HARMONIC SUMMATION EFFECTS OF MODERN LAMP TECHNOLOGIES AND SMALL ELECTRONIC HOUSEHOLD EQUIPMENT

Jan MEYER Peter SCHEGNER
Technische Universitaet Dresden
Germany
Jan.Meyer@tu-dresden.de

Kurt HEIDENREICH
Vattenfall Europe Distribution Hamburg GmbH
Germany
Kurt.Heidenreich@vattenfall.de

ABSTRACT

Due to government policies incandescent lamps are more and more replaced by modern energy saving lamps worldwide. Compared to incandescent lamps luminaries using new technologies (e.g. compact fluorescent and solid state lamps) have a decreased damping effect and significant harmonic emissions, mostly at low order frequencies.
Current harmonic limits for these lamps are specified in IEC 61000-3-2. For lamps with rated power below 25W these limits were defined taking several assumptions into account. One assumption is a significant cancellation effect of harmonics between energy saving lamps and other electronic equipment, like computers or TV sets.
The main intention of the paper is to verify the cancellation effect for currently available lamps and typical electronic household equipment. After a short introduction and description of the test setup the harmonic emissions of more than 100 lamps (CFL and SSL) and more than 50 electronic appliances, mainly with rated power below 75W, are presented. The cancellation effect of the 5th harmonics for different scenarios is discussed and finally some field measurements are analyzed.

ABBREVIATIONS

ISL - incandescent lamp
CFL - compact fluorescent lamp
SSL - solid state lamp
EUT - equipment under test

INTRODUCTION

The first CFLs with socket-integrated electronic ballast were sold in 1985. Over the last 25 years lots of simulations were carried out to analyze the possible impact of a bulk use of CFLs on the grid harmonic voltage. The results of these studies range from positive effects over slight negative effects to high negative effects [e.g. 1, 2]. The results of these studies strongly depend on the underlying assumptions and models they are based on. During the last years the use of CFLs was strongly pushed and the number of harmonic studies has increased again (e.g. at ICHQP 2010 in Bergamo at least 8 papers covered this subject).
Several long-term measurements focused on low order harmonics have shown a stable or slightly decreasing level of 5th harmonic voltage during the last years. Some before/after measurements [e.g. 3, 4] also didn't show a significant impact of CFLs to voltage harmonics. Contrary specific cases are known to the authors, where quality problems have occurred after a complete change from ISLs to CFLs (e.g. in hotels or retirement homes).
The results of simulations and measurements show that impact of modern lamp technologies to the voltage distortion is a quite complex issue and no really consistent conclusion can be drawn up to now.
This paper focuses on one specific, but in the opinion of the authors very important aspect. It tries to quantify the relevance of the cancellation effect between lamps with electronic ballast and other household equipment for managing the low order harmonic voltage levels, especially the 5th harmonic.

MEASUREMENT SYSTEM

In a first step a fully automated test system was set up for comparable measurements of harmonic emissions from lamps and other equipment with stationary operating states (Fig. 1).

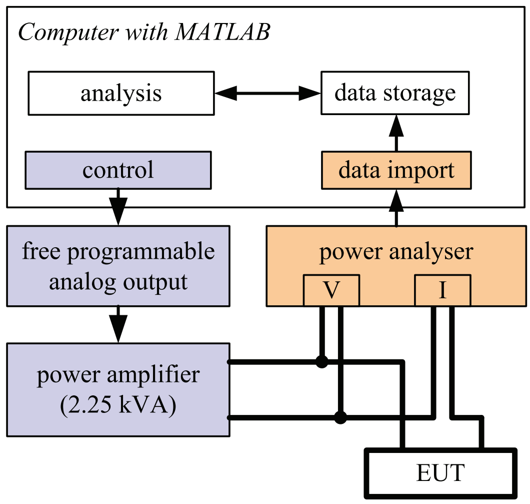

Figure 1: Principal schema of measurement system

The free programmable analogue output allows the generation of different types of supply voltage distortion. The power analyser measures the harmonic spectrum in 25-Hz-steps up to the 99th harmonic. Phase angle of harmonic current is always related to the voltage fundamental.
An individual warm-up time is allowed for each EUT by monitoring the variation of input current. Harmonic currents and voltages are measured multiple times and their consistency is verified by assessing the standard deviation

for selected parameters of the dataset. In addition to the harmonics the raw waveforms are stored for further analyses.
Each EUT is measured at 5 different test points taking typical variations (±10% U_n) and distortions (pure sine, flattened and pointed top with THDu ≈ 4%) of supply voltage into account. All calculations and analyses in the paper are based on nominal voltage magnitude (U_n = 230V) without any distortion.

MEASUREMENT RESULTS

The presentation in the complex plane provides a suitable way for a graphical analysis of the summation effects for the individual harmonics. The harmonic current of a EUT is presented by a circle and not by its complete vector (Fig. 2). For a quantification of the cancellation effect 2 indices are calculated:

(1) Summation exponent $\alpha^{(\nu)}$: $\left|\sum \underline{I}_i^{(\nu)}\right|^{\alpha^{(\nu)}} = \sum \left|\underline{I}_i^{(\nu)}\right|^{\alpha^{(\nu)}}$

(2) Phase angle diversity factor: $k_p^{(\nu)} = \dfrac{\left|\sum \underline{I}_i^{(\nu)}\right|}{\sum \left|\underline{I}_i^{(\nu)}\right|}$

The indices are placed in a box in the lower right corner of each figure. Furthermore the box contains the number n of EUTs and the harmonic order ν.
The summation exponent α is often used in standardization (e.g. IEC 61000-3-6). For combinations of only a few EUTs it is very sensitive and very high values can occur in case of good harmonic cancellation. For the analyses in this paper the phase angle diversity factor is more suitable. It presents the relation between vector sum and arithmetic sum of the harmonic currents of the considered EUTs.
E.g. in Fig. 2 the magnitude of the vector sum of the 2 EUTs for 5^{th} harmonic results in only 79% of their arithmetic sum (k_p = 0,79). The summation exponent α is already 3.11.

Compact-fluorescent lamps

Table 1 gives an overview of the measured CFLs.

Table 1: Measured CFLs

Rated power	Number of EUT	Color in Figure 3
$P_r \le 5$ W	4	black
$5W < P_r \le 11W$	48	red
$11W < P_r \le 20W$	7	green
$20W < P_r \le 25W$	12	blue
$P_r > 25$ W	3	*not shown*

All CFLs were randomly selected and anonymously bought in super markets, electronic shops, per mail order etc. The sample consists of brand products as well as no-name products and presents a good set for the German mass market. Most of the CFLs have a rated power of 11W which corresponds to a 60W incandescent lamp.
Fig. 3 shows 2 main clusters representing at least 2 different input circuit layouts that can be identified by analyzing 5th harmonic current (cluster 1 and 2). The phase angle diversity factor for all 74 lamps is k_p = 0.93, which means only a low cancellation effect between all analyzed CFLs. This corresponds to the results of other studies [5].

Solid state lamps

In total 11 different SSLs were measured (Tab. 2).

Table 2: Measured SSLs

Rated power	Number	Color in Figure 4
$P_r \le 5$ W	7	black
$P_r > 5W$	4	red

The SSLs show in general a higher angle diversity compared to CFLs, which means a better cancellation effect between the SSLs itself (Fig. 4). A possible reason for the better cancellation may be the wider range of possible input circuit layouts and consequential different current waveforms. However the development of SSLs has just started and it can't be ruled out that in future the variety of layouts and with it the angle diversity decreases due to optimizations at manufacturer side.
The wide use of capacitor dividers in the input circuits leads to a usually lower power factor for SSLs compared to CFLs. A possible negative influence on the distribution grid due to

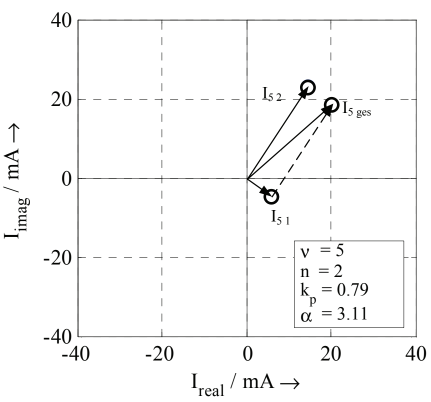

Figure 2: Example for presentation of current harmonics in complex plane

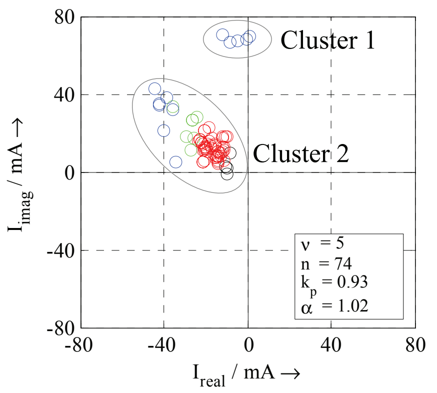

Figure 3: 5th current harmonic of measured CFLs (cf. to Table 2 for color code)

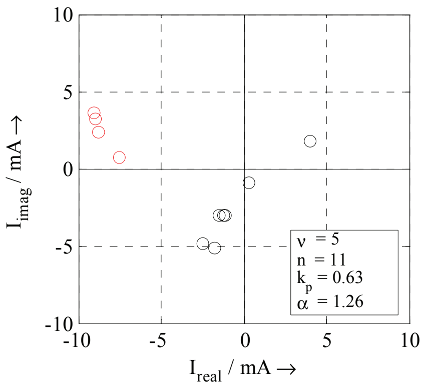

Figure 4: 5th current harmonic of measured SSLs (cf. to Table 3 for color code)

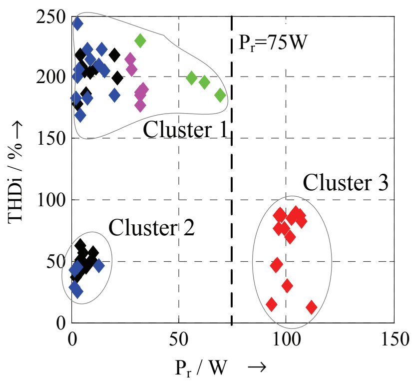

Figure 5: THDi/P_r ratio ...

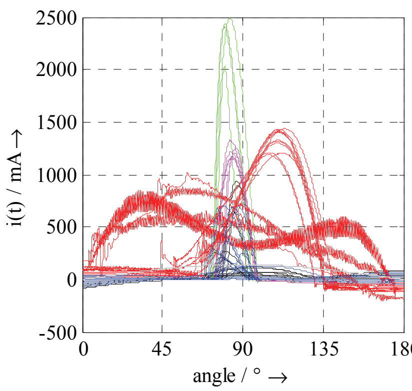

Figure 6: Waveforms ...

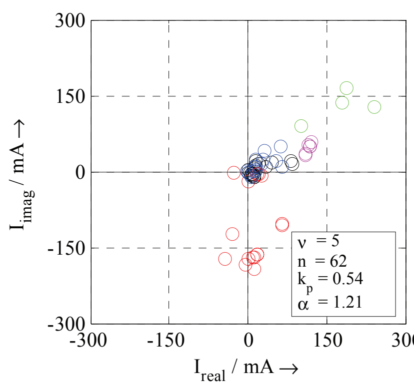

Figure 7: 5th harmonic current ...

... for electronic equipment (cf. to Tab. 3 for color code in Figures 5 - 7)

the loss of damping on one side and the increase of capacitive characteristic on the other side should be considered carefully in future [5].

Electronic equipment

Tab. 3 shows the measured small household and office appliances (in total 62) categorized into 5 groups.

Table 3: Measured electronic equipment

	Group	Number	Color in Figures 5-7
A	Small office equipment (routers, switches, telephone systems, NAS devices, …)	17	black
B	Other household equipment (all kinds of chargers, game consoles, …)	19	blue
C	Power supplies for notebooks	4	green
D	Flat-screen monitors (LCD)	6	pink
E	Computer power supplies (75W load at DC side)	16	red

According to their THDi/P_r - ratio (Fig. 5) all equipment can be divided into 3 main clusters:

(1) $P_r < 75$W, high THDi > 150%, no harmonic limits, significant 5th harmonic magnitudes

(2) $P_r < 75$W, low THDi < 70%, no harmonic limits, small 5th harmonic magnitudes

(3) $P_r > 75$W, moderate THDi < 100%, limits of 61000-3-2 apply, significant 5th harmonic current

Fig. 6 shows the current waveforms and Fig. 7 the location of 5th harmonic currents in the complex plane. The different clusters from Fig. 5 have preferred locations in Fig. 7 (1: $\varphi^{(5)} \approx 40°$; 2: $\varphi^{(5)} \approx -30°$; 3: $\varphi^{(5)} \approx -90°$). The overall index of $k_p = 0.54$ means a good phase angle diversity. However the summation exponent of $\alpha = 1.4$ suggested by several IEC reports is still a bit too high for the considered set of appliances.

CANCELLATION EFFECTS

Fig. 7 shows that the 5th harmonic currents of electronic equipment aren't at all in the 2nd quadrant, where CFLs 5th harmonic currents are located (cf. Fig. 3). Therefore between electronic appliances and CFLs a cancellation effect may be expected.

Fig. 8 shows the summation of 111 lamps with 62 electronic appliances. The phase angle diversity for this combination increases significantly compared to electronic appliances only (Fig. 7). The low factor $k_p = 0.11$ means a very good cancellation effect. But it shows too that the cancellation effect with CFLs significantly depends on the 5th harmonic magnitude and angle of the other equipment.

Fig. 9 shows the 5th harmonic current of 3 different types of computer power supplies representing the development of waveform improvement circuits over the last 10 years from no PFC (no more common), to passive PFC (common today) to active PFC (upcoming). Tab. 4 shows the results of the summation of these 3 different power supplies with a fixed set of 6 CFLs (24W, 20W, 15W, 3x11W). While passive PFC gives the best cancellation effect (situation today), the upcoming active PFC technique doesn't show a significant cancellation effect due to the very low emissions at 5th harmonic. Therefore a decrease of 5th harmonic level today due to an effective harmonic cancellation doesn't mean that the trend cannot turn round in future.

Table 4: Cancellation effect of the 5th harmonic current for different computer power supplies

	k_p	α	abs(ΣI)	arg(ΣI)
(a): no PFC	0.49	>10	253 mA	63°
(b): pass. PFC	0.43	>10	174 mA	-157°
(c): act. PFC	0.88	1.07	202 mA	148°

SIMPLIFIED ESTIMATION OF GRID IMPACT

Based on a typical urban LV-grid (400kVA-transformer, 6 branches with 192 households in total) a very simplified calculation of the impact of CFLs was carried out. It is assumed that each household operates 5 CFLs at the same time and 50% of all operated lamps are connected to one phase (due to installation practices). Neglecting any damping and cancellation effects the CFLs would increase the 5th harmonic voltage at transformer LV-busbar by 0.85%. The total load of the lamps is about 6% of the transformer rated power. The compatibility level for 5th

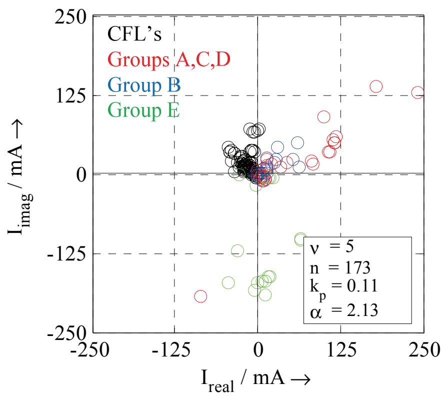

Figure 8: 5th harmonic current for all EUTs (cf. to Tab. 3 for group description)

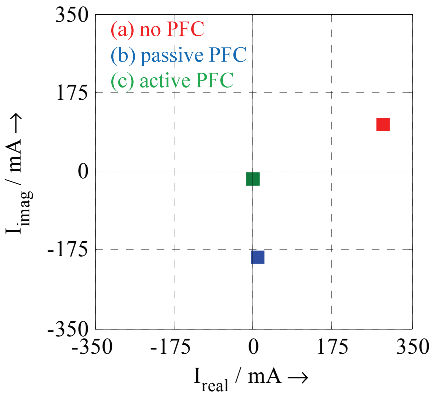

Figure 9: Development of 5th harmonic current for computer power supplies

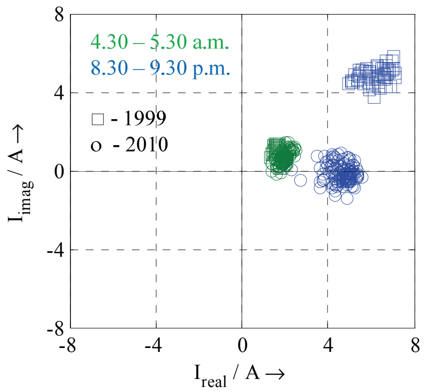

Figure 10: 5th harmonic current for low and high load time interval on Saturday in an urban LV grid

harmonic voltage has to be shared between all network levels. Therefore a contribution of only 1.5% is allowed for the LV-grid. Consequently more than 50% of the available 5th harmonic capacity would be used by only 6% of the load, which would be critical. Therefore in addition to the damping effects by other loads especially the cancellation effect has to be taken into account for such harmonic studies. It should be pointed out that technology changes cannot be neglected. These changes may improve or worsen the cancellation effect significantly.

The changes of 5th harmonic current over the last decade were analyzed by measurements at the LV-busbar of the above mentioned grid in 1999 and 2010 (no significant changes in consumer and network topology). Figure 10 shows virtually no change for the low load state in the early morning hours. For evening hours ("TV-time") a different behavior is observed. Magnitudes are slightly lower and shifted by about -45°. One reason may be the increase of passive PFC technique.

Due to the phase angle of the total 5th harmonic current (nearly opposite of the CFLs current - cf. Fig. 3) a good cancellation effect (even better than 10 years before) can be expected for the considered LV-grid, if number of CFLs will increase. However this cannot be taken as a general conclusion, because the phase angle of the 5th harmonic current may differ between different LV grids. Especially in cases where no significant level of 5th harmonic current exists or the existing current is located in the 2nd quadrant no 5th harmonic cancellation at all is expected to occur.

CONCLUSIONS

Harmonic cancellation effects have an important impact on the total harmonic voltages in the grid and cannot be neglected for realistic simulations. The cancellation effect depends on technology changes and may get better or worse in the future. New techniques may shift harmonic emissions from low order to higher frequency ranges. Research and standardization in this field has to be intensified.

It should be mentioned that an existing voltage distortion influences the magnitude and angle of harmonic current emissions. This should be considered for the simulation of cancellation effects in distribution networks. To increase the reliability of harmonic studies, systematic measurements (including harmonic angles) from LV-grids have to be combined with measurements of actual and upcoming mass equipment.

Within the next 10 years the displacement of CFLs by SSLs is most likely. Therefore care should be taken for emission limits of this new technology with respect to possible mass effects. Depending on changing cancellation effects in the network due to modified technologies of prospective electronic equipment, new harmonic limit approaches (compared to the one for CFLs) may be needed in future.

ACKNOWLEDGMENTS

The authors wish to thank the Forum Grid Technology and Operation within VDE (FNN) (www.vde.com/fnn) for partly funding this study. The VDE is the German Association for Electrical Electronic & Information Technologies.

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