Laboratory and field measurements of the power factor and the harmonic emission from energy-efficient lamps

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Abstract

This paper presents the results of a set of measurements to quantify the impact of energy-efficient lamps on the power system, especially on the distortion of the current waveform. The first set of measurements was performed in the laboratory, where a full-scale electric model of a detached house was equipped with the standard domestic equipment including incandescent lamps. A domestic user pattern was defined based on combinations of equipment switched on and off at predefined instants. The second set of measurements was performed with a medium-size hotel. The measurements show that the replacement of incandescent lamps by LED lamps and CFL's results in some increase of the distortion of the current waveform, as expected, but that there is no reason for concern. The presence of other equipment, like a heat pump or a dish washer, impacts the current waveform much more than the replacement of the lamps. It is also encouraging that no increase in distortion is observed in the most realistic experiment (with the hotel).

Introduction

With the interest to reduce electrical energy consumption there is an upcoming shift from the traditional incandescent lamps to more energy efficient types of lighting. The most common replacements for incandescent lamps are compact fluorescent lamps (CFL). The next stage will be the replacement by lamps based on light-emitting diodes (LED's). This ongoing replacement has raised the concern of a possible adverse effect on the power grid as a resistive load is replaced with an electronic one. The main concerns include the distortion of the current and voltage waveform, losses in the grid, and the angle between voltage and current waveform as quantified through the so-called displacement power factor (cos φ). [1]. The waveform distortion of the current from individual lamps is studied among others in [2][3]. The impact on the voltage distortion of a massive replacement of incandescent lamps by CFL is studied in [4]. A limited increase in emission per building is predicted in [2], whereas [4] predicts a large increase in voltage distortion. The latter is however based on simulations, where the cancellation of the distortion between different types of loads is only partly included.

The study presented in this paper is completely based on measurements. Two experiments have been conducted in which the current distortion of an installation is measured before and after the replacement of all incandescent lamps by energy-saving lamps. The two experiments are described in the forthcoming two sections. After the description of the experiments, the paper continues with a presentation of the results, where a distinction is made based on the different ways in which individual equipment impacts the current of the total installation. The paper also includes an estimation of the strength of the power system needed to maintain voltage distortion within the limits for the observed current distortion.

Experiment 1: Domestic Customer

A full-scale electrical model of a detached house was built in the Pehr Högström laboratory at Luleå University of Technology, Skellefteå, Sweden. The model has realistic cable length and cable areas for an urban residential home in Sweden [5].

The pattern used to represent the variations in consumption, is shown in Table I, where each column represents a three-minute period and each row a part of the load that was switched separately. The time stamps in the upper row indicate the end of the period. Details of the loads are given in Table II and below:

With the exception of the computer and the television, all loads used a certain operating cycle that could not be controlled. The power consumption and harmonic emission from this equipment may therefore not be identical between different scenarios. All LED lamps were 7 W and all CFL's were 11 W, unless otherwise indicated in the table. All CFL and LED lamps had a power factor of 0.6.

Table I. Load switching pattern used during the experiments.

	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72	75	78	81	84	87	90	93	96	99	102	105	108
Lamps A			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
Lamps B					X	X	X	X	X	X	X	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X	X	X				
Lamps C													X	X	X	X	X			X	X	X	X													
Computer and television									X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
Microwave												X	X											X	X											
Dishwasher						X	X	X	X	X	X	X	X	X	X							X	X	X	X	X	X	X	X	X	X					
Induction Stove							X	X	X	X	X	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X						
Heat pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																		
Refrigerator	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table II. Details of the lighting load used for the four scenarios

	"past"	"present"	"future"	"far-future"
Lamps A	12 60-W incandescent	4 halogen + 4 60-W incandescent + 4 CFL	6 LED + 6 CFL	12 LED
Lamps B	18 60-W incandescent	6 halogen + 6 60-W incandescent + 6 CFL	9 LED + 9 CFL	18 LED
Lamps C	2 dimmable 60 W incandescent	2 dimmable 20-W CFL	2 dimmable 20-W CFL	2 dimmable LED
Total	1920 Watt	1150 Watt	310 Watt	224 Watt

A number of different scenarios were tested; all give equal light output in Lumen. Normal household equipment was connected in the house in addition to the lamps. The normal household equipment was kept the same for the five scenarios: the only difference was the lighting. The load was changed in three-minute intervals with a total pattern of 108 minutes, 54 minutes with a heat-pump and 54 minutes mirroring the same pattern without the pump. The pattern was designed so that both high load (morning and afternoon) and low load (night) was simulated. The aim of the pattern was not to reproduce a typical day, but to include a range of combinations of load types. The voltage and current were measured at the delivery point, covering the complete load.

Experiment 2: field measurements with a hotel

Measurements have also been performed on a medium-sized (76 rooms) hotel in the North of Sweden. During the start of the measurements, the majority of lighting used in the hotel consisted of incandescent lamps. All incandescent lamps were replaced by energy saving lamps, both CFL and LED, with a typical power-factor of 0.5 – 0.6. Measurements were performed before, during and after the replacement. A Dranetz Power Visa monitor was used to obtain the harmonic distortion and several other parameters over each 10-minute interval.

Before the change, the lighting in the hotel consisted of 447 incandescent 40-W lamps with E27 fitting and 116 incandescent 40-W lamps with E14 fittings. The E27 lamps have been replaced by 7-W LED lamps and the E14 lamps by 8-W CFLs. A total of about 30 lamps were replaced in the common areas of the hotels; the others were replaced in the guest rooms. In total this would give a reduction in active power up to 18 kW.

Three measurement series have been conducted: before the replacement (26 March – 9 April 2009), during the replacement (13 – 29 April 2009) and after the replacement (4 – 19 May 2009).

In the forthcoming sections, we will refer to the results from Experiment 1 as the “domestic customer” and to the results from Experiment 2 as the “hotel”.

Active Power

The active power for the domestic customer is shown in Fig. 1. The switching pattern is clearly visible as well as the reduction in active power due to the replacement of the incandescent lamps.

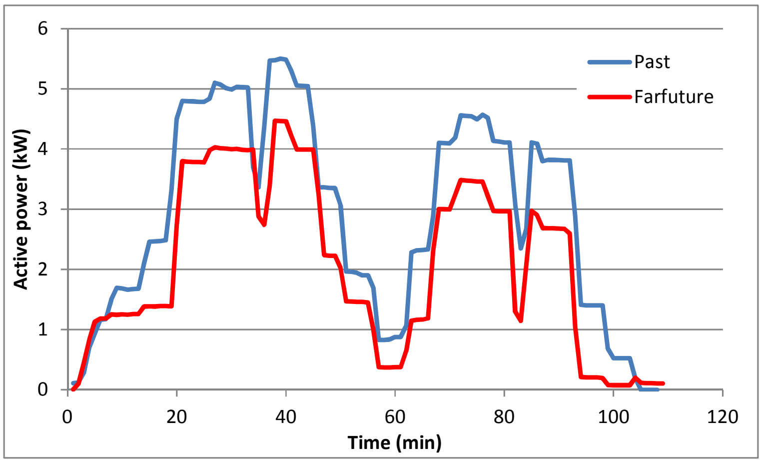

Fig. 1. Active power for the domestic customer as a function of time: two scenarios.

The active power of the hotel also showed a reduction after the replacement compared with before the replacement. This reduction was not as clear as in the controlled experiment for the domestic customer. The active-power consumption depends among others on the number of rooms occupied. To illustrate this, the daily energy-consumption (noon to noon) is shown in Fig. 2 versus the number of rooms occupied, before and after the replacement. The energy consumption is clearly lower after than before the replacement.

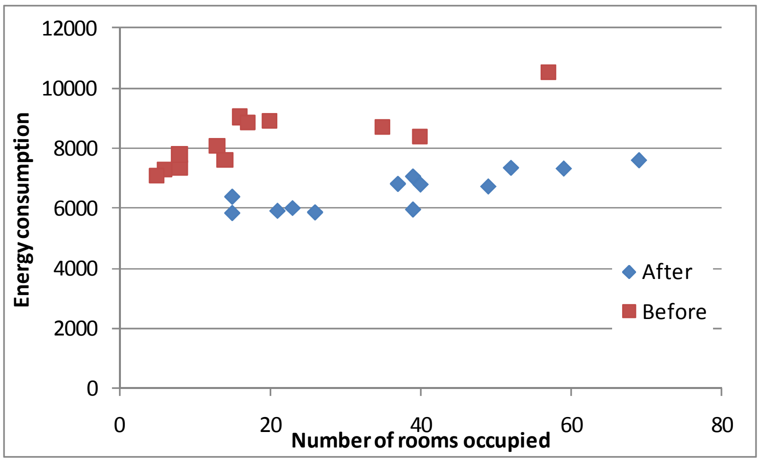

Fig. 2. Relation between daily energy consumption with the hotel (in arbitrary units) and the number of rooms occupied.

Harmonic Emission

The third harmonic versus time for the domestic customer is shown in Fig. 3. The variations versus time are similar for harmonics 5 and 7. The overall pattern does not change despite the replacement of all incandescent lights first by compact fluorescent lamps and next by LED lights. For all three harmonics (3, 5 and 7) are the values significantly higher during the first half of the measurement than during the second half. This is most likely due to the presence of the heat pump during the first half. The replacement of the incandescent lights does result in some increase in the harmonic distortion, especially for the “future” scenario. The increase is however of limited size and smaller than for example the impact of the microwave.

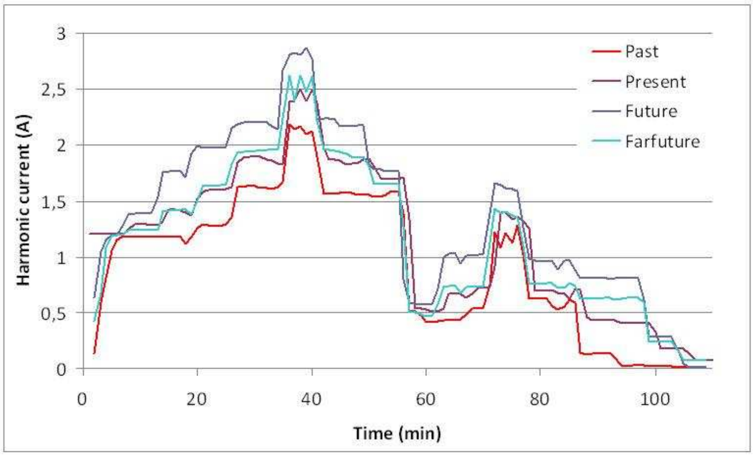

Fig. 3. Third harmonic current for the domestic customer as a function of time

The change in harmonic emission is quantified in Table 3: the 95, 99, and 100% values of the third, fifth and seventh harmonic current are shown for the four scenarios. The relative increase (last row in the table) in the Far Future scenario compared to the Past scenario is about 20% for the third harmonic, about 25% for the fifth harmonic and about 40% for the seventh harmonic.

Table 3. High-percentile values of the harmonic emission from the domestic customer

	Harmonic 3			Harmonic 5			Harmonic 7		
	95%	99%	100%	95%	99%	100%	95%	99%	100%
Past	1.82 A	2.17 A	2.19 A	0.79 A	0.81 A	0.82 A	0.33 A	0.36 A	0.36 A
Present	2.18 A	2.49 A	2.50 A	0.80 A	0.84 A	0.84 A	0.42 A	0.44 A	0.44 A
Future	2.51 A	2.82 A	2.87 A	1.01 A	1.07 A	1.07 A	0.54 A	0.55 A	0.55 A
Far Future	2.23 A	2.62 A	2.62 A	0.98 A	1.00 A	1.08 A	0.47 A	0.49 A	0.49 A
Relative increase	23%	21%	20%	24%	27%	32%	42%	36%	36%

The increase of the seventh harmonic could be some cause for concern. The emission starts however from a rather low value, so that this large relative increase might not pose a concern for the network.

The variation with time for the different harmonics in the supply current to the hotel is determined by many other factors than only the replacement of the lamps. There is no obvious trend visible in the harmonic levels for any of the harmonics. This is illustrated in Fig. 4 for the third harmonic: the levels before during and after the replacement are very similar; the day-by-day variations are bigger than the variations between the three periods (before, during and after the replacement).

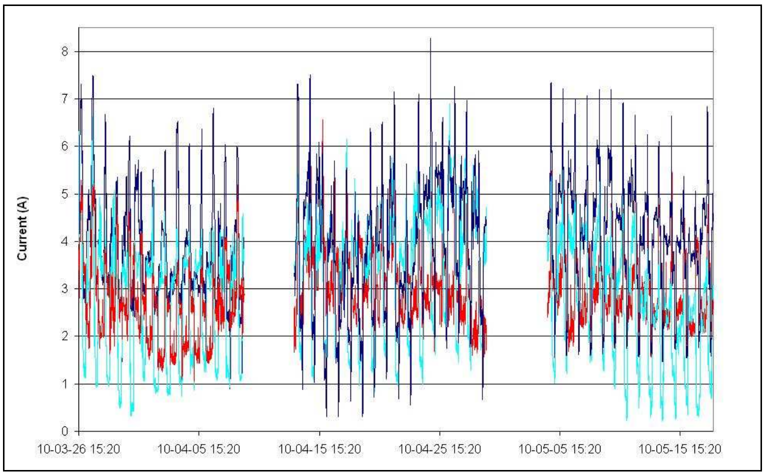

Fig. 4. Third harmonic for the hotel during the whole measurement period

The 95% values of the third, fifth and seventh harmonic for each phase before and after the replacement are shown in Fig. 5. It shows an increase in third harmonic in two of the phases and a decrease in the third phase. The changes in third harmonic are minor however: -3%; +5% and +2%. We conclude that there is no observable difference in the third harmonic current due to the replacement.

The fifth harmonic current shows an increase in two of the phases, with the increase being about 40% in phase A. The third phase does show a decrease in harmonic current however. The increase is biggest in the 95% value; the increase in 99% value is only 15%. It should also be noted that the maximum rms current is over 150 A; the fifth harmonic current after replacement is thus still less than 3% of the rated current. The seventh harmonic goes down in two phases and remains about the same in the third phase. The increase in seventh harmonic current, observed for the domestic customer, is not visible with the hotel at all.

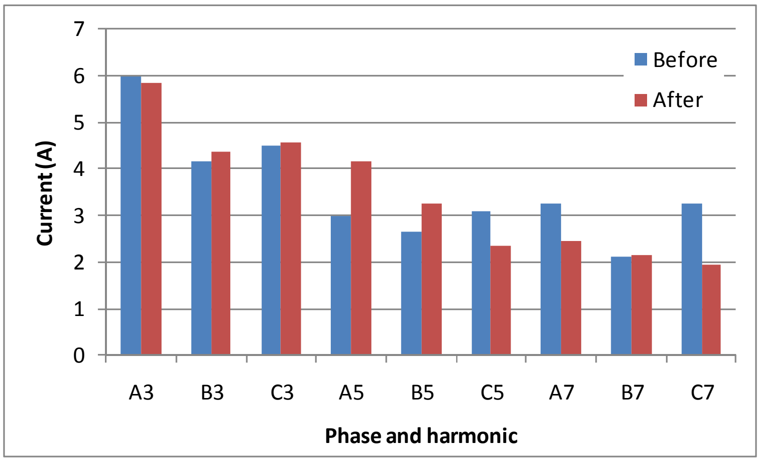

Fig. 5. 95% values of the third, fifth and seventh harmonic with the hotel before and after the replacement.

The harmonic spectrum has been calculated from the 99-percentile of the individual harmonics. The results for the domestic customer are shown in Fig. 6 for the “Past”, “Future”, and “Far Future” scenarios. The lower limit of the vertical axis is slightly above the resolution of the measurements. The even harmonics (lower row of points) do not show any significant increase; whereas also most of the odd harmonics (upper row of points) show only minor changes. Significant increase is only visible for harmonics 9, 13, 19, 21, 23 and 25.

Note that the emission for the Far Future scenario (with only one type of lamp) is higher than for the Future scenario (with two types of lamps: CFL and LED’s) for harmonics 13, 19, 21 and 23. A possible explanation is the cancellation between the two lamp types for these harmonic frequencies.

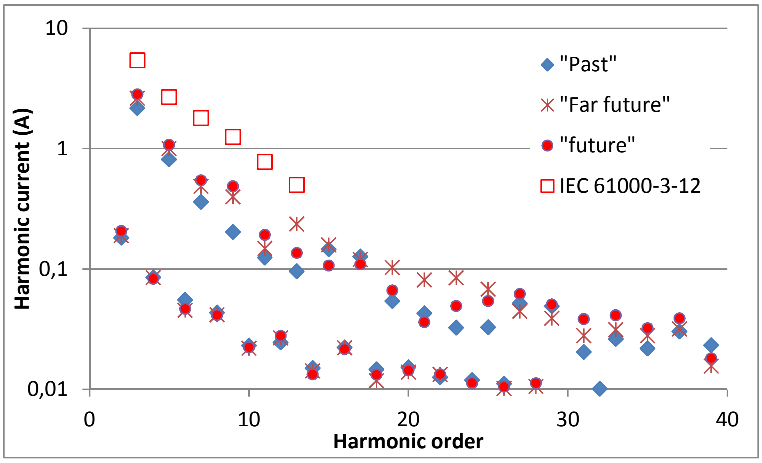

Fig. 6. 99% harmonic spectra for the domestic customer: three scenarios and IEC 61000-3-12 limits.Note the logarithmic vertical scale.

The squares in the figure are the limits that would be placed on the domestic customer in case it would be treated as a device, with a rated current of 25 A, under IEC 61000-3-12. The most strict limits, for a short-circuit ratio of 33, have been used. The harmonic emission increases for some of the frequencies due to the replacement, but for all relevant frequencies is the emission even in the "far future" scenario more than a factor of two below the limits according to IEC 61000-3-12.

The harmonic emission of this hotel is compared with the emission limits for equipment with rated power between 16 and 75 A, according to IEC 61000-3-12, in Fig. 7. The table for unbalanced equipment has been used, for a short-circuit ratio of 33. This results in the strictest limits. A rated power equal to 150 A has been assumed. Although the size of this load is strictly speaking outside the range for this standard, the relative limits have still been applied so as to get an impression of the severity of the emission.

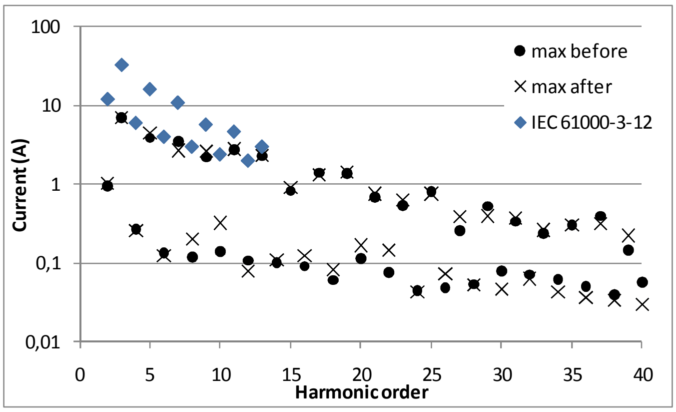

Fig. 7. Maximum of the 99% harmonic current spectra in the three phases for the hotel, before and after the replacement; comparison with the IEC 61000-3-12 limits; note the logarithmic vertical scale

The comparison shows that the current emission is below the limit for all harmonics covered by the standard. Harmonic 13 is closest to the limit, but the value of this one is not impacted by the replacement.

Fault-Level Requirements

The 99-% harmonic currents from the "past" and "far future" scenarios of the domestic customer have been used to estimate the fault-level requirements placed on the distribution network operator by this customer. It has been assumed that the source impedance increases linearly with frequency. The 95% voltage-distortion limits for customers connected to a public low-voltage network, according to EN 50160, have been used. Knowing the current emission I_h and the maximum-permissible voltage distortion $u_{h,max}$, the minimum-required fault level can be calculated, using Ohm's law. As shown in [5] the minimum required short-circuit ratio (ratio between the fault current and the rated current I_{nom}) is obtained from:

$$k_{min} = \frac{h \times I_h}{u_{h,max} \times I_{nom}}$$

Where *h* is the harmonic order. The minimum-required short-circuit ratio, for a rated current of 25 A is shown in Fig. 8 for the “past” and “far future” scenarios.

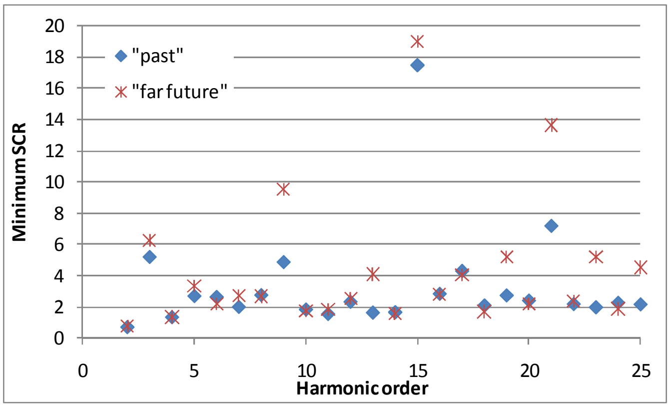

Fig. 8. Minimum-required short-circuit ratio for the domestic customer to keep the voltage distortion below the EN 50160 limits.

The higher the minimum-required short-circuit ratio, the higher the risk that the voltage-distortion limits will be exceeded. The values set by the harmonic emission, and shown in Fig. 8 should be compared with other requirements set on the short-circuit level. A study done by a network operator [7] resulted in a minimum short-circuit ratio of about 30 to prevent excessive steps in voltage due to load switching. The highest values from our measurement are obtained for the triplen harmonics 3, 9, 15 and 21. The voltage-characteristics and compatibility levels have traditionally been rather low for these harmonics. It should further be noted that the model used for the source impedance, linear increase with frequency, probably gives an overestimation of the required fault level for higher-order harmonics.

Reactive Power, THD, and Power Factor

The reactive power at the power-system frequency (“fundamental reactive power”) is plotted versus the active power for the domestic customer in Fig. 9 and for the hotel in Fig. 10. The domestic customer is shown to generate reactive power during most of the measurement period; the hotel always consumes reactive power. For the domestic customer the figure shows a small increase in reactive-power production; the reactive power for the hotel is not impacted by the replacement.

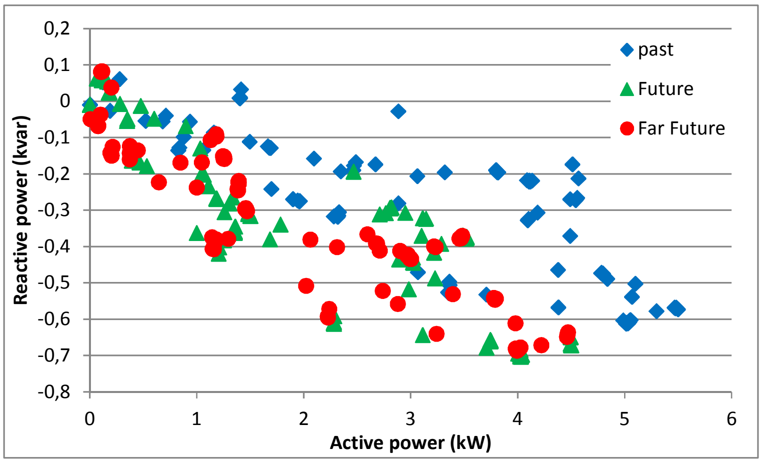

Fig. 9. Active power and (fundamental) reactive power for the domestic customer

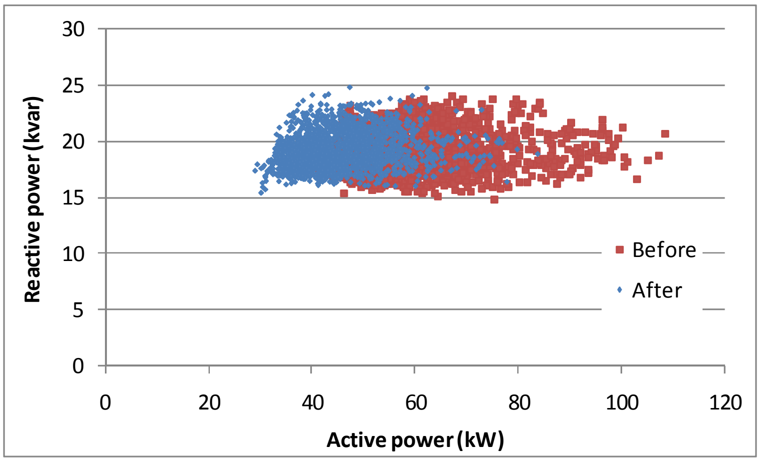

Fig. 10. Active power and (fundamental) reactive power for the hotel

For both customers the reactive power remains about the same whereas the active power becomes less. This will result in a smaller value for the displacement power factor (cos ϕ) of the total load. In the period before the replacement, 90% of the values for the hotel are between 0.86 and 0.99 (5% below and 5% above this range). The corresponding interval for the period after the replacement is between 0.82 and 0.97. The impact of the load on the power system does however not increase; it will sooner decrease because of the reduction in apparent power. The use of the displacement power factor to quantify the impact of a load on the system would result in the wrong conclusion in this case.

The total power factor (often referred to simply as "power factor") is smaller than the displacement power factor; the difference is due to the waveform distortion. The total power factor is often used as an indicator for the impact of a specific device or installation on the power system. This may however again result in the wrong conclusions. The total power factor for the domestic customer is shown in Fig. 11. The values are lower for the Future and Far Future scenarios. These low values are however obtained only when the rms current is low. The total impact on the power system is lower during these periods than during periods of high power factor.

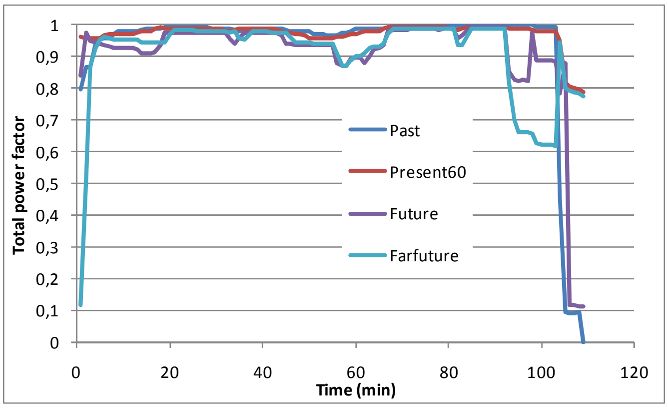

Fig. 11. Total Power Factor versus time for the domestic customer

Very low values of the power factor occur during the beginning and the end of the measurement period. This is when no equipment at all is in operation and the only active-power consumption is formed by the stand-by losses of the equipment. The stand-by current is mainly capacitive, hence the low power factor. A power factor slightly above 0.6 is obtained towards the end of the "far future" scenario; this is when the load only consists of identical LED. In the future scenario, the load consists during this part of the pattern, of a mixture of LED and CFL. Even though both have a power factor of 0.6, the power factor of the combination is over 0.8.

The power factor for the hotel, presented in Fig. 12, shows a decreasing trend throughout the measurement period. This is however almost exclusively due to the reduction in displacement power factor, which in turn is due to the reduction in active power. The total power factor is, throughout the measurement period, 99% or more of the displacement power factor. The waveform distortion thus causes 1% or less of the non-unity power factor, despite all unity-power factor lamps having been replaced by lamps with 0.6 power factor.

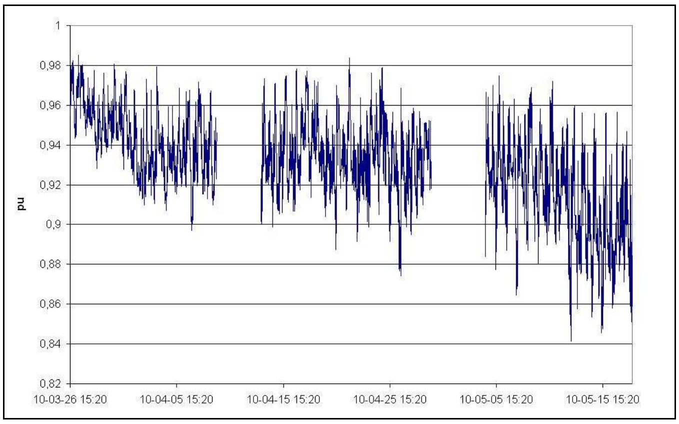

Fig. 12. Total power factor for the hotel during the whole measurement period.

The total harmonic distortion of the current versus time is shown in Fig. 13 for the four scenarios with the domestic customer. The waveform distortion, in terms of THD, shows a significant increase especially for "future" and "far future"; with distortion over 50% during part of the measurement period.

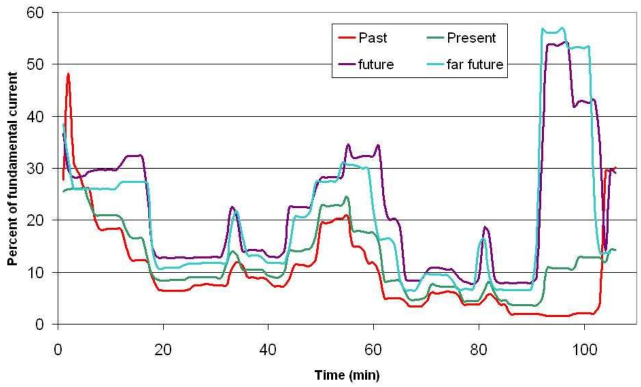

Fig. 13. THD of the current (in percent) versus time for the five different scenarios.

The total harmonic distortion is however only a measure of the non-sinusoidal character of the waveform; it is not a good measure for the grid impact of a load. Comparing Fig. 13 with Fig. 1 shows that high values of the THD occur during periods of low consumption. The impact of heavily-distorted waveform of low amplitude is less than the impact of a less-distorted waveform of high amplitude. What matters for the power system is not the THD in percent but the THD expressed in Ampere. The latter is the root sum square over all harmonic components, which can also be calculated as the product of the THD in percent and the fundamental current in Ampere. The THD in Ampere is shown for the domestic customer in Fig. 14. The highest values for the harmonic emission of the installation occur during the first half of the measurement period, when the heat pump is operating.

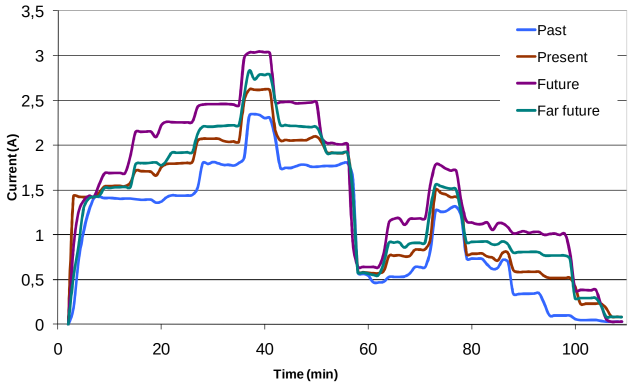

Fig. 14. THD of the current (in Ampere) versus time for the five different scenarios.

Comparing the “relative THD” in Fig. 13 with the “absolute THD” in Fig. 14, shows that the former has no relation with the actual impact of the installation on the grid. The relative THD should thus not be used to quantify the impact of an installation on the grid.

In order to get a fair value of the impact of the lights on the total harmonic distortion for the hotel, two 24-hour periods were selected where the number of rooms occupied was similar. One period with only a few rooms occupied was selected; and one where a large number of the rooms available was occupied. The results are shown in Fig. 15. After the lamps were changed the number of guests in the hotel did not have a strong impact on the current THD; the value is the same in phase three and the increase in phase one and two are 1% and 5% respectively. Before the replacement, the THD value increases in all phases when the number of rooms occupied goes from 15 to 59.

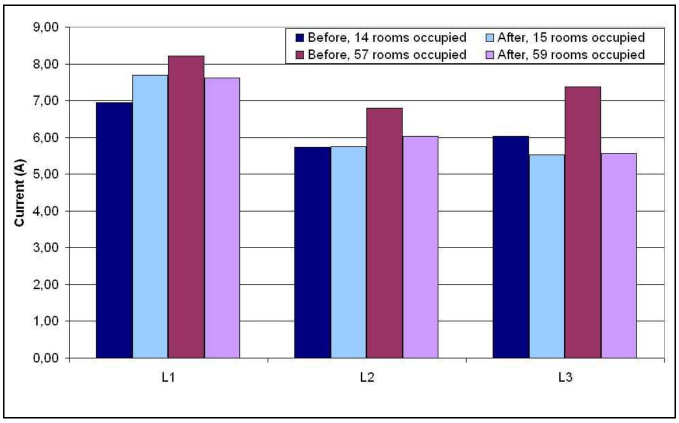

Fig. 15. The 95% value of the current THD, in Ampere with the hotel, for two 24 hour periods; L1, L2 and L3 refer to the three phases

Conclusions

Measurements with a domestic customer emulated in the laboratory and with field measurements of a hotel show that the replacement of incandescent lamps by LED lamps and CFL's gives a reduction in active power consumption (thus a reduction in local energy use), a reduction in peak current (i.e. a reduction in the loading of the grid), and a reduction in distribution-system losses (which gives a further reduction in energy use). All have a positive impact on energy efficiency and on the power-system.

The measurements for the domestic customer also show that the replacement results in an increase of the amount of so-called reactive power produced by the load. This has in most cases an overall positive impact on the grid, but the impact is too small for it to be any real value. For the hotel, no change in reactive power flow was observed.

For the domestic customer the replacement of incandescent lamps by LED and CFL results in an increase of the current distortion. The increase is however less than expected and the distortion from the experimental installation, despite its high amount of lighting, is still more than a factor of two below the limits set in an international standard (IEC 61000-3-12). The presence of other equipment, like a heat pump or a dish washer, impacts the current distortion much more than the replacement of the lamps.

The changes in current distortion for the hotel, before and after the replacement, are small, show increases as well as decreases and no impact is visible of the replacement of incandescent lamps by energy savings lamps. It is important to note that in both experiments so-called "low-power-factor lamps" were used. These are the ones that have the highest impact on the current distortion.

The laboratory experiment in which a full-scale electrical model of the domestic installation is reproduced in the laboratory has shown to be a suitable way of studying the impact of new equipment on the current distortion. It offers a compromise between the flexibility and reproducibility of a simulation and the accuracy of a field test.

With the field experiment at the hotel, other changes in consumption take place next to the replacement of the lamps: seasonal variations in temperature and amount of day light; as well as a variation in the number of rooms occupied. It has not been possible to completely remove the influence of this, so that the actual impact of the replacement could not be quantified. An important conclusion from this study is however that the impact is in any case small and smaller than the impact of other variations in consumption.

A comparison is also made of the additional requirements placed on the system strength by the replacement. These additional requirements are small and do not result in the need for any additional network-planning effort at this stage.

The study also confirms that the power factor is not an appropriate indicator to compare different loads. To compare the impact of different loads on the power system, a set of parameters should be used. The combination of active power, reactive power (in var); harmonic currents (in Ampere) and rms current (in Ampere) is a much better alternative.

Acknowledgements

Financial support from Philips, Skellefteå Kraft and the Swedish Energy Agency is gratefully acknowledged

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