1,8	2,7	2,2	2,5	2,8	3,2	3,7
DVD recorder			5,6	11,1	18,0	22,5	26,9	30,2	39,5
Digital camera					7,5	12,8	17,4	21,3	26,5
Gaming console							6,5	7,5	10,9
Entertainment electronics (EE)	2009	2010	2011	2012	2013	2014	2015	2016	2017
Households projected (1 000)	36 462	36 521	36 640	36 701	36 522	36 343	36 650	37 207	37 381
Share of the households in percent (equipment rate)									
MP3 player	39,8%	41,2%	42,3%	42,2%	45,3%	44,0%	41,4%	40,3%	37,7%
Flat-screen TV	25,8%	36,7%	48,7%	58,9%	67,1%	76,4%	81,3%	84,4%	86,9%
Sat receiver	39,9%	41,0%	42,1%	43,0%	44,6%	42,9%	45,9%	47,3%	47,0%
Pay-TV decoder	5,3%	4,7%	5,2%	6,3%	17,7%	17,6%	17,9%	19,1%	19,0%
DVB-T decoder	19,9%	21,4%	24,6%	27,2%	18,1%	17,9%	16,7%	15,8%	15,1%
Video recorder									
Camcorder	20,4%	20,0%	21,6%	22,0%	18,8%	19,0%	18,3%	17,8%	17,3%
Camcorder, digital	10,9%	11,4%	12,8%	14,0%	12,4%	12,5%	11,9%	12,0%	11,5%
DVD recorder	71,6%	70,8%	71,3%	72,2%	70,8%	74,7%	67,0%	65,3%	64,5%
Digital camera	64,1%	67,7%	71,7%	72,8%	73,3%	75,6%	75,1%	73,6%	72,1%
Gaming console	20,3%	22,5%	23,9%	25,5%	27,8%	26,7%	25,3%	25,8%	26,1%
Number of the goods in millions									
MP3 player	22,8	23,9	25,0	24,7	26,8	24,6	22,7	22,2	20,7
Flat-screen TV	10,9	16,3	23,3	29,2	34,0	40,6	45,3	49,3	52,5
Sat receiver	20,3	21,4	22,3	22,8					
Pay-TV decoder	2,1	1,9	2,1	2,6	8,0	7,8	8,1	8,7	8,6
DVB-T decoder	8,6	9,4	11,0	12,1					
Video recorder									
Camcorder	8,3	8,2	9,1	9,2	7,8	7,9	7,6	7,6	7,4
Camcorder, digital	4,1	4,3	4,9	5,4	4,8	4,9	4,7	4,7	4,6
DVD recorder	41,6	34,5	34,5	34,6	32,9	35,5	33,4	32,9	32,8
Digital camera	31,0	33,5	36,9	37,9	38,1	39,6	39,3	39,1	38,1
Gaming console	12,3	14,3	15,5	16,8	17,3	16,9	16,1	17,3	17,2



Data source: Destatis.de

IEC

Figure 14 – Growth rates of product ownership of entertainment electronics

5.3.4 Capital-income ratio in rich industrial countries

A measure of prosperity and development is the market value of the private capital national income ratio according to [5]. It describes the relation of private capital stock K to national income Y per year according to Formula (10). In the rich industrial countries[6] the private capital national income ratio in the last decades amounts to approximately 600 %. That is the private capital stock which corresponds to six times the annual national income (see Figure 15). The annual national income, equal to the national output Y of the economy is the sum from investments I, consumption C, government expenditure G and the net export $EX./.IM$ according to Formula (11). The national output from capital K and labour L is generated by a production function according to Formula (12). The drivers of the development of capital stock K and income Y are an investment rate (savings rate s) and growth rate g of the output Y. Hence, the development of the private capital national income ratio corresponds in the long term β also to the relation of savings rate s to growth rate g according to Formula (13). The level of the savings rate s in the countries studied varies between 10 % to 14 %. The annual growth rate g of the economy, taking into account the population, is in the order of 2 % per year. Accordingly, therefore, the aggregated private capital stock K is from 5 times to 6 times the annual national income Y. The capital share α of the national income is calculated from the capital income return r and the private capital national income ratio β according to Formula (14), represented by the capital income national income ratio. Typically the long-term capital income returns r lie at approximately 6 %, which corresponds to a private capital national income situation β of 5 to 7 to a capital share α of approximately 30 % to 36 % (see Figure 16). With an assumed Cobb-Douglas production function with a substitution elasticity between capital and labour of $\in = 1$ the capital income national income rate α would become and remain steady, i.e. a sinking capital income return r would become compensated proportionally by a rising private capital national income rate β. Nevertheless, labour L is edged out in the long term by a steadily rising level of automation by capital K. Therefore, the time series according to [5] also show a substitution elasticity of $\in > 1$which is due to the fact that the capital income return r sinks more slowly than the private capital national income rate β rises. In the outcome of that model and empirical evidence, the private capital national income relation rises consecutively.

$$\beta = \frac{K}{Y} \tag{10}$$

$$Y = I + C + G + \left(EX./.IM\right) \tag{11}$$

$$Y = f(K, L) \tag{12}$$

$$\beta = \frac{s}{g} \tag{13}$$

$$\alpha = r \cdot \beta \tag{14}$$

6 AU, US, CA, JP, UK, FR, IT and DE.

The conclusion from the indicated development is that economic growth development has an impact on technology movements. At first, growth generates private and national consumption. In addition, the capital stock grows, which generates production again.

Therefore, a steady but moderate increase of the numbers of pieces of electric appliances can be expected. Further this can be expected from faster growing technology movement (shorter development times) on grounds of the increasing level of automation.

Finally an increased diversity of electrical products and technologies can be expected, because spill-over effects again produce innovations. Observing, however, that many new (electrical) technologies employ established methods to convert AC power to the electricity needed to drive the new technology products, it is unclear as to how much these new technologies will affect the aggregate phase angles of harmonic emissions.

Considering the impact on the prevailing phase angle from certain technologies, the development of new technologies will always be driven by capital and markets. As the foregoing analysis clearly shows, these developments have been rather gradual in the last 10 years to 20 years. Therefore, no major shift in patterns is expected in the next 10 years, even though economic recessions can temporarily cause what appear to be significant changes or transitions.

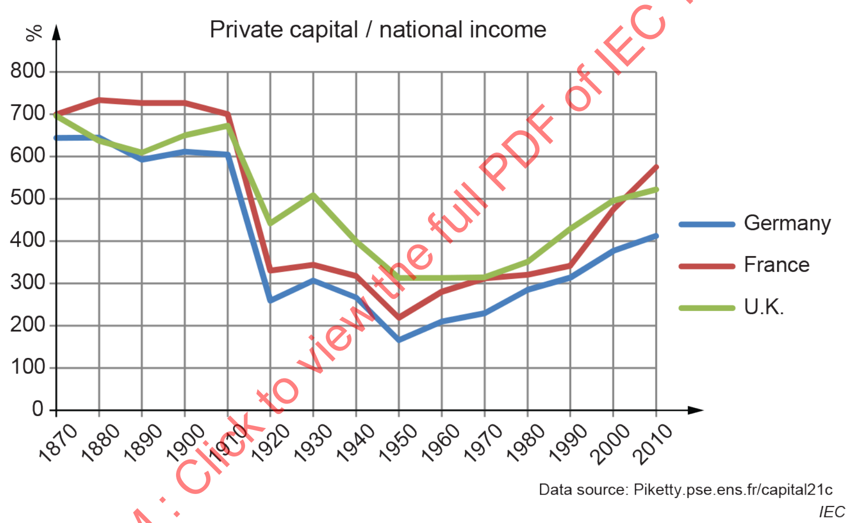


Figure 15 – Capital income ratio [5]

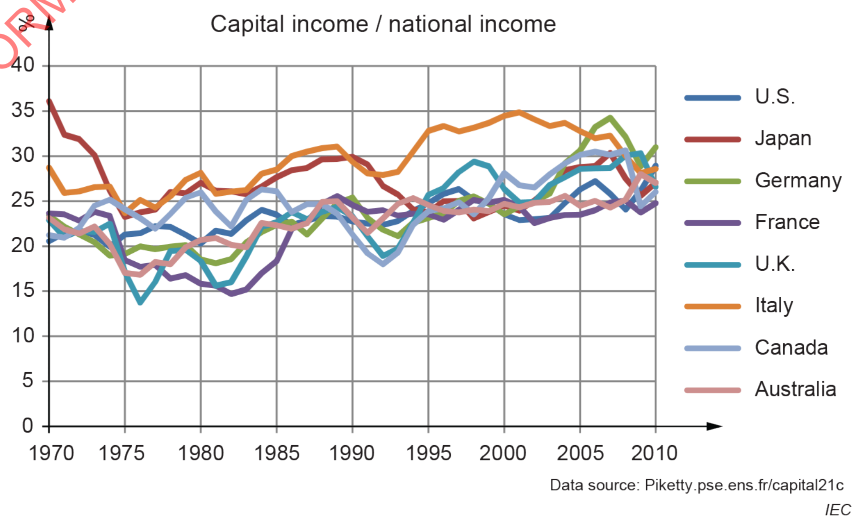


Figure 16 – Capital share of national income [5]

6 Data evaluation concepts and principles

6.1 Concept of data evaluation

The measurement data from a total of 439 measuring days (aggregate from 16 locations) contain approximately 1 million single measurement data sets. The measuring process with time stamp and local information includes a single measurement set along with non-electric characteristics of the particular measurement site. These characteristics are taken from rather detailed databases that are maintained by the network operating authority. Therefore a complete picture is formed of the network structure, size (distance from distribution transformers) and load characteristics.

From the native data (three-phase single measurements of current and voltage), a set of values is derived (calculated):

- phase-neutral voltage (RMS)
- phase current (RMS)
- active power
- reactive power
- apparent power
- power-factor
- cosine φ (fundamental oscillation of voltage and current)
- measurement values of the 2nd harmonic up to the 50th harmonic
  - amplitudes of the harmonic voltages (RMS)
  - amplitudes of the harmonic currents (RMS)
  - phase angles of current harmonics (referenced to the positive zero crossing of the voltage – fundamental).
- total harmonic distortion of the voltage in percent (V-THD in %)
- total harmonic distortion of the current in percent (I-THD in %)
- total harmonic distortion of the current in ampere (I-THC in A)

All measured and derived data (1 million single measurements × number of derived quantities in the set) were transformed into a data format compatible with ***imc***[7] and were stored in a database. By means of an ***imc*** specific script language, modules can be accessed in the whole data pool and analysed/presented in various ways. Analysis methods were developed to present the large amount of data in a comprehensive format, identify abnormalities, and process data statistically. The objective, of course, is to be able to derive meaningful conclusions.

The data analysis essentially includes:

a) time series
  - diurnal (daily) cycle in time windows of 24 h for all days of the whole measuring period
  - minima and maxima envelopes curve of all diurnal cycles in a 24 h time window

b) histogram

c) cumulative frequency distribution

[7] ***imc*** is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

The data analysing software was used with one's own application-specific modules in scripting language.

d) spectra including frequency
e) prevailing angle in polar co-ordinates
f) prevailing vector
g) correlation factors
h) sliding correlation
i) correlation of complex values

The data stream (magnitudes or phases angles) was visualised as a time series in time windows of 24 h in each case. As a rule the measuring duration at individual test sites varies from approximately 30 days to 45 days. Therefore, parameter variations, according to load and generator structure, can be identified and/or correlated against time of day and/or day of the week. The different users' behaviour can therefore clearly be identified between working days and holidays/weekends from the time-variation curves. The information, therefore, may be used to identify causality between harmonics and users' behaviour in the load structure.

In addition the minimum and maximum values are accurately determined from all 30 days to 45 days measurement data (level or phase angles) and envelope curves were calculated for every daily measurement set (1 440 points). The advantage of this method is that (extreme cases of) user behaviour can be identified from the time-of-day information.

The representation in histograms delivers the information of the frequency distributions of the measured or calculated values. On the abscissa the absolute values (level or phase angles) are shown. The ordinate shows the frequencies of the occurrences of specific values in percent. Thus it is possible to directly determine which values occur with the highest frequencies and whether the occurrences of different variables are similarly-distributed or show different central values.

The representation of the sum frequency delivers the additional information of the accumulated frequency of the measured or calculated values compared with the histogram. On the abscissa the absolute values (level or phases angles) are used. The ordinate shows the accumulated frequency of the occurrences in percent. This method provides an easy way to assess the cumulative distribution up to specific values. For example, 60 % of all values are smaller than 230 A, or values greater than 320 A appear only as 10 % of all values.

The harmonics amplitudes are also presented in spectrum format, generally up to the 50th harmonic (2,5 kHz). The spectral values are colour coded to include information about the cumulative distribution for each of the harmonic amplitudes. The dark blue colour identifies the level that is present 50 % of the time. The red colour identifies values that occur 5 % of the time, the orange bar applies to the distribution frequency of 1 % and the light blue bar identifies values that occur 0,1 % of the time.

Given the detailed data with time stamps for each parameter, it is possible to compute correlation factors between amplitude and phase of a given harmonic (H5 mainly) or between H5 and the I-THD, or between H5 amplitude and power, etc. The various correlation factors are displayed in the classical manner on a scale from -1 to +1.

If one lets a time window of the same length of two time series run in defined time steps, one receives a sliding correlation factor, like a sliding average value. This process was carried out in steps of 1 h and in steps of 1 day. A calculation of the correlation factor about the whole time series of, for example, 20 days to 30 days reveals a result that is not easily interpreted nor provides useful information.

6.2 Principles of statistical survey

6.2.1 Correlation

Correlations and correlation factors can be calculated easily from two time series of the same length. If the time series consist of complex numbers, the calculation of the correlation factor with only one component is problematic as a substitute for the scalar time series. The amplitudes can vary, and this can affect the phase angle values, but not always. Thus, for the purpose of the correlation factor calculation, both parameters need to be taken into consideration.

Furthermore there is a problem with the phase angle having a discontinuity – i.e. a jump – from 360° to 0°. Even though two consecutive phase angles may be 2° apart, from 359° to 1° numerical processing will show a large transition. These apparent jumps in the phase angle therefore complicate a sensible interpretation of calculated correlation factors. A secure interpretation of the correlation factors is possible only in temporal segments of the time series in which no change of 360° takes place to 0° or vice versa. An approach to resolve these problems is to transfer the application of the generally-known arithmetic processes to the variance, covariance and correlation factors for scalar time series as a complex time series.

6.2.2 Review of correlation coefficient calculation with complex numerical series

In general the variance of an array of scalar elements can be calculated according to Formula (15), provided that the time series of the scalar numbers has a Gaussian distribution.

$$\text{var}(X) = E\left[(X-\mu)^2\right] \tag{15}$$

$$\mu_x = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{16}$$

$$\text{var}(x) = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \mu_x\right)^2 \tag{17}$$

$$\sigma_x = \sqrt{\text{var}(x)} \tag{18}$$

The mathematical expression μ_x of a time series corresponds to the arithmetic average value of the time series with n elements according to Formula (16). Therefore the variance calculates for discrete values from the average value of the square deviations between the observed values x_i and their mathematical expectation μ_x according to Formula (17). The standard deviation of the time series is defined according to Formula (18) as the square root of the variance (17).

Similar to the calculation of the variance, the covariance calculates from the average value of the deviations between the observed values x_i and y_i as well as their respective mathematical expectation. Instead of the square of the deviations, the product of the deviations from two different time series x and y is used, see Formula (19). The variance can be also interpreted as a covariance with itself.

$$\text{cov}(x,y) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_x)\cdot(y_i - \mu_y) \tag{19}$$

The correlation factor as an absolute measure of the correlation is, according to Formula (20), a general manner of writing the ratio of the covariance and the product of the standard deviations.

$$\rho_{x,y} = \text{corr}(x,y) = \frac{\text{cov}(x,y)}{\sigma_x \cdot \sigma_y} \tag{20}$$

$$\text{corr}(x,y) = \frac{\sum_{i=1}^{n}(x_i - \mu_x)\cdot(y_i - \mu_y)}{\sqrt{\sum_{i=1}^{n}(x_i - \mu_x)^2 \cdot \sum_{i=1}^{n}(y_i - \mu_y)^2}} \tag{21}$$

If Formulae (17) and (19) are used in Formula (20), the correlation factor follows for discrete values according to Formula (21). Formula (21) can be significantly simplified, if the time series are transformed to time series with zero average value. The average value of the time series is subtracted from each term of the series, see Formula (22).

$$x_{\text{zero\_mean}} = x - \overline{x} \tag{22}$$

The mathematical expectations μ_x and μ_y of the time series become zero. Thus the variance simplifies to the quadratic mean (average of the squared values) of the observed values of Formula (23) and the covariance simplifies to the average value of the product of the observed values of Formula (24). The simplified Formulae (23) and (24) in Formula (20) use the simple form of the correlation factor for discrete observed values according to Formula (24).

$$\text{var}(x) = \frac{1}{n-1}\sum_{i=1}^{n} x_i^2 \tag{23}$$

$$\text{cov}(x,y) = \frac{1}{n-1}\sum_{i=1}^{n} x_i \cdot y_i \tag{24}$$

$$\text{corr}(x,y) = \frac{\sum_{i=1}^{n} x_i \cdot y_i}{\sqrt{\sum_{i=1}^{n} x_i^2 \cdot \sum_{i=1}^{n} y_i^2}} \tag{24}$$

Assuming that a time series $\underline{x}_i$ consists of n complex vectors $\underline{x} = a_x + jb_x$, the vectoral average according to Formula (25) applies to the complex mathematical expectation $\underline{\mu}_x$. This vectoral average value is calculated from the arithmetic average values of the real parts and the imaginary parts of the time series.

$$\underline{\mu}_x = \frac{1}{n}\sum_{i=1}^{n}\text{Re}(\underline{x}_i) + j\frac{1}{n}\sum_{i=1}^{n}\text{Im}(\underline{x}_i) \tag{25}$$

$$\underline{x}_{\text{zero\_mean}} = \underline{x} - \underline{\mu}_x \tag{26}$$

After transformation in Formula (26) of the time series with complex measured values to a time series adjusted by subtracting the average value calculated with Formula (25), the simplified approach results in the variance according to Formula (27) and covariance according to Formula (28). Now the complex variance is the square average value of the time series with complex observed values. Analog to this approach, the complex covariance is determined from the average value of the complex products.

$$\text{var}(\underline{x}) = \frac{1}{n-1}\sum_{i=1}^{n}(a_x + jb_x)_i^2 \tag{27}$$

$$\text{cov}(\underline{x},\underline{y}) = \frac{1}{n-1}\sum_{i=1}^{n}(a_x + jb_x)_i \cdot (a_y + jb_y)_i \tag{28}$$

$$\text{corr}(\underline{x},\underline{y}) = \frac{\sum_{i=1}^{n}(a_x + jb_x)_i \cdot (a_y + jb_y)_i}{\sqrt{\sum_{i=1}^{n}(a_x + jb_x)_i^2 \cdot \sum_{i=1}^{n}(a_y + jb_y)_i^2}} \tag{29}$$

Formulae (27) and (28) used in Formula (20) then result in a simplified method of deriving the complex correlation factor (29) which shows the ratio of the complex covariance and the product of the complex standard deviations. Because the complex correlation factor (29) is impracticable for interpretation purposes, this is transformed into the mathematical expression shown in Formula (30).

$$\text{corr}(\underline{x},\underline{y}) = c_{xy} + jd_{xy} = \sqrt{c_{xy}^2 + d_{xy}^2} \cdot e^{j\tan^{-1} d_{xy}/c_{xy}} = K \cdot e^{j\varphi_K} \tag{30}$$

Finally, the real part, imaginary part, magnitude and angle can be separated from the complex correlation factor and used for a comparison of correlation factors from different time series, each with complex observed values.

To obtain a scalar value as a correlation factor, compare either the real part (31) or the imaginary part (32) of the complex time series $\underline{x}_i$ to the time series y_i, which consists of scalar observed values. Both correlation factors (31) and (32) should deliver similar values.

$$\text{corr}\left[\text{Re}(\underline{x}),y\right]=\frac{\sum_{i=1}^{n}\text{Re}(\underline{x}_i)\cdot y_i}{\sqrt{\sum_{i=1}^{n}\text{Re}(\underline{x}_i)^2\cdot\sum_{i=1}^{n}y_i^2}} \tag{31}$$

$$\text{corr}\left[\text{Im}(\underline{x}),y\right]=\frac{\sum_{i=1}^{n}\text{Im}(\underline{x}_i)\cdot y_i}{\sqrt{\sum_{i=1}^{n}\text{Im}(\underline{x}_i)^2\cdot\sum_{i=1}^{n}y_i^2}} \tag{32}$$

Furthermore the comparisons between the real parts and imaginary parts of the time series $\underline{x}_i$ in combination with the real part and imaginary part of the time series $\underline{y}_i$ also deliver useful scalar correlation factors (33), (34) and (35).

$$\text{corr}\left[\text{Re}(\underline{x}),\text{Re}(\underline{y})\right]=\frac{\sum_{i=1}^{n}\text{Re}(\underline{x}_i)\cdot\text{Re}(\underline{y}_i)}{\sqrt{\sum_{i=1}^{n}\text{Re}(\underline{x}_i)^2\cdot\sum_{i=1}^{n}\text{Re}(\underline{y}_i)^2}} \tag{33}$$

$$\text{corr}\left[\text{Re}(\underline{x}),\text{Im}(\underline{y})\right]=\frac{\sum_{i=1}^{n}\text{Re}(\underline{x}_i)\cdot\text{Im}(\underline{y}_i)}{\sqrt{\sum_{i=1}^{n}\text{Re}(\underline{x}_i)^2\cdot\sum_{i=1}^{n}\text{Im}(\underline{y}_i)^2}} \tag{34}$$

$$\text{corr}\left[\text{Im}(\underline{x}),\text{Re}(\underline{y})\right]=\frac{\sum_{i=1}^{n}\text{Im}(\underline{x}_i)\cdot\text{Re}(\underline{y}_i)}{\sqrt{\sum_{i=1}^{n}\text{Im}(\underline{x}_i)^2\cdot\sum_{i=1}^{n}\text{Re}(\underline{y}_i)^2}} \tag{35}$$

6.2.3 Prevailing phase angle and prevailing vector

The vectoral sum (36) of a complex value series is derived from the sum of all real parts and the sum of all imaginary parts. Therefore, the angle (37) of the vectoral sum is calculated from the arctangent of the quotient of the sum of all imaginary parts and the sum of all real parts. Also, the amplitude (39) of the vectoral sum is calculated from the square root of the squared sum of all real parts plus the squared sum of all imaginary parts.

$$\underline{x}_{\text{vs}} = \sum_{i=1}^{n} \text{Re}\left(\underline{x}_i\right) + j\sum_{i=1}^{n} \text{Im}\left(\underline{x}_i\right) \quad (36)$$

$$x_{\text{vs\_ph}} = \tan^{-1}\left(\frac{\sum_{i=1}^{n} \text{Im}\left(\underline{x}_i\right)}{\sum_{i=1}^{n} \text{Re}\left(\underline{x}_i\right)}\right) \quad (37)$$

$$x_{\text{vs\_mg}} = \sqrt{\left(\sum_{i=1}^{n} \text{Re}\left(\underline{x}_i\right)\right)^2 + \left(\sum_{i=1}^{n} \text{Im}\left(\underline{x}_i\right)\right)^2} \quad (39)$$

From the definition of an averaged vector, a prevailing vector can be said to exist if the arithmetic average value of either all real parts or the arithmetic average value of all imaginary parts is non-zero. Nevertheless, the application of this definition can result in a somewhat less representative outcome than the use of the quadratic mean value (38) of all magnitudes (RMS value of the magnitudes $\left|\left(\underline{x}_i\right)^2\right|$) and the application of the angle (37) from the vectoral sum. This above mentioned angle is the prevailing phase angle. The square root of the quadratic mean value is generally according to Formula (38), and is applicable for every current harmonic $\underline{I}_h = I_h \cdot e^{j\varphi_h}$ of the order h determined according to Formula (39).

$$x_{\text{qm}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\left(\underline{x}_i\right)^2\right|} \quad (38) \qquad I_{\text{qm}}^h = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(I_i^h\right)^2} \quad (39)$$

$$\underline{x}_{\text{pv}} = x_{\text{qm}} \cdot e^{jx_{\text{vs\_ph}}} \quad (40)$$

From a series of n vectors (harmonics of a certain order) a prevailing vector $\underline{x}_{\text{pv}}$ can be calculated according to Formula (40) and represented graphically. However, for such a series of vectors that are diverse in phase angle, the prevailing vector amplitude is only a small fraction of individual vector amplitudes. One can set a minimum ratio per (43) as a measure to determine that the prevailing vector is deemed representative for a given situation. Also, the dispersion factor in accordance with (44) can be considered as weighting factor. The in-phase factor according to (43) is the ratio between the magnitude of the vectoral sum (39) and the arithmetic sum (41) of the magnitudes of all observed vectors. This ratio can be computed for any harmonic h according to Formula (42).

$$x_{\text{as\_mg}} = \sum_{i=1}^{n}\left|\left(\underline{x}_i\right)\right| \quad (41) \qquad I_{\text{as\_mg}}^h = \sum_{i=1}^{n} I_i^h \quad (42)$$

$$r_{\text{in\_phase}} = \frac{x_{\text{vs\_mg}}}{x_{\text{as\_mg}}} \quad (43)$$

$$r_{\text{disp\_phase}} = 1 - \frac{x_{\text{vs\_mg}}}{x_{\text{as\_mg}}} \tag{44}$$

The value of the dispersion factor according to Formula (44) is merely the value of the in-phase factor subtracted from unity (43). This ratio therefore might have a value near 1, for a situation where vectors in a time series have a large variation in phase, but the ratio is near 0 where there is very little diversity between the vector phase angles in a time series.

Figure 17 shows a theoretical example where four observations (vector dots) were summarised to a prevailing vector (arrow). In this case the prevailing vector is representative, i.e. it indicates that the individual vector values are in the same general phase range. On the other hand, Figure 18 shows an example with a wide diversity between four individual vector values. The prevailing vector is not representative, if we assume a decision criterion where it is required to have an in-phase factor greater than 0,9 or – differently expressed – a dispersion factor smaller than 0,1. The weighting factors are compared in Table 5.

Table 5 – Example of weighting factor for a prevailing vector

	Example according to Figure 17	Example according to Figure 18
In-phase-factor	0,955 9	0,289 6
Dispersion factor	0,044 1	0,710 4
Interpretation	representative	unrepresentative

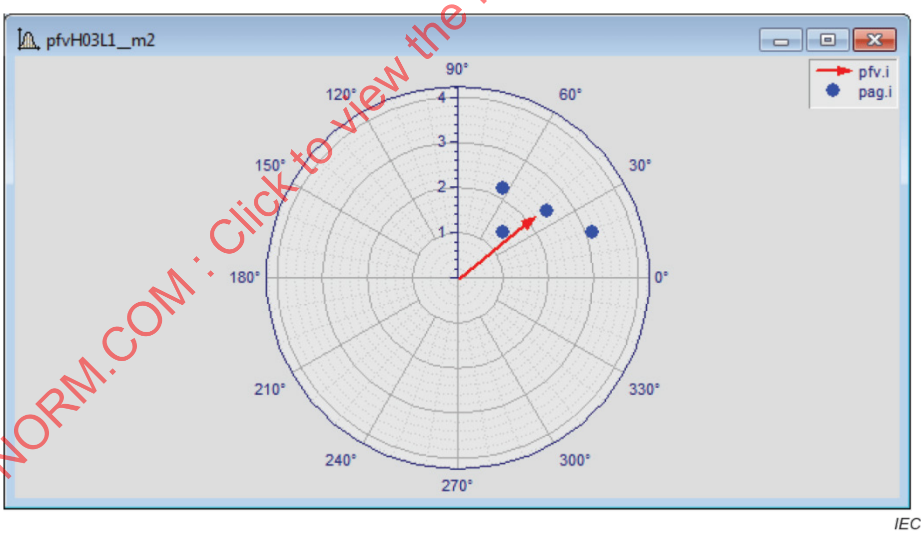


Figure 17 – Representative prevailing vector

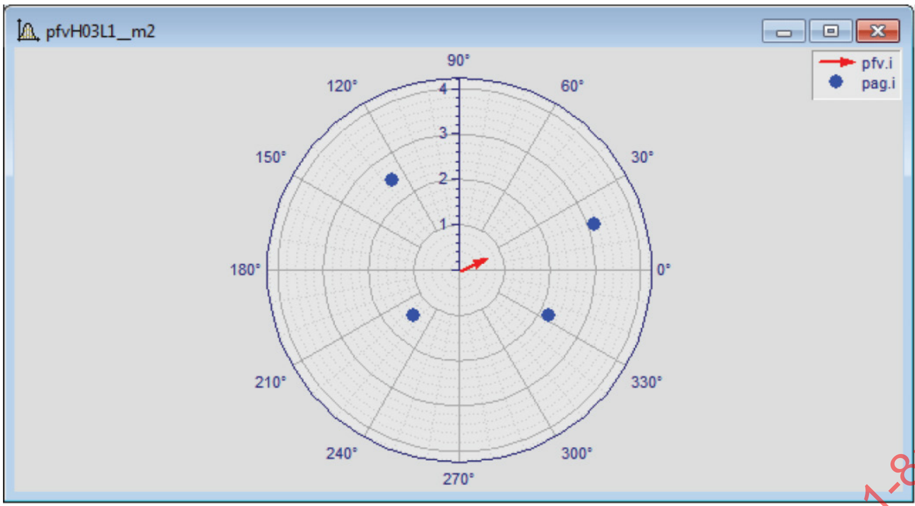


Figure 18 – Unrepresentative prevailing vector

7 Detailed analysis of data

7.1 Overview

All measurement data, initial conclusions, and additional details were introduced in three successive reports. For M1 to M8, the report was [6], for the test sites M9 to M12 the report was that of [7] and for the test sites M13 to M16 the report was that of [8].

7.2 Time series analysis of electrical basic parameters and concept of statistical survey

The time series of voltages and currents, visualised in time windows of 24 h in each case, delivered typical diurnal (daily) cycle patterns according to the load structure and generator structure. The different users' behaviour can be clearly identified from the diurnal cycle lines between working days and holidays. The residential areas typically show a steady pattern from 08:00 to 16:00, with a small midday deviation, and then a distinctive evening peak demand followed by a “valley” in amplitudes during the night hours. The profiles for office and commercial measurement locations closely follow the time of day where the enterprises/businesses operate. In measurement locations where photovoltaic co-generation is present, changes are observed only when there is enough sun for the solar installations to produce a significant share of electric power, with respect to the rated power of the local network transformer.

The calculated envelope curves for voltage and current, which determine the minimum and maximum from all measuring days precisely for every measuring time of one day (1 440 points), identify time-of-day points of extreme values, which in turn allows conclusions about the users' behaviour. In the voltage curves, increases of photovoltaic feed are identifiable. In the current curves, the behaviour is confirmed according to the different load structures in residential areas, trade and office.

The diurnal cycle for active reactive power and apparent power, as well as the courses of the envelope curves of the minimum values and maximum values, show the behaviour patterns as similar, i.e. they correlate to those of the currents. Identification of the different load structures between residential area, trade and office is unequivocal. Only the diurnal cycles of the reactive powers show little correlation to the load structure and are more or less consistently at low levels. At test sites with high photovoltaic shares, the energy recovery system, i.e. the effective power flow, can easily be identified in the diurnal cycles.

The diurnal cycles of the power factors show minimal fluctuations and lie close to unity, in particular in residential areas. With trade and office, the diurnal cycles are more volatile than observed in residential areas. Only test sites with high photovoltaic contribution register a movement in the power-factor from +1 through zero to -1 and back, during the hours of the changeover from energy consumption to energy feed-in.

The time series of cosine φ show similar results as those obtained for the power-factor. Typical values lie between 0° and 20° for residential areas, for office and trade between 0° and -20°, and for locations with high photovoltaic contribution the values are typically between 30° and 180°. All observations of the volatility in the diurnal cycles and envelope curves are similar to the power-factor. The histograms follow the normal distribution and the sum frequencies run near the ideal S-curve.

The histograms of the voltages correspond to a classical normal distribution. Therefore, the cumulative frequency curves for the voltages show an ideal S-curve. Typically, two central values appear in the frequency histograms of the current, which points to the users' behaviour in residential areas. With the load structures of trade and office there is as a rule only one central value, following a normal distribution. Therefore, the cumulative frequency curves for the currents differ from an ideal S-curve.

7.3 Time series analysis of selected harmonics

Initially, the diurnal cycles of the levels of selected harmonics (3^{rd}, 5^{th} and 7^{th}) were observed. The amplitudes of the harmonic voltages are referred to the fundamental component of the phase-to-neutral voltage. The amplitudes of the harmonic currents are shown as absolute values, as well as relative values referred to the fundamental current component.

The representation of the time series per day and per week allows the assessment of dependence in the context of the time-of-day or related to specific days in the week. The mentioned time windows permit to draw conclusions about specific consumer behaviour and operating technologies in the network.

Figure 19 for example, shows the daily pattern during a work day, for harmonic order 5 in percent (for three phases) at test site M1. The relative percentage levels are higher – as expected – during the night hours with low load compared to the hours of higher load in the afternoon and evening. A similar diurnal pattern is shown for the same location and day, for the amplitudes of the 5^{th} harmonic voltages (Figure 20).

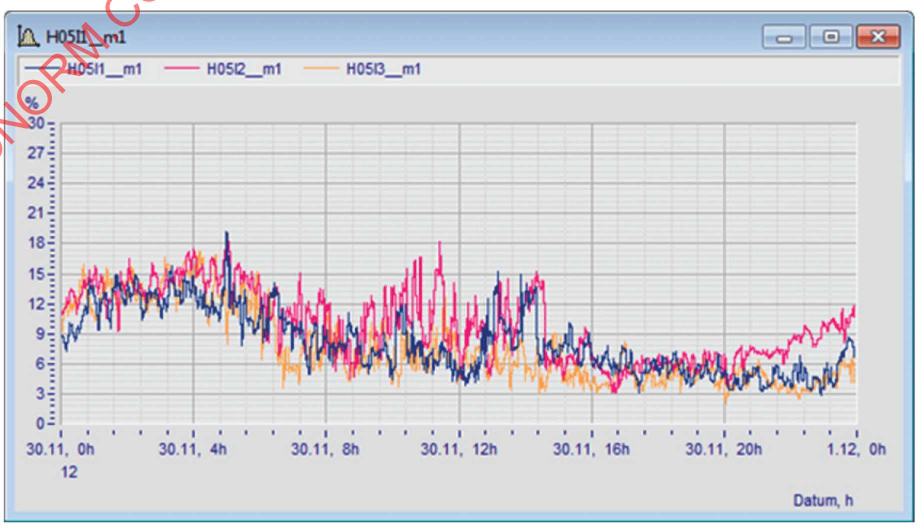


Figure 19 – Diurnal cycle of magnitude of the 5^{th} harmonic current at test site M1

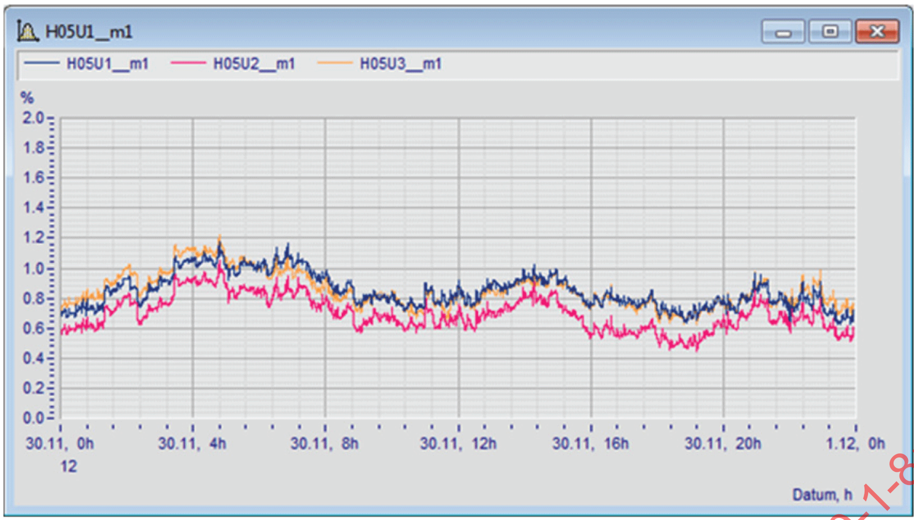


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Figure 20 – Diurnal cycle of magnitude of the 5th harmonic voltage at test site M1

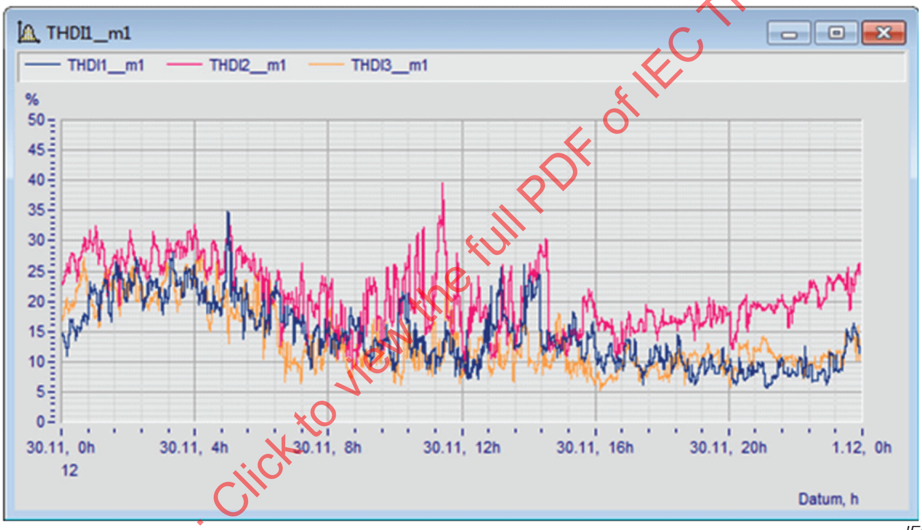

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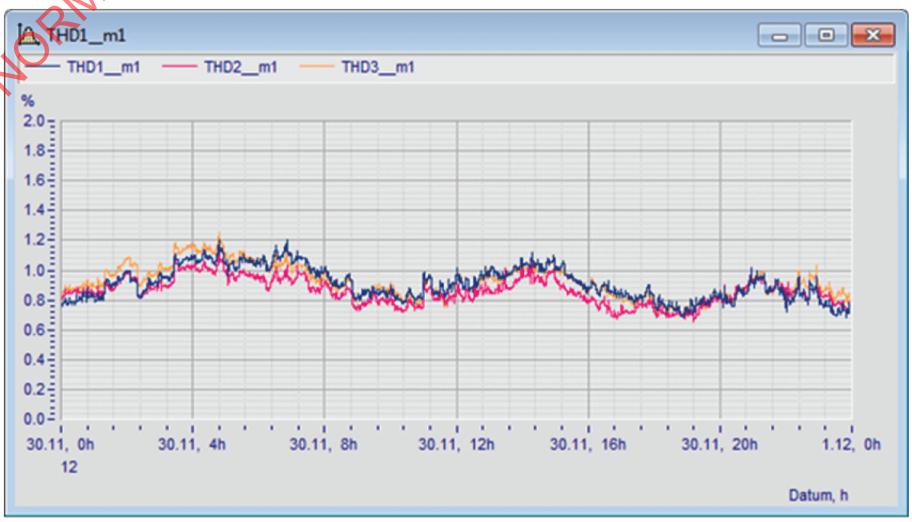
Figure 21 – Diurnal cycle of total harmonic current distortion in percent at test site M1



IEC

Figure 22 – Diurnal cycle of total harmonic voltage distortion in percent at test site M1

If one looks phase-selectively (Phase-1 or THDI1_m1 and THD1_m1)) at the time series of the total harmonic current distortion (Figure 21) and the voltage (Figure 22) in the same work day, somewhat similar trends can be seen.

The calculated 5th harmonic phase envelope curve (Figure 23) of the minima and maxima in the 24-h representation show an inverse correlation with the harmonic current level envelope (Figure 24). The 5th harmonic current level envelope (Figure 24) and the 5th harmonic voltages envelope (Figure 25) also show some correlation for the test site M1. This was observed not only for work days, but over the whole measuring period as well, including when just analysing the 5th harmonics.

The same also applies to the calculated envelope curve of the minima and maxima in the 24-h representation for the total harmonic distortion in the current (Figure 26) and in the voltage (Figure 27) where some correlation is visible.

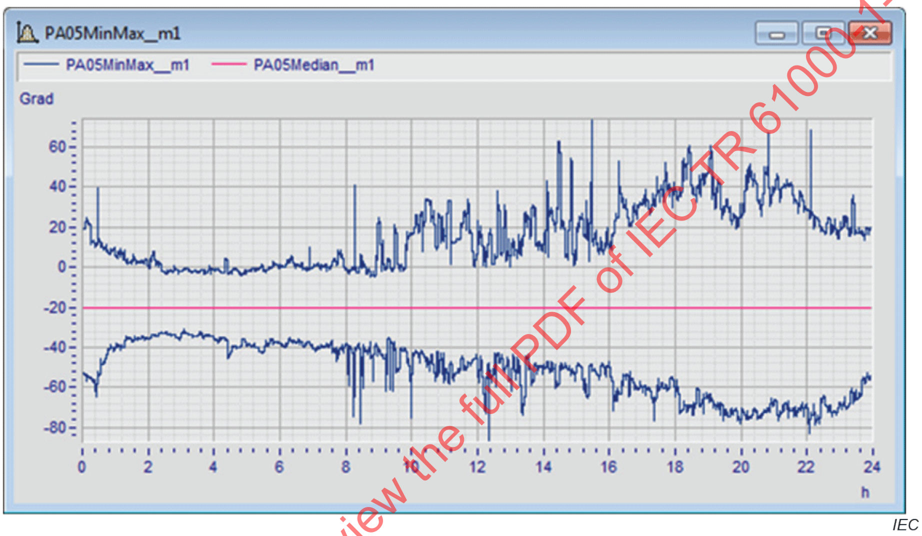


Figure 23 – Minimum-maximum envelope of the 5th harmonic phase angle curve at site M1

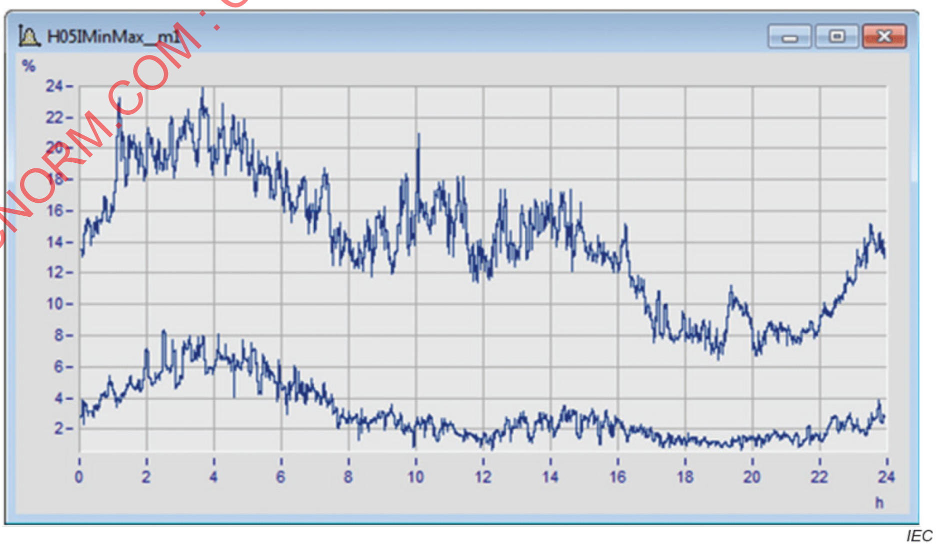


Figure 24 – Minimum-maximum envelope curves of the 5th harmonic current level at site M1

Figure 25 – Minimum-maximum envelope curves of the 5th harmonic voltage level at test site M1

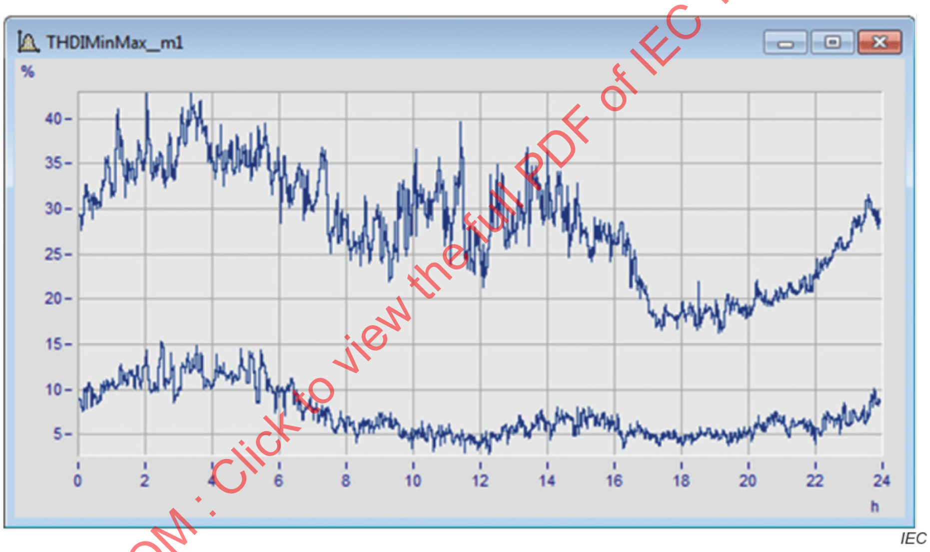


Figure 26 – Minimum-maximum envelope curves of the total harmonic current distortion at site M1

Figure 27 – Minimum-maximum envelope curves of the total harmonic voltage distortion at site M1

The histograms of all 5th harmonic current phase and magnitude (level) measurements (Figure 28 and Figure 29) and 5th harmonic voltages (Figure 30) for test site M1 are relatively wide and the corresponding cumulative-frequency functions of all harmonic current phase angles (Figure 33), harmonic currents (Figure 34), and harmonic voltages (Figure 35) show a flat gradient in the S-curves, which points in general to a large dispersion of the amplitudes. The same also applies to the histograms of the total harmonic distortion in the current (Figure 31) and in the voltage (Figure 32), and the cumulative frequencies of the total harmonic distortion in the current (Figure 36) and in the voltage (Figure 37).

All statements in 7.3 refer to residential area networks. In comparison to the load structures for office and trade, there are no resemblances. In the office and trade load structures, the temporal dependence of the levels strongly follows the business hours of the offices and shops.

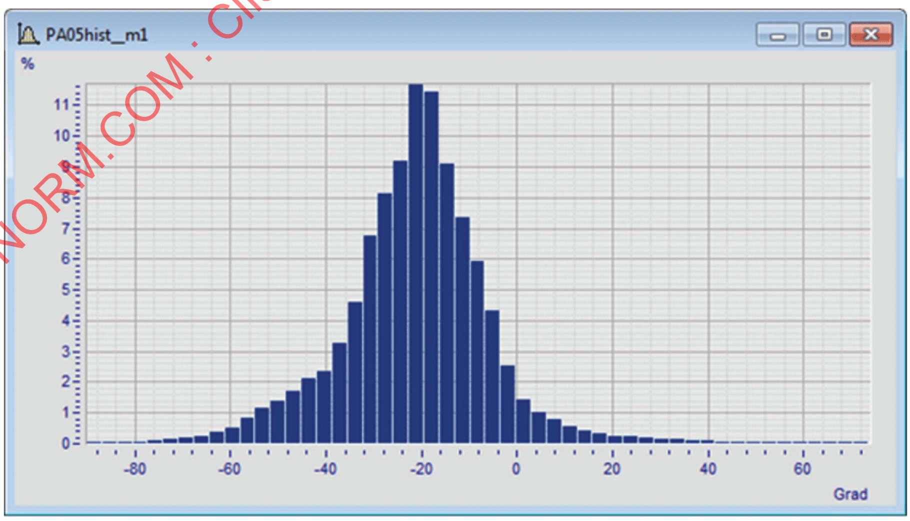


Figure 28 – Histogram of the 5th harmonic current phase angle at test site M1

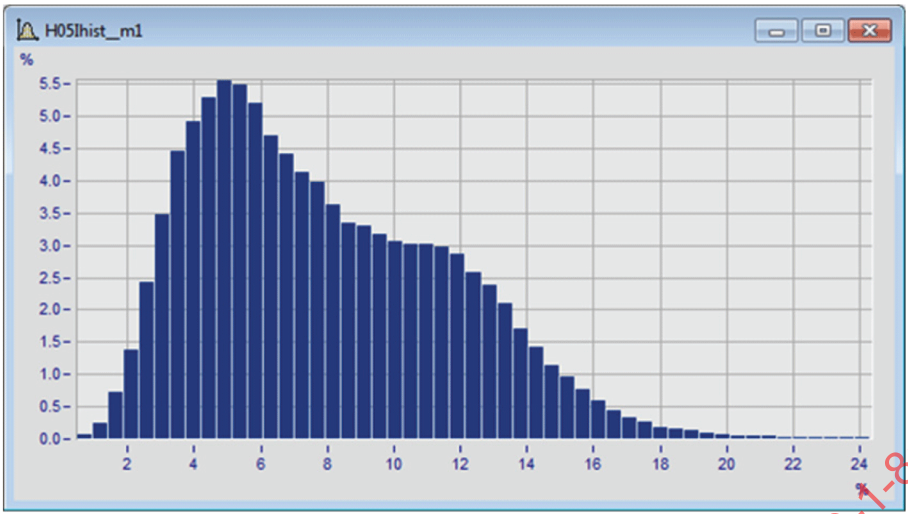


Figure 29 – Histogram of the 5th harmonic current level in percent at test site M1

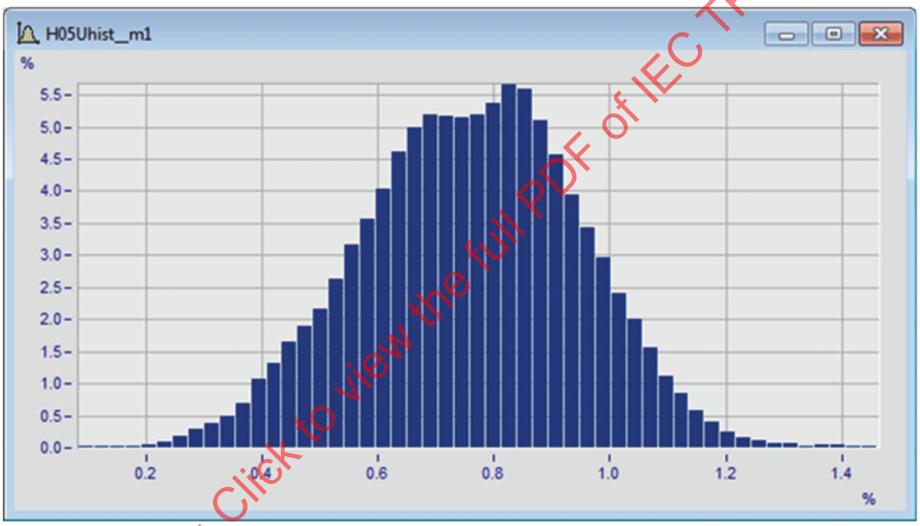


Figure 30 – Histogram of the 5th harmonic voltage level in percent at test site M1

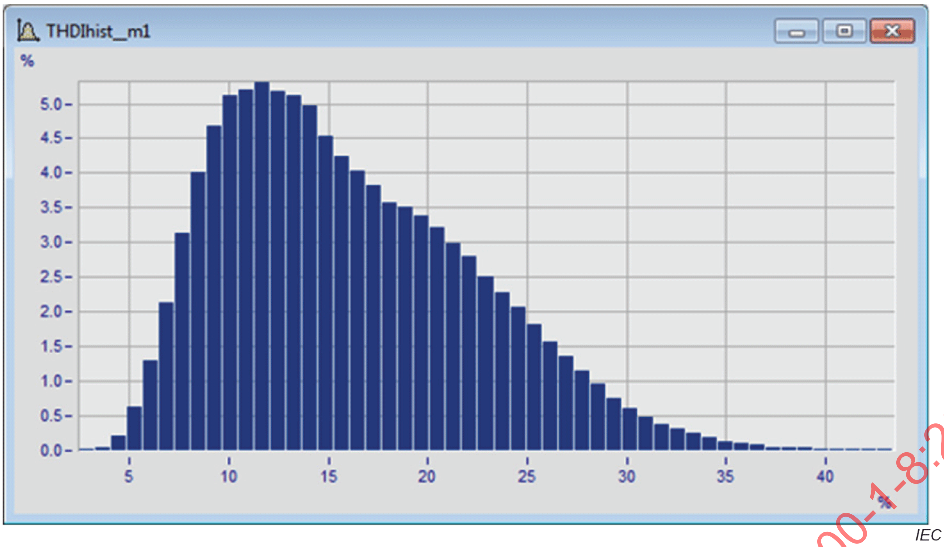


Figure 31 – Histogram of total harmonic current distortion in percent at test site M1

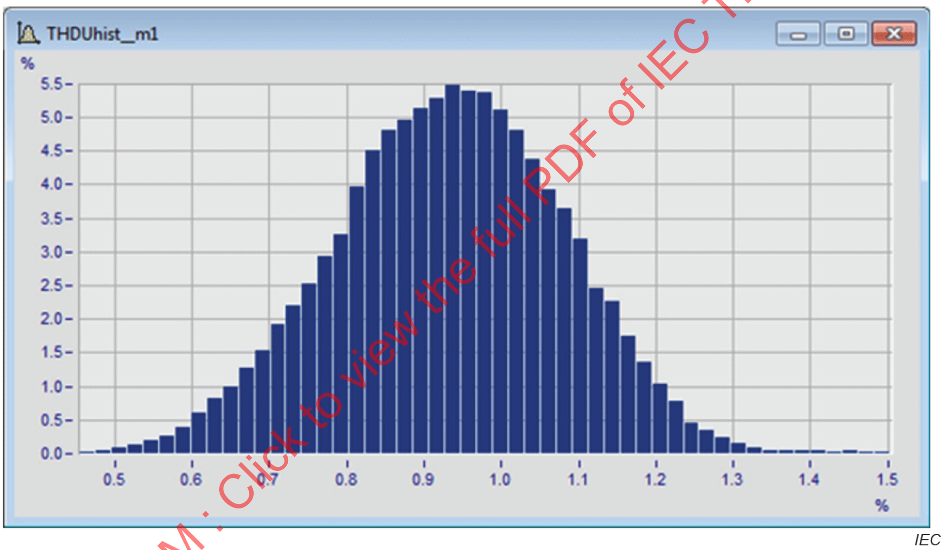


Figure 32 – Histogram of total harmonic voltage distortion in percent at test site M1

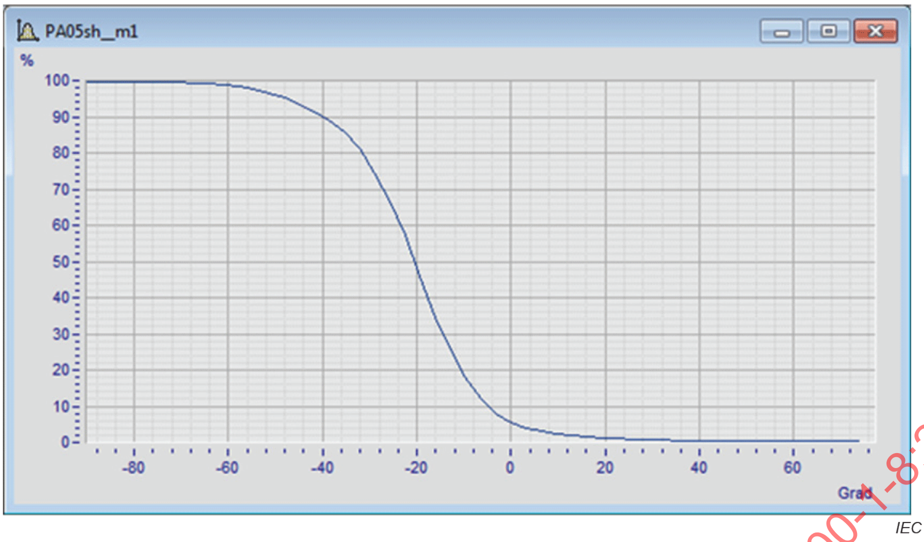


Figure 33 – Cumulative frequency of the 5th harmonic current phase angle at site M1

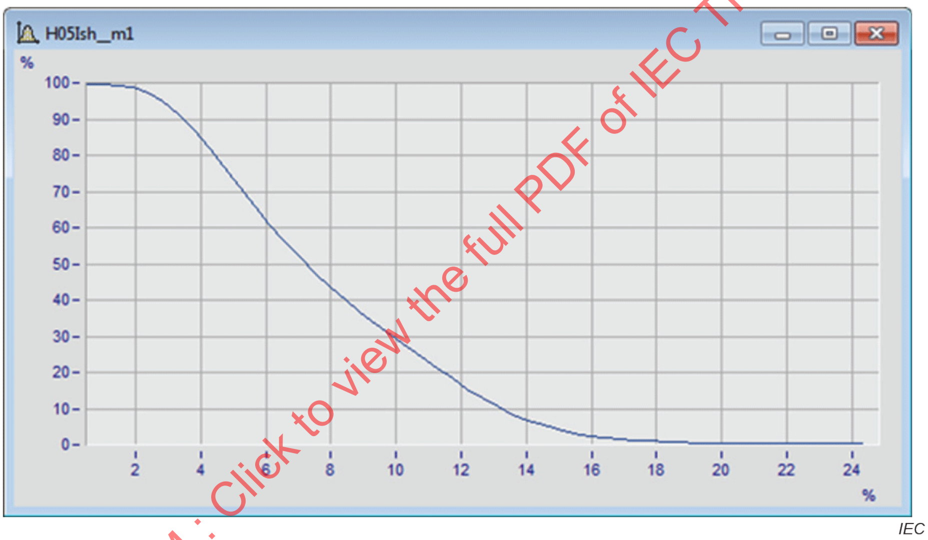


Figure 34 – Cumulative frequency of the 5th harmonic current level at test site M1

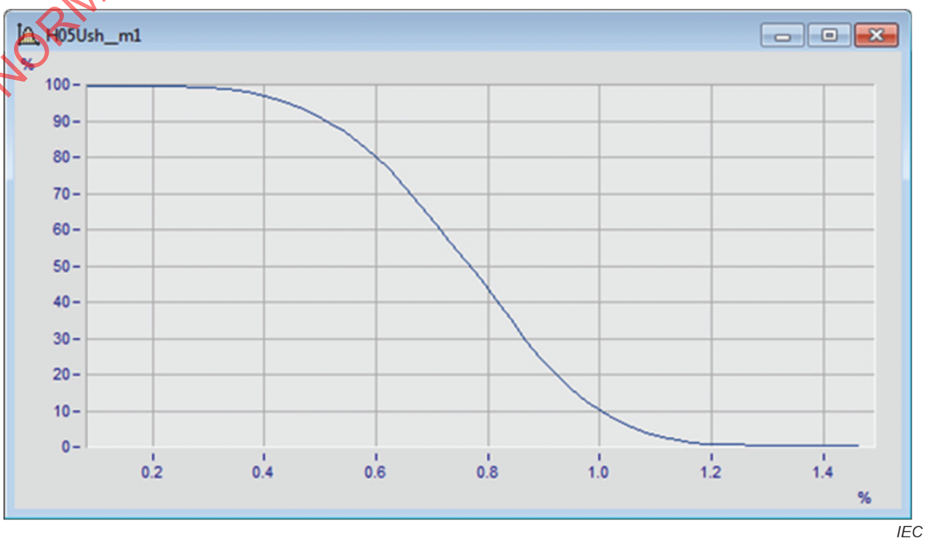


Figure 35 – Cumulative frequency of the 5th harmonic voltage level at test site M1

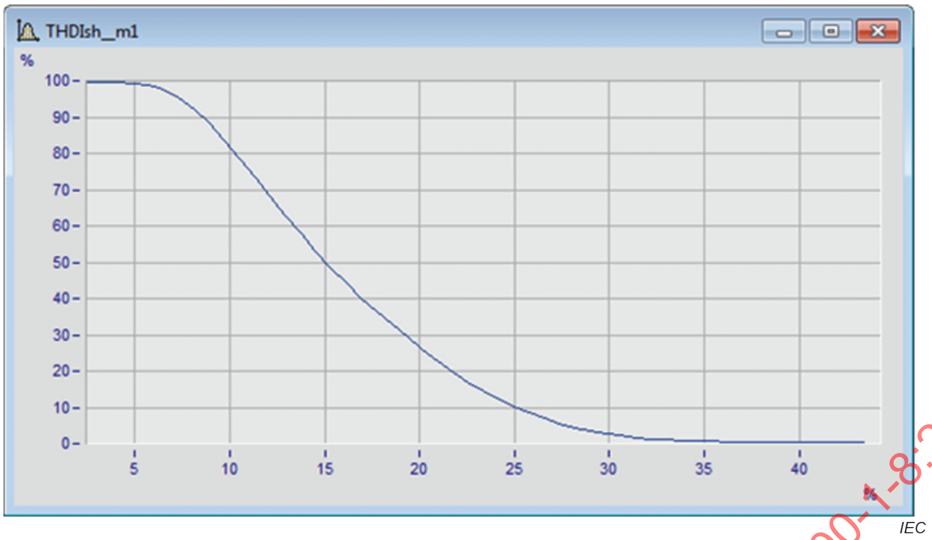


Figure 36 – Cumulative frequency of the total harmonic current distortion at test site M1

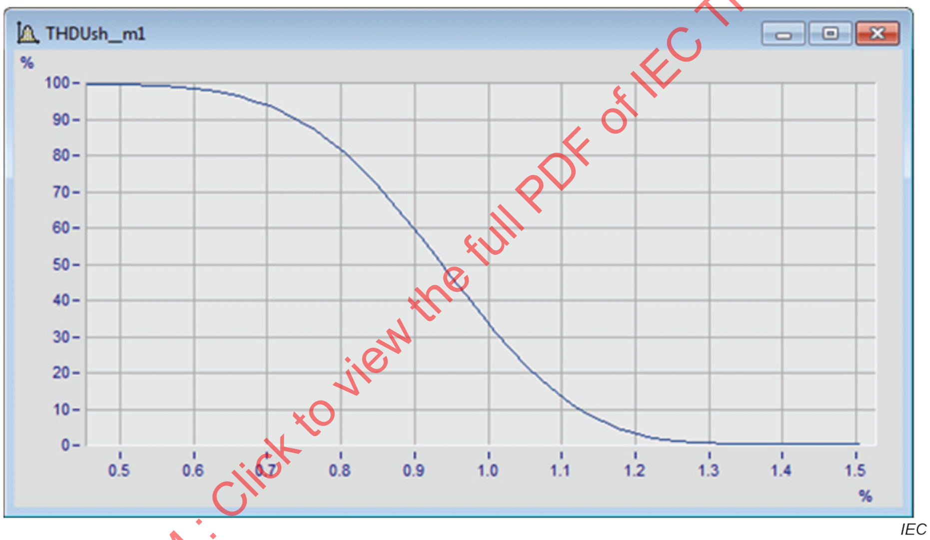


Figure 37 – Cumulative frequency of the total harmonic voltage distortion at test site M1

7.4 Phase angle of selected harmonic currents

7.4.1 Time series analysis of phase angle

An overview has been made of the time series of the phase angles of the 3rd, 5th and 7th current harmonics in each electrical phase, in time windows of 24 h.

Figure 38 illustrates an example for the test site M1 of the time series of the phase angle position of the 5th current harmonics during a work day. The corresponding harmonic current magnitude (level) is shown in Figure 39. During most of the day the phase angle remains relatively stable at -30° in all three electrical phases. Only from the late afternoon (winter month) is a distinctive change peak shown in phases L1 and L3, a little more than -60°. It is assumed that the addition of lighting or other quasi-linear loads in L1 causes this rotation of the phase angle, which returns to about -30° as the evening progresses.

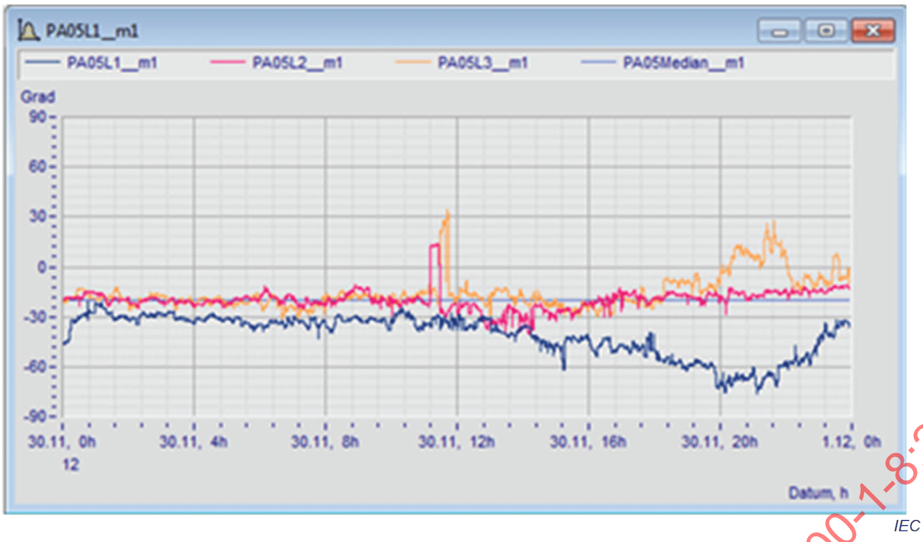


Figure 38 – Daily cycle of the 5th harmonic current phase angle at test site M1

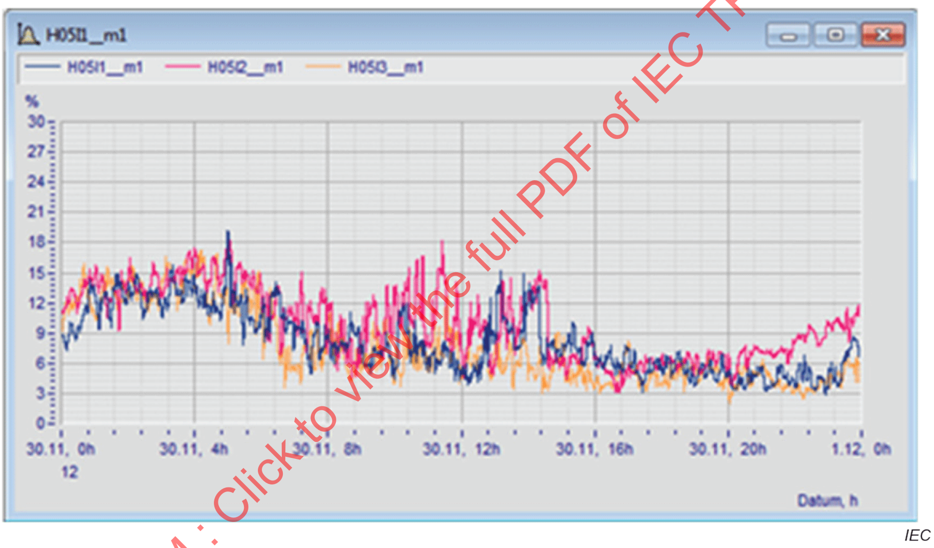


Figure 39 – Daily cycle of the 5th harmonic current magnitude (level) at test site M1

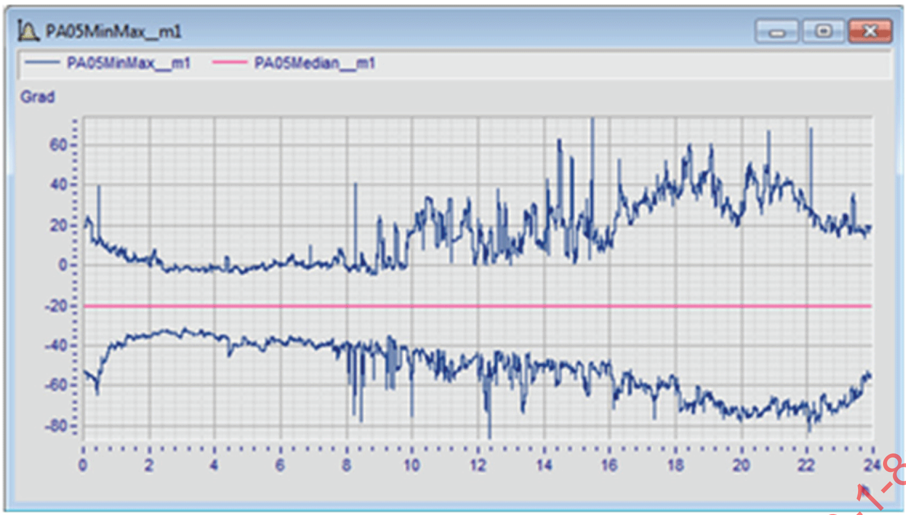


Figure 40 – Minimum-maximum envelope of the 5th harmonic phase angle curve at site M1

If the calculated envelope curve of the minima and maxima is projected according to Figure 40 on the 24-h representation, the assumed users' behaviour at test site M1 is confirmed. The median over all three phases and all measured days lies within ±20°. The dispersion rises in the evening hours by ±60° relative to the median value.

The histogram (see Figure 28) for all phase angle measurements for test site M1 is very narrow and the corresponding cumulative-frequency function (Figure 33) shows a large gradient in the S-curve which points in general to a small dispersion of the phase angle positions.

With the load structures for trade and office, a temporal dependence of the phase angle on the business hours is recognizable.

7.4.2 Phase angle in polar coordinates

The phase angles of the harmonic currents can be visualized in polar coordinates, as illustrated in Figure 41, Figure 42 and Figure 43 which show the 3rd, 5th and 7th harmonic currents for test site M1.

The test site M1, a low-voltage network with single-family dwellings, shows for the 3rd current harmonic a "point cloud" that is predominantly in the third quadrant of the polar coordinate system of the phase angles (Figure 41). Therefore, the phase angles of the 3rd harmonic current lie on average at 210° with a dispersion of approximately ±30°.

For the 5th current harmonic the dominant part of the "point cloud" lies in the fourth quadrant of the polar coordinate system of the phase angle (Figure 42). This signifies that the average of the phase angles of the 5th harmonic current lies at -30° with a dispersion of ±30°.

An unequivocal point cloud also exists for the 7th current harmonic between the second and third quadrants of the polar coordinate system of the phase angles (Figure 43). Therefore, the phase angles of the 5th harmonic current lie at -30° with a dispersion of ±30°.

As already mentioned – and illustrated in Clause 5 – the above statements regarding "predominant values" cannot be generalized for other test sites. If one compares Figure A.1 to Figure A.12, several of the "point clouds" of the phase angles show a much wider distribution in terms of phase angle and also show different prevailing phase angles for the prevailing vector.

The calculated prevailing vectors are shown, so a strong deviation is recognizable between the test sites. In particular the load structure has a large impact on the position and form of the point clouds of the phase angles. This applies for all three orders of the observed harmonic currents. For residential areas with single-family dwellings the dispersion is less prominent. In addition, a trend towards a preferential range from about 30° to -60° is to be observed with the 5th harmonic current. This trend is not so visible with the 3rd harmonic current and is not present at all with the 7th harmonic current.

The results of the dispersion factor calculations for H3, H5, and H7, are shown in Figure 44, Figure 45 and Figure 46. Therefore, the dispersion is smallest for the phase angle of the 3rd harmonic current compared with the higher harmonics. However, for the phase angle of the 5th harmonic current and the 7th harmonic current nearly all values are generally less than 0,2, which would normally be sufficient as satisfactory measure to establish a prevailing phase angle position for each of the measurement sites. It needs to be stated, however, that the prevailing angles differ greatly between various sites.

It can also be noted that the dispersion factors for residential areas are less volatile than for networks with trade and office load structures.

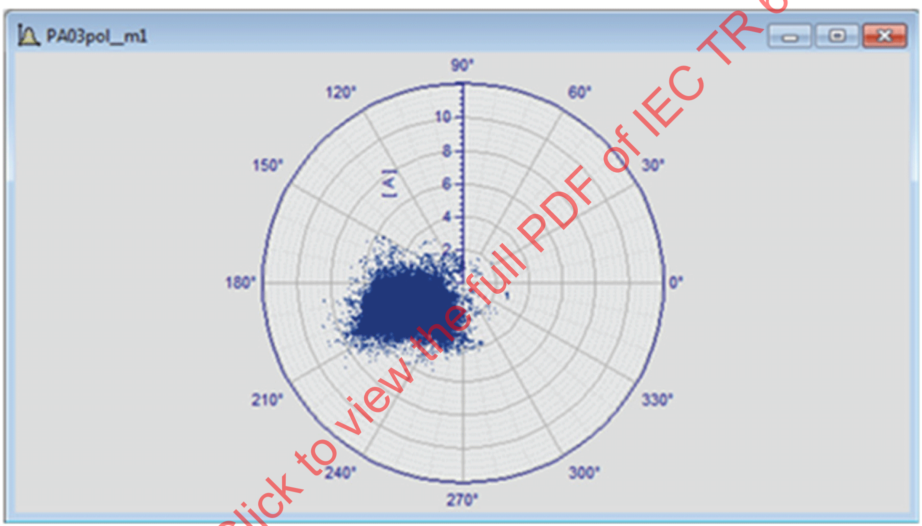


Figure 41 – Phase angle of the 3rd harmonic current at test site M1

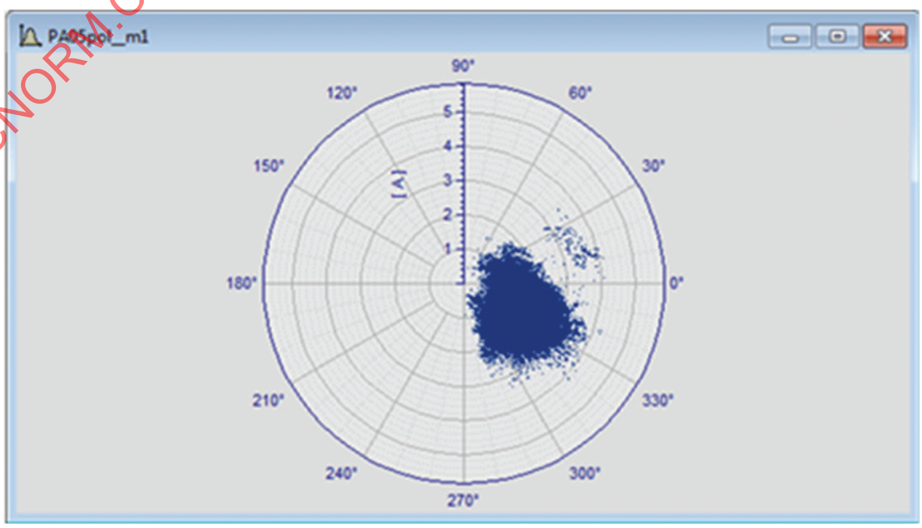


Figure 42 – Phase angle of the 5th harmonic current at test site M1

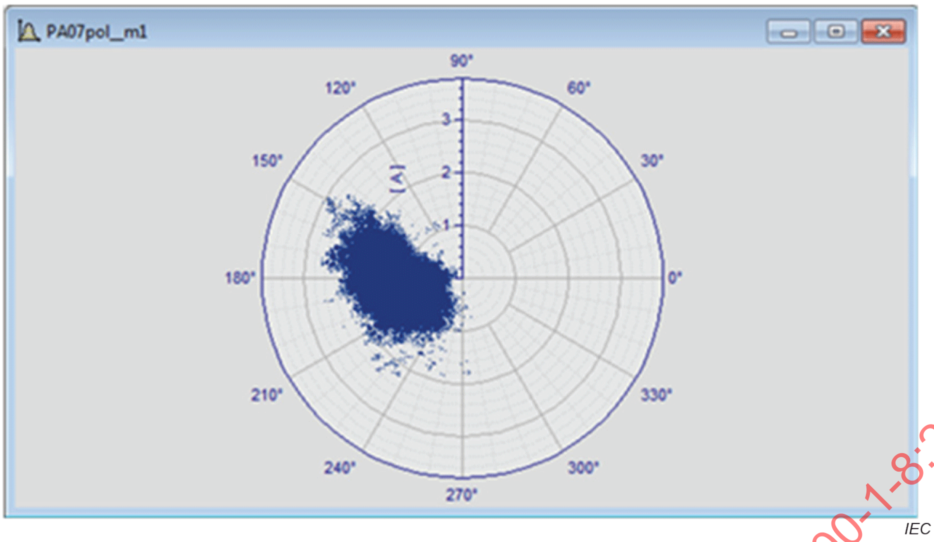


Figure 43 – Phase angle of the 7th harmonic current at test site M1

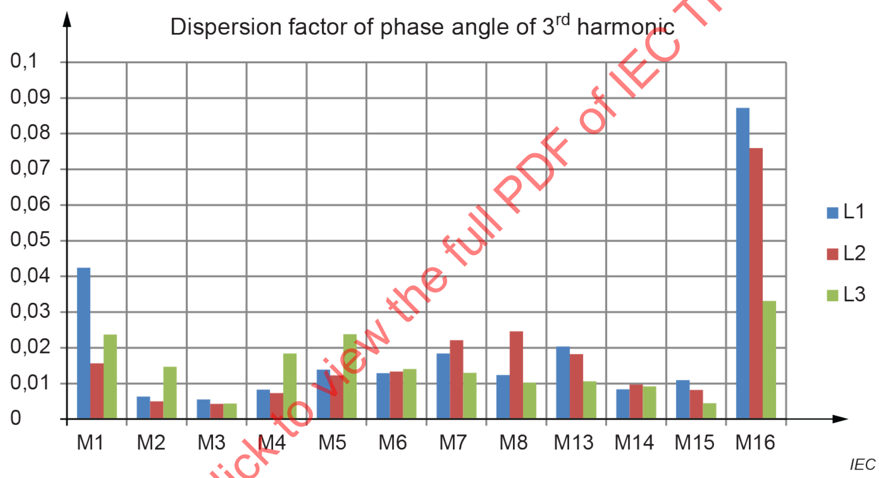


Figure 44 – Dispersion factor of the phase angle of the 3rd harmonic current

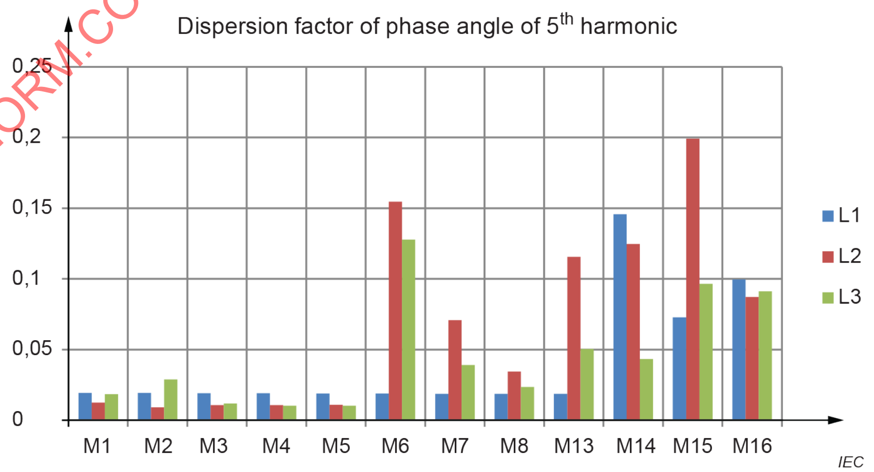


Figure 45 – Dispersion factor of the phase angle of the 5th harmonic current

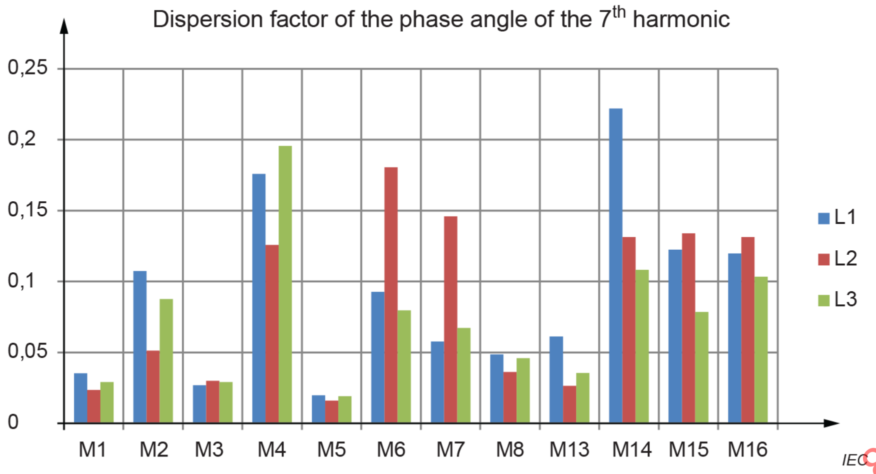


Figure 46 – Dispersion factor of the phase angle of the 7th harmonic current

7.5 Harmonic spectra

For all test sites, the amplitude spectra of the harmonic voltages and harmonic currents (n = 2 to n = 50) including the frequencies of their amplitudes (levels) are calculated.

For interpretation, the dark blue colour represents the harmonic level in percent for a minimum frequency of 50 %, the red bars signify the five-percentile frequency, the yellow indicates values that occur 1 % of the time, and the light blue indicates values that occur 0,1% of the time.

For example, for test site M1 the amplitude spectrum of the harmonic current (Figure 47) shows an increase in level, possibly due to resonance with another slight increase at the 35th harmonic. All the other harmonics fall in level with rising ordinal number. For the 15th harmonic current and above, all amplitudes with occurrence frequencies of 50 % are less than 1 %.

Figure 48 indicates that, also for test site M1, the amplitude spectrum of the harmonic voltages shows two resonances with low level increases at the 23rd and 24th harmonics and a minimal increase around the 35th harmonic. Further, the behaviour pattern of the levels of the low-frequency harmonics, in particular for the 3rd, 5th and 7th harmonics, is as typically expected in its gradation. The information about the frequency shows that only the 5th, 7th, 9th and 11th voltage harmonics have levels around 1 % in magnitude which occur for more than 50 % of the time.

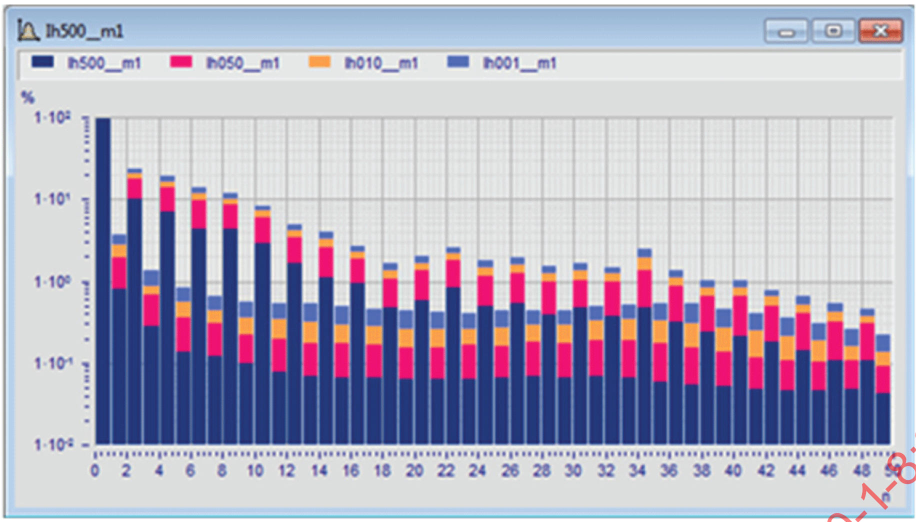


Figure 47 – Harmonic current spectrum including level distribution at test site M1

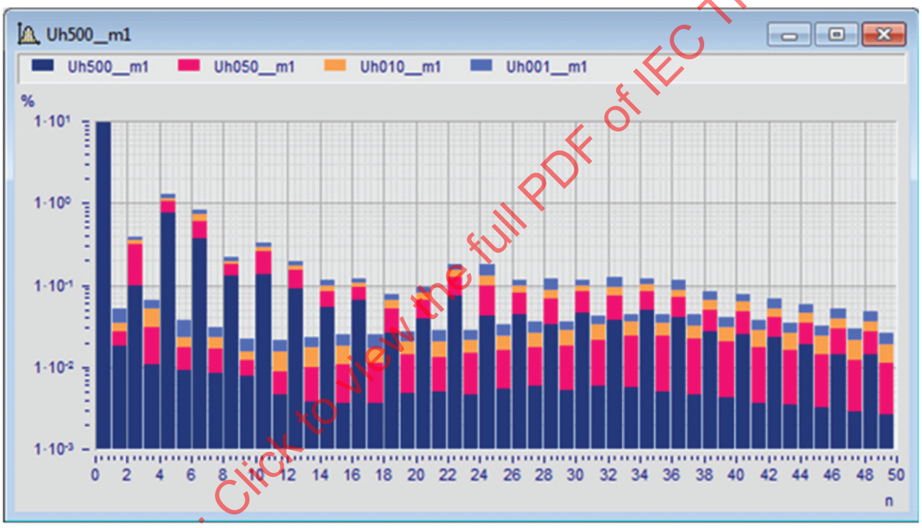


Figure 48 – Harmonic voltage spectrum including level distribution at test site M1

When comparing the spectra of measurement site M1 with spectra from other test sites load structures, a big difference is observed for networks for trade and offices (i.e. compared with residential areas). Furthermore the spectra of networks with photovoltaic installations differ considerably as well from the spectra of networks for residential areas. Also, combining the data from residential networks with office or trade load structures to arrive at some form of generalisation is difficult, because the resonance frequencies are very different for the various networks. This can, of course, be explained as it directly results from different network structures.

The principle of the representation of amplitudes of harmonics as a spectrum is transferable also to the phase angles of harmonics. Figure 49 shows an example for test site M1. All harmonic phase angles as well as their occurrence frequency are shown. The result corresponds to the other representations in Figure 47 and Figure 48 for single harmonics. Thus a phase angle of around 135° can be seen for the 3rd harmonic with 50 % frequency. The 5th harmonic current phase angle appears at 190° with 50 % frequency, and the 7th harmonic at about 200° at 50 % frequency. Further, a quick overview is easily obtained of the dispersion by means of the frequency of occurrence. As expected the volatility in values strongly increases with harmonics of higher order.

For the comparison of the phase angles between the various load structures, generalisation is conceivable only to some extent for the low-frequency harmonics.

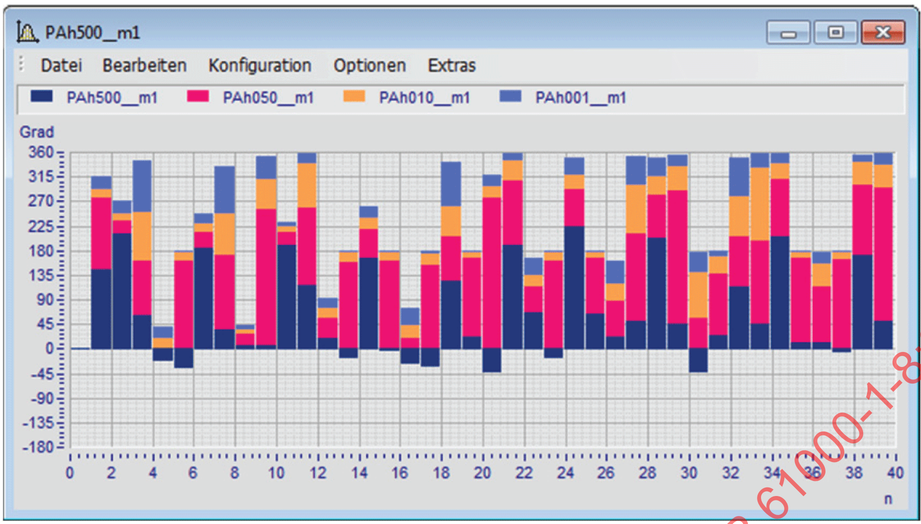


Figure 49 – Harmonic phase angles including phase distribution at test site M1

7.6 Correlations

All the results of the calculations of correlations for the test sites M1 to M8 were introduced in [7] and those for the test sites M13 to M16 were introduced, in detail, in [8]. In [9] the presentation of the complex correlation was presented.

The calculation of the correlation factors and the sliding correlation as well as the application with complex numbers were treated in 6.2.1 and 6.2.2.

In the following the dependence is determined, as an example, between the phase angle of the 5th harmonic current in phase 2 (PA05L2) with selected electrical parameters by means of the correlation factor.

Figure 50 shows the correlation factors with regard to the levels of the 5th harmonic current for all test sites and for the whole measuring period. Clear causalities, i.e. reasonably similar correlation factors, are identifiable in the residential areas (M1 to M8). With factors between -0,5 and -0,8, this means that with rising level in the 5th harmonic current the phase angles become smaller, so are left-rotary. Only at the test sites M4 and M7 do the phase angles not correlate with the levels of the 5th harmonic current. In the office and trade load structures the causalities, i.e. correlations, are evident even more strongly. This is especially pronounced at the test site with an electronics store (M14). The reversal of the signs in the correlation factors of the test sites M13 and M14 (both offices) can be traced back to the change of the rotation direction of the phase angles. For M13, the phase angles become bigger with the rising level of the 5th harmonic current level, and are left-rotary.

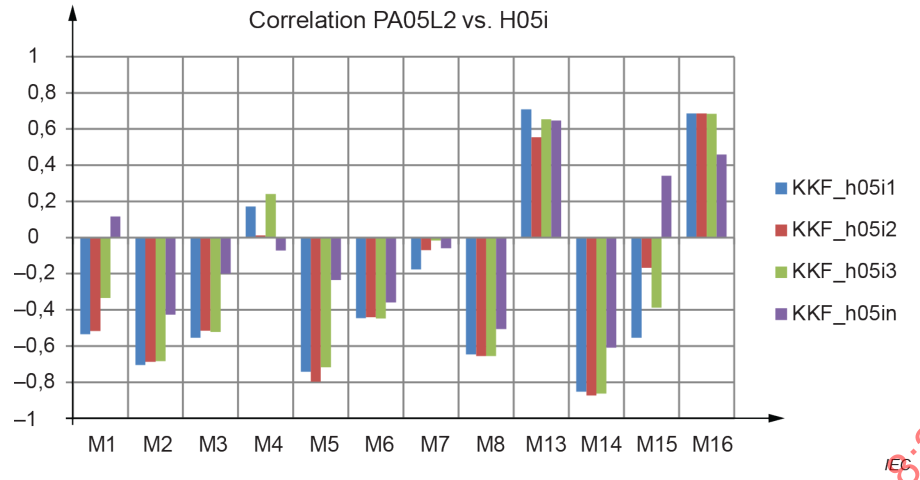


Figure 50 – Correlations between the 5th harmonic current phase angle and the 5th harmonic current H05i

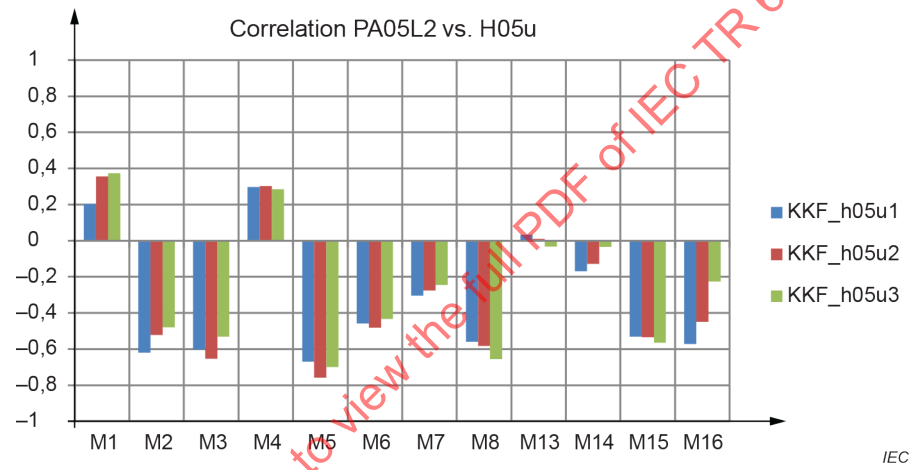


Figure 51 – Correlations between the 5th harmonic current phase angle and the 5th harmonic voltage H05u

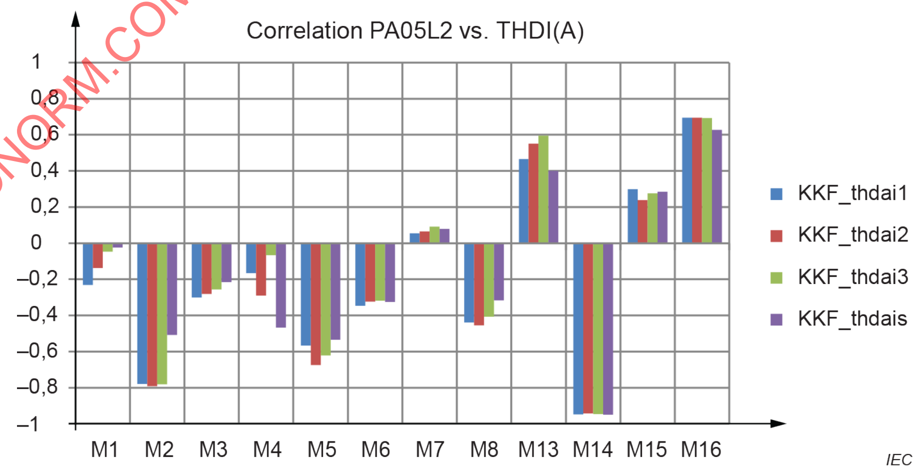


Figure 52 – Correlations between the 5th harmonic current phase angle and THDI

A very similar causality exists between the phase angle of the 5th harmonic current and the level of the 5th harmonic voltage (Figure 51). In total the factors are a little smaller than with the 5th harmonic current, so there is a slightly less pronounced correlation. In other words, current harmonics are more strongly coupled than voltage harmonics to the time series of the phase angle position. Furthermore, the relationship is similar between the level change and rotation direction of the phase angle between the test sites.

Similar causalities are shown by the correlation factors between just the 5th harmonic and the total harmonic distortion factor of the current (Figure 52) and the total harmonic distortion factor of the voltage (Figure 53). From that it can be concluded that the higher harmonics participate in the correlation factor but to a lesser extent. Finally, the correlation factors between the phase angle of the 5th harmonic current and the apparent power (Figure 54) show a direct dependency between the current level (power) and the rotation direction of the phase angle.

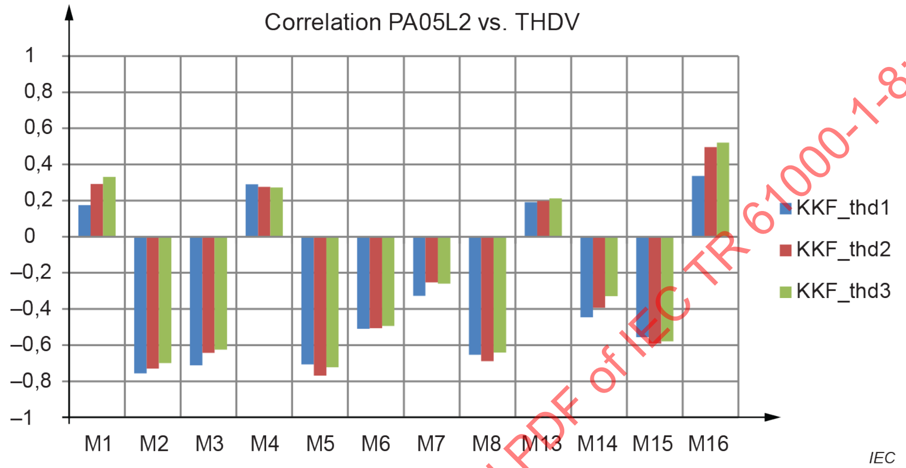


Figure 53 – Correlations between the 5th harmonic current phase angle and THDV

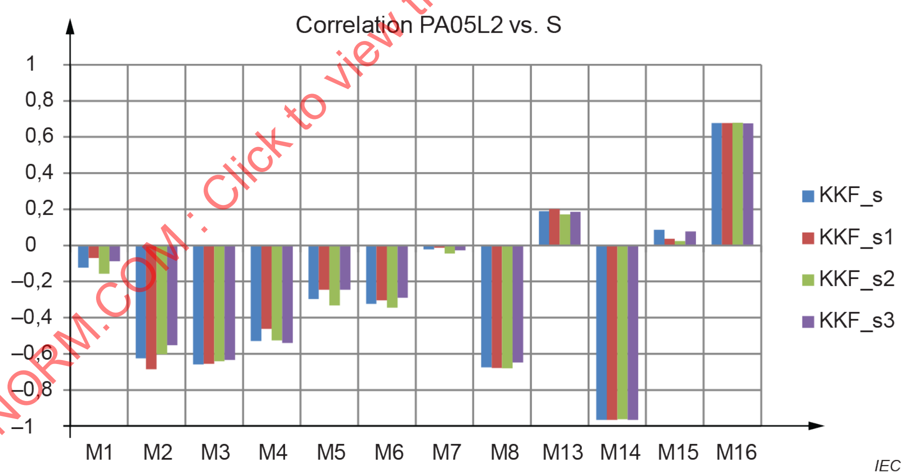


Figure 54 – Correlations between the 5th harmonic current phase angle and apparent power S

An example of the sliding correlation factor over a time period of 24 h is shown for the test site M14 (trade with electronic store). In this case the correlation factors indicate a near perfect correlation between the phase angle position of the 5th harmonic current in phase 1 (PA05L1) and the total harmonic distortion factor. This is true for each of phases 1, 2 and 3 (Figure 55). Exactly the same strong causality can be deduced from the correlation factors between the phase angle of the 5th harmonic current with the active and reactive power in the electrical phases 1, 2 and 3 (Figure 56). The same figure also shows the high correlation between the 5th harmonic phase and apparent power.

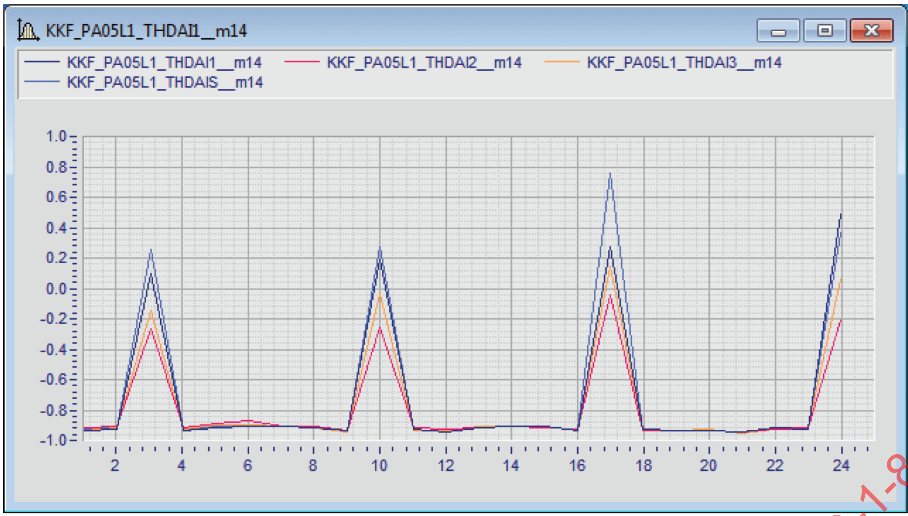


Figure 55 – Correlation trace between the 5th harmonic current phase angle and THD-I

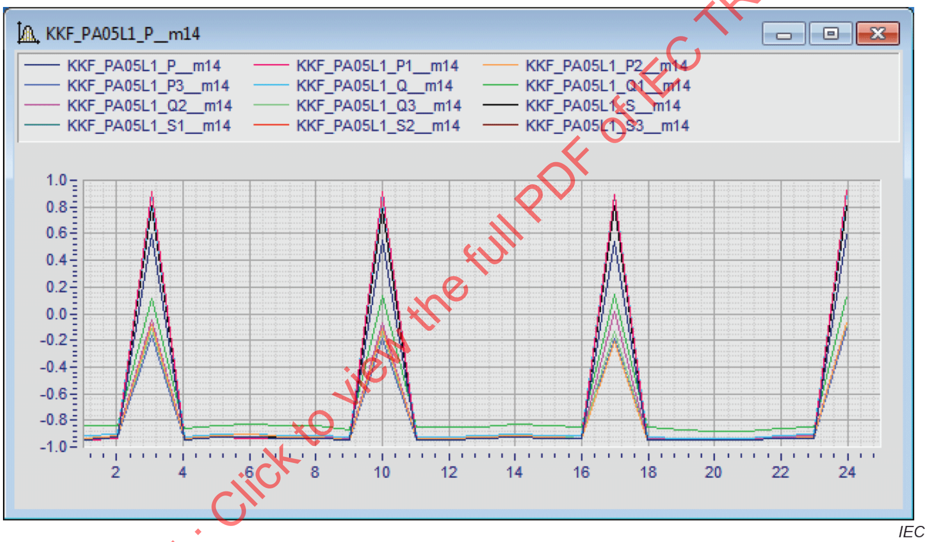


Figure 56 – Correlation trace between the 5th harmonic current phase angle and P, Q and S

8 Empirical evidence

8.1 Inductive versus deductive approach

The answer to the question of whether the combination of different technologies, each with their specific prevailing angles for selected harmonics, produces compensation, can be studied from both a deductive and an inductive reasoning viewpoint. This applies in particular to the 5th harmonic current as compensation between different product categories which could lead thus to a general reduction in the harmonic voltage distortion. Following the deductive method, one would assume compensation to be present between different product categories, and if the assumption is correct, one therefore expects specific patterns to be found.

Contrary to this, inductive reasoning is based on specific observations, with these observations leading one to predict or expect certain patterns, for example compensation between different products or categories.

Following the inductive approach, empirical data have been obtained by methodical collection from laboratory measurements. These data led to a hypothesis that certain technologies, in particular certain lamps, lead to the partial cancellation of the 5th harmonic current from some other products. From the laboratory measurements, prevailing phase angles can be determined for certain technologies. In addition, measurement experience indicates some compensation effect between diverse (different) technologies. This encourages the hypothesis that this compensation can contribute to a reduction in harmonic emissions, by virtually diametrically-opposing prevailing vectors, and thus accomplish an improvement in power quality, i.e. reduced voltage distortion.

Thus, abstracting a general conclusion from observed phenomena corresponds methodically to the inductive approach.

If the hypothesis created from the inductive approach is right, the empirical evidence should inevitably be found in field tests. If prevailing angles are really bound to certain technologies and the diversity of the technologies is really reached in a measure according to the hypothesis, compensation of the 5th harmonic current would in principle be confirmed empirically, by field observations.

Therefore the conclusions from the observations would be the logical consequence to the theoretical model. This corresponds methodically to the deductive approach.

8.2 Laboratory tests

In a laboratory investigation [10][8] the harmonic currents were surveyed in selected electrical product types in terms of magnitude and phase angle position. The laboratory measurements considered 109 energy savings lamps (ESLs) and 61 electronic devices (EDs). The energy savings lamps included compact fluorescent lamp (CFL) and solid state lamp (SSL) types. The electronic devices were distinguished, in addition, between devices with and without power-factor correction (PFC). The power for the surveyed devices was provided by an ideal sinusoidal voltage source, thus no harmonic contribution came from the power source. The initial analysis concentrated on the 3rd and 5th current harmonics. The purpose of the measurements was to identify prevailing phase angle positions for certain technologies. Also, groups of technologies with proven preferential phase angles were overlaid to demonstrate their compensation effect in the laboratory. For this purpose, operation was differentiated between concurrent operation and individual operation of two product groups, on the one hand electronic devices in combination with energy-saving lamps, and on the other hand electronic devices without energy-saving lamps.

Compensation of harmonic currents means that the vectors of individual current harmonics from two products are partially or wholly opposite. Therefore, a critical measure of compensation is both the magnitude and phase angle of a specific harmonic, in particular whether the phase angles are directed close together or are more or less opposed.

The resulting change in the magnitude of the aggregate prevailing vector, when the products are operated together, is a measure of the degree of the compensation.

From this general context, the study for the assessment of the compensation effect uses two definitions, the summation exponent α (quantification of summation effect) and the in-phase factor k. The summation exponent[9] α is a derivate (see the formula in the footnote). Both

8 This investigation was ordered and paid for by the association FNN (Forum Network Technology/Network Operation in the VDE).

9 Example for 5th harmonic and n devices: $\sum_{1}^{n} \underline{I} = \sqrt[\alpha_5]{\underline{I}_1^{\alpha_5} + \underline{I}_2^{\alpha_5} + \ldots + \underline{I}_n^{\alpha_5}}$