TECHNICAL REPORT

Mitigation of Main Factors that Limit the Introduction of Energy-Efficient Lighting Systems

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Summary

This is the final report of the Swedish Energy Agency project (P31550-1) ”Mitigation of main factors that limit the introduction of energy-efficient lighting systems” that was conducted by the power engineering group at Luleå University of Technology. In this project electromagnetic disturbances have been studied in installations with large numbers of fluorescent lamps with high-frequency ballast. Examples of such installations are shops and shopping centres, large offices and storage areas.

The project has resulted in increased knowledge on waveform distortion in the frequency range from 2 to 150 kHz and the spreading of these components, within a lighting installation. The following concrete result can be mentioned:

- ✓ The harmonic emission (below 2 kHz) from a light installation is low compared with similar types of electronic loads
- ✓ The emission in the frequency range between 2 to 150 kHz can be traced to remains from the switching within the ballast and recurrent oscillations that occurs close to the zero-crossing of the fundamental waveform
- ✓ The type emission from light installations in the frequency range 2 to 150 kHz can be categorised into following
  - Narrowband components
  - Broadband components
  - Recurrent oscillations
- ✓ When lights are installed in large groups, the emission remaining from the switching mainly propagate between ballasts while the recurrent oscillations show a significant level of addition.
- ✓ The capacitor of each EMC filter at the AC side will provide a low impedance path to the remains of the switching frequency.

This report also gives some discussions and ideas about proper solutions to avoid different emissions and on how to design the light installation and the EMC filter at each ballast.

The recurrent oscillations are perceived as a potential problem in large installations. There are though no indications yet that recurrent oscillations is either a threat or not, for the expected lifetime of the ballast. For this further research is needed.

Sammanfattning

Detta är slutrapporten från den svenska Energimyndigheten projekt (P31550-1) "Minskat livslängd av energieffektiv belysning på grund av höga nivåer av elektromagnetiska störningar" som utförs av kraftteknik gruppen vid Luleå Tekniska Universitet. I detta projekt har elektromagnetiska störningar studerats i anläggningar med ett stort antal lysrör med högfrekventa förkopplingsdon (HF-don). Sådana belysningsanläggningar återfinns i butiker och köpcentra, stora kontor och lagerutrymmen.

Projektet har resulterat i ökad kunskap om vågformsdistorsion i frekvensområdet 2 till 150 kHz och spridningen av dessa komponenter inom en belysningsanläggning. Följande konkreta resultat kan nämnas:

- ✓ Övertoner (under 2 kHz) från en belysningsinstallation är låg jämfört med liknande typer av elektroniska laster
- ✓ Emission inom frekvensområdet mellan 2 till 150 kHz kan hänföras till rester från om ”switchingen” i HF-donen och återkommande oscillationer som sker nära grundtonens nollgenomgång
- ✓ Typen av emission från belysningsinstallationer i frekvensområdet 2 till 150 kHz kan delas in i följande:
    - Smalbandiga komponenter
    - Bredbandiga komponenter
    - Återkommande oscillationer
- ✓ När belysningen installeras i stora grupper som t.ex. i varuhus så sprids de olika emissionerna på olika sätt. Resterna från switchingen går framförallt mellan armaturerna medan de återkommande oscillationerna adderas i amplitud och sprider sig uppåt i nätet mot transformatorn.
- ✓ Anledningen till att resterna från switchingen till största del stannar i belysningsanläggningen beror på att varje EMC-filter på AC sidan erbjuder en låg impedans för dessa komponenter.

Rapporten diskuterar också idéer om lämpliga lösningar för att minimera olika emissioner och om hur man designar belysningsanläggningar och EMC-filter drivdon.

De återkommande oscillationerna kan uppfattas som ett potentiellt problem i stora anläggningar. Det finns även inga tecken ännu att återkommande oscillationer är antingen ett hot eller inte, för den förväntade livslängden hos drivdonen. Här behövs dock ytterligare forskning.

Contents

1 Introduction

In this project electromagnetic disturbances have been studied in installations with large numbers of fluorescent lamps with high-frequency ballast. Examples of such installations are shops and shopping centres, large offices and storage areas.

The change from incandescent lamps to more energy-efficient lighting technology is, according to a McKinsey study, the most cost-effective way of reducing carbon-dioxide emission. It is therefore important that real and perceived barriers against this change are understood and removed. One of those barriers is the possible reduction in lifetime of fluorescent lamps with high-frequency ballast due to harmonics and other electromagnetic disturbances. It has not yet been possibly to prove any such relation but the lifetime of such lamps in sufficiently important to justify a detailed study after any relation. As a first step the emission of electromagnetic disturbances by fluorescent lamps with high-frequency ballast has been studied. The results from those studies have been published in several papers and in a PhD thesis and are summarized in Chapter 4. This report starts with a discussion on the lifetime of lamps and the various factors that impact it and that may impact it. Harmonic emission, a specific type of electromagnetic disturbance in which equipment connected to the power system draws a non-sinusoidal current, is discussed in Chapter 3. Some examples of harmonic emission are presented as well as the international standards that limit the emission from lighting equipment. The results from the detailed study summarized in Chapter 4 are used to obtain recommendations on immunity of electronic ballasts in Chapter 6 and on installation guidelines in Chapter 7. The results and recommendations are further summarized in Chapter 8.

2 Lifetime

The term "life time" is used in a different way in statistics than in daily life. In daily life one refers to the lifetime of an individual device. This cannot be predicted. In statistics one refers to stochastic properties like the expected lifetime of a group of devices or the probability distribution of such a group. When referring to the lifetime of a component in statistics, one refers to the lifetime as a stochastic variable. The properties of this stochastic variable, like its expected value, can in fact be predicted.

A common misunderstanding, resulting from the term lifetime having different meanings, is that the expected lifetime is interpreted as a kind of guaranteed or minimum lifetime.

An important parameter to describe the probability distribution function of a device is the so-called "failure rate". The failure rate describes how fast in average e.g. a group of ballast is failing. In a case with ballasts, failure rate is calculated by dividing the total number of ballast that has failed with the observation times [1][2][3].

For many products the failure rate as a function of time (i.e. with increasing component age) follows a so-called bath-tub curve: an initially high failure rate associated with wear-in; a constant failure rate during the useful life of the product; and an increasing failure rate associated with wear-out or ageing. For mass consumer products the wear-in period is short and it can be assumed that the failure rate is constant during the useful life.

During the useful life, i.e. as long as the failure rate remains constant, the lifetime can be described through a continuous probability function called the “exponential distribution”.

The exponential distribution function can be described as

$$f(t;\lambda) = \begin{cases} \lambda e^{-\lambda t}, & t \geq 0 \\ 0, & t \leq 0 \end{cases} \quad \text{where } \lambda = \frac{1}{\mu} = \frac{1}{\text{MTTF}}$$

the failure rate μ is constant which means that the time t between failures is the same independent upon when the observation is made [1]. The age of the product does thus, for this distribution, not impact the probability that the product will fail in the near future (e.g. within one year).

Datasheets of HF-ballast is revealing that ballasts will also show a lifetime with an exponential distribution. The total lifetime of the ballast is though determined by each individual component in the ballast. Normally this means that more components lead to a shorter lifetime[1] or as the saying goes “the chain is not stronger than the weakest link”. So of course is the lifetime dependent upon the quality of each component and the lifetime on individual components are dependent upon quality of the material when manufactured.

The lifetime of a ballast is however also dependent upon a number of different parameters:

- Environmental parameters like temperature, temperature variations and humidity.
- Mechanical vibrations and shocks.
- Voltage magnitude and waveform at the terminals of the lamp.

When looking upon datasheets for electronic ballasts it is quite normal that we can find failure rates (µ) ranging from less than 0.05 % per 1000 burning hours to 0.5 % per 1000 burning hours. These failure rates are given under specified conditions regarding casing temperature, ambient temperature, humidity etc. Also the number of switching of the lamp impacts the failure rate.

The exponential distribution of the lifetime is however only valid up to a certain number of hours. After this time has been reached the failure rate, which has been constant, starts to increase and the ballasts has reached the end of useful life. Mainly drying of electrolytic capacitors and degradation of soldier contacts is given as the reason to this. The time when this is occurring is also strongly depending upon the working environment of the ballast.

As described above the lifetime of ballasts is quite dependent upon temperature, number of starts etc. and this is quite well understood. According to a manufacturer of ballasts: “For most ballasts in normal operation, this constant failure rate is approximately 50 000 h at a fixed specified case temperature (65°C). A temperature increase of 10 degrees halves this average service lifetime (thus, 75°C gives 25 000 h), while 10 degrees lower doubles this figure (55°C gives 100 000 h)” [4]. How

[1] Here a simple system is assumed, in stochastic terms: a system with non-redundant non-repairable components. This is an acceptable model for consumer products like lamps,

different voltage quality parameters impact e.g. the temperature of the ballast is not so well understood.

It is at this stage not possible to give any quantitative information on how much certain voltage quality disturbances impact the lifetime. However from the general knowledge on lifetime of ballasts and our detailed knowledge on voltage-quality disturbances we can draw some general qualitative conclusions.

It was mentioned before that end of useful life is mainly due to drying of electrolytic capacitors and degradation of solder contacts. The heat produced inside the capacitor depends on the ripple current through the capacitor and the equivalent series resistance (ESR) where the ripple current is the square root sum of each frequency components in the current. Note that this resistance is also frequency dependent and that the sum of all individual components will contribute to the heating [5].

Degradation of contacts is related to the temperature of the contacts, especially high temperature and temperature variations are expected to reduce the lifetime. In terms in electrical parameters: high currents and fast variations in currents reduce the lifetime.

Next to these, high voltages will degrade the insulation and cause short circuits. This is only expected for very high voltages like those due to lightning strokes. This is a rather well understood phenomenon that we will not consider here.

Voltage variations: increase in voltage gives a higher current through the capacitor; reduction in voltage makes that the current taken by the ballast is higher. Both will reduce the lifetime of the ballast.

Short duration events like dips, swells and switching transients will typically have limited impact because they are too short to impact the temperature. Only severe dips, short interruptions, etc will have a similar effect as switching the ballast. There are however cases when the electronics in the ballasts, for whatever reason does not tolerate voltage dips. This is a general issue with any type of equipment and not specifically related to electronic ballasts.

3 Harmonic emission

The power system is designed to transmit electrical power through the grid from the generating source to the load. Equipment connected to the power system is designed for a perfect sinusoidal waveform with a constant voltage amplitude and frequency, although the equipment obviously also functions as intended for certain deviations from this ideal situation. Any deviation from the perfect sinusoidal waveform is referred to as distortion. However some loads have nonlinear impedance and will draw a current from the grid that is deviating from this sinusoidal waveform which is a waveform distortion. In most cases when transferring the distorted waveform into frequency domain desecrate components of multiples of the fundamental will show up, that is often referred as harmonics. Harmonics is in many cases created by loads and therefor this is defined as a harmonic emission from equipment.

Harmonic emission from equipment can cause several problems in the grid like [6][7][8]

- Transformers overheating
- Overheating of neutral conductors
- Inadvertent trip of circuit breakers
- Capacitor problems; mal-trip of capacitor fuse
- Digital clocks running fast
- Malfunction of electronic equipment
- Overheating of induction motors

In order to minimize harmonic emission and waveform distortion there is a set of standards covering the harmonic emission from various types of loads.

3.1 Emission standards

IEC 61000-3-2 [10] is dealing with limiting harmonic current injection into the public grid from equipment up to 16 A per phase. This standard is covering most of the lighting equipment and includes fluorescent lamps powered by a HF-ballast. When comparing with other types of small equipment covered by the same standard, harmonic emission limits applying to light are more restrictive than for the other classes. This will in the end lead to that some type of power factor correction (PFC) is needed to comply with the standard. Note that this class is restricted to equipment above 25 W; lighting equipment below this is restricted by Class D or a similar limit. The most common way to handle these harmonic limitations at lighting equipment with HF-ballast is to use active PFC. A number of different solutions and topologies are in use for this.

Table 1. Emission limits for lamps with a rated power above 25 Watt

Harmonic order N	**Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency** %
2	2
3	$\lambda \cdot 3$*
5	10
7	7
9	5
$11 \leq n \leq 39$ (odd harmonics only)	3
* λ is the circuit power factor	

Table 2 Emission limits for lamps with a rated power up to 25 Watt

Harmonic order N	**Maximum permissible harmonic current per watt** mA/W	**Maximum permissible harmonic current** A

3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13 ≤ n ≤ 39 (odd harmonics only)	3.85/n	0,15*15/n

EN 55015 (CISPR 15) [11] which is standard to protect the radio service band is also in fact regulating conducted disturbances from 9 kHz and up to 30 MHz by limiting levels on the mains terminal. The standard is, for the lower frequency band (9 to 150 kHz), setting quasi peak limits.

Table 3 Emission limits for lamps in the frequency range 9 kHz to 30 MHz.

Frequency range	Limits (dBμV)
9 – 50 kHz	110
50 – 150 kHz	90 to 80*
150 – 500 kHz	66 to 56*
0.5 – 5 MHz	56
5 – 30 MHz	60
*decreasing linearly with logarithm of the frequency	

These two above described standards are both setting limits to the emission from ballasts.

3.2 Examples of harmonic emission

Some example of waveforms measured at the interface of customer equipment is shown in Fig. 1. The corresponding harmonic spectra are shown in Fig. 2. Roughly speaking we can divide the equipment into two groups, where it concerns their waveform distortion:

- equipment that takes a sinusoidal current (incandescent lamp) or a more or less sinusoidal current (laptop, LCD TV).
- equipment that takes a current consisting of one positive peak and one negative peak. Most other equipment.

The VCR appears to be a combination of these two types. The first group contains equipment that is inherently free from harmonics (the incandescent lamp) or that is equipped with active switching technology to create a more or less sinusoidal current waveform. The second group typically contains a power supply with a diode rectifier.

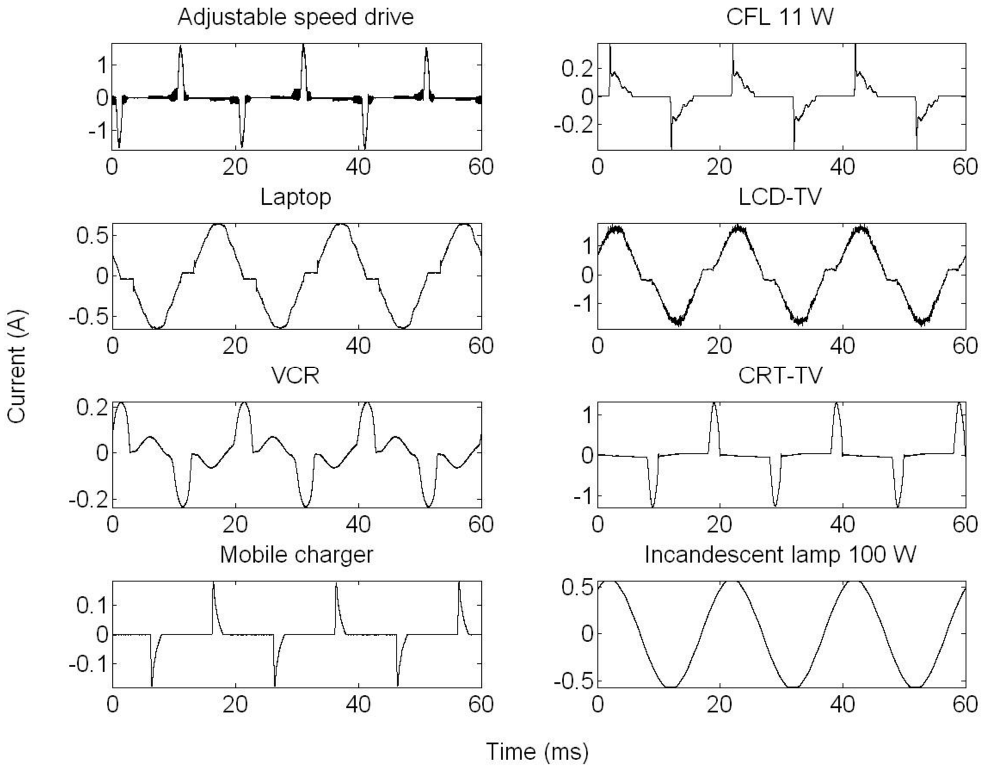

Fig. 1 Examples of small electronic devices containing power electronics (plus an incandescent lamp). Note the difference in vertical scale between the different waveforms.

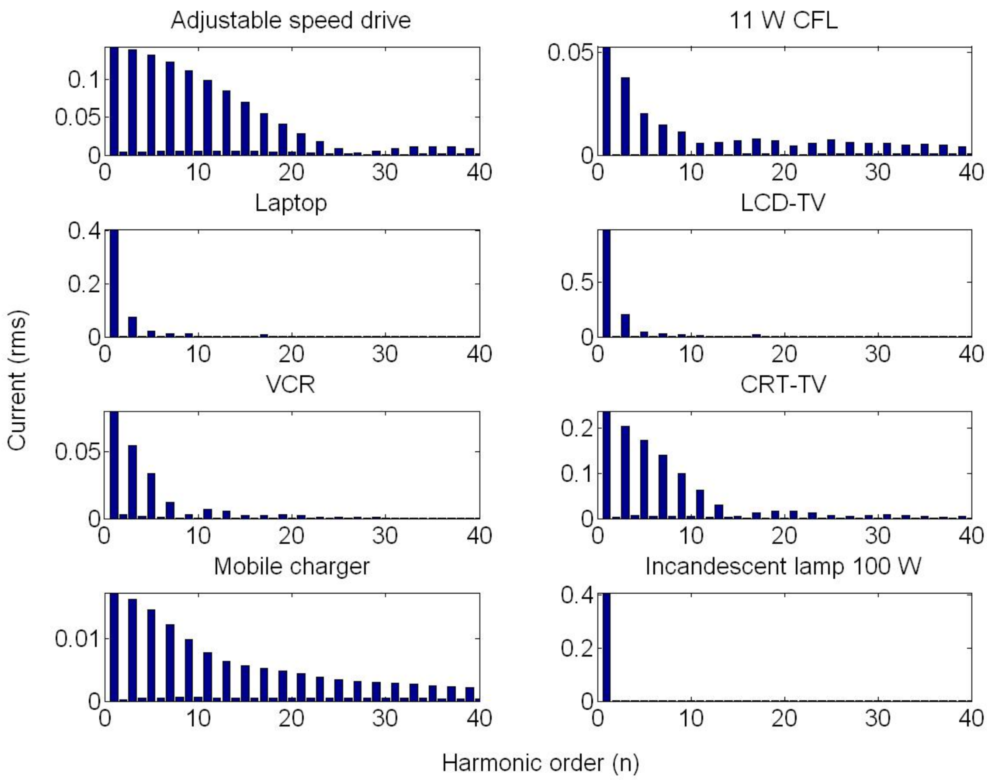

Fig. 2 Harmonic spectra of the current waveforms shown in Fig. 1. Note the difference in vertical scale between the different spectra.

3.3 Power factor

Within the lighting industry it is quite common to describe the emission with the power factor (PF), also referred to as "total power factor". PF is defined as the ratio of the measured active input power to the product of the supply voltage (r.m.s) and the supply current (r.m.s).

$$PF = \frac{P}{S}$$

Although the definition of the power factor is very clear and generally accepted, there is significant confusion in its practical use as a performance indicator. The power factor is a combined index, where different characteristics of both the voltage and the current waveform influence the result. In the general case, it is not possible to uniquely identify the influence of any single characteristic on the value of the power factor.

Another common way of describing emissions is to use the total harmonic distortion (THD). The THD is defined as the square root of the sum of squares of each individual harmonic divided by the fundamental.

$$THD = \sqrt{\left(\sum_{h=2}^{40} \frac{Y_{H,h}}{Y_{H,1}}\right)^2}$$

The definition by many standards is to give the THD as a percentage of the fundamental component but sometimes an absolute value in ampere is a more appropriate index. A THD in percent will tell how much emission a load is in relation to its size while THD in ampere will tell how much the equipment is impacting the grid. The THD in Table 4 is given as a percentage according to the standard.

Table 4	I_{RMS} (A)	I_{THD} (% of fund.)	S (VA)	P (W)	PF	DPF
Adjustable speed drive	0.34	212.8	76.6	32.4	0.423	0.998
CFL 11 W	0.076	98.8	17.1	10.5	0.614	0.886
Laptop	0.41	20.0	93.0	89.5	0.962	0.983
LCD-TV	1.0	21.3	228.3	218.5	0.957	0.981
VCR	0.1	82.1	23.4	17.2	0.733	0.948
CRT-TV	0.40	137.9	91.2	53.3	0.584	0.999
Mobile Charger	0.037	183.6	8.4	3.9	0.464	0.982
Incandescent lamp	0.41	1.43	92.95	92.93	0.999	0.999

When considering the impact of equipment and the power system it is strongly recommended to not use the power factor as defined above as an indicator. Instead the power factor for the fundamental component (the so-called “displacement power factor”, DPF in the table) should be used. The harmonic distortion should instead be quantified by using the THD in Ampere or the harmonic spectrum [9].

4 Emission from fluorescent light powered by HF-ballast

4.1 Measurement on site

A number of measurements on different sites where large number of lamps were installed were conducted. The locations where mainly grocery stores where the number of fittings ranged from about 100 up to roughly 1100. Measurement on site is often not so easy to perform since one does not have access to measure at any given point in the system. Either it is impossible to connect or the need to break the current is not allowed. Measurements were though carried out both on HF components out in the stores at the lamps and also measurement of the total current was done using ordinary power quality instrument.

Below in Fig. 3 a snapshot of the three phase voltage and current supplying a group of lamps is shown. The RMS current is between 6 and 7 amps and the outgoing group has 10 amps fuses. In this case, the main cables feeding the building, where possible to access during the measurements.

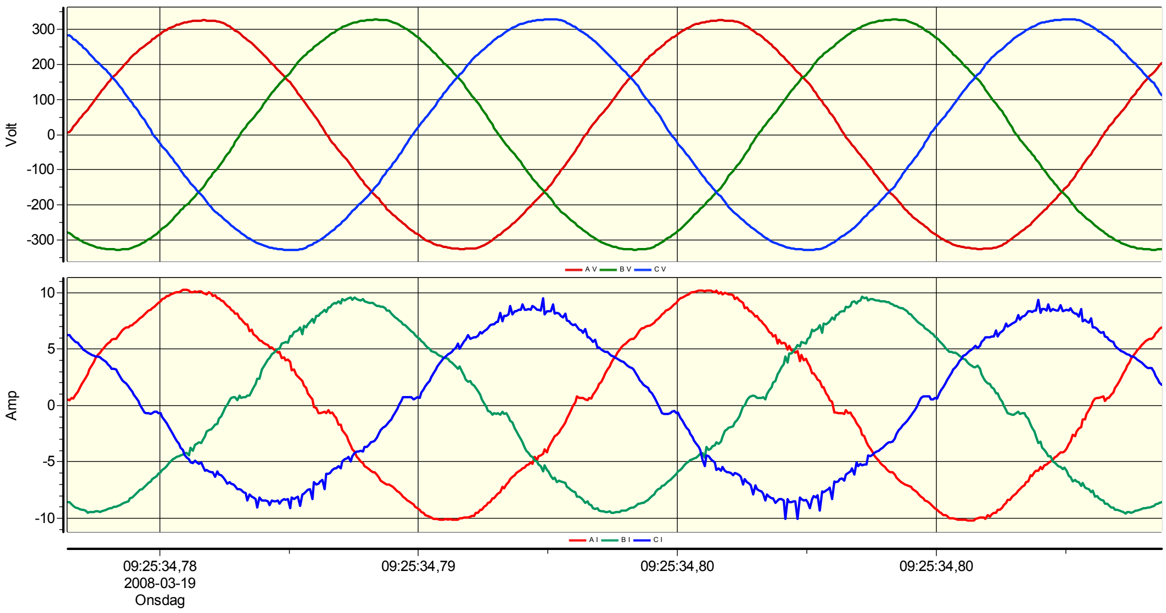

Fig. 3 Snapshot of the three phase voltage (upper graph) and three phase current (lower graph) drawn by the lamps in a grocery store holding roughly 1100 fittings. Note that the measurements is taken on a group consisting of roughly 45 lamps (2x49 W)

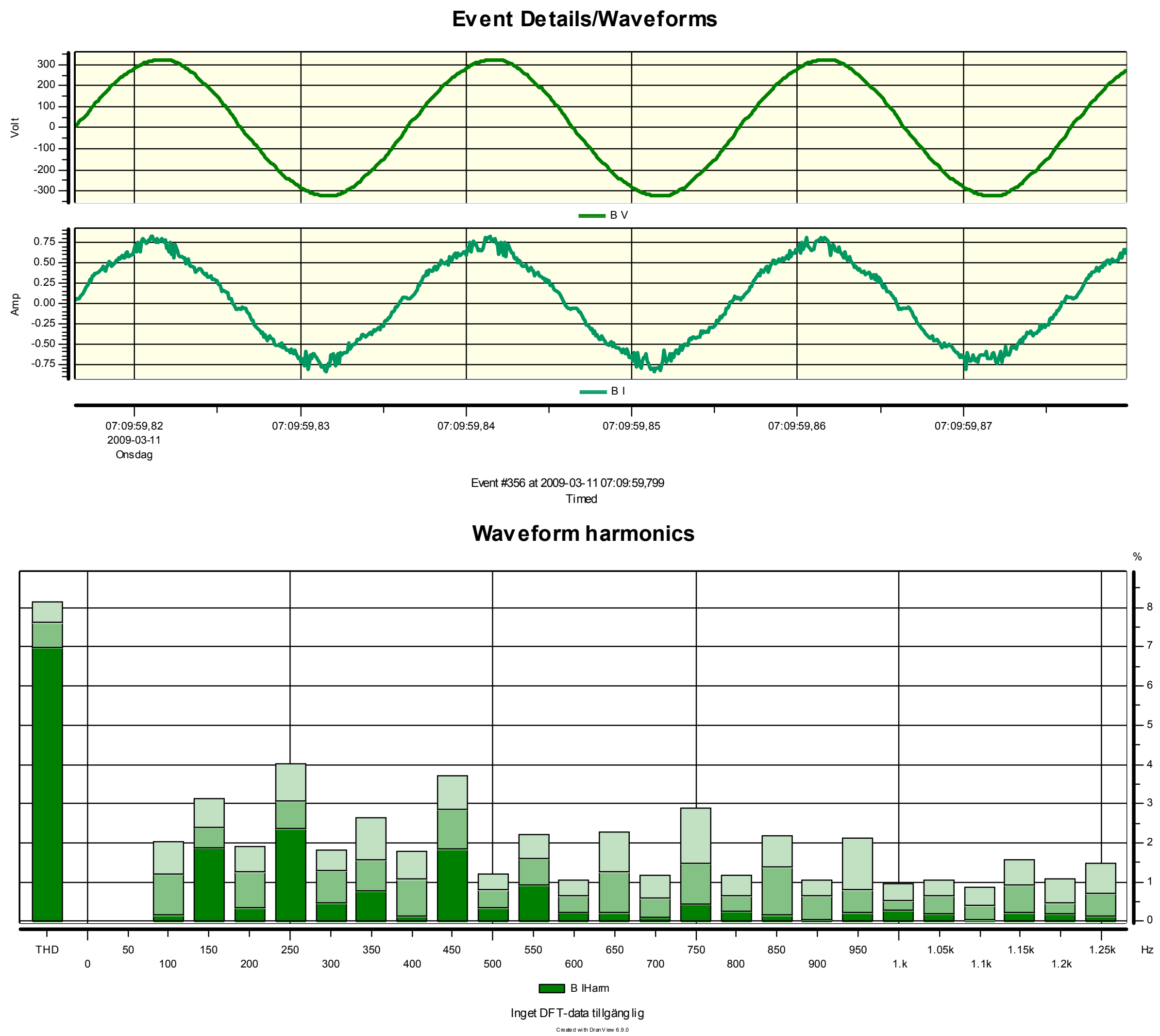

Fig. 4 Voltage (upper) and current (middle) drawn by one of the fluorescent lamps and the resulting harmonic current spectrum (lower).

The current waveforms are close to sinusoidal, but with a rather large amount of distortion at higher frequencies. When considering the spectrum, and comparing this with the spectra in Fig. 2, a more flat spectrum is visible; the reduction in current magnitude with frequency is not visible here. The highest harmonic components (5 and 9) have an amplitude of about 4% of the fundamental. The other components, including even harmonic components, which are typically not present in emission from consumer equipment, have an amplitude between 1 and 2% of the fundamental.

4.2 Harmonic emission from individual lamps

To get a better view of lamp emission, eight individual ballasts of five commonly used brands of ballast where selected and measurements were performed in the laboratory. Ballast 6 and 7 are from the same manufacturer and ballast 1, 2 and 3 are from the same manufacturer. These brands are commonly found at stores in Sweden. Each ballast has a power rating of 2x49 W and powers two T5 fluorescent tubes.

Error! Reference source not found. Fig. 5shows the measured current drawn by the 8 different ballasts. All the ballast shows a current that is fairly sinusoidal and only some minor deviation is visible. Some of the lamps show a high-frequency oscillation at the positive and negative peak of the current. Also almost all of the ballast shows some deviation from the sinusoidal waveform close to the zero-crossing.

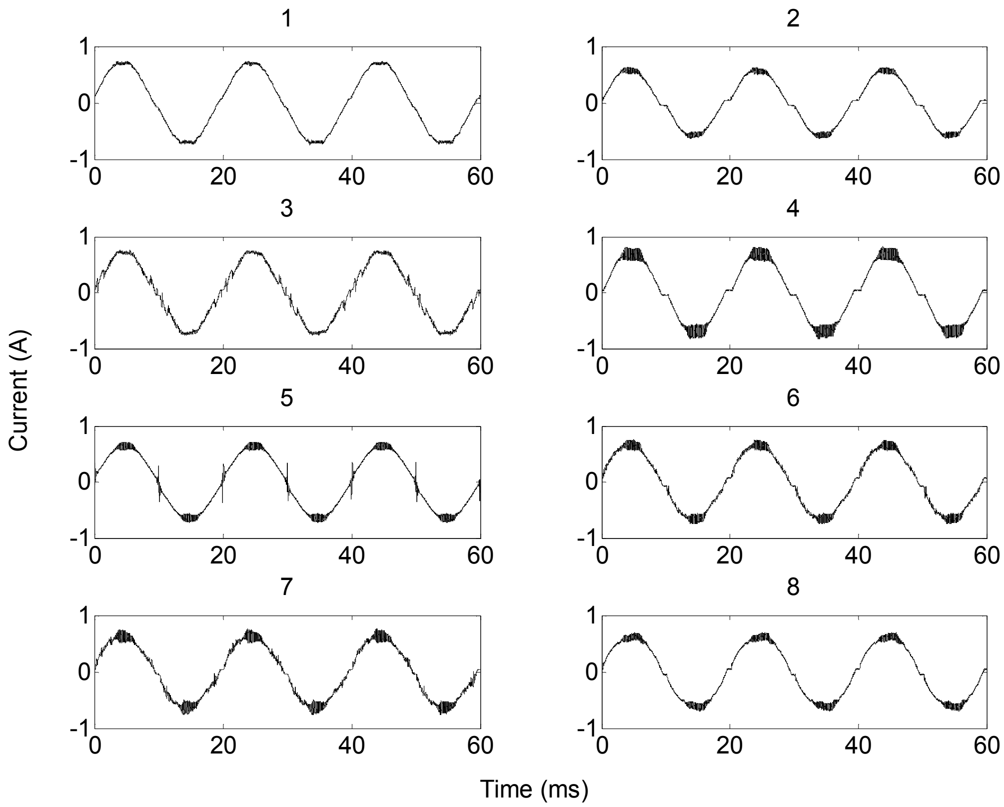

Fig. 5 Current drawn by 8 different ballasts.

When looking upon the harmonic spectra of the current drawn by the ballast, as shown in Fig. 6, we see that the harmonic emission levels are low. The dominant harmonics (3, 5 or 9 depending on the type of ballast) are between 2 and 6 % of the fundamental current. The reason for this is that all of these ballasts are equipped with some kind of active power factor correction to comply with the emission limits discussed in Section 4.1. The differences in design between the power-factor correction circuits cause the apparent difference in waveform, as is clearly visible in Fig. 5.

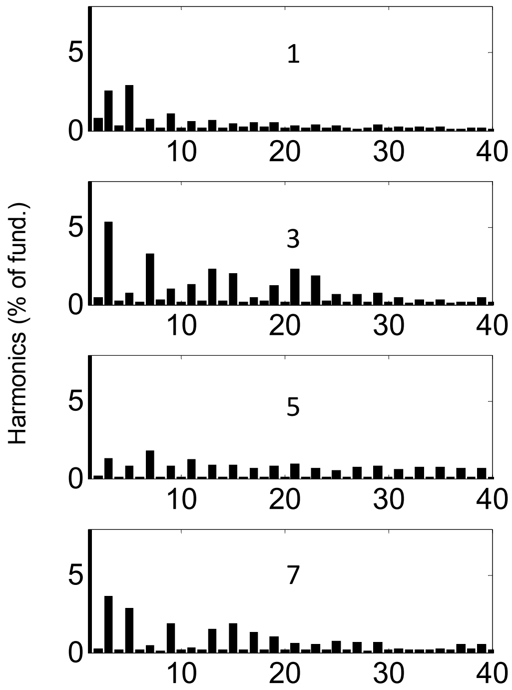

Fig. 6 Resulting harmonic spectra.

An overview of the performance of the 8 ballasts in given in Table 5. The harmonic emission, calculated here as a THD up to 2 kHz, is between 4 and 10%. These are low values and harmonic emission from ballasts in this frequency range is therefore not a concern. The power factor is close to unity, which shows that not only is the current close to sinusoidal, also is the current closely in phase with the voltage.

Table 5 Overview of the performance of 8 different ballasts

	1	2	3	4	5	6	7	8
P (W)	114	90.2	114	111	107	106	103	103
I_{THD} (%)	4.49	9.53	8.12	9.29	3.97	4.89	6.12	4.96
PF	0.99	0.98	0.99	0.98	0.99	0.98	0.98	0.99

An interesting observation, although beyond the aim of this project, is that the energy consumption from different ballasts varies by about 25% between the difference ballasts, although the same fluorescent tubes were used. No measurements of light production were made so that these differences in energy consumption cannot be related to differences in efficiency.

4.3 HF emission from individual lamps

Many types of modern equipment use some type of power electronics that is switching the current on and off with a frequency much higher than 50 Hz. The benefits of using this technology are among others to save energy, reduce the size and weight and it, is also allow better control of the power flow. The switching frequency is different for different applications and depends upon many things like: power rate; and environment, but the switching frequency can typically be found in the kHz range. Even though a filter (EMC filter) is used to attenuate remains from these switching frequencies we can measure these components on the grid as a waveform distortion.

Fig. 7 shows the result when applying a high-pass filter, with a pass-band starting at 2 kHz, to the measured current shown above in Fig. 5. In the figure all currents are plotted with the same amplitude scale so that the difference in HF emission between different ballasts becomes visible. We can also notice that certain signals are present in the emission from all or most different types of ballast. Around 5 ms into the window and repeating every 10 ms is a high-frequency oscillation signal visible; starting 0 ms and repeating every 10 ms is a recurrent oscillation visible.

These two types of signals in the frequency range 2 to 150 kHz have been analyzed in detail; results from this analysis can be found in e.g. [12][13][14][15][16]. As a result of this detailed analysis it is possible give a better explanation of these two signals. The first type of waveform distortion mentioned above consists of the remnants from the switching by the active power factor correction (APFC) circuit. The origin of the second one, the so-called recurrent oscillations or zero-crossing distortion, is more difficult to explain but it also originates from the APFC. In some of the ballasts we can also detect remnants of the output stage but this is not further addressed in this report.

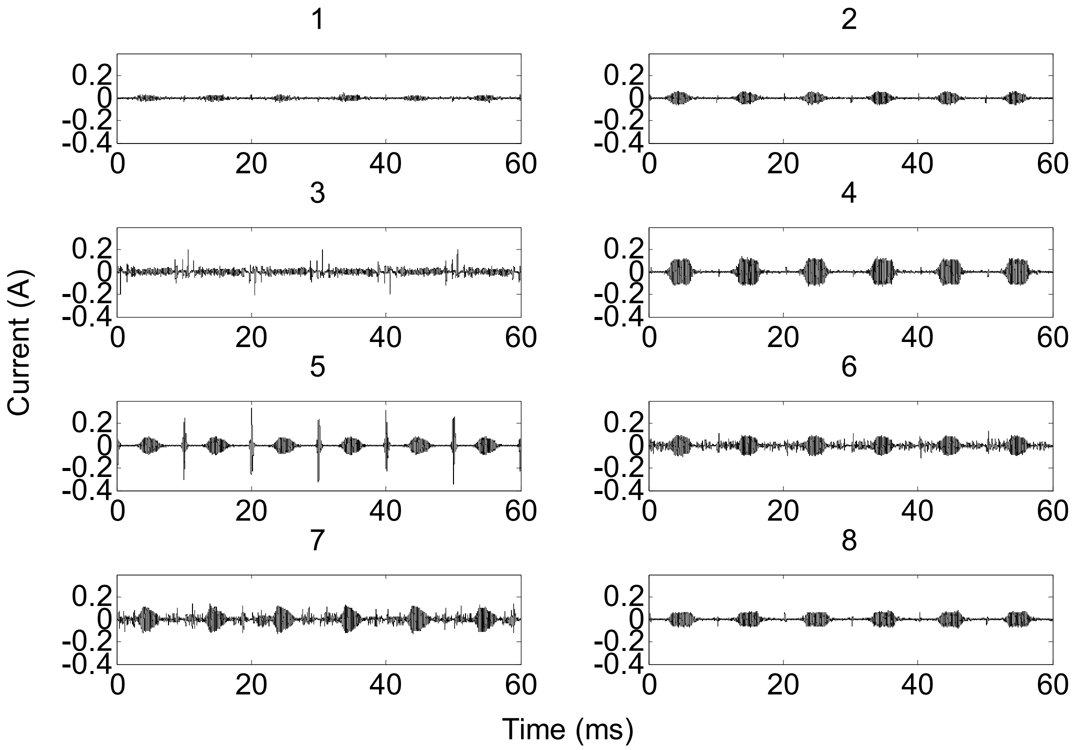

Fig. 7 Filtered current drawn by 8 different ballasts

Fig. 8 shows the resulting spectra in the range from 2 to 150 kHz obtained from the DFT, grouped into 200 Hz bands, of the currents shown above. The current spectra of the different ballasts show that the highest emission can generally be found as a broadband component starting between 40 and 50 kHz. This component consists of the remnants from the APFC. The spectra of ballast 1 and 3 deviate somewhat from the rest: the amplitude of the broadband component is much less. Some other frequency components are visible below 20 kHz for all ballasts.

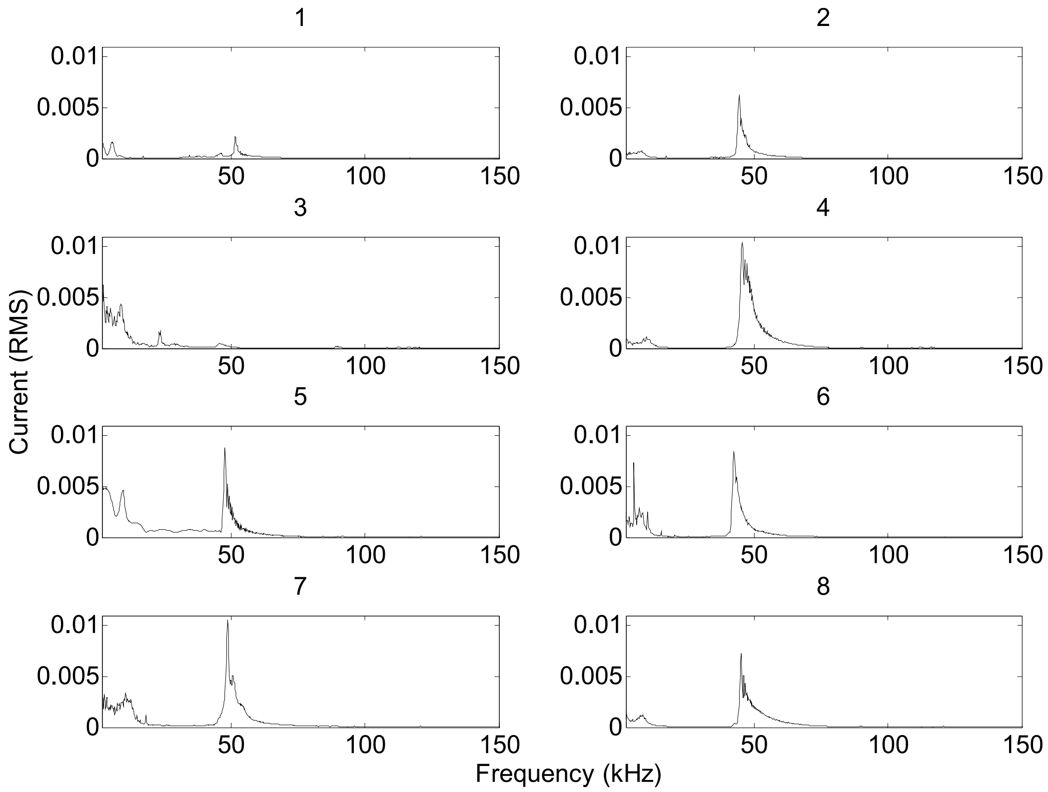

Fig. 8 Resulting spectra of current drawn by the eight different ballasts.

4.4 HF emission from many lamps

To get further insight in the emission from large installations, 48 identical lamps where mounted in the laboratory. The installation is shown, in Fig. 9. The lamps where equipped with ballast number 1 shown above. The purpose of the installation was to bear a resemblance to a typical installation with a large number of lamps for example in a supermarket. Measurement results shown below are taken at the point of common coupling (PCC).

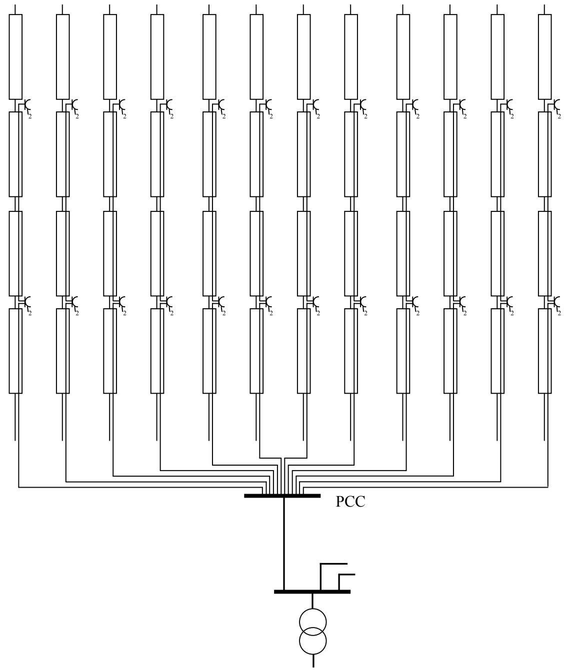

Fig. 9 Experimental light system setup in the lab.

In order to analyze the remnants of the switching frequency, the components belonging to that were analyzed by showing how the current in a frequency band around the switching frequency, changes with the number of lamps being turned on. The result is shown in Fig. 10. It can be noticed that current in this frequency band increases when one lamp is turned on but decrease when additional lamps are turned on. Since the sensitivity of the measurement device had to be changed during the measurement of the total current there is a step between 14 – 15 lamps and between 27 – 28 lamps being turned on since the noise level increases.

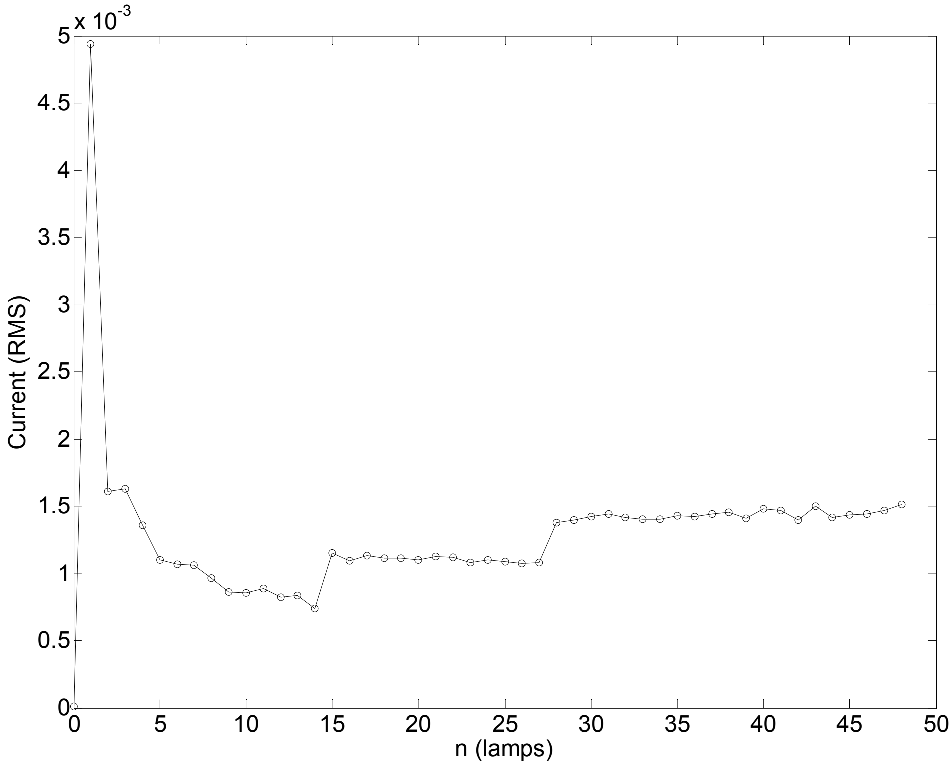

Fig. 10 Resulting r.m.s of the spectrum of the total current in the range from 50 to 60 kHz as a function of the number of lamps being turned on.

The decrease in current in this frequency band as a function of number of lamps being turned on indicates that the remains of the switching are mainly staying within the groups of lamps instead of traveling towards the grid. Theoretical models have confirmed this observation and shown that the grid-side capacitor of the EMC filter in the ballast absorbs a large part of the emission from neighboring lamps. With increasing number of lamps the number of capacitors increases as well, with as a result that the total emission flowing towards the grid reduces [17].

The recurrent oscillation at the PCC was analyzed by taking the absolute value of the maximum during 9.5 to 11 ms into each window of the filtered total current and Fig. 11 shows the result. The figure shows an increase with the number of lamps being turned on. A visual inspection shows that the increase is close to linear up to about 15 lamps and increases slower after that. Curve fitting presented in Fig. 18 in [12] show that the peak current increases with the number of lamps to the power of 0.7.

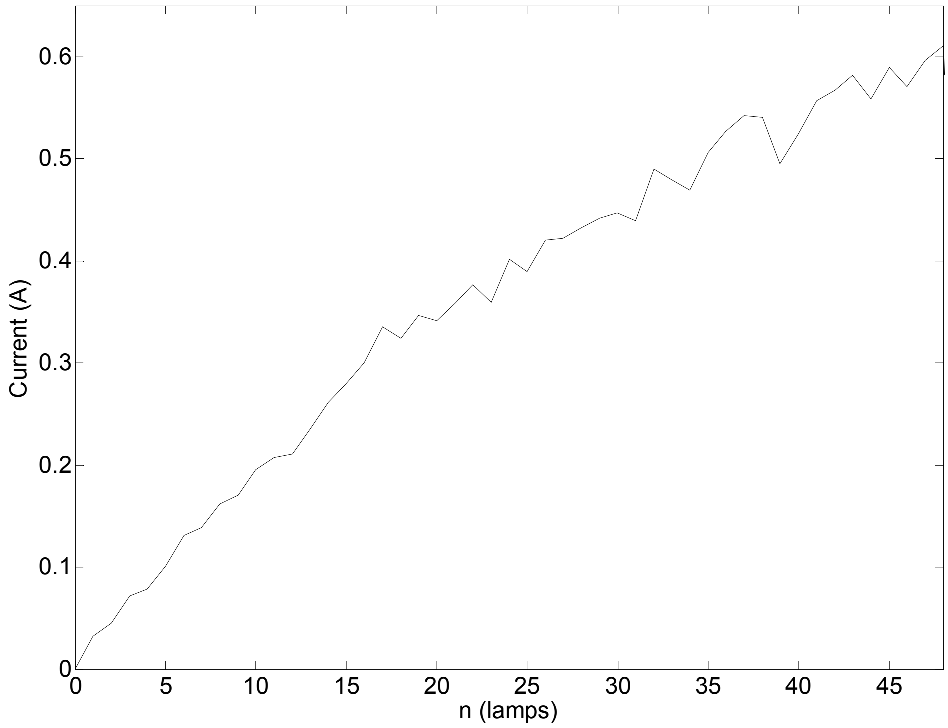

Fig. 11 Maximum value of the filtered current in a 1.5 ms window around the zero-crossing of the current.

The increase of the amplitude of the recurrent oscillation with the number of lamps being turned on in the total current indicates that this part of the waveform distortion, in contradiction with the remnants of the switching, is traveling towards the grid.

A further analysis of the recurrent oscillations, not shown here, showed that the frequency of the oscillation decreases from 3.0 kHz with one lamps being turned on down to about 1.5 kHz when all the lamps are turned on [16].

5 Immunity

The international standards on electromagnetic compatibility contain limits on emission (as discussed in Chapter 3) but also limits on immunity of equipment against voltage-quality disturbances. Examples of such documents are:

- IEC 61000-4-5 Surge immunity test
- IEC 61000-4-6 Immunity to conducted disturbances, induced by radio-frequency fields
- IEC 61000-4-11 Voltage dips, short interruptions and voltage variations immunity tests
- IEC 61000-4-13 Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests
- IEC 61000-4-14 Voltage fluctuation immunity test for equipment with input current not exceeding 16 A per phase

The disturbance levels to which ballasts are exposed are not different from the ones to which other equipment is exposed, for most voltage disturbances. The exception, in installations with many such ballasts / lamps are those disturbances that are generated by the lamps themselves. Here we distinguish between the three types of disturbances described in Chapter 4.

- waveform distortion below 2 kHz. The emission from ballasts at those frequencies is much lower than the emission from most other equipment. The voltage distortion at the lamp terminals, for these frequencies, is determined almost exclusively by the background distortion. Therefore the existing immunity limits are deemed to be sufficient.
- remnants of the switching frequency, typically in the frequency band 40 to 60 kHz. Simulations as well as measurements have shown that the level of distortion in this frequency range does not increase with increasing number of lamps. In fact, the voltage distortion reduces with increasing number of lamps in the frequency domain [17].
- The recurrent oscillations have shown to increase in amplitude and decrease in frequency with increasing number of lamps. This is a phenomenon that is very specific for installations with large numbers of lamps. Although we cannot directly link these recurrent oscillations actual reduction in lifetime of lamps, there is sufficient suspicion to start discussing the need for immunity requirements.

The impact of recurrent oscillations on the lifetime of ballasts clearly requires further investigation. Immunity limits against harmonic voltage distortion are given in IEC 61000-4-13. These limits are summarized in Fig. 12. The limits for (integer) harmonics are set by the compatibility levels whereas the limits for interharmonics are set by power-line communication.

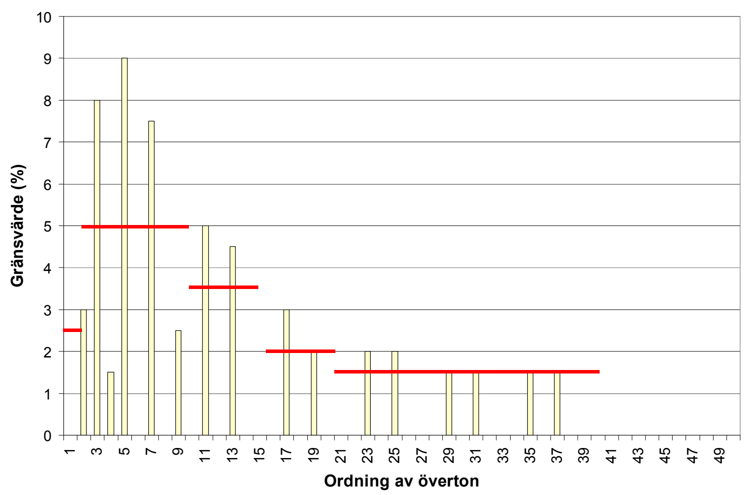

Fig. 12. Immunity limits for harmonics (bars) and interharmonics (horizontal lines), according to IEC 61000-4-13.

Recurrent oscillations have frequencies of 1 to several kHz, which is partly in the same frequency range as the highest harmonic frequencies in Fig. 12. The limits for these frequencies are thus an indication for what equipment should at least tolerate where it concerns recurrent oscillations. The limits given in IEC 61000-4-13 are 1.5% (of 230 Volt) or 3.45 Volt. During our measurements recurrent oscillations in voltage up to 5-10 Volt have been observed. This clearly exceeds the 3.45 Volt set in the immunity standard.

Recurrent oscillations occur at higher frequencies, which will like reduce the immunity level. On the other hand they occur only during part of the cycle, which will increase the immunity level. Which phenomenon dominates is impossible to say without very specific measurements and other studies.

The immunity test according to IEC 61000-4-13 is only conducted during a limited duration and does not apply to all products. (Within the European Union it is not a product standard and therewith not a harmonized standard.) Equipment manufacturers are not always aware of harmonic issues, so that long-term tests using the distortion levels indicated in this standard might be uncommon.

It is strongly recommended that equipment manufacturers perform long-term tests of ballasts using either harmonic voltage distortion of several percent at higher frequencies or something else representing recurrent oscillations.

Note: we do not consider in the discussion here any general need to change immunity limits of equipment. We only consider the need for raised immunity limits for equipment in installations with large numbers of ballasts.

Similar levels of recurrent oscillations may occur in installations with many other devices equipped with active power factor correction, the component that causes there recurrent oscillations. A possible example in the future is a server hall or a computer room in a school, as a growing number of modern computers is equipped with active power factor correction.

6 Installation guidelines

There are different methods for preventing the reduction in lifetime due to voltage quality disturbances. This holds generally for most disturbances, not only for the ones discussed here:

- Limit the emission of the disturbances. In this case that would require emission limits for the recurrent oscillations associated with the zero-crossing distortion. Adding such limits to the EMC standard will require measurement methods, testing methods, and testing levels and could take several years.
- Increase the immunity of equipment against voltage disturbances. This might be somewhat easier as manufacturers could voluntary develop lamps that are more immune to voltage disturbances. The increase in lifetime would be a sales argument and the incentive for manufacturers to make this improvement. With emission there is no such incentive.
- Make changes in the network, in this case in the lighting installation, to prevent the spread of the disturbances. For the relatively low frequencies of the recurrent oscillations (up to a few kHz) passive filters are the most appropriate solution in the installation.

As the result from the measurements shows that remains from the switching frequency is kept within the group of lamps this of no problem if one does not care about electro-magnetic fields from this. Important though, to keep the remains from the switching within the group of lamps, is to make sure that the electrical distance is kept as short as possible.

7 Conclusions

The emission of electronic ballasts within the normal frequency range is small and can be neglected compared to the emission from other equipment in domestic or commercial installations. This low emission is a direct consequence of the introduction of strict emission limits for lamps in IEC 61000-

3-2. These low emission levels are achieved by using active power factor correction based on power-electronics control circuits.

An adverse side-effect of these power-electronic circuits is the emission of distortion at frequencies above 2 kHz. A large number of measurements resulted in the conclusion that two types of distortion are present in the frequency range from 2 to 150 kHz. Remains from the switching frequency are found in the band from 40 to 50 kHz and recurrent oscillations with a frequency up to a few kHz occur twice every cycle around the current zero-crossing.

Measurements and theoretical studies on installations with large numbers of ballasts show that the remains from the switching frequency mainly propagate between ballasts instead of flowing to the grid. With increasing number of lamps the emission level into the grid actually reduces due to the presence of increasing numbers of EMC filters as well. The recurrent oscillations however show a significant level of addition and flow for a large part to the grid. The emission from 100 ballasts is estimated to be 25 times the emission from one ballast.

From this it is concluded that the emission of the remains from the switching frequency is not a serious concern. Existing standards, including standards aimed at avoiding radio-interference above 150 kHz, are sufficient. Here it should be pointed out however that the reduction in total emission with increasing number of lamps is due to the presence of the grid-side shunt capacitor with the EMC filter. When future EMC filters for electronic ballasts were to be equipped with a grid-side series inductor, this reduction in total emission would no longer occur.

The recurrent oscillations are perceived as a potential problem in large installations. Although we did still not achieve a link between recurrent oscillations and damage to ballasts, we do believe there is a potential link here. Limits on both emission and immunity are deemed the best long-term solution. On emission side the development of international standards is the way forward. This should be part of the work on emission in the frequency range 2 to 9 kHz having started recently in a task forced created by IEC TC77A, WG1. The power-engineering group at Luleå University of Technology is represented in this task force.

Also on the immunity side international standards should be the long-term aim. But also improvements by manufacturers of ballasts without any obligation in standardization should be recommended. Contrary to reduced emission there are marketing advantages with an increased lifetime of equipment.

In the installation, when neither improved immunity nor reduced emission is a solution, the use of a passive shunt filter could be a solution. The design of such a filter should take into consideration the properties of the recurrent oscillations as well as the presence of background distortion in the same frequency range.

The work towards establishing relation between reduced lifetime for modern lighting and electromagnetic disturbances should continue. Initially the before-mentioned recurrent oscillations should be studied in further detail in relation to their potential impact on electronic ballasts. The work should next be extended towards other voltage quality disturbances, specifically voltage magnitude variations.

Another case that requires further study is the mixture of equipment with different rating. A small amount of emission from the large device could result in large currents through the small device with accelerated ageing or even damage as a result. The typical example mentioned in such discussion is the charger of the electric car in the garage with LED lamps on the same group. This situation has not been studied in this project but is of sufficient interest to be part of a future project. After all it might result in a significant reduction of the lifetime of the lamp and result in the public losing trust in the reliability of the technology behind energy-efficient lightning.

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