The Importance of Illumination for the Operational Cost and the Integration of Lighting Equipment with the Ship Network

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On passenger vessels lighting accounts for 20 % - 40 % of the total energy consumption excluding propulsion. The power consumption depends on the type and quality of the lamp, ballast or control gear (if applicable). Studies of different lamps and the simulation of the interaction with the ship's electrical system on an actual vessel show, that special considerations are required, if lighting is the major electrical consumer in a certain area of a vessel.

KEY WORDS
Lighting, energy, lamps, passenger vessel, harmonic distortion

NOMENCLATURE
All types of lamps are identified by their names in the OSRAM product lines. Similar lamps with different names are available from other makers.

CCG: Conventional Control Gear
ECG: Electronic Control Gear
THD: Total Harmonic Distortion
LED: Light-Emitting Diode
PAX: Passengers

INTRODUCTION
On passenger vessels lighting accounts for 20 % - 40 % of the total energy consumption excluding propulsion. The power consumption for a certain required lighting depends on the type and quality of the lamp, the type and quality of the ballast or control gear (if applicable) and the quality of the voltage in the ship network. Trivial products like lamps have not been in the centre of focus in the marine equipment for years. Tests show that a passenger vessel in service since 2000 would save up to 30 % on illumination if modern equipment is used. This is an estimated saving of 400,000 USD per annum for a big cruise vessel. If the vessel is operated in warm climes, then in addition the energy consumption of the air condition system can be reduced due to lower intake of heat in the rooms.

By far, the most lamps on board are equipped with fluorescent lamps or compact fluorescent lamps, but also halogen lamps are used. These types of lamps need ballasts or control gears, which have an important influence on the power consumption but also on the electromagnetic compatibility and the harmonic current emission to the ship network. This is also valid for lamps with light-emitting diodes (LED), which might be installed more often in the future.

Lighting equipment typically fulfils the rules for use on shore in households, hotels or offices; this ensures a proper function and fair distortions of the voltage. Studies of different lamps and the simulation of the interaction with the ship's electrical system on an actual vessel show, that special considerations are required, if lighting is the major electrical consumer in a certain area of a vessel. It depends on the type and some details of the design of the lighting equipment, how many lamps of a certain mixture can be connected to one power distribution without breaking the rules of the classification societies regarding distortions of the voltage.

LIGHTING TECHNOLOGY ON MODERN CRUISE LINERS

On most cruise liners the specific energy demand amounts to 10 kWh – 12 kWh a day per person, respectively in total 20 % - 40 % of the ships energy without propulsion. Depending on the actual fuel price this is in the range of 1 Mio USD per annum for a 2500 PAX cruise liner. Typical on such cruise liners is also the big amount of light sources and a lot of different types of lamps. On a couple of ships it was counted:

- 30,000 – 80,000 light sources
- 100 – 500 different types of lamps

Most of these lamps are switched on for 24 h per day. This gives an average lamp life time of one year. This show, that material and working hours for lamp replacement are also remarkable parts of the annual costs for lighting.

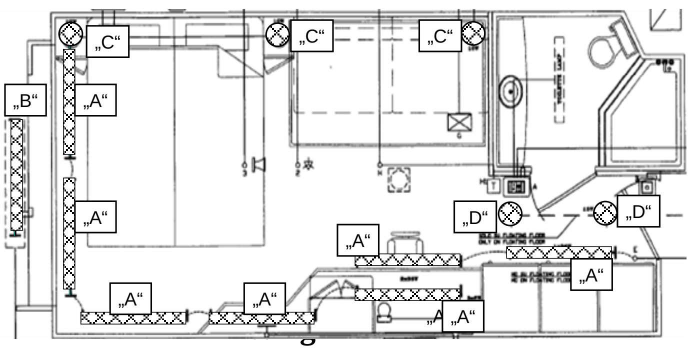

Fig. 1: Lighting in a typical cabin; types A – D refer to table 1.

In a study, all lamps on a 2500 PAX passenger vessel in service since 2000 have been evaluated. For most of the 39400 lamps it was found, that a replacement by newer equipment would save energy and reduce the cost for lamp replacement. This would save up to 30 % on illumination which is estimated 400,000 USD per annum.

Figure 1 shows the illumination of a typical cabin. There are four types of lamps A – D (table 1). In a first step, each type of the actual interior can be replaced by a more economic type. This should be a one-by-one replacement without changing the quality of the illumination. As table 1 shows, this simple replacement reduces the energy consumption by 50 %. A further reduction of the power demand is possible for a new building or when the equipment on an existing vessel is completely renewed. This would for example allow to redesign the illumination and to install the most actual equipment. The last column in table 1 shows this alternative for actual available lamps.

Using this method to analyze the complete 2500 PAX cruise liner gives the result shown in table 2. With a fuel price of 500 USD/t (mean of last months) the fuel saving counts in the range of 300,000 USD per annum and a time for the return on invest (ROI) in the range of 1 – 2 years. In addition, there is a remarkable reduction of CO_2 emission, which might be a cost saving in the future.

Table 1. Illumination improvement of a typical cabin (fig. 1) with respect to energy consumption.

Pos. in fig. 1	**Actual inventory**	**Improved (one-to-one replacement)**	**Improved (new build.)**
A	7 fluorescent lamps L 36W CCG	7 fluorescent lamps Lumilux T5 FH 21 W ECG	4 compact fluorescent lamps Dulux D/E 13 W ECG
B	1 exterior fluorescent lamp L36 W	1 exterior fluorescent lamp Lumilux F4 Y 36W	1 exterior fluorescent lamp Lumilux T5 HE 14 W
C	3 incandescent lamps CLAS B 40 W	3 compact fluorescent lamps Dulux EL Classic 9W	3 compact fluorescent lamps Dulux EL Classic 9W
D	2 compact fluorescent lamps Dulux D 10 W CCG	2 compact fluorescent lamps Dulux D/E 10 W ECG	2 halogen lamps DECOSTAR 20W IRC
Watt, %	**450 W 100 %**	**220 W 50 %**	**140 W 30 %**

Table 2. Illumination improvement on a 2500 PAX passenger vessel

Connected Load of Illumination	**Act.**	**Improved (one-to-one replacement)**	**Improved (new build.)**
Loads			
Fixtures to optimize in kW	1,175	806	728
Other fixtures in kW	295	295	295
Total connected load in kW	1,470	1,101	1,023
Savings			
Savings in kW (load) (without air conditioning)		369	447
Reduction of power consumption		25.1 %	30.4 %
Fuel savings kg/h		73.8	89.4
CO2 reduction t/a		1900	2304

INTEGRATION OF LIGHTING EQUIPMENT INTO THE SHIP NETWORK

The Problem of Harmonics

The voltage in the ship electrical system should be sinusoidal. In practice it is only approximately sinusoidal. The difference to the ideal sinusoid is measured on the base of a Fourier Analysis of the voltage, where the amplitude of the fundamental voltage and the amplitudes of the harmonics are calculated. Harmonics cause additional losses in motors and other devices but may also disturb electronic equipment. This is why the rules of the most classification societies define limits for the harmonics. In most cases, two upper limits for the harmonics are given: Firstly, each single harmonic up to order 100 must not exceed a given limit. Secondly, the total harmonic distortion (*THD*) up to a defined maximum order (typically 50) is limited:

$$THD_{50} = \frac{\sqrt{\sum_{n=2}^{50} U_n^2}}{U_1} \le THD_{50,\max}$$

where

U_n rms amplitude of a voltage of order n

U_1 rms amplitude of the fundamental voltage

$THD_{50,\max}$ limiting value 5 % -10 % depending on the rules (Some ship owners and ship operators specify a lower *THD*)

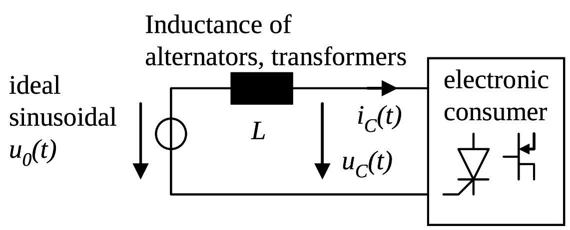

Fig. 2: Current $i_C(t)$ of an electronic consumer as a source of harmonics in the voltage $u_C(t)$

The main sources of harmonics are consumers with electronic power supplies. If the current to the consumer (fig. 2) is non-sinusoidal

$$i_C(t) = \sum_{n=1}^{\infty} \hat{I}_n \cdot \sin(n \cdot \omega_1 \cdot t + \varphi_n)$$

then due to the inductance the voltage u_C will be disturbed by harmonics:

$$u_C = u_0 - L \cdot \frac{di_c}{dt} = u_0 - \omega_1 \cdot L \cdot \sum_{n=1}^{\infty} n \cdot \hat{I}_n \cdot \cos(n \cdot \omega_1 \cdot t + \varphi_n)$$

This gives the *THD* of the voltage u_C:

$$THD_{50}(U) = \frac{\omega \cdot L \cdot \sqrt{\sum_{n=2}^{50} n^2 \cdot I_n^2}}{U_1} = \frac{\omega \cdot L \cdot I_1}{U_1} \cdot WTHD_{50}(I)$$

$$WTHD_{50}(I) = \frac{\sqrt{\sum_{n=2}^{50} n^2 \cdot I_n^2}}{I_1}$$

$WTHD_{50}(I)$ is the weighted *THD* of the current. Using the p. u. system gives:

$$THD_{50}(U) = x^* \cdot \frac{I_1}{I_n} \cdot WTHD_{50}(I) \quad \text{with } x^* = \frac{\omega \cdot L}{U_1 / I_n} \qquad (1)$$

where I_n is the nominal current of the system and x^* is the p. u. reactance of the ship's supply system.

A typical value is $x^* = 6\ \%$, this gives for a limit of *THD* of 5 %, at full load ($I_1 = I_n$) that $WTHD(I) < 5/6 = 83\ \%$ is required. This is a rough estimation for a limiting value for the *WTHD* of a single consumer.

It has to be emphasized that it is not possible to calculate a total *WTHD* for a group of different consumers from the known *WTHD* values of the single consumers.

Rules and regulations

The rules and regulations cover two ways to limit the effect of harmonic distortions: Firstly, requirements are defined for the quality of the voltage in the ship network. Classification societies like Germanischer Lloyd (GL), Lloyds Register (LR) or American Bureau of Shipping (ABS) typically define a maximum allowed *THD* and in addition maximum values for single harmonics. For public low and medium voltage distribution networks on shore in Europe, the European Standard EN 50160 (2008) defines limits in a similar way. All limits are roughly in the same range, but nevertheless there are remarkable differences (appendix fig. A1).

Secondly, there are standards for public low voltage distribution networks on shore that give limits for the current of consumers. In Europe, the European Standard EN 61000-3-2 is applicable for lamps up to a current of 16 A. The main goal is to control the *THD* without the need, that the electric supply companies monitor all lamps in all households. One idea behind this standard is, that in households, small offices and small workshops the electrical power of the lamps is typically low compared with other consumers like electric cooking ranges or washing machines. Therefore, the given limits in the standard are rather weak. The limits correspond with a $WTHD_{50}(I)$ of 330 % (for lamps < 25 W much more). For the typical values as given in the paragraph after eq. 1 follows, that a load of 25 % (of the rated power of the supply transformer) causes a *THD* of 5 %.

This is not applicable for ships. The types and the characteristics of all consumers are well known, the *THD* can be controlled without the need of general limits for the currents. But it is also important to note, that existing standards like EN 61000-3-2 are not strong enough to avoid a too high *THD* in the ship electrical system, because there is a complete other mix of types of consumers than in the public distribution networks on shore.

Lighting Equipment as a Source of Harmonics

With respect to harmonics, there are four different types of lighting equipment:

Non electronic lamps: These are traditional incandescent lamps but also high voltage halogen lamps. They produce a strong and very short inrush current, but they do not cause any harmonic distortion.

Fluorescent lamps with CCG: Fig. 3 shows, that the current of this type of lamps is nearly sinusoidal and with $WTHD_{50}(I)$ = 35 % there is no risk with respect to harmonics in the ship's supply. The phase shift can be compensated with capacitors.

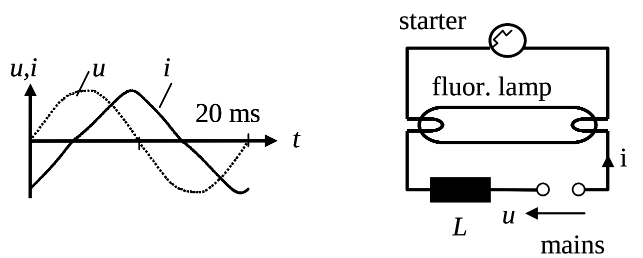

Fig. 3: Principle of a fluorescent lamp with CCG and the corresponding voltage and current (measured)

Fluorescent lamps with ECG (active front-end):
Electronic control gears instead of simple ballasts as shown in fig. 3 have a lower loss of energy and extend the life time of the lamp. All ECG firstly convert the AC voltage from the mains into a DC voltage. Secondly, the DC voltage is fed to a high frequency generator, which controls and supplies the fluorescent lamp. The frequency is in the range of some 10 kHz.

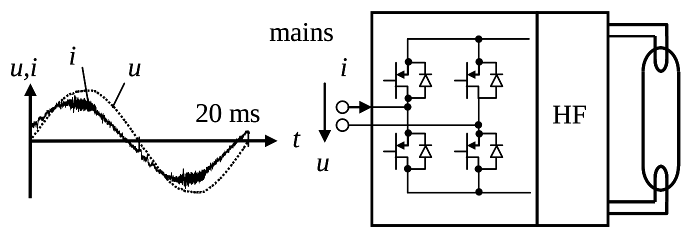

Fig. 4: Principle of a fluorescent lamp with ECG with active front-end and the corresponding voltage and current (measured at a 36 W lamp)

If an ECG is used for lamps with a rated power of 25 W or more it is typically equipped with an active front-end (fig. 4). In lamps with less than 25 W sometimes this type is also used. It is also called a power factor controlled (PFC) supply. The AC voltage from the mains is converted into a DC voltage by means of pulse width modulation. This allows to control the shape of the current and to adjust the phase shift to a small value. Fig. 4 gives an impression, that the current is in deed nearly sinusoidal, but that there are harmonics of very high order due to the modulation. This is typical for ECGs of this type. Measurements at seven different ECGs from two different makers gave $WTHD_{50}$ = 60 % … 120 %.

Lamps with ECG (passive rectifier): For lamps with a power lower than 25 W (mainly compact fluorescent lamps, but also LEDs) frequently a more simple control gear as that type shown in fig. 4 is used. The active rectifier is replaced by a diode bridge or even by a simple half-wave rectifier.

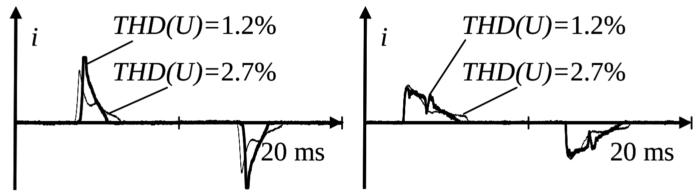

Fig. 5: Measured currents in two (left and right) different 5 W compact fluorescent lamps, measured in two different supplies with different *THDs*

The current of these ECGs is far away from any sinusoidal shape (fig. 5) $WTHD_{50}$ is in the range of 1000 % (fig 5., right) up to 2500 % (fig. 5, left). This indicates, that care must be taken, if many lamps of this type are installed in a certain section of a ship. As usual for rectifier circuits with charging capacitor these ECGs are sensitive against harmonics in the voltage. The results from measurements (fig. 5) show, that even a small *THD* has a remarkable influence on the shape of the current. In the example shown in fig. 5 the *THD* of 2.7 % mainly is caused by a harmonic of 3^{rd} order.

Simulations for an Actual Ship

In order to estimate the influence of ECGs on the voltage in the ship's supply, the proposed improvement of table 2 is simulated for an actual ship. The ship is a 2500 PAX cruise liner with an electric propulsion system as it is quite usual today (fig. 6). The alternators, the propulsion drives and some big consumer like thrusters or the air conditioning plants are connected to the medium voltage switchboard. The low voltage consumers are supplied via transformers, which are distributed on the ship.

The detailed list of the actual inventory and the possible replacements was sorted by the type of control gear and secondly by the total power of all lamps with this type. It was found, that four types of control gears cover 97 % of the total power (table 3).

Table 3: Mainly used types of control gears and typical lamps

Type 0	Without control gear (incandescent lamps, halogen)
Type 1	compact fluorescent lamps (DULUX S/E 9 W and similar)
Type 2	23 W compact fluorescent lamps (Dulux EL C R80 and similar)
Type 3	18 W – 58 W fluorescent lamps with ECG

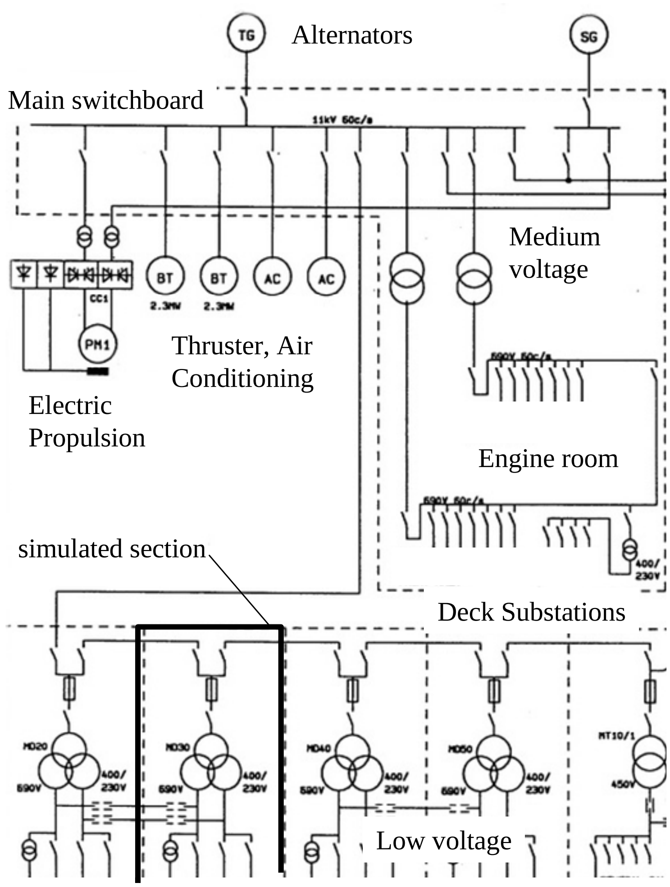

Fig. 6: Portside part of the ship's supply of a cruise liner with electric propulsion. (Meyer Werft GmbH)

Due to the high power of the alternators (due to the electric propulsion) and the motors for the compressors in the air conditioning system, the impedance at the medium voltage bus bar is very low compared with the impedance of the transformers for lighting. Seen from the low voltages side of the transformers, the impedance of the medium voltage system is negligible. Only the leakage inductance of the transformers, typically given as relative short-circuit voltage u_K, is in effect. There is no interaction between different transformers in this sense. This is why the simulation can be limited to one transformer (marked in fig. 6).

The data of the simulated transformer are:

2 x 900 kVA (two low voltage windings)
u_k = 6 %
Dd0Yn11

Because some transformers are loaded with more lighting and others with less, it is a reasonable to assume for the simulation, that the transformer is loaded with 30 % of its rated load with lighting. That means that 25 % of the total lighting of the ship is connected to this transformer. Because only the active power of the different lamps easily can be added and because the power factor is expected near to one, a power factor of 1.0 is assumed for this estimation and the active power (in kW) can be set equal to the apparent power (in kVA).

The last column of table 4 shows the mixture of different types of control gears used for the simulation.

Table 4. Total power of lamps depended on the type of control gear. The last column is the mixture of lamps used for the simulation. (Transformer loaded with 30 % of its rated load).

	P_{total}		$P_{transfo\_30\%}$
Type 0	112.8 kW	11.8 %	31.8 kW
Type 1	62.6 kW	6.5 %	17.7 kW
Type 2	125.1 kW	13.1 %	35.3 kW
Type 3	657.2 kW	68.6 %	185.3 kW
Sum	957.5 kW	100.0 %	268.1 kW

For the different types of control gears the currents $i(t)$ are measured in a test stand. The functions of time for the four types are weighted according the power given in table 4 and then superposed to get the input for the simulation (fig. 7). The lamps are connected between line and neutral. There are harmonics of order $3 \cdot k \cdot$(k: positive integer) so that there is a zero-sequence component in the linkage of the low voltage windings. This is compensated by a circular current in the delta-connected medium voltage winding. Due to this the single phase equivalent circuit of the transformer is not applicable. The simulation is done in the frequency domain using symmetrical components.

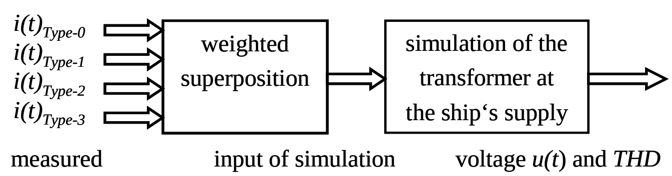

Fig. 7: Dataflow in the simulation

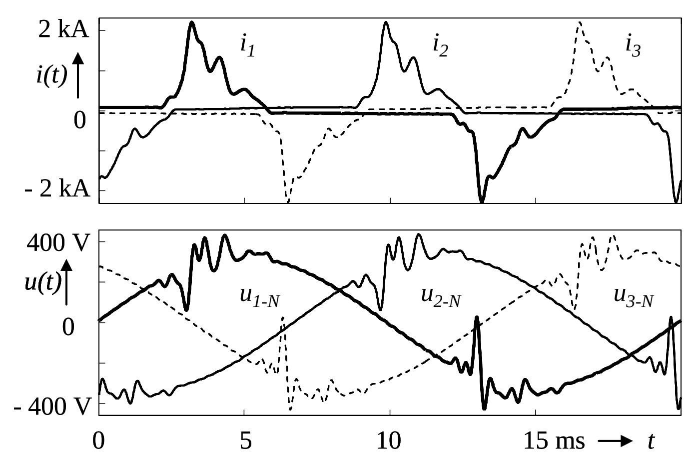

Fig. 8: Result of a simulation with control gears as listed in table 3. For type 3 ECGs with passive rectifier are used.

In a first simulation, for type 3 simple ECGs with passive rectifier have been installed. Fig. 8 shows, that this causes serious distortions in the voltage. The analysis of the curves gives a value $THD_{50}(U)$ = 17.3 %, which is not acceptable.

In a second simulation better ECGs with active front-ends are installed for type 3 and the ECGs for type 1 are replaced by CCGs. Fig. 9 shows, that this reduces the distortions. With a $THD_{50}(U)$ = 3.3 % and no significant single harmonics this is in accordance with all applicable rules.

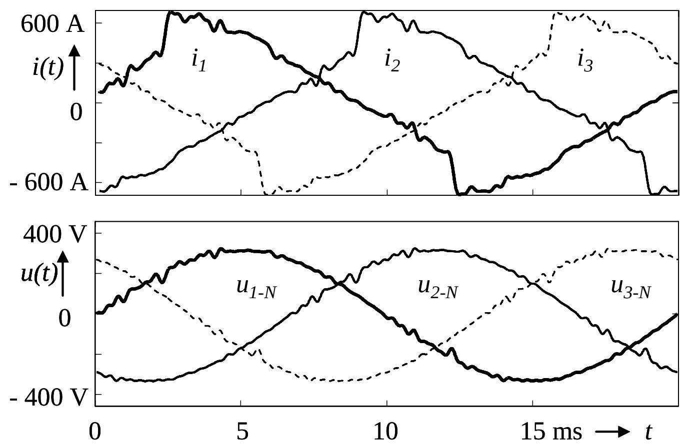

Fig. 9: Result of a simulation with control gears as listed in table 3. For type 3 ECGs with active front-ends are used, the ECGs of Type 1 are replaced by CCGs.

Comparing fig. 8 and fig 9. shows, that the use of ECGs with passive rectifier must be avoided. The influence of these ECGs can be estimated with eq. 1:

$$\frac{I_1}{I_n} = \frac{THD_{50}}{WTHD_{50} \cdot x^*}$$

For the lamps used for the measurements shown in fig. 5 with $WTHD_{50}$ = 1000 % resp. $WTHD_{50}$ = 2500 %, THD_{50} < 5 % and $x^* = u_k$ = 6 % for the transformer used in the simulation gives the estimation

$$\frac{I_1}{I_n} = \frac{0.05}{10.0 \cdot 0.06} = 8.3\% \text{ resp. } \frac{I_1}{I_n} = \frac{0.05}{25.0 \cdot 0.06} = 3.3\% .$$

This gives in principle the same result as the simulation, the percentage of lamps with simple ECGs must be rather low.

CONCLUSION

Based on strongly rising fuel prices an additional investment in energy efficient lighting is justified. The return on invest lies within 6 to maximum 24 months. This applies to new buildings as well as for the retrofitting of cruise liners in operation.

The carbon footprint of modern cruise liners will be positively affected by ‘Green Lighting Systems’ on board, thus resulting in the lowering of environmental costs and image benefits.

Electronic control gears are advantageous with respect to the energy consumption. The harmonics in the ship’s supply caused by these devices can be controlled during the design of the plant. Care must be taken, if a big number of lamps with simple ECGs shall be installed in a certain area.

APPENDIX

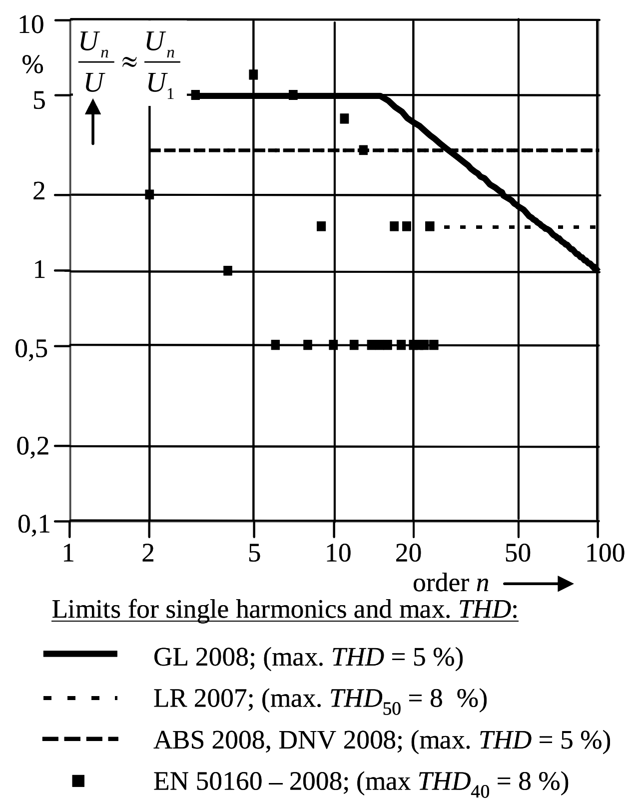

Fig. A1: Limits for single harmonics and for the *THD* according to different rules and standards