Light Intensity Behavior of LED Lamps within the Thermal Stabilization Period

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***Abstract*— Visible changes in the light intensity of lamps, referred to as flicker, are quantified based on definitions such as normalized gain factor and relative light intensity variation. However, those values also change depending on the time after an LED lamp has been switched on. An experiment has been carried out to analyze this phenomenon. A new metric, a "thermal stabilization time", has been proposed to identify the time to reach steady state light intensity. Although rare, the change in light intensity can reach up to 68% during the thermal stabilization time. Consequently, acquiring data at different intervals can lead to incorrect estimation of critical metrics. Stabilization is an essential factor that should be taken into consideration in LED lamps' measurement. It is recommended by the authors that 60-minute operation is required before acquiring data.**

***Index Terms*—LED lamps, lighting, power quality, thermal stability, voltage fluctuations**

I. Introduction

LED lighting technology offers an efficient way of lighting and has many benefits over incandescent lamps such as long lifetime and low power consumption as well as controllability in terms of light and color temperature. As all light technologies, LED lamps also suffer a risk of light intensity variations due to disturbances in the voltage feeding the lamp [1], [2]. How severe the light intensity variations can be depends on the complex relation between driver circuits, dimmers and supply voltage variations. Furthermore, proper calculation and measurement of flicker metrics is necessary in order to be able to interpret results, correctly [3], [4].

Lighting parameters of LEDs are highly dependent on its thermal characteristic [5]. In a typical datasheet [6], it is indicated how the parameters are affected by the temperature variation. By keeping the temperature constant at an efficient operating point, the performance of the LED lamps can be maintained at the optimal level. Street lamps are a good example of successful thermal management [7].

In [7], an experiment was carried out with an 80 W LED street lamp. It shows that the temperature of the LED lamp is stabilized only after an operation time of several hours. The temperature of the lamp varied from 11˚C to 42˚C during this period. The aforementioned study only considered the thermal characteristic of the LED lamp. It handled neither light output nor electrical quantities. In another study [8], the lamps were subjected to rectangular modulated voltage variations for immunity testing. Although the focus of this study was rather immunity testing, the sufficient stabilization time was indicated between 10 min. and 15 min. depending on the lamp. On the standardization side, the stabilization time is stated as 15 minutes in IEC 62612:2013 [9]. IEEE standard 1789-2015 [1], despite presenting many results of LED lamps' measurement as well as presenting lighting metrics, gives no information regarding the stabilization period. In the same manner, IEC immunity standards 61000-4-13 [10] and 61000-4-15 [11] contain no suggestion for stabilization in lighting equipment. Consequently, the question that shows up is "at which time do LED lamps become stabilized after switching on?" Since a different acquirement period for the measurements could lead to different results because of temperature variation, this is important in terms of compliance testing and benchmarking.

This paper presents the results of an experimental study on residential LED lamps regarding their characteristics during the thermal stabilization. The experimental setup and test method are presented in Section II. Section III shows the results of light intensity and input power variations during stabilization. Metrics defined in related studies [12], [13], such as normalized gain factor and relative light intensity variation have been evaluated at different stabilization intervals in order to analyze the difference between measurements. Results are presented in Section IV.

II. Experimental Setup and Method

A. Experimental Setup

In order to analyze the behavior of the LED lamps within the thermal stabilization, the experimental setup as shown in Fig.1 is used. During the measurements, the lamp is placed in an enclosure to avoid light disturbances. To generate the voltage waveforms, a four channels arbitrary waveform

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generator is utilized as well as an amplifier. Superimposing voltage disturbances on background grid voltage can be adjusted by using Matlab. The created waveform is sent to a signal generator supplying the lamps. For measurement of electrical and lighting waveforms, a Yokogawa DL850 oscilloscope is used with up to 10 MS/s sampling frequency. Hagner S2 photometer is used to measure the light intensity variations as luminance. The distance between the lamp and photometer is kept constant at 0.26 m, enabling conversion among lighting quantities.

Whereas the purpose of the paper is to analyze the variation in the light intensity during thermal stabilization of the LED lamps, 33 Hz sinusoidal voltage fluctuation was chosen for this application as specified in IEC 61000-4-15 [11]. This fluctuation was superimposed on the artificial grid voltage. The magnitude of the fluctuation is designed to create unity instantaneous voltage flicker sensation value (P_{inst}) that means perceptibility threshold in the light intensity variation for a 60 W incandescent lamp.

To evaluate the difference in response at different instances, the normalized gain factor and relative light intensity variation were selected as metrics. Detailed information about these metrics is presented in Section IV.

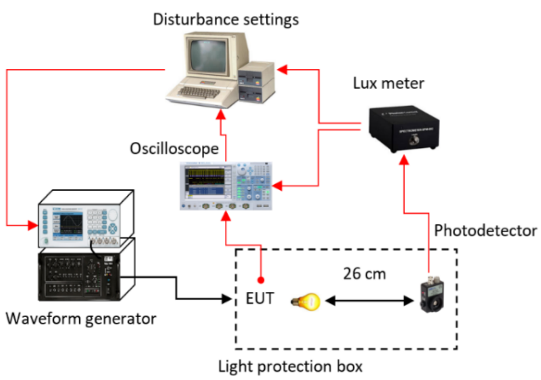

Figure 1. Experimental setup

B. LED Lamps Tested

The list of LED lamps tested is given in Table 1. LED lamps currently available in the Swedish market have been tested within a period of 160 minutes. Eight different brands have been chosen, the power varies from 0.9 W to 22 W. The total quantity of the illuminance emitted by the lamps changes from 50 lm to 1800 lm. The 60 W incandescent lamp is utilized as a reference lamp.

TABLE I. DATA OF TESTED LAMPS, PROVIDED BY THE MANUFACTURER

LED Number	Power (Watts)	Lumen (lm)	LED Number	Power (Watts)	Lumen (lm)
LED 01	7	470	LED 13	3.3	250
LED 02	11	810	LED 14	0.9	50
LED 03	12	806	LED 15	6.5	NA
LED 04	10	1055	LED 16	7	345
LED 05	10	NA	LED 17	4	250
LED 06	3	250	LED 18	4	230
LED 07	6	470	LED 19	22	1800
LED 08	11	810	LED 20	2	180
LED 09	9	806	LED 21	7.5	500
LED 10	4	470	LED 22	7	470
LED 11	11	470	LED 23	8	470
LED 12	2	136	LED 24	3.2	NA

C. Thermal Stabilization Time

In LED lamps, the light intensity decreases with time until a level that can be accepted as steady state after switching on. The concept of thermal stabilization is presented in Fig.2.

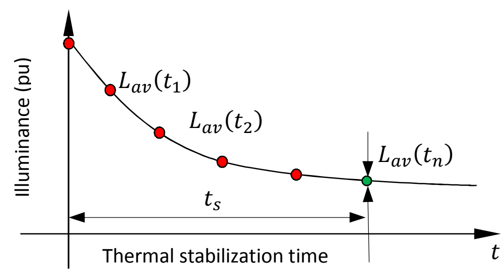

Figure 2. The concept of the thermal stabilization time

where $L_{av}(t_n)$ is the light intensity measured at equal-distant instants t_n and ΔL is the light intensity difference between two consecutive instances:

$$\Delta L(t_n) = {[L_{av}(t_{n-1}) - L_{av}(t_n)]}/{L_{av}(t_{n-1})} \quad (1)$$

The thermal stabilization time t_s is defined as the lowest value to t_n for which the following inequality holds:

$$\Delta L(t_n) \leq c \quad (2)$$

where c is a predefined threshold for the difference in light intensity. In order to make a decision for the thermal stabilization time, the condition of (2) is tested. When the condition is fulfilled, t_n is considered as the thermal stabilization time (t_s). In this study, 15 minutes (Δt) was used. To calculate the thermal stabilization time, c is chosen as 0.5%.

III. MEASUREMENT RESULTS

To analyze the response of the lamps during stabilization, the data is recorded during 160 minute to allow the LED lamps to stabilize, with grid voltage only. In Fig. 3(a) and 3(b) the illuminance (a) and input power (b) of the different lamps are shown during stabilization. The last record at 160th minute is taken as a reference, hence all the variations end up at 1 pu (per unit). The thermal stabilization times calculated based on (1) and (2) are given in Table 2 for each of the LED lamps. At worst case, the average light intensity reaches the steady state value after 75 min for LED 19, but for all other lamps the stabilization time was 60 minutes.

TABLE II. THERMAL STABILIZATION TIME

	LED 03	LED 09	LED 17	LED 19	LED 22
t_s(min)	60	60	60	75	60

As shown in Fig. 3, the tested lamps have different stabilization curves. For instance, LED 17 shows a 16% degradation. The same percentage for LED 03 is 5.6%. The variation in the active power is 3.4% and 7.4% for LED 03 and LED 17, respectively.

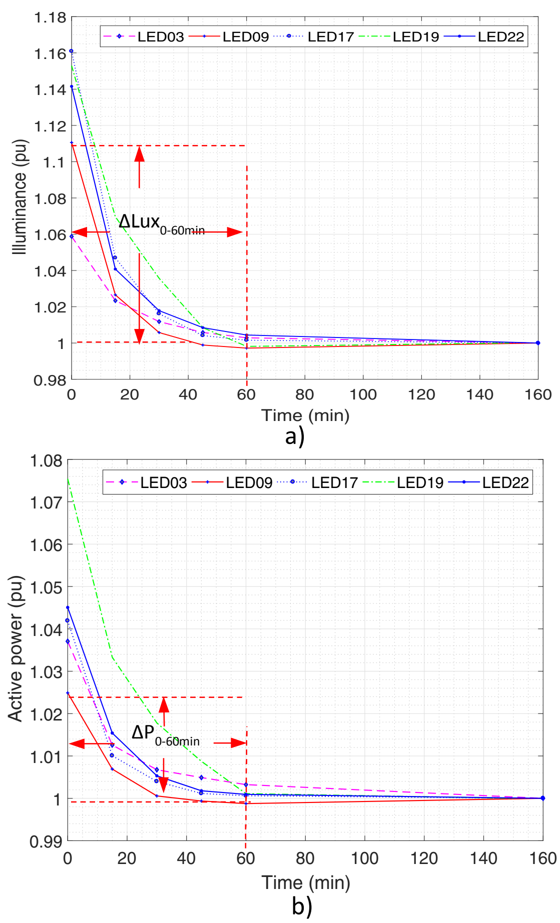

Figure 3. Variations in measured parameters during stabilization; *a)* illuminace, *b)* input active power

To get an overview of all lamps, the difference at 60 minutes is shown in Fig.4 (a) and (b). ΔLux and ΔP represent the difference in the light intensity and input active power between starting point (t=0) and 60 minutes operating time, respectively. The difference in the illuminance varies between 0.2% (LED 06) and 68% (LED 16) for the first 60 minutes period. The input power decrease varies from 0.5% to 2.9% for LED 06 and LED 16, respectively. It is worth noting that the changes in the light intensity and active power always occur as a drop. The drop in the light intensity might not reflect a similar change in the input power. Variation in the average light intensity is usually higher than input power variation as a percentage. The three exceptions (LED 06, LED 15 and LED 23) are for lamps that show very small change in light intensity (2% or less).

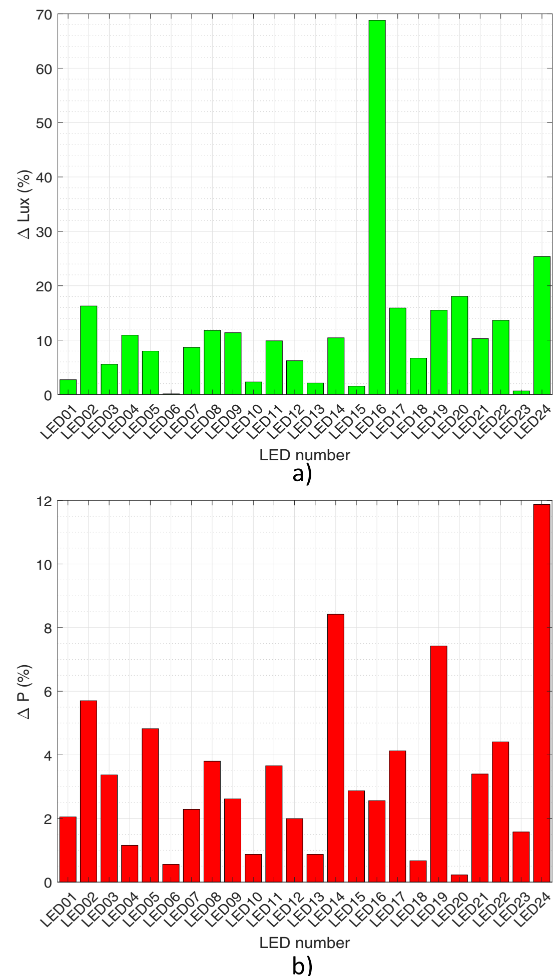

Figure 4. The difference in measured metrics between starting point (t=0) and 60th minute of the experiment *a)* Light intensity difference, *b)* input active power difference

IV. IMPACT OF STABILIZATION ON METRICS

In this section, the effect of the thermal stabilization on the light intensity metrics is investigated by analyzing those variations at different instances up to 60 minutes.

LED manufacturers typically specify the decrease ratio of forward voltage with temperature such as -3mV/˚C [5]. In practice, it means that if the LED is driven at constant current, forward voltage decreases as it warms up. As a result, the average light intensity goes down as well as the input power. The phenomenon is described in, for example, [7]. As a result, the LED lamps are inherently affected by the temperature variation that could lead to change in the response of the LED lamps under test profiles.

To present the response of the LED lamps in terms of normalized gain factor and relative illuminance variation, the sinusoidal voltage fluctuation test profile has been applied on the lamps at 33 Hz [10]. The results are given in Section A and B below:

A. Normalized Gain Factor

The normalized gain factor is defined as the change in the light intensity with respect to applied voltage magnitude for corresponding modulation frequency by considering the 60 W incandescent lamp as a reference [13]. The gain factor is firstly defined as:

$$GF = \frac{L_{fm}(f_m)/L_{av}}{\Delta V(f_m)/V_b} \tag{3}$$

where L_{av} is the average light intensity variation and V_b is the background applied rms voltage without any added test profile. $L_{fm}(f_m)$ is the magnitude of the light intensity at corresponding modulation frequency (f_m), and $\Delta V(f_m)$ is the rms voltage magnitude modulation applied. Voltage fluctuation $\Delta V(f_m)/V_b$ is chosen as 2.128% at 33 Hz. The normalized gain factor is determined based on incandescent lamp's gain factor

$$gf = \frac{\frac{L_{fm}(f_m)/L_{av}}{\left[\Delta V(f_m)/V_b\right]}}{GF_{inc}} \tag{4}$$

In (4), GF_{inc} is the gain factor value for the 60 W incandescent lamp under given test profile. gf defines the sensitivity of the lamps against applied voltage fluctuation compared to the incandescent lamp. If the gf value is higher than one, the LED lamp is more sensitive than the incandescent lamps.

Fig. 5 shows the normalized gain factor calculated during stabilization for 33 Hz voltage fluctuation. As shown in Fig. 5, the response of the lamps is different at different instants. The gf tends to decrease with time. This indicates that the change in temperature has an effect on the gf metric.

The slope of the gf for each 10 minutes interval is calculated and given in Fig. 6. Each point in this figure shows the slope between corresponding 10 min intervals as shown in Fig.6. Hence, interpretation of the variation becomes easier in terms of metrics. For better understanding, an example to calculate the slope is shown in Fig. 6 between 10 minutes and 20 minutes interval. In Fig. 6, LED 08 exhibits -0.0024 $(-)/\text{min}$ variation in the normalized gain factor value between 10 min and 20 min. This equals to 0.024 variation within the given period. If it is assumed that it reaches stabilization at 60th min, this value is equivalent to 4.6% of the stabilized gf. The variation starts to become flat after 40 min operation time. For the same lamp, the slope is 0.0002 $(-)/min$ between 30 min and 40 min. This equals 0.4 % of the stabilized gf. If the error margin is required to be kept below 1%, 40 min is enough for LED 08 to calculate consistent metrics. LED 11 demonstrates the minimum slope that means less variation between intervals.

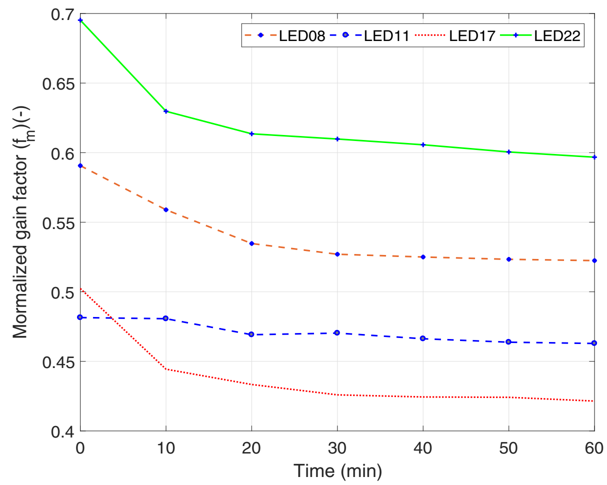

Figure 5. Normalized gain factor at 33 Hz during stabilization

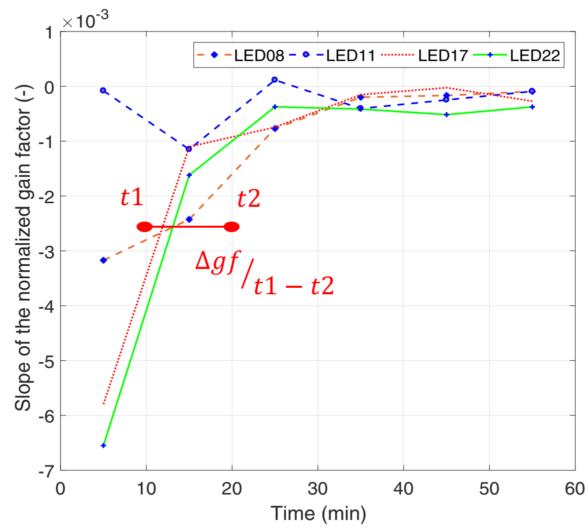

Figure 6. Slope of the normalized gain factor during stabilization

B. Relative Light Intensity Variation

Another index that can be utilized for interpretation of light intensity variation is the relative light intensity variation at corresponding modulation frequency [12]. It can be determined as follows:

$$L_{rv}(f_m) = \frac{L_{fm}(f_m)}{L_{av}} \times 100 \tag{5}$$

In (5), L_{fm} is the magnitude of the light output at the corresponding modulation frequency (f_m), L_{rv} is the relative light intensity variation and L_{av} is the average light intensity of the whole signal. Equation (5) shows the relative variations in the corresponding modulation as a percentage. This helps to quantify the impacts of the modulation on the LED lamps.

A normalization is performed on the relative light intensity variation to obtain per unit values, as shown in (6):

$$L_{rv-pu}(f_m) = \frac{L_{fm}(f_m)}{L_{av}} \Big/ L_{rv-ref}(f_m) \qquad (6)$$

where $L_{rv-ref}(f_m)$ is the stabilized relative light intensity value at 60th min. In Fig. 7, the relative light intensity variation is presented for LED 08, LED 11, LED 17 and LED 22. For instance, in LED 22, the relative light intensity variation is still higher than 2% at 30th min with respect to stabilized light intensity value. At 40th min, it is around 1% for LED 08, LED 11 and LED 17. Depending on the desired tolerance, the measurement or application of test profiles can be executed after stabilization. For example, if the desired tolerance is 1%, 50 min thermal stabilization is necessary to obtain consistent results in light intensity measurements of LED lamps. Since the threshold used in this study is 0.5% variation in metrics, 60 min should be utilized to obtain enough accuracy in the results.

As a result, the relative light intensity keeps changing during stabilization. Indeed, since the LED lamp is under operation during stabilization, recording data within this period is still correct. However, those who performs tests for compliance or benchmarking shall be aware of thermal stabilization as it will impact the metrics. Especially, the response of the LED lamps changes swiftly during the first 30 minutes. Recording data earlier during the test could cause overestimation of the metrics. The results also show that when the operation time is continuing, LEDs start to become less sensitive to the voltage fluctuation in terms of light intensity variation as given in Fig. 5, with the exception of LED 11.

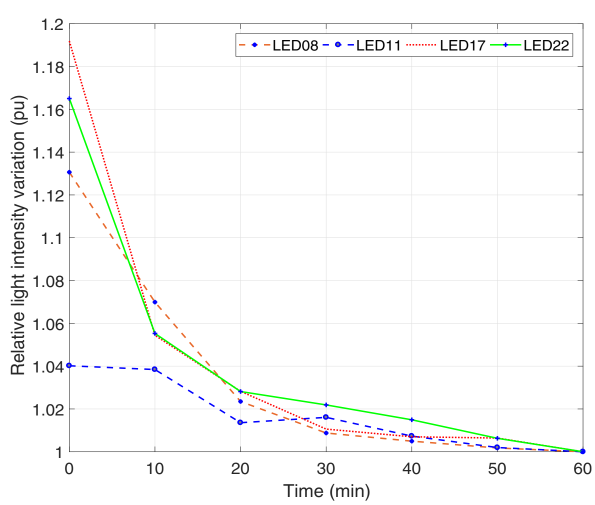

Figure 7. Relative light intensity variation for 33 Hz sinusoidal voltage fluctuation during stabilization

C. *Time Domain Light Intensity Variation and Light Flicker*

In Fig. 8 the time domain variations of the illuminance are presented before and after the thermal stabilization for LED 08 (a) and LED 11 (b). As well as the 100 Hz variation, 17 Hz fluctuation is observed in the light intensity signal due to the applied test profile. In Fig. 8 (a), while the depth of the modulation (ΔD) that is calculated based on the stabilized average light intensity is 4.25% at the beginning, it becomes 3.60% at the end of the thermal stabilization. This indicates that the light flicker could disappear after the thermal stabilization time. This has been validated by the authors through a subjective observation during the experiment. While the light flicker is visible at the beginning of the test, perception is lost after the thermal stabilization time. An objective measurement will be carried out during future experiments.

On the other hand, LED 11 behaves differently in that sense that the depth of modulation increases from 3.70% to 4.34% during stabilization as given in Fig.8 (b). Although the average light intensity goes down, rising in the depth of the modulation implies an increasing risk of the light flicker after stabilization.

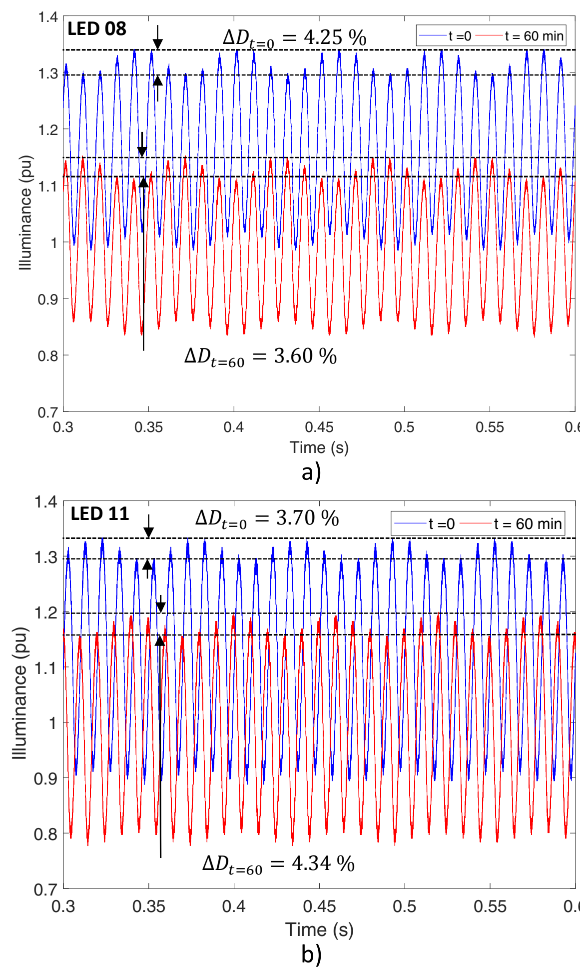

Figure 8. Light intensity variation in the time domain before and after thermal stabilization for a) LED 08 and b) LED 11

V. CONCLUSION

After performed tests on the thermal stabilization of LED lamps, the main findings of the paper are:

- The drop in the average light intensity can reach up to 68 % within 60 minutes. The average light intensity variation (drop) is above 10% for 12 of the 24 lamps included in this study. The input power also tends to decrease during stabilization.

- Together with those variations in light intensity, metrics such as relative light intensity variation and normalized gain factor are also affected. In other words, acquiring data at different times causes inconsistent results in terms of metrics. This situation can lead to incorrect estimation of metrics for compliance or benchmarking. The metrics tend to decrease with time making the LED lamps less sensitive for voltage fluctuation. The first 30 minutes is crucial for metrics' determination because of faster changes. It is recommended that the stabilization is a necessary factor that should be considered in LED lamps' measurement.

- Authors recommend at least 60 minutes measurement with residential LED lamps or identifying the thermal stabilization time individually for each lamp.

- The behavior of an LED lamp in terms of light intensity variations during stabilization is still important. To get comparable results between lamps, for compliance testing and benchmarking, measurements after stabilization are recommended. To get the highest value of light intensity variation i.e. the "worst case", measurements are needed also during stabilization.

- In the future, the test profiles and variety of the LED lamps will be extended to observe the behavior of the lamps under different voltage disturbances.

REFERENCES

[1] *IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*, IEEE Std. 1789-2015, March 2015.

[2] M. O. Mattsson, T. Jung, and A. Proykova, "Health Effects of Artificial Light," Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), Tech. Rep., July 2011.

[3] B. Lehman, A. Wilkins, S. Berman, M. Poplawski, and N. J. Miller, "Proposing measures of flicker in the low frequencies for lighting applications," In *Proc. 2011- IEEE Energy Conversion Congress and Exposition (ECCE) Conf.,* pp. 1-8.

[4] M. Perz, D. Sekulovski, I. Vogels, and I. Heynderickx, "Quantifying the visibility of periodic flicker," *The journal of the Illuminating Engineering Society of North America*, vol. 3, Issue 3, pp. 127-142, Feb 2016.

[5] R. Lenk and C. Lenk, *Practical Lighting Design with LEDs*, 1st ed., New Jersey: Wiley, 2011, p. 62.

[6] Cree, Xlamp, XM-L LEDs. [Online]. Available: http://www.cree.com/led-components/media/documents/XLampXML-11E.pdf

[7] X. Luo, T. Cheng, W. Xiong, Z. Gan, and S. Liu, "Thermal analysis of an 80 W light-emitting diode street lamp," *IET Optoelectronics*, vol. 1, issue. 5, pp. 191- 196, Oct. 2007.

[8] J.J. Gutierrez, P. Beeckman, and I. Azcarate, "A protocol to test the sensitivity of lighting equipment to voltage fluctuations," In *Proc. 2015-23rd International Conference on Electricity Distribution,* pp. 1-5.

[9] *IEC 62612: Self-ballasted LED- lamps for general lighting services-performance requirements,* IEC Std. 62612:2015, Oct. 2015.

[10] *EMC- Part 4-13: Testing and Measurement techniques- Harmonics and Interharmoncis Including Mains Signaling at a.c Power Port, Low Frequency Immunity Tests*, IEC Std. 61000-4-13, July 2009.

[11] *EMC- Part 4-15: Testing and Measurement techniques- Flickermeter-Functional and design specifications*, IEC Std. 61000-4-15, August 2010.

[12] R. Cai, J. F. G. Cobben, J. M. A. Myrzik, J. H. Blom, and W. L. Kling, "Flicker responses of different lamp types," *IET Generation, Transmission and Distribution*, vol. 3, issue 9, pp. 816- 824, Sep. 2009.

[13] A. Gil-de-Casrtro, S. K. Rönnberg, and M. H. J. Bollen, "Light intensity variation (flicker) and harmonics emission related to LED lamps," *Electric Power System Research*, vol.146, pp. 107- 114, May 2017.

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