Sensitivity of Modern Lighting Technologies to Rapid Voltage Changes

Stefano Lodetti*, Izaskun Azcarate†, José Julio Gutiérrez†,
Koldo Redondo†, Purificación Sáiz†, Julio J. Melero*, and Jorge Bruna*
*CIRCE - Universidad de Zaragoza, Zaragoza, Spain
†University of the Basque Country (UPV/EHU), Bilbao, Spain

***Abstract*—Rapid Voltage Changes (RVCs) are one of the Power Quality disturbances that are recently receiving a lot of attention from the point of view of international standards. However, although they can cause or contribute to flicker, IEC 61000-4-15 only addresses periodic amplitude fluctuations and more effort is needed to regulate the occurrence of RVCs, according to their effect on flicker perceptibility. Alongside, flicker perception is challenged by the integration of modern lighting technology, whose response is different from the traditional incandescent lamp. This paper studies the connection between the increasing importance of RVCs and the evolution of illumination technologies. Sensitivity of modern lighting technologies to RVCs is studied by measuring flicker with a high precision light flickermeter. A large set of modern lamps is tested and the relationship between RVCs parameters and flicker perceptibility is analyzed.**

***Index Terms*—Energy-efficient Lighting, Flicker, Light Flickermeter, Power Quality, Rapid Voltage Changes (RVCs).**

I. Introduction

Grid integration of illumination devices is constantly challenged by their extremely fast technological evolution. The majority of modern lamp technologies, which replaced incandescent lamps, employ electronic circuitry which provides higher energy efficiency, but at the same time they should guarantee a high quality of power i.e., they should not introduce electromagnetic disturbances into the grid [1]. Moreover, the correct operation of illumination devices (and their electronics) should not be affected by the presence of unplanned disturbances in the grid. It is therefore important to analyze them, in particular voltage fluctuations, which can cause variations in the illuminance (flicker), since they can be annoying for the power grid users and can lead to complaints, with which utilities have to cope.

In the last decade, several works studied the sensitivity of modern lighting technologies to voltage fluctuations, but with discordant results: the first studies indicated that newer lighting technologies were less sensitive to flicker than incandescent lamps [2], [3]. As lighting technology evolved, more studies started to question those first results [4], [5], [6], until reaching today the common conclusion of not considering newer lighting technologies as a priori immune from flicker [7]. Indeed, it already exists a protocol to test the sensitivity of lighting equipment to voltage fluctuations during their design process, developed by the working group (MT 1) of IEC-TC34 [8], with the support of IEC-SC77A-WG2. Until now, flicker sensitivity has been studied with respect to classical voltage fluctuation patterns, known to be causing light flicker: periodic fluctuations, with a specific amplitude, characterized by the $P_{\mathrm{st}} = 1$ curve, and measured according to the International Electrotechnical Commission (IEC) 61000-4-15 standard [9].

Nevertheless, there is a type of voltage fluctuation which has not been considered in the IEC 61000-4-15 standard. It is the case of Rapid Voltage Changes (RVCs). They are defined as a rapid change of the voltage Root Mean Square (RMS) value, occurring between two steady-state conditions, and during which the RMS voltage does not exceed the dip/swell thresholds [10]. Detection and analysis of such fluctuations are subject to IEC 61000-4-30 standard [11].

The present work aims at extending the knowledge about the influence of voltage fluctuations on newer lighting techniques, analyzing their behavior when subjected to RVCs. In order to do that, a large set of Compact Fluorescent Lamps (CFLs) and Light Emitting Diode (LED) lamps, covering a broad range of electric power, have been tested. A light flickermeter ([8], [12], [13]) has been used to measure their light output response when the supply voltage is affected by RVCs. The study allows to achieve two main goals. On one hand, the evaluation of the response to RVCs of modern lighting technologies, compared with the current standard [9], and on the other hand, the evaluation of the dispersion in the response of the different kind of lamps, according to the used technology, power and manufacturers.

II. Experimental Setup

A. Lamps under test

The analyzed lamps corresponds to LED and CFL technology, as well as a 60 W incandescent lamp, used as reference. The lamps have been chosen between the commercially available technologies, from different manufacturers, and giving more emphasis to LED over CFL lamps, with the aim of reproducing the current trend of the market. The lamps present different values of power, from 3 W to 23 W, luminous flux, from 250 lm to 2452 W, and energy efficiency rating, and all of them are made for 230 V/50 Hz systems. Their characteristics are shown in Table I.

978-1-5386-0517-2/18/$31.00 ©2018 IEEE

TABLE I
SET OF LAMPS UNDER TEST.

ID	Technology	Power [W]	Luminous Flux [lm]	Manufacturer
I01	Inc	60	710	General Electrics
C01	CFL	23	1380	Lexman
C02	CFL	11	570	Megaman
C03	CFL	11	570	Philips
L01	LED	23	2452	Lexman
L02	LED	15	1200	CristalRecord
L03	LED	13	1521	Philips
L04	LED	12	1100	CristalRecord
L05	LED	12	650	Osram
L06	LED	12	1521	Philips
L07	LED	11	1055	Philips
L08	LED	11	1055	Xanlite
L09	LED	10	806	Eglo
L10	LED	10	1100	Lexman
L11	LED	10	470	Sylvania
L12	LED	9.5	806	Lexman
L13	LED	9.5	806	Philips
L14	LED	8	1020	Garza
L15	LED	8	806	Osram
L16	LED	8	470	Philips
L17	LED	7	560	Awox
L18	LED	6	806	Lexman
L19	LED	6	370	Philips
L20	LED	5.5	345	Xanlite
L21	LED	5	470	aDeo
L22	LED	3.3	250	Osram
L23	LED	3	250	Lexman

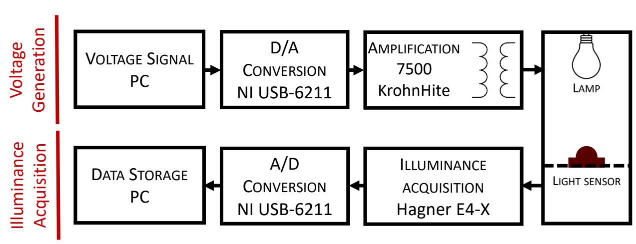


Fig. 1. Block diagram of the experimental setup, including a PC, the acquisition card, the amplifier, the voltage transformer, the luxmeter and the white box used to enclose the lamp under test and the light sensor.

B. Measurement System

Fig. 2 shows a block diagram of the experimental setup employed to achieve the following tasks:

- generation of the input voltage signals, containing the RVCs to be supplied to the lamps,
- acquisition of the illuminance produced by the lamps.

A PC is used to generate the lamp's input voltages containing RVCs, whose characteristics are described in Section III-A, using a Matlab based software. The digital to analog conversion is performed using a NI USB-6211 acquisition card, at a rate of 6400 Hz. The analog output signal from the NI USB-6211 card is then amplified using a 7500 Krohn-Hite amplifier (75 W, from DC to 1 MHz) first, and then a 120/230 V transformer to achieve a level of 230 V. This makes the voltage signal suitable for all the employed lamps.

The lamp under test, together with the light sensor of a Hagner E4-X digital luxmeter, is placed inside a white box, in order to avoid interference from any external light source. The box dimensions are $65 \times 65 \times 122$ cm, being 122 cm the height of the box. The source-detector distance can be adjusted to 17 different values, by moving a shelf on the bottom side of the box, where the light sensor is placed. The luxmeter is characterized by a spectral sensitivity that follows the eye sensitivity function and is fully cosine corrected, in accordance with the International Commission on Illumination (CIE) standards. Since the illuminance signal acquired by the luxmeter is an analog signal, an A/D conversion is provided by the NI USB-6211 card at 6400 Hz and 16 bit. The signal is then stored in the PC.

C. Light Flickermeter

The light flickermeter is an instrument developed to evaluate flicker directly measuring the illuminance produced by the lamp, instead of measuring the supply voltage, as it is specified in IEC 61000-4-15 [9]. This allows the correct estimation of flicker for any kind of lamp. The detailed definition of the light flickermeter is given in IEC TR-61547 [8]. It is based on the implementation of the IEC flickermeter, as in [9], but removing the characteristic related to the response of the incandescent lamp. Block 1 and 2 from the IEC flickermeter are removed and the weighting filter of block 3 is modified so that only the eye-brain system response is preserved. A diagram of the light flickermeter is shown in Fig. 2, whose four blocks are described in the following. The illuminance signal $l(t)$, once acquired and digitized as described in Section II-B, is the input signal of the light flickermeter. In Block A the illuminance signal is normalized, in order to make the measurement independent from the illuminance level. In Block B the demodulation process is completed as it is done in the IEC flickermeter, but with the weighting filter modified as described in [12], to remove the dependence from the incandescent lamp. Block C and D are identical to the IEC flickermeter's block 4 and 5, providing the instantaneous flicker sensation (P_{inst}) and the short-term flicker values (P_{st}), respectively. The instantaneous flicker sensation P_{inst} is given in perceptibility units, where a unit value corresponds to the reference human flicker perceptibility threshold, indicating a flicker visible to 50 % of the population.

The light flickermeter used in the present work is a highly accurate flickermeter, which meets all the requirements of the flickermeter described in IEC 61000-4-15 [9] and that can be validated as a Class-F1 flickermeter. The light flickermeter is implemented as described in [12].

III. RVC AND THEIR EFFECT ON FLICKER

A. Rapid Voltage Changes

According to IEC 61000-4-30 standard, a RVC is a quick transition in the RMS voltage beween two steady-state conditions that does not exceed the dip/swell threshold [11]. RVCs

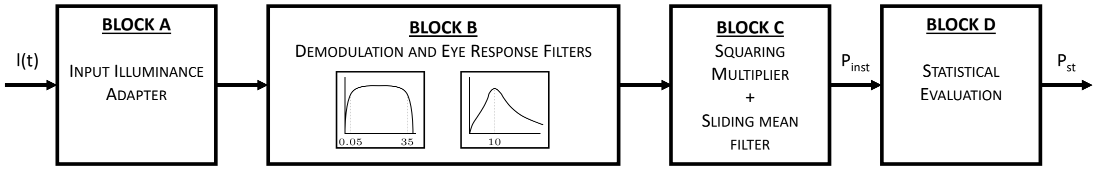


Fig. 2. Block diagram of the light flickermeter implementation.

can therefore be of many types, and a classifications is needed in order to systematically analyze their effect on flicker. In the following sections, a description of the employed types of RVCs is given, along with the analysis of simple cases and their expected effect on flicker. Following the approach introduced in [10] and due to the *rapid* nature of these voltage changes, the effect of RVCs on flicker is studied through the instantaneous flicker sensation P_{inst} (and its maximum value, $P_{\text{inst,max}}$), rather than the short-term flicker P_{st}.

B. Types of RVCs

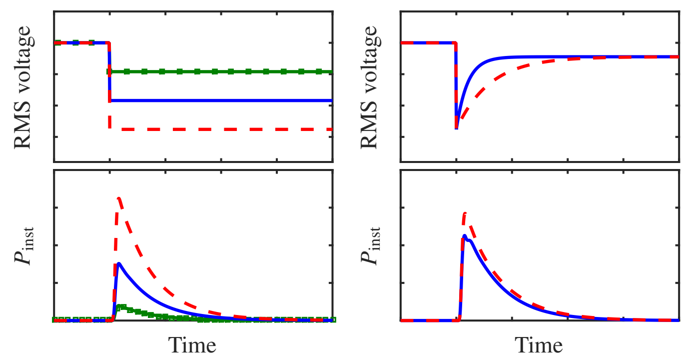
In order to organize and classify the types of RVCs supplied to the lamps, the classification given in [14] is considered, where different types of RVCs have been studied, mainly considering two characteristics: the RVC shape (*ramp* or *motor-type*) and the rate of change of the RMS voltage, which can be infinite (instantaneous RVC) or finite (gradual RVC). According to this description, four types of RVCs have been defined for the present study. Before analyzing their effect on the different lamp technologies, a study of how these RVCs are perceived has been conducted, using the human eye-brain model of the IEC 61000-4-15. To do so, the different RVCs signals have been analyzed by the IEC flickermeter and the P_{inst} signal has been studied. The most representative results are shown in Fig. 3 and 4, where no numerical values are represented, being the qualitative behavior the main interest.

1) Instantaneous Ramp RVC: Fig. 3a shows a ramp type RVC, whose transition is instantaneous, with three different amplitudes. As it can be easily expected, a RVC with larger amplitude, gives rise to a P_{inst} whose maximum, $P_{\text{inst,max}}$ is higher i.e., a more visible flicker.

2) Instantaneous Motor-Start RVC: Fig. 3b shows a motor-start type RVC, whose transition is instantaneous, but where the original steady-state voltage level is partially recovered. It can be observed that, although the amplitude of the RVC is the same as in the previous case (instantaneous ramp), $P_{\text{inst,max}}$ is now smaller. Moreover, the value of $P_{\text{inst,max}}$ depends on how fast the steady-state level is recovered: as the recovery time gets smaller, the flicker is less visible. The reason of this lies in the integration time needed by the human eye-brain system to perceive the change in illuminance. If the transition is not long enough for the eye to fully integrate the illuminance variation effect, a less visible flicker will be perceived.

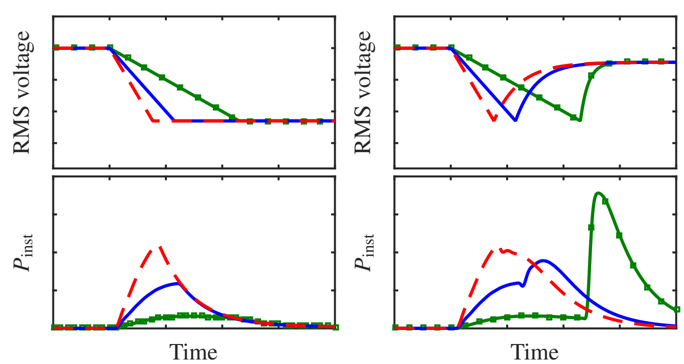
3) Gradual Ramp RVC: Fig. 4a shows a ramp type RVC, where the gradual transition allows to study the effect of the rate of change of the RMS voltage. It can be seen that a slower downwards transition, as it can be expected, causes a smaller value of $P_{\text{inst,max}}$, which also needs more time to be reached. Once again, it can be observed that the RVC amplitude is not the only parameter affecting $P_{\text{inst,max}}$ i.e., the visibility of flicker.

4) Gradual Motor-Start RVC: lastly, Fig. 4b shows a motor-start type of RVC, with a gradual transition. This case shows the sum of the previously described effects. In this case the P_{inst} has two components corresponding to the moments when the RMS voltage experiences a change. The first part, corresponding to the voltage drop, is similar to Fig. 4a and depends on the rate of change. The second part, instead, corresponding to the recovery, has a peak whose maximum value depends on how fast the recovery happens. A fast recovery (green line in Fig. 4b) is similar to the instantaneous transition in Fig. 3a, but being upwards instead of downwards.



(a) Instantaneous Ramp (b) Instantaneous Motor Start

Fig. 3. RMS voltage (top) and P_{inst} obtained with the IEC flickermeter (bottom) in two cases: (a) instantaneous ramp and (b) instantaneous motor-start RVCs.



(a) Gradual Ramp (b) Gradual Motor Start

Fig. 4. RMS voltage (top) and P_{inst} obtained with the IEC flickermeter (bottom) in two cases: (a) gradual ramp and (b) gradual motor-start RVCs.

IV. RESULTS

Measurements were conduced with the set of lamps described in Table I, supplying them with the four types of RVC previously described. Their illuminance signals have been measured and digitized by the measuring system of Section II-B, and then processed by the light flickermeter described in Section II-C, in order to obtain the instantaneous flicker sensation P_{inst}. According to Section III, the effect of the RVC amplitude and the effect of the RVC rate of change have been studied. In what follows, the performed tests are described and then the results, in terms of P_{inst} and $P_{\text{inst,max}}$, are presented. Firstly, in Section IV-B, the results of the measurements of the incandescent lamp response and then, in Section IV-C, the response of the different lighting technologies.

A. Description of the tests

1) Instantaneous Ramp RVC: different values of RVC amplitude have been analyzed, from $0.5\,\%$ to $7\,\%$ of the nominal RMS voltage.

2) Instantaneous Motor-Start RVC: different values of RVC amplitude have been analyzed, from $2\,\%$ to $6\,\%$ of the nominal RMS voltage, with two different values of total duration of the RVC: $0.5\,\text{s}$ and $1.5\,\text{s}$.

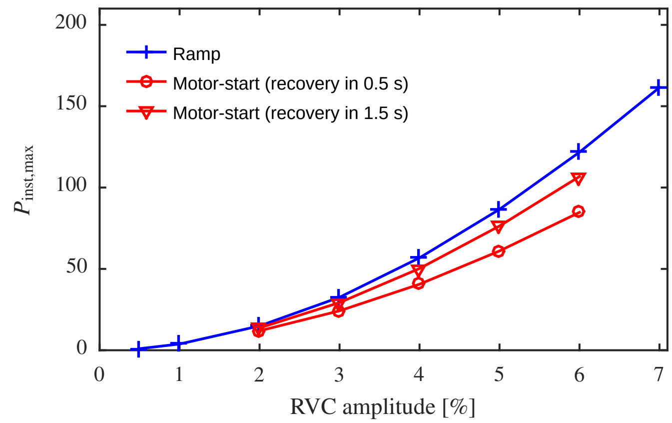
3) Gradual Ramp RVC: different values of rate of change of the RMS voltage have been analyzed: from $10\,\text{V/s}$ to $50\,\text{V/s}$ (which corresponds to $4.3\,\%/\text{s}$ to $21.7\,\%/\text{s}$). Two different RVC amplitudes have been studied: $4\,\%$ and $5\,\%$.

4) Gradual Motor-Start RVC: different values of rate of change of the RMS voltage have been analyzed: from $10\,\text{V/s}$ to $50\,\text{V/s}$ (which corresponds to $4.3\,\%/\text{s}$ to $21.7\,\%/\text{s}$). Two different RVC amplitudes have been studied: $4\,\%$ and $5\,\%$. The total duration of the RVC has been set to $1.5\,\text{s}$.

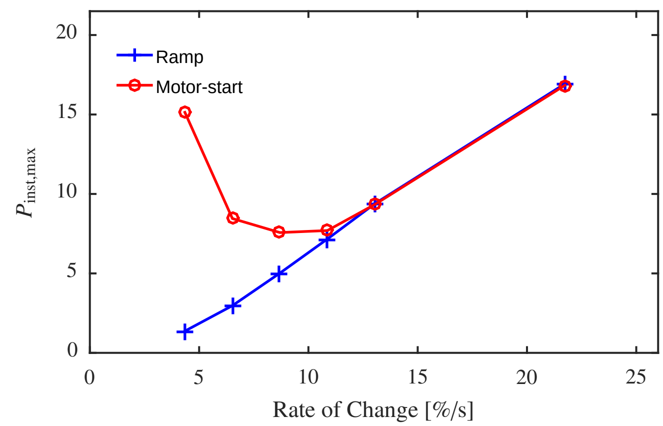
B. Response of the incandescent lamp

In Fig. 5, the maximum values of P_{inst} obtained with the $60\,\text{W}$ incandescent lamp (L01) are presented. In Fig. 5a it can be seen that, for instantaneous RVCs, the results confirm the expected behavior, as described in Section III-B. As the RVC amplitude increases, $P_{\text{inst,max}}$ increases. Moreover, the increments follow a quadratic law. Moreover, in case of motor-start RVCs, the $P_{\text{inst,max}}$ values tend to be lower than for the ramp type, but with the same quadratic relationship. $P_{\text{inst,max}}$ values are even lower when the recovery time is shorter. This is in agreement with the behavior represented in Fig. 3a.

In Fig. 5b, the case of gradual RVCs is shown. It is possible to see that, again, the results confirm the expected behavior for the incandescent lamp. For ramp type RVCs, for the same amplitude, lower rates of change correspond to a lower flicker perception. But the motor-start behavior has an additional characteristic. A high rate of change (fast voltage drop) results in high values of $P_{\text{inst,max}}$, since a quick drop is similar to the ramp type RVC. As the rate of change decreases (slower voltage drop), the flicker is less visible. Finally, the high values of $P_{\text{inst,max}}$ at low rates of change are due to the fast recovery of the RVC. It must be considered, indeed, that in this experiment, the total duration of the RVC is kept constant. This means that



(a) Instantaneous RVC



(b) Gradual RVC

Fig. 5. Instantaneous flicker sensation $P_{\text{inst,max}}$ measured with the incandescent lamp when supplied with instantaneous (a) and gradual (b) RVCs. $P_{\text{inst,max}}$ is plotted against the RVC amplitude in the case of instantaneous RVC (a), and against the rate of change in the case of gradual RVC (b). Both ramp type and motor type RVCs are shown.

when the voltage drop is slow, the recovery is quicker, thus generating high values of $P_{\text{inst,max}}$. The minimum of the red curve in Fig. 5b correspond to a smooth voltage drop and an equally smooth voltage recovery.

C. Response of Different Lighting Technologies

The results of the $P_{\text{inst,max}}$ measured with the CFL and LED lamps are presented in Fig. 6 to 9. Considering the high number of measured lamps, it has been decided to group the results according to the values of $P_{\text{inst,max}}$. In the following graphs, lamps whose $P_{\text{inst,max}}$ is always less than 0.5 units of perceptibility (i.e. well below the perceptibility threshold $P_{\text{inst}} = 1$) are not plotted, although they have been measured. This is done in order to make the graphs as clear as possible for reader. The test have been conduced according to Section IV-A:

Fig. 6 presents the dependence of $P_{\text{inst,max}}$ on the RVC amplitude for the case of instantaneous ramp, while Fig. 7 shows the dependence on amplitude for the case of instantaneous motor-start. Fig. 8, instead, illustrates the dependence on the RMS rate of change in the case of gradual ramp RVCs. In this case the amplitude is kept constant at $5\,\%$, while the rate of

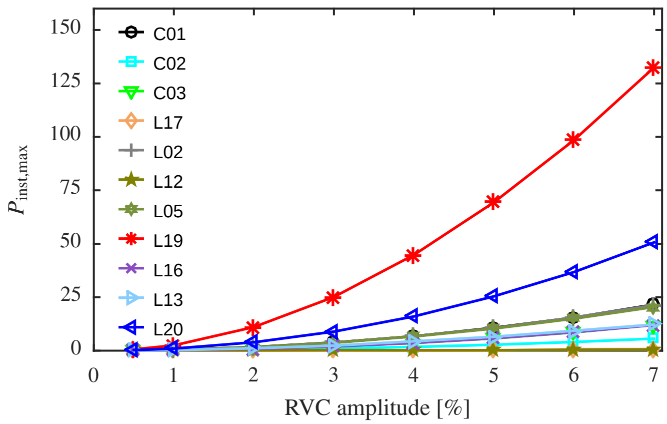


Fig. 6. *Instantaneous ramp RVC*: $P_{\text{inst,max}}$ with varying RVC amplitude, measured with CFL and LED lamps.

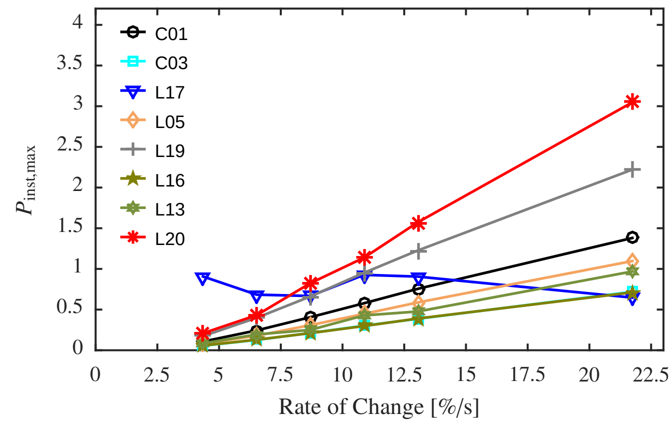


Fig. 8. *Gradual ramp RVC*: $P_{\text{inst,max}}$ with varying RMS rate of change, measured with CFL and LED lamps.

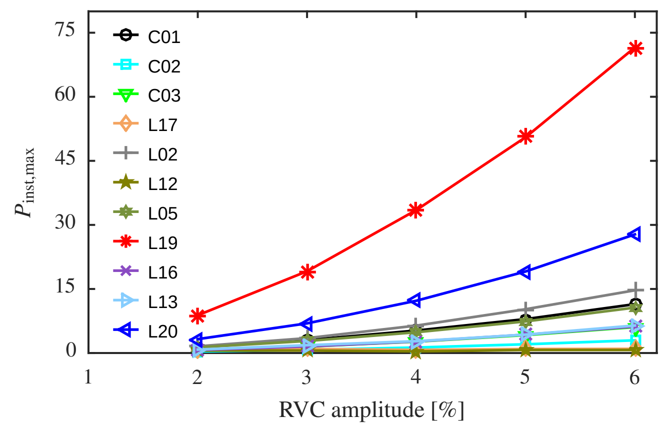


Fig. 7. *Instantaneous motor-start RVC*: $P_{\text{inst,max}}$ with varying RVC amplitude, measured with CFL and LED lamps.

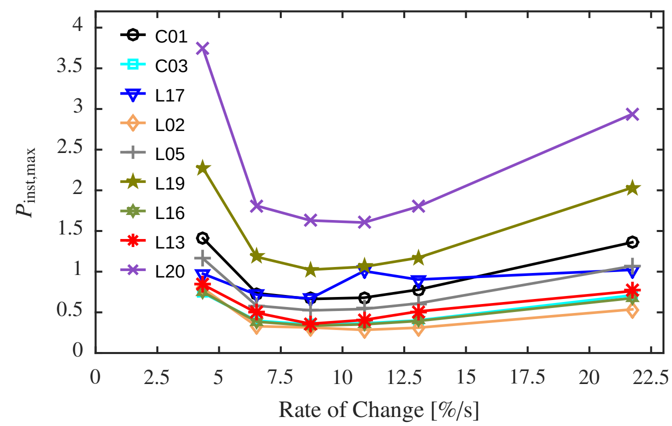


Fig. 9. *Gradual motor-start RVC*: $P_{\text{inst,max}}$ with varying RMS rate of change, measured with CFL and LED lamps.

change varies from $10\,\text{V/s}$ to $50\,\text{V/s}$ ($4.3\,\%/\text{s}$ to $21.7\,\%/\text{s}$). Using the same values of amplitude and rate of change, in Fig. 9 the dependence on the rate of change is shown for the case of gradual motor-start RVCs.

For the case of instantaneous ramp, Fig. 6 shows how the different lighting technologies follow the same behavior as the incandescent, but with lower values. The same happens with the instantaneous motor-start RVCs (Fig. 7), although with smaller $P_{\text{inst,max}}$ values, which once again confirms what discussed for the incandescent lamp in Section III-B.

Fig. 8 and Fig. 9 show the response to gradual RVCs, and in both cases (ramp and motor-start) it can be seen that, once more, the $P_{\text{inst,max}}$ curves are similar to the incandescent ones, with lower values. In general, for the same amplitude, lower rate of change values correspond to a lower flicker perception. As a general observation, it can be seen that there is no dependence of $P_{\text{inst,max}}$ on the power of the lamp. It is possible to observe high power lamps as well as low power lamps showing both high and low $P_{\text{inst,max}}$ values. However, a common trend between lamps from the same manufacturer has been observed, suggesting the production process or the design could be a factor. Moreover, it can be observed that is not easy to find lamps whose behavior gets close to the incandescent lamp and that, in general, CFLs show relatively high $P_{\text{inst,max}}$ values. Another observation that can be made is that the tested lamps show a dispersion in the response to RVCs, which is independent on the technology or the power of the lamp.

The majority of the tested lamps showed very low values of P_{inst}, below the perceptibility threshold in the majority of the experiments. However, we found lamps that showed values above that threshold when subjected to voltage fluctuations of $3\,\%$ of amplitude, or even less, depending on the type. Based on the study done in [14], the tendency of international regulation is to set limits on RVCs with amplitude greater than $5\,\%$. Considering the results of the present study, this threshold could be too permissive, as exist lamps that show perceptible flicker at lower amplitude values. Moreover it has been show that other factors affect the perceptibility, such as type of RVCand rate of change.

D. Response of Dimmable Lamps

In the present section, the response of three dimmable LED lamps at different intensity levels is studied. The different lamps have different way to regulate the light intensity. The first one,

TABLE II
RESPONSE OF DIMMABLE LAMPS AT DIFFERENT INTENSITY LEVELS, COMPARED TO THE INCANDESCENT LAMP.

Amplitude [%]	$P_{\mathrm{inst,max}}$ Incandescent	$P_{\mathrm{inst,max}}$ L09			$P_{\mathrm{inst,max}}$ L12				$P_{\mathrm{inst,max}}$ L17		
		10 %	60 %	100 %	25 %	50 %	75 %	100 %	5 %	60 %	100 %
1	3.835	0.012	0.002	0.003	0.023	0.150	0.084	0.148	6.641	0.131	0.028
3	32.567	0.080	0.004	0.004	0.516	0.161	0.082	0.244	5.884	0.132	0.031
5	86.621	0.168	0.011	0.010	0.608	0.190	0.217	0.202	6.493	0.124	0.038

L09, is a simple lamp, whose intensity is mechanically switched between three possible levels by subsequently turning on and off the lamp. The second one, lamp L12, has its own remote control which allows to control light intensity. In this case, four different intensity levels are available. Lastly, L17, is remotely controlled by a smartphone with which the light intensity can be controlled, as well as other light characteristics. The results are presented for the case of instantaneous ramp RVC only, since the behavior is similar for all the tested cases. As before, different amplitudes are tested: $1\,\%$, $3\,\%$ and $5\,\%$. Results are shown in Table II where it can be seen that dimmable lamps confirm the trend of increasing $P_{\mathrm{inst,max}}$ with increasing RVC amplitude. The response of these dimmable lamps is less than the incandescent lamp and it never exceeds the perceptibility threshold of $P_{\mathrm{inst}} = 1$, except for the case of lamp L17. For this lamp it can be seen that at the minimum intensity level ($5\,\%$ of the full intensity), $P_{\mathrm{inst,max}}$ is always greater than one and, for $1\,\%$ is even greater than the correspondent value for the incandescent lamp. Moreover, the $P_{\mathrm{inst,max}}$ values do not increase with the amplitude of the RVC.

V. CONCLUSION

The sensitivity of modern lighting technologies to RVCs has been studied by an extensive experimental campaign, where RVCs of different kinds have been supplied to a large number of CFLs and LED lamps. Their response, in terms of illuminance, has been measured using a high precision light flickermeter, which allowed to accurately evaluate the instantaneous flicker sensation P_{inst}. A correlation between P_{inst} and RVC amplitude, already expected for the incandescent lamp, has been found also for modern lighting technologies. Moreover, the dependence on the type of RVC and the rate of change have been measured. The majority of the tested lamps showed the same behavior as the incandescent lamp, but with lower values of perceptibility i.e., less visible flicker. However, several lamps exhibited P_{inst} values above the perceptibility threshold, even for RVC amplitudes less than $3\,\%$. This result questions the limits given in IEC 61000-3-7 [15], where only RVCs with amplitude grater than $3\,\%$ are considered. However, work remains to be done in order to evaluate the relationship with the annoyance that such RVCs can cause to customers.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 676042, from the Spanish MINECO through project the DPI2014-53317-R (cofinanced with the European Regional Development Fund) and from the Basque Government (Basque Country, Spain) through the project IT1087-16.

REFERENCES

[1] A. Gil-de Castro, A. Moreno-Munoz, A. Larsson, J. J. G. de la Rosa, and M. H. Bollen, "LED street lighting: A power quality comparison among street light technologies," *Lighting Research and Technology*, vol. 45, no. 6, pp. 710–728, 2013.

[2] R. Cai, J. Cobben, J. Myrzik, J. Blom, and W. Kling, "Flicker responses of different lamp types," *IET Generation, Transmission & Distribution*, vol. 3, no. 9, p. 816, 2009.

[3] CIGRE/CIRED, "Review of flicker objectives for HV, MV and LV systems," *Final Report CIGRE/CIRED WG C4.108*, 2009.

[4] K. Chmielowiec, "Flicker effect of different type of light sources," in *11th International Conference on Electrical Power Quality and Utilisation (EPQU)*, 2011, pp. 3–8.

[5] I. Azcarate, J. J. Gutierrez, P. Saiz, A. Lazkano, L. A. Leturiondo, and K. Redondo, "Flicker characteristics of efficient lighting assessed by the IEC flickermeter," *Electric Power Systems Research*, vol. 107, pp. 21–27, 2014.

[6] J. Drapela, M. Krátký, L. Weidinger, and M. Závodný, "Light Flicker of Fluorescent Lamps with Different Types of Ballasts Caused by Interharmonics," *IEEE Russia Power Tech, PowerTech*, pp. 1–7, 2005.

[7] I. Azcarate, J. J. Gutierrez, A. Lazkano, P. Saiz, K. Redondo, and L. A. Leturiondo, "Towards limiting the sensitivity of energy-efficient lighting to voltage fluctuations," pp. 1384–1395, 2016.

[8] "Equipment for general lighting purposes - EMC immunity requirements - Part 1: An objective light flickermeter and voltage fluctuation immunity test method," *IEC TR 61547-1*, 2017.

[9] "Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications," *IEC 61000-4-15 Ed.2*, 2010.

[10] J. Barros, J. J. Gutierrez, M. De Apraiz, P. Saiz, R. I. Diego, and A. Lazkano, "Rapid Voltage Changes in Power System Networks and Their Effect on Flicker," *IEEE Transactions on Power Delivery*, vol. 31, no. 1, pp. 262–270, 2016.

[11] "Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods," *IEC 61000-4-30 Ed.3*, 2015.

[12] I. Azcarate, J. J. Gutierrez, A. Lazkano, L. A. Leturiondo, P. Saiz, K. Redondo, and J. Barros, "Type Testing of a Highly Accurate Illuminance Flickermeter," *International Conference on Harmonics and Quality of Power, ICHQP*, pp. 897–903, 2012.

[13] D. Gallo, C. Landi, and N. Pasquino, "Design and Calibration of an Objective Flickermeter," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 6, pp. 2118–2125, dec 2006.

[14] K. Brekke, H. Seljeseth, and O. Mogstad, "Rapid Voltage Changes - Definition and Minimum Requirements," *20th International Conference on Electricity Distribution (CIRED)*, 2009.

[15] "Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems," *IEC 61000-3-7*, 2008.