CHARACTERISTICS OF THE INPUT CURRENT OF ENERGY SAVING LAMPS AND THEIR IMPACT ON POWER QUALITY

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ABSTRACT

Awareness of increasing energy consumption and targets to enhance energy efficiency of home appliances leads to an increasing contribution of Energy Saving Lamps (ESL) to the LV load. In contradiction to the input current of incandescent lamps, ESLs have distinctive non-sinusoidal input currents with high content of harmonics. In this paper the dependencies of the input current of ESL to supply voltage harmonics as well as the impact of the increasing amount of ESL in the low distribution grid is presented. On over 70 different and 30 identical types of ESL measurements show the influence of harmonics magnitude and phase angle in the supply voltage. A simulation model, implemented in MATLAB, including the ESL, considering these measurement results and a low voltage distribution grid, helps to estimate the effect of ESL on power quality.

INTRODUCTION

The general ambition of the European Union to reduce primary energy consumption about 20 % until 2020 should be supported by the "Eco-Design-Directive" [2] with predicted energy savings of 39 TWh/a. Amongst others, the "Eco-Design-Directive" has enforced the stepwise replacement of incandescent lamps by the promoted alternative ESL.
The used principle for light generation in ESL is electrical gas discharge. Therefore a high-frequency voltage (20…40 kHz) in the gas-filled fluorescent lamp is used, generated via electronic ballast. Following this, general characteristics of ESL can be determined.

- An approximately by factor 5 higher efficiency in light generation compared to incandescent lamps.
- Non-sinusoidal input current of ESL with high content of harmonics (THD_I over 100 %) due to electronic ballast
- A low power factor (PF) between 0.5 and 0.6 (PF of incandescent lamps is 1) with a leading fundamental

While the input power of a single ESL is quite insignificant, typically 10 W to 20 W, the large number of customers using several ESLs per household would create a remarkable total load. This load may lead to unacceptable voltage distortion at some points of the grid. When the impact of ESL on power quality was investigated via simulations so far, the influence of the pre-distorted supply voltage was neglected in most cases, thus the pre-distortion of the supply voltage is taken into consideration in this paper.

CHARACTERISTICS OF THE INPUT CURRENT

Measurement Procedure

A power amplifier with low internal impedance controlled by LabVIEW software creates the specified supply voltage for the ESL. Voltage and input current of the ESL at steady state were recorded for 200 ms, sampled at a frequency of 25 kHz and evaluated using the complex FFT.
To cover a wide range of ESLs, **70 different** commercial types were analysed with regard to their current spectrum. Additionally **30** ESLs of the **same** type were investigated to take into account the effect of component tolerances.
In order to have a reference value, all ESLs were first supplied with a pure sinusoidal voltage.
The measurement of the influence of voltage harmonics was executed by applying single harmonics and combinations of them.
The amplitude was varied from 0.5 % to 4 % of the fundamental (single harmonics and combinations) and the phase angle from 0 ° to 360 ° (only single harmonics).

Measurement Results

In Figure 1 the voltage and input current of a typical ESL is shown.
The resulting harmonic characteristic of the input current of a typical ESL is shown in Figure 2. Generally values of about 80 % for the 3rd harmonic, 50 % for the 5th harmonic and about 20 % for the 7th and 9th harmonic of the fundamental can be observed.
Although, the EN 61000-3-2 [3] standard set limits for the input current of ESLs (e.g. start current flow before 60 °, stop current flow after 90 °, 3rd harmonic current below 86 %, 5th harmonic below 61 %), a standardised input current of ESLs can´t be assumed.
In Figure 3 the band width of the range of complex input current for 70 tested ESLs is shown. Maximum and minimum of magnitudes and phase angles of the input current of ESLs are shown in Table 1. For the sake of better comparability the input current is related to input power.

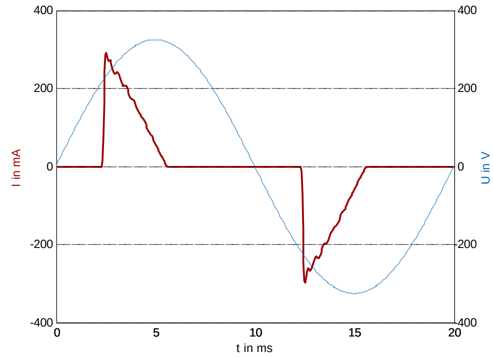

Figure 1 Voltage and current of typical ESL

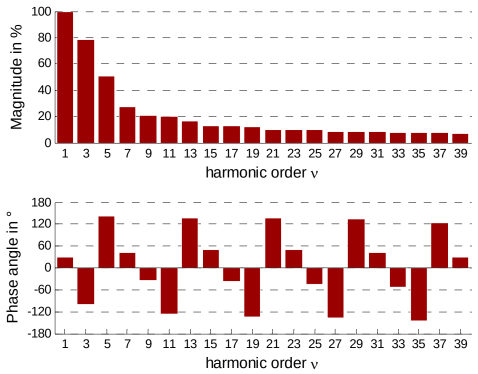

Figure 2 Harmonic currents and angles of typical ESL

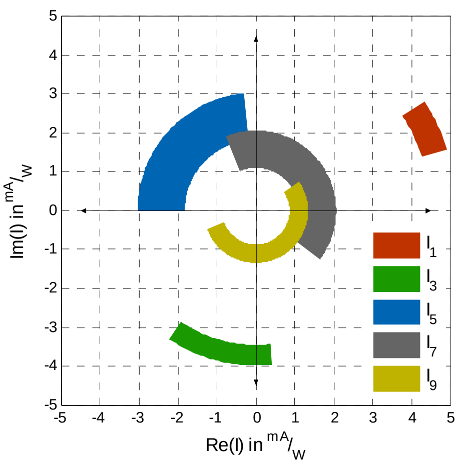

Figure 3 Band width of harmonic currents of 70 ESLs expressed in real and imaginary part – sinusoidal supply

Order	Magnitude		Phase Angle	
I_v	Min.	Max.	Min	Max.
	mA/W	ma/W	°	°
1	4.5	5.2	18	34
3	3.4	4.0	-123	-83
5	1.8	3.0	96	180
7	1.1	2.1	-36	112
9	0.9	1.3	-158	34

Table 1 Maximum and minimum magnitudes and phase angles of 70 ESLs of different type

ESLs of the same type nearly show identical amplitudes and phase angles of harmonic currents, while different types show in some cases considerable spreads. Especially the range of the phase angles increases with higher order of the harmonic. These are important facts for handling extensive collectives of ESLs in electrical facilities and grids.

In the low voltage level variations of the magnitude of the supply voltage appear regularly. Additionally harmonic voltages varying in time in their magnitude and phase angle are present. Long term measurements in the low voltage grid resulted in harmonic magnitudes between 0.5 % to 2 % of the fundamental and phase angle differences up to 60 °.

The results of the measurements with single harmonic voltages (3rd, 5th, 7th and 9th) and combinations of them (3rd and 5th, 5th and 7th, 3rd and 5th and 7th) demonstrate the dependency of the input current on voltage harmonics and describe the non-linear behaviour.

For example the dependency of the 5th and 9th harmonic input current of the ESLs due to changes in the 5th harmonic magnitude and phase angle of the supply voltage is shown in Figure 4. A 4 % increase in the 5th harmonic voltage causes a significant decrease of the 5th harmonic current, while the 9th harmonic increases nearly to the double.

When investigating the impact of ESL on power quality, these influences and non-linear characteristics can't be ignored, because of the pre-distorted voltage in the mains power supply.

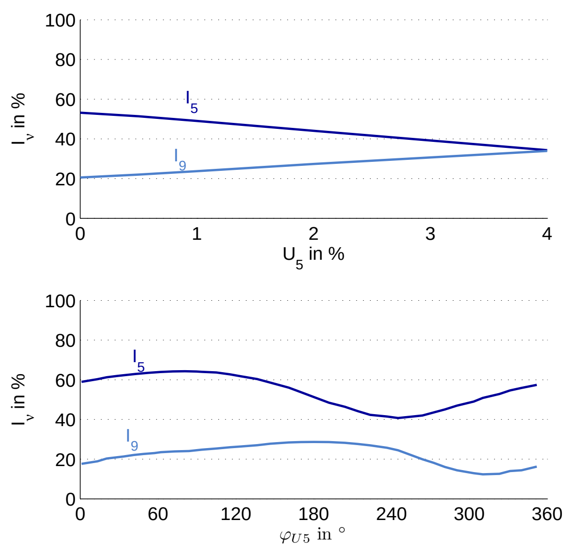

Figure 4 Dependency of the 5th harmonic current on 5th harmonic voltage. Upper diagram: Varying magnitude, constant phase angle (-150 °); lower diagram: constant magnitude (2 %) varying phase angle

IMPACT ON POWER QUALITY

ESL Simulation Model

For the purpose to evaluate system disturbances due to ESL the knowledge of these measurements results in a simulation model. The developed model for the ESL (see Figure 5) based on a bridge-rectifier is as simple as effective and considers the non-linear behaviour of ESLs. The correctness of the simulation model was verified by the comparison of measurement data with simulation results (see Figure 6 and Figure 7) especially regarding the behaviour of the input current in distorted environment.

Measured differences of the input current of ESLs had been simulated by variation of R and C. R is primarily required to attenuate an oscillation generated by inductive grid elements and the capacity of the simulation model.

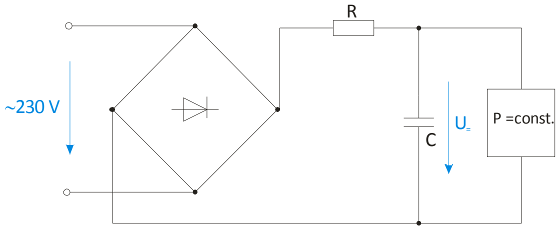

Figure 5 Simulation model of ESL

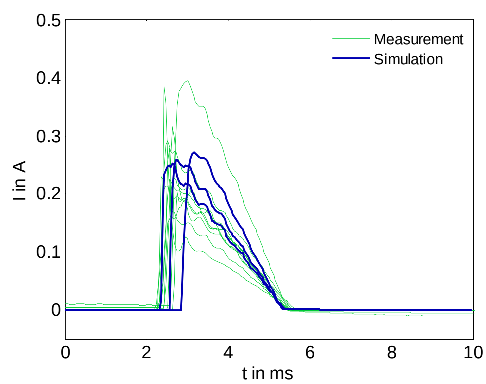

Figure 6 Comparison of measurement (10 ESL) and simulation (3 model parameter sets) for current in time domain

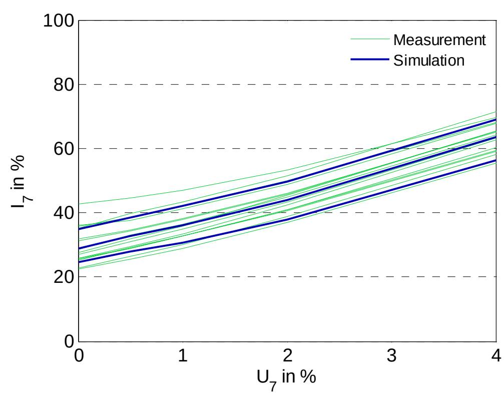

Figure 7 Comparison of dependency of 7th harmonic current on 7th harmonic voltage of measurement (15 ESL) and simulation (3 model parameter sets)

LV Grid Simulation Model

case		ΔS in kVA	THD_I in %
1	no ESL	--	12.3
2	3 ESL/customer	1.88	12.5
3	8 ESL/customer	5.01	17.3

Table 2 Total power differences of simulated cases

To develop a significant simulation the knowledge of load, structure and components of the LV grid is essential. Based on the grid impedances provided by the local distribution grid operator, a realistic three-phase LV grid model including load was developed to investigate the influence of the ESLs.

The simulation model consists of a 10 kV voltage source, representing the MV grid, feeding a LV grid via a 10/0.4 kV transformer. Customers in rural and suburban sectors are supplied by overhead lines and cables. Table 2 gives specification of the three simulated cases.

For a realistic presumption of the consumer load, long term measurements on a MV/LV-transformer are evaluated to get an overview of the PF and typical types of load. The measurements in the LV grid resulted in about 85 % ohmic-inductive load with a PF from 0.95 to 0.98 and about 15 % non-linear load (devices using switching power supply, PCs, TVs), which is responsible for existing harmonic distortion of the current in the grid. Also the initial level of voltage harmonics transmitted from MV level was detected by the measurements.

Simulation Results

Magnitudes of harmonic currents calculated at the feeder of transformer are shown in Figure 8. The phase angle differences between the harmonic currents caused by ESL and other non-linear loads (see Figure 9) are the reason for the individual trends because of additional ESLs. Small Phase angle differences below 30 ° result in increasing the 3rd and 9th harmonic significantly. The decrement of the 5th harmonic is due to phase angle differences in the range of 150 °. A phase angle difference around 100 ° for the 7th harmonic currents leads to small changes in sum depending on the amount of ESLs installed in the grid. For only 3 ESLs installed per customer the 7th harmonic current at the feeder is lightly decreasing and for 8 ESLs per customer it is increasing.

The harmonic voltages (Figure 10) calculated at the end of the feeder show in case of the 3rd, 5th and 9th order same trends like the harmonic currents.

In Figure 11 the influence of the pre-distortion from the MV level on the 7th harmonic voltage is shown. While the 7th harmonic current stays more or less constant, the changing phase angle of the 7th harmonic voltage, caused by additional ESLs, leads in sum with from MV level transmitted harmonic voltage to an increasing voltage in the LV grid.

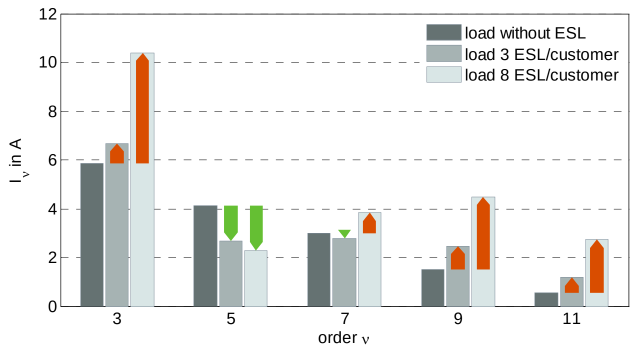

Figure 8 Magnitudes of harmonic load currents on changing load of ESL

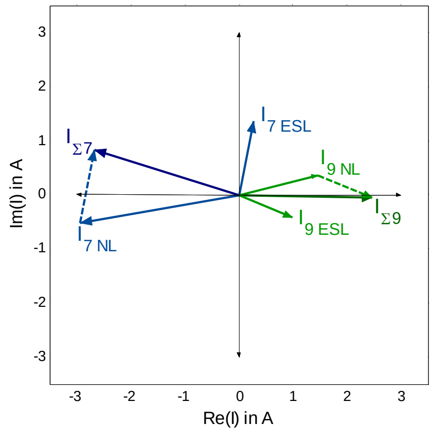

Figure 9 Vectorial addition for 7th and 9th harmonic currents caused by 3 ESL/customer and other non-linear loads (NL)

Figure 10 Magnitude of harmonic voltages on changing load of ESL

Although single harmonic voltages increase, limits for harmonic voltages set by the EN 50160 [4] standard are not reached in the investigated case.

Beside the changing harmonic currents and voltages a positive effect of increasing PF in the LV grid can be detected. The fundamental reactive power Q_1 of ESL is capacitive while the dominating load in the LV grid is inductive. Therefore a compensation effect can be observed increasing the PF from 0.95 to 0.97.

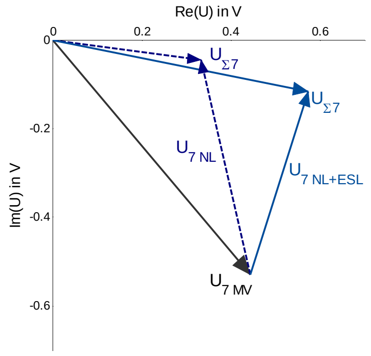

Figure 11 Vectorial addition of 7th harmonic voltage considering non-linear load (NL), 3 ESL/customer and pre-distortion from MV level

CONCLUSIONS

A representative number of ESL have been analysed to get distinctive information of the characteristics of the harmonic emission of ESLs and of impact on power quality due to the intensive installation in households.

Analysis of the measurement data in combination with the developed simulation model lead to following results.

- A significant spread of harmonic currents between different types of ESLs was detected. When observing the behaviour of extensive collectives of ESL in the grid the superposition due to spreading of single ESL types has to be considered.
- Magnitude and phase angle of harmonic voltages in mains power supply have significant influence on the harmonic emission of ESL. However, increasing distortion of voltage doesn't result stringently in higher harmonic currents.
- The impact of ESLs on the power quality of the grid depends on the percentage of ESL in the total load and other present non-linear loads in the grid. Phase angles of harmonic voltages resulting from ESL, other non-linear loads and pre-distortion from the MV level play a vital role in superposition, thus amplifying or eliminating each other.

REFERENCES

[1] J. Ferstl, 2010, *Characteristic of the Input current and the Influence on Power Quality of Energy Saving Lamps,* diploma thesis, Graz, Austria.

[2] European Parliament and the Council, July 2005, Directive 2005/32/EC, "Eco-Design-Directive"

[3] IEC, March 2010, EN 61000-3-2, *Limits for harmonic current emission (equipment input current ≤ 16 A)*

[4] IEC, May 2008, EN 50160, *Voltage characteristics of electricity supplied by public distribution systems*