# Assessment of Light Fluctuations of LED Lamp at Different Pulse Mode Regulation Methods

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***Abstract*—Solid state lighting at this moment looks the most promising among other lighting technologies. One of the advantages of LEDs is the ability to change light output of LED in wide range. Different light regulation techniques have been discussed previously in the literature: fluent (amplitude mode), step and pulse mode regulation techniques. Pulse mode regulation method is one of the simplest, however, the significant drawback such as stroboscopic effect, has been mentioned previously in the literature. The aim of this paper is to evaluate light fluctuations (and undesired stroboscopic effects) of LED lamps operating under different pulse mode light regulation approaches as well as to found the conditions to accomplish acceptable level of this effect. The evaluation criteria of light fluctuations are discussed at the beginning of this article. Then the different pulse mode regulation approaches are described. The results of experiments and the conclusions are discussed at the end of the paper.**

***Index Terms*—Design for quality, fluctuations, LED lamps, measurement standards.**

## I. INTRODUCTION

Recently, much attention is paid to the comfort and quality of life of people. Variety of items, devices and systems surround a person and affect the health, mood, mental and physical condition of the person in a greater or a lesser extent. Physiological characteristics of man must be taken into account during design process of these devices and systems in order to improve surrounding conditions of the person.

Artificial lighting is one of such important systems which may affect human health and performance [1]. Therefore variety of parameters discussed in lighting standards [2]–[4] plays significant role: illuminance, light spatial distribution, light colour temperature, colour rendering index (CRI) etc. Light fluctuations also are discussed in these standards but the performance of incandescent lamps or fluorescent lamps at low frequencies usually is considered.

For incandescent lamps light fluctuations at higher frequencies are limited by inertia of thermal processes in filament. Fluorescent lamps are less inertial therefore light fluctuations at the frequency of power grid (50 Hz or 60 Hz) are more visible than in the case of incandescent lamp (fluorescent lamps with electromagnetic ballast). Flickering effect for fluorescent lamps can be reduced by using of electronic ballasts [5].

With the development of new lighting technologies (solid state lighting) the problem of light fluctuations becomes relevant again. The luminous flux of LED follows the forward current (voltage) at very high speed [6] making possible undesired stroboscopic effects under certain conditions (considered in the following sections).

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## II. FLICKERING AND STROBOSCOPIC EFFECT

### *A. Flickering*

Flickering is the light fluctuations that can lead to unsteadiness of human vision. Visual perception of flicker can be characterized in two ways: a) direct perception of flickering at frequencies < 80 Hz; b) indirect perception of stroboscopic effect [7]. According to the latest studies direct perception of flickering can lead to a different kind of hallucinations depending on frequency of flickering [8]. The International Electrotechnical Commission (IEC) has defined the standard instrument for the measurements of light flicker (IEC flickermeter). Functional block diagram of this instrument is shown in Fig. 1 [9]. Detailed description of the blocks shown in Fig. 1 is described in [10].

The flickermeter provides the insight about the impact of flickering on the human brain. The output of this device is the Instaneous Flicker Sensation (IFS) expressed in perceptibility units. The instrument makes assessment of flickering in indirect way by measuring voltage fluctuations and then predicting the light flux pulsations of the standard 60 W/230 V incandescent lamp (block 2) and human eye-brain chain (blocks 3–5) which is not suitable for new lighting technologies. Therefore in [11] the new approach is described by measuring luminous flux fluctuations in direct way from light sensor (photodiode) which is suitable for all kinds of lamps.

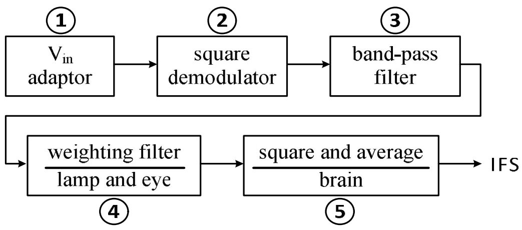



Fig. 1. Block diagram of IEC flickermeter.

### B. Stroboscopic Effect

Objects may appear to move discretely rather than continuously under flickering illumination; this is known as the stroboscopic effect (can be perceived by human eye indirectly). The magnitude of the effect depends on the rate and amplitude of the flicker, the rate of object motion, and the viewing conditions [7].

To quantify the stroboscopic effect first of all it is necessary to define photometric flicker quantities. According to [12] lighting experts have proposed and used two metrics for this purpose. First and the best known is percent flicker $P$. It describes peak-to-peak contrast and can be expressed by equation

$$P = \frac{A - B}{A + B} \cdot 100\%, \tag{1}$$

where $A$ is the maximum value of periodical waveform of light output (can be in relative units) of the lamp, but $B$ is the maximal value of this waveform as shown in Fig. 2 [12].

The second is flicker index $I$ which is more reliable than percent flicker when comparing periodic waveforms with different shapes or duty cycles. The expression of flicker index is

$$I = \frac{Area1}{Area1 + Area2} \cdot 100\%, \tag{2}$$

where *Area1* is the area enclosed by the average value line and the waveform above this average value, but the *Area2* is the area enclosed by the average value line and the waveform below this average value as shown in Fig. 2 [12].

The detection of stroboscopic effect (percent likelihood of detection $d$, in percent) for rectangular waveforms operated so that the maximum light output is produced 50 % of the time and the minimum light output is produced 50 % of the time (50 % duty cycle), has been described in [7] by the equation

$$d = \frac{25P + 140}{f + 25P + 140} \cdot 100\%, \tag{3}$$

where $f$ is the frequency of analysed waveform and $P$ is the percent flicker of this form. In the scope of this paper the waveforms with duty cycles different from 50 % are analysed, so the approach described in [7] and (3) are not suitable for assessment of flickering in whole regulation range. Therefore the flicker index $I$ is more preferable for our purpose.

For the data sequence taken from the light sensor by measurement instrument, for example, by oscilloscope, the expression of the flicker index $I$ can be written as

$$I = \left( \sum_{n=0}^{N-1} \left| AVG - R_n \right| \right) \Bigg/ \left( 2 \cdot \sum_{n=0}^{N-1} R_n \right), \tag{4}$$

where $R_n$ is the sequence of samples from light sensor during period $T$, $N$ is the number of samples in one period, but $AVG$ is average value of the waveform, which can be found from

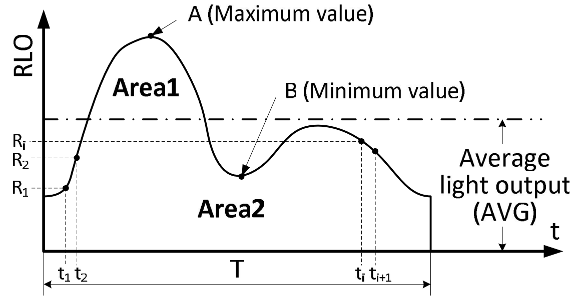



Fig. 2. Example of relative light output (RLO) variation from a lamp during one period and the explanation of method for calculation of percent flicker and flicker index.

$$AVG = \frac{1}{N} \sum_{n=0}^{N-1} R_n. \tag{5}$$

It should be noted that (4) and (5) are true if time interval between measured points of data sequence is constant ($\Delta t = t_n - t_{n+1} = const$).

## III. Light Fluctuations at Different Pulse Mode Regulation Approaches

Different kind of amplitude mode light regulation techniques have been considered previously in [13]–[15], however the stroboscopic effect usually is insignificant for these regulation approaches.

Pulse mode light regulation technique is the most interesting from the point of view of stroboscopic effect. In the simplest case the light output of led lamp is varying at relatively high frequency between no light output and maximal light output. The average light output is regulated by duty cycle $D$ (Fig. 3(a)) and can be found from

$$AVG = R_{\max} \cdot D \cdot 100\% = D \cdot 100\%, \tag{6}$$

but the flicker index according to (2) and Fig. 3 a can be expressed as

$$I = (1 - D) \cdot 100\%. \tag{7}$$

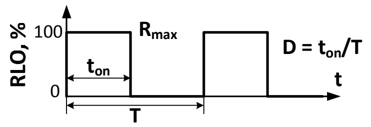
In [16], [17] the bi-level pulse mode light regulation of LED lamp has been described. Two power sources are used providing two light output levels $R_{max}$ and $R_{min}$ (Fig. 3(b)). This method allows to increase efficacy of dimming process as well as to reduce stroboscopic effect. For bi-level regulation average light output can be found from

$$AVG = D \cdot R_{\max} + R_{\min}(1 - D), \tag{8}$$

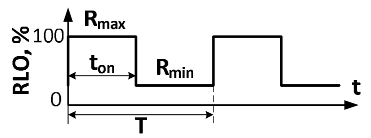
but the flicker index according to (2) and Fig. 3 b can be written as

$$I = \frac{(R_{\max} - R_{\min}) \cdot (1 - D)}{R_{\max} + R_{\min} \cdot \left( \frac{1}{D} - 1 \right)}. \tag{9}$$

The stroboscopic effect also can be reduced by using of several LED matrices with interleaved control signals [18] as shown in Fig. 3(c).




a)

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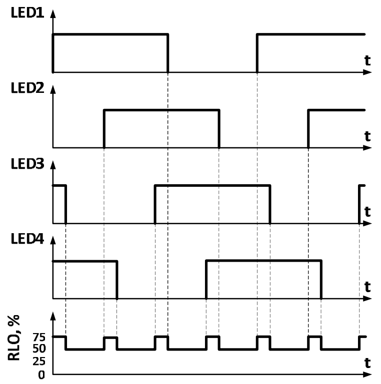



c)

Fig. 3. Different kind of LED lamp pulse mode light regulation methods: a) standard PWM; b) bi-level regulation; c) interleaved regulation.

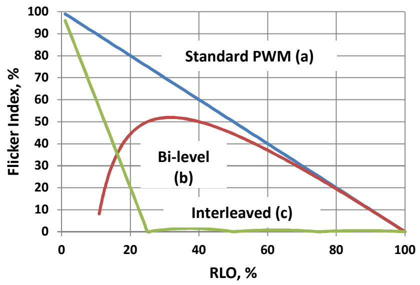
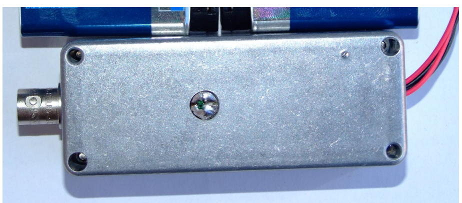



Fig. 4. Dependence of flicker index from relative light output at different pulse mode light regulation techniques: a) standard PWM; b) Bi-level ($R_{min}$ = 10 %); c) interleaved (4 levels).

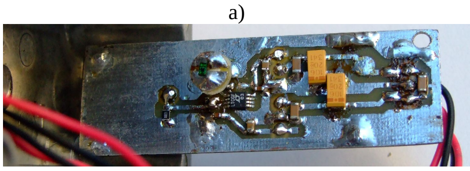
The relative light output for interleaved regulation method can be found from (6), but the flicker index from (9). Dependence of the flicker index from the relative light output at different pulse mode regulation techniques is shown in Fig. 4.

## IV. Assessment of Light Fluctuations

### A. Photodetector



a)



b)

Fig. 5. Picture of the photodetector: a) assembled; b) printed circuit board.

The most of amplified pfotodetectors available on the market has an integrated filter to reduce influence of light fluctuations at frequency of power grid. In the same time LED lamps are least inertial and are capable to create light fluctuations at high frequencies, therefore it was decided to build photodetector with the ability to determine light fluctuations at higher frequencies.

The main elements of photodetector are photodiode TEMD6200FX01 (with small diode capacitance for improved performance) and low noise 50MHz operational amplifier LTC6244HV. The principal circuit of photodetector is given in Fig. 8. Printed circuit board was placed in metal box to minimize influence of ambient noise (Fig. 5).

### B. Experiments and Results

The experimental setup consists of LED lamp under study, photodetector, digital oscilloscope with the capability of data acquisition and box with dark walls where to place lamp and sensor (to minimize interference of ambient light).

The measurements for different pulse mode light regulation techniques have been taken at different RLO values in whole regulation range with 5% step. The operation frequency for all techniques during all experiments was the same – 20 kHz. The example of data taken from pfotodetector in case of 4-level interleaved regulation approach at ≈55 % RLO is shown in Fig. 6.

The data of experiments have been analysed using (5) and (7) and the results are summarized in Fig. 7.

The experimental results are in good agreement with analytical part confirming the correctness of calculations.

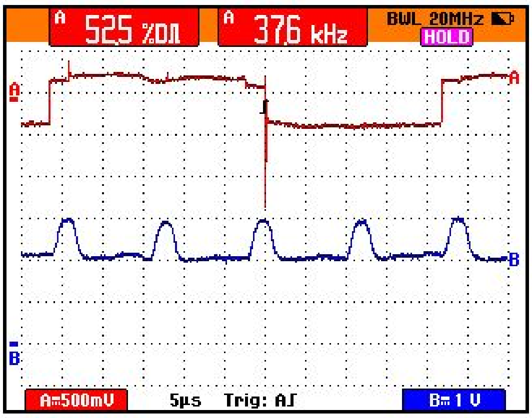



Fig. 6. Data from the light sensor (Channel B) at ≈55 % of RLO.

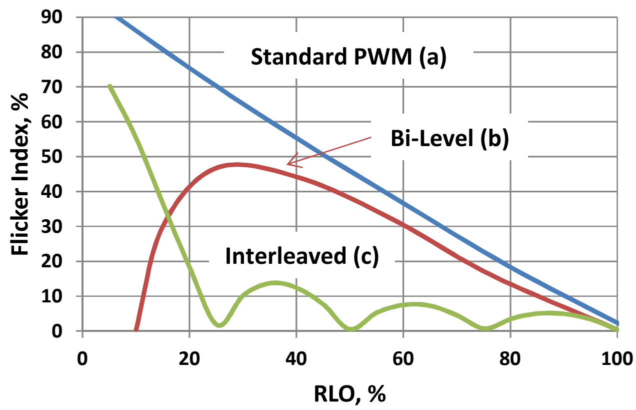



Fig. 7. The results of flicker index measurements at different pulse mode light regulation techniques.

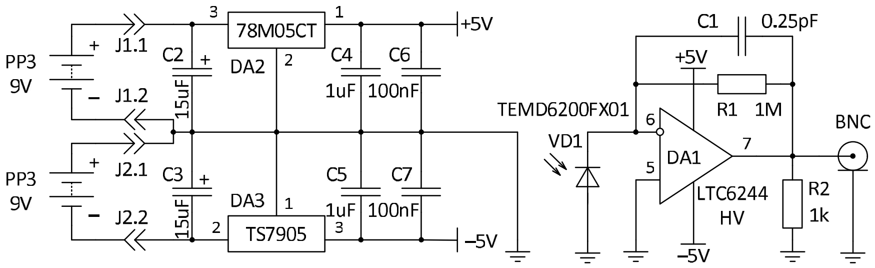



Fig. 8. The principal circuit of photodetector used for the experiments.

The relationship between the percent flicker (flicker index), flicker frequency and the acceptability of stroboscopic effect is given in [7]. According to this relationship and Fig. 7 the acceptable level of stroboscopic effect for standard PWM and bi-level approach can be achieved at operation frequencies higher than 1.5 kHz almost regardless of the flicker index therefore also RLO level, at frequencies above 750 Hz for 2-level approach, and at frequencies above 400 Hz for 4-level approach.

The similar relationship for percent likelihood of detection of stroboscopic effect is also given in [7]. If we consider 5 % ... 100 % RLO range, then the operation frequency must be above 10 kHz for standard PWM approach to achieve less than 20 % of likelihood of flicker detection in whole regulation range, above 5 kHz for bi-level approach, and above 2 kHz for 4-level interleaved approach.

## V. CONCLUSIONS

The assessment of light fluctuations at different pulse mode light regulation approaches has been considered in the scope of this article. Analytical expressions as well as expressions for the analysis of registered by pfotodetector data are given in the paper. Three pulse mode light regulation methods have been tested using described approach: standard PWM, bi-level, and 4-level interleaved approach. Using studies from [7] and results from Fig. 7 it was found conditions to accomplish acceptable level of stroboscopic effect in whole regulation range: operation frequency above 1.5 kHz for standard PWM and bi-level approach; above 400 kHz for 4-level interleaved approach (for general purpose lighting).

To minimize the likelihood of flicker detection (less than 20 %) the operation frequency must be even higher: 10 kHz for standard PWM; 5 kHz for bi-level approach; 2 kHz for 4-level interleaved approach. Also it is worth to mention that in case of standard PWM there is only one point in whole RLO range with 0 % of the likelihood of flicker detection, 2 such points in case of bi-level approach, and 4 such points in case of 4-level interleaved approach (Fig. 7), which may be useful in applications with very stringent light quality requirements.

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