Open access • Journal Article • DOI:10.1049/IET-GTD.2008.0429

Flicker responses of different lamp types — Source link

R Rong Cai, Jfg Sjef Cobben, Jma Johanna Myrzik, J.H. Blom ...+1 more authors

Institutions: Eindhoven University of Technology

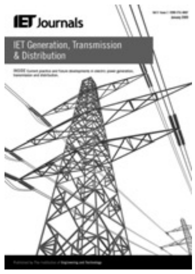
Published on: 11 Sep 2009 - Iet Generation Transmission & Distribution (Institution of Engineering and Technology (IET))

Topics: Flicker

Flicker responses of different lamp types

DOI:
10.1049/iet-gtd.2008.0429

Published in IET Generation, Transmission & Distribution
Received on 2nd September 2008
Revised on 10th March 2009
doi: 10.1049/iet-gtd.2008.0429



ISSN 1751-8687

Flicker responses of different lamp types

R. Cai J.F.G. Cobben J.M.A. Myrzik J.H. Blom W.L. Kling
Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
E-mail: c.rong@tue.nl

Abstract: Nowadays, more and more lamp types are being used. Since different lamp types have different working principles, they also have different flicker responses. This paper shows the measurement results of different flicker responses for various types of lamps. These results prove that the UIE/IEC flickermeter, which has been used widely around the world for many years, cannot be used to advise on the flicker level of all lamp types. This is because of the fact that this flickermeter is based on a 230 V, 60 W or 120 V, 60 W incandescent lamp and can be used as reference only for this type of lamp or as reference to the standard. The UIE/IEC (International Union for Electricity Applications/International Electrotechnical Committee) flickermeter and the existing standards are therefore insufficient for other lamp types. This paper describes a proposal to improve the UIE/IEC flickermeter.

1 Introduction

Flicker is the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time [1]. It is caused by rapid voltage fluctuations in the electric power system, which are usually caused by industrial loads, for example arc furnaces, resistive welding machines and so on. In the low-voltage grid, elevators, welding machines and copiers often cause flicker problems. Flicker can create distress and annoyance for sensitive persons who are exposed to it. There are several standards that prescribe requirements for the flicker emission level of equipment in the electric power system, for example IEC 61000-3-3, IEC 61000-3-5 and so on.

In the Netherlands, the grid operators' database of complaints on voltage quality shows that almost 60% of all complaints concern flicker [2]. From [3] it is clear that the average values of the long-term flicker indicator P_{lt} increased from 1996 to 2004 in the low-voltage grid in the Netherlands. Furthermore, it can be concluded that the number of customers with a higher P_{lt} value (higher than the limit of 1) increases if all values of P_{lt} are assumed to be distributed normally. Grid operators in the Netherlands are already aware that the flicker problem is the main source of customers' complaints. The evaluation and measurement of flicker therefore becomes an important topic of research.

The well-known UIE/IEC flickermeter [4, 5] has been used extensively for many years for flicker measurement. The short- and long-term flicker indicators P_{st} and P_{lt} can be obtained directly by using the UIE/IEC flickermeter. Fig. 1 shows the structure of the UIE/IEC flickermeter, which is composed of five blocks. A 'lamp–eye–brain' system is imitated successfully by using a weighting filter, a squaring multiplier and a smoothing filter in the UIE/IEC flickermeter to simulate three functions: (i) the lamp response to the supply voltage variation, (ii) the perception ability of the human eye and (iii) the memory tendency of the human brain [6]. However, the weighting filter, which is used to simulate the combined lamp illuminance response to the voltage fluctuation and the eye response to the lamp illuminance, is only based on the flicker response to sinusoidal voltage fluctuations of a coiled filament gas-filled 230 V, 60 W or 120 V, 60 W incandescent lamp [5].

Nowadays, there are numerous different types of residential lamps available on the market. Fluorescent lamps, compact fluorescent lamps (CFLs) and halogen lamps are becoming increasingly popular for residential lighting. Because of the different working principles of the various lamp types, the flicker responses of these lamps to voltage fluctuations differ considerably.

In this paper, Section 2 gives a simple comparison of the working principles for various types of lamps, whereas Section 3 shows the flicker response measurements for

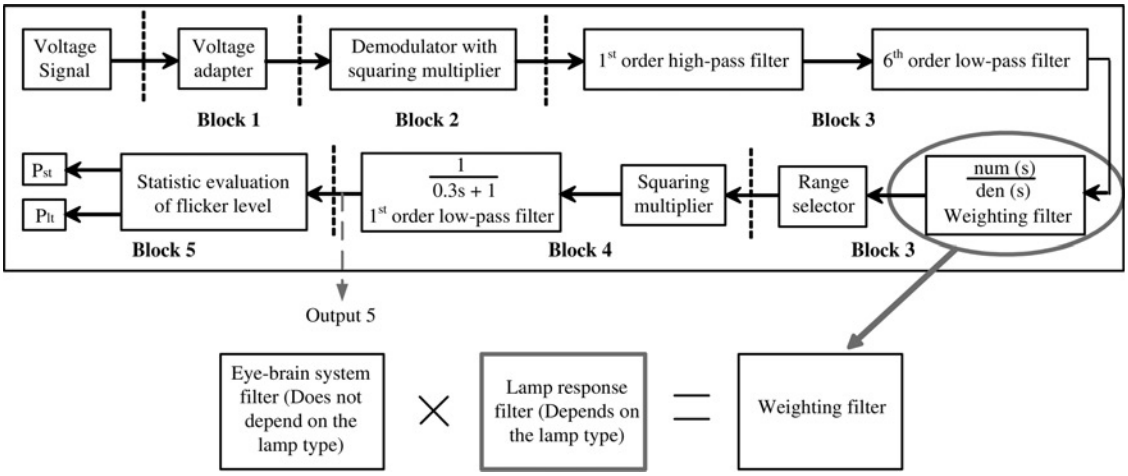


Figure 1 *Structure of the UIE/IEC flickermeter*

various lamp types. A proposal for improving the UIE/IEC flickermeter is given in Section 4.

2 Working principle of lamps

The lamp converts electrical energy into visible light. However, different types of lamps have different processes for converting this electrical energy into visible light [7].

The incandescent lamp converts electrical energy into electromagnetic radiation by heating the filament when electrical current flows through it. The electromagnetic radiation then produces visible light and other invisible radiation. The lamp voltage and current have a sinusoidal waveform, with no phase shift between them [4]. Fig. 2 shows the measured voltage and current characteristic curve of a 230 V, 60 W glass incandescent lamp. The measurement results demonstrate that the incandescent lamp features a resistive load characteristic [8]. The illuminance (the luminous flux received by an elementary surface divided by the area of this surface; it is expressed by lux [1]) of the incandescent lamp has also a sinusoidal waveform, similar to the waveform of the electrical power of this lamp [4].

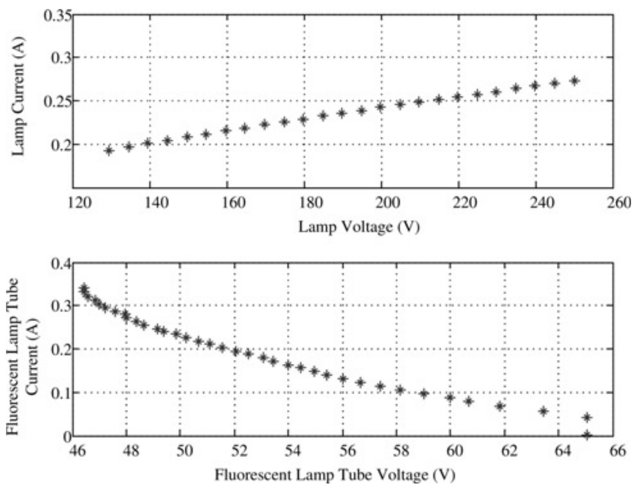


Figure 2 *V–I curve of a 60 W glass incandescent lamp (top) and a 15 W fluorescent lamp tube (bottom)*

The working principle of a halogen lamp is the same as that for an incandescent lamp. The lamp contains a small inner bulb filled with halogen. The tungsten molecules evaporate from the filament and cause a chemical reaction with the halogen molecules. This reaction in turn causes the tungsten molecules to re-deposit onto the filament surface instead of the bulb surface, as happens with an incandescent lamp. The halogen lamp therefore shines brighter at a higher temperature or has a longer lifespan than an incandescent lamp.

The fluorescent lamp has a totally different working principle than the incandescent lamp. It is composed of a lamp tube (which contains two electrodes in a glass tube filled with gas and mercury) and ballast (which is an essential component to control the current of the tube). The inner surface of the lamp tube has a phosphor coating. The electrical current, which passes through the electrodes, causes mercury atoms to release ultraviolet photons. These photons in turn stimulate the phosphor, which emits visible light photons. The measured voltage and current of the lamp tube are shown in [3]. The lamp tube voltage is a square wave with switching transients instead of a sinusoidal wave. This voltage shape is caused by the quantum energetic threshold for the excitation of the mercury atoms inside the lamp tube, which is related to the energy of the electrons [9]. For the lamp tube, the energy of the electrons cannot exceed the energy needed for excitation of the mercury atom. This is because of the fact that the electrons start to lose their energy as the excitations of the mercury atoms intensify. The energy of the electrons increases monotonically with the voltage across the lamp tube. The electron energy limitation must limit the lamp tube voltage as a result. Therefore any further increase in the lamp tube current cannot increase the lamp tube voltage and will only increase the illuminance of the fluorescent lamp. The measured voltage and current characteristic curves of a 15 W fluorescent lamp tube are shown in Fig. 2. When the supply voltage (the voltage of the fluorescent lamp) increases from 80 to 260 V, the voltage across the lamp tube decreases from 65 to 45 V and the lamp current increases from 0 to 0.34 A. The resistance of the lamp tube decreases when the supply voltage increases. This is because of the fact that, when the voltage between the electrodes increases, the number of discharged electrons also increases, and the discharge current also increases. This ultimately results in a decreased lamp resistance.

The measured instantaneous illuminance of a 15 W fluorescent lamp, an 11 W energy-saving lamp and a 9 W CFL with electromagnetic ballast is shown in [10]. The illuminance is a half-cycle sinusoidal waveform instead of a whole-cycle sinusoidal waveform of an incandescent lamp. This is because of the fact that the current of a fluorescent lamp is modulated by the ballast. Furthermore, the electronic ballast has a better modulation characteristic than electromagnetic ballast (operation frequency 50 Hz) because of the higher operation frequency (>20 kHz).

3 Flicker responses of different lamp types

Since the different lamp types have different working principles, their flicker responses differ. This section shows the flicker responses of different lamp types using experimental tests. The tested lamps are

- 60 W glass incandescent lamp,
- 20 W brilliantline pro-tungsten halogen lamp,
- 15 W four-foot fluorescent lamp,
- 11 W CFL with electronic ballast, that is energy-saving lamp,
- 9 W CFL with magnetic ballast and
- 3.4 W light-emitting diode (LED) lamp.

3.1 Experimental test set-up

The flicker response measurement set-up is shown in Fig. 3. A programmable power source, remote-controlled by a computer, is used to generate an arbitrary voltage waveform. The average and instantaneous illuminances of the lamps are measured using a photodetector and an illuminance meter (luxmeter). The power quality monitor, which is based on the UIE/IEC flickermeter principle, measures the short-term and long-term flicker indicators P_{st} and P_{lt}. The oscilloscope is used to record all measurement data, which are transferred to a computer. The tested lamp and photodetector are enclosed in a box coated with a white colour on the inner surface.

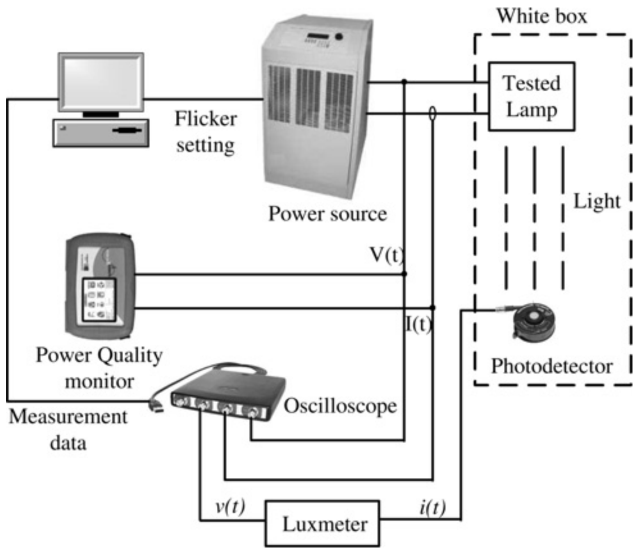


Figure 3 *Scheme of the flicker response measurement set-up*

3.2 Mathematical analysis of measurement results

All measurements stated in this paper were carried out using a sinusoidal modulated voltage waveform. The illuminance of all lamp types depends on the electrical power consumed by the lamp. The illuminance of the lamp should therefore be proportional to the electrical power consumed by the lamp. Under flicker conditions, the modulated voltage can be described as follows

$$\begin{aligned} V(t) &= A\cos(\omega t)(1 + m\cos(\omega_m t)) \\ &= A\cos(\omega t) + \frac{Am}{2}\cos(\omega - \omega_m)t + \frac{Am}{2}\cos(\omega + \omega_m)t \end{aligned} \quad (1)$$

where ω is the carrier voltage angular frequency (it equals $2\pi f$), f is the carrier voltage frequency, ω_m (it equals $2\pi f_m$) is the modulating voltage angular frequency, f_m is the modulating voltage frequency, m is the amplitude modulation factor.

The square of the modulated voltage is

$$\begin{aligned} V(t)^2 = {} & \frac{A^2}{2}\left(1 + \frac{m^2}{2}\right) + \frac{A^2}{2}\left(1 + \frac{m^2}{2}\right)\cos 2\omega t \\ & + \frac{m^2A^2}{8}\cos 2(\omega + \omega_m)t + \frac{m^2A^2}{8}\cos 2(\omega - \omega_m)t \\ & + \frac{mA^2}{2}\cos(2\omega + \omega_m)t + \frac{mA^2}{2}\cos(2\omega - \omega_m)t \\ & + mA^2\cos\omega_m t + \frac{m^2A^2}{4}\cos 2\omega_m t \end{aligned} \quad (2)$$

If the lamp is assumed as a linear load, the electrical power consumed by the lamp will be proportional to the square of the modulated voltage. The electrical power consumed by the

doi: 10.1049/iet-gtd.2008.0429

lamp will therefore be a harmonic-rich waveform instead of a perfect sinusoidal waveform. As the amplitude modulation factor m is less than 0.1, the frequency components with an angular frequency of $2(\omega + \omega_m)$, $2(\omega - \omega_m)$ and $2\omega_m$ should be very small and can be neglected. The noticeable frequency components in the electrical power should be a dc component plus components with an angular frequency of 2ω, $2\omega + \omega_m$, $2\omega - \omega_m$ and ω_m.

If the carrier voltage frequency is 50 Hz and the modulating voltage angular frequency is ω_m, the instantaneous electrical power consumed by the lamp should include a relatively high dc component and components with a frequency of 100 Hz, ω_m, $100 + \omega_m$ and $100 - \omega_m$. The corresponding illuminance of the lamp is also expected to include the relatively high dc component and components with a frequency of 100, ω_m, $100 + \omega_m$ and $100 - \omega_m$ Hz. Fourier analysis is used to analyse the illuminance of the lamp. The Fourier analysis results of the illuminance of a 230 V, 60 W glass incandescent lamp under flicker (with 4.6 V modulating voltage amplitude and 10 Hz modulating voltage frequency) are presented in Table 1 as an example. As expected, the values of the dc component and components with a frequency of 100, 10, 90 and 110 Hz are relatively high. However, the frequency components with $100 + \omega_m$ and $100 - \omega_m$ are not interesting flicker frequencies. The measurement results shown in Section 3 are the illuminance amplitudes of the components with the modulating voltage frequency (f_m).

The relative illuminance variation is used to evaluate the illuminance variation for the various types of lamps since the average illuminance is not exactly the same for different lamps. This relative illuminance variation can be calculated using the following equation

$$L_r(f_m) = \frac{L_{f_m}}{L_{av}} \times 100 \qquad (3)$$

where L_r is the relative illuminance variation of the f_m component for different lamp types, L_{f_m} is the absolute illuminance of the f_m component and L_{av} is the average illuminance of this type of lamp. It is obtained using a luxmeter and selected as a base value in the calculation.

In order to show the different flicker responses of different lamp types, the per unit value of the relative illuminance variation for different types of lamps is used (see Fig. 4). Since the incandescent lamp is used as a standard lamp in

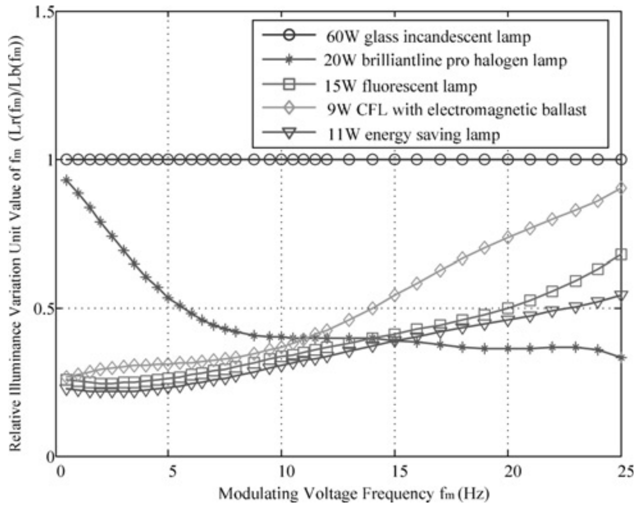


Figure 4 *Flicker response of different types of lamps (with modulating voltage amplitude for $P_{inst,max} = 1$)*

[5], the illuminance variation of the incandescent lamp for different modulating voltage frequencies is selected as base value L_b. The relative illuminance variation per unit can be calculated by

$$L_{unit}(f_m) = \frac{L_r(f_m)}{L_b(f_m)} \qquad (4)$$

where $L_{unit}(f_m)$ is the relative illuminance variation per unit value of f_m.

3.3 Measurement results

Four types of measurements have been conducted for six different types of lamps. The measurement results are shown in this section.

3.4 Standard modulating voltage amplitude

In order to show the different flicker responses of different lamp types, a measurement was carried out using the modulating voltage amplitude (ΔV) shown in Table 2, which is calculated from the values of the relative voltage fluctuation shown in Table 2. Since the relative voltage fluctuation values in Table 2 are obtained from Table 1 of standard IEC 61 000-4-15, these modulating voltage amplitudes are called 'standard modulating voltage amplitudes' in this paper. The relative voltage fluctuation $\Delta V/V$ shown in Table 2 is equal to two times the

Table 1 Fourier analysis results of the illuminance of a 60 W glass incandescent lamp under 10 Hz modulating voltage frequency

frequency (Hz)	**DC**	**10**	20	30	40	50	60	70	80	**90**	**100**	**110**
illuminance (lux)	**1869.3**	**36.5582**	0.3721	1.7828	0.0517	3.8393	0.0453	0.5011	0.0383	**4.0711**	**144.774**	**3.3086**

doi: 10.1049/iet-gtd.2008.0429

Table 2 Normalised flickermeter response to sinusoidal voltage fluctuation (input relative voltage fluctuation $\Delta V/V$ for one unit of the maximum perceptibility at output 5 [see Fig. 1])

Hz	Voltage fluctuation (230 V lamp 50 Hz system)		Hz	Voltage fluctuation (230 V lamp 50 Hz system)		Hz	Voltage fluctuation (230 V lamp 50 Hz system)	
	Relative voltage fluctuation ($\Delta V/V$) (%) (from standard [5])	Modulating voltage amplitude (ΔV) (V) (calculated value)		Relative voltage fluctuation ($\Delta V/V$) (%) (from standard [5])	Modulating voltage amplitude (ΔV) (V) (calculated value)		Relative voltage fluctuation ($\Delta V/V$) (%) (from standard [5])	Modulating voltage amplitude (ΔV) (V) (calculated value)
0.5	2.340	2.691	6.5	0.300	0.345	14.0	0.388	0.446
1.0	1.432	1.647	7.0	0.280	0.322	15.0	0.432	0.497
1.5	1.080	1.242	7.5	0.266	0.306	16.0	0.480	0.552
2.0	0.882	1.014	8.0	0.256	0.294	17.0	0.530	0.610
2.5	0.754	0.867	8.8	0.250	0.288	18.0	0.584	0.672
3.0	0.654	0.752	9.5	0.254	0.292	19.0	0.640	0.736
3.5	0.568	0.653	10.0	0.260	0.299	20.0	0.700	0.805
4.0	0.500	0.575	10.5	0.270	0.311	21.0	0.760	0.874
4.5	0.446	0.513	11.0	0.282	0.324	22.0	0.824	0.948
5.0	0.398	0.458	11.5	0.296	0.340	23.0	0.890	1.024
5.5	0.360	0.414	12.0	0.312	0.359	24.0	0.962	1.106
6.0	0.328	0.377	13.0	0.348	0.400	25.0	1.042	1.198

amplitude modulation factor m (mentioned in (1)) [5]. As described in standard IEC 61 000-4-15, the voltage fluctuation shown in Table 2 can generate one unit of the maximum instantaneous flicker level $P_{\text{inst,max}}$ (i.e. the maximum perceptibility at output 5 of the UIE/IEC flickermeter) (see Fig. 1). The short-term flicker indicator P_{st} should be less than one when the maximum instantaneous flicker level $P_{\text{inst,max}}$ reaches one.

The average illuminance of the tested lamps under normal voltage condition (without flicker) was recorded. Then a total of 36 different modulated voltages with different modulating voltage frequencies and the corresponding modulating voltage amplitudes, which are shown in Table 2, were supplied to the tested lamps by the programmable power source. The absolute illuminance variations of the tested lamps under each modulated voltage condition were recorded as well. The relative illuminance variations of the tested lamps for each modulating voltage frequency (totally 36 frequencies) were calculated by (3). These relative illuminance variation values demonstrate the flicker response of the tested lamps. As mentioned in Section 2, the relative illuminance variation per unit value is used to compare the different flicker responses of various lamp types better. By selecting the relative illuminance variation of the incandescent lamp for each modulating voltage frequency as the base value, the values of the relative illuminance variation per unit of the tested lamps were calculated by (4). The relationship between the relative illuminance variation per unit value L_{unit} and the modulating voltage frequency for different types of lamps is presented in Fig. 4.

Fig. 4 shows that the incandescent lamp is most sensitive to flicker. The energy-saving lamp is most insensitive to flicker when the modulating voltage frequency is less than 15 Hz. The halogen lamp becomes the most insensitive to flicker when the modulating voltage frequency varies between 15 and 25 Hz. This is because of the fact that the tested halogen lamp operates at 12 V instead of a 230 V supply voltage level. An additional electronic transformer is used for this halogen lamp. This electronic transformer therefore influences the flicker response of the halogen lamp. For the energy-saving lamp, the specific working principle of the lamp tube and additional electronic ballast results in a more stable lamp voltage and current under flicker conditions. It is therefore insensitive to flicker [11, 12].

The results in Fig. 4 also demonstrate that the lamps might not be obviously annoying to human beings, except for the incandescent lamp when the modulation voltage amplitude is as high as the value given in Table 2.

doi: 10.1049/iet-gtd.2008.0429

3.5 Instantaneous flicker curves measurements

To evaluate the flicker level, the simplest method used by grid operators is to use flicker curves ($P_{st} = 1$), which are given in the IEEE standard and UIE publication [5, 13]. These indicate the modulating voltage amplitude with respect to the modulating voltage frequency. IEEE 141-1993 and the UIE publication give the flicker curves ($P_{st} = 1$) for a 120 and 230 V lamp. These flicker curves are obtained from the flicker response to rectangular modulated voltage of a coiled filament gas-filled 230 V, 60 W or 120 V, 60 W incandescent lamp.

As shown in Fig. 4, different types of lamps have different flicker responses to the same voltage fluctuation. The flicker tolerance to the modulated voltage should therefore be different for each lamp, that is the modulating voltage amplitude should be different when the illuminance variation is the same for the various lamps tested. To prove this, a measurement was made. Since a 230 V, 60 W incandescent lamp is used in several standards, the illuminance variation of a 60 W glass incandescent lamp under the sinusoidal voltage fluctuation, whose modulating voltage amplitudes are shown in Table 2, was selected as the reference illuminance variation for this measurement. The modulating voltage amplitude was recorded in the lab for different types of lamps until the illuminance variation of the tested lamp becomes the same as the reference illuminance variation. The instantaneous flicker curves (relative voltage fluctuation [$\Delta V/V$] against modulating voltage frequency when $P_{inst,max} = 1$) of different types of lamps under sinusoidal voltage fluctuation are presented in Fig. 5. The differences between the instantaneous flicker curve and the normal flicker curve are (i) the instantaneous flicker curve is only used for the sinusoidal modulated voltage instead of rectangular-modulated voltage in the normal flicker curve and (ii) the instantaneous flicker curve is used for the condition of $P_{inst,max} = 1$ instead of $P_{st} = 1$, which is used for the normal flicker curve.

It can therefore be concluded that the incandescent lamp is most sensitive to the sinusoidal modulation voltage and the energy-saving lamp is most insensitive to the sinusoidal modulation voltage. These conclusions are in agreement with the results of the previous section.

3.6 Constant modulating voltage amplitude

The third type of measurement was carried out using the constant modulating voltage amplitude and observing the illuminance variation against the modulating voltage frequency. For the incandescent lamp, halogen lamp and energy-saving lamp, the applied relative voltage fluctuations are 0.5, 1 and 2%, respectively, based on the 230 V voltage level (i.e. the modulating voltage amplitudes are 1.15, 2.3 and 4.6 V, respectively). A 3% relative voltage fluctuation (i.e. the modulating voltage amplitude is 6.9 V) is also used for the fluorescent lamp and the CFL with electromagnetic ballast. Relative voltage fluctuations of 1, 2 and 3% are used for the LED lamp. The results of the relative illuminance variations against the modulating voltage frequencies for different types of lamps are shown in Figs. 6–11. The relative illuminance variation is calculated using (3).

The relative illuminance variation of all types of lamps, with the exception of the CFL with electromagnetic ballast, decreases with the modulating voltage frequency. The relative illuminance variation of all lamp types also increases with the modulating voltage amplitude when constant modulating voltage amplitude is applied. This is mainly because of the fact that the illuminance of the lamp depends on the thermal emission of the filament or the electrode. This process cannot change as fast as the input voltage. The relative illuminance variation of a CFL with

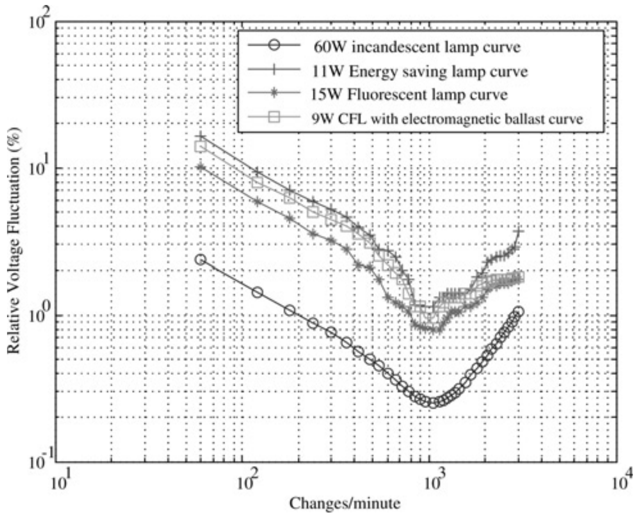


Figure 5 *Instantaneous flicker curves for different types of lamps ($P_{inst,max} = 1$) and sinusoidal modulated voltage*

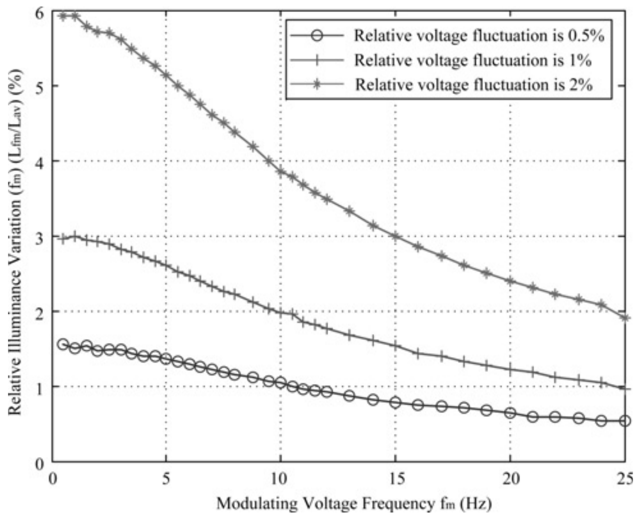


Figure 6 *Relative illuminance variation of a 60 W glass incandescent lamp against modulating voltage frequency*

doi: 10.1049/iet-gtd.2008.0429

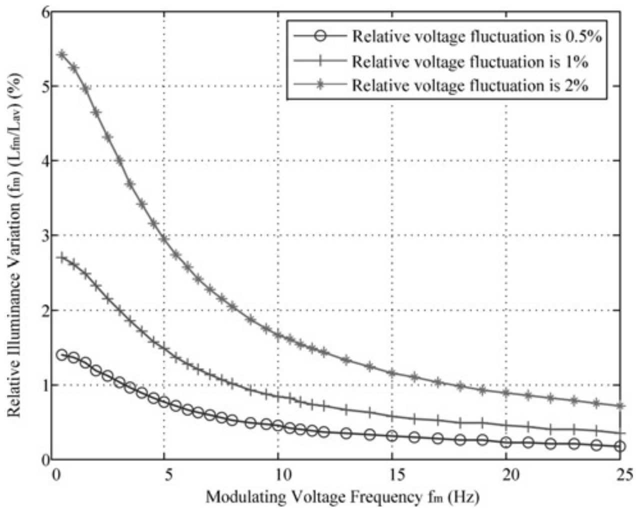


Figure 7 *Relative illuminance variation of a 20 W halogen lamp against modulating voltage frequency*

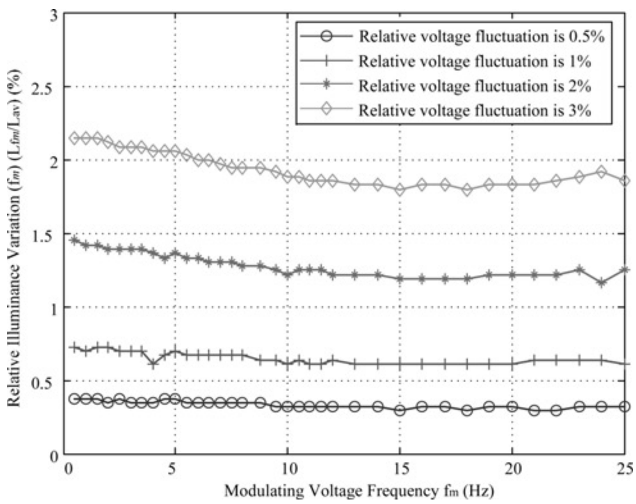


Figure 8 *Relative illuminance of a 15 W fluorescent lamp against modulating voltage frequency*

electromagnetic ballast increases slightly when the modulating voltage frequency increases. This is because of the fact that the illuminance of this kind of lamp is affected by the electromagnetic ballast. This ballast shows different properties with the electronic ballast under flicker conditions.

Another important conclusion from the above measurement results is that the illuminance amplitude variation of the modulating voltage frequency component is linearly proportional to the modulating voltage amplitude for all lamp types. To further prove this conclusion, linearity measurements were carried out in the lab for various lamp types.

3.7 Linearity measurements

This measurement is used to analyse the relationship between the modulating voltage amplitude and the relative illuminance

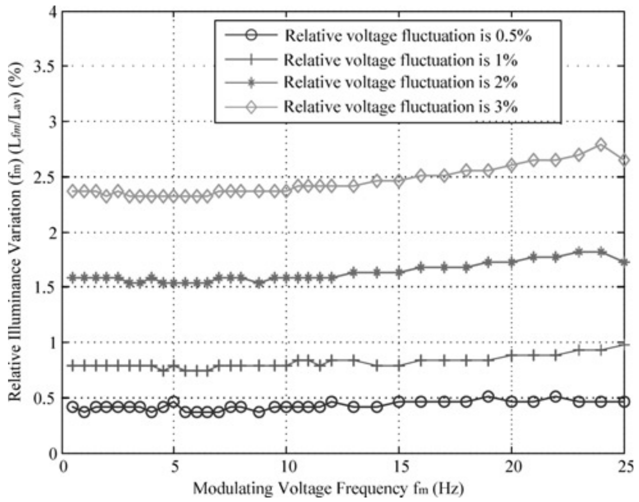


Figure 9 *Relative illuminance variation of a 9 W CFL with electromagnetic ballast against modulating voltage frequency*

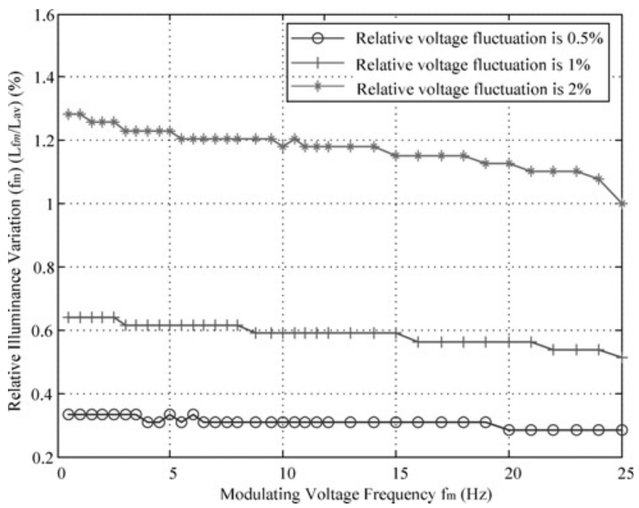


Figure 10 *Relative illuminance variation of an 11 W energy-saving lamp against modulating voltage frequency*

variation when the modulating voltage frequency is kept constant (e.g. 10 Hz). Examples of measurement results for an 11 W energy-saving lamp and 3.4 W LED lamp are presented in Fig. 12. The results shown in the figures agree with the conclusion mentioned earlier, that is there is a linear relationship between the relative illuminance variation of the modulating voltage frequency component and the modulating voltage amplitude. However, this conclusion is only true within the flicker frequency range of interest (0.5–25 Hz) for all lamp types.

4 Proposal for improving the UIE/IEC flickermeter

The UIE/IEC flickermeter simulates the lamp–eye–brain response to the voltage fluctuation in the weighting filter using a linear transfer function. As shown in Fig. 1, this filter

doi: 10.1049/iet-gtd.2008.0429

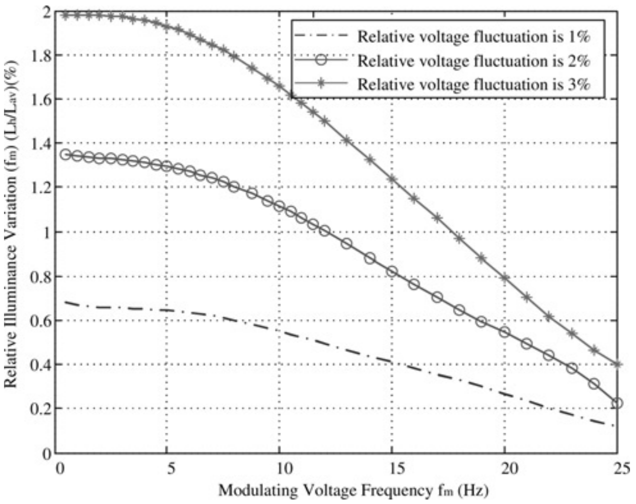


Figure 11 *Relative illuminance variation of a 3.4 W LED lamp against modulating voltage frequency*

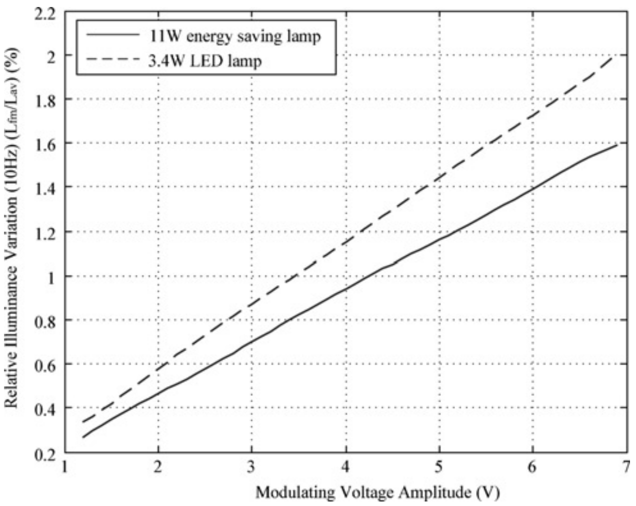


Figure 12 *Relative illuminance variation of 10 Hz against modulating voltage amplitude with a 10 Hz modulating voltage frequency: 11 W energy-saving lamp (solid line); 3.4 W LED lamp (dashed line)*

can be considered as a combination of two filters: one is the lamp response filter that depends on the lamp type whereas the other is the eye–brain filter that depends on the perception of the persons exposed to the flicker [14]. To simplify the research problem, it is assumed that the average eye–brain filter is identical for all people. The eye–brain filter can be obtained using the weighting filter of the UIE/IEC flickermeter divided by the incandescent lamp flicker response filter. The parameters of the weighting filter described in the UIE/IEC flickermeter are derived from the flicker response of a 230 V, 60 W and a 120 V, 60 W incandescent lamp [5]. The measurement results in Section 3 show the different flicker responses of different lamp types. A modification of the parameters of the weighting transfer function should therefore be adapted to the lamp type, that is different parameters of the weighting filter should be used for different lamp types. The flicker level obtained by the UIE/IEC flickermeter can currently be used for incandescent lamps and as a reference level for standards. The simplest way to resolve flicker problem could be to advise customers to switch to a different lamp type.

In order to determine the parameters of the lamp response filter for different types of lamps, it is necessary to study the relationship between the illuminance variation and the modulated voltage. This can be started by studying the relationship between the modulating voltage amplitude and the relative illuminance variation for each modulating voltage frequency. As explained in Section 3, illuminance waveform is a harmonic-rich waveform under flicker. The measurement results presented earlier proved that the relative illuminance variation of the modulating voltage frequency component is linearly proportional to the corresponding modulating voltage amplitude within the flicker frequency range of interest (0.5–25 Hz). After Fourier analysis of the measurement data of the instantaneous illuminance, it is also apparent that the illuminance amplitudes of the modulating voltage frequency components, with $100 + \omega_m$ and $100 - \omega_m$, are relatively high (see Table 1). A linear relationship between the illuminance amplitude of these two components and the voltage modulation amplitude could not be found, as shown in Fig. 13. As mentioned earlier, the frequency components with $100 + \omega_m$ and $100 - \omega_m$ are not interesting flicker frequencies because the human eye is not sensitive to such high frequencies.

The linear system identification method can therefore be used to define the transfer function of the lamp flicker response for different lamp types. A system identification model should be built for each type of lamp. The input of the lamp system identification model is the measured modulating voltage amplitude. The output of the lamp system

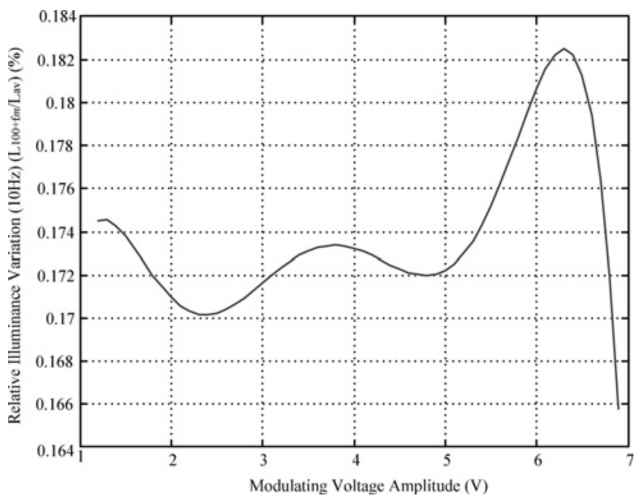


Figure 13 *Relative illuminance variation ($100 + \omega_m$ component) of a 3.4 W LED lamp with a 10 Hz modulating voltage frequency*

identification model is the measured illuminance variation. The transfer function derived from the identification model is the mathematical description of the lamp response filter for different lamp types. The weighting filter of the UIE/IEC flickermeter can therefore be improved for different lamp types by using the linear transfer function of lamp's flicker response. Finally, it is possible to develop a flickermeter for different lamp types.

5 Conclusions

The flicker responses of six types of lamps were measured in the lab. The Fourier analysis was used to analyse the measurement data of the flicker responses of the different lamp types. The analysis results of the flicker responses show that the different types of lamps have different flicker responses. This is because they have different working principles. The relative illuminance variation of the modulating voltage frequency (ω_m) is linearly proportional to the modulating voltage amplitude within the flicker frequency range of interest (0.5–25 Hz) for all lamp types. This linear relationship can be used to define the parameters of the lamp response filter in order to develop the weighting filter for different lamp types using linear system identification method. Finally, the flickermeter can be improved for different lamp types using this improved weighting filter.

6 Acknowledgments

This research was conducted at the Eindhoven University of Technology within the framework of the IOP–EMVT research project on 'intelligent power systems'. This project is supported financially by SenterNovem, an agency of the Dutch Ministry of Economic Affairs.

Rong Cai thanks Ir. M.A.M. Hendrix of Electromechanics and Power Electronics group at TU/e for the interesting discussion on lamp load characteristics.

7 References

[1] International Electrotechnical Vocabulary: IEC Standard 60050

[2] COBBEN J.F.G.: 'Power quality implications at the point of connection'. Ph.D. thesis, Eindhoven University of Technology, The Netherlands, 2007, ISBN: 978-90-386-1030-6

[3] CAI R., COBBEN J.F.G., MYRZIK J.M.A., KLING W.L.: 'Flicker curves of different type of lamps'. Proc. China Int. Conf. Electricity Distribution, Beijing, P.R. China, 17–20 September 2006

[4] UIE Guide to 'Quality of Electrical Supply for Industrial Installations. Part V: Flicker', ISBN 2-9507878-5-1, 1999

[5] Electromagnetic compatibility (EMC) – Part 4: 'Testing and measurement techniques – Section 15: Flickermeter – functional and design specifications'. IEC Standard 61000-4-15, 1.1 edn., February 2003

[6] HALPIN S.M., BERGERON R.T.M., BURCH R.F., CONRAD L.E., KEY T.S.: 'Voltage and lamp flicker issues: should the IEEE adopt the IEC approach', *IEEE Trans. Power Deliv.*, 2003, **18**, (3), pp. 1088–1097

[7] COATON J.R., MARSDEN A.M.: 'Lamps and lighting' (Wiley, New York, 1997, 4th edn.), pp. 161–199

[8] PERETTO L., EMANUEL A.E.: 'A theoretical study of the incandescent filament lamp performance under voltage flicker', *IEEE Trans. Power Deliv.*, 1997, **12**, (1), pp. 279–288

[9] GLUSKIN E., FRANGISKOS V., KATERI T.I., BISKETZIS N.: 'The instantaneous light-intensity function of a fluorescent lamp', *Phys. Lett. A*, 2006, pp. 355–363

[10] CAI R., COBBEN J.F.G., MYRZIK J.M.A., KLING W.L.: 'Proposal for improving UIE/IEC flickermeter'. Proc. Third IEEE Young Researchers Symp. Electrical Power Engineering, Gent, Belgium, 27–28 April 2006

[11] EMANUEL A.E., PERETTO L.: 'The response of fluorescent lamp with magnetic ballast to voltage distortion', *IEEE Trans. Power Deliv.*, 1997, **12**, (1), pp. 289–295

[12] MADER U., HORN P.: 'A dynamic model for the electrical characteristics of fluorescent lamps'. Industry Applications Society Annual Meeting, 1992, Conf. Record 1992 IEEE, 4–9 October 1992, vol. 2, pp. 1928–1934

[13] IEEE standard 141–1993: 'IEEE recommended practice for electric power distribution for industrial plants'. IEEE, 1993

[14] WANG C.-S., DEVANEY M.J., YANG S.-W.: 'Decomposition of the IEC flickermeter weighting curves'. Instrumentation and Measurement Technology Conf., IMTC 04, Proc. 21st IEEE, 18–20 May 2004, vol. 2, pp. 1378–1382

doi: 10.1049/iet-gtd.2008.0429