Grid control with LED lamps

Eberhard Waffenschmidt, Andre Kores, Desiree Fuhs, (TH-Köln)
Lee Chi Kwan, Liu Heng, (The University of Hong Kong)

Corresponding author: E. Waffenschmidt
CIRE (Cologne Institute for Renewable Energy) at
TH-Köln (Cologne University of Applied Sciences)
Betzdorferstraße 2, 50679 Cologne, Germany
eberhard.waffenschmidt@th-koeln.de

***Abstract*— Renewable energy supply is worldwide emerging. The aim is a 100% supply with renewable energies. This way, conventional electrical power generators will be replaced by decentralized power sources, which feed in power to the grid using electrical power converters. Rotating inertia and speed controllers used for the control of the power grid will disappear and must be replaced by a suitable control of the future grid devices. However, not only feed in devices may contribute to the grid control, but also electrical loads may contribute their part.**

In this publication options to use LED lamps as variable loads are investigated. As a comparison, the brightness of incandescent lamps (“light bulbs”) may vary approximately +/ 20% of their nominal power at +/ 10% of the nominal voltage. It is known that slow variations of the lamp brightness are not perceived by users. Here, suitable ramp rates are determined by a survey with a number of test persons in Köln, Germany, and Hong Kong. It turned out that the possible ramp rates and the possible power change, which are not perceivable, can be a significant fraction of the nominal lamp power, such that Primary Control Power and Fast Frequency Control might be provided with LED lamps.

1 INTRODUCTION

Renewable energy sources gain higher and higher shares of the electrical power supply. Recently, on 1. May 2018, renewable energy sources contributed already more than 100% to the power consumption in Germany [1] for two hours, and soon shares of 100% for longer periods are expected [2]. Most of this power is generated by electronic power converters, which do neither provide rotating inertia nor frequency control at the current state of the art.

Luckily, the German grid is part of the ENTSO-E, European Network of Transmission System Operators for Electricity, and today the missing inertia and primary frequency control can be compensated by the other members, which have less renewable energies [3]. There are various proposals for the provision of virtual inertia with electronic power converters [4] [5] [6] [7] and primary frequency control with renewable energy generators and batteries [8] [9].

However, not only generators may contribute to grid control. In [10] using the intermediate voltage electrolytic capacitor (elcap) in the rectifier part of power supplies and especially in LED lamp drivers to provide virtual inertia is proposed.

Here, it is investigated how such a LED lamp driver can in addition provide primary frequency control (also known as Primary Reserve Control, PRC [11]) or fast frequency control as needed in islanding grids. Here, a general reaction on a power demand is investigated. It is assumed that such a power demand may be caused by PRC or fats frequency demand or any other kind of control. While the intermediate voltage elcap can provide a fast reaction on power demand, the amount of energy is limited and not suited to provide such a frequency control.

As basic idea the lamp power, and such the lamp brightness, is varied to provide power to the primary frequency control. It is known by experience that slow brightness changes are not perceivable by humans. Therefore, as a general idea, slow power changes are provided by slow changes of the LED brightness, while fast changes are mitigated by the intermediate voltage elcap (compare also Figure 1). This idea has been elaborated in a parallel submitted publication by the authors [12].

Here, in this publication, we focus on presenting empirical investigations on the perception of brightness changes. With these results, a maximum input power step, which can be provided without perception, is calculated. Finally, such a system has been evaluated by a further empirical investigation.

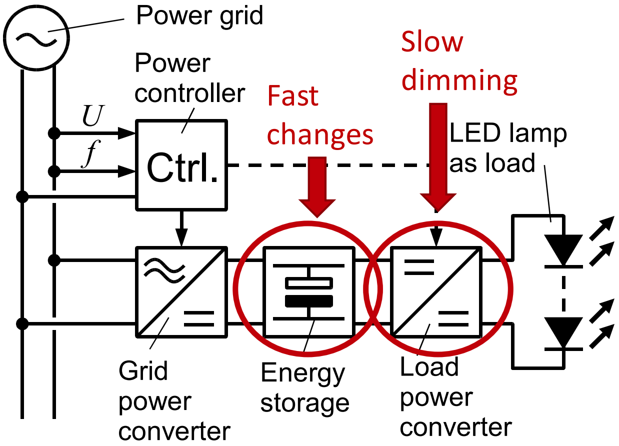

Figure 1: Considered topology and parts used to mitigate power changes.

2 GENERAL IDEA

As mentioned, the basic idea is to provide control power by varying the lamp power and thus its brightness. Varying the light brightness due to the power grid supply is not new. In fact, old fashioned incandescent lamps (“light bulbs”) are more or less Ohmic loads and thus vary their light power according to the grid voltage. Since the grid voltage may fluctuate by +/- 10% in Europe, the light power fluctuation may reach +/-20% of the nominal power. Because of spectral shifts at higher power the light emission ha even a wider range. Figure 2 shows the light emission of a typical Philips Halogen Lamp as the function of the relative supply voltage [13]. Here, light fluctuations of more than +/-20% can be expected already in a voltage range of +/-5% of the nominal voltage.

This behaviour is accepted by users and show the potential of possible power variation. On the other hand, users are now accustomed to constant light provided by LED lamps. If it would be possible to use a similar lamp power range as with incandescent lamps with LED without notice of the user, a significant power potential for grid control could be raised.

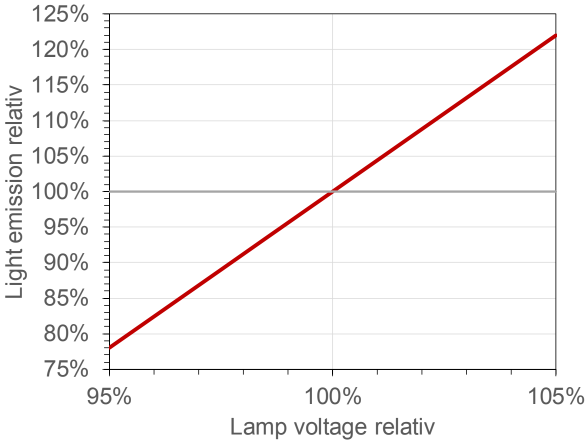

Figure 2: Light emission of a halogen lamp as a function of lamp voltage. Data based on [13]

3 USED HARDWARE

For the experiments a high power LED lamp is used. It is a Philips Fortimo LED DLM, Module 2000 32W/840 with a typical power of 15 W (maximum power 33 W) and a typical LED forward voltage of 35 Vdc (see Figure 3).

Figure 3: Used LED lamp

The luminous flux of this LED was measured as a function of the LED current in a laboratory setup using an Ulbricht Sphere. The result is shown in Figure 4. Further results are based on LED current and this figure can be used to convert it to the LED brightness.

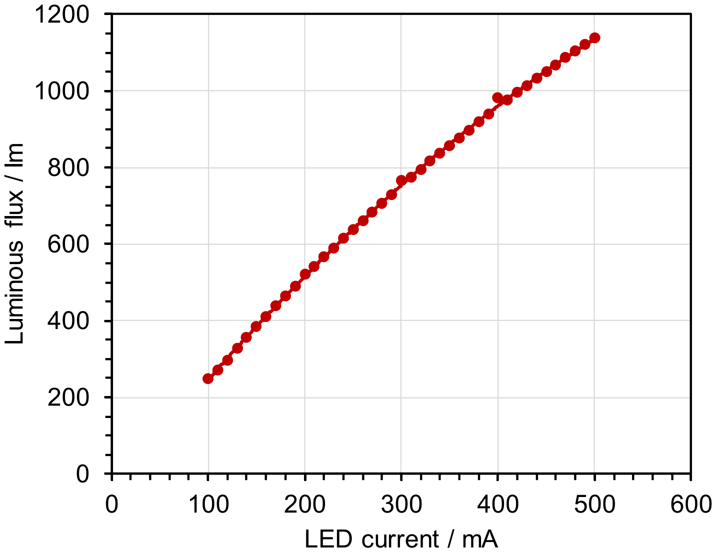

Figure 4: Luminous flux of the LED as a function of LED current

For visual perception experiments the LED was connected to various remotely controllable laboratory power supplies.

To demonstrate the general functionality of the collaboration between elcap and lamp brightness the original driver of this LED is modified. It is a Philips Fortimo LED Driver 1100-2000 TD/I, which may provide up to 46 W at an output voltage range of 20 V to 80 V and an output current of 200 mA to 700 mA with a stabilized output current (see Figure 5). The modification allows controlling the intermediate DC voltage by an external voltage as described in [10]. This corresponds to the “fast changes” path in Figure 1. An additional modification controls the lamp output current by an additional external voltage, corresponding to “Slow dimming” in Figure 1. Both external voltages are connected to a digital-to-analogue interface of a computer with a control software developed in LabView.

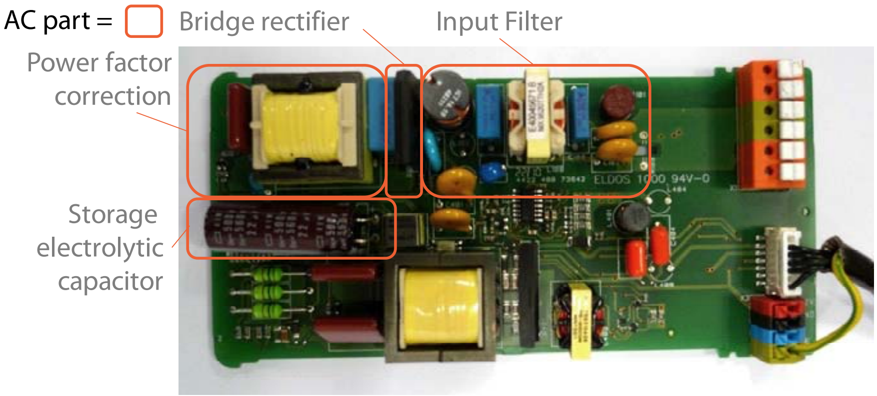

Figure 5: Printed circuit board of the modified LED driver.

The final power step experiment (chapter 6) was performed with a self-developed lamp driver. More details can be found in a related publication [12].

4 EMPIRICAL BRIGHTNESS PERCEPTION EXPERIMENT

To investigate the perceivable brightness change, two empirical experiments were performed, a first at the University of Hong Kong and a second at TH-Köln. The test persons were subjected to different brightness slopes at different light levels.

4.1 Experimental setup

For the first experiment in Hong Kong the test persons were place in a shielded light chamber as shown in Figure 6. The LED light was the only light source and was directed towards a white desk plate. The LED current was programmed to follow the curves shown in Figure 7. In total 10 individual slopes were performed.

Figure 6: Shieled light chamber for the perception experiments in Hong Kong.

In total 13 test persons participated this tests. Each person had to fill in a questionnaire. It contains a few general questions, which are listed with averaged answers in Table 1. After each step of the experiment (as indicated in Figure 7) the test person was asked four questions as listed in Table 2.

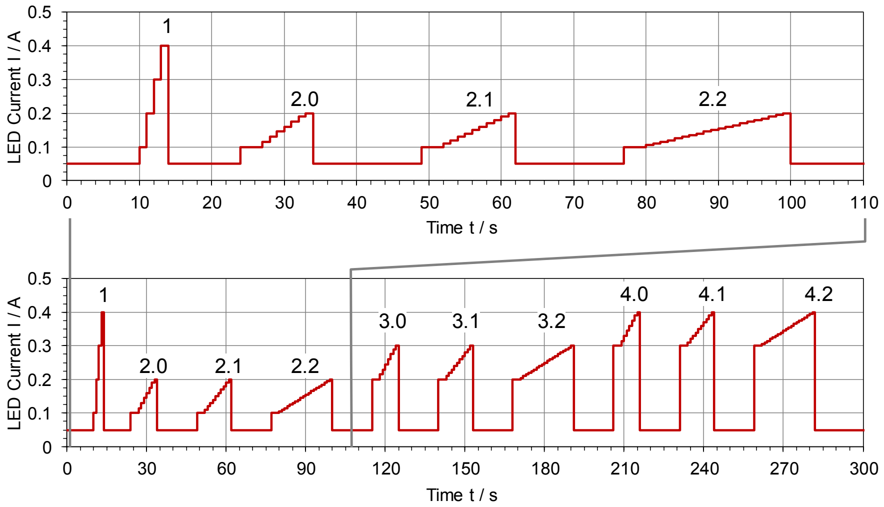

Figure 7: LED current variation during the first experiment in Hong Kong. The numbers note the test parts of the experiment.

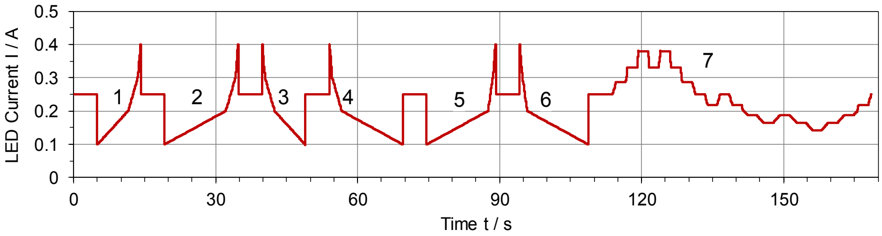

Figure 8: LED current variation during the second experiment at TH-Köln. The numbers note the test parts of the experiment.

The first question “Did you see different levels of brightness?” was get a general impression of the perception. The second question “How extreme did you notice the variation?” allows a more detailed evaluation of the perception experience. A level of 10 corresponds to a strong perception. Since the power supply was not able to generate an arbitrary smooth curve, the third question “Was the increase and decrease of brightness smooth or stepped?” was asked to get more insight in the kind of perception experience. The final question “are you able to work under this brightness conditions?” is asked to evaluate the personal severity of the light modulation.

The experiment at TH-Köln in Cologne was performed similarly. However, the brightness curve to which the test persons were subjected, was different, as shown in Figure 8. In addition, here the test persons were asked to mark, when they notice a brightness change for each individual step of the experiment. This was recorded as noticed current value. In total 10 persons participated the tests at TH-Köln.

Table 1: General questions of the questionaire including results:

What is your gender?
☐ male 9
☐ female 4

How old are you?

Average 29.4 years ______________

Do you wear glasses/ contact lenses?
☐ Yes 8
☐ No 5

Table 2: Experiment specific questions:

1. Did you see different levels of brightness?
☐ Yes
☐ No
☐ Not sure

2. How extreme did you notice the variation?
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

3. Was the increase and decrease of brightness smooth or stepped?
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

4. Are you able to work under this brightness conditions?
☐ Yes
☐ No
☐ Not sure

4.2 *Empirical results*

The results of the empirical investigation in Hong Kong are illustrated for the 10 steps of the experiment in Figure 9 for question 1, in Figure 10 for question 2, in Figure 11 for question 3 and in Figure 12 for question 4. For question 1 and question 4 a “Yes” corresponds to a level of 1, a “No” to a level of -1 and a “Not sure” to a level of 0. As “average perception value” the average of the levels is shown. For question 2 and 3 the “average perception value” is derived from the average of the cross-marked values corresponding to the question.

The answers of the first question show that the selected brightness slopes are in most cases visible. Especially at low light levels the confidence to detect a change is high. At higher light levels (experiment 4, 4.1 and 4.2) some of the test persons are uncertain or don’t notice a change. The answers to question 2 show a more detailed result. The same brightness slope is less severe perceived at high load levels (compare e.g. 2.1., 3.1. and 4.1). The answers to question 3 reveal one problem with the experimental setup in Hong Kong. The used power supply was not able to generate short steps with a low current increase. Therefore, the steeper slopes appear “stepped”, which can much easier be perceived, as the answers reveal. For most test persons this was the reason to feel uncomfortable as answered at question 4.

The answers to question 2 (Figure 10) shows that the design of the experiment did not include a test with an invisible slope. To reveal a power slope, which is just not perceivable an extrapolation of these results is performed in the following way (see also Figure 13). To make the results at different power levels comparable, the power slope is related to the average power of the test parts. The horizontal axis shows this relative power slope. Since a logarithmic perception of the brightness is assumed, it is scaled logarithmically. The vertical axis shows the average perception value (according to Figure 10) related to the test with the corresponding power slope (the test parts are marked in Figure 13. For each absolute power level, a logarithmic trend can be recognized, which appears as a straight line in the logarithmic diagram. It can be assumed that with more shallow power slopes the perception value would decrease according to such trends. The crossing at the perception value of 1 marks the point, where the brightness change would not be noticed any longer. As a global resulting value the geometric average of these three crossing points is assumed a probable general value for the perception limit. This value of a light power change of 0.3%/s of the actual power can be assumed as probable perception limit.

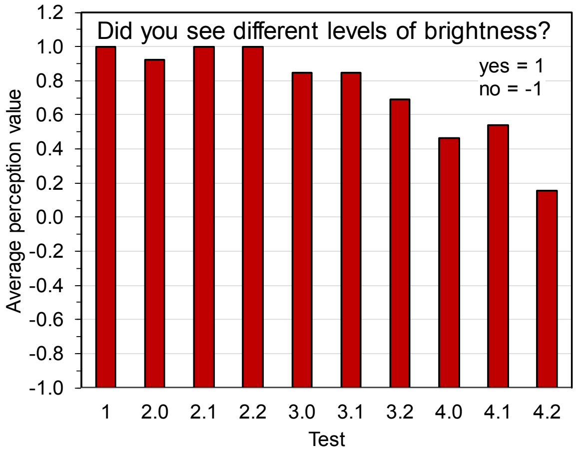

Figure 9: Summary of answers to question 1 of the first experiment in Hong Kong.

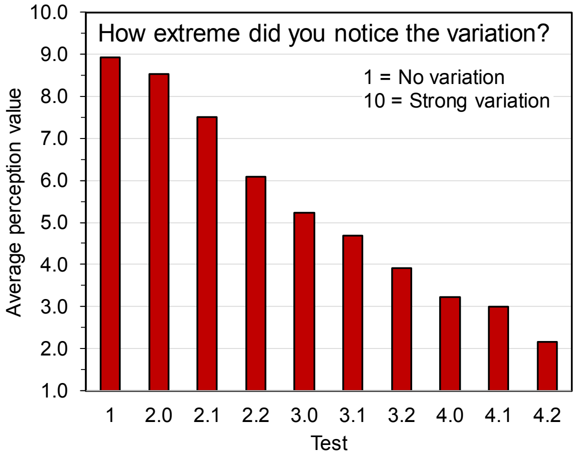

Figure 10: Summary of answers to question 2 of the first experiment in Hong Kong.

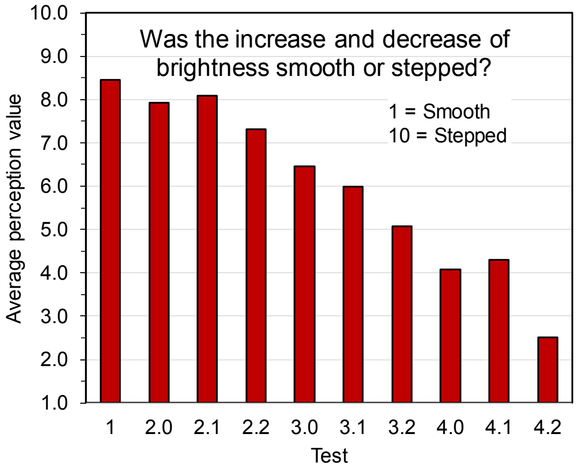

Figure 11: Summary of answers to question 3 of the first experiment in Hong Kong.

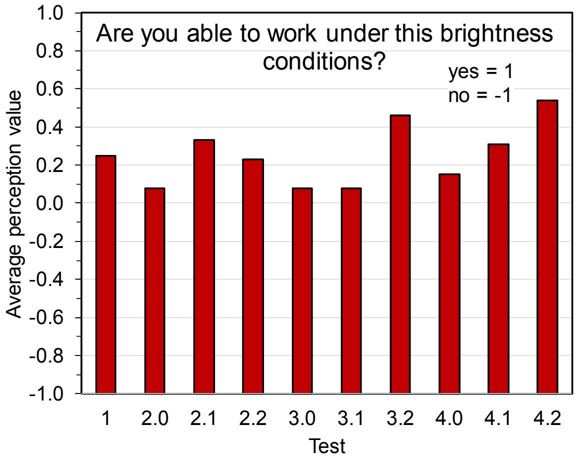

Figure 12: Summary of answers to question 4 of the first experiment in Hong Kong.

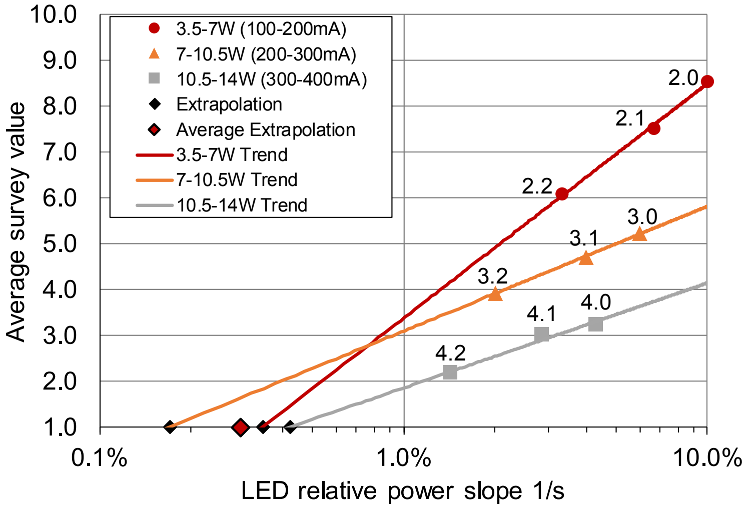

Figure 13: Extrapolation of the LED brightness visual perception experiment "How extrem do you notice the variation?"

If a sudden power step is requested to be taken over by the LED lamp, the brightness should not be stepped in order not to be noticed. Instead, the intermediate voltage elcap shall be used to store the energy, which cannot be delivered to the LED immediately. Figure 14illustrates the behaviour: While the input power P_{in} increases step-wise, the LED power P_{LED} is increased with a slope (period I). During this time the elcap is charged with the remaining energy. Therefore, the intermediate voltage increases (not shown in the figure). To come to new stable condition with a nominal intermediate voltage, the elcap must get rid of the excess energy. Therefore, the LED brightness is even increased above the input power to discharge the elcap to its nominal value (period II). A negative input power step is handled inversely (period III and IV).

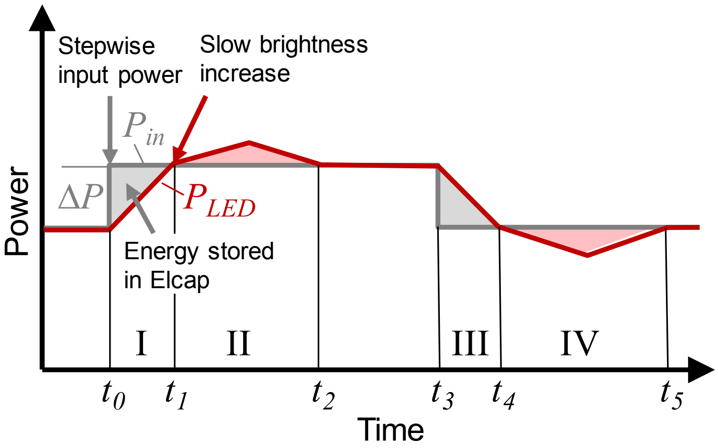

Figure 14: Power and energy flow in the LED lamp system at an input power step.

This behaviour is the base for the calculation of a possible input power step, which is derived now:

The input power must equal the power P_{cap} taken by the elcap and the LED power P_{Lamp} (same as P_{LED}):

$$P_{in} = P_{cap} + P_{Lamp}$$

Then do integration for the energies:

$$\int_{t0}^{t1} P_{in}\,dt = \int_{t0}^{t1} P_{cap}\,dt + \int_{t0}^{t1} P_{Lamp}\,dt$$

Resulting in

$$P_{step} * T = \Delta E_{Cap} + 0.5 * P_{step} * T$$

where $T = t1 - t0$

For the capacitor the energy, which can be taken is

$$\Delta E_{Cap} = 0.5C * (U_1^2 - U_0^2)$$

Therefor we have

$$0.5 * P_{step} * T = 0.5C * (U_1^2 - U_0^2)$$

Also, we know for the LED output

$$P_{step} = K * T$$

where K is the increasing rate of the output power for lamp

Thus, it follows

$$0.5 * \frac{P_{step}^2}{K} = 0.5C * (U_1^2 - U_0^2)$$

Resulting finally in:

$$P_{step} = \sqrt{K * C * (U_1^2 - U_0^2)}$$

With this equation a possible input power step can be calculated. Table 3 list some exemplary results for suitable assumptions. The capacitor size and voltage relate to the Philips lamp driver described in the previous chapter. The power slopes are estimated from the results leading to Figure 13 and the initial power level relate to brightness levels used in the previous experiments. As can be seen, input power steps of 1.1% to 1.9% can be mitigated, with a low probability of visual perception.

Table 3: Assumed parameters for possible input power steps

Capacitor Size C [F]	**Inter-mediate Voltage U_1 [V]**	**Upper Voltage Limit U_0 [V]**	**Invisible LED-Power Slope K [W/s]**	**Input Power step P_{step} [W]**	**Initial Power P_0 [W]**	**relative input power change dP**
22.0E-6	400	440	0.018	**0.115**	6	1.9%
22.0E-6	400	440	0.036	**0.163**	12	1.4%
22.0E-6	400	440	0.054	**0.200**	18	1.1%

6 EMPIRICAL EXPERIMENT OF PERCEPTION OF A POWER STEP

With such a final setup, visual perception experiments were performed, where the input power of the lamp was stepwise or ramp-wise. The input lamp power and the LED output power was controlled in four different experiments as illustrated in Figure 15. Details are about the setup is explained in [12]. In Test I, the input power step was passed to the lamp output. A high perception is expected. In the corresponding Test II, this power step is converted to a ramp increase at the LED. Here, a much lower visibility is expected. In Test III, a brightness ramp over a wide range is applied. A medium perception is expected. In the corresponding Test IV this ramp is divided in two parts, where the part at low light levels has a reduced slope, while the part at higher light levels has an even increased slope. Here a lower visibility is assumed.

During the experiments, the test persons were asked to “click” a mouse button, when a brightness change is perceived. Thus, the number of clicks related to a test indicate, how much visible the brightness change is.

The results are shown in Figure 16. As expected, the stepped brightness change in Test I is very well perceived with 28 clicks. The smoothing of the brightness change in the corresponding Test II shows a significant reduction in visibility from initially 28 clicks to only 6 clicks. This shows that indeed the concept of using the intermediate elcap for the fast response can work as expected. The results of Test III and Test IV show that indeed a splitting of the slope steepness into two parts reduces the perception even further. In Test IV only 2 clicks were noticed (compared to 7 clicks for the single wide slope in Test III). And even a bigger difference of brightness has been set compared to the initial Test I only less than 7% of the clicks were noticed.

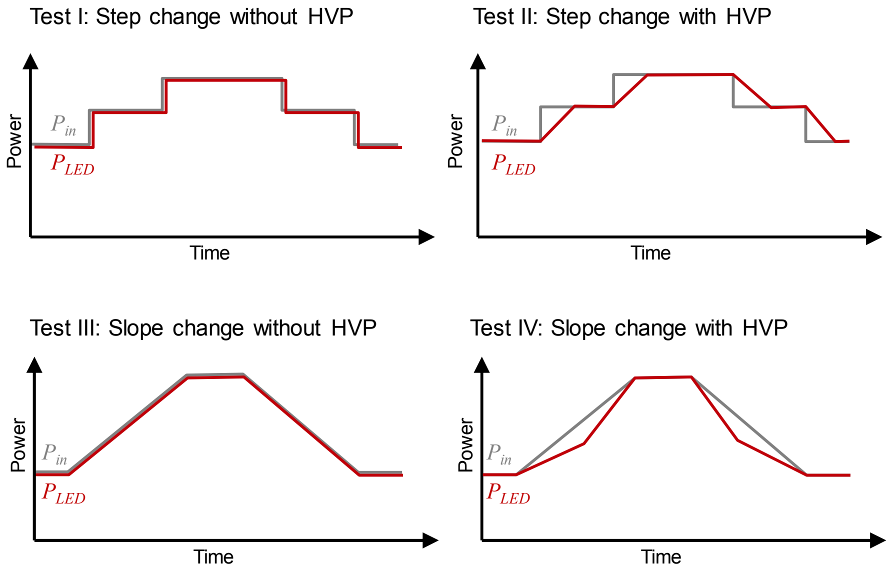

Figure 15: Overview of the Human Visual Perception (HVP) experiments with load steps.

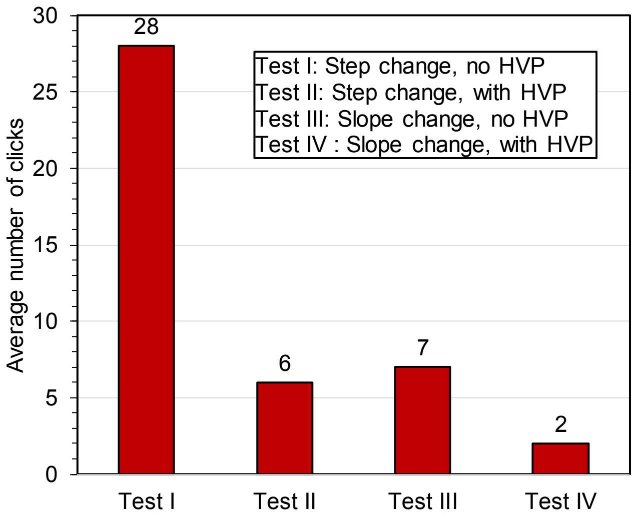

Figure 16: Results of the Human Visual Perception (HVP) experiments with load steps.

7 CONCLUSION AND SUMMARY

Concluding, a concept for using an LED lamp for grid control is proposed. It includes using the intermediate voltage electrolytic capacitor as storage to mitigate fast power changes and using the modulation of the LED lamp brightness to allow slow but longer lasting power changes.

The concept includes the fact that slow brightness changes are less likely noticed by users. From empirical experiments with test persons a light power change of 0.3%/s of the actual power can be assumed as probable perception limit. This curves includes the effect that at higher brightness levels a faster brightness increase can be tolerated. As an exemplary estimation, a power step of 1.1% to 1.9% of the intial power could be mitigated with brightness change which has a low probability to be noticed. This can provide a significant potential for grid control.

Finally, a lamp driver according to the proposed concept could be realized and tested in an empirical test with test persons.

ACKNOWLEDGMENT

This work was supported by Deutsche Akademische Austauschdienst (DAAD) e.V., PPP Hongkong, Projekt-ID 57216001.

REFERENCES

[1] SMARD Energiedaten, available online (2.May.2018), https://www.smard.de/blueprint/servlet/page/home/marktdaten/78?marketDataAttributes={"resolution":"hour","region":"DE","from":1525125600000,"to":1525211100000,"moduleIds":[5000410,1000103,1001226,1001225,1000100,1000102,1001228],"selectedCategory":null,"activeChart":true}

[2] Bodo Giesler, Bruno Burger, "Erneuerbare Energien konkurrieren zunehmend mit Grundlastkraftwerken", Proceedings of the 2. Otti-Konferenz „zukünftige Stromnetze für Erneuerbare Energien", 27.-28.Jan. 2015, p. 52-57.

[3] A.-C. Agricola, H. Seidl, S. Mischinger, et al., „dena-Studie Systemdienstleistungen 2030 - Sicherheit und Zuverlässigkeit einer Stromversorgung mit hohem Anteil erneuerbarer Energien", Deutsche Energie-Agentur GmbH (dena), Energiesysteme und Energiedienstleistungen, Berlin, Germany, Feb. 2014.

[4] Eberhard Waffenschmidt, Ron S.Y. Hui, "Virtual inertia with PV inverters using DC-link capacitors", EPE'16 ECCE Europe - 18th European Conference on Power Electronics and Applications, 5.-9. Sep. 2016, Karlsruhe, Germany

[5] Yong Chen, Ralf Hesse, Dirk Turschner, Hans-Peter Beck, "Improving the grid power quality using virtual synchronous machines", Proceedings of the International Conference on Power Engineering, Energy and Electrical Drives (POWERENG 2011), 11.-13. May 2011, Malaga.

[6] Visscher, K.; de Haan, S.W.H.; Virtual synchronous machines for frequency stabilisation in future grids with a significant share of decentralised generation, Proceedings of the CIRED SmartGrids conference; June 2008; Germany

[7] Pedro Rodriguez, "Control of Grid-Interactive Power Converters: The Synchronous Power Controller", Presentation at ECPE-Workshop "Power Electronics in the Electrical Network", Kassel, Germany, 12. March 2013.

[8] Eberhard Waffenschmidt, "Degrees of freedom for primary control with batteries", 11th International Renewable Energy Storage (IRES 2017), 14.-16.Mar.2017, Düsseldorf, Germany

[9] Eberhard Waffenschmidt, "Primary control with batteries", 5th International Energy and Sustainability Conference 2016 (IESC 2016), Cologne, Germany, 30. Jun. – 1. Jul. 2016

[10] Eberhard Waffenschmidt, "Virtual inertia grid control with LED lamp driver", 5th International Energy and Sustainability Conference 2016 (IESC 2016), Cologne, Germany, 30. Jun. – 1. Jul. 2016

[11] "ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators", ENTSO-E, 8 March 2013.

[12] C.K. Lee, H. Liu, D. Fuhs, A. Kores, E. Waffenschmidt, "Human Visual Perception Modelling for Smart LED Lighting Control", submitted to IEEE Transactions on Power Electronics, 8.May 2018

[13] "Halogenlampen", Online-Schulung, Stand 10/2005, downloaded 25. Apr. 2012 from www.philips.de/akademie, no longer available online.