

A Light-flickermeter – Part I: Design

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ABSTRACT

Voltage variation is one of lamps flickering main cause; thus evaluation of a disturbing light flicker is a part of voltage quality classification. The instrument for flicker level measurement by means of voltage variation analysis is named flickermeter and is specified in standard EN 61000-4-15. The flickermeter is a specialized analyzer modeling response of a chain consisting of reference 60W incandescent lamp – eye – brain of an average observer. Hence, other lamp types like discharge are mainly used in illumination systems at present, significant difference between flicker measurement using the standard flickermeter and observation can appear. In the paper, there is proposed a light flicker measurement method based on analysis of an irradiance (radiant flux) waveform, where the output flicker index is independent on the lamp type. With regard to expected properties the proposed light-flickermeter can be called objective flickermeter. Nevertheless the range of application of the objective flickermeter is limited as it is also shown.

Keywords: Voltage fluctuation, Interharmonics, Light flicker, Light-flickermeter, Matlab Simulink

1 INTRODUCTION

As it is known, the visible light variation may leads to disturbance of human's visual perception. The origin of such negative effect is in the eye anatomy and physiology [7]. The major influence on the flickering light perception can be found in eye viewing field, photoreceptors (cones of three types and rods) and their distribution at retina as a part of eye anatomy and in eye adaptation mechanisms like pupil, photochemical and neural adaptation (response) to luminous variations (including the photoreceptors spectral luminous efficiency [15]) as a part of eye physiology [7]. The human eye can be seen as specialized luminance multi-detector. Nevertheless the stimulation contrast is as important as radiant density. Thus visual perception as well as flicker perception can be specified on the basis of following parameters of visual stimuli: object and background luminance and luminance nonuniformity, contrast, object and background light spectrum, object size, object location compared with main axis of view, and mainly in point of view of flicker perception: time changes in luminance and color of stimuli, and movement or spatial changes of stimuli in viewing field, etc. [7] [15]. On the basis of the described perceived luminous variations, there are differentiated three types of flicker: temporal, spatial

and chromatic [7][8]. All of these flickers are joyless and may involve many psychological interactions.

In artificially illuminated areas, lamps light variations due to variations in supply voltage may also lead to flicker perception. Such lamp possibly will produce light with time-varying radiant flux and its spectral distribution. As the principal cause of lamps light flicker, there is viewed, for historical reasons, a voltage amplitude modulation (AM) by a periodical and/or stochastic signal due to varying loads. Nevertheless the lamps flickering is produced also by a phase voltage modulation, mainly by phase jumps [12] and by the interharmonic voltages superimposed on a voltage waveform [11][3]. A lamp ability to transfer such changes in supply voltage on generated luminous time-spectrum changes is given by its transfer function which depends on the lamp function principle and type as well as on the wiring, circuit designing and dimensioning [2].

From the point of view of the perception of a lamp light variation by a human eye, changes within the range of (0.1 ÷ 35 (40)) Hz are significant. And the visual perception is disturbed in a case when the magnitude of variation exceeds a corresponding threshold value within this frequency range. It stands to reason that the disturbing level of initiating voltage variations depends on the lamp type, observer, and on given observation conditions. Since the flicker is matter of voltage variation, the flicker severity is currently evaluated by means of voltage measurement using a specialized voltage analyzer called flickermeter. The flickermeter is based on modeling of the reference 60W incandescent bulb – human eye – brain of average observer chain response obtained under specific observation conditions. The EN standard for flicker measurement is published in [5] and provides design specifications for an analogue flickermeter, including validation methods. Taking into account the standard flickermeter design specification, the flicker severity measurement results and observation can differ significantly in a case of different lamp for illumination will be used and/or observation conditions will not be the same as reference and/or the observer response will be different from the eye–brain response of the average observer.

A possible solution in the first step is to exclude the light source form the flicker severity evaluation process and to measure the flicker severity directly by means of light measurement and eye-brain of the average observer response simulation [6][14], thus a light-flickermeter is going to be realized. In the paper, the light-flickermeter topology is designed including proposal of light measurement technique

and corresponding signal processing on the basis of the standard UIE/IEC flickermeter, in the light of current and future technologies towards the light flicker objective measurement. Moreover a model of a simplified light-flickermeter for certain applications in Matlab Simulink is realized and preliminary verification results in terms of numerical simulations are shown.

2 LIGHT-FLICKERMETER

The light-flickermeter is designed to have two main parts which are light measurement and consequent luminous variation signal processing. Assuming that the human eye is a luminance detector the spectral radiance time behaviour has to be measured then the spectral luminous efficiency of elementary photoreceptor can be modeled. Since the eye perception system is composed of really large number of photoreceptors of fourth types (long, middle and short cone and rod) [7] each of them or sufficient number of them has to be represented by correspondent spectral radiance detector including the detectors surface distribution as it is across the retina and including an optical system mediating visual stimuli from all viewing field to corresponding segment of the detectors. Unfortunately realization of such multi-detector modeling in fact particular anatomy of the human eye is a technological problem at present. Technically realizable there is a detector containing four elementary detectors each representing one of the basic photoreceptors, but typically a single detector is available. Furthermore the detectors output signals processing modeling all the described adaptation mechanisms, the eye physiology in fact, taking into account also neural interconnections in visual system [15] is necessary to perform. Any deviation from introduce measurement system makes the light flicker measurement non-objective.

In a case the objective light flicker measurement is not required, the light flickermeter is suppose to be used for comparative measurements only then a significant simplification in measuring process can be made. Considering that the light flicker measurement result is subject to the same observation condition whereat the reference eye-brain response of average observer was obtained, a single spectral radiance or irradiance detector and signal processing based on the standard flickermeter can be used. Another simplification consists in presumption that the spectral luminous efficiency of the average observer is invariable and is equal to the spectral luminous efficiency of the normalized observer for photopic vision. Then luminance or illuminance detector with built-in special light filter can be introduced instead of spectral measurements. In the same time it means that the eye adaptive mechanisms are supposed to be dependent on only on the light intensity, not at the light spectral distribution. Because comparative measurement also implies that just relative variations in light are significant for light flicker measurement, the luminance or illuminance can be substituted by luminous flux in connection with lamps flickering. Resulting simplified block diagram of the light-flickermeter flowing from the standard flickermeter block diagram [5] is at Fig. 1.

The light-flickermeter architecture can be divided into three parts:

- light measurement provided by block 1,
- eye-brain response modeling implemented in blocks 2, 3 and 4,

- statistical analysis of the instantaneous flicker readings in real time realized by block 5.

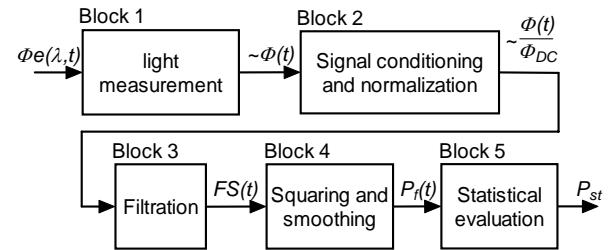


Fig. 1. A simplified block diagram of the light-flickermeter

Block 1 – performs luminance or illuminance measurement using a detector with appropriate characteristics.

Block 2 – carries out signal normalization without modifying the resulting relative fluctuation. The output signal from block 1 is normalized by its smoothed DC value.

Block 3 – also consists of a cascade of three filters as well as in case of the standard flickermeter [5]. The first it is the high pass filter for DC component elimination. The 6th order Butterworth low pass filter removing frequency components at frequencies over 35 Hz is the second. As the last one, there is the weighting filter modeling the eye-brain response of average observer.

Blocks 4 and 5 – are identical to the standard UIE/IEC flickermeter.

2.1 Luminous measurement

For a case of light detection, utilization of a silicon photodiode (solid-state detector) having appropriate spectral responsivity, low noise, good stability and detectability is the best solution suitable for extremely accurate measurements. In consonance with previous, the basic detector has to be equipped by additional light filter ensuring that the detector overall spectral responsivity will be the same as it is shown on the Fig. 2. Then the sensor becomes to be an illuminance detector.

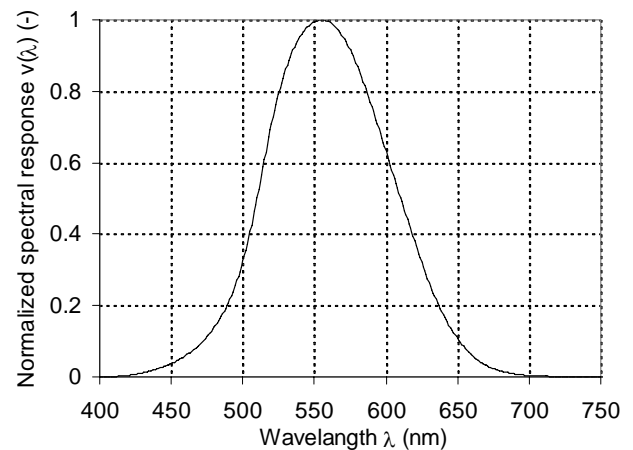


Fig. 2. Normalized spectral luminous efficiency for photopic vision

Another option is to use a spectroradiometer where the output light spectrum will be weighted by spectral luminous efficiency for photopic vision Fig. 2. However usage of a

spectroradiometer for such instance (to measure illuminance) is inefficient. The spectroradiometer utilization is substantiated in the case when the output spectrum will be decomposed to get the spectrum parts perceived by each type of the eye photoreceptors, thus it is possible way to evaluate also influence of variations in light spectrum on the flicker perception [15]. Nevertheless adaptation mechanisms for this decomposed scheme are not sufficiently described at this time.

When a silicon photodiode is subject to light, a photocurrent I_P is generated. The photodiode signal can be measured as a voltage or a current. Current measurement demonstrates far better linearity, offset, and bandwidth performance. The photodiode is considered linear, as it is needed, if the generated photocurrent increases linearly with the incident light power. Then the photocurrent at a given light wavelength is [9]:

$$I_{P\lambda}(\lambda) = \Phi_{e\lambda}(\lambda) \cdot \rho_{\lambda}(\lambda) \quad (1)$$

where $\Phi_{e\lambda}(\lambda)$ is the incident spectral radiant flux on equivalent active surface of the detector S_D and $\rho_{\lambda}(\lambda)$ is the detector spectral responsivity. If the detector is equipped by photopic correction for illuminance measurement, the spectral responsivity is in shape of $V(\lambda)$ curve, thus the generated photocurrent is proportional to detector illumination (if the size of S_D is suitable) and is as:

$$I_P = \int_{\lambda} I_{P\lambda}(\lambda) d\lambda \quad (2)$$

The linearity is in principle ensured if the photodiode load impedance is becoming to zero. Utilization of a linear measuring operational amplifier in transimpedance configuration seems to be the best measurement option from many reasons. A scheme of a solid-state photo-detector with an operational amplifier with single stage amplification which is reasonable for intended application is at Fig. 3.

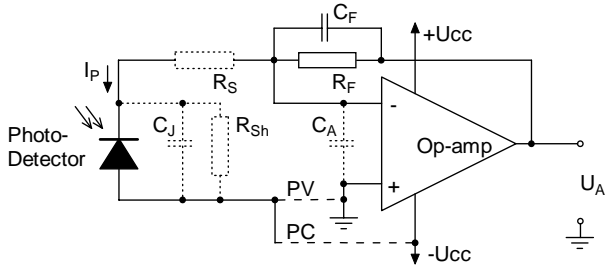


Fig. 3. Scheme of a solid-state photo-detector with an operational amplifier

The scheme at Fig. 3 makes it possible to operate the photodiode in Photo-Voltaic (PV) or Photo-Conductive (PC) mode. The PC mode is set when a reverse bias is applied and it can significantly improve chosen sensing parameters like the speed of response and linearity. The circuitry also includes (parasitic) elements of equivalent diagram which are essential for the Photodiode-Amplifier (PA) combination performance formulation [13]. The shunt resistance R_{sh} is used to determine the noise current in the photodiode with no bias (photovoltaic mode). For best photodiode performance the highest shunt resistance is desired. The series resistance R_s of a photodiode arises from the resistance of the contacts and the resistance of the undepleted silicon. Series resistance is used to determine the linearity of the photodiode in PV

mode. Although an ideal photodiode should have no series resistance. Connection parameters between the diode and amplifier can also contribute by series resistance and inductance causing impairment of linearity and introducing possible signal oscillations. For that reason the connection should be as close as possible to prevent. The boundaries of the depletion region act as the plates of a parallel plate capacitor. The junction capacitance C_j is directly proportional to the diffused area size S_D and inversely proportional to the width of the depletion region. In addition, higher resistivity substrates have lower junction capacitance. The larger detection area S_D photodiode has the higher sensitivity and capacitance C_j are. Furthermore, the capacitance is inversely dependent on the reverse bias voltage magnitude. The junction capacitance is used to determine the response of the photodiode.

The resistance R_F in the amplifier feedback determines directly the amplifier gain and indirectly amplifier bandwidth. Then the amplifier output voltage U_A is as:

$$U_A = I_P \cdot R_F \quad (3)$$

Value of R_F has also effect on the amplifier thermal noise current whereas higher resistance is desired. The frequency response of the photodiode-amplifier combination is determined by the characteristics of the photo-detector, pre-amplifier as well as the feedback resistor R_F and feedback capacitor C_F which limits the frequency response to avoid gain peaking and to prevent instability. Cut-off frequency of the detector-amplifier combination frequency response set by the amplifier feedback is given by eq.:

$$f_A = \frac{1}{2\pi \cdot R_F \cdot C_F} \quad (4)$$

However, the desired frequency response is limited by the Gain Bandwidth Product (GBP) of the op-amp and by spurious components of the equivalent circuitry at Fig. 3. In order to have a stable output, the values of the amplifier feedback have to be chosen such that the f_A frequency is less than:

$$f_A \leq \sqrt{\frac{GBP}{2\pi \cdot R_F \cdot (C_F + C_A + C_J)}} \quad (5)$$

where C_A is amplifier input spurious capacitance.

In term of the comparative flicker measurement, there is necessary to choose a Filter-Photodiode-Amplifier Combination (FPAC) having characteristics allowing accurate measurements of light flickering up to 100Hz and/or of changes in light with fall/rise time about 200 μ s, in illuminance range from 1 lx to 100 klx with that the maximal output voltage U_A of 10 V seems to be optimal regarding the amplifier power supply level and output signal processing.

2.2 Signal processing

A block diagram of proposed signal processing of the FPAC output signal, which is proportional to incident luminous flux, in blocks 2-5 of Fig. 1 is at Fig. 4.

An input analog signal of optimal magnitude is normalized dividing the signal by its DC component in first two blocks, since the normalization is also provided by the standard flickermeter [5]. The DC component is obtained using the 1st order low pass filter transfer function with analogue frequency response as follows:

$$F_{LPSC}(s) = \frac{1}{\tau_{LPSC} \cdot s + 1} \quad (6)$$

where s is a complex Laplace variable and τ_{LPSC} is the filter time constant pre-set to 10 s. Corresponding filter cut-off frequency is 0.016 Hz. In [5] is defined with a view to prevent from affecting of very slow or isolated changes that the rise/fall time of the normalization process response on step change in input signal has to be equal to 1 minute. But it was proved that such rise time can be shortened to 30 s without any influence on result. The time constant of 10 s was chosen with respect to reduction of the filter transition time after start.

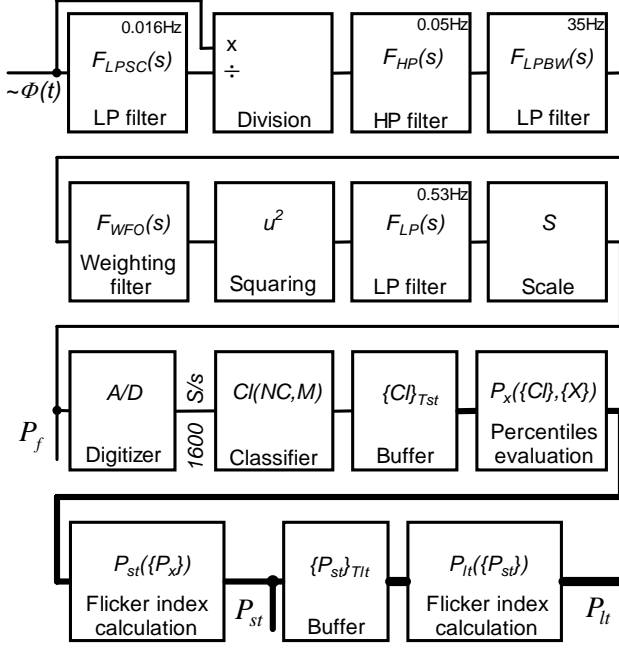


Fig. 4. Block diagram of the luminous variation signal processing

Applying the signal normalization makes the flicker perception measurement independent on illuminance (luminance) level which is in conflict with observations [7]. So it should be better to remove this stage in future, but changes in eye-brain response model have to be performed as well.

Transfer function with analogue frequency response of the following 1st order high pass filter eliminating DC component is as follows:

$$F_{HP}(s) = \frac{s \cdot \tau_{HP}}{1 + s \cdot \tau_{HP}} \quad (7)$$

where τ_{HP} is the filter time constant equal to: $\tau = 1/(2\pi \cdot f_{HP})$, and f_{HP} is the cut off frequency of the high pass filter having attenuation of 3dB at $f_{HP}=0.05\text{Hz}$.

The (pre-warped) 6th order Butterworth low pass filter transfer function with analogue frequency response can be given in cascade form as follows:

$$F_{LPBW}(s) = \prod_{i=1}^3 \left[\frac{\omega_i^2}{\left(\frac{s}{2 \cdot \pi \cdot f_{LPBW}} \right)^2 + \left(\frac{2 \cdot \zeta_i \cdot \omega_i \cdot s}{2 \cdot \pi \cdot f_{LPBW}} \right) + \omega_i^2} \right] \quad (8)$$

where $\omega_1=\omega_2=\omega_3=1$, $\zeta_1=0.26$, $\zeta_2=0.71$, $\zeta_3=0.97$ and f_{LPBW} is the cut off frequency of the low pass filter with attenuation of 3dB at frequency of 35Hz.

The next weighting filter modeling the average observer eye-brain frequency response is one of the most important part of the designed light-flickermeter. Its transfer function with analogue frequency response $F_{WFO}(s)$ can be obtained by decomposition of known standard flickermeter weighting filter transfer function $F_{WF}(s)$ using a procedure applied in [16]:

$$F_{WFO}(s) = \frac{F_{WF}(s)}{F_L(s)} \quad (9)$$

where $F_L(s)$ is a transfer function with analog frequency response of the reference 60W incandescent lamp. The transfer function of the standard flickermeter weighting filter is defined in [5] and consists of these two parts:

$$F_{WF}(s) = \frac{k \cdot \omega_1 \cdot s}{s^2 + 2\lambda s + \omega_1^2} \cdot \frac{1 + \frac{s}{\omega_2}}{\left(1 + \frac{s}{\omega_3}\right) \cdot \left(1 + \frac{s}{\omega_4}\right)} \quad (10)$$

where the transfer function parameters for 230V/50Hz system are: $k=1.74802$, $\lambda=2\pi 4.05981$, $\omega_1=2\pi 9.15494$, $\omega_2=2\pi 2.27979$, $\omega_3=2\pi 1.22535$, $\omega_4=2\pi 21.9$.

The reference lamp transfer function has been found as approximation of measured gain factor curves of 10 bulbs 60W/230V from different producers using measurement method published in [2]. Then the measured curves have been fitted by 2nd order low-pass filter transfer function as:

$$F_L(s) = \frac{K}{\tau_{L1} \cdot s^2 + \tau_{L2} \cdot s + 1} \quad (11)$$

where the time constants τ_{L1} and τ_{L2} and the gain K were obtained using method of least squares and are $K=3.57$, $\tau_{L1}=0.02$ ms, $\tau_{L2}=21.2$ ms.

After substitution of eq. (11) and (12) into (10) the light-flickermeter weighting filter transfer function can be expressed as

$$F_{WFO}(s) = \frac{0.041661s^4 + 44.758s^3 + 2715.6s^2 + 29839s}{s^4 + 196.32s^3 + 11781s^2 + 534820s + 3505380} \quad (12)$$

Comparison of the standard and light-flickermeter weighting filters amplitude response is at Fig. 5.

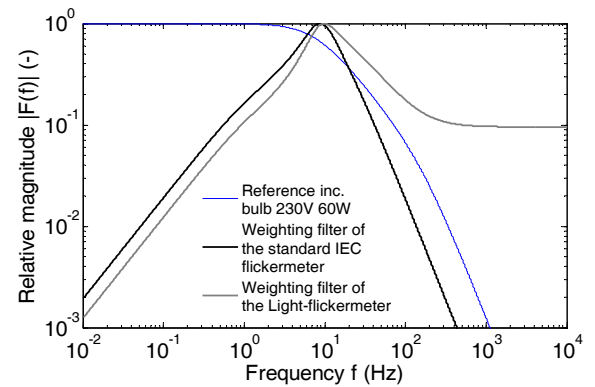


Fig. 5. Amplitude response of chosen filters

Then the flicker signal (FS) is squared within the frame of simulation of the non-linear perception during flicker transfer from eye to brain (block 4 of the flickermeter) and is filtered to simulate memorization effect in the brain using the first order low-pass filter with following transfer function:

$$F_{LP}(s) = \frac{s}{1 + s \cdot \tau_{LP}} \quad (13)$$

The time constant of the filter is $\tau_{LP}=300\text{ms}$.

The output signal is normalized using scaling factor S to give a maximum value of instantaneous flicker level index $P_f=1$, when a sine wave modulated input signal with fundamental frequency $f_f=50\text{ Hz}$, the modulation frequency $f_M=8.8\text{ Hz}$ and the modulation depth $\Delta U/U=0.25\%$ [5], is applied.

In consonance with the standard [5], the analog signal has to be converted to digital for evaluation in last block. The required sampling rate is at least 50 Hz . In the proposed instrument there is used a 16-bit/ 1.6 kHz digitizer.

The classification routine in the block 5 is based on sorting of instantaneous flicker level samples $P_f(k)$ into logarithmically spaced classes using following equation:

$$Cl(k) = \text{floor} \left(\frac{NC}{2} \left(1 + \frac{\log_{10}(P_f(k))}{\log_{10}(M)} \right) \right) \quad (14)$$

where NC is total number of used classes and M is a constant defining the classifier range. The equation (14) provides that half number of classes from NC is designed for $P_f \leq 1$ and the second half for $P_f > 1$. The classifier parameters $NC=100000$ (which is much more than it is required according the standard [5]) and $M=1000000$ was chosen (Fig. 6).

Subsequently the classes $Cl(k)$ are recorded for a short time period T_{st} into a buffer. The short time period is set to 10 minutes, but can be changed to another time interval. At the end of each successive T_{st} period a Cumulative Probability Function (CPF) is calculated by means of the number of samples to fall into each class. The percentiles defined in [5] are searched consequently as class numbers of the flicker levels exceeded for various percentages of the test time. Linear interpolation is used between classes where the percentile value does not fall exactly into a particular class. The class percentiles Cl_x calculation process using standard Matlab functions can be expressed as:

$$Cl_x = \text{prctile}(Cl, (100 - X)) \quad (15)$$

where X is the percentile number defined in [5], $X=0.1, 0.7, 1, 1.5, 2.2, 3, 4, 6, 8, 10, 13, 17, 30, 50, 80\%$.

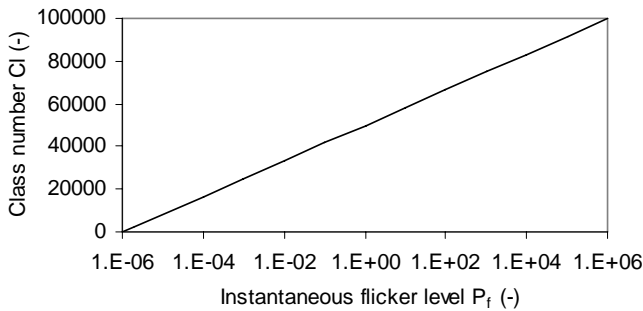


Fig. 6. Classification function

The corresponding percentile values of the instantaneous flicker level P_x can be then calculated using the following equation:

$$P_x = 10^{\left(\log_{10}(M) \left(\frac{Cl_x}{NC/2} - 1 \right) \right)} \quad (16)$$

And finally, the short-term flicker severity index P_{st} according to the equation given in [5] is calculated from P_x percentiles as follows:

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1.5} + 0.0657P_{3.5} + 0.28P_{10.5} + 0.08P_{50.5}} \quad (17)$$

where

$$\begin{aligned} P_{1.5} &= \frac{P_{0.7} + P_1 + P_{1.5}}{3} \\ P_{3.5} &= \frac{P_{2.2} + P_3 + P_4}{3} \\ P_{10.5} &= \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \\ P_{50.5} &= \frac{P_{30} + P_{50} + P_{80}}{3} \end{aligned} \quad (18)$$

The P_{st} values can be also logged into another buffer for long time period T_{lt} of 2 hours in case of T_{st} is equal to 10 minutes and then a long-term flicker severity index P_{lt} at the end of each successive T_{lt} period is calculated using equation:

$$P_{lt} = \sqrt[3]{\frac{1}{N} \sum_{i=1}^N P_{st}^3} \quad (19)$$

where N is the number of P_{st} periods within the T_{lt} , i.e. 12.

3 PRELIMINARY VERIFICATION

For a verification of the proposed light-flickermeter, its implementation in Matlab-Simulink has been realized. Since there are not defined testing points for flickermeter based on the evaluation of luminous variation, the verification procedure for standard flickermeter has been adopted. In other words, the test signals for the light-flickermeter model were obtained by simulation of simplified reference 60W incandescent lamp model (Fig. 7) response on testing signals defined in [5]. A block diagram of entire model for simulations in Simulink is composed of diagrams at Fig. 7 and Fig. 4.

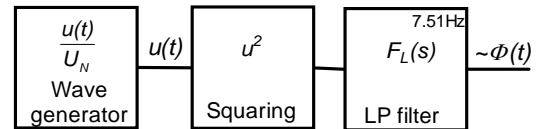


Fig. 7. Block diagram of the reference incandescent lamp luminous flux fluctuation generation in Matlab Simulink

A sinusoidal/rectangular amplitude modulated normalized signals with modulation parameters given in tables 1, 2 and 5 of [5] were generated using Matlab-Simulink signal sources and have been subsequently coupled to a part simply modeling transfer of the input voltage on output luminous flux in reference bulb, where the transfer function $F_L(s)$ is defined by eq. (11). Then the implemented light-flickermeter model is depicted on Fig. 4 and described in section 2.2. The photo-detector is supposed to be an ideal in the model and is in fact a part of the lamp model.

The results of performed preliminary compliance tests are shown at Fig. 8 and Fig. 9. Whereas the required accuracy is $\pm 5\%$ of the reference value which is $P_{st}=1$ or $P_f=1$. As it can be seen the deviations from expected values of P_{st} and P_f are in allowed tolerance except testing points at modulation frequency of $33\frac{1}{3}$ Hz. However it can be adjusted by setting the scaling factor S .

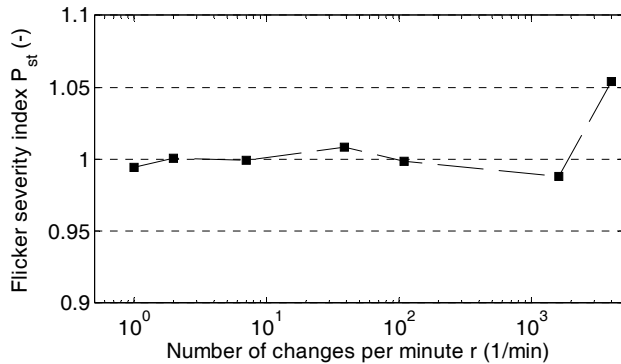


Fig. 8. Rectangular voltage AM performance test results, test No.1

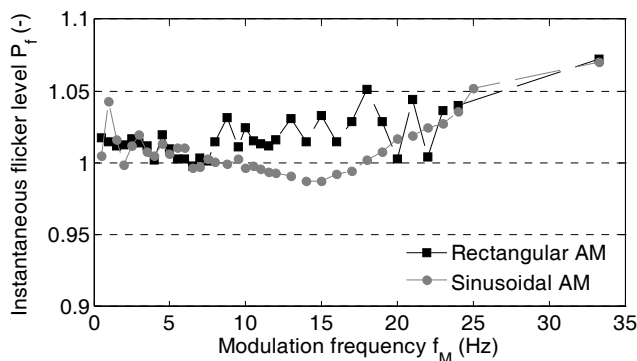


Fig. 9. Flickermeter compliance test results to normalized sinusoidal and rectangular voltage AM, test No.2, 3

4 CONCLUSION

The paper introduced the light-flickermeter intended for comparative measurements of disturbing light flicker produced by light sources of various types. The light-flickermeter was designed on the basis of the standard IEC flickermeter and its performance was verified by means of simulations in Matlab-Simulink.

Even if such simple light-flickermeter has very short range of applications and is far from an objective light-flickermeter which could be used without any limitation, the presented concept shows possibilities for future improvements.

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