An Analysis of Diversity Factors applied to Harmonic Emission Limits for Energy Saving Lamps

V. Ćuk, J.F.G. Cobben, W.L. Kling, and R.B. Timens

Abstract—**An experimental investigation of diversity factors for CFLs (compact fluorescent lamps) in combination with LED (light emitting diode) lamps is presented in this paper. Diversity factors were calculated for different configurations of lamps connected to the same feeder in one phase. It was found that the presence of LED lamps with a high apparent power input can lead to considerable damping of harmonics. If the number of CFLs is much greater, this effect was found as very low. Harmonic emission limits for lamps were also analyzed. A conclusion has been made that with a sufficient variety of energy saving lamps phasing out of incandescent lamps should not significantly impact the resultant harmonic distortion.**

Index Terms--**Power quality, Power system harmonics, Attenuation, Lamps, Standards.**

I. INTRODUCTION

RECENT governmental initiatives of a number of countries to ban selling of incandescent light bulbs have brought some attention on the question of the quality of current drawn by energy saving lamps. Energy saving lamps require considerably smaller amounts of active power than incandescent lamps when they have the same luminous flux. On the other hand, due to their non-linear characteristics, energy saving lamps inject harmonic currents into the network. That creates a concern that a very high penetration level of these types of lamps may increase the overall voltage harmonic distortion considerably.

Most literature on this topic is focused on CFLs (compact fluorescent lamps) [1] – [7], due to their wide usage. It is found that most new designs of CFLs with low power rating (<25 W) have a *PF* (Power Factor) up to 0.6 [1] – [3], and

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their current *THD* (total harmonic distortion) is close or above 100 % [1] – [6]. LED (light emitting diode) lamps are not yet addressed on this issue, because they have lower power ratings, and are rarely used for home or office lighting.

When considering a large number of harmonic loads, the resultant harmonic current is not a mere arithmetical sum of individual harmonic currents of loads. There are two diminishing effects influencing the resultant harmonic current of a large group of loads.

The first thing affecting the aggregated current is the attenuation effect. The attenuation effect is defined in the literature as a decrease of the load's current distortion caused by a certain increase of the voltage distortion (it is not applicable for any general configuration of voltage distortions, but it exists in a certain range of harmonic amplitudes and phases). This effect is noticed for CLFs some other types of equipment, and mixtures of equipment. It is described in [4], [5], [7] - [10].

The second thing affecting the summation is the diversity effect. Diversity of topologies in different appliances causes a diversity of phase angles of harmonic currents generated by devices. This leads to a lower vector sum than the arithmetical sum (which neglects phase angles) when different types of loads are present, as described in [8], [9], [11] - [15].

The diversity factor is defined as the ratio between the vector sum (as measured) and the arithmetical sum of harmonics.

Harmonic emission of individual lamps is restricted by the standard IEC 61000-3-2 [16]. Limitations are divided in two categories: lamps with an active input smaller or equal to 25 W and lamps with an active input exceeding 25 W.

Lamps with active power up to and including 25 W have a higher margin for emitting harmonics in terms of percents. It is assumed that a larger number of smaller lamps will emit less harmonics than a small number of bigger lamps (due to attenuating effects). However, when examining the absolute currents permitted for both groups (Discussion section), it was noticed that lamps below 25 W are allowed to emit much higher values of harmonic currents (e.g. with a *PF* equal to 0.6, a lamp of 25 W can emit almost twice as much harmonic current in comparison to a lamp of 50 W with the same *PF*).

This was a reason to further investigate the diversity factors of energy saving lamps without other equipment, using CFLs and LED lamps with an active power under 25 W. A series of

experiments was conducted, in which the summation of harmonic currents was measured for different numbers of lamps along a low voltage feeder in the laboratory. The addition of LED lamps made it possible to make a restricted generalization of the diversity factors among energy saving lamps. The attenuation effect was not examined in these experiments, all experiment were done with an almost sinusoidal voltage waveform (*THD* was about 0.25 %).

When comparing the measured values to arithmetical sums of harmonics (calculated), it was found that the combination of CFLs and LED lamps can lead to relatively high damping effects. In the case when almost only CFLs are present, it was found that reduction due to diversity is limited to small effects (when using a clean sine wave voltage).

The analysis of diversity factors was extended with a theoretical analysis of harmonic emission limits for lamps, to bring some insight into the absolute values of harmonic currents allowed. That brought to a conclusion that present limits are effective enough when there is a sufficient variety of types (operating principles) of lamps used. In another case, if the lighting becomes almost completely made of CFLs, stricter harmonic limits may be needed to limit the voltage distortion.

II. EXPERIMENTAL METHOD

Experiments were conducted in the Power Quality laboratory of the Eindhoven University of Technology. Before the experiments with groups of lamps, measurements on single pieces of lamps were done, to obtain characteristics of each type. Powers and the harmonic content of each lamp type were measured according to the instructions from [16]. Some of the type characteristics are presented in Table I. Once the individual current spectrums were known, it was possible to calculate resultant currents of groups of lamps.

TABLE I
MEASURED CHARACTERISTICS OF LAMP TYPES USED

Type	P [W]	PF [-]	THD$_I$[%]
CFL 1	12.8	0.59	112.4
CFL 2	18.2	0.59	115.0
CFL 3	10.0	0.59	102.2
CFL 4	11.9	0.62	101.8
CFL 5	10.9	0.59	103.8
CFL 6	10.2	0.57	117.8
LED	3.3	0.05	9.3

The experimental setup for experiments with groups of lamps is schematically presented in Fig. 1.

Voltage was generated by a programmable voltage source, California Instruments MX 45, as a one phase clean sine wave voltage of 230 V, 50 Hz. Voltage was fed to the loads through a 4x150 mm^2 Al cable with a length of approximately 100 m. At the end of the cable, five radial branches are made at every 20 m. Each branch had a 4x10 mm^2 Cu cable, 20 m long. This setup is similar to a household distributive feeder in terms of cable lengths and cross-sections. At the end of each branch, a group of six energy saving lamps was connected.

Voltages and currents were measured by an oscilloscope, and later processed in Matlab to obtain their harmonic spectra's, and calculate arithmetic sums of current harmonics. After a measurement was done on several groups of lamps, resultant harmonic currents were compared to values calculated from individual lamp measurements, with phase angles included and without phase angles (arithmetic sum).

Having the measured values of harmonic currents and calculated arithmetic sums, diversity factors for different configurations can be calculated.
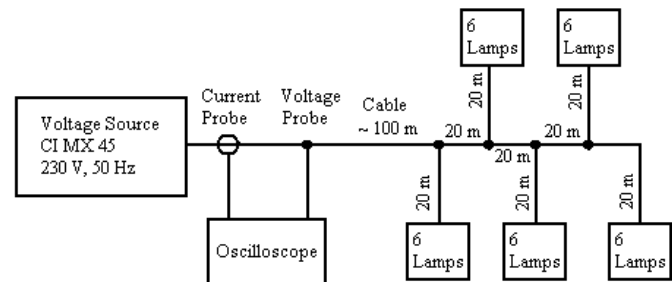

Fig. 1. Schematic diagram of the experiment

In total, 30 lamps were used with seven different types, spread in five groups of six lamps as even as possible. Six types of CFLs with electronic ballasts and one type of LED lamps were used. Different numbers of pieces per type were used. Numbers of pieces used per type are presented in Table II.

TABLE II
NUMBERS OF PEACES USED PER TYPE

Type	Number of peaces		Type	Number of peaces
CFL 1	9		CFL 5	4
CFL 2	3		CFL 6	2
CFL 3	5		LED	2
CFL 4	5		-	

Only two LED lamps were used, because presently it is not likely to have a large number of these lamps in comparison to the number of CLFs (mainly due to their lower luminous output). This type of LED lamps has a very low active power input (only 3.3 W), but it has a *PF* equal to 0.05, resulting in an apparent power of 64.4 VA. The number of peaces per CFL type was mainly based on their price. Lamps with a lower price were used in a greater number, based on an assumption that they are used more often than the expensive types.

III. MEASUREMENT RESULTS

Several current waveforms of individual lamps are presented in Fig. 2, synchronized to a same phase angle reference. It can be seen that waveforms of CFLs have very similar shapes (scaled by their powers), so it is hard to distinguish the waveforms of CFL 1 and CFL 6 on the picture. The waveform of the LED lamp used has a waveform similar to a capacitor's (because of the phase angle) with some distortion added.
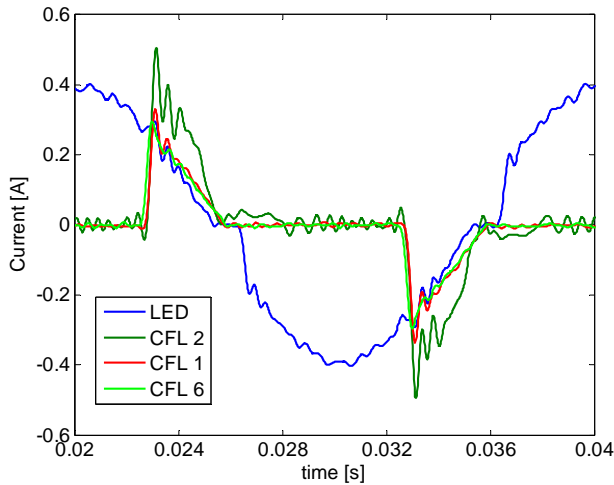
Fig. 2. Current waveforms of several types of lamps used

Relative amplitudes of harmonic currents of all types of lamps are presented in Fig. 3 and their phase angles are given in Fig. 4. Similarities between the waveforms of CFL currents are a consequence of their similar harmonic contents, both in terms of relative harmonic amplitudes and phase angles. Phase angles differ more as the order of harmonics increase, as can be seen in Fig. 4. At certain harmonic orders, the 15th and above the 19th, phase angles among CFLs differ significantly. Diversity at these orders does not influence the overall *THD* considerably, because these orders have low relative amplitudes.

The harmonic content of the LED lamp used is very different, both in terms of amplitudes and phase angles. An important fact is that it has a different phase angle for the 3rd and the 5th harmonic, which have the largest amplitudes among harmonics. Looking at LED's low relative amplitudes (Fig. 3), one may come to a conclusion that it is negligible in comparison to the other lamps used. Still, due to its very low power factor (and relatively high apparent power, see Table I), its harmonic currents are comparable (but still lower than the CFLs).

Measurements with groups of lamps were conducted in the following way: at first, only one group of six lamps was connected at the end of the feeder and the aggregated current was measured; then, measurements were repeated with other groups added, one by one, until all five groups were connected (and all 30 lamps).

Comparisons of measured values and calculated arithmetic sums for 6 lamps are presented in Fig. 5. Diversity factors are presented in Fig. 6. In Fig. 6, diversity factors for even order harmonics are not displayed. These harmonics have very small values, and because of that, calculation is very inaccurate (and also not important). Calculated vector sums are not given in these figures, because they mostly differed only for a few percents from measured values.

It is important to mention that one of the six lamps from the measurement in Fig. 5 and Fig. 6 is a LED lamp. That is the reason for a relatively large difference between the measurement and the arithmetic calculation. In this case the overall current *THD* was only 60.3 %, because from the total
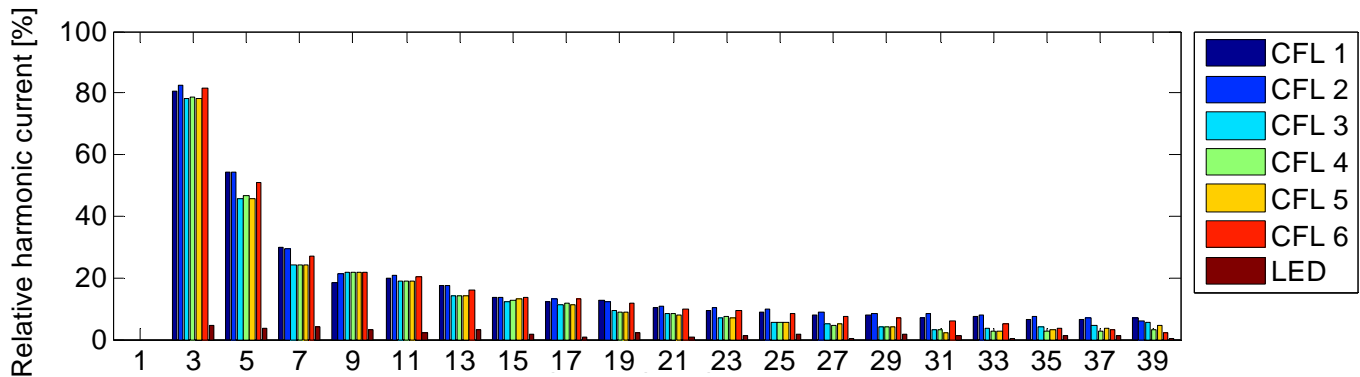

Fig. 3. Relative amplitudes of harmonic currents for all types of lamps used
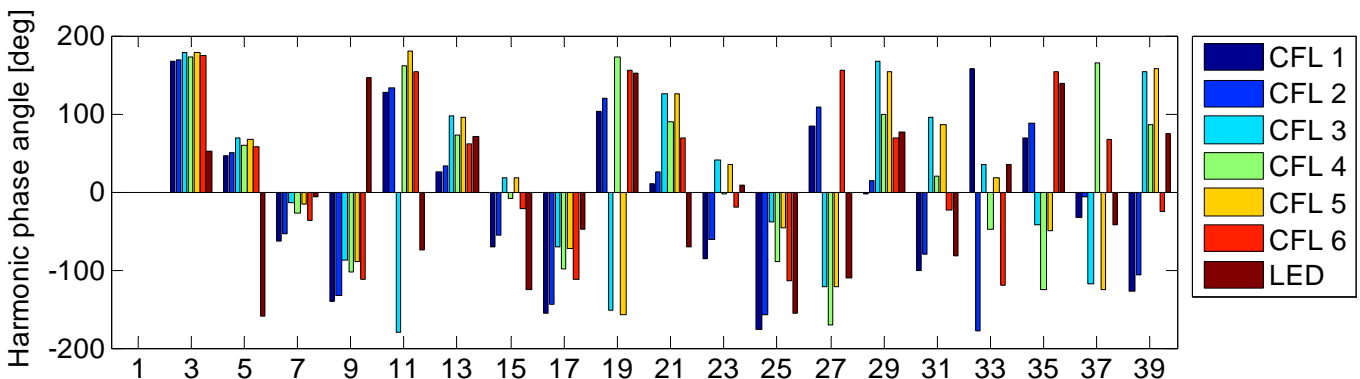

Fig. 4. Phase angles of harmonic currents for all types of lamps used

148.3 VA the LED part was 64.4 VA (about one third) with a *THD* of only 9.3 %.

Comparisons of measured values and calculated arithmetic sums for 30 lamps are presented in Fig. 7. Diversity factors in this case are presented in Fig. 8. As in Fig. 5, diversity factors for even harmonics are not displayed in Fig. 8.
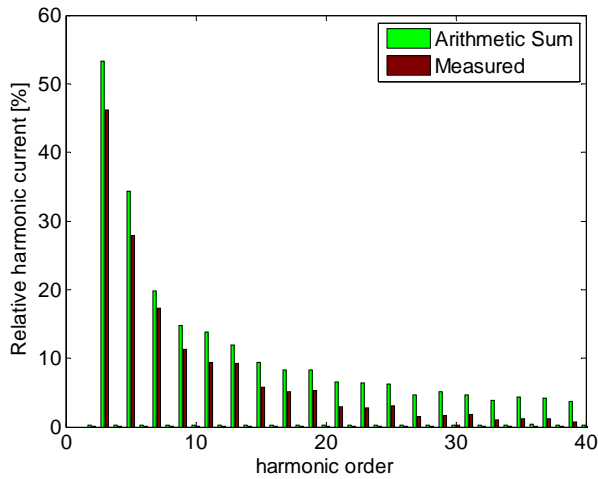

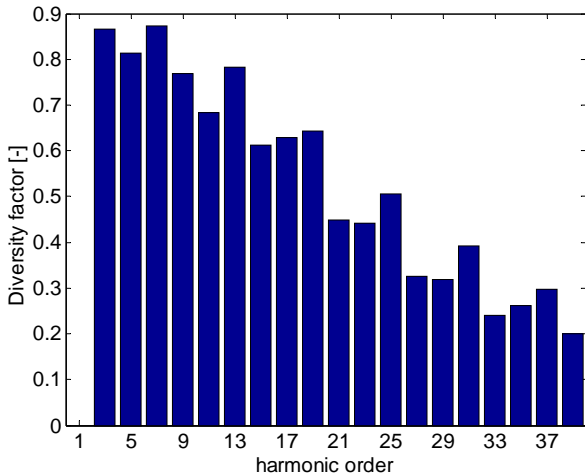Fig. 5. Comparison of measured harmonics and the arithmetic sum for six lamps

Fig. 6. Diversity factors for different harmonic orders – six lamps

In this case the overall *THD* was 86.1 % due to the larger content of CFLs (LED lamps represented about one fifth of the apparent power). Also, all diversity factors are higher for 30 lamps (Fig. 6 and Fig. 8) due to the very small diversity among different CFLs. The change of the diversity factor with the number of lamps is further discussed in the Discussion chapter.

IV. DISCUSSION

A. *Diversity factors from measurements*

All devices have a more pronounced diversity on higher harmonic orders, because phase angles of higher frequency components are more sensitive to differences in topology (even for elements that have the same nameplate characteristics).

This property is easily seen on Fig. 6 and Fig. 8. When we look at the situation with only six lamps, all orders above the 25th are reduced from 60 to 80 %. With 30 lamps (less LED content) this effect is less visible. The reduction on same orders was from 15 to 30 %.
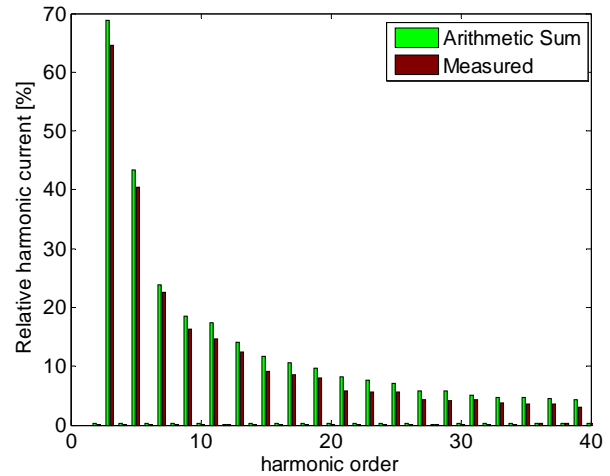

Fig. 7. Comparison of measured harmonics and the arithmetic sum for 30 lamps
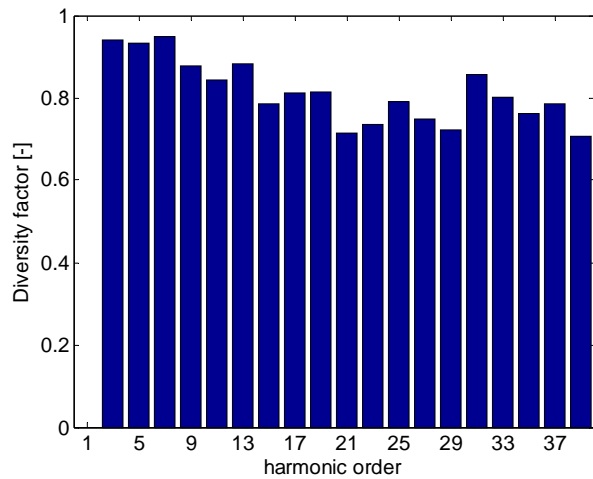

Fig. 8. Diversity factors for different harmonic orders – 30 lamps

On low harmonic orders, up to the 11th, diversity factors had larger values, with up to 30 % reductions. Also, they were changing less with the addition of more lamps.

Diversity factor changes for several harmonic orders caused by the increase of the number of lamps are shown in Fig. 9. These changes can not be generally used for any configuration of lamps, but they show a clear trend. As the lighting becomes predominantly made of CFLs, even different types of CFLs, reduction due to diversity becomes smaller.

This increase in diversity factors (Fig. 9) is showing a convergence from a case with LED lamps and CFLs to a case with only CFLs. If only CFLs were used, a decrease is expected with a higher number of lamps. The trend would then start from a higher point, and than it would converge towards the same point as this trend, but from the upper side.

It is important to mention that the situation would be different in the presence of voltage distortion and other loads.

Attenuation due to voltage distortion would probably further reduce the values of harmonic currents. The diversity trend (with the number of lamps) would probably not be changed much, because similar devices react in a similar way to voltage distortion.

Addition of other loads would reduce the values of diversity factors. That is the reason why currents of households do not have a *THD* close to 100 %. The amount of compensation caused by other devices is highly dependent on the timing of their instantaneous operation, but it should be taken into account when emission limits are considered.
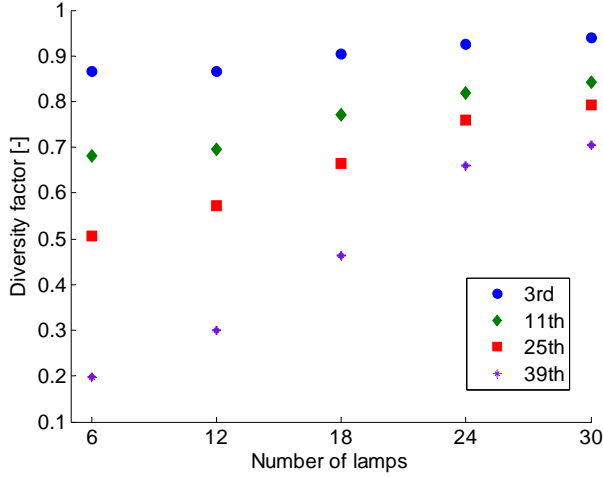

Fig. 9. Changes of diversity factors with the number of lamps

B. Harmonic emission limits for lamps

As it was mentioned in the introduction, harmonic emission limits for lamps are defined in [16]. They are subdivided into limits for lamps up to the active power of 25 W, and above the active power of 25 W.

Lamps above 25 W have fixed relative harmonic limits for all orders except the third harmonic (usually the predominant harmonic). The third harmonic has a relative limit related to the *PF* of the lamp, which means that most of the overall harmonic current is restricted by the lamps apparent power. Using the limits for individual orders, we can calculate the maximal current *THD* allowed for this power range (maximum is at *PF* = 1), which has a value of 35 %.

Lamps with an active power up to 25 W have to satisfy at least one out of two criterions.

One of the criteria is that the third harmonic should not exceed 86 % of the fundamental and the fifth harmonic should not exceed 61 %. That results in a current *THD* of approximately 103 % (almost three times higher than in the range above 25 W).

The other criterion is given as a table of limits for each harmonic order, where limits are expressed as absolute currents per one watt of active power (mA / W).

The maximum *THD* for this range falls into the second criterion and has a very high value (296 %), but it would be applicable only if the *PF* would have a value of 1. If the *PF* has a value of up to 0.75 (and that is usually the case), the first criterion is applicable, and the maximum of 103 %.

More important than the relative limits are the absolute limits (in A). Smaller power inputs do not necessarily ask for a proportionally higher number of units. A comparison of allowed absolute harmonic currents in a range from 0 to 50 W is presented in Fig. 10, as a function of active power and *PF*. Allowed currents are calculated from individual harmonic components as

$$I_{absh} = \sqrt{\sum_{n=2}^{40} I_n^{2}} \qquad (1)$$

where I_{absh} is the absolute harmonic current, and I_n are harmonic components of order n.
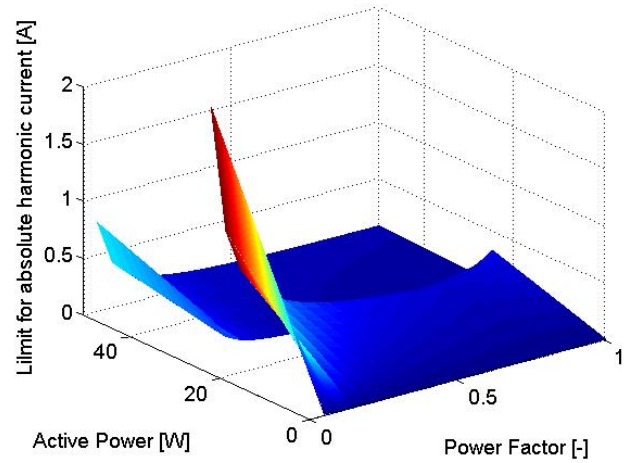

Fig. 10. Absolute harmonic current limits for lamps up to 50 W

Limits are higher in the range up to 25 W, even in terms of absolute currents. The big peak at power factors close to 0 (part of the surface that is red) is not of big concern, because it is not likely that a lamp has such a *PF* and distortion at the same time.

All CFLs used had a *PF* between 0.57 and 0.62, which makes it interesting to look at the limits from Fig. 10 only for *PF* = 0.6. This is displayed in Fig. 11, together with measured values of *P* and I_{absh} for all CFLs used.
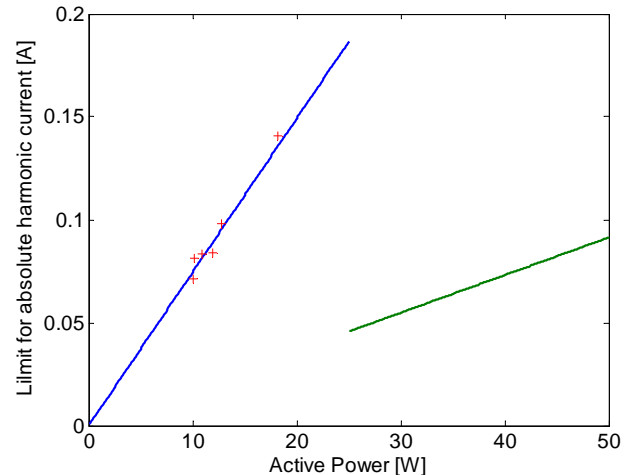

Fig. 11. Harmonic current limits for PF = 0.6 and lamp measurements

As can be seen on Fig. 11, all CFLs used in the experiments are just below or just above the limits. If we consider the diversity factors measured in the laboratory, it can be concluded that only a big variety of energy saving lamps can achieve considerable harmonic reductions among them. If that variety is not available, reduction will depend only on other devices, to compensate for their currents with a *THD* around 100 %.

This does not necessarily mean that stricter rules have to be applied to energy saving lamps because incandescent lamps are being phased out, but if voltage distortions start increasing, that would be one way to influence it.

V. CONCLUSIONS

An analysis of diversity factors for energy saving lamps is presented in this paper. Several configurations of CFLs and LED lamps were connected to a radial low voltage feeder and measurements of harmonic currents and diversity factors were conducted.

Measurements showed that a mixture of LED lamps and CFLs can considerably decrease the amount of higher order harmonics. On the other hand, the lower order harmonics did not exhibit a very large reduction.

Harmonic emission limits were also analyzed, and allowed amounts of harmonic currents in both active power ranges were calculated. It was concluded that every time a lamp from a range above 25 W is substituted by a lamp with up to 25 W, harmonic current is significantly increased.

Phasing out of incandescent lamps will definitely lead to an increase of harmonics in networks. If almost only CFLs are used in that process, it may require stricter harmonic emission limits for lamps. If a bigger mixture of lamp types is used in the process, the harmonic distortion impact will be reduced. The overall diversity factor of a group of customers separated by cables will lead to further reduction of harmonic distortion.

VI. ACKNOWLEDGMENT

VII. REFERENCES

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