Flicker interaction studies and flickermeter improvement

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Flicker Interaction Studies and Flickermeter Improvement

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To my parents and my husband

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Flicker Interaction Studies and Flickermeter Improvement

Summary

Flicker is one of the most important power quality aspects. It is the noticeable light intensity variation of a lamp caused by rapid voltage fluctuations in the electrical power system. It is annoying to human eyes. In the Netherlands, the grid operators' database of complains on voltage quality shows that almost 60% of all complains are about flicker. The statistical measurement database shows that the average long-term flicker indicator P_{lt} increased from 1996 to 2004 in the low-voltage grid in the Netherlands. The evaluation and measurement of flicker becomes therefore an important issue.

Firstly, the research aimed at the improvement of the classical flicker measurement method, i.e. the UIE/IEC flickermeter method. Since nowadays more and more lamp types are applied in the market, the world-wide used UIE/IEC flickermeter cannot generate results (P_{st}) that correlate well with the customer sensitivity for different lamp types. This is due to the fact that the UIE/IEC flickermeter model is built by only considering the incandescent lamp as the reference lamp. Flicker response (illuminance flicker response) measurements of five lamp types (the incandescent lamp, fluorescent lamp, halogen lamp, energy saving lamp and LED lamp) have been made in the Power Quality Lab of TU/e. To analyze and evaluate the measured data, Fourier analysis is done and different filter types are tested using Matlab. The five lamp types flicker response models are derived by using linear system identification methods based on the results of the flicker response (illuminance flicker response) measurements. The lamp flicker response models are studied and tested by using the Matlab/System Identification Toolbox. These lamp flicker response models are implemented into the improved flickermeter models, which can provide the better match between the output and customer complains for specific lamp types.

Secondly, light spectrum flicker response measurements of different lamp types are made in the PQ lab of TU/e since the human eye is sensitive to the light color. The measurement results are analyzed by FFT and the wavelength contributions to flicker of different lamp types are presented in this thesis. It provides important information on the light color variation of different lamp types under flicker conditions. Weighting factors of various lamp types are obtained by the corresponding wavelength contribution to the flicker weighted with the CIE photopic luminosity curve. These weighting factors indicate the human eye flicker response from the human eye spectrum sensitivity point of view. Then it is possible to develop a simplified flicker measurement method for different lamp types by adding an eye-brain flicker response model. A discussion about the simplified flicker measurement method and the eye-brain model is given in this thesis.

Finally, the interaction between flicker and dimmers (the phase controlled dimmer and reverse phase controlled dimmer) is studied based on experimental work. The measurement results show that the phase controlled dimmer will increase the flicker problem. Solutions to avoid the flicker influence of dimmers are discussed in this thesis.

Flikker Interactie Onderzoek en Verbetering van de Flikkermeter

Samenvatting

Flikker is een van de belangrijkste power quality kenmerken. Het is de zichtbare verandering van de lichtintensiteit van een lamp veroorzaakt door snelle spanningsvariaties in het elektriciteitsnet. Het is hinderlijk voor mensen. In Nederland blijkt uit de klachtenregistratie van de netbeheerders dat 60% van de klachten flikker betreffen. Statistische meetdata geeft aan dat de gemiddelDe Lange termijn flikker indicator P_{lt} in het laagspanningsnet in Nederland gedurende de jaren 1996 tot 2004 is gestegen. De evaluatie en meting van flikker wordt daarom een belangrijk onderwerp.

In eerste instantie beoogt het onderzoek de verbetering van de klassieke flikker meetmethode, dat is de UIE/IEC flikkermeter methode. Aangezien er tegenwoordig meer verschillende lamptypen worden toegepast in de markt kan de wereldwijd gebruikte UIE/IEC flikkermeter geen resultaten (P_{st}) genereren die goed correleren met de gevoeligheid van gebruikers voor verschillende typen lampen. Dit vanwege het feit dat de UIE/IEC flikkermeter is ontworpen voor de gloeilamp als referentie lamp. Flikker responsie (verlichtingsniveau flikker responsie) metingen van vijf lamp typen (de gloeilamp, fluorescentielamp, halogeenlamp, spaarlamp en LED lamp) zijn uitgevoerd in het Power Quality lab van de TU/e. Om de meetresultaten te analyseren en te evalueren is Fourier analyse toegepast en zijn met gebruik van Matlab diverse filter types getest. De flikker responsie modellen van de vijf lamptypen zijn afgeleid door gebruikmaking van lineare identificatie methoden gebaseerd op de flikker responsie (verlichtingsniveau flikker responsie) metingen. De flikker responsie modellen zijn bestudeerd en getest met gebruikmaking van een Matlab/System Indentificatie toolbox. Deze lamp flikker responsie modellen zijn geïmplementeerd in de verbeterde flikkermeter modellen, die een betere overeenkomst geven tussen de output en de klachten van de gebruikers van specifieke lamptypen.

Ten tweede zijn er lichtspectrum flikker responsie metingen van verschillende lamptypen uitgevoerd in het PQ lab van de TU/e. Dit omdat het menselijke oog gevoelig is voor de lichtkleur. De resultaten van de metingen zijn geanalyseerd met

FFT en de bijdrage tot flikker van de golflengte van verschillende lamptypen is gepresenteerd in dit proefschrift. Dit geeft belangrijke informatie over de lichtkleur variatie van verschillende lamptypen onder flikkercondities. Weegfactoren voor verschillende lamptypen zijn verkregen door voor de overeenkomstige golflengte de bijdrage tot de flikker te wegen met de CIE photopic helderheidskromme. Deze weegfactoren bepalen de flikker responsie van het menselijke oog bekeken vanuit de gevoeligheid van het menselijke oog voor het lichtspectrum. Vervolgens is het mogelijk om een vereenvoudigde flikker meetmethode te ontwerpen voor verschillende typen lampen door het toevoegen van een oog-hersenen flikker responsie model. Een discussie over de vereenvoudigde flikker meetmethode en het oog-hersenen model is gegeven in dit proefschrift.

Tenslotte, is de interactie tussen flikker en dimmers (de fasegestuurde en de inverse fasegestuurde dimmer) bestudeerd, gebaseerd op experimenteel onderzoek. De resultaten van de metingen laten zien dat de fasegestuurde dimmer het flikkerprobleem vergroot. Ten slotte worden oplossingen om de invloed van dimmers op flikker te voorkomen beschreven in dit proefschrift.

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Chapter 1

Introduction

1.1 Introduction

Since this thesis deals with research on flicker which is one of the important aspects of power quality, the power quality aspects related knowledge is introduced in this chapter. The research background will be described and the research objectives will be defined. The study methods used in this research are introduced. The thesis outline and the introduction of the IOP project are presented in this chapter as well.

1.2 Power quality, general introduction

Power quality is defined as a global term for the characteristics of electricity at a given point in an electrical system, evaluated against a set of reference technical parameters [1]. It is an issue related to both voltage quality and current quality. Nowadays, both the utilities and customers are more and more interested in power quality. This is mainly caused by three reasons [2]:

1) Equipment becomes more sensitive to voltage disturbances in electrical power systems. Production processes become less tolerant of incorrect

operation of equipment. This results in much higher costs for customers due to poor power quality than before. The power quality cost survey reports of the Leonardo Power Quality Initiative team show that the yearly power quality problem related costs of industrial customers in the European Union increased from €10 billion in 2001 to €150 billion in 2008 [3] [4].

2) Equipment causes more current disturbances into electrical power systems than before. This is due to the fact that the use of the power electronic devices, which can cause current disturbances, significantly increases in the electrical power system.
3) The deregulation of the electricity supply had led to an increased need for power quality indicators. Customers are demanding and getting more information on power quality performance [12].

The aspects which cause power quality problems are: harmonics (related to current quality), voltage dips and flicker etc. Except for harmonics, all other aspects mentioned above are related to voltage quality. The brief introduction of these aspects is given in the text below.

The harmonic is the sinusoidal component of a complex waveform whose frequency is an integral multiple of the frequency of the fundamental [5]. It is caused by the non-linear loads in the electrical power system. The general level of harmonics can be described by the total harmonic distortion (THD). It is the ratio of the rms value of the sum of all the harmonic components up to a specified order (recommended notation "H") to the rms value of the fundamental component [6]. It can be calculated as [6]

$$THD = \sqrt{\sum_{n=2}^{n=H} \left(\frac{Q_h}{Q_1} \right)^2} \tag{1.1}$$

where:

Q represents either current or voltage;

Q_1 is the rms value of the fundamental component;

Q_h is the rms value of the harmonic component of order h;

h is the harmonic order;

H is 50 for the purpose of the compatibility levels in standard IEC 61000-2-4.

Harmonics can cause problems of voltage distortion, overloading of the neutral and overheating of transformers etc. These problems can therefore cause economic effects of shorter equipment lifetime, reduced energy efficiency and nuisance tripping. Harmonics can be mitigated by passive filters and active filters that are described in detail in [7].

A **Voltage dip** is defined as the temporary reduction of the voltage magni tude at a point in the electrical system below a certain threshold [1]. It is caused by a short-duration increase of the current, which causes a momentary decrease in the rms voltage magnitude. The most common causes of overcurrents leading to voltage dips are short-circuit faults, motor starting, transformer energizing, and overloads. There are three types of short-circuit faults in the electrical power system: single phase, two-phase and three-phase faults. The important characteristics of a voltage dip are the depth and duration of the dip.

- The depth of a voltage dip is the difference between the reference voltage and the residual voltage [8]. The depth of the voltage dip may be expressed as a value in volts or as a percentage or per unit value relative to the reference voltage. Generally, the depth of the voltage dip is within the range of 10% - 90% of the reference voltage.
- The duration of the voltage dip is the time between the instant at which the voltage at a particular point in an electricity supply system falls below the start threshold and the instant at which it rises to the end threshold [8].

Voltage dips can cause malfunctioning of equipment. It is the most costly power quality problem. It can be mitigated by a static transfer switch (STS), a dynamic voltage restorer (DVR) or a shunt connected compensator (STATCOM) etc. Detailed information can be found in [9].

Flicker is the impression of unsteadiness of the visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time [1]. It is caused by the regular or irregular voltage fluctuations (modulating voltage frequency is between 0.5Hz and 35Hz) in the electrical power system. The fluctuating loads in the electrical power system, e.g. welding machine and arc furnaces etc, are the main sources of these voltage fluctuations. The modulating voltage amplitude of these voltage fluctuations is less than 10% of the reference voltage. Flicker can be measured by the UIE/IEC flickermeter, which is an instrument designed to measure any quantity representative of flicker [10]. Detailed information about the flickermeter is given in chapter 2. The short-term and long-term flicker indicators P_{st} and P_{lt}, which are the output of the UIE/IEC flickermeter, are used to describe the characteristics of flicker. The short-term flicker indicator P_{st} is the flicker severity evaluated over a short period (10 minutes is used in practice). $P_{st} = 1$ is the conventional threshold of irritability [10]. The long-term flicker indicator P_{lt} is the flicker severity evaluated over a long period (two hours is used in practice) using successive P_{st} values [10]. The detailed equations used to calculate P_{st} and P_{lt} are presented in section 2.4.5. Flicker can bring annoyance to the human eye and affect the health of human beings. It can be mitigated by a static var compensator (SVC) or shunt connected compensator (STATCOM) etc [11].

The research presented in this thesis has its focus on flicker..

1.3 Research background

In the Netherlands, the grid operators' database of complaints on voltage quality shows that almost 60% of all complaints concern flicker [12]. Figure 1.1 shows the average long-term flicker indicator P_{lt} in the low-voltage grid in the Netherlands from 1996 to 2004. It is clear that the P_{lt} increased from 1996 to 2004. Furthermore, it can be concluded that the number of customers with a higher P_{lt} value (larger than the limit of 1) increases if all values of P_{lt} are distributed normally. Grid operators in the Netherlands are already aware that the flicker problem is the main source of customers complaints. Thus, to make an evaluation and to do measurements on flicker is an important topic of research.

According to the standard EN 50160, the short-term flicker indicator P_{st} and the long-term flicker indicator P_{lt} should not be larger than 1 in the low-voltage network. However, in several countries, practical flicker measurement results show that the measured flicker level at the locations, where the customer complains about the flicker problem, is quite higher than the limit value equal to 1. As an example, figure 1.2 shows the measured long-term flicker indicator P_{lt} for 100 locations where customers complain about the flicker problem in Slovenia [13]. These P_{lt} values are obtained by the 95% measurement method (One week measurement is performed. The P_{lt} value is calculated every 2 hours. The calculated P_{lt} values are sorted and the 95% percentile value is obtained and defined as the final long-term flicker indicator) [12]. Figure 1.2 shows that almost 50% of the measured flicker levels are above 2 when the customer complains about the flicker problem. This flicker level value is quite above the required limit of 1 in standard IEC 61000-3-3. The measurement results shown in figure 1.2 are obtained by using the UIE/IEC flickermeter, which is built based on the flicker response of a 60W 230V or 60W 120V incandescent lamp. However, more and more new lamp types are used in the market, e.g. energy saving lamp etc. These lamp types have different flicker responses compared to the incandescent lamp. Therefore, the UIE/IEC flickermeter can not generate an output that correlates well with the customer complaints for other lamp types except for the incandescent lamp. Therefore, the following general question can be raised: Is it still necessary to define the flicker level boundary value equal to one?

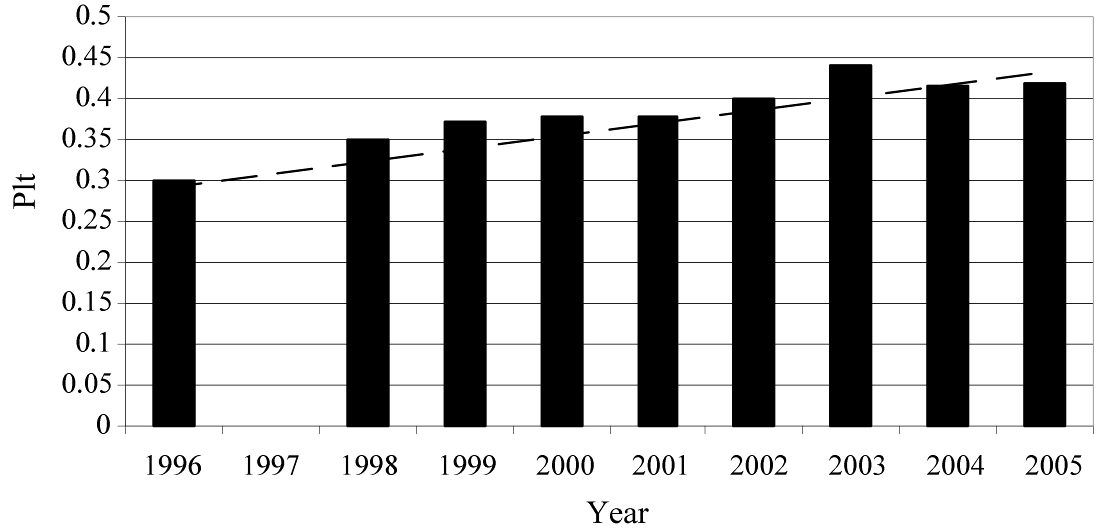


Figure 1.1 Average P_{lt} in low-voltage grid in the Netherlands [12]

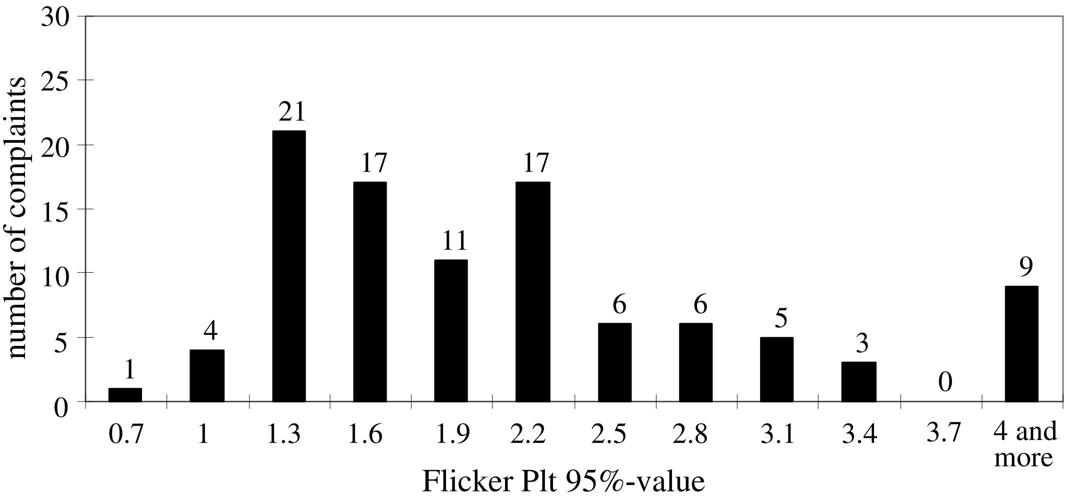


Figure 1.2 Actual flicker levels for 100 customer complaints in Slovenia [13]

To give a contribution to answer the above question, the flicker sensitivity of different lamp types should be known and compared. A new flickermeter, whose output can correlate well with the customer complaints for other lamp types, is urgently needed. This requires new research as performed in this thesis.

Nowadays more and more lamp types are entering the market. For the purpose of saving energy, the incandescent lamp is replaced by other higher efficiency lamp types in the residential lighting market, e.g. fluorescent lamps and energy saving lamps etc. Many countries already strive to stop the use of the low efficiency incandescent bulb [14] – [17]. Since the UIE/IEC flickermeter can not give the P_{st} value well correlated with the customer complaints for other lamp types, the improvement of the flicker measurement methods is an urgent topic for research.

Through the development of power electronic technology, more and more power electronic devices are used in the power system. These devices generate power quality problems into the network, e.g. harmonics and possibly also flicker etc. This polluted network also affects the performance of these power electronic devices. The interaction between the power quality aspects and the power electronic devices also asks for further research.

1.4 Research objectives

The objectives of the research in this thesis are:

1) The flicker response (illuminance flicker response) sensitivity of different lamp types should be measured. The results for different lamp types should be compared. The insufficiencies of the UIE/IEC flickermeter for different lamp types should be described and corrected by analysis of the experimental results.
2) Since the human eye is sensitive to the light color, the lamp light spectrum flicker response that indicates the light color variation under flicker conditions should be explored. A new flicker measurement method, which would be easier and could improve the correlation between the measured flicker level and customer complaints for different lamp types, should be explored based on the lamp light spectrum flicker response.
3) The interaction between flicker and power electronic devices should be investigated. Since flicker is an essential issue related to the lamp, the effect of power electronic devices used in the lighting control system must be examined and solutions should be proposed.

1.5 Research methods

Experimental work is the basis of the research presented in this thesis. The scheme of the measurement set-up is shown in figure 3.1. The detailed explanation of this set-up is given in section 3.2. Both the illuminance flicker responses and the light spectrum flicker responses of different lamp types are obtained by measurements made in Power Quality lab of TU/e.

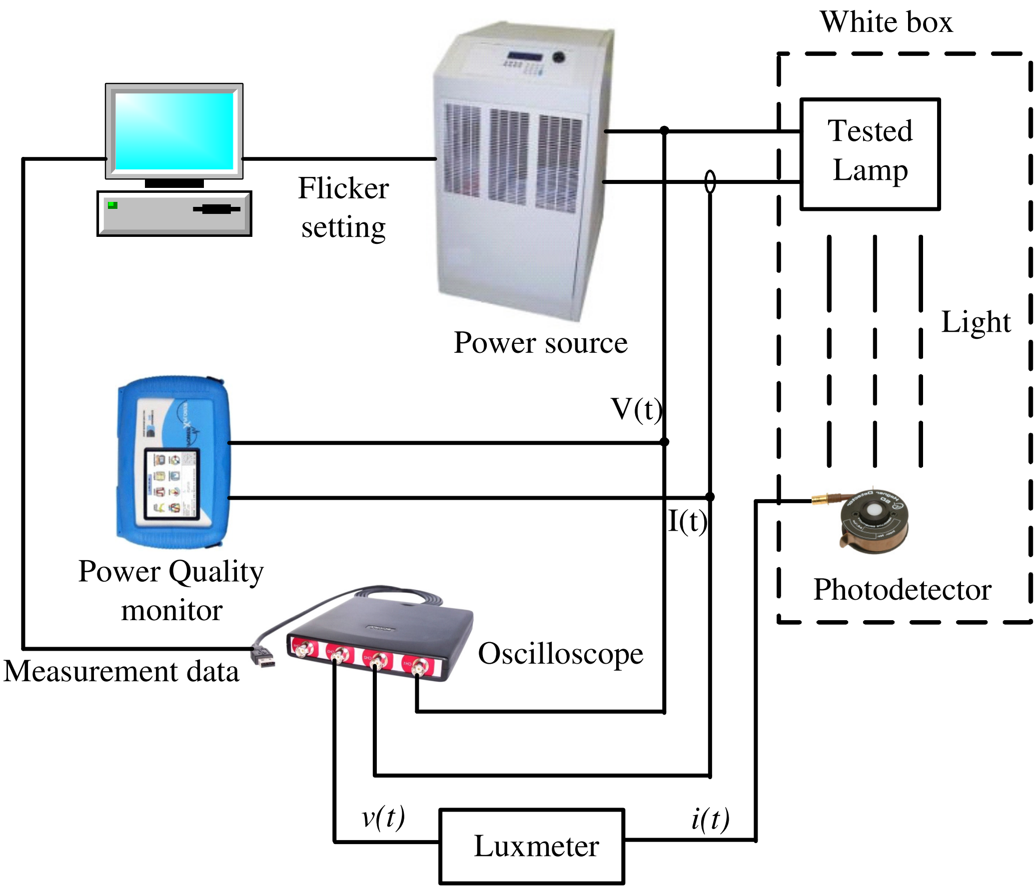


Figure 3.1 The scheme of flicker response measurement in the lab

The measurement results are further analyzed by Fast Fourier Transform (FFT) using Matlab. The analyzed measurement results are used to develop the lamp flicker response model by a linear system identification method. It is tested by the system identification toolbox in Matlab. The improved flickermeter models for different lamp types are tested by simulation, which is carried out in Matlab/Simulink.

1.6 Thesis outline

The outline of the thesis is:

- Chapter 1 gives the general introduction of power quality aspects. The definition, sources, measurement and mitigation of flicker are introduced in this chapter. The research background and objectives are described
- Chapter 2 introduces the background knowledge of flicker measurement research, the human visual system, light measurement and the flicker fusion boundary. For further understanding the flicker

measurement, the development history and the structure of the classical flicker measurement tool, the UIE/IEC flickermeter, are also treated in detail in this chapter.

- In chapter 3, the flicker response measurements for different lamp types are described. The measurement results and further analysis are presented in this chapter. As additional background knowledge, the working principles and the voltage-current characteristics of the tested lamp types are introduced as well. At last, the deficiencies of the UIE/IEC flickermeter are discussed.
- Chapter 4 describes the development of the lamp flicker response models for different lamp types, using a linear system identification method. These models are used to develop new weighting filters for different lamp types. The improved flickermeter models of the different lamp types, which are obtained by the use of the improved weighting filters instead of the classical weighting filter in the UIE/IEC flickermeter, are given. These models are tested by simulation and the results are presented in this chapter.
- Chapter 5 presents the measurement results of the lamp light spectrum flicker response for different lamp types. The derivation of the weighting factors of different lamp types, which can indicate the human eye flicker response from the human eye spectrum sensitivity point of view, are described in this chapter. The discussion about the development of the new flicker measurement method based on the lamp light spectrum flicker response is given in this chapter as well.
- In chapter 6, the measurements of the interaction between flicker and dimmers are presented. The measurement results and further analysis are given in this chapter. Based on the measurement results, the solutions to solve flicker caused by dimmers are discussed as well.
- Chapter 7 gives the general conclusions of the research work presented in this thesis and highlights the thesis contribution. Finally, suggestions for future work are presented.

1.7 IOP project

The research presented in this thesis has been performed within the framework of the ‘Intelligent Power Systems’ project. The project is part of the IOP-EMVT program (Innovation Oriented research Program – Electro-Magnetic Power

Technology), which is financially supported by SenterNovem, an agency of the Dutch Ministry of Economical Affairs. The 'Intelligent Power Systems' project has been initiated by the Electrical Power Systems and Electrical Power Electronics groups of the Delft University of Technology and the Electrical Power Systems and Control Systems groups of the Eindhoven University of Technology. In total 10 Ph.D. students are involved in this project and work closely together. The research of the IOP project focuses on the effects of the structural changes in generation and demand taking place in the electricity supply system, e.g. the large scale introduction of distributed (renewable) generators [18]. The project consists of four parts as illustrated in figure 1.3.

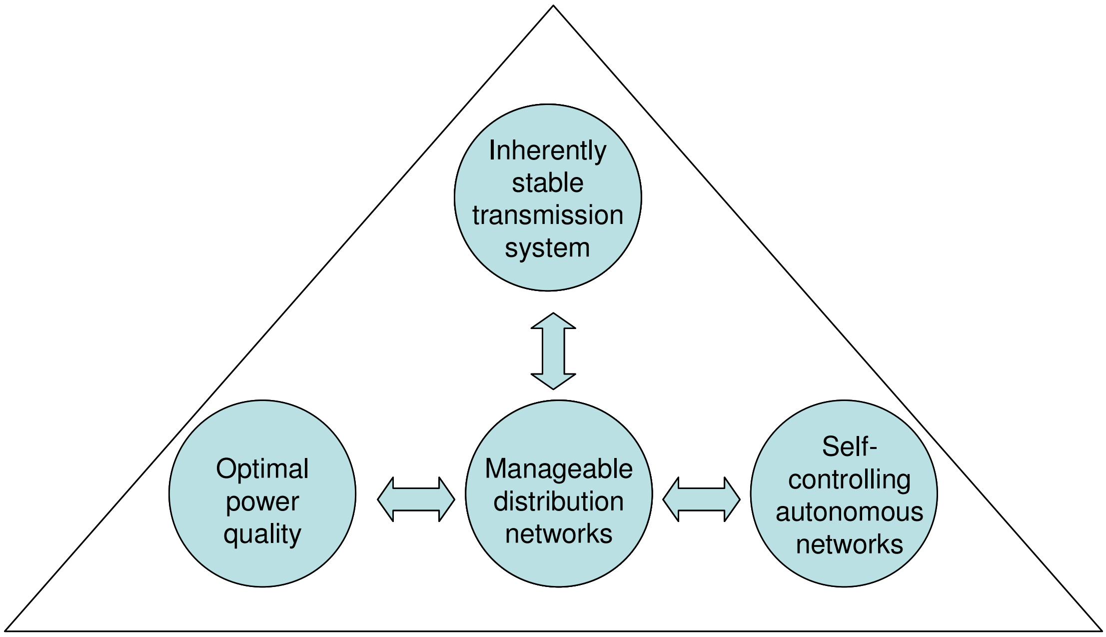


Figure 1.3 The structure of the IOP project [18]

The first part, inherently stable transmission system, investigates the influence of uncontrolled decentralized generation on stability and dynamic behavior of the transmission network. As a consequence of the transition in the generation, less centralized plants will be connected to the transmission network as more generation takes place in the distribution networks, whereas the remainder is possibly generated further away in neighbor systems. Solutions that are investigated include the control of centralized and decentralized power, the application of power electronic interfaces and monitoring of the system stability.

The second part, manageable distribution networks, focuses on the distribution network, which becomes 'active'. Technologies and strategies, which can operate the distribution network in different modes and support the operation and robustness of the network, have to be developed. The project investigates how the power electronic interfaces of decentralized generators or between network parts can be used to support the grid. The stability of the distribution network and the effect of the stochastic behavior of decentralized generators on the voltage level are investigated as well.

Autonomous networks are considered in the third part, self-controlling autonomous networks. When the amount of power generated in a part of the distribution network is sufficient to supply a local demand, the network can be operated autonomously but as a matter of fact remains connected to the rest of the grid for security reasons. The project investigates the control functions needed to operate the autonomous networks in an optimal and secure way.

The interaction between the grid and the connected appliances has a large influence on the power quality. The fourth part of the project, optimal power quality, analyses all power quality aspects. The aim is to provide the necessary information for the discussion between the polluter and the network operator who has to take measures to comply with the standards and grid codes. Setting up a power quality test lab is an integral part of the project. The research presented in this thesis fits within research part four.

Chapter 2

Flicker Measurement – the UIE/IEC Flickermeter

2.1 Introduction

This chapter gives a brief overview about the flicker measurement tool – the UIE/IEC flickermeter. After a long development of flicker measurements, the current UIE/IEC flickermeter has been obtained. However, this flickermeter still has limitations on some applications. This will be discussed in detail in this thesis.

2.2 Background on flicker research

Flicker is defined as the impression of unsteadiness of the visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time [5]. It is caused by voltage variations in the electrical power system and brings annoyance to human beings. The human eye is the most important responder to the light. In order to start flicker research, a review of some information about the human visual system and light measurement is given in this section.

2.2.1 Human vision

When people look at light and lighting or reflecting surfaces of objects, the color and brightness are two important features that people notice. Flicker is a kind of sensation of the human eyes. Any sensation of the eyes depends on the structure of the visual system. It is important to know the physiology structure of the human visual system.

The basic physiology structure of the human visual system is shown in figure 2.1 [19].

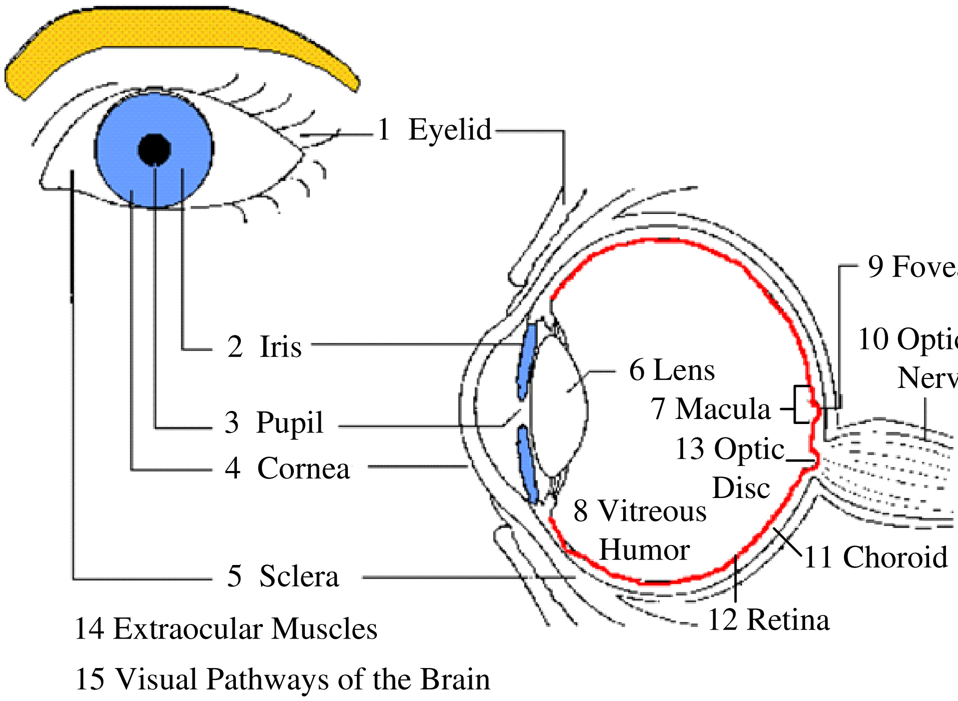


Figure 2.1 The physiology structure of the human eye [19]

In principle, there are 3 layers of cells that compose the human eye: the sclera, the choroids and the retina [20]. The sclera is the outer layer of the eye. It is tough and white. Its function is to protect the inner part of the eye and to maintain the shape of the eye. In front of the sclera is the transparent cornea. It is used to allow rays of light to enter the eye and help to focus them on the retina. The choroid is the middle layer of the eye. It absorbs excessive light, controls the iris and the pupil. The choroid also controls the ciliary body that consists of circular ciliary muscles. The lens is attached to the ciliary body and is biconvex, elastic and transparent. It helps to focus the light on the retina so that the human being can see the objects both far and near clearly and sharply. By adjusting the size of the pupil, the iris controls the amount of light that enters the eye. The retina is the innermost layer of the eye. There are many receptors on the retina to be used to absorb the light and start the electrophysiological process that sends visual signals to the brain. According to the shape of these receptors, they are classified as two types: the rods and the cones. Rods are used to see during the night or under very low illumination. They are very sensitive but color blind. The rod receptors are absent in the central (fovea) area of the retina. Since the vision mainly depends on the rod receptors at very low luminance levels, the object is seen easier 'out of the corner of the eye' than when it is on the centre of visual observation. Furthermore, the world in the dark is colorless [21]. According to the wavelength sensitivity, the cone receptors can be sorted on three classes: L-receptors are most sensitive to long wavelength light (e.g. red light), M-receptors are most sensitive to middle wavelength light (e.g. green light) and S-receptors are most sensitive to short wavelength light (e.g. blue light). The ends of all receptors are called the outer segments. These outer segments contain photopigments with known spectral absorbencies which starts the neurophysiological process that sends signals to the brain finally when they receive light.

Vision is the end-product of a number of stages of coding and analysis which together give meaning to the various patterns of ambient luminance and chromaticity [20]. The visual process is initiated when the light rays, focused by the lens, hit receptors of the retina. These receptors contain photosensitive pigments that act as transducers, effectively converting light energy into the nerve impulses that initiate the visual process. The eye of human beings works as a camera. The first stage of vision happens when the rays of the light enter the eye. The lens projects an inverted image onto the retina. Its curvature, and hence its focal length, is controlled by the ciliary muscle. This operation, known as accommodation, makes that both far and near objects can be perceived by the retina clearly and sharply. The aperture of the lens is governed by the iris, which determines the pupil diameter. The same as in an automatic camera, the aperture is enlarged at low luminance and constricted at high luminance. The retina is the interface between the optical processes and the electrophysiological processes of vision. It is the place where the first stages of visual information processing take place. The transmission, analysis and coding of the retina image are carried out by a network of nerve cells or neurons. These communicate through nerve impulses, which are sudden changes in the interior electrical potential.

2.2.2 Light measurement

Generally light can be measured by two types of measurement instruments: the radiometer and the photometer [19]. Radiometers measure the radiant energy (the unit is Joule) emitted or reflected by the light source, i.e. the radiance of the light. This is a strictly physical measurement. However the measurement results of radiometers are not the same as what human beings see. For example, red, yellow and green light can be adjusted to emit equal energies of light. The observers will still say that yellow light is much brighter than red and green light. They would also say that green light is brighter than red. Why do these observers give these conclusions? This is due to the fact that the sensitivity of the human visual system depends on the wavelength of the light, i.e. the spectral sensitivity. Therefore radiometers are inadequate to measure the human visual perception.

Photometers measure the luminous flux (the unit is lumen) of the light. They attempt to take into account the average spectral sensitivity of the observer [19]. The sensitivity of the human eye is not uniform over the whole visible spectrum. For the spectral sensitivity of the human being, the Commission Internationale de l'Eclairage (CIE) defined a luminous efficiency function as a standard, shown in figure 2.2.

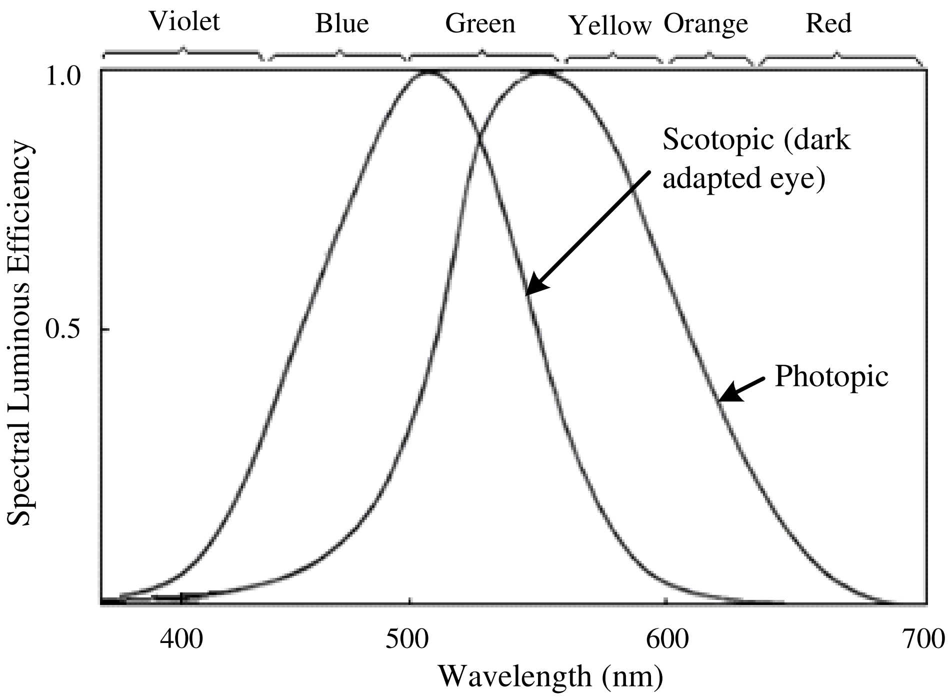


Figure 2.2 Relative spectral sensitivity of the human eye [21]

The right-hand curve is for the human view under bright viewing conditions, the so called photopic vision. For this vision, the luminance surrounding is generally above 10 cd/m^2. The maximum visual sensitivity is in the yellow-green range of the spectrum, at a wavelength of 555 nm. The left-hand curve is for the human view under dark conditions, the so named scotopic vision. The surrounding luminance is normally below 10^{-2} cd/m^2 and the eye has an adaption time to the dark up to 30 minutes. As the curve shows, the peak of the scotopic spectral sensitivity is located at 507 nm. This shows a shift towards the blue compared with the photopic curve. According to CIE comments, the photopic and scotopic curves are only correct for the targets that are presented within a 2 degree visual angle (i.e. the observed targets are put in front of the eye of the observer). Mostly the photopic vision commands draw greater attention because the relatively high brightness is normally considered in the lighting technology. There are several photometric techniques, e.g brightness matching and heterochromatic flicker photometry etc.

2.2.3 Flicker fusion boundary study

The flicker problem was noticed quite early. At the beginning of the twentieth century, the first flicker fusion boundary measurements were made [22]. These measurements studied the relationship between the light intensity threshold and the luminance variation frequency as observed by human beings. The effort was to find the condition in which the observer can not see flickering light while the fluctuation with the same amplitude can cause flickering sensation with a lower variation frequency.

T. C. Porter is the first person who determined the critical modulating voltage frequency f_c at which the flickering sensation disappears for an observer, as a function of the illumination of the flickering light. He produced flickering light by the use of a rotating sectored disc with one white and one black sector of equal widths. From his experimental work, he derived the equation below, the so called 'Porter's law' [23]:

$$f_c = k \log E + k' \tag{2.1}$$

Where E is the illumination

k and k' are constants, both depending on the shape of the brightness (sinusoidal or rectangular) versus time.

Simons also did an investigation and presented his results in a paper in 1917 [24]. He showed that under certain conditions the critical modulating voltage frequency of the flickering light at the flicker fusion boundary is directly proportional to the logarithm of the illumination level of the light. This conclusion confirms Porter's law.

After Porter, more research was done by R. J. Lythgoe and K. Tansley in 1929 [25]. They proved that the critical modulating voltage frequency f_c not only depends on the average brightness of the flickering field but also on the degree of adaptation, the illumination of the environment and the location of the flickering spot on the retina [25]. Therefore, it is necessary to specify the conditions in which the experiments are carried out. H. de Lange did further measurements to prove the flicker fusion boundary as well. This work will be described in detail in the next section.

From all the investigations made later, D. H. Kelly's work is worth to be particularly mentioned here. He did measurements on the amplitude sensitivity of the visual response to time-dependant stimuli. In his papers [26] [27], he presented several plots based on the measurement of the visual response to the sinusoidal stimuli of one typical observer. He made five types of tests. These are:

1) The relative amplitude sensitivity versus the modulation frequency at six adaptation levels;
2) The absolute amplitude sensitivity versus the modulation frequency at six adaptation levels;
3) The relative amplitude sensitivity versus the adaptation level at six modulation frequencies;
4) The threshold frequency versus the adaptation level at seven relative amplitudes with a logarithmic frequency unit;
5) The threshold frequency versus the adaptation level at seven relative amplitudes with a linear frequency unit.

The conclusion of his work is that it is worthwhile to pursue the hypothesis that the present results represent some sort of average photopic behavior of individual retinal channels in response to time-dependent white-light stimuli [26] [27].

The experimental work on flicker fusion as described above studied the luminance variation which causes human beings to have a flicker sensation. However, the current research work wants to establish the relationship between voltage fluctuations and the visual perception because today fluctuating loads are used in the power system, e.g. welding machines etc. These can cause fluctuating voltages and therefore cause luminance variations.

2.3 UIE/IEC flickermeter development

To evaluate the flicker level in power systems, it is necessary to develop a measurement tool that can represent the relationship between voltage fluctuations and the human vision system. Therefore, an instrument called a flickermeter has been designed to measure any quantity representative of flicker and has been improved continually. Currently, the UIE/IEC flickermeter is well-known. In this section, two important developments during the history of the UIE/IEC flickermeter are described.

2.3.1 De Lange experiments

After other researcher's valuable work, De Lange did further experimental work to find the flicker fusion boundary in the 1950s. Based on his measurement results, an analogue model that can reconstruct the flicker fusion boundary has been built. His model became an important basis for the weighting filter of the UIE/IEC flickermeter. His experimental work is briefly described in this section.

2.3.1.1 Measurement set-up

As mentioned in section 2.2.3, the flicker fusion experimental results of Lythgoe and Tansley proved that it is important to know the conditions in which the measurements are made. De Lange selected a fovea (in front of the eye) flickering field with an visual angle of 2 degrees and a surrounding field with a constant brightness, equal to the average brightness of the flickering field in his measurements [28]. De Lange described his measurement set-up in detail in his thesis [29].

Figure 2.3 shows the light path in the measurement set-up of De Lange. The light source L, a 6V car lamp with a coiled filament, was put inside a lamp housing, which has two holes with an area 2 x 2 mm^2 on the left and right walls. The observer sat before a light box and had the eye at the observation position, which was 22cm away from the front wall of the light box. The pupil of the observer and the central point of two holes on the front and back wall of the light box were in line. The size of the hole Ea on the back wall of the light box was specially designed to limit the light observed by the observer's pupil to a visual field of 2 degrees.

As shown in figure 2.3, the light beams generated by L pass through the holes of the lamp housing and are bent by two surface mirrors A and B. After passing the photographic objectives O_{a1} and O_{b1}, both of them are imaged on the same spot of the opaline glass plate S_a. The light spot can be reflected on the pupil of the observer through the holes of the light box by adjusting the lens O_{a2}, whose surface gave a uniform luminance.

In De Lange's measurement set-up, the intensity of the light beams generated by light source L can be reduced in thirty stages by putting Kodak density stripes (F_{a1} and F_{b1}) and neutral filters (in the holders H_{a1} and H_{b1}) between the lamp housing and the surface mirrors A and B. Furthermore, the luminance of each light image on S_a can be continuously adjusted by the apertures D_a and D_b.

To get 100% sinusoidal modulated light, each light beam should pass through a fixed polaroid filter (P_{a1} and P_{b1}) and a rotating polaroid disc (P_{a2} and P_{b2}), which were put between the Kodak density strips (F_{a1} and F_{a2}) and the neutral filters (in the holders H_{a1} and H_{b1}). This is due to the fact that the polaroid filter and disc can prevent certain light to pass. The experimental results proved that ±5% luminance variation will occur because of the rotation of the rotating polaroid disc if the light beam does not pass through the fixed polaroid filter. It is therefore important to let the light beam pass the fixed and the rotating Polaroid filters following the sequence shown in figure 2.3.

In De Lange's experimental work, the measurement set-up and the method to get the modulated light are complicated. This is due to the limitation of the technology during that period. Nowadays, the modulated light can be easily obtained by feeding a modulated voltage to the lamp.

2.3.1.2 Measurement results with white light

De Lange defined flicker fusion curves from the measurement results of the observers. The observer was presented a new modulated voltage each time and answered "yes" or "no". "Yes" means that somewhere in the test field a variation can be seen. When the answer is "no", there is no variation to be seen in the test field. The flicker fusion has just been reached when the observer says "no" which follows the last position with the answer of "yes". The lowest modulating voltage frequency used in the experiments is 1.5Hz. In the thesis of De Lange, he said "the lowest frequencies are the most difficult to observe because of the rhythm of the heart beat and also the difference in the nature of the flicker perception depending on the frequency" [29].

Similar flicker feeling measurements were made in the PQ lab of TU/e. The results show also that the low frequencies (lower than 2Hz) are more difficult to be observed by male observers than the high frequencies (higher than 2Hz). However, this phenomenon does not exist for female observers (see appendix C).

The measurement results of two observers are presented in De Lange's thesis [29]. To better understand his results, one important ripple-ratio he used should be known. It can be written in equation from:

$$r = \frac{\text{amplitude of fundamental frequency (modulating voltage frequency)}}{\text{average brightness}} \tag{2.2}$$

For both observers in De Lange's measurements the critical value r_0 at the threshold shows only a small variation for an average brightness between 3 and 1000 photons (The photon corresponds to the retinal illumination level and equals the amount of light that reaches the retina through a 1mm^2 of pupil area from a surface with distance of 1m and the illumination level of 1cd/m^2). For one observer V, r_0 varies in the value from 2.1 to 1.8. For another observer L, this ratio varies from 2.2 to 1.2. Below 3.75 photons r_0 rapidly increases. The measurement results of the observer V are shown in figure 2.4. The results show the relationship between the ripple-ratio and the critical modulating voltage frequency (in Hz) for different values of the average brightness (in the unit of photons). At high illumination levels, the ripple-ratio is lower than the ratio under lower illumination levels for the same modulating voltage frequency. For the same ripple-ratio, the modulating voltage frequency is higher at higher illumination levels.

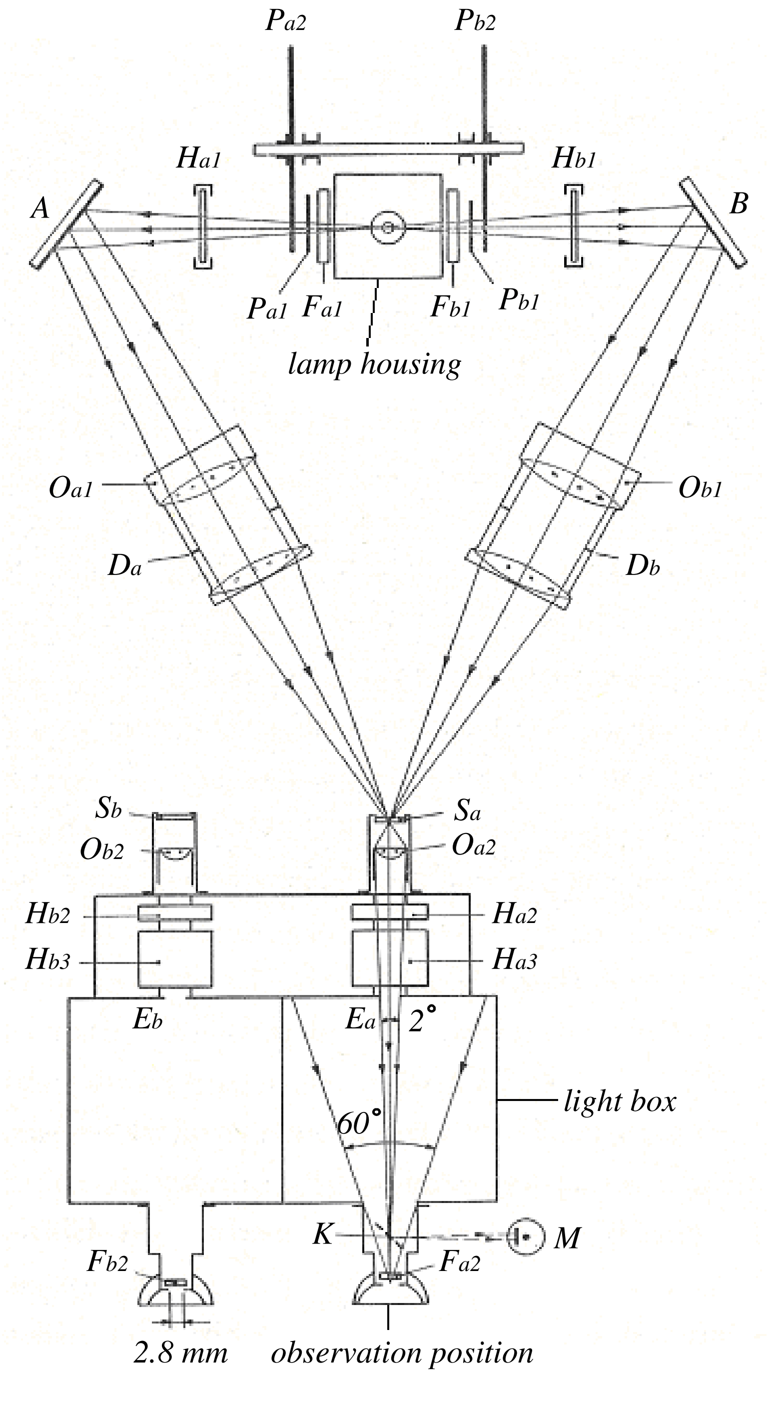


Figure 2.3 Light paths in the flicker apparatus of De Lange [29]

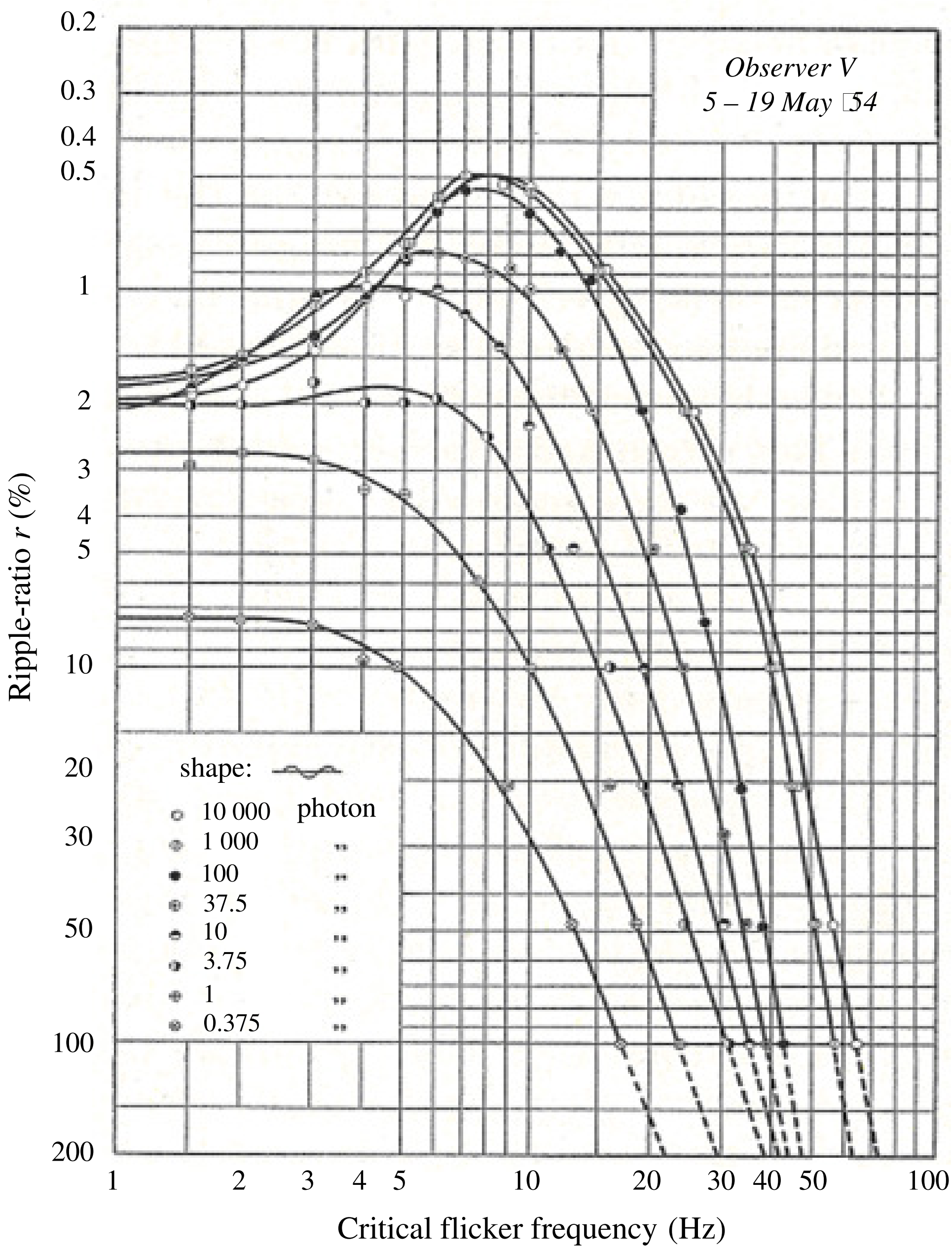


Figure 2.4 Measurement results of De Lange [29]

2.3.1.3 Flicker fusion analog model

In De Lange's work, an important assumption is that each fovea system (the combination of the light sensitive element (cone), the nerve elements and the brain) shows the characteristics as a low-pass filter. When the frequency is equal to the critical modulating voltage frequency at constant average brightness, the human eye reacts on any periodic brightness variation as a linear system [28].

From the flicker fusion measurement results, an analog model was obtained to rebuild the flicker fusion curves by using resistors and capacitors. This analog model is based on this important linear assumption and offers the possibility to develop the flickermeter. This is the most important contribution made by De Lange to the development of the UIE/IEC flickermeter.

2.3.2 The Rashbass model

Another investigator C. Rashbass also contributed significant flicker knowledge to the UIE/IEC flickermeter. Part of the flickermeter model has originally been developed from the Rashbass model.

De Lange tested the flicker fusion boundary (i.e. the light intensity threshold vs. the illuminance variation frequency when the human being can see the illuminance variation) for symmetric and asymmetric sinusoidal illuminance variations. However, Rashbass would find the general relationship between the light intensity threshold (i.e. the light intensity values when the human being can see the illuminance variation) and the duration of the illuminance variation, for different illuminance variation shapes, e.g. the rectangular illuminance variation and the sawtooth illuminance variation etc.

First, Rashbass did measurements to find the light intensity threshold of the rectangular illuminance variation versus their duration. The measurements were made using single positive or negative going flashes with a duration from 2ms to 120ms. (These two types of flashes were used to improve the measurement accuracy. By increasing the amplitude of flashes until the light intensity threshold is found, these flashes are called positive going flashes. By decreasing the amplitude of flashes until the light intensity threshold is reached, these flashes are called negative going flashes). The measurement results are shown in figure 2.5. The horizontal axis shows the duration of the positive or negative going flash in milliseconds. The vertical axis shows the per unit value of the light intensity threshold of the flash. The light intensity threshold of a 2ms positive going flash was considered as unity [22]. The measurement results show that the relative light intensity threshold decreases when the duration of the flash increases up to 64ms. The minimum threshold intensity appears when the flash duration is 64ms. In his measurement, the results did not show a clear difference between positive and negative going flashes.

Secondly, Rashbass made his measurements with two brief flashes. A brief flash is a flash with a duration which is much smaller than the time interval between the flashes. He tested the relationship between the light intensity threshold of the first flash and the second flash, called A and B respectively, for different time intervals between them. The light intensity threshold A was plotted against B for different time intervals between the two brief flashes and these plots are shown in figure 2.6.

The horizontal and the vertical axis's represent the light intensity threshold A and B respectively. However, the detailed values are not mentioned in the literature.

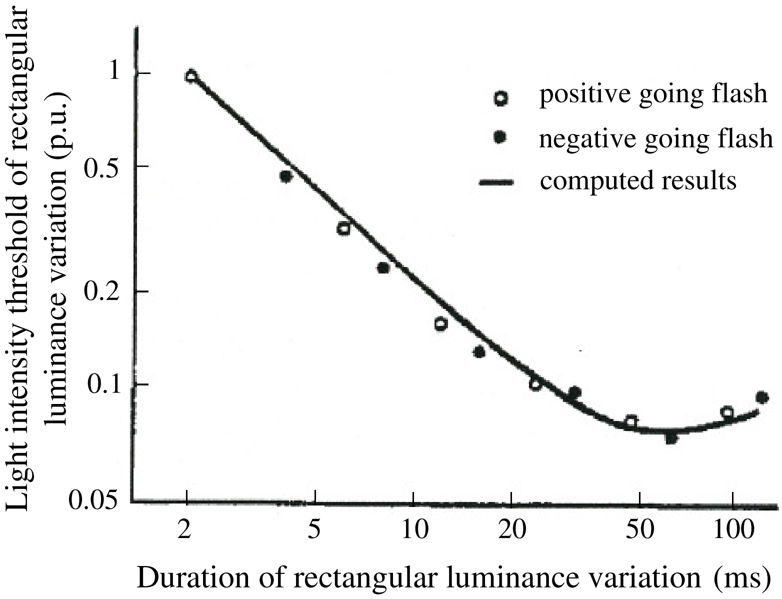


Figure 2.5 Per unit values of the light intensity threshold of rectangular illuminance variation versus their duration [22]

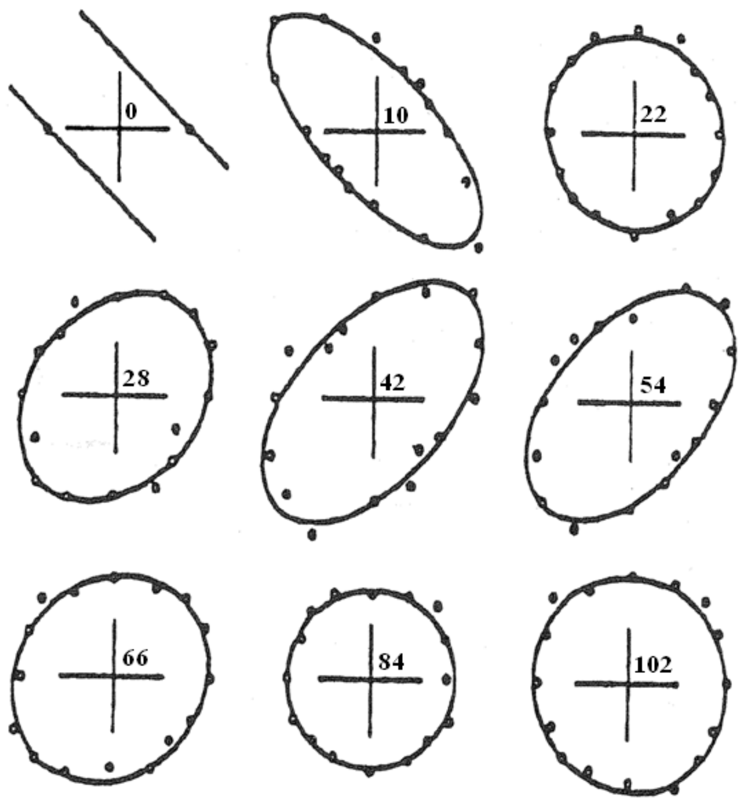


Figure 2.6 Light intensity thresholds of two brief flashes with different time intervals between them. The time interval between the flashes is marked in ms on each plot. The horizontal and vertical axises of all plots are the light intensity threshold A (of one flash) and B (of another flash) respectively [30]

After many tests, Rashbass drew the conclusion that an ellipse is the best fit to the experimental points of the light intensity thresholds of two brief flashes for a corresponding given flash interval (see figure 2.6) [30]. This important conclusion offers the possibility to build a model that can evaluate the human flicker sensation. This is due to the fact that the human flicker sensation is caused by flickering light that can be simplified as the combination of two illuminance changes, e.g the flashes used in the measurements of Rashbass. If the magnitudes of the light intensity of two illuminance changes at threshold (i.e. the threshold that the human being can see flicker) can be defined, the human flicker sensation will be known. The elliptical characteristic of the relationship between the magnitudes of the light intensity of two illuminance changes at the threshold, which are obtained by Rashbass, solves the problem mentioned above. The human flicker sensation therefore can be evaluated.

In [30], Rashbass shows a simple model that can reproduce the ellipses experimental results. This model has three important elements:

1) The first element is a linear filter whose characteristics are similar to those of the filter proposed by De Lange [30]. Since the very brief flash was used in the experimental work of Rashbass, the duration of this brief flash defines the frequency of the flash (the flash is considered as a signal of one cycle). As known from the flicker fusion boundary studies and De Langes experimental work, the light intensity of the illuminance change should reach a certain value for a given frequency of illuminance change when the human being can see the flicker. Thus, Rashbass proposed a filter as the first element in his model to represent the relationship of the light intensity threshold of the illuminance change versus the frequency of the illuminance change. For simplicity, this filter was assumed to be linear.
2) The second element is the generation of the square of its input. Figure 2.6 shows the elliptical relationship between the light intensity threshold (A and B) of two brief flashes. To represent this elliptical characteristic, the square function is required.
3) The third element is an integrator. It is used to represent the independence of the light intensity threshold from the sequence. This means that the human being will have the same flicker feeling whatever the sequence of the two flashes, e.g. the flash with the light intensity threshold A occurs first and the flash with the light intensity threshold B occurs secondly, or these two flashes occur in reverse sequence. This function is taken into account by the integration over the whole waveform.

The Rashbass model can be understood as: if the input waveform is F(t), it will be linearly transformed into another function f(t) after passing through the first filter element. Then f(t) will appear in the form of the following equation after the next two steps:

$$\int_{0}^{\tau} f^{2}(t)dt \tag{2.3}$$

Where τ is the integration time that is longer than the stimulus duration. Rashbass proposed this integration time as a constant of 150ms to 250ms [30] that gives a good matching to his results. He proved that his mathematical equation can represent the elliptical characteristics of his measurement results.

The block diagram of the Rashbass model is shown in figure 2.7. As explained earlier, the Rashbass model can be used to evaluate the human flicker sensation due to its three elements. It is the basis of the flickermeter.

Input	Model blocks			Output
	I	II	III	
Luminance variations (voltage fluctuations)	Weighting filter (De lange)	Squaring circuit	First order low-pass filter	Instantaneous flicker sensation

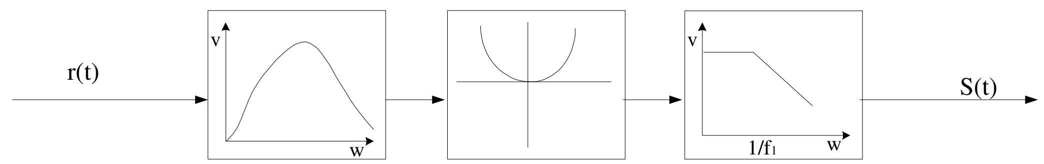


Figure 2.7 Block diagram of the vision perception model proposed by Rashbass and Koenderink [22]

Rashbass used his model to compute the solid curve in figure 2.5 that gives the perception threshold of flash. It matched well with the experimental results. He made more measurements to verify his model by using different combinations of two arbitrary flash shapes, e.g. two rectangular flashes of unequal duration etc. The detailed measurement results can be found in [30]. All experimental results fit the ellipse as described by his model shown in figure 2.7. Later, J.J. Koenderink and A. J. van Doorn proved the validity of the analogue model proposed by Rashbass.

2.4 UIE/IEC flickermeter structure

The UIE/IEC flickermeter has been developed based on several flicker measurement instruments in France, Germany, the United Kingdom and Japan. There are four important national flickermeters, which existed already before the UIE/IEC flickermeter. These national flickermeters have been used for many years to give the evaluation of the maximum tolerable limits for voltage disturbances caused by arc furnaces or other equipment.

- **The ERA (Electrical Research Association, British) meter**
  This meter measures the rms voltage with the variation frequency from 0.5Hz to 27Hz. By using a time constant of approximately 100s, a reasonable steady output is obtained. This meter has been used to give the guidelines for the supplies of electric arc furnaces in the United Kingdom [22].
- **The EDF (Electricité de France) meter**
  The voltage fluctuation from 0.5Hz to 25Hz can be detected by this meter. Inside the meter, the voltage fluctuation signal passes the weighting filter, followed by squaring and averaging. Finally the A/D converter will transfer the digital results to a magnetic tape recorder. The result is called flicker dose which can indicate the flicker level of the fluctuating voltage.
- **The FGH (Forschungsgemeinschaft für Hochspannungs und Hochstromtechnik, German) meter**
  The modulated voltage signal is detected and demodulated by an incandescent lamp and a demodulator filter. Then the signal is weighted by a set of 12 filters, which have centre frequencies in the range of 0.7 to 28Hz. These weighting filters have different sensitivities to the perceptibility for periodical signals. This meter can accurately measure the triangular and saw-tooth shaped waveforms. The highest output of the weighting filters are smoothed and give the instantaneous flicker level as the output of the meter. This meter is also capable to do long period flicker measurements.
- **The ΔV_{10} (Japanese) meter**
  This is a meter built in Japan to measure flicker. The most popular one is called $\Delta V_{10.}$ It is similar to the EDF meter. The biggest difference is the sensitivity curve based on a 100V filament lamp.

Since the above national meters did not give the universal results which can indicate the flicker level, UIE started to build an international used flickermeter. Thus, the UIE/IEC flickermeter should meet the following requirements [11] [22]:

1) Indicate the instantaneous values of flicker ('sensation').
2) For the same feeling ('sensation') of flicker, the flickermeter should give the same indicated value whatever the modulation form of the voltage. It should work well for different environments, e.g. arc furnace or welding machine etc.
3) Capable of long-term duration measurements.
4) Give results as a simple function of the amplitude of the voltage fluctuations.
5) Capable to measure regular and irregular voltage fluctuations in a frequency range of at least between 1 and 35Hz in 50Hz systems or between 1 and 40Hz in 60Hz systems.
6) Easy to handle the instrument by one single person.
7) Possible to easily check the correct operation by simple methods.
8) Give a simple numerical result that can be compared with the admissible value.

There is a lamp-eye-brain model built inside the UIE/IEC flickermeter. It is able to simulate the physiological sensitivity of the human eye that is subjected to a reference incandescent lamp (60W, 230V).

In total the UIE/IEC flickermeter includes 5 blocks. Figure 2.8 shows the schematic structure of the flickermeter. Each block is described in detail in the text below:

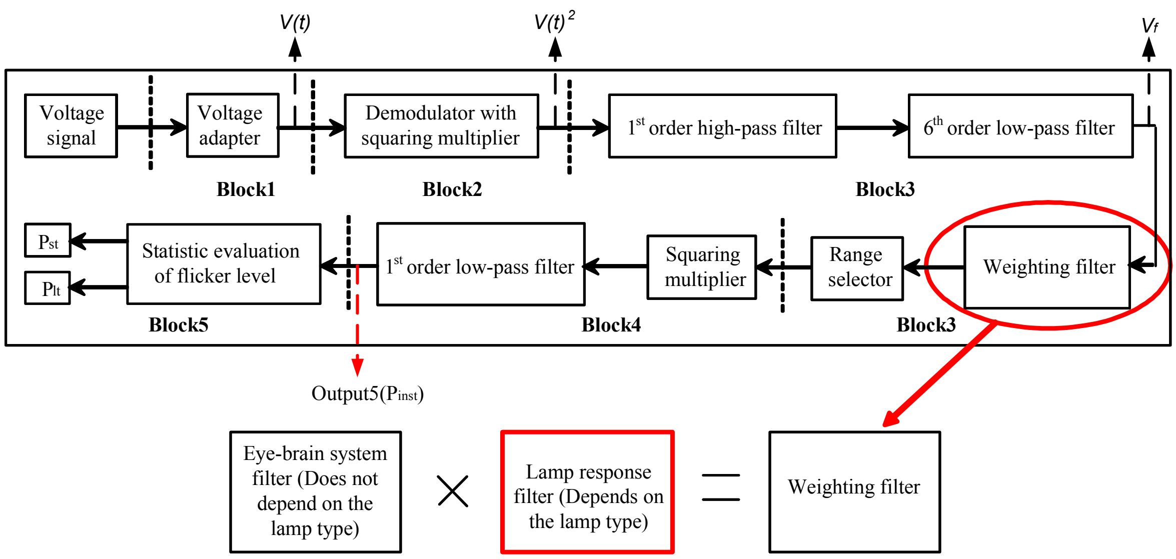


Figure 2.8 The structure of the UIE/IEC flickermeter

2.4.1 Block 1 - input voltage adapter

The supply voltage is the input of this block. In this block, there is a voltage adapting circuit that can scale the rms value of the input voltage down to an internal reference level and does not modify the modulated voltage waveform. This makes that all flicker measurements can be done independently from the input carrier voltage level. The output of this block is the normalized rms value of the input voltage.

2.4.2 Block 2 - squaring multiplier

For the referenced incandescent lamp, the light produced by the lamp depends on the energy consumed by the lamp. The consumed energy by the lamp is proportional to the square of the input lamp voltage. This block is used to simulate this squaring behavior of the lamp. Since the incandescent lamp has a thermal time constant because of the filament of the lamp, a low pass filter function is used to present this time constant function and it is part of the weighting filter in block3.

Let

$$V(t) = A(\cos \omega t)(1 + m \cdot \cos \omega_m t) \tag{2.4}$$

Where *V(t)* is the supply voltage with amplitude *A* and angular frequency ω, which is modulated by a sinusoidal waveform with the amplitude *m* and angular frequency ω_m.

The signal at the output of the squaring multiplier has the following form:

$$\begin{aligned} V(t)^2 = {} & \frac{A^2}{2}(1+\frac{m^2}{2}) + \frac{A^2}{2}(1+\frac{m^2}{2})\cos 2\omega t + \frac{m^2A^2}{8}\cos 2(\omega+\omega_m)t \\ & + \frac{m^2A^2}{8}\cos 2(\omega-\omega_m)t + \frac{mA^2}{2}\cos(2\omega+\omega_m)t + \frac{mA^2}{2}\cos(2\omega-\omega_m)t \\ & + mA^2\cos\omega_m t + \frac{m^2A^2}{4}\cos 2\omega_m t \end{aligned} \tag{2.5}$$

2.4.3 Block 3 – filters

This block consists of series circuits of two filters.

- Demodulator filter (high-pass filter + low-pass filter)

  The demodulator filter includes a first order high-pass filter (3dB cut-off frequency at 0.05Hz) to filter the DC-component caused by the squaring function in block 2 and a low-pass filter to filter all components that are equal to or greater than the fundamental frequency of the carrier voltage. A 6^{th} order low-pass Butterworth filter (gives 3dB cut-off frequency at 35Hz for a 50 Hz system and 3dB cut-off frequency at 40 Hz for a 60 Hz system) is recommended in this block.

  By filtering the DC-component and all frequency components higher than the fundamental angular frequency ω, only the following terms are remaining:

$$V_f = mA^2 \cos \omega_m t + \frac{m^2 A^2}{4} \cos 2\omega_m t \tag{2.6}$$

- Weighting filter
  The weighting filter simulates the frequency response of a coiled filament gas filled lamp and the human visual system. As mentioned in block 2, the filament lamp has a thermal time constant function, it is considered as a low-pass filter with a cut-off frequency of about 6 Hz. The weighting filter is designed based on the German and French flickermeters that existed in the 70s. The transfer function of the weighting filter is described as:

$$F(s) = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2} \times \frac{1 + s/\omega_2}{(1 + s/\omega_3)(1 + s/\omega_4)} \tag{2.7}$$

For a 60W 230V incandescent lamp:
$k = 1.74802$
$\lambda = 2\pi 4.05981$
$\omega_1 = 2\pi 9.15494$
$\omega_2 = 2\pi 2.27979$
$\omega_3 = 2\pi 1.22535$
$\omega_4 = 2\pi 21.9$
For a 60W 120V incandescent lamp:
$\lambda = 2\pi 4.167375$
$\omega_1 = 2\pi 9.077169$
$\omega_2 = 2\pi 2.939902$
$\omega_3 = 2\pi 1.394468$
$\omega_4 = 2\pi 17.31512$

2.4.4 Block 4 - non-linear variance estimator

This block consists of a squaring block and a first-order low-pass filter with a time constant of 300 ms. This block is used to simulate the delay effect of the human brain. The output of this block is called “output 5” of the flickermeter [31]. It is the instantaneous flicker level. A flickermeter is calibrated to produce a maximum instantaneous flicker value of 1 when the amplitude and frequency of the modulated voltage as shown in table 3.2 in chapter 3. A value of one unit of flicker levels is based on the human perceptibility threshold for 50% of observers looking a 60W 230V incandescent lamp.

The output of this block is the instantaneous flicker level P_{inst}. Since the input signal (voltage) of the flickermeter is a periodical signal, P_{inst} is also periodical signal. The maximum value of $P_{inst,}$ which is also called the maximum perceptibility at output 5 in [31], is an important value in the flicker measurement. It is used in standard IEC 61000–4–15 to define the voltage modulation amplitude for each specific voltage modulation frequency. The information of the modulated voltage can be used also to evaluate the performance of the flickermeter. There is a ratio of 0.68 between the maximum value of P_{inst} and the short-term flicker level indicator P_{st} for the voltage modulation frequency range 0.5Hz – 25Hz.

2.4.5 Block 5 - statistical calculation block

This block 5 is used to do the statistical calculation for the short-term flicker indicator P_{st} and the long-term flicker indicator P_{lt} by using the time-at-level method [31].

- Short-term flicker indicator (P_{st})

  The P_{st} value presents the perceived flicker severity averaged over a ten-minutes measurement interval. A value of 1.0 or higher represents a flicker level that will bring annoyance to an observer. The P_{st} value can be calculated by the equation:

$$P_{st} = \sqrt{0.0314 P_{0.1} + 0.0525 P_{1s} + 0.0657 P_{3s} + 0.28 P_{10s} + 0.08 P_{50s}} \quad (2.8)$$

  Where the percentiles $P_{0.1}$, P_1, P_3, P_{10} and P_{50} are the instantaneous flicker levels exceeded 0.1%, 1%, 3%, 10% and 50% of the time during the observation period. The suffix s in the equation indicates that the smoothed values should be used, which are shown in the equation below. P_{1s}, P_{3s}, P_{10s} and P_{50s} can be determined as:

$$P_{1s} = (P_{0.7} + P_1 + P_{1.3})/3 \quad (2.9)$$

$$P_{3s} = (P_{2.2} + P_3 + P_4)/3 \quad (2.10)$$

$$P_{10s} = (P_6 + P_8 + P_{10} + P_{13} + P_{17})/5 \quad (2.11)$$

$$P_{50s} = (P_{30} + P_{50} + P_{80})/3 \quad (2.12)$$

  The IEC standard gives four observation intervals (1-min, 5-min, 10-min and 15-min). However, only the 10-min interval shall be used for the P_{st} assessment during field measurements. The other three intervals can be used for the laboratory measurements. A ten minutes interval is chosen because it is sufficiently short to characterize a load in detail whose operating cycle is long (e.g. arc furnace) and also sufficiently long so that it is not affected by very isolated short-term variations.

- Long-term flicker indicator (P_{lt})

Since the short-term flicker indicator is only suitable to assess flicker caused by an individual source with a short duty-cycle, another flicker indicator, which can assess the combined effect of several flicker sources (e.g. welders, motors) operating randomly or flicker sources having a long and variable duty-cycle, should be defined. The long-term flicker indicator P_{lt} has been defined for this purpose. It can be derived from the short-term flicker indictor P_{st} values over a certain measuring period that relates to the duty-cycle of the flicker sources. The mathematical equation to calculate P_{lt} is shown below:

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{st_i}^3}{N}} \tag{2.13}$$

Here N is the number of the P_{st} measurements during the P_{lt} observation period. Normally in practice, 2 hours is selected as the observation period for the long-term flicker indicator P_{lt}. To calculate P_{lt} values, 2 hours must be a discrete time interval. Two hours sliding windows are not allowed to use. Since the P_{st} observation interval is 10 minutes and the P_{lt} interval is 2 hours, the number of measurements N will be 12.

2.5 Summary

As background knowledge, the human vision system, light measurements and some important flicker fusion boundary studies are presented in this chapter. From the flicker fusion boundary studies, the relationship between the magnitude of the illuminance variation and the frequency of the illuminance variation when the human being can see flicker are found. De Lange did detailed measurements and built an analog model to rebuild the flicker fusion boundary curve. His model became an important basis of the weighting filter of the flickermeter. In this chapter, an overview of his valuable work is given. Another model called the 'Rashbass model' is also discussed because it is the basis of the flickermeter. Then the current well-known UIE/IEC flickermeter has been described in this chapter in detail.

Chapter 3

Flicker Response of Different Lamp Types

3.1 Introduction

Since the lighting technology has been developed for more than hundred years, more and more new lamp types appear in the market. Nowadays, the incandescent lamp is replaced by other higher efficiency lamp types in the residential lighting market, e.g. fluorescent lamps and energy saving lamps etc. Many countries already strive to stop the use of the low efficiency incandescent bulb [14] – [17].

Since different lamp types have different working principles, the flicker responses of these lamp types are significantly different. Since the UIE/IEC flickermeter has been built by only considering the 230V 60W and 120V 60W incandescent lamp as reference lamps, it is not capable to evaluate the flicker level correlated with the customer sensitivities for other lamp types. The UIE/IEC flickermeter should be improved, so it can be used for other lamp types as well. To do this development, the flicker responses of the other lamp types must be known first. This chapter describes the flicker response measurements for different lamp types. Based on these measurement results, a proposal to improve the UIE/IEC flickermeter is discussed.

3.2 Measurement set-up

The experimental work on flicker response was done in the Power Quality (PQ) lab of the Eindhoven University of Technology (TU/e). The scheme of the measurement set-up is shown in figure 3.1. A programmable power source, remotely-controlled by a computer, is used to generate an arbitrary voltage waveform, e.g. the expected voltage fluctuation waveform. These waveforms are sent to the lamp to be tested as input voltage. The average and instantaneous illuminance (the luminous flux received by an elementary surface divided by the area of this surface, expressed in lux [5]) of the tested lamps are measured by a photodetector and an illuminance meter (i.e. luxmeter). A 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} as reference. An oscilloscope is used to record all measurement data which are transferred to a computer. The tested lamp and the photodetector are enclosed in a box, which is coated with a white color on the inner surface to solve the light reflection problem.

In this research work, only residential lamp types are investigated. There are six lamp types which have been tested in this work. They are:

- The 60W glass incandescent lamp
- The 20W brilliantline pro halogen lamp
- The 15W linear fluorescent lamp
- The 11W energy saving lamp
- The 9W compact fluorescent lamp (CFL) with electromagnetic ballast
- The 3.4W LED lamp

3.3 Lamp characteristics

A lamp is a device that converts electrical power into the light. However, the conversion methods are essentially different for the different lamp types. The characteristics of the different lamp types are therefore also different. In this section, the working principles and characteristics of the tested lamp types are compared and introduced.

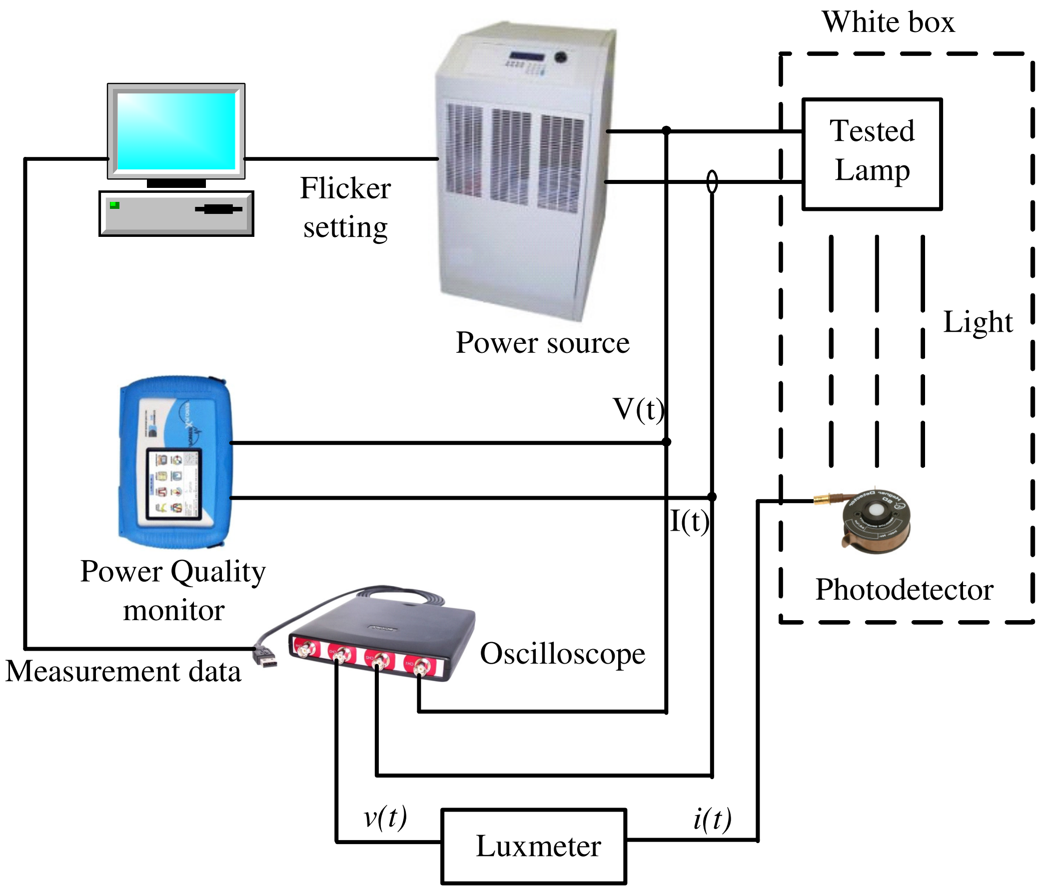
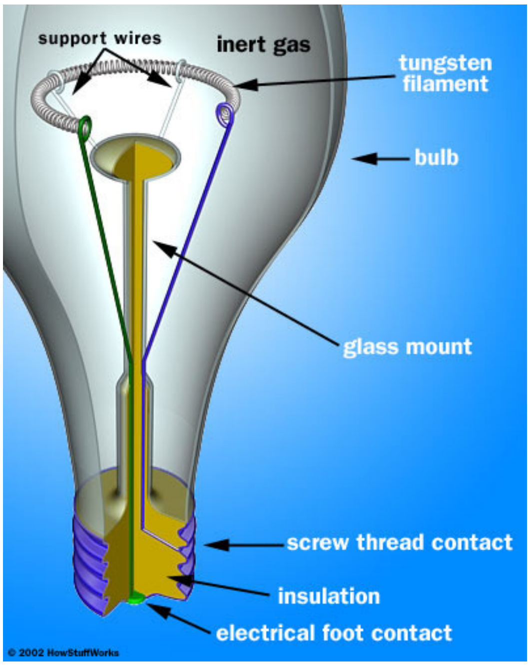


Figure 3.1 The scheme of the flicker response measurements in the lab

3.3.1 Comparison of different lamp types

3.3.1.1 Incandescent lamp

The incandescent lamp uses the oldest lighting technology. It has the worst efficiency (the lowest lumen per watt) and the shortest lifetime [21] [32]. Figure 3.2 [33] shows the basic structure of an incandescent lamp. When the electrical current flows through the tungsten filament of the incandescent lamp, the filament becomes hot and starts glowing. The visible light, part of the radiation from the filament, can be seen by human beings. During the process that the electrical power converts into visible light, there are lots of losses, e.g. tungsten gas losses and conduction losses of leads and supports etc. This explains the low efficiency of the incandescent lamp. The light output level of an incandescent lamp depends on the temperature of the filament. However, a high temperature of the filament will cause the evaporation of the tungsten filament and therefore reduces the lifetime of the lamp. The lifetime of the lamp is inversely proportional to the rate of evaporation of the tungsten. Thus there is a trade-off between the light intensity and the lifetime of the incandescent lamp.



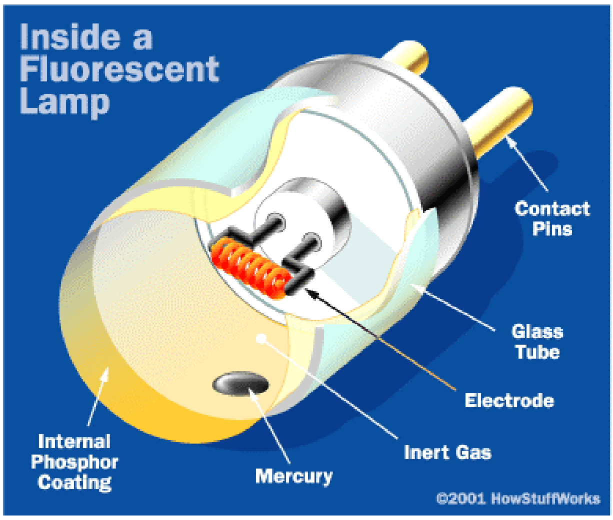


Figure 3.2 The basic structure of the incandescent lamp (left figure) and fluorescent lamp (right figure [33]

3.3.1.2 Halogen lamp

The halogen lamp is a kind of enhanced performance incandescent lamp. It has the same basic working principle as the incandescent lamp. The improvement of the halogen lamp is that the tungsten filament of the halogen lamp is sealed in a small tube filled with halogen, which causes the evaporated tungsten to re-deposit on the filament. A smaller and mechanically stronger bulb is required for a halogen lamp to sustain the thermal conditions needed by the halogen cycle. Consequently it is possible to get a higher lamp operating pressure and to use a filling gas with higher density in a halogen lamp. This slows down the rate of the tungsten diffusion at any temperature and hence extends the lifetime of the lamp. Alternatively, the filament temperature can be increased for the same lifetime and therefore the efficiency of the lamp is increased [21].

3.3.1.3 Fluorescent lamp

The fluorescent lamp is composed of a lamp tube and ballast. In the beginning of its development, the fluorescent lamp had a starter or a power switch with a 'start' position which provided a sufficiently high voltage to the lamp tube to allow the electrode to heat up and to start the lamp. However, nowadays, this function is integrated into an electronic ballast. Some cheap fluorescent lamps might still use the old technology.

Lamp tube

The most common lamp tube used is the linear lamp tube. The basic structure of the lamp tube is shown in figure 3.2. The outer glass of the lamp tube is normally soda lime silicate glass. The electrodes are located at the two ends of the lamp tube. The lamp tube is filled with gas and mercury. The inner surface of the lamp tube is coated to a uniform thickness with a phosphor coating. The mercury atoms are excited and release ultraviolet photons when the electrical current passes through the lamp tube. These ultraviolet photons stimulate the phosphor and so visible light photons are emitted. The thickness of the phosphor coating is one of the essential elements which determines the efficiency of the lamp tube since it effects the amount of the emitted visible light photons [21].

Ballast

The ballast is the device used with a fluorescent lamp tube and other discharge lamps to provide the required voltage and current to the lamp tube. It has two main functions: 1) provide the lamp tube with the proper voltage and electrode heating to start the lamp tube; 2) stabilize the discharge between the electrodes by limiting the electrical current of the lamp during the operation of the lamp. As additional function, the ballast can perform power quality corrections and can have dimming capabilities [34].

There are two basic types of ballast: electromagnetic and electronic. The electromagnetic ballast converts the input voltage and current to the required voltage and current for the starting-up and operation of the lamp tube. The frequency of the output voltage and current is same as the frequency of the input voltage, i.e. 50Hz or 60Hz. The electronic ballast rectifies the 50Hz or 60Hz input voltage and current to DC and converts the DC values to a high frequency output (normally 20 – 120kHz) using an inverter. Due to the use of an integrated circuit in the electronic ballast, several benefits can be obtained, e.g. energy saving, reduced flicker, noise and weight etc [21].

3.3.1.4 Compact fluorescent lamp (CFL)

A compact fluorescent lamp combines both the high efficiency of the fluorescent lamp and the convenience of the incandescent lamp fixture. There are two types of compact fluorescent lamps. One has integrated the lamp tube and the electronic ballast into one whole lamp, the so called energy saving lamp. Another type has a separated lamp tube and ballast. This ballast can be an electromagnetic ballast.

3.3.1.5 LED lamp

A LED is a light-emitting diode. The PN junction semiconductor diode emits a single color light when the diode operates in a forward biased direction, as shown in figure 3.3 [10]. The material of the PN junction determines the light color produced by the LED. In 1995, the first white light LED was developed. LED lighting is becoming one of the advanced residential and decorative lighting technologies. It has the advantage of high efficiency, longer lifetime etc. However, the luminance of LED lamps available in the market is still lower than the luminance of other lamp types.

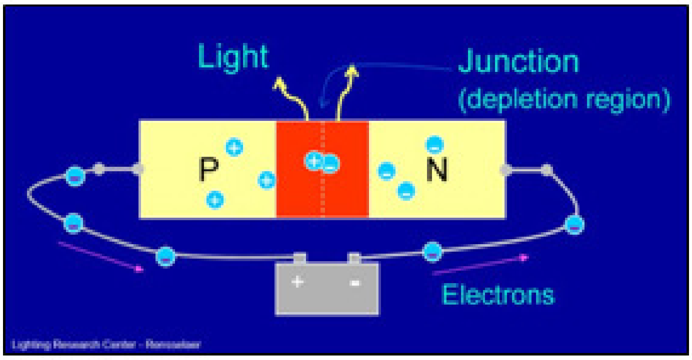


Figure 3.3 The working principle of a PN junction [35]

3.3.2 Lamp load characteristic measurements

Measurements of the lamp load characteristics were made in the PQ lab of TU/e to obtain more knowledge about the lamps. Three lamp types (60W incandescent lamp, 15W linear fluorescent lamp and a 9W compact fluorescent lamp with electromagnetic ballast) were tested in these measurements. The results are presented in this section.

60W incandescent lamp

A 230V 60W incandescent lamp was tested in the lab. The input voltage of the tested lamp, which was varied from 130V to 260V in 5V steps, was supplied by a programmable power source. The measured voltage – current (V-I) characteristic of the tested lamp is plotted in figure 3.4. The curve shows that the lamp is a resistive load. The measured instantaneous lamp voltage and current are shown in figure 3.5. There is no phase shift between the lamp voltage and current because of the pure resistive characteristic of the incandescent lamp.

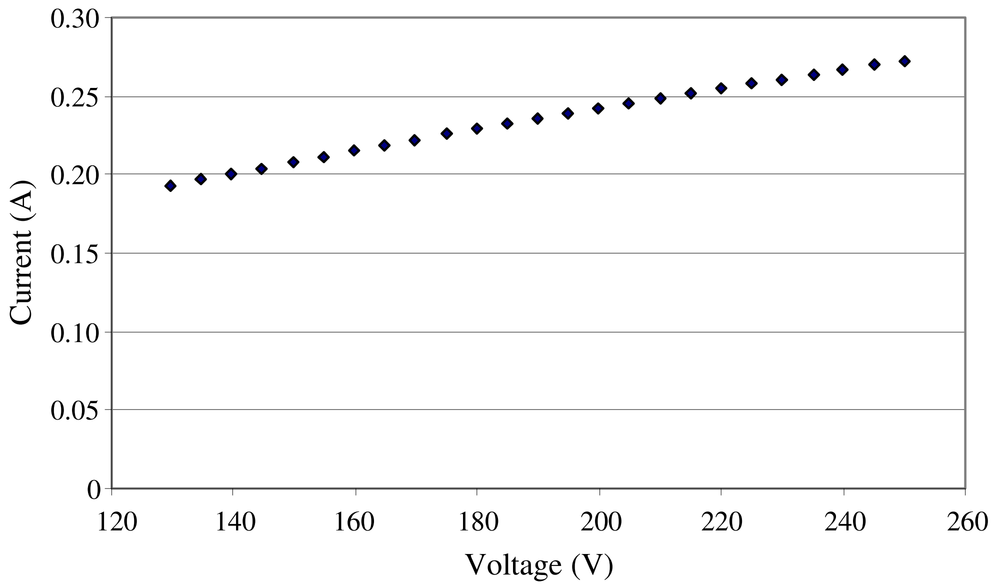


Figure 3.4 The voltage – current (V-I) curve of a 60W incandescent lamp

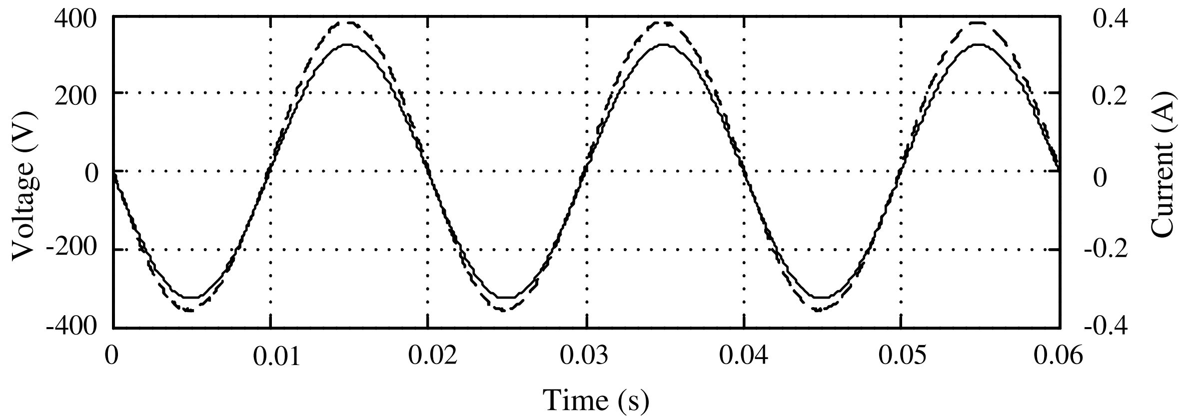


Figure 3.5 The measured lamp voltage and current of a 60W incandescent lamp (input voltage of the lamp is 230V). Solid line is the lamp voltage; dashed line is the lamp current

15W fluorescent lamp

To compare with the incandescent lamp, the load characteristic of a 15W fluorescent lamp was tested in the lab. The lamp tube is connected to the programmable power source via an electromagnetic ballast. The output voltage of the power source, i.e. supply voltage of the lamp, is varied from 90V to 260V in 5V steps. With increasing supply voltage, the lamp tube voltage decreases. In figure 3.6, the measured V–I curve of the fluorescent lamp tube demonstrates the negative impedance characteristic. This is due to the fact that the lamp tube voltage is the voltage between the electrodes. When this voltage increases, the electron density increases. Then the discharge current increases subsequently. Therefore, the lamp impedance decreases.

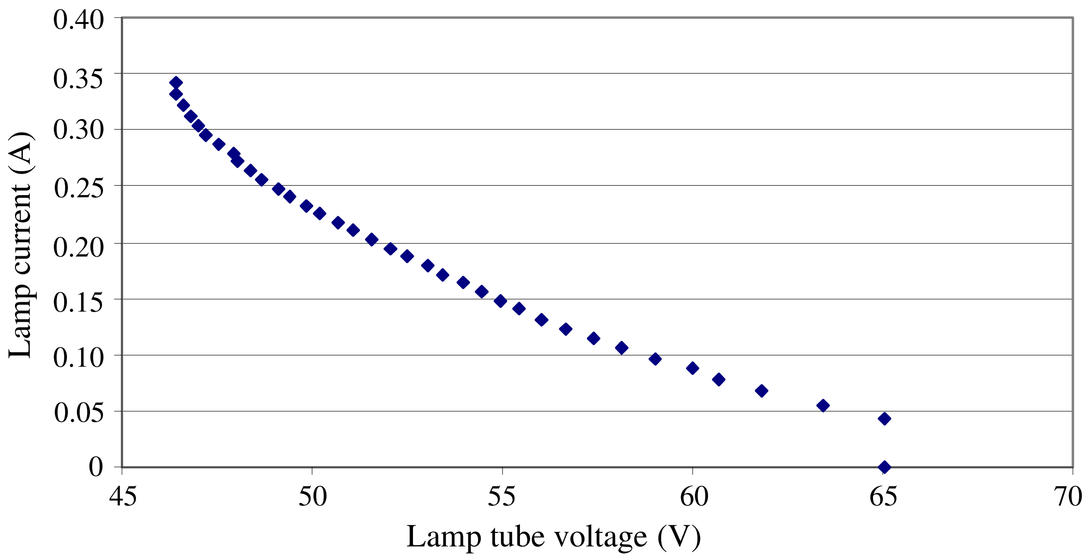


Figure 3.6 The V-I (voltage – current) curve of a 15W fluorescent lamp tube with electromagnetic ballast

The measured instantaneous lamp tube voltage and current are shown in figure 3.7. The fluorescent lamp tube voltage is a square wave with switching transients instead of a sinusoidal waveform. This is due to the fact that the excitation of the mercury atoms inside the lamp tube depends on the energy of the electrons [36]. For the fluorescent lamp, the energy of the electrons cannot exceed the energy needed for excitation of the mercury atom. This is due to the fact that the electrons start to lose their energy when more mercury atoms get excited. The energy of the electrons increases monotonically with the voltage across the lamp. Thus the limitation of the electron energy will limit the lamp tube voltage. Therefore, any further increase of the lamp current cannot increase the lamp tube voltage, but only increase the light intensity.

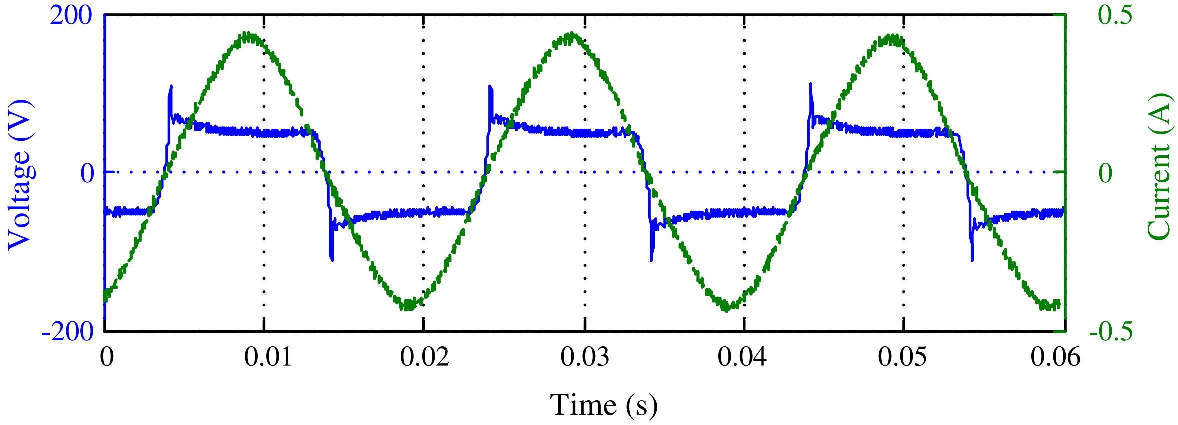


Figure 3.7 The measured instantaneous voltage and current of a 15W fluorescent lamp tube. Blue solid line is the lamp tube voltage; green dashed line is the fluorescent lamp current

9W CFL with electromagnetic ballast

The same measurement as for the above two lamp types was done for a 9W compact fluorescent lamp (CFL) tube with electromagnetic ballast as well. The measured V–I curve is shown in figure 3.8. As expected, the curve shows the same negative impedance characteristic as the linear fluorescent lamp tube.

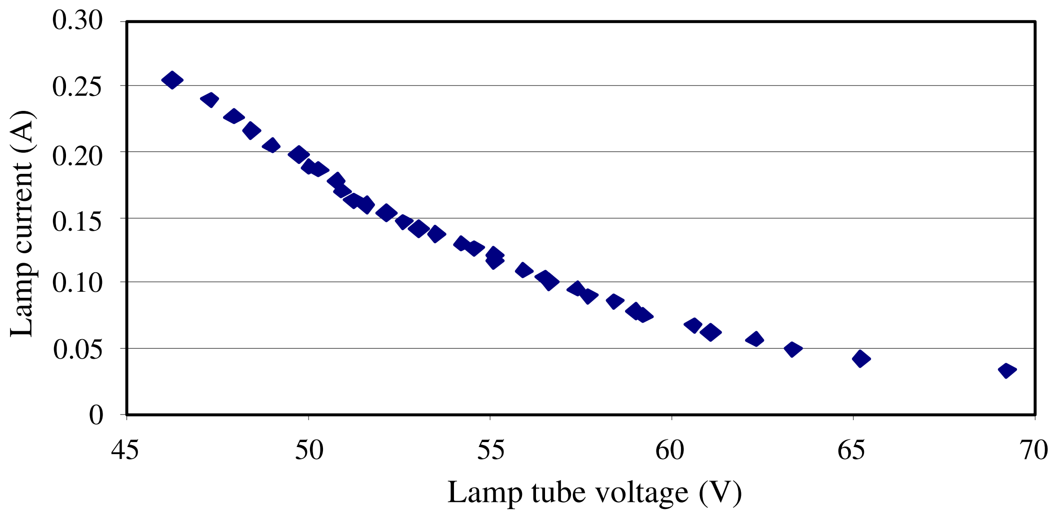


Figure 3.8 The V-I (voltage – current) curve of the tube of a 9W CFL with electromagnetic ballast

Figure 3.9 shows the measured instantaneous lamp tube voltage and current of a 9W CFL with electromagnetic ballast.

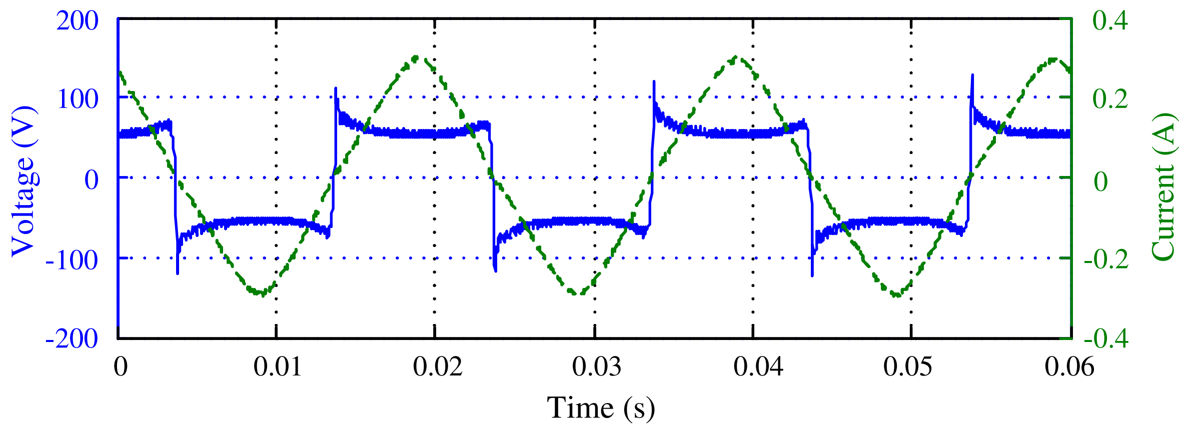


Figure 3.9 The measured instantaneous voltage and current of a 9W CFL tube with electromagnetic ballast. Blue solid line is the lamp tube voltage; green dashed line is the lamp current

3.3.3 Lamp illuminance measurements

The illuminance of the lamps is not a constant value even with a stable input voltage. This is due to the fact that the illuminance of the lamp is power dependent. When a normal lamp is connected to a 50Hz power source, the fundamental frequency of the illuminance of the lamp is 100Hz, the same frequency of the electrical power consumed by the lamp. However, the human eye is only sensitive in a certain low frequency range (e.g. 0.5Hz – 25Hz) with a certain magnitude. For small amplitude variations and high frequencies (e.g. 100Hz) of the illuminance of the lamp, most people cannot detect it.

The instantaneous illuminance waveforms of different lamp types are not the same. As examples, the measured instantaneous illuminance of a 60W incandescent lamp and a 11W energy saving lamp are presented in figure 3.10 and 3.11. Comparing figure 3.10 to 3.11, the instantaneous illuminance waveform of the incandescent lamp is a full cycle sinusoidal waveform instead of the half cycle sinusoidal waveform of the energy saving lamp. The latter is caused by the characteristic of the ballast in the energy saving lamp.

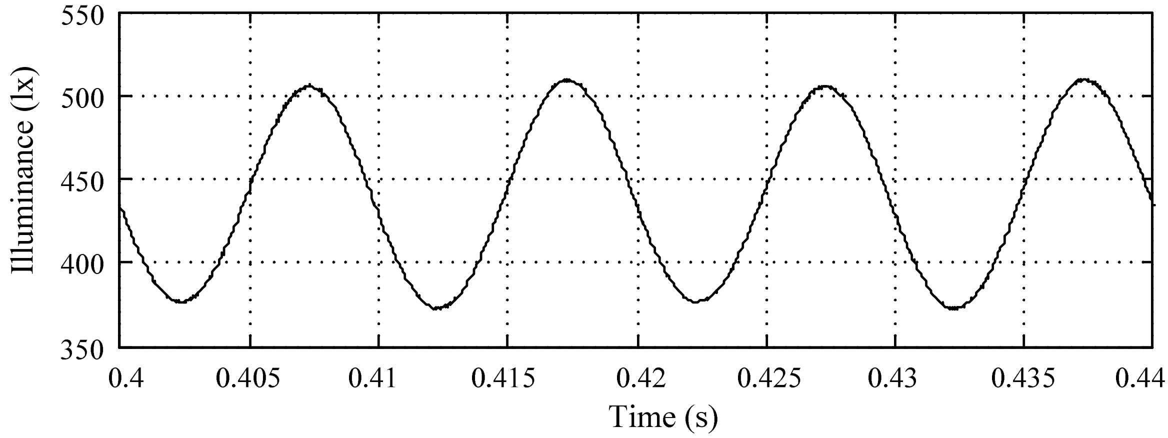


Figure 3.10 The instantaneous illuminance of a 60W incandescent lamp

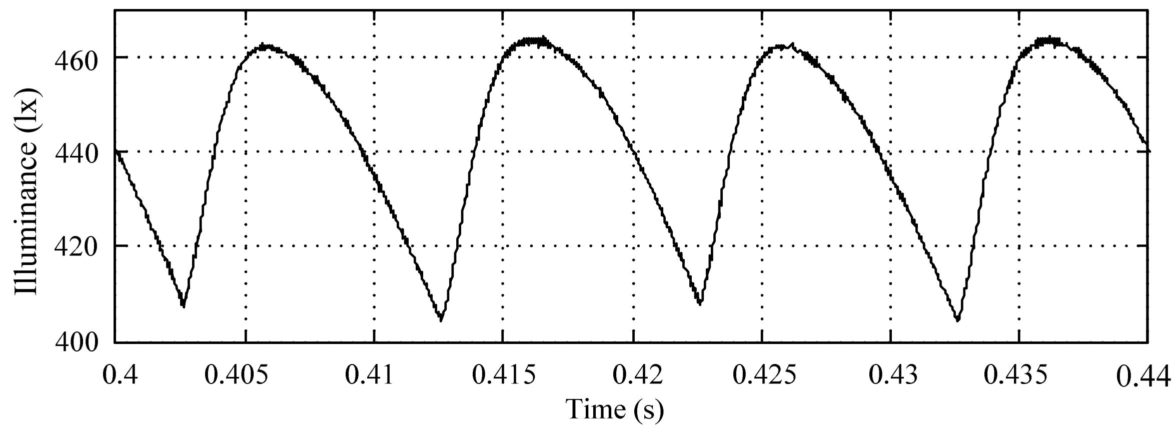


Figure 3.11 The instantaneous illuminance of a 11W energy saving lamp

3.4 Flicker response measurement

In table 1 of the standard IEC61000-4-15, the values of the modulating voltage amplitude and corresponding modulating voltage frequency are given, which can cause the maximum instantaneous flicker sensation to reach one ($P_{inst,max} = 1$). As mentioned in section 2.4.4, the instantaneous flicker sensation is the output of block 4 of the UIE/IEC flickermeter (see figure 2.8 in chapter 2). The maximum instantaneous flicker sensation is an important term used in the standard IEC 61000–4–15 to evaluate the performance of the UIE/IEC flickermeter. The standard gives separate values of modulating voltage amplitude and frequency for the sinusoidal modulated voltage waveform and the rectangular modulated voltage waveform. In this chapter, only the sinusoidal modulated voltage is studied. Some flicker response measurement results with rectangular modulated voltages are presented in Appendix B.

3.4.1 Theoretical analysis

The illuminance of all lamp types depends on the electrical power consumed by the lamp. Under flicker conditions, the modulated voltage can be described as already indicated in chapter 2 by equation 2.4. The square of the modulated voltage is given in equation 2.5 of chapter 2.

If the lamp is assumed to be a linear load, the electrical power consumed by the lamp will be proportional to the square of the modulated voltage supplied to the lamp. The electrical power consumed by the lamp will therefore be a waveform with several frequency components 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 fundamental frequency of the supply voltage is 50Hz and the modulating voltage 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 100Hz, ω_m, $100+\omega_m$ and $100-\omega_m$. The corresponding illuminance of the lamp is also expected to include a relatively high dc component and components with a frequency of 100Hz, ω_m,, $100+\omega_m$ and $100-\omega_m$. Fast Fourier Transform (FFT) analysis is used to analyze the frequency of the illuminance of the lamp. The analysis results of the illuminance of a 230V, 60W incandescent lamp under flicker (with 4.6V modulating voltage amplitude and 10Hz modulating voltage frequency) are presented in table 3.1 as an example. As expected, the values of the dc component and components with a frequency of 100Hz, 10Hz, 90Hz and 110Hz are higher than other frequency components. However, the frequency components with 100+ω_m and 100-ω_m are not relevant flicker frequencies since the human eye is not sensitive to such high frequencies. The small values of the 50Hz frequency components indicate the presence of a DC bias of less than 1% in the lamp current. This has no influence on the frequency components of interest for this study. The measurement results shown further are only the illuminance amplitude of the modulating voltage frequency component (ω_m).

Table 3.1 FFT analysis results of the illuminance of a 60W incandescent lamp under flicker (4.6V modulating voltage amplitude and 10Hz modulating voltage frequency)

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

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

$$L_r(f_m) = \frac{L_{f_m}}{L_{av}} \times 100 \tag{3.1}$$

Where: L_r is the relative illuminance variation of the ω_m component for different lamp types

L_{fm} is the absolute illuminance of the f_m component

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 is used. Since the incandescent lamp is used as a reference lamp in the standard [31], the relative illuminance variation of the incandescent lamp for different modulating voltage frequencies is selected as the base value L_b. The relative illuminance variation per unit value can be calculated by:

$$L_{unit}(f_m) = \frac{L_r(f_m)}{L_b(f_m)} \tag{3.2}$$

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

3.4.2 Measurement results

3.4.2.1 The Standard modulating voltage amplitude

The first measurement is carried out using the standard modulating voltage amplitude ($\triangle V$), which is shown in table 3.2. These are calculated from the values of the relative voltage fluctuation ($\triangle V/V$, V equals 230V in this thesis) given in table 1 of standard IEC 61000–4-15. These modulating voltage amplitudes are called ‘standard modulating voltage amplitudes’ in this chapter. The relative voltage fluctuations shown in table 3.2 are equal to two times the amplitude modulation factor m (mentioned in equation (2.4)) [31]. As described in IEC 61000–4–15, the modulating voltage amplitudes shown in table 3.2 can generate a maximum instantaneous flicker sensation $P_{inst,max}$ of 1, which is the output of the block 4 of the UIE/IEC flickermeter (see figure 2.8 in chapter 2). As mentioned in section 2.4.4, the short-term flicker indicator Ps_t will be less than one when the $P_{inst,max}$ reaches one. This is due to the fact that an experiential ratio between the P_{st} and $P_{inst,max}$ is approximately 0.68.

All 36 different modulated voltages with the different modulating voltage frequencies and the corresponding modulating voltage amplitudes, which are shown in table 3.2, are offered to the tested lamp by the programmable power source. The average illuminance variation of the tested lamps under normal voltage condition (no flicker) was recorded. The absolute illuminance variations of the tested lamps under each voltage fluctuation condition were recorded as well. The relative illuminance variations of the tested lamps for each modulating voltage frequency (in total 36 frequencies) were calculated by equation 3.1. These relative illuminance variation values demonstrate the flicker response of the tested lamps. As mentioned in section 3.4.1, the relative illuminance variation per unit is used to compare the flicker response of the different 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 equation 3.2.

The relationship between the relative illuminance variation per unit value L_{unit} and the corresponding modulating voltage frequency for different lamp types is plotted. The curves of the relative illuminance variation per unit values for different lamp types are smoothed by a 6th order polynomial fitting method and shown in figure 3.12.

Table 3.2 Standard modulating voltage amplitudes for sinusoidal voltage fluctuation (modulating voltage amplitude for a maximum instantaneous flicker sensation $P_{inst,max} = 1$)

Frequency (Hz)	Voltage Fluctuation (230 V lamp 50 Hz system)		Frequency (Hz)	Voltage Fluctuation (230 V lamp 50 Hz system)	
	Relative Voltage Fluctuation ($\Delta V/V$) (%) (From standard [12])	Modulating Voltage Amplitude (ΔV) (Volts) (Calculated value)		Relative Voltage Fluctuation ($\Delta V/V$) (%) (From standard [12])	Modulating Voltage Amplitude (ΔV) (Volts) (Calculated value)
0.5	2.340	2.691	10.0	0.260	0.299
1.0	1.432	1.647	10.5	0.270	0.311
1.5	1.080	1.242	11.0	0.282	0.324
2.0	0.882	1.014	11.5	0.296	0.340
2.5	0.754	0.867	12.0	0.312	0.359
3.0	0.654	0.752	13.0	0.348	0.400
3.5	0.568	0.653	14.0	0.388	0.446
4.0	0.500	0.575	15.0	0.432	0.497
4.5	0.446	0.513	16.0	0.480	0.552
5.0	0.398	0.458	17.0	0.530	0.610
5.5	0.360	0.414	18.0	0.584	0.672
6.0	0.328	0.377	19.0	0.640	0.736
6.5	0.300	0.345	20.0	0.700	0.805
7.0	0.280	0.322	21.0	0.760	0.874
7.5	0.266	0.306	22.0	0.824	0.948
8.0	0.256	0.294	23.0	0.890	1.024
8.8	0.250	0.288	24.0	0.962	1.106
9.5	0.254	0.292	25.0	1.042	1.198

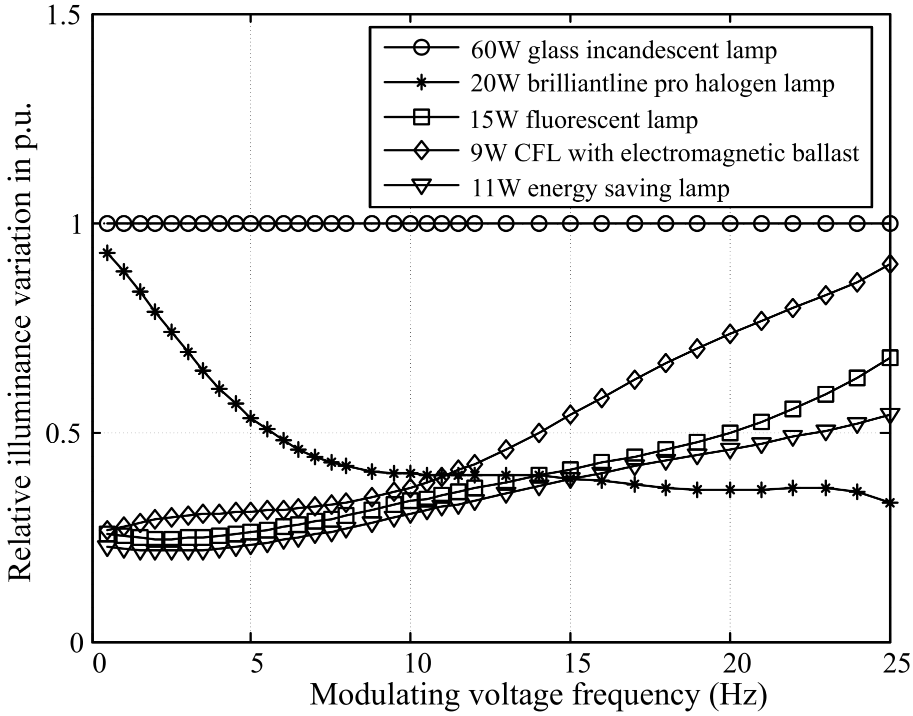


Figure 3.12 The flicker response of different lamp types (with modulating voltage amplitude for $P_{inst,max} = 1$)

Since the relative illuminance variation of the incandescent lamp for each modulating voltage frequency is the base value to calculate the relative illuminance variation per unit values for the tested lamps, the per unit values of the incandescent lamp are equal to one for every modulating voltage frequency, as shown in figure 3.12. It is clear from figure 3.12 that the incandescent lamp is the most sensitive to flicker because its relative illuminance variation per unit values are higher compared with the other lamp types. The energy saving lamp is most insensitive to flicker when the modulating voltage frequency is less than 15Hz because of the lowest relative illuminance per unit value. The halogen lamp is the most insensitive to flicker for a modulating voltage frequency variation between 15Hz and 25Hz. This is due to the fact that the tested halogen lamp operates at 12V instead of a 230V supply voltage level. An additional electronic transformer is used for this halogen lamp. This electronic transformer 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 result in a more stable lamp voltage and current under flicker conditions, i.e. less sensitive to flicker [37] [38].

The results in figure 3.12 also demonstrate that the "modern" lamps might not be as annoying to human beings, as the incandescent lamp when the modulating voltage amplitude is as high as the value given in table 3.2.

3.4.2.2 Instantaneous flicker curve measurements

As shown in figure 3.12, different lamp types have different flicker responses to the same voltage fluctuation. Therefore, the modulated voltage amplitude should be also different for different lamp types to cause the same flicker feeling of a human being, which can be represented by the flicker level.

To estimate the flicker level, the simplest method used by grid operators is to use flicker curves, which are given in the IEEE standard and the UIE publication [11] [39]. Figure 3.13 shows the flicker curves presented in IEEE 141-1993 and the UIE guide of 1999. The unit of changes/minute is used as the unit for the modulating voltage frequency in figure 3.13. For a modulating voltage, one cycle is two changes. Thus, 120 changes per minute are equal to 1 Hz.

The IEEE 141 and 120 V UIE curves shown in figure 3.13 are obtained from 230V and 120V, 60W incandescent lamp measurements with a rectangular modulated voltage respectively. These curves indicate the relative voltage fluctuation (△V/V) with respect to the modulating voltage frequency. The flicker curves shown in figure 3.13 give the boundary values of the relative voltage fluctuation for a corresponding modulating voltage frequency when the short-term flicker indicator P_{st} is equal to one. A relative voltage fluctuation below the flicker curve will cause P_{st} to be less than one. A relative voltage fluctuation above the flicker curve will cause P_{st} to be higher than one.

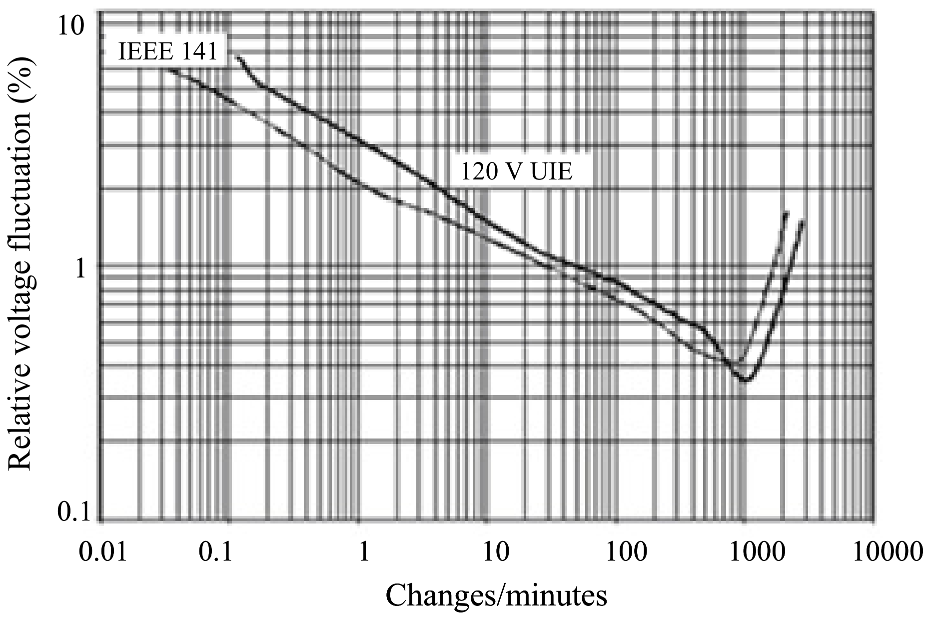


Figure 3.13 P_{st} = 1 flicker curves presented in IEEE 141-1993 and UIE guide of 1999 [40].

As the flicker curve is the simplest way to estimate the flicker level, the relative voltage fluctuations for different lamp types to obtain the same flicker level can be compared using the flicker curves of different lamp types. To obtain the flicker curves of different lamp types, the reference flicker level needs to be defined. Therefore, the reference values of the relative voltage fluctuations and corresponding modulating voltage frequencies, which can cause the reference flicker level, should be defined first. Since only the sinusoidal modulated voltage is studied in this research, the reference values of the sinusoidal modulated voltages are required. However, there are no reference values of the sinusoidal modulated voltage, which can cause the short-term flicker indicator P_{st} to be equal to one, presented in the standard or other literature. But standard IEC 61000–4–15 gives the values of the sinusoidal modulated voltage for the 230V incandescent lamp when the maximum instantaneous flicker sensation $P_{inst,max}$ equals one. As mentioned before, there is a linear ratio between P_{st} and $P_{inst,max}$. $P_{inst,max}$ can indicate the flicker level and the flicker feeling of a human being as well. If the values of the sinusoidal modulated voltage, which can cause $P_{inst,max}$ to be equal to one, are used as the reference voltage values, the obtained curve should be called 'instantaneous flicker curve'. This instantaneous flicker curve can indicate the boundary values of the relative voltage fluctuation ($\triangle V/V$) for corresponding modulating voltage frequencies when the maximum instantaneous flicker sensation $P_{inst,max}$ equals one. So, the differences between the instantaneous flicker curve and the normal flicker curve are:

1) The instantaneous flicker curve is only used for the sinusoidal modulated voltage instead of the rectangular modulated voltage in the normal flicker curve.
2) 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.

The goal of the measurements performed is to find the instantaneous flicker curve for different lamp types. As mentioned above, the voltage fluctuation values of a 230V incandescent lamp, which can cause $P_{inst,max}$ to be equal to one, are selected as the reference voltage values. These values are shown in table 3.2. In a total of 36 modulated voltages with the reference modulating voltage amplitudes and the corresponding modulating voltage frequency were generated by a programmable power source and sent to the tested incandescent lamp. The absolute illuminance variations of the tested lamps were measured and analyzed by FFT. The average illuminance of the tested lamps under normal voltage condition (no flicker) was recorded as well. The relative illuminance variations of the tested incandescent lamp for each modulating voltage frequency were calculated using equation 3.1 and were selected as the reference relative illuminance variations. The relative illuminance variation can indicate the flicker level, therefore the flicker feeling of a human being. And, for different lamp types, the assumption that the flicker feeling of a human being is same if the relative illuminance variation is same is made in this research[1].

The instantaneous flicker curve measurements were done for three lamp types (11W energy saving lamp, 15W fluorescent lamp set and 9W CFL with electromagnetic ballast) with the following steps:

1) The average illuminance of the tested lamps under normal voltage condition (no flicker) was recorded.
2) The voltage fluctuations with the reference modulating voltage amplitude and the corresponding modulating voltage frequency were supplied to the tested lamps by the programmable power source. The corresponding absolute illuminance variations of the tested lamps were recorded and analyzed by FFT.
3) The relative illuminance variations of the tested lamps were calculated using equation 3.1.
4) The calculated relative illuminance variations of the tested lamps were compared to the reference relative illuminance variations. The corresponding modulating voltage amplitude and the modulating voltage frequency were recorded if these two relative illuminance variation values are the same.
5) If the relative illuminance variations of the tested lamps are smaller than the reference relative illuminance variations, new voltage fluctuations with increased (0.5V increment step) modulating voltage amplitude were supplied to the tested lamp again. The steps 2), 3) and 4) were repeated until the relative illuminance variations of the tested lamps are the same as the reference one.
6) All recorded modulating voltage amplitudes of the tested lamps, which can cause the same relative illuminance variation as the reference values, were transformed to the corresponding relative voltage fluctuation values using the base voltage equal to 230V. The calculated relative voltage fluctuation values are plotted against the corresponding modulating voltage frequency for the tested lamps.

These plots are shown in figure 3.14. They are the instantaneous flicker curves of the three tested lamp types. The ‘standard curve’ shown in figure 3.14 is the instantaneous flicker curve for the 230V 60W incandescent lamp. It is plotted using

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[1] This assumption was tested by ten people for two lamp types: incandescent lamp and energy saving lamp. The measurement results show that the flicker feeling of a human being is similar when the relative illuminance variations of different lamp types are the same. Thus, this assumption is reasonable. This experimental work is described in detail in appendix C.

the relative voltage fluctuation values shown in table 3.2 and the standard IEC 61000-4-15. To be consistent with the flicker curve shown in figure 3.13, the unit ‘changes/minute’ is used in figure 3.14 instead of the unit ‘Hz’.

Figure 3.14 shows that the incandescent lamp is the most sensitive to flicker since its modulating voltage amplitudes are the lowest when $P_{inst,max}$ equals one. The energy saving lamp is the most insensitive to flicker because of its highest modulating voltage amplitudes. These conclusions are in agreement with the results of the section before. All instantaneous flicker curves show that the most sensitive modulating voltage frequency lies around 9Hz.

The instantaneous flicker curves shown in figure 3.14 can be used to estimate the maximum instantaneous flicker sensation for the tested lamp types. And the flicker level of the tested lamp types can be estimated as well.

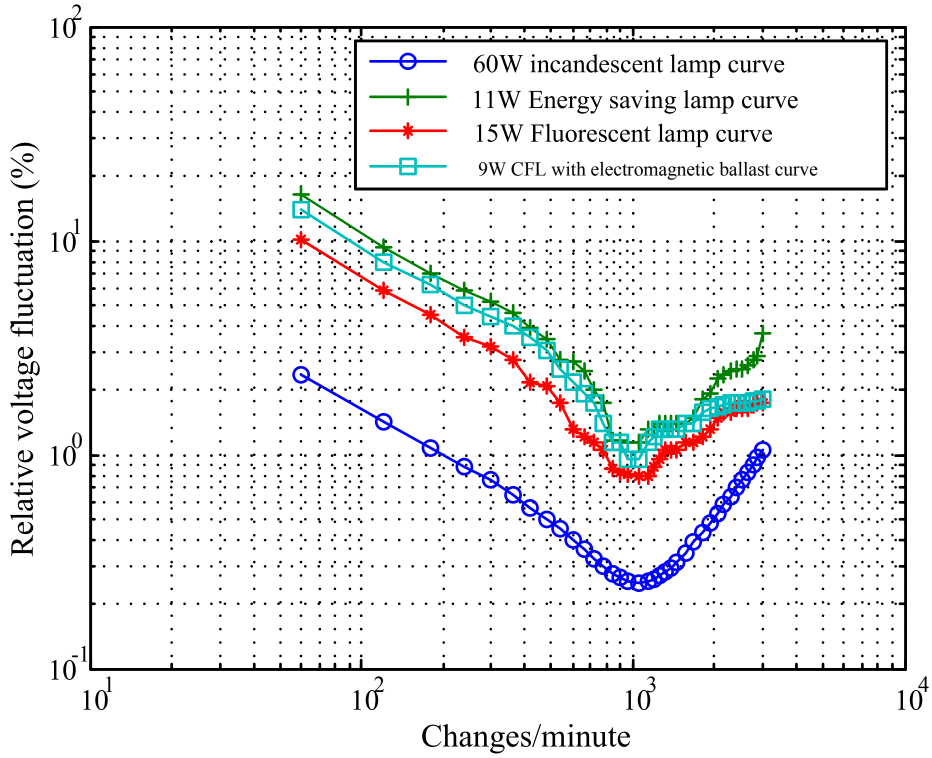

Figure 3.14 Instantaneous flicker curves for different lamp types and sinusoidal voltage fluctuations

3.4.2.3 Constant modulating voltage amplitude

In the measurements presented in the two previous sections, various modulating voltage amplitudes were used for different modulating voltage frequencies. The measurement results are used to compare the different flicker responses of different lamp types. However, the lamp flicker responses of each modulating voltage frequency for the same modulating voltage amplitude are also of interest. These are tested in the measurements which will be described in this section.

The measurements are made using voltage fluctuations with a constant modulating voltage amplitude, i.e. the same modulating voltage amplitude for each modulating voltage frequency (0.5Hz – 25Hz). For the incandescent lamp, halogen lamp and energy saving lamp, the applied relative voltage fluctuations are 0.5%, 1% and 2% (i.e. the modulating voltage amplitudes are 1.15V, 2.3V and 4.6V respectively) based on the 230V voltage level. A 3% relative voltage fluctuation (i.e. the modulating voltage amplitude is 6.9V) is also applied for the fluorescent lamp and CFL with electromagnetic ballast. Relative voltage fluctuations of 1%, 2% and 3% are used for the LED lamp. Equal to the measurements reported in the two previous sections, the average illuminance of the tested lamps under normal voltage condition (no flicker) and the absolute illuminance variation of the tested lamps under flicker conditions were recorded during the measurements. The relative illuminance variations of the tested lamps were calculated using equation (3.1). The results of the relative illuminance variations versus the modulating voltage frequencies for different lamp types are presented in figures 3.15 – 3.20.

Due to the limited accuracy of the hardware used in the measurements (e.g. the programmable power source and the oscilloscope) and the unavoidable disturbances in the measurements, some relative illuminance variation curves are not exactly smooth, e.g. the curves shown in figure 3.17. However, the data on these unsmoothed curves are within the deviation range of 5%. Since a deviation of $\pm 5\%$ is used in the flicker measurements related to standard IEC 61000-4-15, measurement errors of 5% are accepted in this research.

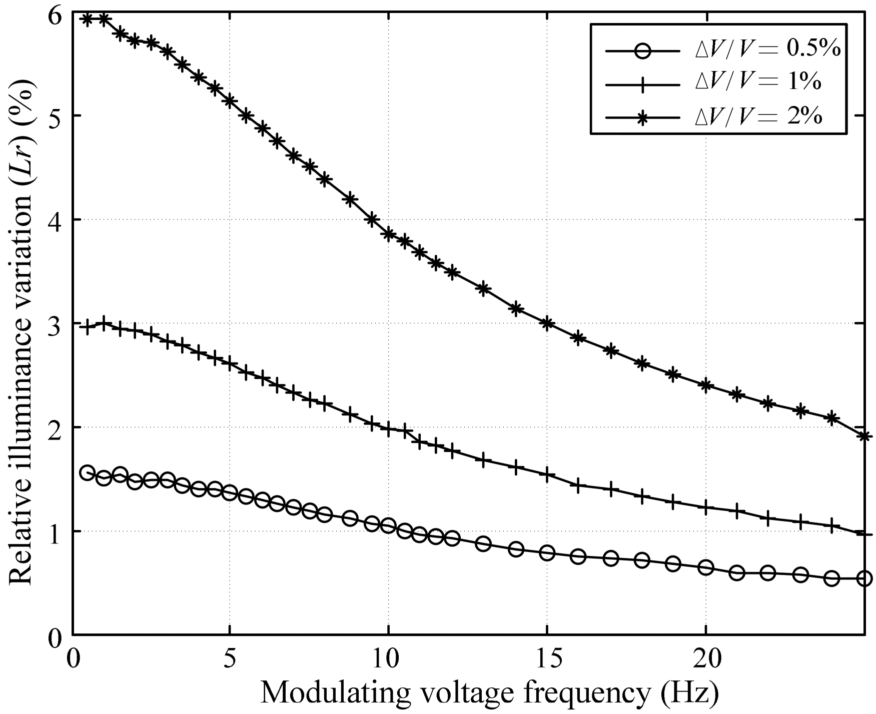

Figure 3.15 Relative illuminance variation of a 60W glass incandescent lamp versus the modulating voltage frequency

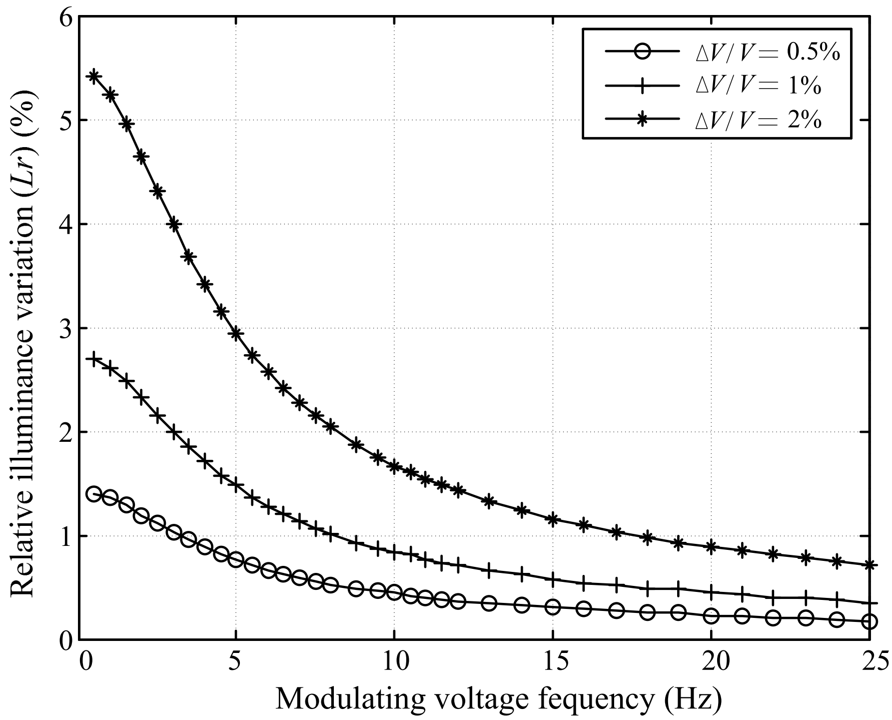

Figure 3.16 Relative illuminance variation of a 20W halogen lamp versus the modulating voltage frequency

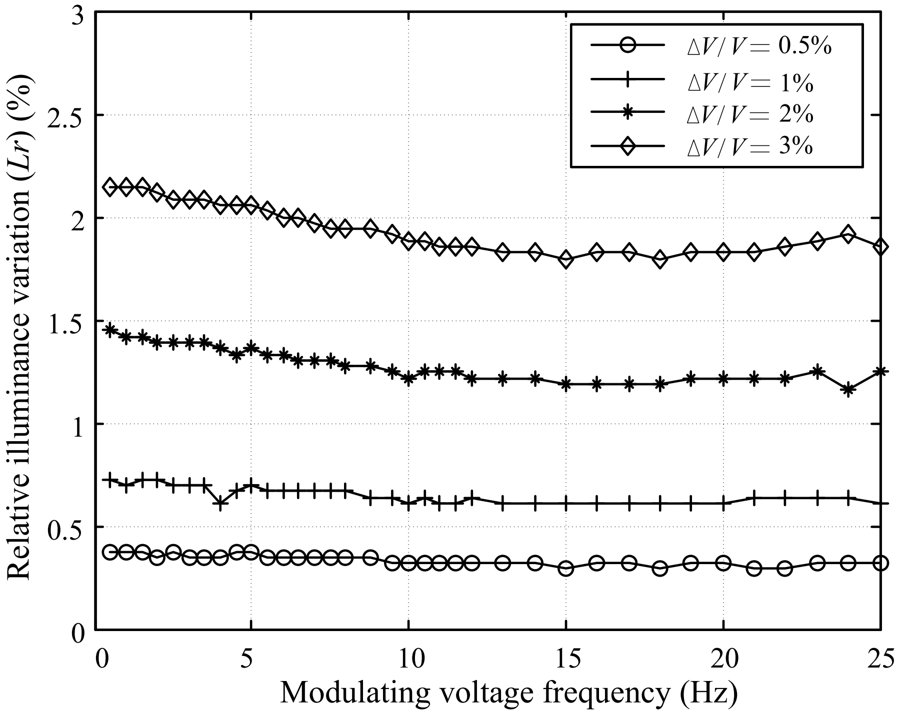

Figure 3.17 Relative illuminance of a15W fluorescent lamp set versus the modulating voltage frequency

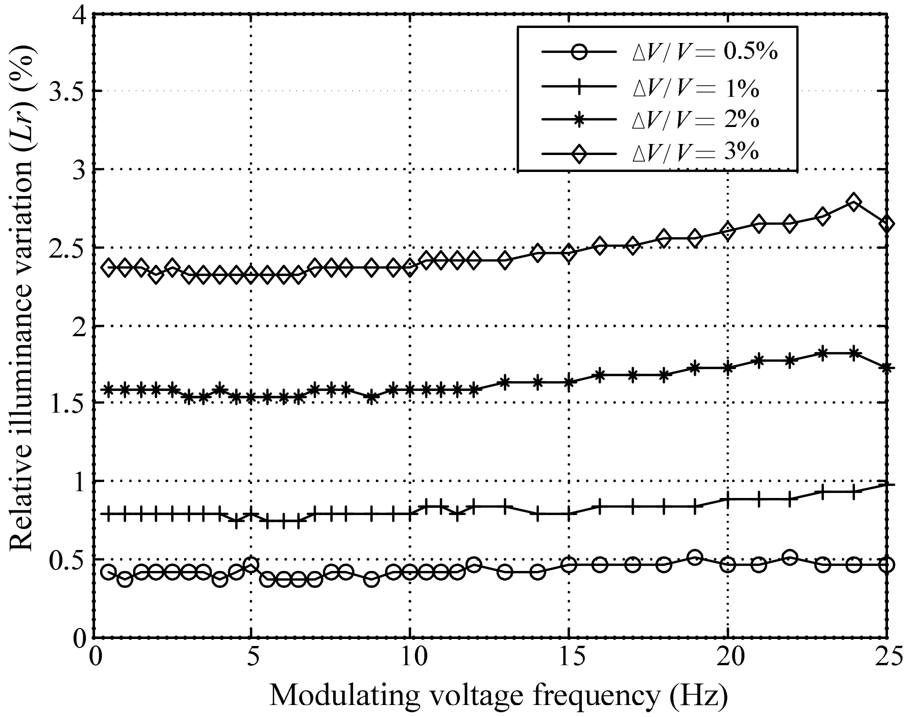

Figure 3.18 Relative illuminance variation of a 9W CFL with electromagnetic ballast versus the modulating voltage frequency

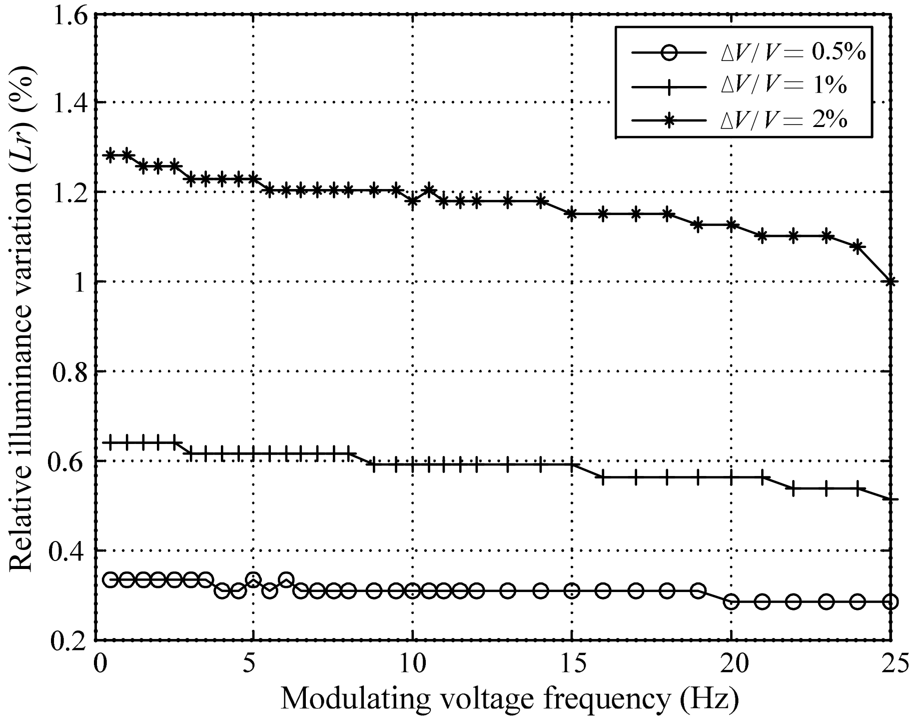

Figure 3.19 Relative illuminance variation of an 11W energy saving lamp versus the modulating voltage frequency

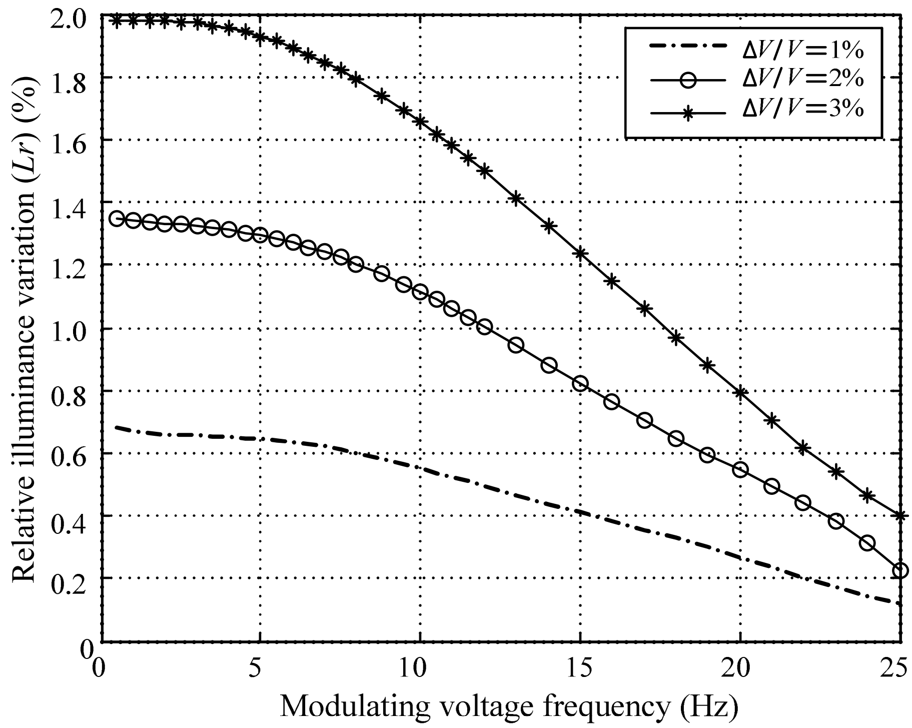

Figure 3.20 Relative illuminance variation of a 3.4W LED lamp versus the modulating voltage frequency

Figure 3.15 to 3.20 show that 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 a constant modulating voltage amplitude is applied. This is mainly due to the fact that the illuminance of the lamps depends on the thermal emission of the filament or the discharge of the electrode. This process can not follow the changes in the supply voltage of the lamp or the lamp tube. The relative illuminance variation of a CFL with electromagnetic ballast increases slightly when the modulating voltage frequency increases. This is due to the fact that the illuminance of this kind of lamp is affected by the electromagnetic ballast. This ballast shows different properties under flicker conditions.

Another important conclusion from the above measurement results is that the relative illuminance variation of the modulating voltage frequency component is linearly proportional to the modulating voltage amplitude for all lamp types. To further prove this conclusion, specific measurements were carried out in the lab which will be described in the next section.

3.4.2.4 Measurements to prove linearity

The goal of these measurements is to analyze the relationship between the modulating voltage amplitude and the relative illuminance variation when the modulating voltage frequency is kept constant (10Hz). The voltage fluctuations with a constant modulating voltage frequency (10Hz) and different modulating voltage amplitudes (1.2V – 6.9V) were generated by the programmable power source and supplied to the tested lamps. Like with the other measurements in section 3.4.2, the absolute illuminance variations of the tested lamp were recorded. The relative illuminance variations under flicker conditions were calculated by equation 3.1.

Examples of the measurement results of an 11W energy saving lamp and a 3.4W LED lamp are presented in figure 3.21. The results shown in the figure agree with the conclusion mentioned in section 3.4.2.3, i.e. there is a linear relationship between the relative illuminance variation and the modulating voltage amplitude of the modulating voltage frequency component. However, this conclusion is only true within the modulating voltage frequency range of 0.5Hz – 25Hz for all lamp types. The modulating voltage frequencies outside this range may be of interest. The consideration of these frequencies should be the subject for future work.

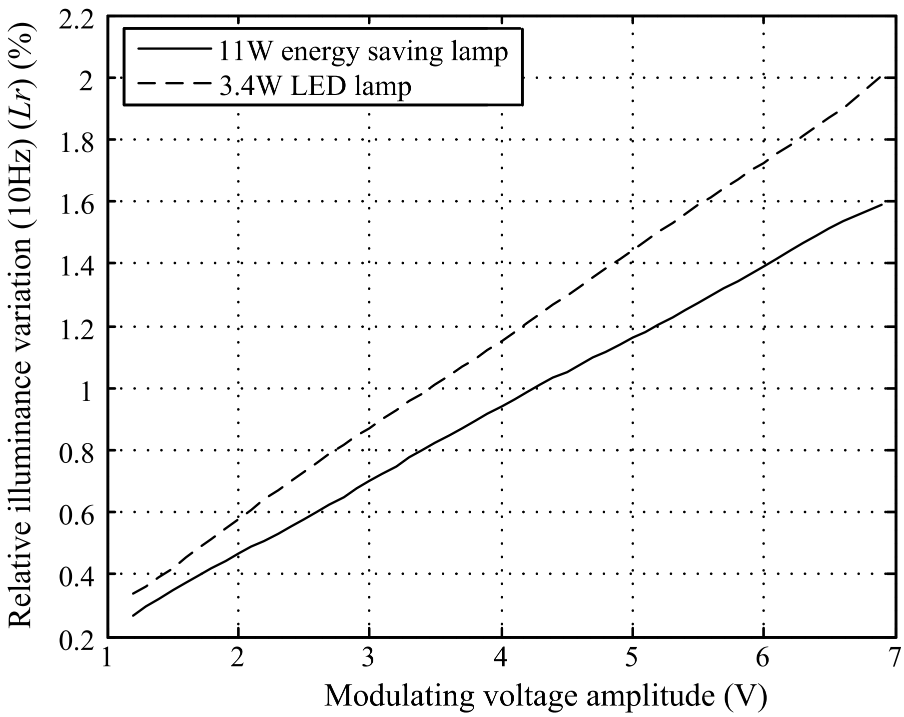

Figure 3.21 Relative luminance variation versus the modulation voltage amplitude with a 10Hz modulating frequency: 11W energy saving lamp (solid line); 3.4W LED lamp (dashed line)

3.5 The deficiencies of the UIE/IEC flickermeter

The UIE/IEC flickermeter is a popular instrument to evaluate the flicker level in the network. However, the UIE/IEC flickermeter is built only based on the existence of 230V 60W or 120V 60W incandescent lamps. So this UIE/IEC flickermeter is not designed to handle modern lamp types.

3.5.1 Improved lighting technology

Nowadays, there are more and more lamp types in the market. Every lamp converts electrical energy into visible light. However, different lamp types have different processes to convert the electrical energy into visible light [32].

Since there is a big difference of working principles between the different lamp types, the light spectrum of different lamp types are also quite different. It is therefore unavoidable that different lamp types have different sensitivities to flicker. The flicker response measurements results presented in section 3.4 proves that different lamp types have different flicker sensitivities. However, the UIE/IEC flickermeter is only based on the reference lamps: the 230V 60W and 120V 60W incandescent lamp. Therefore, the flicker level obtained by the UIE/IEC flickermeter can currently only be used for incandescent lamps and can act as a reference level for standards. The output of the UIE/IEC flickermeter can not correlate well with the customer sensitivities for other lamp types.

3.5.2 Flicker caused by interharmonics

Interharmonics are the spectra whose frequencies are non-integer multiples of the fundamental supply frequency [41]. It can generate both voltage peaks and RMS fluctuations. This is due to the fact that the frequency of the interharmonics is not synchronous with the fundamental supply frequency. It is therefore a source of flicker. The modulating voltage frequency caused by interharmonics can be determined by equation 3.3

$$f_{flicker} = |f_{IH} - f_H| \tag{3.3}$$

Where f_{IH} is the interharmonics frequency

f_H is the harmonic frequency closest to f_{IH}

The UIE/IEC flickermeter is designed mainly for the detection of peak variations. Thus, it has the deficiency not to be able to detect flicker caused by interharmonics [41] [42]. It is shown that the P_{st} value becomes very small when the interharmonic frequency is very high, even though the interharmonic voltage variation magnitude equals to that of the supply fundamental frequency [41].

The UIE/IEC flickermeter uses a squaring of the input voltage signal to demodulate the fundamental and the modulation voltage signal. The cut-off frequency of the low-pass filter (part of demodulate filter) used in the UIE/IEC flickermeter to filter the high frequency signal is 35Hz (50Hz power system) and 42Hz (60Hz power system). This low-pass filter completely eliminates input of frequencies higher than 100Hz (50Hz power system) and 120Hz (60Hz power system). Thus, the UIE/IEC flickermeter only can detect the flicker caused by interharmonics with frequencies lower than 85Hz (50Hz electrical power system) and 102Hz (60Hz power system). It cannot detect correctly the flicker caused by interharmonics with higher frequencies (e.g. higher than 85Hz in 50Hz electrical power system), which can normally be found in the electrical power system.

3.6 Improvement of the UIE/IEC Flickermeter

As mentioned in section 3.5, the UIE/IEC flickermeter is incapable to measure the flicker level for some new lamp types and flicker caused by interharmonics. In the research work presented in this thesis, only the improvement of the UIE/IEC flickermeter for different lamp types has been studied.

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 figure 2.8 in chapter 2, this filter can be considered as a combination of two filters: one is the lamp response filter that depends on the lamp type, while the other is the eye-brain filter that depends on the perception of the persons exposed to the flicker [43]. 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 230V, 60W and a 120V, 60W incandescent lamp [31]. Since different lamp types have different working principles, they should have different flicker sensitivities. This is proved by the experimental work presented in section 3.4. A modification of the parameters of the weighting transfer function should therefore be adapted to the lamp type, i.e. different parameters of the weighting filter should be used for different lamp types.

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 modulating voltage amplitude for each modulating voltage frequency. As explained in section 3.4.1, the illuminance waveform is a harmonic rich waveform under flicker. The measurement results presented in section 3.4.2 prove 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 (0.5Hz – 25Hz).

From the Fourier analysis of the measurement data of the instantaneous illuminance, it became clear that the illuminance amplitudes of the modulating voltage frequency components, with $100+\omega_m$ and $100-\omega_m$, are relative high (see table 3.4). The linear relationship between the illuminance amplitude and the modulating voltage amplitude for these two frequency components is not found as shown in figure 3.22. As mentioned in section 3.4.1, the frequency components with $100+\omega_m$ and $100-\omega_m$ are not of much interest for the flicker observation because the human eye is not sensitive to such high frequencies.

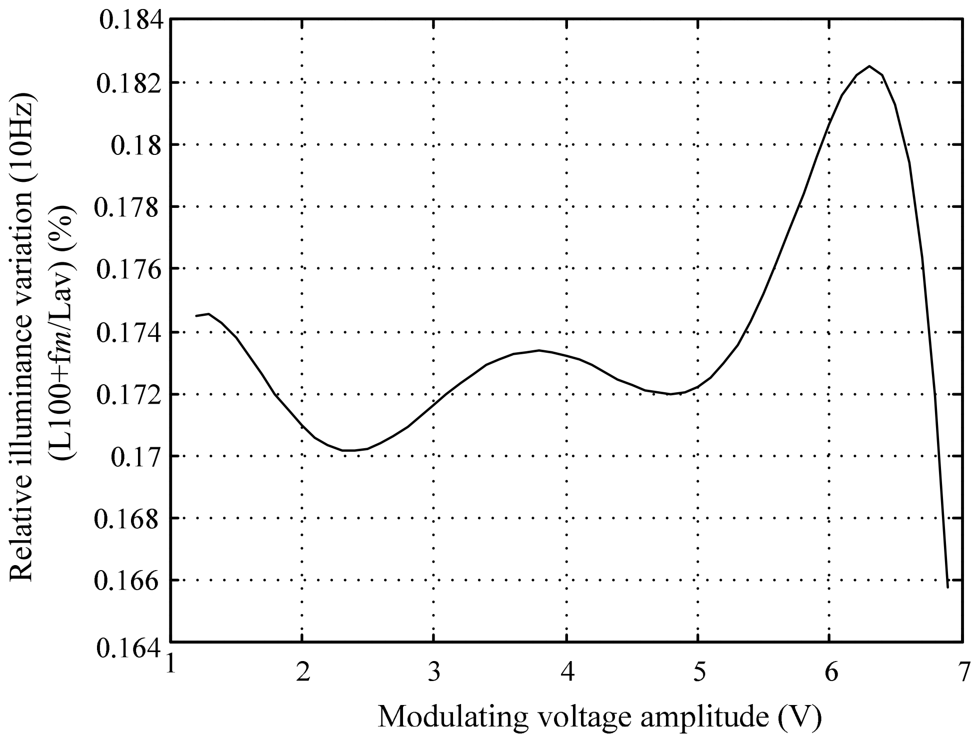

Figure 3.22 Relative illuminance variations (110Hz (100Hz +10Hz) component) of a 3.4W LED lamp with a 10Hz modulating voltage frequency

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 identification model is the calculated relative illuminance variation, which is obtained using the measured absolute illuminance variation under flicker condition and the average illuminance under normal voltage conditions. The transfer function derived from the lamp system identification model is the mathematical description of the lamp flicker response filter for different lamp types. The weighting filter of the UIE/IEC flickermeter can then be improved for different lamp types by using the linear transfer function of different lamp's flicker responses. Finally, it is possible to develop a flickermeter for different lamp types. The next chapter will further elaborate on this.

3.7 Summary

To get knowledge about the flicker responses of different lamp types, flicker response measurements were done for six lamp types. The measurement results have been presented in this chapter. The measurement results show that there is big difference of flicker sensitivity between different lamp types. The incandescent lamp is the most sensitive to flicker. It can also be concluded from the results that the relative illuminance variation is linearly proportional to the modulating voltage amplitude for all lamp types within the frequency range of interest (0.5Hz – 25Hz). The instantaneous flicker curves of the 11W energy saving lamp, 15W fluorescent lamp and CFL with electromagnetic ballast for sinusoidal modulated voltages are also presented in this chapter. These curves show that the energy saving lamp is the most insensitive to flicker. Such curves can be used to estimate the flicker level of different lamp types.

Based on these measurement results, a proposal to improve the UIE/IEC flickermeter to be able to handle different lamp types was discussed.

Chapter 4

Improved Flickermeter Model

4.1 Introduction

In the previous chapter, the flicker response measurement results for different lamp types showed that there is a large difference in the flicker response of these lamp types. This means that the UIE/IEC flickermeter is not suitable to evaluate the flicker level for all lamp types. This is due to the fact that only the incandescent lamp is used in the UIE/IEC flickermeter as reference lamp. A proposal to improve the flickermeter for other lamp types is made in this chapter.

The main steps to improve the flickermeter are:

1) Derive the lamp flicker response models for different lamp types using a system identification method.
2) Decompose the weighting filter of the UIE/IEC flickermeter to be able to obtain the eye-brain flicker response. This can be done by division of the weighting filter given in the UIE/IEC flickermeter through the incandescent lamp flicker response model.
3) Develop the weighting filters for different lamp types from the multiplication of the flicker response model of each lamp times the eye-brain flicker response.
4) Replace the weighting filter of the UIE/IEC flickermeter by the improved weighting filter for each lamp type. The flicker level of each lamp type

evaluated by the improved flickermeter is now better correlated with customer sensitivity.

These steps will be explained in detail in this chapter. Furthermore, a discussion on a more direct way to obtain the lamp flicker response curves is made.

4.2 The lamp flicker response model

A flicker response model for each lamp type will be derived in this section using a system identification method. These models only focus on the relationship between the lamp input voltage variation and the lamp illuminance variation. The derived lamp flicker response models will be used to develop the weighting filter for each lamp type.

4.2.1 Introduction of system identification

Through the fast development of information technology, a mathematical model of dynamic systems is very useful in many areas and applications. System identification is an experimental approach to built mathematical models. It generates mathematical models for a dynamic system based on the observed data from the system [44] [45]. The general procedure of system identification is shown in figure 4.1.

As shown in figure 4.1, the system identification procedure starts from the determination of the dynamic system of interest. The experimental design is made after the input, output and disturbance of the dynamic system have been defined. Meanwhile the suitable system identification model structure (identification method) used for the parameter estimation of the system under study is selected. The parameters of the system are estimated using the selected identification methods and the experimental data. A simulation model of the studied system is now obtained. This simulation model is then validated by experimental data, which needs to be different from the data used for the model parameter estimation. There are several methods to check the quality of a model, e.g. the fitting rate between the simulation model and the validation data, and the residue analysis etc. Depending on the application, the related validation methods are selected. If the validation meets the requirement of the application, the mathematical model of the studied system can be accepted. Otherwise, the steps should be repeated as the sequence from (1) to (6), which is shown in figure 4.1, until the successful mathematical model is found.

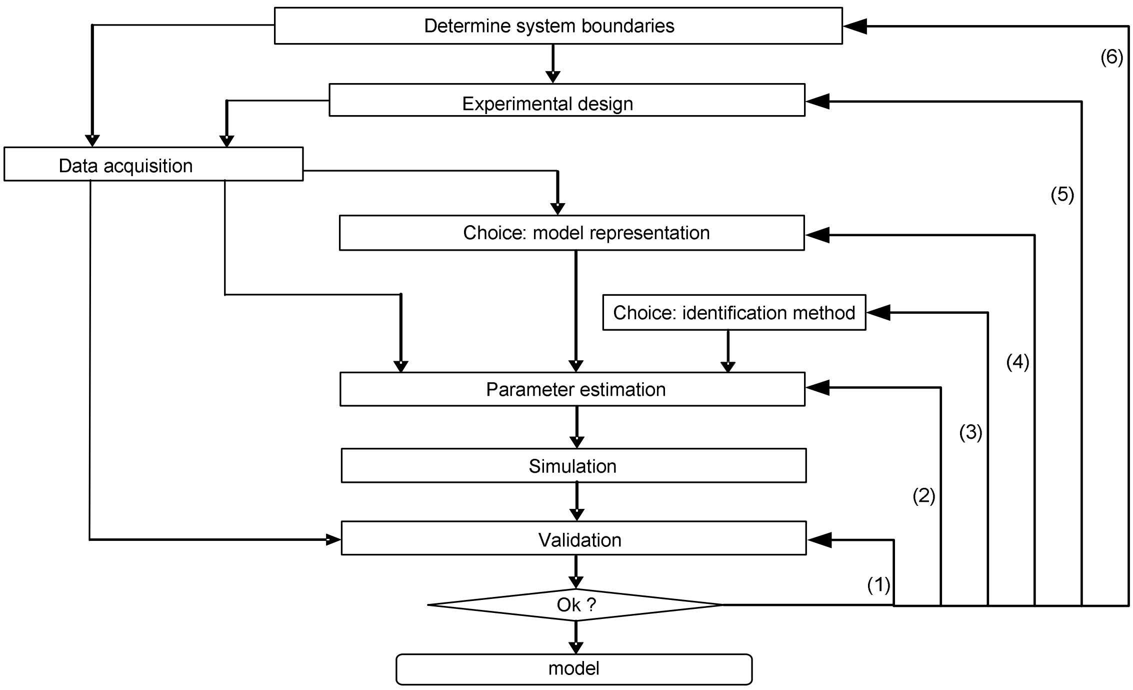

Figure 4.1 The general procedure of system identification

Due to the different applications, different models are used for linear and non-linear systems. There are many identification methods for the system identification of dynamic systems, e.g. parametric estimation and non-parametric estimation etc [44] [45] [46].

As mentioned in chapter 3, the relative illuminance variation is linearly proportional to the modulating voltage amplitude for all lamp types within the frequency range of interest. Therefore, a parametric linear system identification method is used in the research presented in this thesis. The typical parametric identification model structures used for a linear system are explained below.

Auto-Regressive with eXogenous input model (ARX) model

The model structure is shown in equation (4.1)

$$A(q)y(k) = B(q)u(k) + e(k) \tag{4.1}$$

Where q is the time shift operator
k is the discrete time step
u(k) is the input of the model
y(k) is the output of the model
e(k) is the error of the model
A(q) and B(q) are the parameters to be estimated of the model.

This is a kind of equation error model. It is the simplest model structure. However, the model lacks adequate freedom to describe the properties of the disturbance term.

Auto-Regressive Moving Average with eXogenous input (ARMAX) model

$$A(q)y(k) = B(q)u(k) + C(q)e(k) \tag{4.2}$$

The structure of the ARMAX model is shown in equation (4.2). C(q) is the extra parameter of the model to be estimated. It is a kind of equation error model as well. Compared with the ARX model, this model adds the flexibility to describe the properties of the disturbance term because of the additional parameter C(q).

Output Error (OE) model

The OE model is a kind of output error model. Compared to the equation error model, the error in the output error model is independent of the estimated parameters of the model. It is more natural than the equation error model and is able to describe the disturbance of the system better. However, this model is more complex than the ARX model. The structure of the OE model is presented in equation (4.3).

$$y(k) = [B(q)/F(q)]u(k) + e(k) \tag{4.3}$$

Where B(q) and F(q) are the parameters to be estimated of the model.

Box-Jenkins (BJ) model

The BJ model is also a kind of output error model. The structure of the BJ model is described in equation (4.4).

$$y(k) = [B(q)/F(q)]u(k) + [C(q)/D(q)]e(k) \tag{4.4}$$

Where B(q), C(q), D(q) and F(q) are the parameters to be estimated. Due to the additional parameters C(q) and D(q), the BJ model has a more natural development than the OE model on the properties of the output error. The system disturbance can be better described by this model. However, it is also more complicated to use.

State-Space model

This model describes the system using the state vector. The structure of the state-space model is shown in equations (4.5) and (4.6).

$$x\,(k+Ts) = Ax(k) + Bu(k) + Ke(k) \tag{4.5}$$

$$y(k) = Cx(k) + Du(k) + e(k) \tag{4.6}$$

Where x(k) is the state vector

Ts is the step time that indicates the time of the next state

A, B, K, C and D are the parameters of the system to be estimated.

This model has more flexibility in the choice of representation what can improve the properties of the estimated parameters of the model. But it is also a more complex model to apply.

These model structures have been tested in this thesis to find the most suitable model structure for the application in this research. The detailed comparison results are shown in section 4.2.3 and table 4.1. To match the application goal of the research presented in this thesis, the OE model is selected as the final model structure. The reasons will be explained in detail in section 4.2.3 as well.

4.2.2. Existing lamp model

Many researchers did studies on lamp models. Basically, there are two types of models. One type is derived from the physical characteristics of the lamp. These models are normally quite complicated because several factors have to be considered, e.g. lamp temperature, chemical reaction etc. Paper [47] gives the relationship between the lamp input voltage and the light intensity of the incandescent lamp, as shown in equation (4.7):

$$\lambda = \beta \cdot e^{\frac{-t}{R_\theta C_\theta}} \cdot [\frac{1}{C_\theta}\int_0^t \frac{v^2}{52.05v^{0.42} - 148.8} \cdot e^{\frac{-t}{R_\theta C_\theta}} dt + c]^{1.7} \tag{4.7}$$

Where: λ is the luminous flux, β is a constant number, $R_\theta C_\theta$ is the lamp thermal time constant, C_θ is the thermal capacitance of the lamp filament, v is the lamp input voltage and c is the ambient temperature.

For a fluorescent lamp, the physical description is totally different from an incandescent lamp. Moreover, the equation is even more complicated because it is a gas-discharge lamp [48]. In brief, the physical model is not so convenient to be used in our application – the flickermeter. Furthermore, the temperature of the lamp filament is not necessary information in the research presented in this thesis. This is due to the fact that the lamp flicker response measurements presented in this thesis are always made after the lamp reach stable condition, i.e. the lamp filament temperature and illuminance do not change anymore.

The incandescent lamp has a resistive load characteristic. The incandescent lamp illuminance depends on the temperature of the filament. Thus, there is always a time delay between the lamp input voltage and the illuminance of the lamp, the so called lamp time constant. Based on these two facts, paper [49] describes a simplified incandescent lamp model – a first order low pass filter. The transfer function of this simplified model is given in equation (4.8).

$$F(s) = \frac{k}{1 + s\tau} \tag{4.8}$$

Where $k = 1$ is the gain factor and $\tau = 22$ ms is the lamp time constant. To test if this simplified lamp model can be used for the application of this thesis, the flicker response measurement results of a 230V, 60W incandescent lamp presented in chapter 3 section 3.4.2.3 are used. The lamp input voltage variation (36 voltage fluctuations with 1% modulating voltage amplitude and 36 corresponding modulating voltage frequencies) is used as the input of this simplified lamp model. The simulation output of the model (i.e. the simulated lamp illuminance variation) is compared to the corresponding measured illuminance variation. The average fitting rate between the lamp illuminance simulation data estimated by this model and the measurement results is 4.88%. The reason is that the simplified model only describes the relationship between the lamp input voltage and lamp illuminance under normal conditions (no flicker), i.e.

$$L = F(s) \times V \tag{4.9}$$

Where L is the lamp illuminance and V is the lamp input voltage. This model is not accurate enough to describe the relationship between the lamp input voltage variation and the lamp illuminance variation, as indicated in equation (4.10).

$$\Delta L = f(\Delta V) \tag{4.10}$$

Here ΔL is the lamp illuminance variation and ΔV is the lamp input voltage variation. This relationship is important during flicker measurements because of the use of the flickermeter. So, in this chapter, lamp models that can describe the relationship presented in equation (4.10) adequately are derived mathematically for different lamp types. They are derived by using a linear dynamic system identification method.

4.2.3. Lamp flicker response model

Under flicker conditions, the measurement results presented in chapter 3 show that the lamp illuminance amplitude always varies linearly with the voltage variation amplitude within the flicker frequency range (0.5Hz – 25Hz) for all tested lamp types. Thus, the lamp can be assumed as a linear dynamic system within the flicker frequency range of interest. To simplify the research problem, the lamp is assumed as a black-box without considering internal components and physical characteristics, i.e. a so-called black-box model. The parameters of this model only serve to adjust the fitting to the experimental data and do not consider any physical or electrical characteristics of the lamp system. Due to the fact that our focus is only on the relationship between the lamp input voltage variation and the lamp illuminance variation, the input of the black-box model is the lamp input voltage variation amplitude. The output of the black-box model is the lamp illuminance variation amplitude. The basic structure of the lamp flicker response model is shown in figure 4.2.

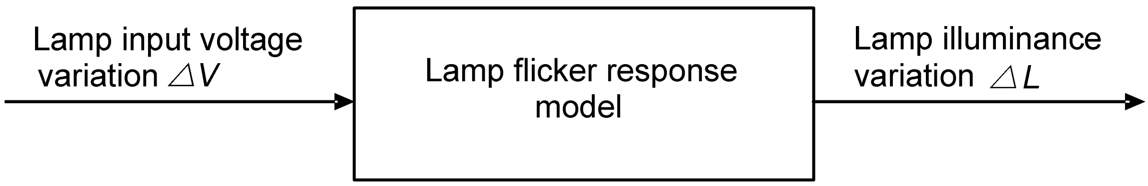

Figure 4.2 The basic structure of the lamp flicker response model

The input and output data are obtained from measurements. The measurement set-up is the same as the one described in chapter 3. The measured lamp input voltage variation and the illuminance variation are treated as the estimated data set of the corresponding lamp black-box model. Based on the measured data, the parameters of the black-box model are estimated.

For the black-box model in our application, several model structures that can describe the parametric linear system can be used, as was explained in section 4.2.1. However, the most suitable model structure depends on the application. The goal of our application is to find a simple and easy to use model that is able to represent the illuminance variation under flicker conditions. The properties of the feedback and the white noise of the model are not of main concern in our application. A better fitting rate is the first criterion to select the model structure in our case. Moreover, the size and complexity of the model structure is also an important criterion. According to these criteria, four model structures: the ARX model, output error model (OE) and state-space model have been tested with the same estimation data set of a 230V 60W incandescent lamp. The average fitting rates between the simulation results of the system identification model and the validation data within the frequency range of interest (0.5Hz – 25Hz) are shown in table 4.1.

Table 4.1 Average fitting rate between simulation results of different identification model structures and measurement results

Model structure	ARX	OE	State-space
Order	8	8	6
Average fitting rate (%)	92.54	91.71	85.63

The results show that the ARX and OE models can be used to describe the lamp system with high correctness. Both the ARX model and OE model can be selected as the lamp flicker response identification model. The structures of the ARX and the OE model are shown in equation (4.1) and (4.3). Comparing equation (4.1) to equation (4.3), it can be noticed that the output is not affected by the error in equation (4.3). Thus, the OE model can represent the reality more natural than the ARX model and is more suitable for our application. So, the OE model is selected as the lamp flicker response identification model structure for this research.

The lamp flicker response models are derived using the system identification toolbox in Matlab/Simulink [50]. The experimental set-up is the same as described in chapter 3 section 3.2.

Incandescent lamp flicker response model

A 60W 230V incandescent lamp was measured in the PQ lab of the TU/e. An example of a voltage fluctuation with 10Hz modulation frequency and the corresponding illuminance of a 20W fluorescent lamp is given in figure 4.3 and 4.4.

In total 36 voltage fluctuations (with the same modulating voltage amplitude and different modulating voltage frequencies) were given to the lamp. The corresponding lamp voltages and illuminances were recorded. FFT analysis was used to extract the modulating voltage frequency (0.5Hz – 25Hz) components from the measured lamp voltage and illuminance. As mentioned in section 4.2.2, the lamp flicker response identification models used in this thesis only focus on the relationship between the voltage variation and the illuminance variation. Totally 36 data sets of the voltage variation and the corresponding lamp illuminance variation are rebuilt by the modulating voltage frequencies (0.5Hz – 25Hz) and the amplitudes of the components extracted using FFT analysis. The sampling frequency and the sample time of the data sets are 200Hz and 2sec. These data sets are used for the lamp system identification. The input of the lamp flicker response identification model is the sum of 36 voltage variations with a frequency between 0.5Hz and 25Hz. The output of the lamp flicker response identification model is the sum of 36 corresponding illuminance variations. Figure 4.5 and 4.6 show an example of the input and output of the lamp flicker response identification model. Each rebuilt data set of the voltage variation and the illuminance variation, which has only a single modulating voltage frequency, is used as the validation data for the lamp flicker response identification model. Since both the input and output of the lamp flicker response identification model are discrete points, a linear discrete-time system identification model was developed. Different orders of OE models have been tested by using a Matlab/system identification toolbox.

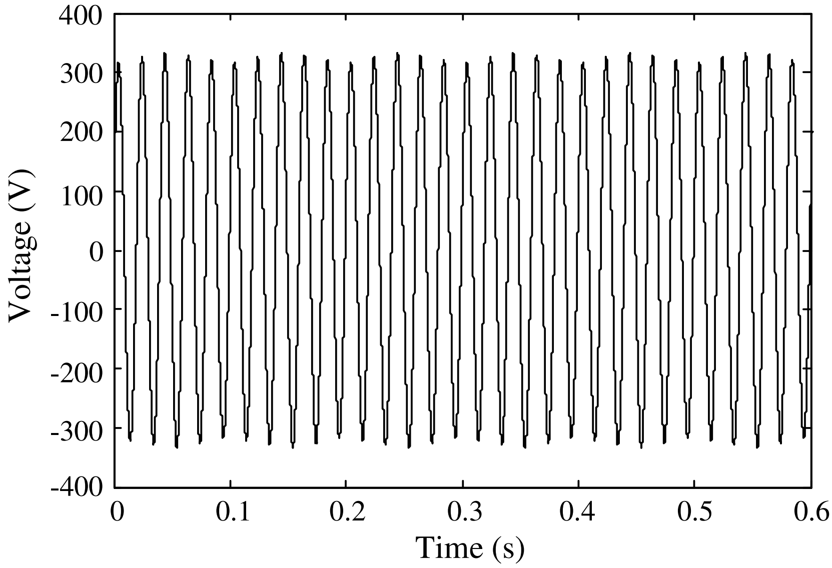

Figure 4.3 An example of a voltage fluctuation with 10Hz modulation frequency

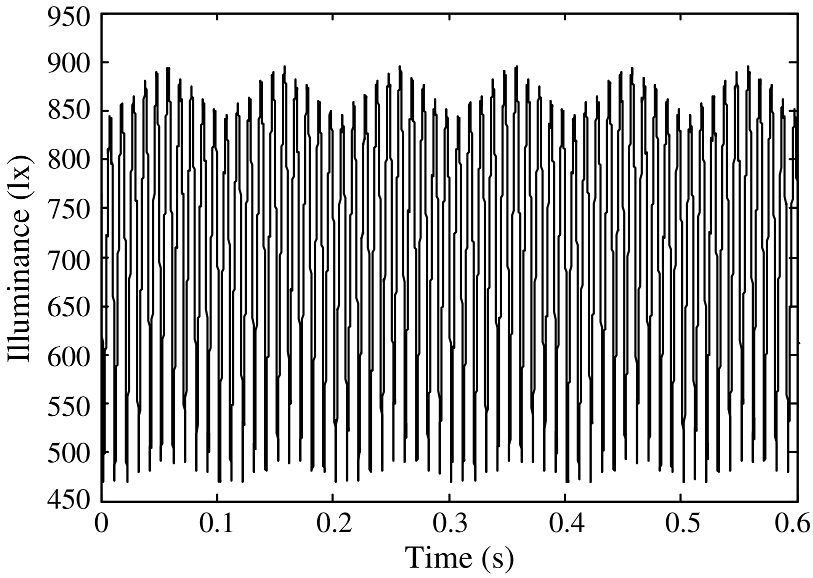

Figure 4.4 The illuminance of a 20W fluorescent lamp with 10Hz voltage fluctuation

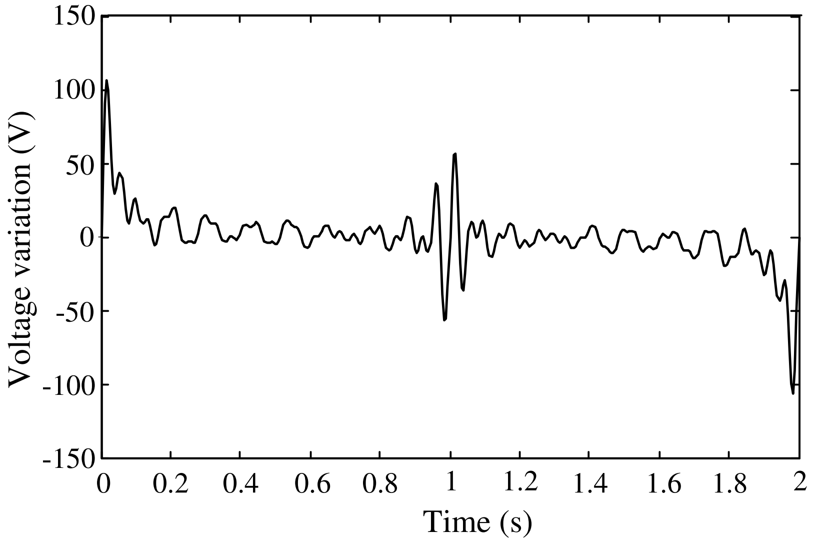

Figure 4.5 An example of the input estimation data of the lamp flicker response identification model

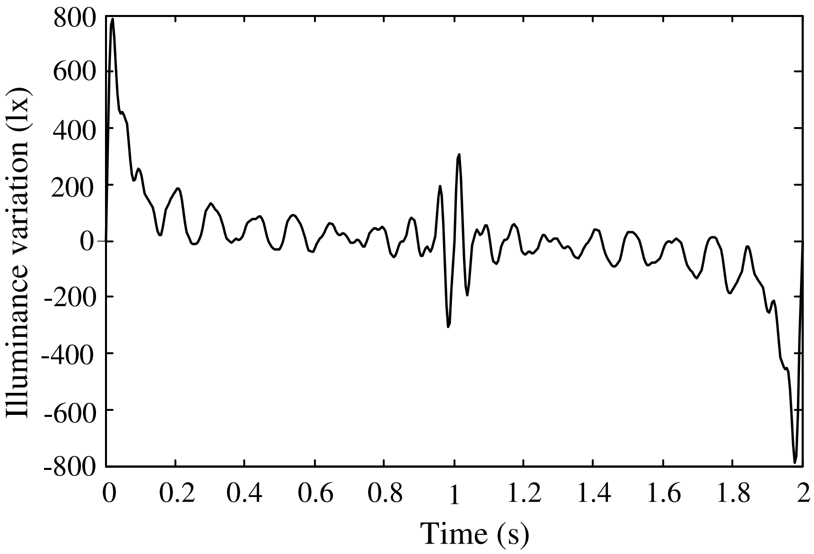

Figure 4.6 An example of the output estimation data of the lamp flicker response identification model

To decide if a system identification model is applicable, the two properties below should be checked:

1) The fitting rate between the simulated and measured results (i.e. the validation data).

   The fitting rate can show how large the prediction error is. The identification model is better if the fitting rate is higher. It is calculated by equation (4.11) in this thesis.

$$FIT = [1 - NORM(Y_m - Y_{sim}) / NORM(Y_m - MEAN(Y_m))]*100 \tag{4.11}$$

Where Y_m is the measured data of the model output

Y_{sim} is the simulated data of the model output

2) The residue analysis.

The residue analysis includes two types of correlation functions: the auto correlation of residues for the model output is used to check the residues produced by the identification model; the cross correlation of the model input and output residues is used to check if the model output residues are independent on the model input, i.e. the model can be applied to other inputs. For a good identification model, these two types of correlation functions should not fall significantly outside the confidence intervals.

After the tests with different orders of the OE model, an 8^{th} order OE model (5 poles) is chosen for the incandescent lamp flicker response identification model. This is because of the fact that it has the best fitting rate and the auto correlation of residues for the model output and the cross correlation of the model input and output residues are acceptable.

Figure 4.7 shows an example of the fitting results between the simulated and measured results of the 8^{th} order OE model for the 10Hz modulating voltage frequency. The calculated fitting rate is 90.83%. Examples of the fitting rate for different flicker frequencies by using the 8th order OE incandescent lamp model are presented in table 4.1. The average fitting rate of this model is 91.71%.

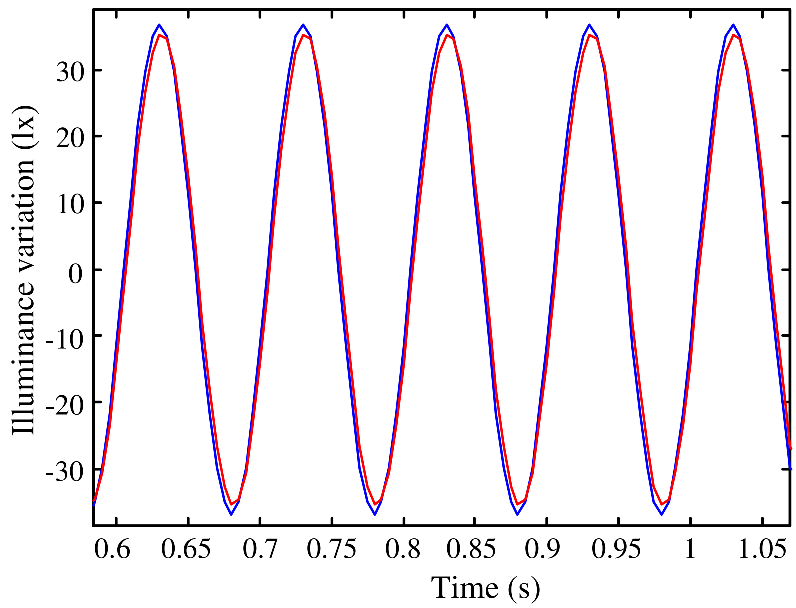

Figure 4.7 The fitting results between the simulated and measured results of an 230V 60W incandescent lamp. Blue line: simulation results; red line: measurement results

Table 4.1 Fitting rate of different lamp flicker response identification models

Flicker frequency (Hz)	Fitting rate (%)				
	Incandescent lamp	Fluorescent lamp set	Energy saving lamp	Halogen lamp	LED lamp
0.5	91.92	96.58	97.2	92.62	96.92
2.0	92.46	90.96	98.32	92.56	96.46
4.0	94.89	90.41	98.9	92.54	94.89
6.0	91.81	90.85	99.26	92.49	91.81
8.0	92.5	90.25	99.23	90.57	92.5
10.0	90.83	95.64	99.03	90.05	92.63
12.0	92.03	99	99.27	90.83	93.82
14.0	95.4	94.28	99.37	91.63	96.4
16.0	95.75	92.11	98.92	91.85	93.38
18.0	89.9	91.68	98.48	90.16	89.9
20.0	88.42	93.53	98.18	89.99	88.42
22.0	88.72	96.71	98.59	93.69	88.72
24.0	87.65	89.74	98.29	89.74	87.65
Average	91.71	93.21	98.7	91.44	92.58

Figure 4.8 shows an example of the residue analysis results of the 8^{th} order OE model when the modulating voltage frequency is 10Hz. As shown in figure 4.8, the cross correlation of the model input and the model output residues lies inside the 99.9% confidence region. This means that this identification model can be applied for other inputs. The auto correlation of the residues for the model output is not fully inside the 99.9% confidence region. This indicates that the identification model could still be improved. In this thesis, this is not done. The reason is the fact that the lamp flicker response identification model is an open-loop system. The auto correlation of residues for the model output given in figure 4.8 does not seriously affect the quality of the open-loop system. As mentioned before, the input, and output estimation data as well as the validation data of the lamp flicker response identification model are reconstructed using the FFT analysis results. Thus, the residue of the lamp flicker response identification model is not related to measurement noise, but it is the identification model error itself.

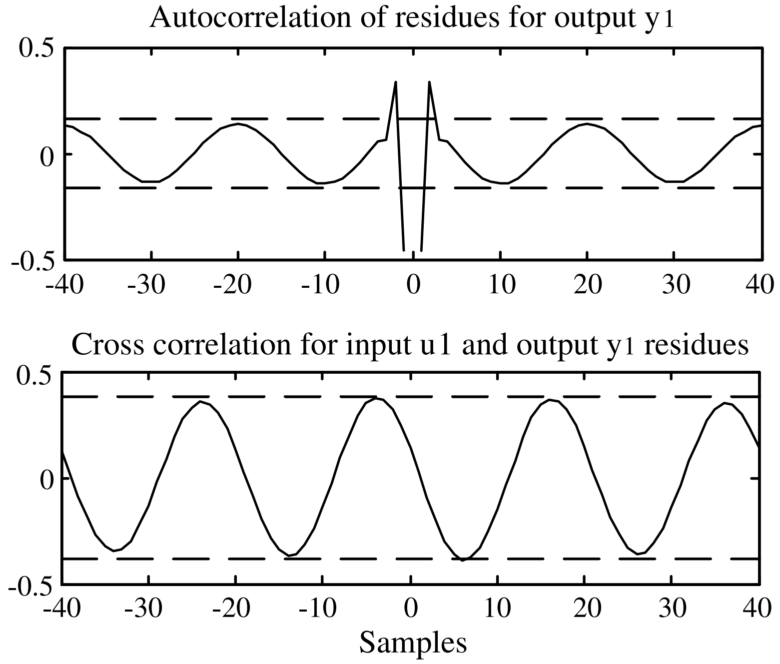

Figure 4.8 The residues analysis of a 230V 60W incandescent lamp with the 10Hz modulating voltage frequency. Solid line: the correlation results; dashed line: the 99.9% confidence interval.

In order to use the lamp flicker response identification model in the flickermeter, this model should be translated into a mathematical equation, i.e. a voltage-illuminance variation transfer function. The 8th order OE incandescent lamp model that is derived for the 60W, 230V incandescent lamp can be written as a transfer function, given in equation (4.12):

$$F_{lamp\_inc}(q) = \frac{b_1q^{-1} + b_2q^{-2} + b_3q^{-3} + b_4q^{-4} + b_5q^{-5} + b_6q^{-6} + b_7q^{-7} + b_8q^{-8}}{1 + f_1q^{-1} + f_2q^{-2} + f_3q^{-3} + f_4q^{-4}} \tag{4.12}$$

With $b_1 = 67.91$, $b_2 = -316.1$, $b_3 = 670$, $b_4 = -822.6$, $b_5 = 621$, $b_6 = -280.4$, $b_7 = 66.43$, $b_8 = -5.351$, $f_1 = -2.171$, $f_2 = 1.629$, $f_3 = -0.3144$, $f_4 = -0.06603$

The loss function of the model is 56466.1. The finite predict error (FPE) of the model is 60118.9. The loss function and FPE are quite large. This is caused by the high order of the model and the model error. A lower order of the model has been tested; however, the fitting rate was not good. To balance the fitting rate and the model order, the 8^{th} order OE model is selected.

To show the characteristics of the incandescent lamp flicker response identification model, the zero-pole plot and the frequency response of the model are shown in figure 4.9 and 4.10. As shown in figure 4.9, all poles and zeros of the incandescent lamp flicker response identification model lie inside the unit circle. Thus, the system presented by the model is stable. However, there are two overlapping poles and zeros. From theory, the order of this model should be decreased. After checking the fitting rate and the residue analysis of a lower order model, the 8^{th} order is kept because the lower order model gives a significantly decrease of the fitting rate and worse correlation functions. This indicates that maybe the measured data includes small non-linearity characteristics. This should be checked in the future. Figure 4.10 shows both the amplitude and phase response of the incandescent lamp flicker response identification model. It should be noted that the model is developed for a frequency range of up to 25Hz. Furthermore, the phase response in figure 4.6 is not of concern because the lamp flicker response identification model studied in this thesis only focuses on the amplitude responses.

Fluorescent lamp flicker response model

The measurement for a 15W 230V fluorescent lamp was also done in the PQ lab of the TU/e. The same procedures as for the incandescent lamp model have been carried out to obtain the suitable fluorescent lamp model. After testing the OE model structure with different orders, the 5th order OE model (3 poles) was chosen finally because of the relative high fitting rate (as shown in Table 4.1) and better correlation functions. The average fitting rate is 93.21%. The plot of the correlation functions, the zero-pole and the frequency response plots of the model are presented in Appendix E.

The transfer function of the 5th order OE fluorescent lamp model can be written as equation (4.13):

$$F_{lamp\_flu}(q) = \frac{b_1 q^{-1} + b_2 q^{-2} + b_3 q^{-3} + b_4 q^{-4} + b_5 q^{-5}}{1 + f_1 q^{-1} + f_2 q^{-2}} \tag{4.13}$$

With $b_1 = 12.81$, $b_2 = -32.51$, $b_3 = 36.36$, $b_4 = -21.27$, $b_5 = 5.232$, $f_1 = -\ 0.6554$, $f_2 = -0.1514$.

The loss function of the model is 2160.26. The FPE is 2239.02. The same as with the incandescent lamp flicker response model, these are caused by the high order of the model and the model error. However, by balancing the fitting rate and the model order, the current model order has been defined. The same is the case with the following three lamp flicker response models.

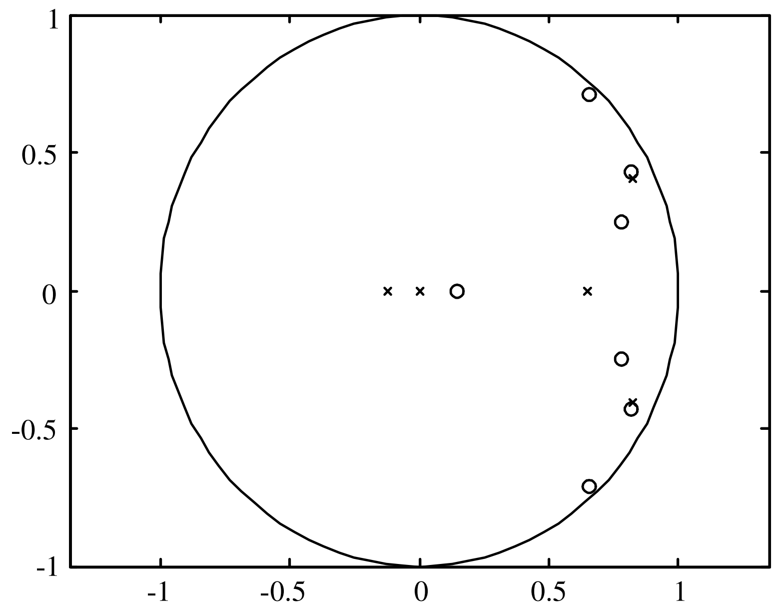

Figure 4.9 The zero-pole plot of a 230V 60W incandescent lamp flicker response identification model. Poles: x; zeros: o

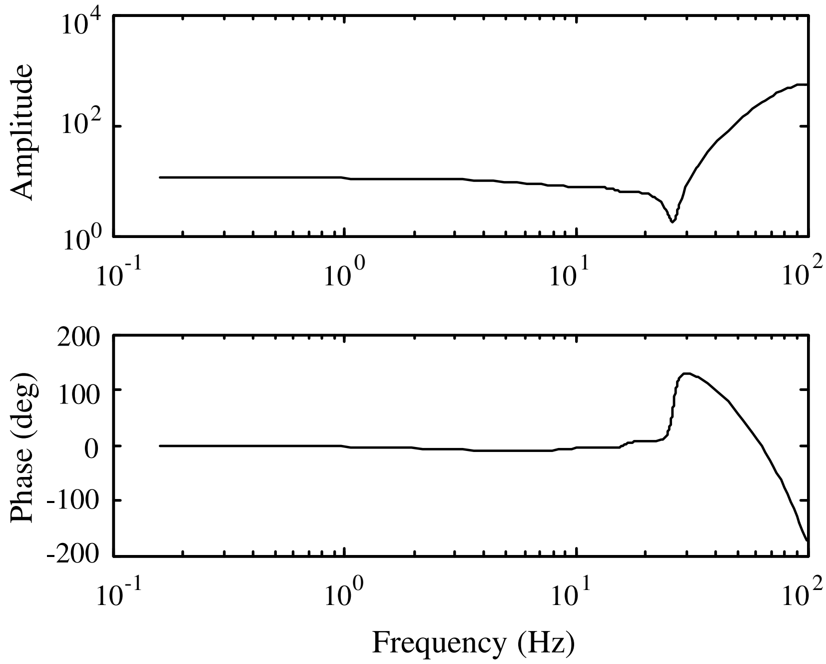

Figure 4.10 The frequency response of the 230V 60W incandescent lamp flicker response identification model

Energy saving lamp flicker response model

The flicker response of a 11W 230V energy saving lamp was tested in the lab. The OE model structure was also selected for this lamp. After testing the OE model structure with different orders, the 6th order OE model (3 poles) was chosen because of the relative high fitting rate (as shown in Table 4.1) and better correlation functions. The average fitting rate is 98.7%. The plot of the correlation functions, the zero-pole and the frequency response plots of the model are presented in Appendix E.

The 6th order OE energy saving lamp model can be written as equation (4.14):

$$F_{lamp\_CFL}(q) = \frac{b_1 q^{-1} + b_2 q^{-2} + b_3 q^{-3} + b_4 q^{-4} + b_5 q^{-5} + b_6 q^{-6}}{1 + f_1 q^{-1} + f_2 q^{-2}} \tag{4.14}$$

With b_1 = 18.35, b_2 = -44.95, b_3 = 59.28, $b4$ = -44.84, $b5$ = 18.66, $b6$ = -3.335, f_1 = 0.02689, f_2 = 0.01016.

The loss function and FPE of the model are 5468.04 and 5697.67.

Halogen lamp flicker response model

A 40W 230V Halogen Spot lamp was selected as halogen lamp example and tested in the lab. The same procedures are carried out as for the lamp models above. A 6th order OE model (2 poles) was chosen because of the better correlation functions (see the plot in Appendix E) and the relative high fitting rate, shown in Table 4.1. The average fitting rate is 91.44%.

The 6th order halogen lamp model can be written as a transfer function, which is given in equation (4.15):

$$F_{lamp\_hal}(q) = \frac{b_1 q^{-1} + b_2 q^{-2} + b_3 q^{-3} + b_4 q^{-4} + b_5 q^{-5} + b_6 q^{-6}}{1 + f_1 q^{-1}} \tag{4.15}$$

With b_1 = 45.85, b_2 = -135.8, b_3 = 192.2, b_4 = -147.7, b_5 = 60.35, b_6 = -9.966 and f_1 = -0.09855

The loss function and FPE of the model are 47281.2 and 49009.5 respectively.

LED lamp flicker response model

A 3.4W 230V LED lamp was measured in the lab to build the LED lamp model under flicker. Equal to the other lamp flicker response identification model tests, finally the 6th order OE model (2 poles) was the best order because of the relative high fitting rate as shown in table 4.1 and the better correlation functions (see the plot in Appendix E). The average fitting rate is 92.58%.

The transfer function of the 6th order OE LED lamp model can be written as equation (4.16):

$$F_{lamp\_LED}(q) = \frac{b_1 q^{-1} + b_2 q^{-2} + b_3 q^{-3} + b_4 q^{-4} + b_5 q^{-5} + b_6 q^{-6}}{1 + f_1 q^{-1}} \tag{4.16}$$

With b_1 = 23.87, b_2 = -73.28, b_3 = 105.5, b_4 = -82.03, b_5 = 34.15, b_6 = - 5.911 and f_1 = 0.0234

The loss function of the model is 38520.9. The FPE of the model is 39929.

4.3 Weighting filter improvement for different lamp types

As mentioned before, the weighting filter is an important part of the UIE/IEC flickermeter. It simulates the lamp-eye system flicker response. Since this transfer function is available for a 230V 60W incandescent lamp, the flicker response of eye-brain system can be obtained by using equation (2.7) divided by equation (4.12). To be consistent with the format of the current weighting filter, the discrete lamp flicker response transfer functions given in equation (4.12) – (4.16) are transformed into continuous functions by a bilinear approximation method.

The derived eye-brain flicker response transfer function is shown in equation (4.17):

$$F_{eye-brain}(s) = F_{lamp-eye-brain}(s) / F_{lamp\_inc}(s) = \frac{num(s)}{den(s)} \tag{4.17}$$

With

$$\begin{aligned} num(s) = & -7437s^9 - 1.67\cdot10^7 s^8 - 1.545\cdot10^{10} s^7 - 7.572\cdot10^{12} s^6 - 2.116\cdot10^{15} s^5 \\ & - 3.452\cdot10^{17} s^4 - 3.476\cdot10^{19} s^3 - 2.503\cdot10^{21} s^2 - 1.039\cdot10^{23} s - 1.063\cdot10^{24} \end{aligned}$$

$$\begin{aligned} den(s) = & -564.5s^{12} + 1.272\cdot10^5 s^{11} - 3.627\cdot10^7 s^{10} - 1.763\cdot10^{10} s^9 - 5.639\cdot10^{12} s^8 \\ & - 1.128\cdot10^{15} s^7 - 1.545\cdot10^{17} s^6 - 1.648\cdot10^{19} s^5 - 1.244\cdot10^{21} s^4 - 7.19\cdot10^{22} s^3 \\ & - 2.637\cdot10^{24} s^2 - 6.711\cdot10^{25} s - 3.892\cdot10^{26} \end{aligned}$$

The bode diagram of the weighting filter given in the UIE/IEC flickermeter (the lamp-eye-brain flicker response), the incandescent lamp flicker response and the eye-brain flicker response are shown in figure 4.11 [43].

In this research, the average eye-brain flicker response is assumed to be identical for all people. Hence, new weighting filters for different lamp types can be derived by using the corresponding lamp flicker response transfer function multiplied by the eye-brain transfer function. The new weighting filters for fluorescent lamps, energy saving lamps, halogen lamps and LED lamps are given in equation (4.18) – (4.21) respectively:

$$F_{flulamp-eye-brain}(s) = F_{lamp\_flu}(s) \times F_{eye-brain}(s) \tag{4.18}$$

$$F_{CFLlamp-eye-brain}(s) = F_{lamp\_CFL}(s) \times F_{eye-brain}(s) \tag{4.19}$$

$$F_{hallamp-eye-brain}(s) = F_{lamp\_hal}(s) \times F_{eye-brain}(s) \tag{4.20}$$

$$F_{LEDlamp-eye-brain}(s) = F_{lamp\_LED}(s) \times F_{eye-brain}(s) \tag{4.21}$$

These new weighting filters represent the flicker responses of different lamp types. If they are used in the flickermeter, the new flickermeter can be used to measure the flicker level for all such lamp types better correlated with customer complaints.

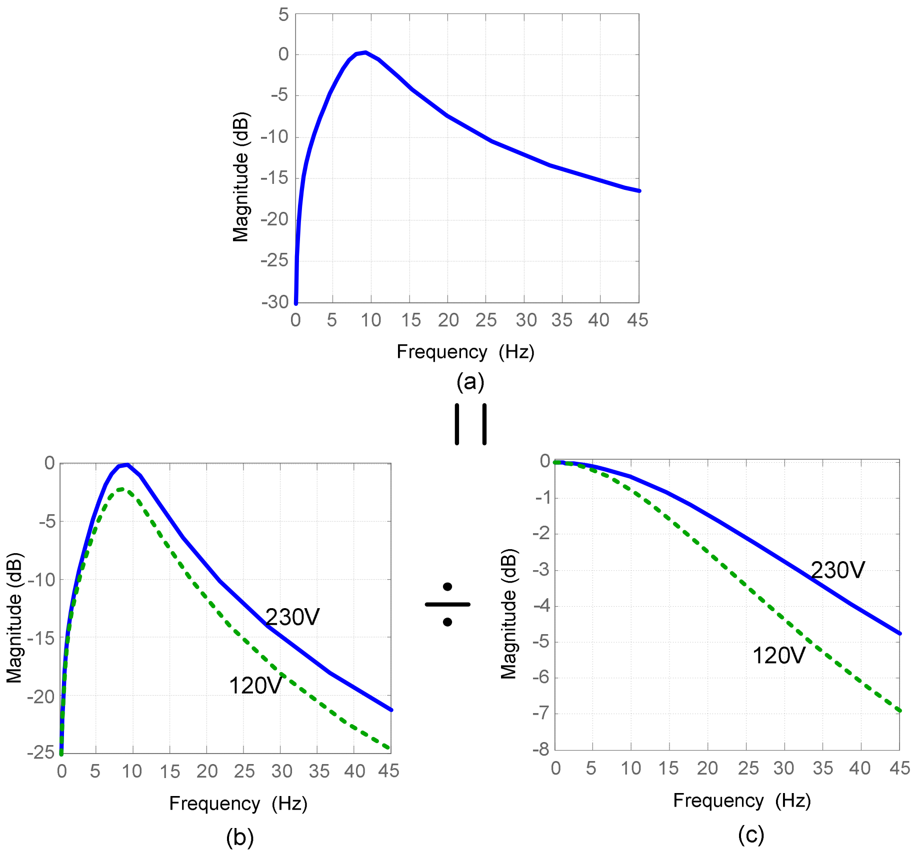

Figure 4.11 The bode diagram of (a) the eye-brain flicker response, (b) the weighting filter and (c) the incandescent lamp flicker response. Solid line: 230V lamp; dashed line: 120V lamp.

4.4 Simulation results of the improved flickermeter

In this section, first the UIE/IEC flickermeter simulation model is built and tested according to the standard IEC 61000–4–15. The simulation models of the improved flickermeter for other lamp types are then also tested by using Matlab/simulink. The results of the energy saving lamp are presented in section 4.4.2. The simulation test results of the other lamp types are presented in Appendix D.

4.4.1. The UIE/IEC flickermeter simulation model

According to the UIE/IEC flickermeter structure described in [11] [31], a UIE/IEC flickermeter simulation model is built using Matlab/Simulink. The scheme of this simulation model is shown in figure 4.12.

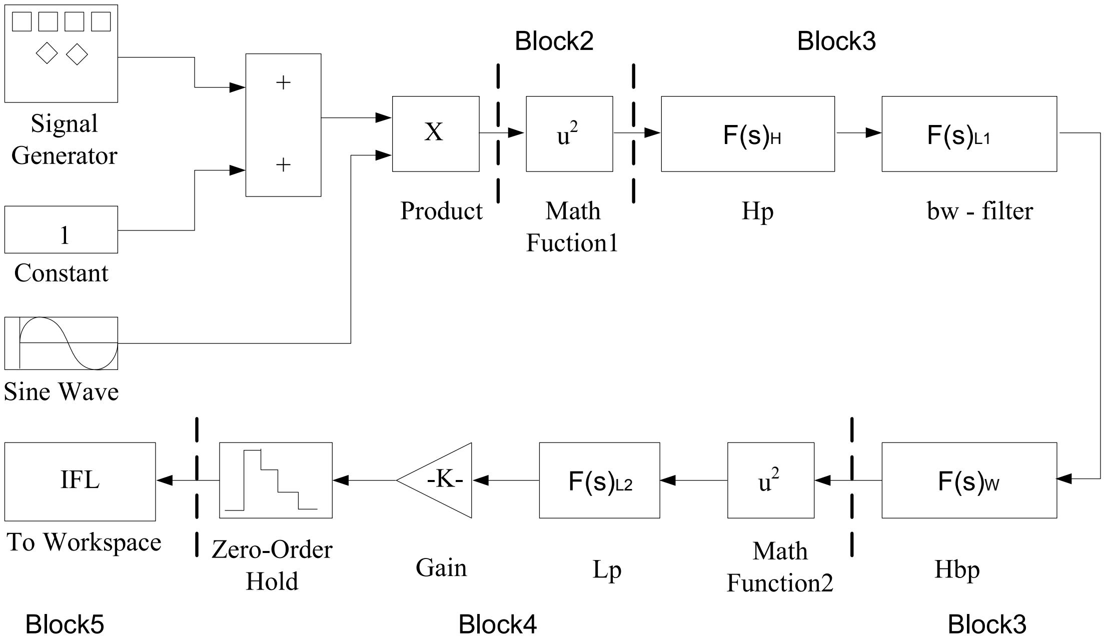

Figure 4.12 The scheme of the UIE-IEC flickermeter simulation model

The input signal of the UIE/IEC flickermeter simulation model is the voltage fluctuation. It is generated by the signal generator block of Matlab/Simulink. There are two filters in the structure of the UIE/IEC flickermeter, the so-called demodulator filter (it is composed of a 1st order high-pass filter and a 6th order low-pass filter) and the weighting filter. In the simulation model, these filters are written as a transfer function. According to the recommended values of [11] [31], the demodulator filter includes a first order high-pass filter with a cut-off frequency of 0.05Hz and a 6th order low-pass filter with a cut-off frequency of 35Hz. The transfer functions of these two filters as used in the simulation model are given in equations (4.22) and (4.23).

$$F(s)_H = \frac{\frac{s}{\omega_{cH}}}{1+\frac{s}{\omega_{cH}}} = \frac{s}{s+(2\pi\cdot 0.05)} \qquad (4.22)$$

$$F(s)_{L1} = \frac{1}{1+b_1(\frac{s}{\omega_{cL}})^1 + b_2(\frac{s}{\omega_{cL}})^2 + b_3(\frac{s}{\omega_{cL}})^3 + b_4(\frac{s}{\omega_{cL}})^4 + b_5(\frac{s}{\omega_{cL}})^5 + b_6(\frac{s}{\omega_{cL}})^6}$$
$$= \frac{(2\pi\cdot 35)^6}{(2\pi\cdot 35)^6 + 3.864s\cdot(2\pi\cdot 35)^5 + 7.464s^2\cdot(2\pi\cdot 35)^4 + 9.141s^3\cdot(2\pi\cdot 35)^3 + 7.464s^4\cdot(2\pi\cdot 35)^2 + 3.864s^5\cdot(2\pi\cdot 35)} \tag{4.23}$$

Where $\omega_{cH} = 2\pi \bullet 0.05$ and $\omega_{cL} = 2\pi \bullet 35$.

The transfer function of the weighting filter used in the simulation model is according to equation 2.7:

$$F(s)_W = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2} \cdot \frac{(1+\frac{s}{\omega_2})}{(1+\frac{s}{\omega_3})(1+\frac{s}{\omega_4})}$$
$$= \frac{100.5499s}{s^2 + 2\lambda s + \omega_1^2} \cdot \frac{73.9606(s+14.324)}{(s+7.6991)(s+137.602)} \tag{4.24}$$

Where ω_1, ω_2, ω_3, ω_4 and k are the values given in [31] for the 230V 60W incandescent lamp.

Equation (4.25) shows the transfer function of the first order low pass filter in the non-linear variance estimator.

$$F(s)_{L2} = \frac{1}{0.3s+1} \tag{4.25}$$

In IEC 61000–4–15, the performance testing requirements, where the P_{st} values should be 1±5% for certain rectangular modulating voltage frequencies and the related modulating voltage amplitudes, are given for the UIE/IEC flickermeter. The simulation results of the performance testing are shown in table 4.2. The error between the simulation results and the required values (P_{st} is one) is less than 5%. So the performance of this simulation model meets the requirements. The test results shown in table 4.3 and 4.4 also prove that the performance of the simulation model meets the requirements because all $P_{inst,max}$ values are within the range of 1 ± 0.05.

Table 4.2 The performance test results of the simulation model

Rectangular changes per minute	Voltage changes ΔV/V (%)	Simulated P_{st}	Error (%)
1	2.724	0.9981	0.19
2	2.211	0.9991	0.09
7	1.459	1.0013	0.13
39	0.906	1.0101	1.01
110	0.725	1.0005	0.05
1620	0.402	0.9831	1.69
4000	2.4	1.0245	2.45

Table 4.3 Testing results of the simulation model using values in IEC 61000–4–15 table 1 (sinusoidal voltage)

Frequency (Hz)	Voltage fluctuation (%)	$P_{instmax}$		Frequency (Hz)	Voltage fluctuation (%)	$P_{instmax}$
0.5	2.34	1.0071		10.5	0.27	1.0299
1.0	1.432	1.0387		11.0	0.282	1.0284
1.5	1.08	1.0316		11.5	0.296	1.0267
2.0	0.882	1.0263		12.0	0.312	1.0258
2.5	0.754	1.0351		13.0	0.348	1.0236
3.0	0.654	1.0408		14.0	0.388	1.0207
3.5	0.568	1.0358		15.0	0.432	1.0195
4.0	0.5	1.0348		16.0	0.48	1.0208
4.5	0.446	1.0395		17.0	0.53	1.0207
5.0	0.398	1.036		18.0	0.584	1.0232
5.5	0.36	1.0386		19.0	0.64	1.0246
6.0	0.328	1.0387		20.0	0.7	1.0279
6.5	0.3	1.0315		21.0	0.76	1.0277
7.0	0.28	1.0317		22.0	0.824	1.029
7.5	0.266	1.0345		23.0	0.89	1.0291
8.0	0.256	1.0332		24.0	0.962	1.0321
8.8	0.25	1.0321		25.0	1.042	1.0387
9.5	0.254	1.0331		33.33	2.13	1.0363
10.0	0.26	1.0292				

Table 4.4 Test results of the simulation model using values in IEC 61000–4–15 table 2 (rectangular voltage)

Frequency (Hz)	Voltage fluctuation (%)	$P_{instmax}$		Frequency (Hz)	Voltage fluctuation (%)	$P_{instmax}$
0.5	0.514	0.9560		10.0	0.205	1.0262
1.0	0.471	0.9594		10.5	0.213	1.0398
1.5	0.432	0.9929		11.0	0.223	1.0395
2.0	0.401	0.9986		11.5	0.234	1.0383
2.5	0.374	1.0099		12.0	0.246	1.0397
3.0	0.355	1.0237		13.0	0.275	1.0440
3.5	0.345	1.0259		14.0	0.308	1.0362
4.0	0.333	1.0252		15.0	0.344	1.0417
4.5	0.316	1.033		16.0	0.376	1.0336
5.0	0.293	1.0243		17.0	0.413	1.0335
5.5	0.269	1.0304		18.0	0.452	1.0408
6.0	0.249	1.0324		19.0	0.498	1.0397
6.5	0.231	1.0315		20.0	0.546	1.0210
7.0	0.217	1.0336		21.0	0.586	1.0299
7.5	0.207	1.0353		22.0	0.604	1.0119
8.0	0.201	1.0413		23.0	0.68	1.0333
8.8	0.199	1.0486		24.0	0.743	1.0417
9.5	0.200	1.0409		33.33	1.67	1.0410

4.4.2. Improved flickermeter simulation results

Based on the knowledge of the UIE/IEC flickermeter simulation model, the new weighting filters of different lamp types, which can replace the weighting filter given in [31], are implemented into the improved flickermeter simulation model. The performance of this improved flickermeter simulation model is tested. In this section, the test results of the improved flickermeter simulation model for the energy saving lamp are shown and discussed. The test results of the simulation model for other lamp types are shown in Appendix D.

The assumption that people have the same flicker feeling to different lamp types when they have the same illuminance variation, is used in this research. This assumption has been checked by the measurement of the flicker feeling of an energy saving lamp and an incandescent lamp of a few test persons. The results of this test are presented in Appendix C. The results show that this assumption is basically right. Using this assumption, the voltage variation values of the energy saving lamp, which result in the unit value of the maximum instantaneous flicker sensation, are obtained from the measurement in the lab. These values are shown in column 2 of table 4.5. The expected maximum instantaneous flicker sensation should be 1. The energy saving lamp flickermeter simulation results are shown in column 3 of table 4.5. The error values shown in column 4 of table 4.5 are the percentage value of the error between the simulated and expected maximum instantaneous flicker sensations based on the expected values. All errors between the simulation results and the expected values are smaller than ±5%. According to the standard [31], an error of ±5% is allowed. The performance of this flickermeter meets therefore the requirements.

Tests for the difference in flicker levels between the other lamp types and the incandescent lamp for the same voltage modulation are also of interest. The voltage fluctuation values of table 3.2 of chapter 3 are used in this test. As an example, the results of the performance of the energy saving lamp flickermeter are presented in table 4.6.

As stated in the standard IEC 61000–4–15, the UIE/IEC flickermeter has a linear characteristic, e.g. the ratio between two voltage variations should be same as the ratio between the corresponding P_{st} values. Since the experienced ratio between the P_{st} and the maximum instantaneous flicker sensation $P_{inst,max}$ is always 0.68, the ratio between two voltage variations should be the same as the ratio between the corresponding $P_{inst,max}$. Based on the above principle, the ratio between the values in the column 2 of table 4.5 and table 4.6 should be same as the ratio between the corresponding $P_{inst,max}$ values. As mentioned before, the voltage variation values in the table 4.5 can cause $P_{inst,max}$ equals one. Therefore, the expected $P_{inst,max}$ caused by the voltage variation values in the table 4.6 can be calculated. The calculated values are presented in the column 4 of the table 4.6. For the 60W 230V incandescent lamp, it should be equal to 1 when these voltage fluctuations, shown in the column 1 and 2 in the table 4.6, are applied. However, for the energy saving lamp, the maximum instantaneous flicker sensation is much smaller. The simulation results in table 4.6 prove that the energy saving lamp has lower flicker levels than the incandescent lamp for the same voltage variation. The errors between the simulation and the expected values, shown in the table 4.6, are within ±5%. These errors are allowed.

Table 4.7 gives typical results when the different flickermeter models measure the same voltage variation. The values in column 2 of table 4.7 are taken from table 3.2. For these voltage variation values, the UIE/IEC flickermeter should give the values of 1±0.05, as shown in the column 4 of table 4.7. The test results in table 4.7 show that the other lamp types give lower flicker levels than the incandescent lamp. The LED lamp gives the lowest flicker level for the same voltage variation.

Table 4.5 Performance test results of the energy saving lamp flickermeter

Flicker frequency (Hz)	Voltage variation (%)	$P_{inst,max}$	Error (%)
0.5	16.4	1.0483	4.83
1.0	9.5	1.0055	0.55
1.5	7.18	0.9868	-1.32
2.0	5.75	0.9789	-2.11
2.5	5.25	0.9757	-2.43
3.0	4.62	0.9742	-2.58
3.5	3.99	0.9717	-2.83
4.0	3.46	0.9705	-2.95
4.5	2.67	0.9693	-3.07
5.0	2.61	0.9690	-3.10
5.5	2.40	0.9686	-3.14
6.0	2.01	0.9682	-3.18
6.5	1.96	0.9671	-3.29
7.0	1.42	0.9676	-3.24
7.5	1.37	0.9675	-3.25
8.0	1.30	0.9675	-3.25
8.8	1.30	0.9674	-3.26
9.5	1.59	0.9675	-3.25
10.0	1.59	0.9674	-3.26
10.5	1.60	0.9674	-3.26
11.0	1.60	0.9674	-3.26
11.5	1.60	0.9674	-3.26
12.0	1.60	0.9673	-3.27
13.0	1.65	0.9673	-3.27
14.0	1.70	0.9673	-3.27
15.0	1.90	0.9673	-3.27
16.0	1.99	0.9673	-3.27
17.0	2.39	0.9674	-3.26
18.0	2.42	0.9674	-3.26
19.0	2.53	0.9674	-3.26
20.0	2.60	0.9674	-3.26
21.0	2.60	0.9674	-3.26
22.0	2.70	0.9674	-3.26
23.0	2.82	0.9674	-3.26
24.0	2.95	0.9674	-3.26
25.0	3.80	0.9677	-3.23

Table 4.6 Performance evaluation results of the energy saving lamp flickermeter

Flicker frequency (Hz)	Voltage variation (%)	$P_{inst,max}$	Expected $P_{inst,max}$	Error (%)
0.5	2.340	0.1574	0.1552	1.42
1.0	1.432	0.1498	0.1516	-1.19
1.5	1.080	0.1494	0.1484	0.67
2.0	0.882	0.1492	0.1502	-0.67
2.5	0.754	0.1431	0.1401	2.14
3.0	0.654	0.1384	0.1376	0.58
3.5	0.568	0.1395	0.1383	0.87
4.0	0.500	0.1415	0.1399	1.14
4.5	0.446	0.1496	0.1519	-1.51
5.0	0.398	0.1491	0.1478	0.88
5.5	0.360	0.1491	0.1453	2.62
6.0	0.328	0.1517	0.1580	-3.99
6.5	0.300	0.1490	0.1482	0.54
7.0	0.280	0.1852	0.1908	-2.94
7.5	0.266	0.1886	0.1879	0.37
8.0	0.256	0.1896	0.1905	-0.47
8.8	0.250	0.1843	0.1860	-0.91
9.5	0.254	0.1580	0.1546	2.20
10.0	0.260	0.1577	0.1582	-0.19
10.5	0.270	0.1603	0.1632	-1.78
11.0	0.282	0.1684	0.1705	-1.23
11.5	0.296	0.1752	0.1790	-2.12
12.0	0.312	0.1806	0.1886	-4.24
13.0	0.348	0.1980	0.2040	-2.94
14.0	0.388	0.2176	0.2208	-1.45
15.0	0.432	0.2167	0.2200	-1.5
16.0	0.480	0.2253	0.2333	-3.43
17.0	0.530	0.2250	0.2145	4.90
18.0	0.584	0.2275	0.2334	-2.53
19.0	0.640	0.2407	0.2447	-1.63
20.0	0.700	0.2508	0.2605	-3.72
21.0	0.760	0.2794	0.2828	-1.20
22.0	0.824	0.2809	0.2952	-4.84
23.0	0.890	0.2913	0.3053	-4.59
24.0	0.962	0.3061	0.3154	-2.95
25.0	1.042	0.2583	0.2653	-2.64

Table 4.7 Test results of the flickermeter for different lamp types

Flicker Frequency (Hz)	Voltage Variation (%) [31]	Maximum Instantaneous Flicker Level						
		Standard Values [31]	Simulation Results					
			UIE/IEC model	Fluorescent lamp	Energy saving lamp	Halogen lamp	LED lamp
2.0	0.882	1	1.0009	0.2384	0.1492	0.8003	0.175
4.0	0.500	1	1.0063	0.2379	0.1415	0.7129	0.171
6.0	0.328	1	1.0093	0.2895	0.1517	0.7016	0.186
8.0	0.256	1	0.9966	0.3146	0.1896	0.7785	0.192
10	0.260	1	0.9875	0.2977	0.1577	0.7521	0.157
12	0.312	1	0.9801	0.2894	0.1806	0.7434	0.169
14	0.388	1	0.9699	0.3297	0.2176	0.7468	0.207
16	0.480	1	0.9697	0.3551	0.2253	0.7435	0.162
18	0.584	1	0.9738	0.3682	0.2275	0.7214	0.160
20	0.700	1	0.9827	0.4175	0.2508	0.7208	0.145
22	0.824	1	0.9844	0.4902	0.2809	0.7319	0.135
24	0.962	1	0.9901	0.5513	0.3061	0.7345	0.134

4.5 Discussion on the lamp flicker response identification model method

In section 4.2, five lamp flicker response identification models have been developed for different lamp types using the OE model structure. The identification method used in this thesis deviates from the general application used in the control field. Due to the specific application described in this thesis, the lamp flicker response identification model only focuses on the amplitude response within specific frequency range (0.5Hz – 25Hz). The phase response of the model is not of concern in this thesis. As mentioned in section 3.6 and 4.3, the eye-brain flicker response transfer function can currently only be obtained indirectly by using the existing weighting filter of the UIE/IEC flickermeter divided by the (60W 230V) incandescent lamp flicker response transfer function. Then, improved weighting filters for other lamp types can be implemented into the flickermeter model. To derive the lamp flicker response transfer functions a system identification method has been used. From a practical point of view, it is easier to implement the improvement into the current flickermeter model if the lamp flicker response identification model and the improved weighting filter are described as a transfer function in the s domain, because this is the format of the existing weighting filter. The developed system identification models can easily be tested in the Matlab/system identification toolbox.

An alternative method could have been used to obtain the lamp flicker response curve fitting. C.K. Sanathanan and J. Koerner presented a method to derive a transfer function as a ratio of two complex polynomials in [51], which can be used to derive a transfer function to fit the frequency response of the measurement data. Figure 3.15 – 3.20 have shown the measured lamp flicker response curves, i.e. the illuminance variation versus the different modulating voltage frequencies. The corresponding transfer functions of these curves can be found by the method described in [51]. This method can be further improved by the constrained technique discussed by P.A. Payne in [52]. Then the lamp flicker response transfer function can be obtained directly. Since the parameters of such a transfer function are only available for a specific curve, a norm factor should be used when the flickermeter evaluates the flicker level of a voltage fluctuation with different modulating voltage amplitudes. This method should be tested and compared to the method used in this thesis in the future.

4.6 Summary

Based on the flicker response measurement for different lamp types, the lamp flicker response models are derived for different lamp types using the linear system identification method. For the purpose of this research, the OE model is used to develop the lamp flicker response models. After the eye-brain flicker response transfer function is obtained, the improved weighting filters for different lamp types are developed by the lamp flicker response model times the eye-brain flicker response. Finally, the improved flickermeter that can generate the output (i.e. P_{st}) better correlated with customer sensitivities, is obtained by implementing the improved weighting filters. A simulation model of the improved flickermeter was built. The simulation results of the performance of the energy saving lamp simulation flickermeter model are shown in this chapter. All errors between the simulation results and the expected results are less than 5%. This means that the performance of the energy saving lamp simulation model meets the requirements. Finally, a discussion about an alternative method to derive the lamp flicker response transfer function is presented..

Chapter 5

The Lamp Light Spectrum Response to Flicker

5.1 Introduction

As mentioned in chapter 2, the human visual system is sensitive to both the light intensity and light color [21]. The light spectrum determines the color of the light. The sensitivity of the human eye is not the same for the whole visible light spectrum range. The CIE defined the standard luminous efficiency curves for photopic and scotopic conditions respectively, i.e. the human eye spectrum sensitivity curves (see figure 2.2 in chapter 2).

Since each lamp type has a different working principle, the lamp light spectrum of each lamp type is different. Under flicker conditions, the lamp light spectrum of different lamp types varies differently as well. Measurements of the lamp light spectrum response to flicker have been made and the experimental results are presented in this chapter.

The well-known UIE/IEC flickermeter measures the flicker level based on the lamp light intensity response to flicker. Hence, in the previous chapters the light intensity flicker response of different types of lamps has been analyzed. However, in view of the light spectrum properties of the lamp, the flicker level can also be estimated by considering the lamp light spectrum response to flicker. A weighting factor that represents the lamp-eye spectrum sensitivity under flicker is defined in this chapter. It is the result of the lamp light spectrum variation under flicker weighted with the human eye spectrum sensitivity. It gives the possibility to develop a simplified flicker measurement method if an eye-brain model is added. Such a simplified flicker measurement method is discussed in this chapter.

5.2 Lamp light spectrum measurements

The purpose of these measurements is to find the response of the lamp light spectrum of different lamp types under flicker.

Three lamp types have been tested in this work: a 230V 60W incandescent lamp, a 230V 11W energy saving lamp and a 230V 3.4W LED lamp. The lamp light spectrum is measured under normal and flicker voltages. The required voltage is generated by the programmable power source. The lamp light spectrum is measured by a spectrometer using an optical fiber sensor. The measuring sensitivity range of the spectrometer and the optical fiber sensor matches the visible light wavelength (380nm – 750nm). This spectrometer can capture the spectra by a speed up to 1000 full spectra/s. This is sufficiently fast to catch the spectrum variation under flicker. The measurement set-up is shown in figure 5.1.

5.2.1 The light spectrum of different lamp types

A stable 230V voltage was supplied to the lamps to be tested. The lamp spectrum was measured by the spectrometer. Figure 5.2 to 5.4 show the spectrum of the 60 W incandescent lamp, the 11 W energy saving lamp and the 3.4W LED lamp. The incandescent lamp shows a continuously increasing and decreasing spectrum. The maximum light intensity of the incandescent lamp occurs around 590nm. In contrast to the incandescent lamp the energy saving lamp shows a few specific wavelengths that have a relatively high light intensity in the spectrum. The maximum light intensities are located around 420nm, 550nm and 610nm. This is due to the fact that the energy saving lamp is a gas discharge lamp and the spectrum depends on the coating inside the lamp tube. The light spectrum of a LED lamp shows three peak values with wavelengths of 455nm, 510nm and 635nm. These belong to the wavelength range of the blue, green and red color respectively.

It clearly shows that the white color of the LED lamp is the combination of blue, green and red color LEDs.

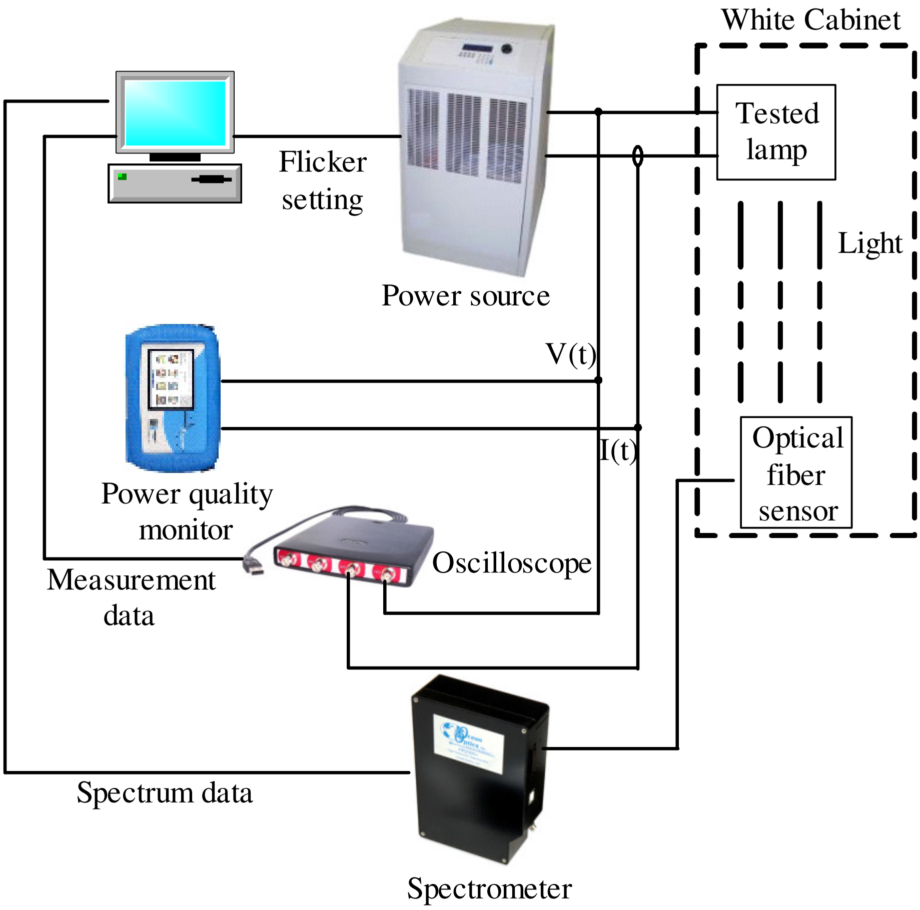

Figure 5.1 The lamp light spectrum measurement set-up

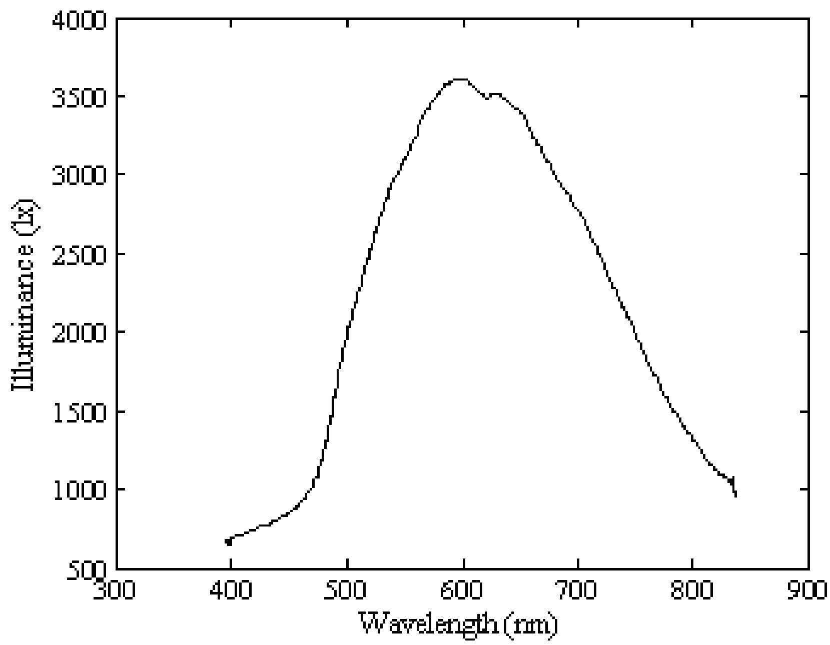

Figure 5.2 The light spectrum of a 230V 60W incandescent lamp

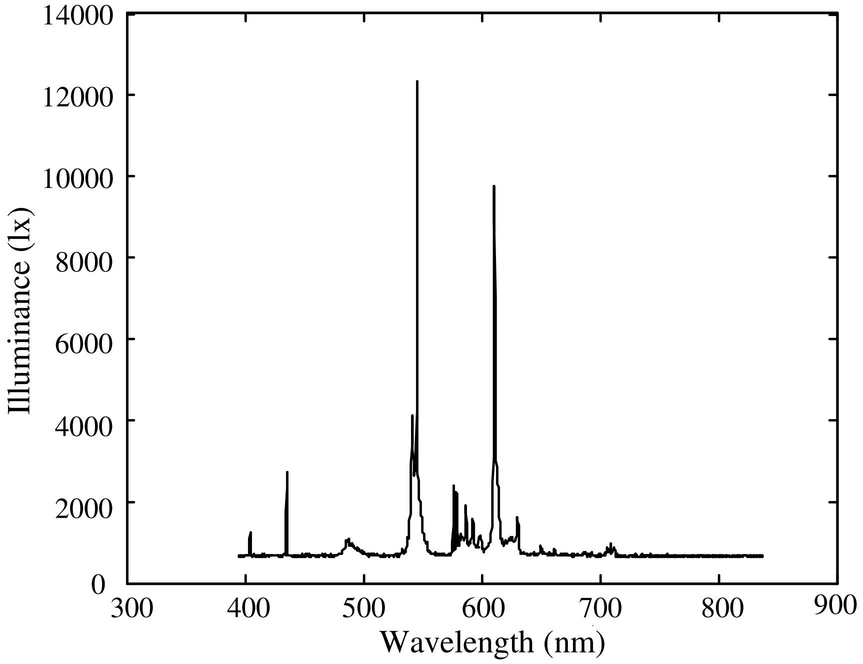

Figure 5.3 The light spectrum of a 230V 11W energy saving lamp

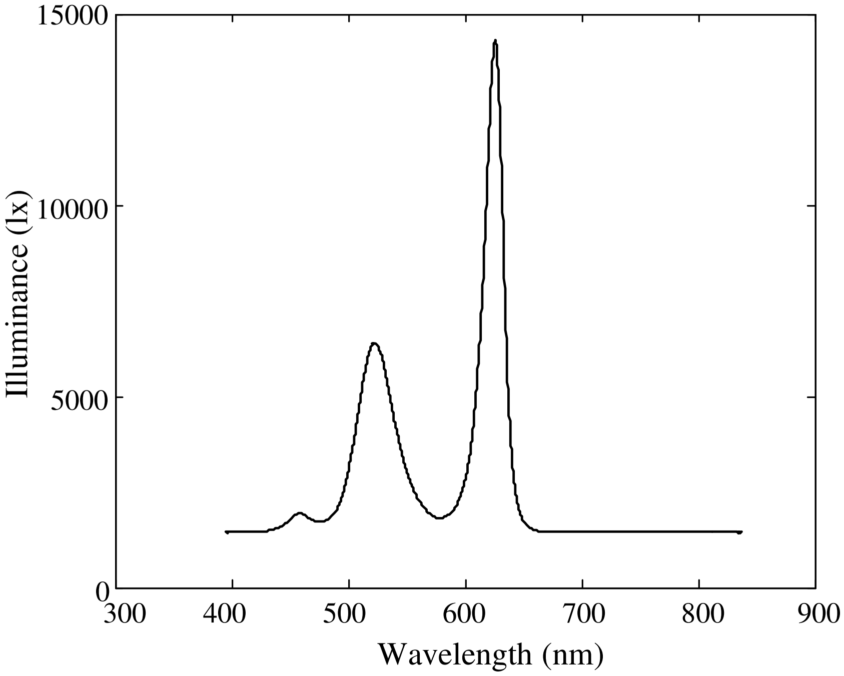

Figure 5.4 The light spectrum of a 230V 3.4W LED lamp

5.2.2 Lamp light spectrum under flicker

Since the spectrometer can capture 1000 full spectra per second, the lamp light spectrum variation under flicker could be measured using this spectrometer. As an example, a sinusoidal voltage fluctuation with 2Hz modulating frequency and 10V modulating amplitude was applied to the tested lamp as input voltage. The lamp light spectrum was measured during 5sec with a 1000Hz sampling frequency. Figure 5.5 and 5.6 show in a three-dimensional way the lamp light spectrum variations of a 60W incandescent lamp and an 11W energy saving lamp with 2Hz flicker. The X, Y and Z axis represent the wavelength, light intensity and the time respectively.

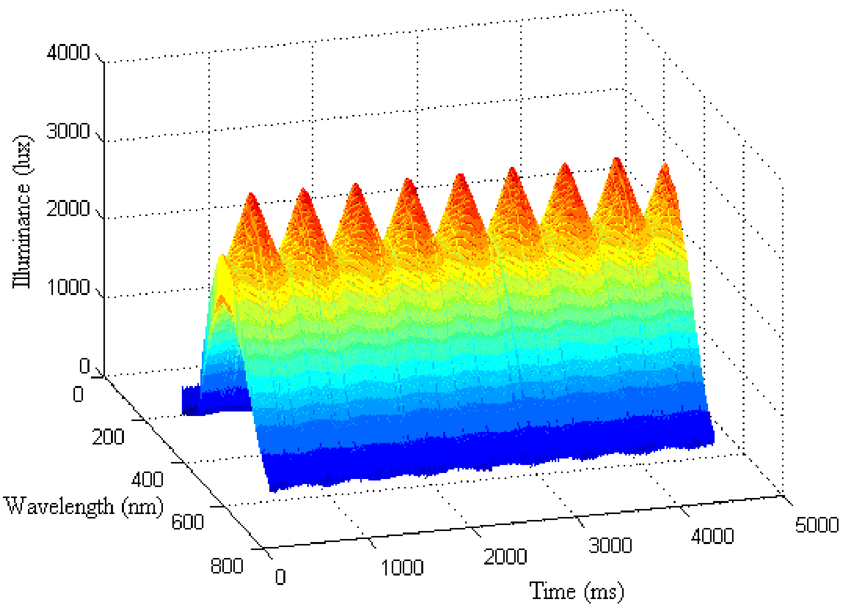

Figure 5.5 The 3-D light spectrum of a 230V 60W incandescent lamp with a 2Hz flicker voltage

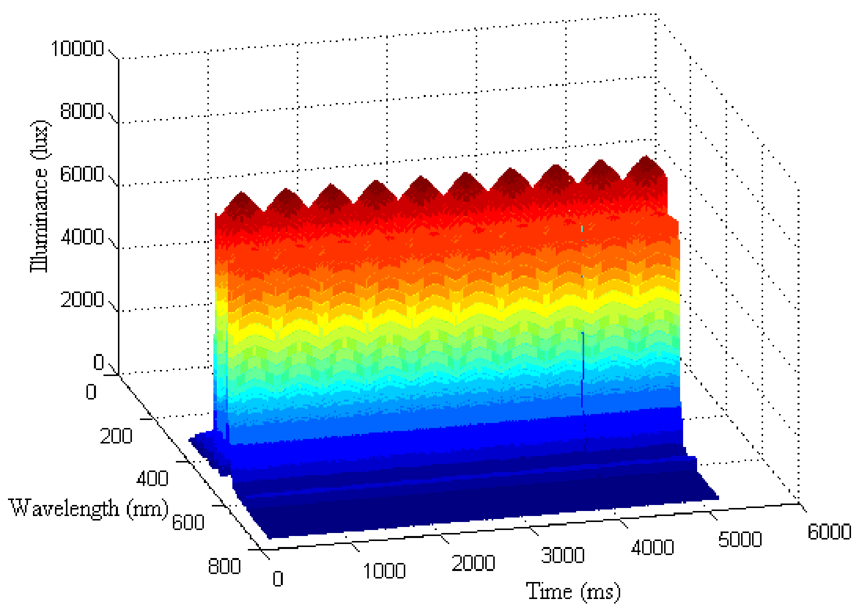

Figure 5.6 The 3-D light spectrum of a 230V 11W energy saving lamp with a 2Hz flicker voltage

The fundamental frequency of the lamp light spectrum is 100Hz. This illustrates that the lamp light depends on the electrical power consumed by the lamp. Figure 5.5 and 5.6 show the expected amplitude modulation with the modulating frequency of the flicker voltage.

5.2.3 Light spectrum responses of different lamp types under flicker

To find the light spectrum responses of different lamp types under flicker, more measurements have been made in the lab. Sinusoidal voltage fluctuations with different modulating frequencies (1Hz – 25Hz, in total 25 frequencies were used) and a 5V modulating amplitude were applied to the tested lamps as input voltage. Voltage fluctuations with a modulating amplitude of 10V were tested as well. The three-dimensional data of the light spectrum responses to flicker of different lamp types were recorded by the spectrometer with a 1000Hz sampling frequency.

To analyze the light spectrum responses, the wavelength contribution under flicker (light intensity variation of each wavelength under flicker) was studied. The measured light intensities of 90 wavelengths with a 5nm step along the time axis were analyzed. Since the light intensity of each wavelength is a harmonic rich waveform, the FFT method is used to obtain the absolute light intensity variation for each wavelength. In this chapter only the absolute light intensity variations of the modulating voltage frequency component are studied. This is due to the fact that the FFT analysis results show that other frequency components are sufficiently small to be neglected. The relative light intensity variation value of each wavelength is calculated for each tested lamp by:

$$L_{re\_s} = \frac{\text{light intensity variation of wavelength s}}{\text{maximum light intensity of the lamp under normal voltage}} \cdot 100 \qquad (5.1)$$

Where L_{re_s} is the relative light intensity variation value of each wavelength, in percent, resulting from a voltage fluctuation with a certain modulating amplitude and frequency. The relative light intensity variations with respect to the wavelength for each modulating voltage frequency can be seen as the wavelength contributions to flicker of the tested lamp.

Figure 5.7 shows the wavelength contributions of a 230V 60W incandescent lamp for a certain voltage fluctuation (2Hz modulating frequency and 10V modulating amplitude). Comparing figure 5.7 to the figure 5.2, it can be noticed that the largest light intensity variation under flicker is around 570nm instead of the wavelength of 590nm presented in the figure 5.2. The shape of the light spectrum response is also different to the shape presented in figure 5.2. So, under a certain modulating voltage frequency, the light intensity variation for different wavelengths is different.

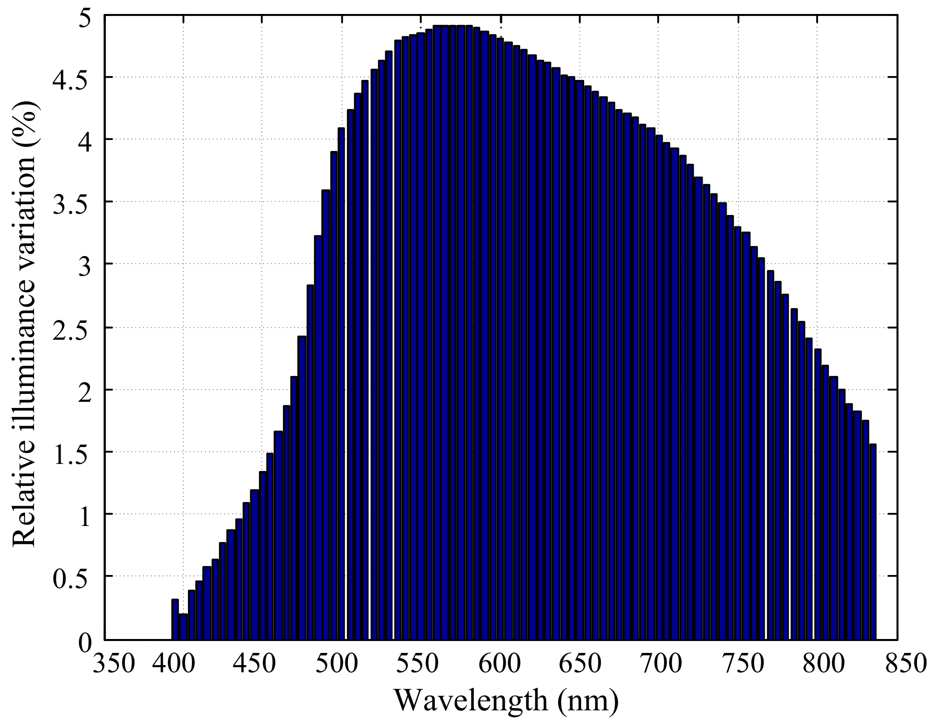

Figure 5.7 The wavelength contribution of a 230V 60W incandescent lamp at 2Hz flicker

The wavelength contributions of a 230V 11W energy saving lamp and a 230V 3.4W LED lamp are presented in figure 5.8 and 5.9. The same flicker voltages as for the incandescent lamp were applied to these two lamps.

Comparing figure 5.8 to figure 5.3, the wavelength contribution to the flicker of the energy saving lamp also has different shape with the lamp spectrum under normal voltage (no flicker). The highest light intensity variation is located at 575nm instead of 545nm under normal conditions. The wavelength contribution of the LED lamp shows a relative similar shape as the lamp spectrum under normal voltage. The wavelength contribution figures show that different lamp types have a different wavelength contribution to the same flicker voltage. This is due to the fact that they have a different light spectrum under normal conditions. Since the human eye is sensitive to the light color, the wavelength contribution to the flicker of different lamp types gives the information about the light color variation of different lamp types under flicker. As the human eye spectrum sensitivities are already known, this information is important for understanding the human eye response to the flicker. Furthermore, the human flicker sensation can be obtained as a consequence.

For each tested lamp, the relative light intensity variation of a single wavelength decreases when the modulating voltage frequency increases (see figure 5.10). These results confirm the conclusions from chapter 3

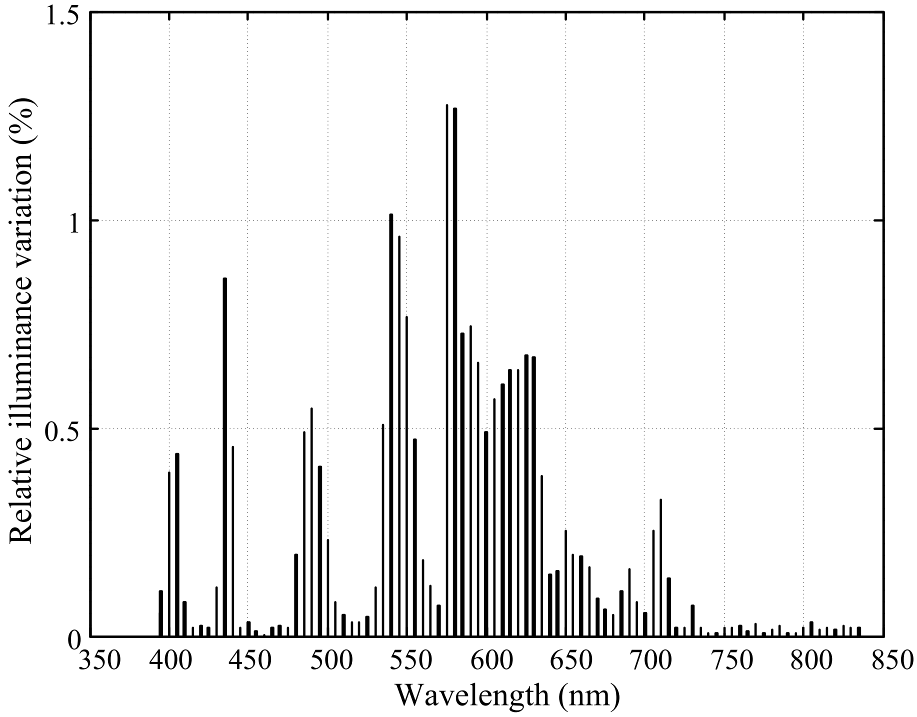

Figure 5.8 The wavelength contribution of a 230V 11W energy saving lamp at 2Hz flicker

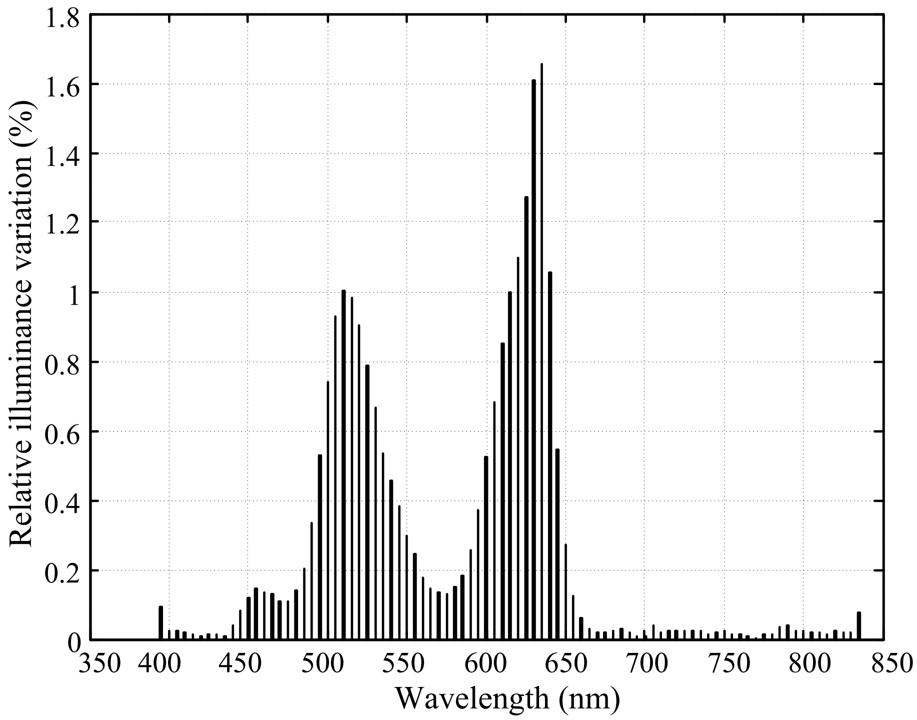

Figure 5.9 The wavelength contribution of a 230V 3.4W LED lamp at 2Hz flicker

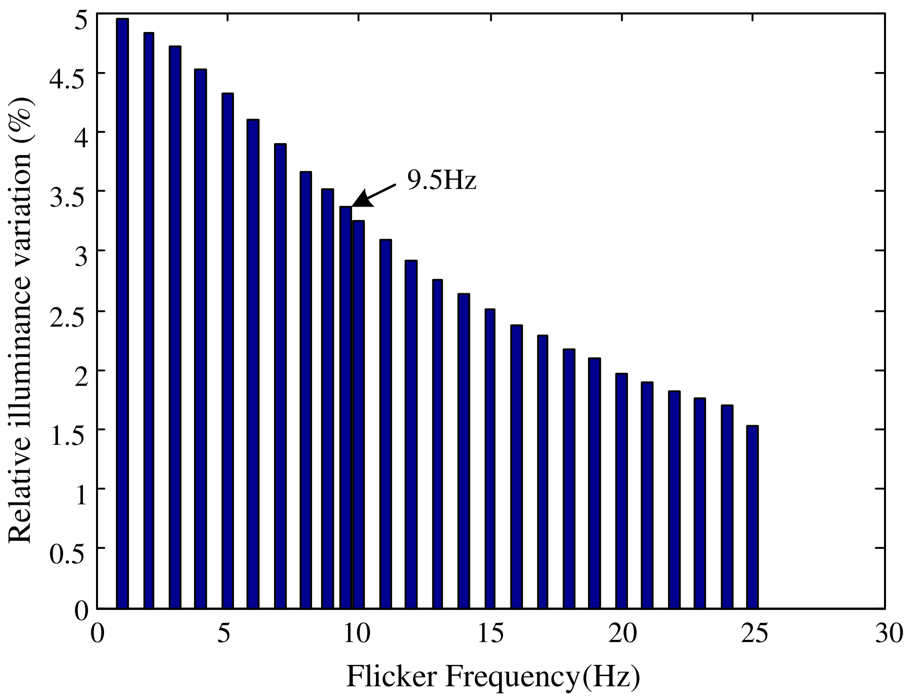

Figure 5.10 Light intensity variation versus modulating voltage frequency of a 230V 60W incandescent lamp for the wavelength of 545.14nm

5.3 Flicker sensitivity weighting factor

The lamp spectrum is different for different lamp types. Each wavelength has different contributions under the same flicker. In 1924, the CIE (International Commission on Illumination) gave a standard photopic luminosity curve to show the human eye sensitivity to light during daytime. This curve is shown in figure 5.11 [53] [54]. This curve shows that human eyes are most sensitive to the wavelengths around 555nm.

The curve in figure 5.11 shows the human eye has a different sensitivity to each wavelength. Based on the experimental results of the wavelength contributions to flicker, flicker sensitivity weighting curves of different lamp types can be obtained using the wavelength contribution to the flicker weighted with the CIE photopic curve. These weighting curves should represent the lamp–eye response to flicker. Figure 5.12 - 5.14 show the weighting curves of a 230V 60W incandescent lamp, a 230V 11W energy saving lamp and a 230V 3.4W LED lamp for a flicker voltage (2Hz modulating frequency and 5V modulating amplitude) respectively. Figure 5.12 shows that the peak weighting value of the incandescent lamp is around 555 nm. Furthermore, there is a small hollow point around 550 nm. The peak weighting values of the energy saving lamp and LED lamp are around 545 nm and 520 nm respectively. The unit of the y axis in figure 5.12 – 5.14 is arbitrary number. It is the product of the relative light intensity variation (see figure 5.7 – 5.9) of each lamp types and the photopic luminous efficiency (see figure 5.11) for each wavelength.

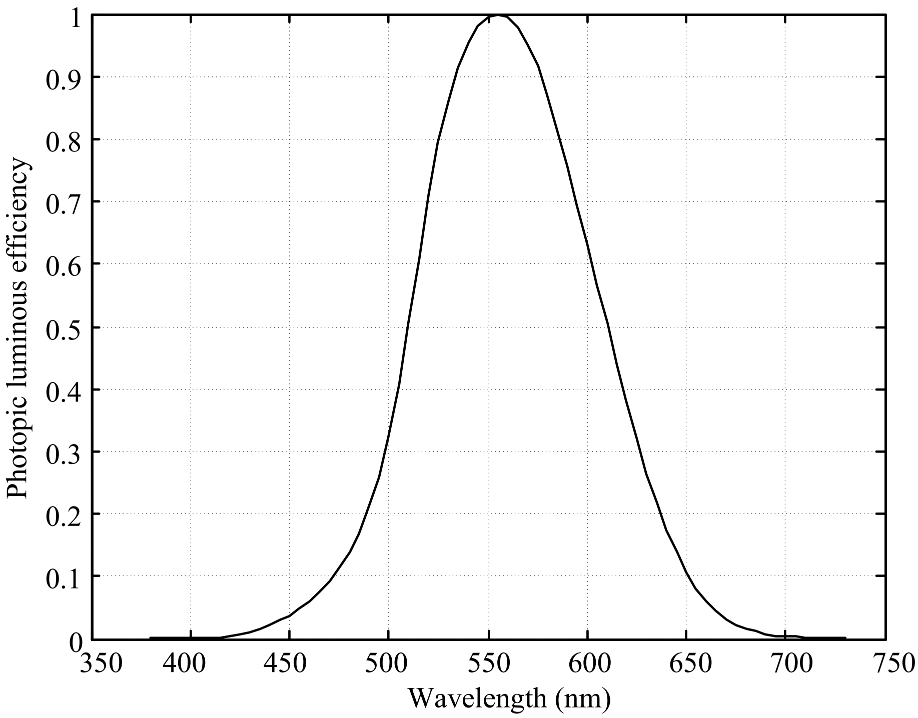

Figure 5.11 CIE standard photopic luminosity curve

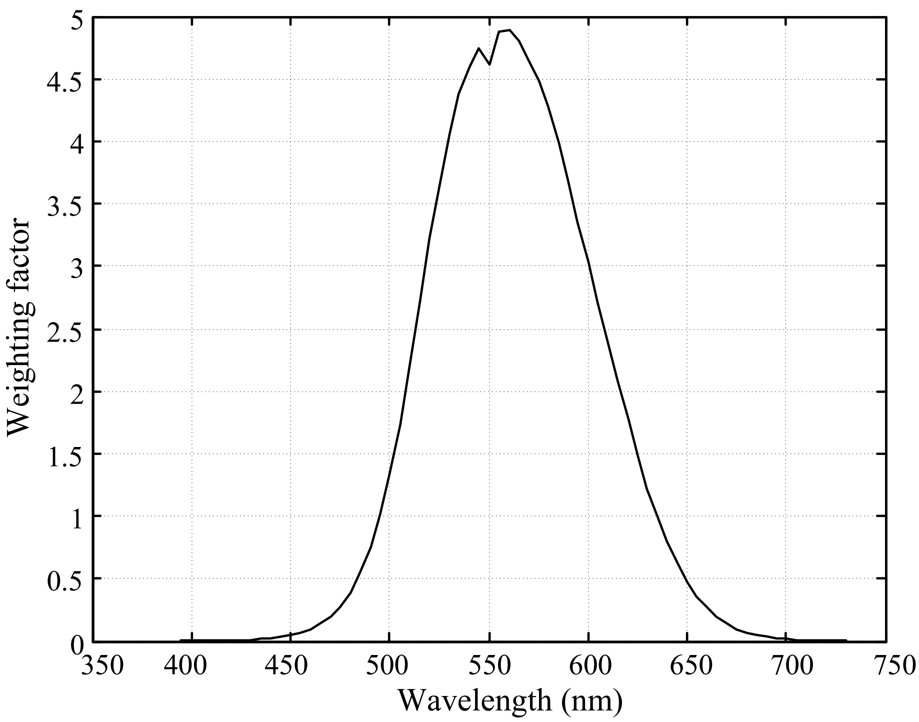

Figure 5.12 The weighting curve of a 230V 60W incandescent lamp for a voltage fluctuation with 2Hz modulating frequency and 5V modulating amplitude

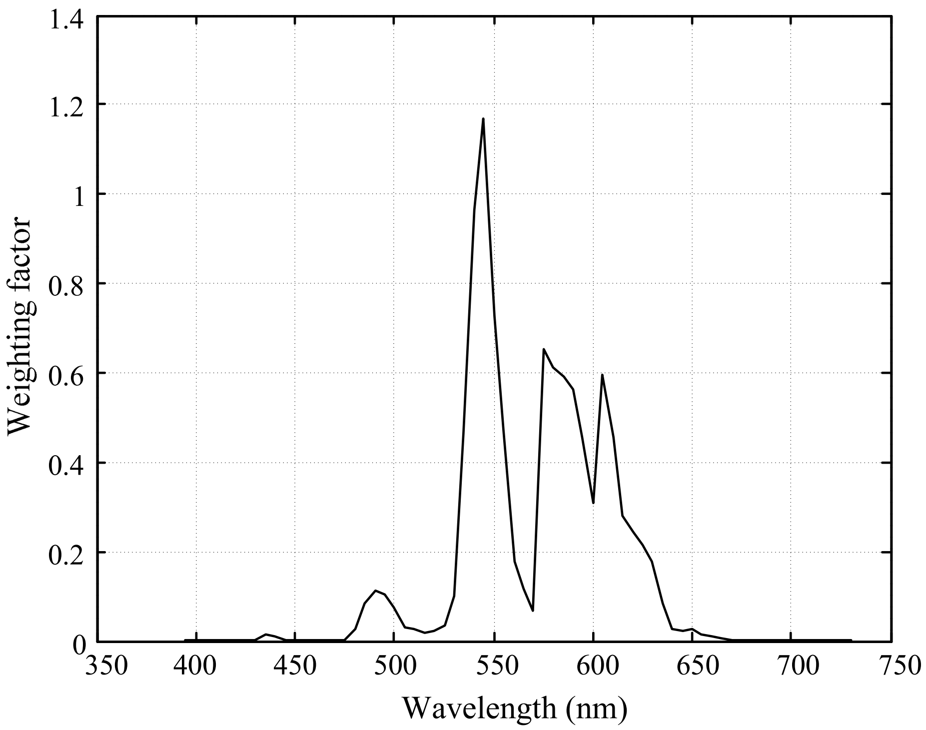

Figure 5.13 The weighting curve of a 230V 11W energy saving lamp for a voltage fluctuation with 2Hz modulating frequency and 5V modulating amplitude

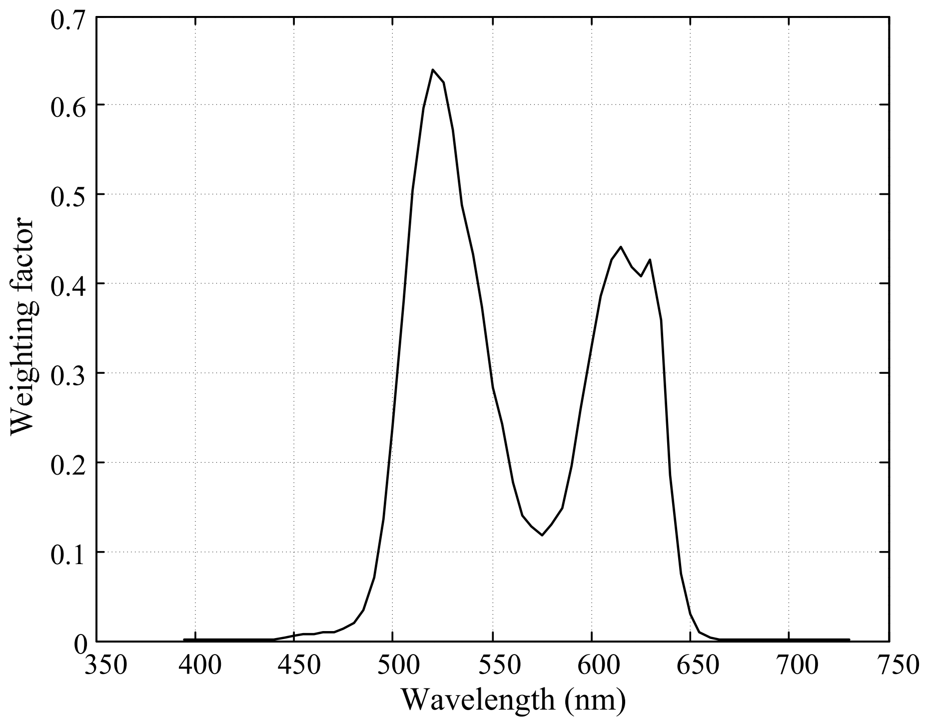

Figure 5.14 The weighting curve of a 230V 3.4W LED lamp for a voltage fluctuation with 2 Hz modulating frequency and 5V modulating amplitude

The weighting factor of each modulating voltage frequency is defined as the sum of the weighting factors of each wavelength for the corresponding modulating voltage frequency f_m. Since 68 wavelengths are used in the CIE photopic curve, the weighting factor calculation uses the same number of wavelengths. The weighting factor of each modulating voltage frequency should give the sum of these 68 items. It can be calculated by:

$$W(f_m) = \sum_{i=1}^{68} W_i(f_m) \tag{5.2}$$

Where i is each wavelength

$W_i(f_m)$ is the weighting factor of each wavelength for the modulating voltage frequency f_m *(it indicates each wavelength contribution to the flicker)*

$W(f_m)$ is the weighting factor of the modulating voltage frequency f_m

Using the measured data in the light spectrum response measurements, the weighting factors of the three tested lamp types for different modulating voltage frequency are calculated. The weighting factors for the flicker voltage with 5V modulation amplitude and different modulation frequency are presented in table 5.1. For each modulating voltage frequency, the weighting factors of the incandescent lamp shown in table 5.1 are higher than the weighting factors of the other two lamp types. This shows that the incandescent lamp is more sensitive to flicker than the energy saving lamp and LED lamp. For all lamp types, the weighting factors decrease when the modulating voltage frequency increases. The same results of the light intensity response to the flicker are also found and presented in chapter 3. Comparing the weighting factors presented in the column 2 and 3 of table 1, the energy saving lamp has the similar light spectrum response to flicker as the LED lamp.

The weighting factors for a flicker voltage with 10V modulating amplitude and different modulating frequencies are also calculated. The results are presented in table 5.2.

Comparing the weighting factors of the energy saving lamp and the LED lamp, which are presented in table 5.2, the weighting factors of the LED lamp are higher than these of the energy saving lamp. This means that the light spectrum output of the LED lamp is more sensitive to flicker with large modulating amplitudes (e.g. 10V modulating voltage amplitude) than the energy saving lamp.

Figure 5.15 – 5.17 present graphs for the weighting factors of the three tested lamp types versus the modulating voltage frequency for different modulating voltage amplitudes.

Table 5.1 The spectrum weighting factor of different lamp types for the flicker with 5V modulation amplitude

Frequency (Hz)	Weighting factor		
	Incandescent lamp	Energy saving lamp	LED lamp
2	98.72	10.53	10.48
4	92.19	10.31	10.33
6	83.9	10.22	10.27
8	76.4	10.09	10.08
10	66.39	9.94	9.98
12	59.71	9.98	9.77
14	53.56	9.64	9.25
16	48.51	9.71	9.35
18	44.26	9.52	8.97

Table 5.2 The spectrum weighting factor of different lamp types for flicker with 10V modulating amplitude

Frequency (Hz)	Weighting factor		
	Incandescent lamp	Energy saving lamp	LED lamp
2	214	31.9	41.7
4	200	31.4	42
6	182	30.8	41.7
8	162	31.6	41.2
10	144	30.5	39.6
12	124	30.5	39.7
14	117	30.1	38.76
16	105.2	29.6	37.75
18	94.7	28.9	36.64

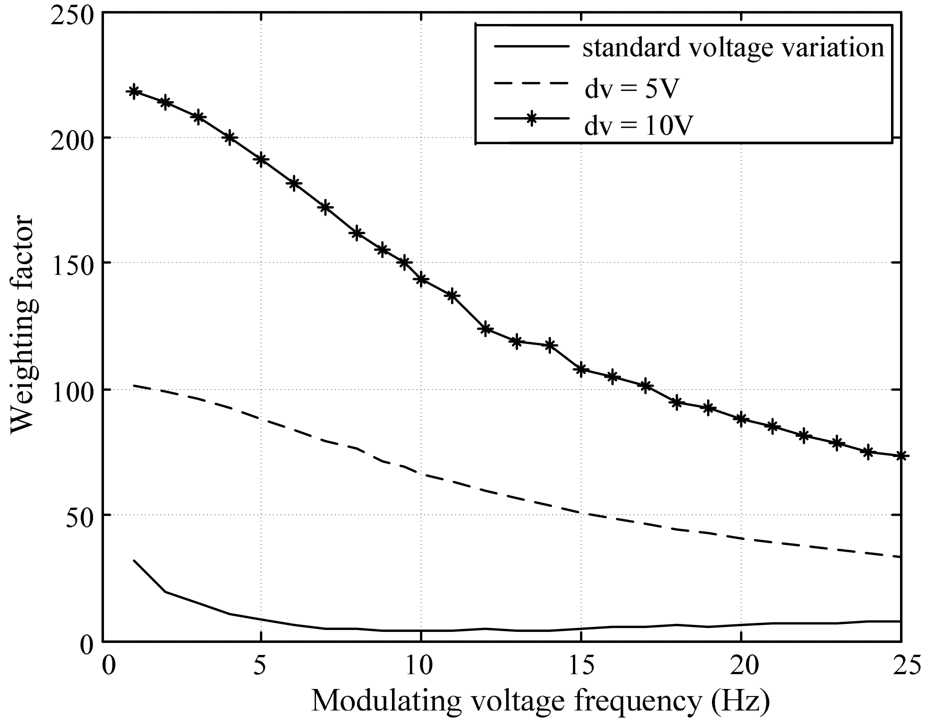

Figure 5.15 The weighting factors of a 60W incandescent lamp for various voltage modulating values. Solid line: modulating voltage amplitude as given in table 3.2 of chapter 3; dashed line: modulating voltage amplitude 5V; star line: voltage modulating amplitude 10V

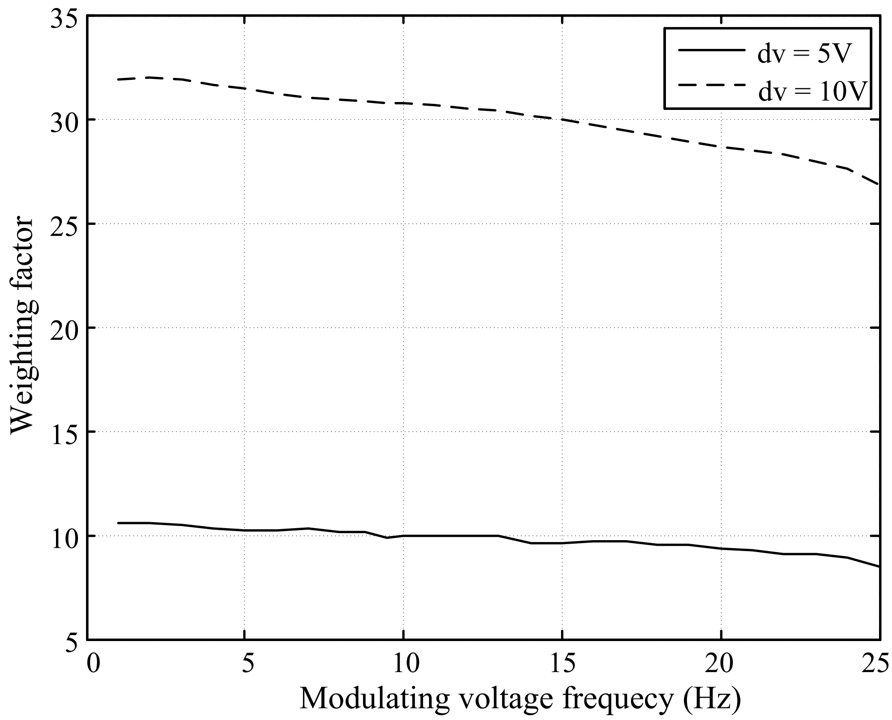

Figure 5.16 The weighting factors of a 11W energy saving lamp for different voltage modulating values. Solid line: modulating voltage amplitude 5V; dashed line: modulating voltage amplitude 10V

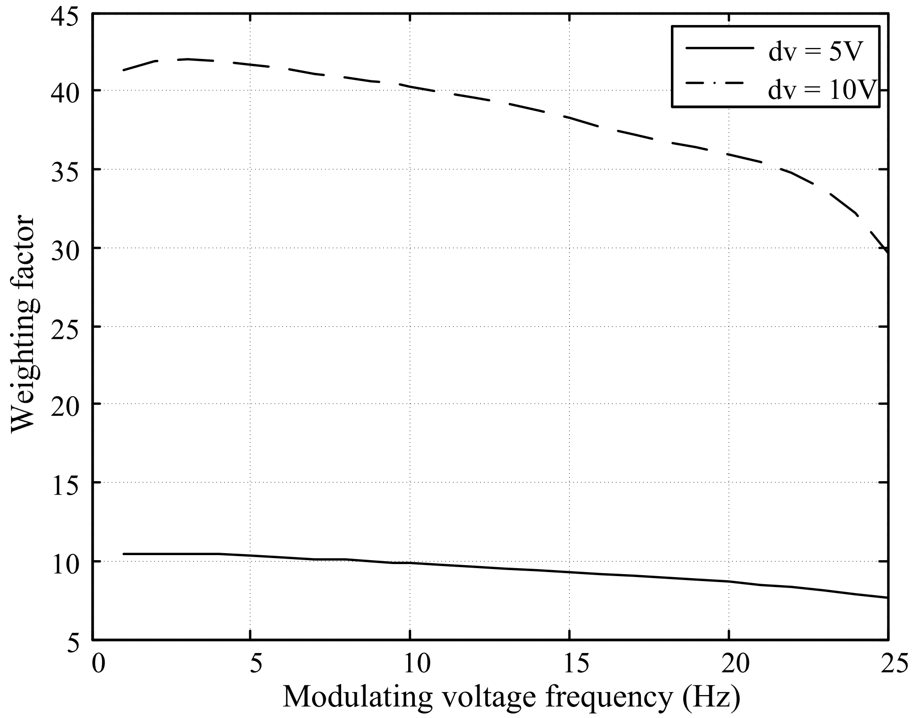

Figure 5.17 The weighting factors of a 3.4W LED lamp for different voltage modulating values. Solid line: modulating voltage amplitude 5V; dashed line: modulating voltage amplitude 10V

The graphs for each lamp type show a linear characteristic between the modulating voltage amplitude and the weighting factors, only the linearity ratio is different. The relationship between the modulating voltage amplitude and the weighting factor is presented in equation (5.3):

$$\frac{\Delta V_2}{\Delta V_1} = k_l \cdot \frac{W(f_m)_2}{W(f_m)_1} \tag{5.3}$$

$\triangle V_1$ and $\triangle V_2$ are the different modulating voltage amplitudes. $W(f_m)_1$ and $W(f_m)_2$ are the corresponding weighting factors. k_l is the linearity ratio of the relationship between the modulating voltage amplitude and the weighting factor. For a 60W incandescent lamp, k is 0.94. For an 11W energy saving lamp, k is 0.6515, k is 0.489 for a 3.4W LED lamp. This ratio is obtained from the experimental data. The ratio of a 3.4W LED lamp is smaller than the ratio of an 11W energy saving lamp. This means that the weighting factor of a 3.4W LED lamp will be higher than the weighting factor of an 11W energy saving lamp when the modulating voltage amplitude is sufficiently large. This is in agreement with the experimental data shown in table 5.2.

As an example, the verification for a 60W incandescent lamp is shown in table 5.3. The error between the calculated $W(f_m)_2$ and the measured $W(f_m)_2$, which is presented in the column 7 of table 5.3, is smaller than 2%. Since the standard IEC-

61000-4-15 gives the accepted deviation of the flicker measurement as ±5%, the error of 2% is accepted in this research.

Table 5.3 The example verification of the linearity ratio for a 60W incandescent lamp

Frequency (Hz)	$\triangle V_1$ (V)	$\triangle V_2$ (V)	$W(f_m)_1$ (measured)	$W(f_m)_2$ (calculated)	$W(f_m)_2$ (measured)	Error (%)
4	5	10	92.19	196.15	200	1.925
6	5	10	83.9	178.51	182	1.917
8	5	10	76.4	162.55	162	0.341

5.4 Discussion on a simplified flicker estimation method

In the UIE/IEC flickermeter, the flicker level is evaluated by demodulating the voltage fluctuation signal, and then weighted with the lamp-eye-brain simulator (a weighting filter and a non-linear variance estimator [11]). Finally the short-term flicker indicator P_{st} and long-term flicker indicator P_{lt} are obtained using a statistical calculation. It takes a long time to get the statistical results: 10 minutes measurement to obtain a P_{st} value and a 2 hours measurement to get a P_{lt} value. Several literature references discuss faster and simpler flicker measurement methods, e.g. [55] [56] etc. The goal of the work in this chapter is to explore a simplified flicker estimation method. Since the parameters of the filters used in the UIE/IEC flickermeter were obtained based on several human being flicker response measurement results, this measurement method includes the subjective human being feeling. The flicker measurement method explored in this chapter will use more objective way, i.e. the method will be explored more depend on the results from the physical instruments.

The human eye is sensitive to the light color. The weighting factors mentioned in section 5.3 can indicate the light spectrum response characteristics of different lamp types under flicker conditions. To evaluate the human visual sensation under flicker condition, the brain storage function should be taken into account. This is due to the fact that the voltage fluctuation signal might be an irregular signal. Then the human being can realize a flicker unless the human brain can remember the fluctuation signal (illuminance fluctuation) happened last time. Rashbass work introduced in chapter 2 shows that the brain storage function is an important factor for the human visual sensation. By using the weighting factors mentioned in section 5.3, the flicker sensation can be evaluated if the brain storage function can be added. Thus, it is necessary to find an eye-brain model under flicker to complete the flicker estimation method by using light spectrum flicker response. This work is recommended to be done in the future.

There is an eye-brain model presented in [57] [58], which is developed using a physiological mechanism model to simulate the simplified human eye-brain response to flicker. This model can be an interesting eye-brain model to be used for the flicker estimation method mentioned above. Unfortunately, the parameters of the model, which can adapt to the application of the research presented in chapter 5, are still missing.

5.5 Summary

Since the lamp light spectrum might vary under flicker conditions, the light spectrum responses to flicker of three lamp types have been measured. The experimental results have been presented in this chapter. The results show that the lamp light spectrum is different for different lamp types because of the different working principles. For the same modulating voltage frequency, different wavelengths give different contributions to flicker. For a single wavelength, the light intensity variation decreases when the modulating voltage frequency increases. By weighting with the CIE standard photopic luminosity curve, which represents the eye sensitivity to light, the weighting curves and weighting factors of a 230V 60W incandescent lamp, a 230V 11W energy saving lamp and a 230V 3.4W LED lamp have been obtained. The relationship between the weighting factors and the corresponding modulating voltage amplitudes is linear for these measured lamp types. The linearity ratio is different for different lamp types. A discussion on a simplified flicker estimation method has also been given in this chapter. If an adequate eye-brain model would be available the weighting factors could enable this simplified method.

Chapter 6

Interaction between Flicker and Power Electronic Devices

6.1 Introduction

Nowadays, more and more lighting control systems containing power electronic devices are used to improve the performance and the convenient use of the lamp. For example, a dimmer can freely vary the light intensity of the lamp from zero to maximum. This improves the flexibility of the use of the light intensity. It also helps to save energy and extends the lifetime of the lamp when less light intensity of the lamp is used. The data presented in [59] shows that 10% the energy will be saved and the lifetime of the lamp will be 2 times longer if the light of an incandescent lamp is dimmed for 10%. Flicker is an important issue related to lamps. It is interesting to study the interaction between flicker and the lighting control devices, e.g.

1) Do these lighting control devices effect the performance of the lamp under flicker conditions?
2) Does the performance of these lighting control devices change under flicker conditions?

To answer these questions, some experimental work has been performed.

The measurement of the interaction between flicker and dimmers is described in detail and the results are presented in this chapter. A further discussion on the interaction between flicker and dimmers is made as well.

6.2 Interaction between flicker and dimmers

6.2.1 Dimmer introduction

A dimmer has been used for many years to control the light output of lamps. At earlier stages, the dimmer was made from an adjustable resistor or auto transformer. By a series connected adjustable resistor or auto transformer, the input voltage of the lamp can be changed. So, the light output of the lamp can also be changed. However, this type of dimmer is bulky, inefficient and expensive [59].

After the thyristor appeared in the market, modern dimmers are constructed through the use of a thyristor or TRIAC (triode for alternating current). A TRIAC is a form of thyristor that conducts in both positive and negative direction [59]. These dimmers are also called electronic dimmers. By changing the phase angle at which the thyristor is triggered, the duty cycle (on/off time) of the voltage applied to the lamp is changed. The power level consumed by the lamp is then also changed and, therefore, the light intensity of the lamp as well. For instance, if only a half cycle of the AC voltage (see figure 6.1 (b)) is applied to the lamp, the lamp will show less bright than at the full cycle AC voltage (see figure 6.1 (a)).

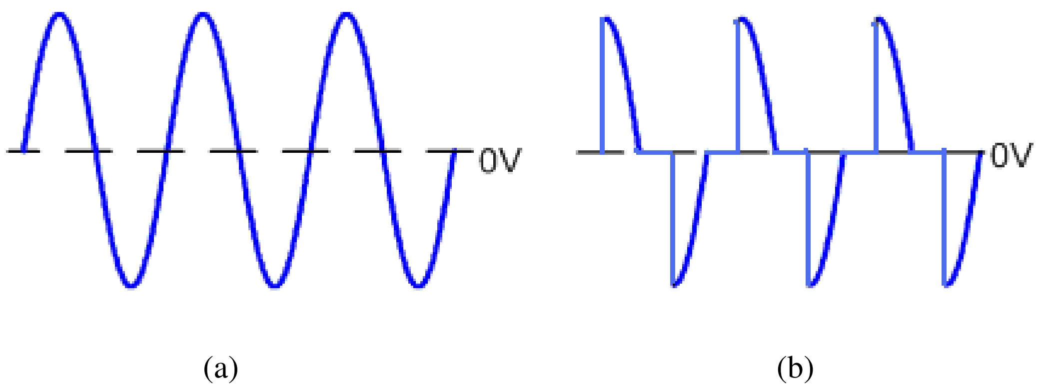

Figure 6.1 The AC voltage applied to a lamp: (a) full cycle voltage; (b) half cycle voltage

As the lamp light intensity depends on the shape of the duty cycle of the AC voltage, the control methodology used in the dimmer is very essential. The conventional dimmer types are phase controlled dimmers or reverse phase controlled dimmers.

For the phase controlled dimmer, the thyristor or TRIAC turns on at the desired voltage level during a half cycle and it turns off at the end of the half cycle, i.e. the zero crossing point. Figure 6.1 (b) shows the typical voltage waveform of a phase controlled dimmer. The phase controlled dimmer has the disadvantages of harmonic pollution and noise. The noise is due to the fact that the current surges through the lamp filament creates an intense magnetic filed in the lamp when the thyristor turns on. This magnetic field causes the contraction of the filament and its support and leads to shaking of the lamp [60]. However, the noise can be reduced by a large inductor choke. A typical circuit diagram is shown in figure 6.2.

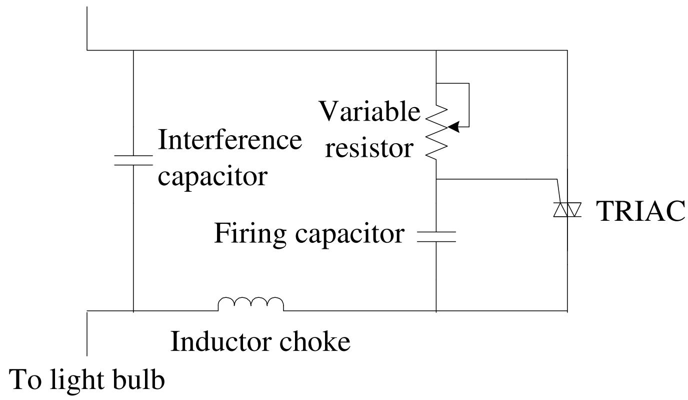

Figure 6.2 A typical circuit diagram of a phase controlled dimmer [61]

In the circuit of figure 6.2, the trigger angle of the TRIAC can be changed by the value of the variable resistor. So the light output of the lamp can be controlled. The inductor choke and the interference capacitor are used to filter the disturbances caused by the TRIAC.

The reverse phase controlled dimmer turns on at the zero-crossing point of the half cycle (current) and turns off at the desired voltage level during the half cycle. Figure 6.6 shows the typical voltage waveform of this type of dimmer. A MOSFET or IGBT is normally used in reverse phase controlled dimmers instead of a conventional thyristor in phase controlled dimmers. A circuit scheme of the reverse phase controlled dimmer is presented in figure 6.3. The MOSFETs Q1 and Q2 turn on at the zero crossing of the current and turn off at the desired phase angle that is set by the controller.

Comparing the reverse phase controlled dimmer to the phase controlled dimmer, the advantage of the reverse phase controlled dimmer is that it has better performance on maintaining a stable output when the supply voltage varies [60]. This is due to the fact that the working methodology of these two dimmers is different. Since the thyristor or TRIAC in a phase controlled dimmer turns on at the desired phase angle and turns off at the zero-crossing of the current, the desired phase angle has to be pre-set and adjusted the next cycle by a feed-back controller that detects the voltage fluctuations of the supply voltage. Therefore the voltage regulation of the phase controlled dimmer has a delay with respect to the supply voltage fluctuation. However, the MOSFETs or IGBTs used in a reverse phase controlled dimmer turn on at the zero-crossing of the current and turn off at the desired phase angle. During the turn on period of the MOSFET or IGBT, the controller of the reverse phase controlled dimmer can detect the voltage fluctuations of supply voltage and adjust the desired phase angle in time. Thus, the performance of the voltage regulation of the reverse phase controlled dimmer is better than the phase controlled dimmer. However, both of them generate harmonics.

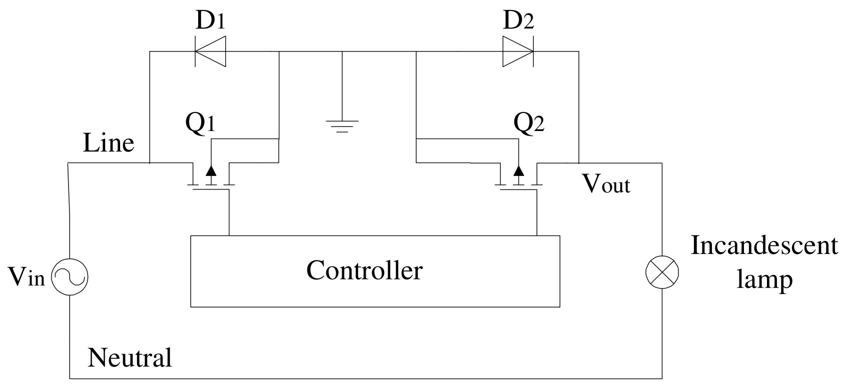

Figure 6.3 A circuit scheme of a reverse phase controlled dimmer [62]

There are also other newer dimmer types in the market for modern lighting systems, e.g. the so-called sine wave dimmer (power factor controlled). This dimmer uses the pulse width modulated control waveform generated by a micro controller to control the trigger angle of an IGBT [63]. It can obtain better performance than the conventional dimmer types, i.e. less harmonics. However, they are more expensive. So, normally this type of dimmers is used only for a lighting system with high power, e.g. 3kW.

6.2.2. Interaction measurements

Measurement set-up

Interaction measurements were done in the PQ lab of TU/e. The purpose of these measurements is to investigate how the dimmer and the lamp operate under flicker conditions. Three conventional dimmers A, B and C, from different manufacturers, were selected for this study. Two of them are phase controlled dimmers. One is a reverse phase controlled dimmer. The measured output voltages of these dimmers are presented in figure 6.4 to 6.6. The figures show that dimmers A and B are phase controlled dimmers. The dimmer B has voltage spikes at the trigger point. The dimmer C is a reverse phase controlled dimmer. A 230V 60W incandescent lamp has been used as the tested lamp.

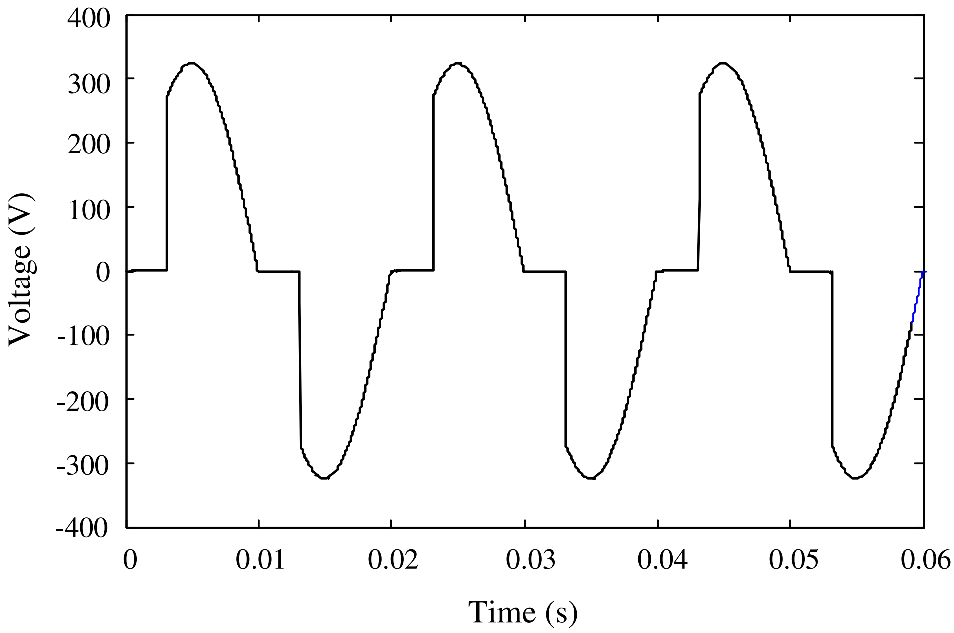

Figure 6.4 The output voltage of the dimmer A

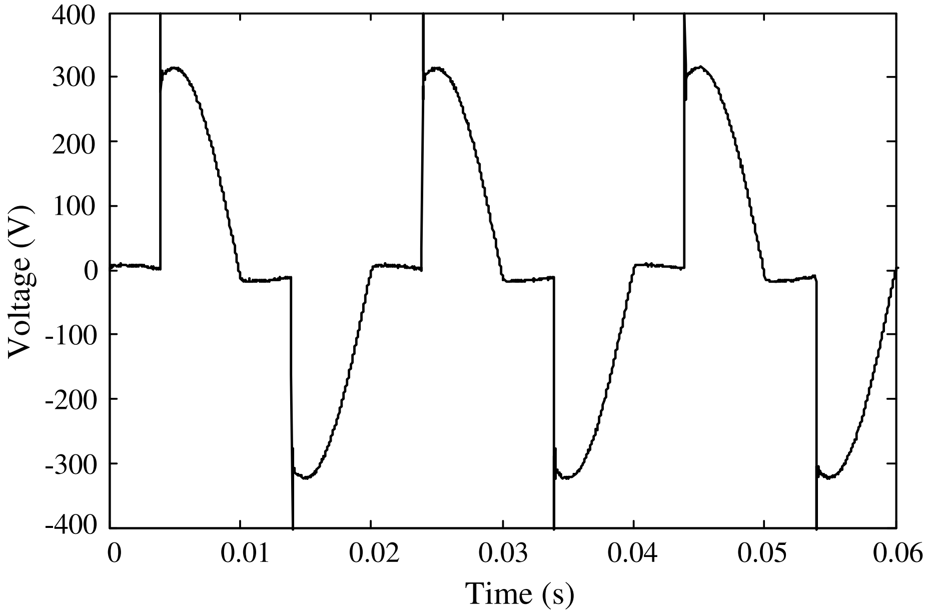

Figure 6.5 The output voltage of the dimmer B

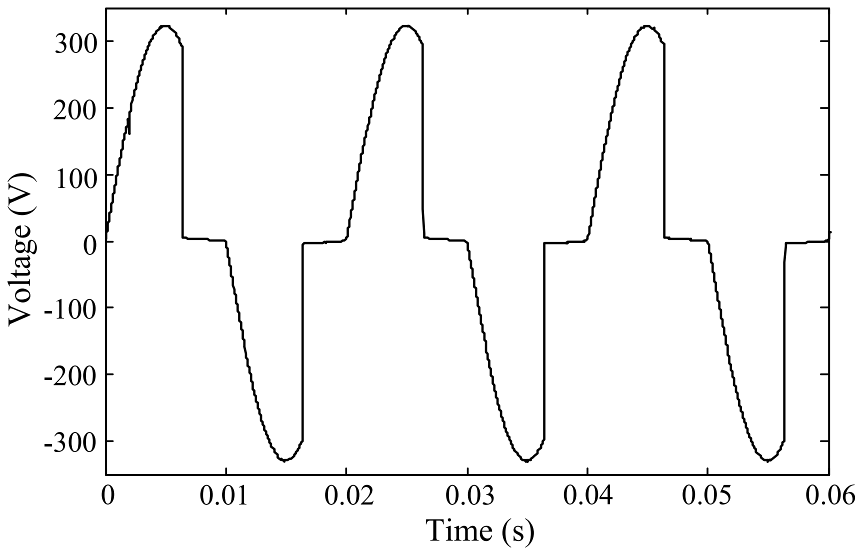

Figure 6.6 The output voltage of the dimmer C

The measurement set-up is shown in figure 6.7. The voltage fluctuations were generated by the programmable power source. The dimmer was connected between the power source and the tested lamp. The light output of the lamp was measured by the illuminance meter (luxmeter) through a photodetector. To avoid disturbances from other light sources, the tested lamp and photodetector were put inside a white box. The output voltage of the programmable power source and the voltage after the dimmer were measured. The current of the tested lamp was measured as well. All measured data were recorded by a computer connected to an oscilloscope.

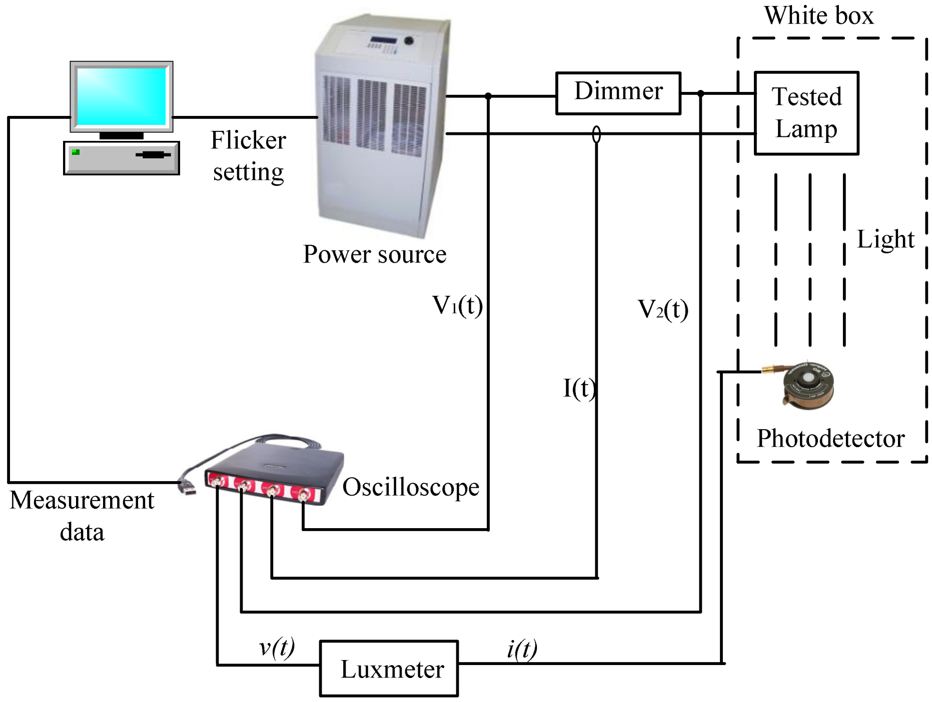

Figure 6.7 The scheme of the measurement set-up

Measurement results

In the measurements, each dimmer was tested with three dimming positions. These positions are:

1) The maximum output voltage (position 1)
2) The medium output voltage (position 2)
3) The lowest output voltage at which the tested lamp has still visible light output (position 3)

The input voltage of each tested lamp was measured without the dimmer as well. Voltage fluctuations with different modulating frequency (0.5Hz – 25Hz) and a constant modulating amplitude (6.9 V) were applied to the dimmer and the lamp.

The measured illuminance was analyzed by FFT. For the same reason mentioned in the measurements of chapter 3, only the components with the corresponding frequency as the modulating voltage frequency were compared in this chapter. To compare the illuminance variations without dimmer and the three dimmer positions, the relative illuminance variation is used. It can be calculated from equation (3.1) of chapter 3.

The relationship between the relative illuminance variation and the modulating voltage frequency was plotted for each tested lamp with different dimmers. To show the measurement results better, the results are smoothed by polynomial fitting with an order of 6 and these are presented in figure 6.8 to 6.10.

Figures 6.8 and 6.9 show that the relative illuminance variation is higher when the dimmer gives the lowest output voltage (position 3). Except for the dimming position 1, the relative illuminance variation of the lamp is always higher than the condition without a dimmer. This means that dimmers A and B increase the flicker level. Comparing figure 6.10 to figure 6.8 and 6.9, it is clear that the relative illuminance variation of each tested condition in figure 6.10 does not show the same large differences as presented in figure 6.8 and 6.9. All curves in figure 6.10 are within the deviation range of 2%. Thus, dimmer C does not increase the flicker level. This is due to the fact that dimmer C is a reverse phase controlled dimmer. This dimmer type can maintain the voltage when the supply voltage fluctuates. This has been explained in section 6.2.1.

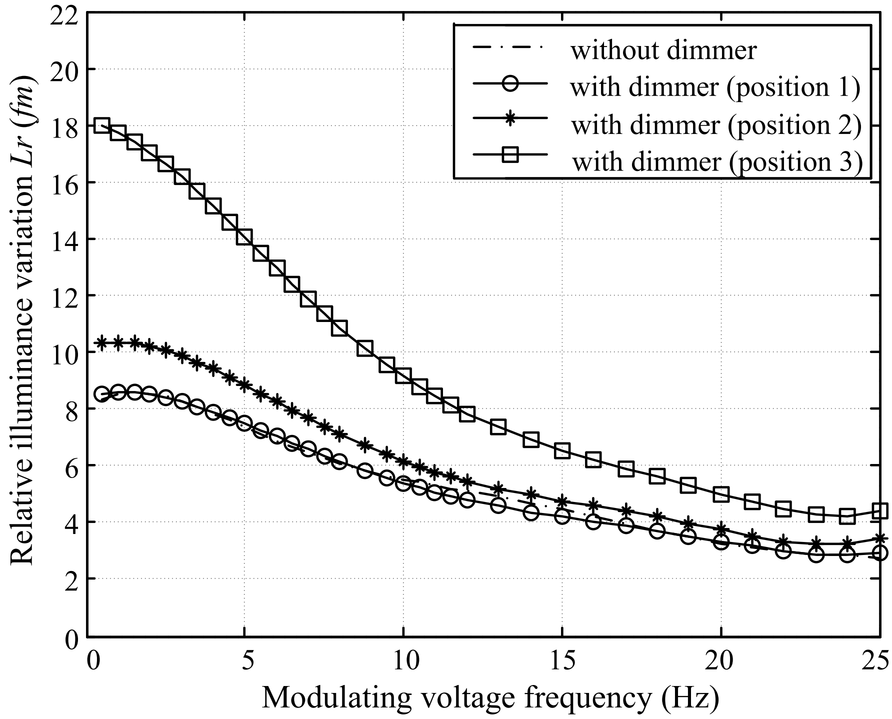

Figure 6.8 The relative illuminance variation of a 60 W incandescent lamp versus the modulating voltage frequency (dimmer A))

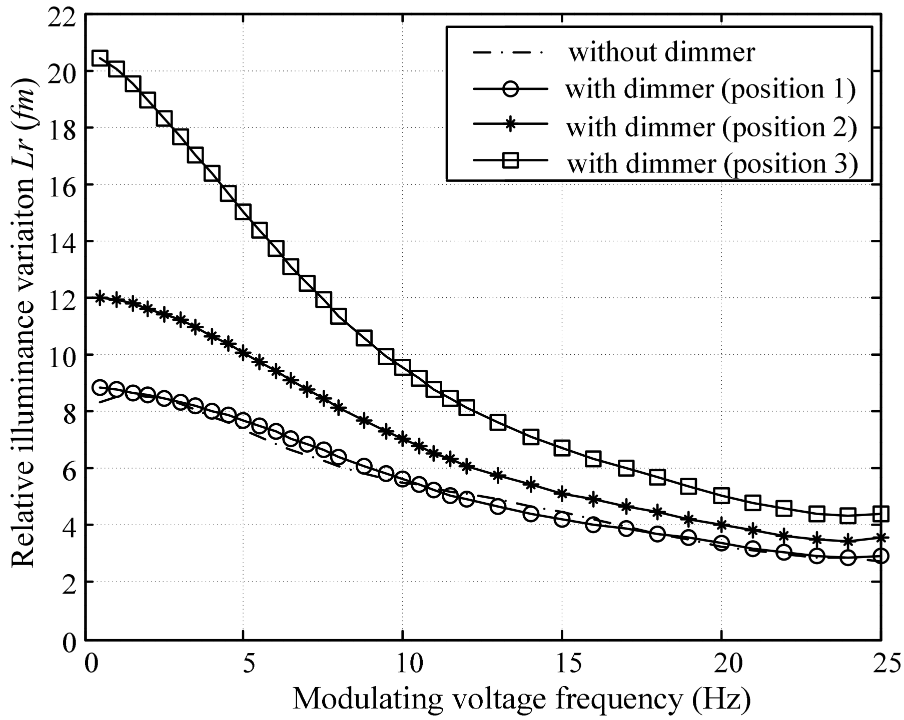

Figure 6.9 The relative illuminance variation of a 60 W incandescent lamp versus the modulating voltage frequency (dimmer B)

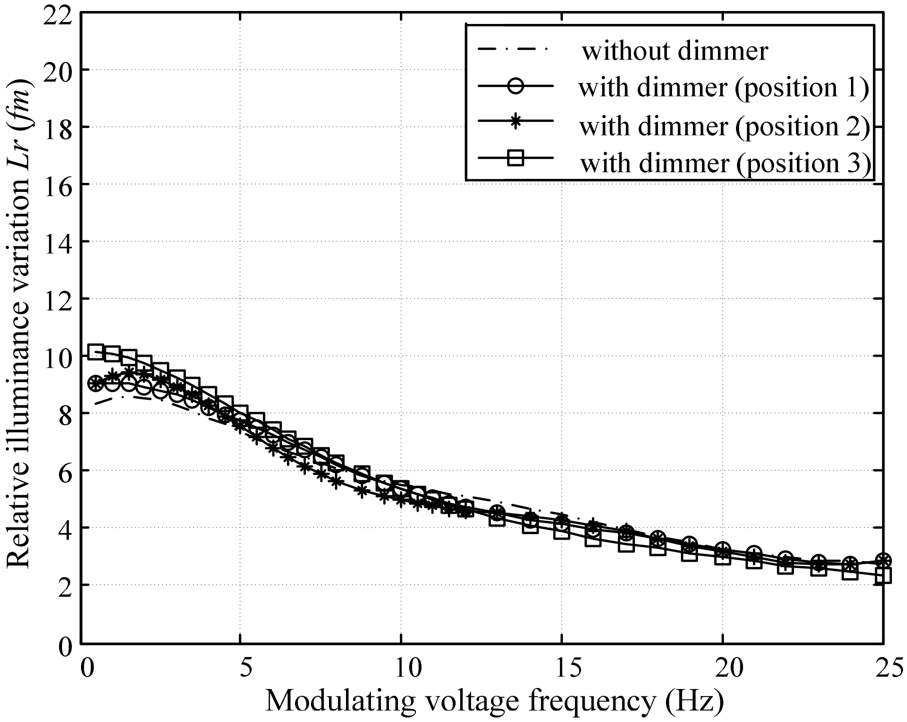

Figure 6.10 The relative illuminance variation of a 60 W incandescent lamp versus the modulating voltage frequency (dimmer C)

6.3 Discussion on dimmers

The measurement results of the interaction between flicker and dimmers have been presented above. The experimental results show that the tested phase controlled dimmers increase the flicker level. The relative illuminance variation is higher when the output voltage of the phase controlled dimmer is lower. This is caused by the specific working principle of the phase controlled dimmer. Figure 6.11 shows the peak value of the supply voltage and the trigger voltage level of dimmer A when the dimmer was put on dimming position 2 under a modulating voltage frequency of 0.5Hz.

As figure 6.11 shows, since the supply voltage varies with a frequency of 0.5Hz, the trigger voltage level of the dimmer also varies with the same frequency. The modulating amplitude of the trigger voltage level is smaller than the one of the supply voltage. However, the relative illuminance variation value is still bigger than the one without the dimmer. This is due to the fact that the total average illuminance under dimming conditions is smaller than the illuminance without a dimmer. Although the absolute illuminance variation is smaller, the ratio between the absolute illuminance variation and the total average illuminance is increased, i.e. the relative illuminance variation is increased.

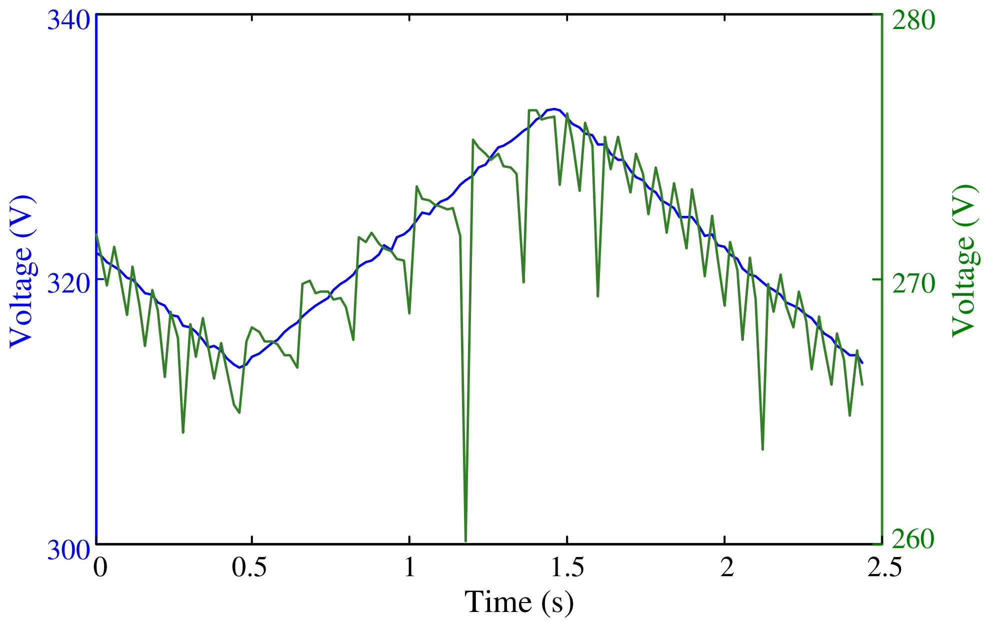

Figure 6.11 The supply voltage (modulating voltage frequency is 0.5Hz) and the trigger voltage of dimmer A when the dimmer was put on dimming position 2. The blue line is the supply voltage; the green line is the trigger voltage level of the dimmer

To solve the problem that the phase controlled dimmer increases the flicker level, the output voltage of the dimmer should be kept as stable as possible under flicker. Thus, a proper controller to control the trigger angle of the dimmer is very important. Since the amplitude of the supply voltage varies under flicker, the trigger angle of the dimmer should be controlled to compensate for this voltage fluctuation amplitude. The output voltage of every cycle should be compared and kept same by compensation. Then the light output of the lamp will not change anymore. Therefore, a fast response controller with close control loop should be used in the dimmer to reduce the flicker influence. An example of a flicker insensitive dimmer is given in [64]. In the experimental work presented in this chapter, the reversed phase controlled dimmer shows a better performance under flicker than the phase controlled dimmer. Thus, the reverse phase control dimmer is also a solution to eliminate the enlarged flicker problem caused by dimmers.

6.4 Summary

The interaction between flicker and dimmers is studied in this chapter. It has been studied based on experimental work. The measurement results show that the phase controlled dimmer will increase the flicker problem. The relative illuminance variation is higher when the output voltage of the phase controlled dimmer is lower. This is caused by the inadequate trigger angle control of the phase controlled dimmer. Solutions to eliminate the flicker influence of dimmers are discussed in this chapter.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

Power quality problems become more and more important in the electrical power system. The research presented in this thesis is focused on the study of flicker, currently one of the most important power quality aspects. The main goal of this research is to improve the current flicker measurement instrument – the UIE/IEC flickermeter and explore methods to improve the flicker measurement technology. As a further understanding of the flicker phenomenon, the interaction between flicker and power electronic devices is also studied. Based on this research, the following conclusions could be drawn.

7.1.1 Lamp flicker response of different lamp types

The UIE/IEC flickermeter cannot generate the output (P_{st}) that correlates well with customer sensitivities for different lamp types. This is due to the fact that the flicker level for different lamp types depends on the flicker response of each lamp type, which is different for various lamp types. To obtain knowledge of the flicker response of different lamp types, flicker response measurements were done for six lamp types in the PQ lab of TU/e. The conclusions from these measurement results are:

1) The flicker responses of different lamp types are significantly different because of their different working principles. The incandescent lamp is the most sensitive to flicker. Compared to other tested lamp types, the halogen lamp that uses an electronic transformer is more sensitive to flicker than other lamp types when the modulating voltage frequency is lower than 12Hz. However, this halogen lamp is less sensitive than other lamp types when the modulating voltage frequency is higher than 15Hz. The energy saving lamp is the most insensitive to flicker. Thus, the output of the UIE/IEC flickermeter, which is built based on the incandescent lamp flicker response, does not give a good correlation between the measurement and customer sensitivity for other lamp types.
2) The instantaneous flicker curves of the energy saving lamp, the fluorescent lamp and the CFL with electromagnetic ballast can be used to estimate the maximum instantaneous flicker sensation $P_{inst,max}$ of these lamp types. The experimental results demonstrate clearly that these three lamp types are less sensitive to flicker than the incandescent lamp. Since the experimential ratio between P_{st} and $P_{inst,max}$ is 0.68, these instantaneous flicker curve results can be used to estimate the flicker level of the corresponding lamp types.
3) The relative illuminance variation of the modulating voltage frequency (f_m) is linearly proportional to the modulating voltage amplitude within the frequency range of interest (0.5Hz – 25Hz) for all lamp types. This linear relationship has been used to define the parameters of the lamp response filter to develop the weighting filter for the different lamp types using a linear system identification method.

7.1.2 Improvement of the UIE/IEC flickermeter

The lamp flicker response models, which represent the relationship between the illuminance variation and the modulating voltage amplitude, have been derived for different lamp types by a linear system identification method. As discussed in section 4.5, this identification method used in this thesis is different from the general application used in the control field due to the specific purpose of this research. The phase response of the model is not of concern in this thesis. The OE identification model has been used for these lamp flicker response models. The new derived models avoid the complication of the physical lamp model and improve the accuracy of the current simplified lamp model. The average fitting rate between the simulation results of the derived model and the measured results is better than 90%. The residue analysis has been done for all models and the results show that these OE identification models can be accepted. The improved weighting filters for different lamp types have been obtained using the corresponding lamp flicker response model (transfer function) multiplied by the eye-brain transfer function. These improved weighting filters have been implemented into the structure of the UIE/IEC flickermeter to replace the current weighting filter, which is only valid for the 230V or 120V, 60W incandescent lamp. Hence, the improved flickermeter is now capable to measure the flicker level and give a better correlation between the measured flicker level and customer complaints for all specific lamp types. The performance of this improved flickermeter has been verified by simulation. The simulation results demonstrate that the error between the simulation results and the expected results of the improved flickermeter is within $\pm 5\%$. This accuracy meets the deviation requirement given in standard IEC 61000-4-15.

7.1.3 Measurements of the light spectrum flicker response

The research reported in section 7.1.1 and 7.1.2 is based on the human eye sensitivity to the illuminance variation. To explore a new flicker measurement method, the lamp light spectrum response to flicker of three lamp types has also been measured as the sensitivity of the human eye in dependence of the light spectrum. The conclusions are:

1) The lamp light spectrum flicker response is different for different lamp types. For the same modulating voltage frequency, the different spectrum wavelengths of each lamp type give different relative light intensity variation values. For a single wavelength, the relative light intensity variation decreases when the modulating voltage frequency increases.
2) Spectrum weighting factors have been obtained for each lamp type by the wavelength contribution to flicker weighted with the CIE standard photopic luminosity curve. This presents the human eye flicker response based on the light color variation under flicker conditions. The relationship between the spectrum weighting factors and the corresponding modulating voltage amplitudes is linear for these measured lamp types within the frequency range of interest (0.5Hz-25Hz). The linearity ratios are 0.94, 0.6515 and 0.489 for the 60W incandescent lamp, the 11W energy saving lamp and the 3.4W LED lamp respectively. These values can be used to predict the weighting factor for different modulating voltage amplitudes.

3) It has been confirmed that the incandescent lamp is the most sensitive to flicker compared with the other lamp types. The energy saving lamp is more sensitive to flicker than the LED lamp when the modulating voltage amplitude is small (e.g. 5V), however, the LED lamp becomes more sensitive to flicker when the modulating voltage amplitude is large (e.g. 10V). The spectrum weighting factor increases when the modulating voltage amplitude increases.

7.1.4 Interaction between flicker and power electronic devices

The experimental results show that the phase controlled dimmer will increase the flicker problem. The relative illuminance variation is higher when the output voltage of the phase controlled dimmer is lower. This is caused by inadequate trigger angle control of the phase controlled dimmer. The measurement results show that the reverse phase controlled dimmer does not increase the flicker level. To solve the flicker problem caused by dimmers, there are two solutions presented in this thesis. One is to use the reverse phase controlled dimmer instead of the phase controlled dimmer. Another solution is to use a proper controller to control the trigger angle of the dimmer according to the flicker conditions. In that case the modulated supply voltage will be compensated and the lamp voltage is kept stable.

7.2 Thesis contribution

The lamp flicker response measurement results presented in this thesis prove that the UIE/IEC flickermeter is not capable to give a good correlation between the measured flicker level and customer sensitivities for different lamp types. These measurement results can be used as the reference to improve the standard IEC 61000-4-15. Furthermore, these results have been involved in the draft of the technical report of CIGRE Working Group C4.108 [13]. The measured flicker level obtained by the improved flickermeter proposed in this thesis for different lamp types can correlate much better with the customer sensitivities than the current UIE/IEC flickermeter. These results also provide a solution to solve the flicker problem in practice. The network operator can suggest the customers to change the lamp type (e.g. the lamp that is less sensitive to the flicker) when they meet flicker problems [65]. The flickermeter simulation model introduced in section 4.4.1 can be used for studying the flicker propagation in a network as well [66].

In this thesis, the lamp light spectrum flicker response measurements are also presented. The experimental results of the wavelength contribution to the flicker of different lamp types give information about the light color variation of different lamp types under flicker conditions. This is important for understanding the human eye response to flicker from the human eye spectrum sensitivity point of view. A spectrum weighting factor of different lamp types, which is obtained by the wavelength contribution to the flicker weighted with the CIE standard photopic luminosity curve, has been defined in this thesis. This factor can indicate the human eye flicker response based on the light spectrum flicker response characteristics of different lamp types. Through the use of the weighting factors, it is possible to develop a new flicker measurement method if an eye-brain model could be added.

The study of the interaction between flicker and power electronic devices provides a practical solution for flicker caused by dimmers. It also indicates that the design of a proper controller in power electronic devices helps to solve the flicker problem.

7.3 Future work

Lamp flicker response (lamp illuminance flicker response) measurements for different lamp types have been made in this research work. However, more measurements on more lamp types should be done in the future as each specific lamp type might have different flicker responses, e.g. a lamp with a different power rating or a fluorescent lamp with a different ballast structure. An average flicker response curve of each specific lamp type, which can help to improve the flickermeter for corresponding lamp types, should be developed in the future.

The linear system identification method has been used in this thesis to develop the lamp flicker response model. The use of this method is based on the experimental proof that the relative illuminance variation amplitude varies linearly with the modulating voltage amplitude within the frequency range of interest (0.5Hz–25Hz). From a physical point of view, a lamp shows a nonlinear relationship between the illuminance and the voltage. However, the existing nonlinear physical lamp models are not sufficient to present the lamp flicker response because they are derived for normal operating conditions and no flicker (the test results show that the average fitting rate between the model simulation results and the measurement results is only 4.88%). Nonlinear system identification methods may be used to develop the lamp flicker response model in the future. The nonlinear lamp flicker response model can then be compared with the linear flicker response model. The comparison results may help to obtain a better lamp flicker response model and therefore a more accurate flickermeter.

An alternative method to derive the flicker response model by doing the lamp flicker response curve fitting directly is discussed in section 4.5. This method should be tested and compared to the lamp flicker response identification method used in this thesis in the future.

As mentioned in section 7.2, the spectrum weighting factor that can indicate the human eye flicker response has been defined for three lamp types. It can be predicted directly from the modulating voltage amplitude by using the experiential ratio of different lamp types given in chapter 5. By using the spectrum weighting factor, it is possible to develop a new flicker measurement method from the human eye spectrum sensitivity point of view. However, an eye-brain model is needed to complete the human visual sensation for flicker in the new flicker measurement method. This is due to the fact that the human visual sensation under flicker conditions includes the human eye flicker response and the human brain storage function. This eye-brain model and the new flicker measurement method have to be developed in the future.

The interaction between flicker and different structures of the electronic ballast could be studied further to get a better knowledge about the flicker problem caused by electronic devices.

Appendix A

Additional Lamp Load Characteristics and Illuminance Measurement Results

A.1 Lamp load characteristics measurements

To obtain more knowledge about the lamps, the lamp load characteristics of three lamp types (60W incandescent lamp, 15W fluorescent lamp and 9W CFL with magnetic ballast) have been measured in the PQ lab of TU/e. The measured voltage - current (V-I) characteristic curves of the lamps are presented in section 3.3.2. More detailed measurement results (including the lamp (lamp tube) voltage, the lamp current, the consumed active power and the lamp (lamp tube) resistance) are presented in this appendix.

A.1.1 Incandescent lamp

As mentioned in section 3.3.2, the input voltage of the tested lamp, which is varied from 130V to 250V in 5V steps, was supplied by a programmable power source. The lamp voltage, the current, the active power consumed by the lamp and the illuminance were recorded. The corresponding resistance of the lamp has been calculated. The results are presented in table A.1. The input voltage shown in column 1 of table A.1 is the preset value, which was given to the programmable power source. This is the same in table A.2 and A.3. The measurement results show that the incandescent lamp acts as a resistive load.

A.1.2 Fluorescent lamp

A 15W fluorescent lamp tube was connected to the programmable power source via an electronic ballast. The input voltage of the ballast was varied from 90V to 250V, which is presented in column 1 of table A.2. The lamp tube voltage, the current, the active power consumed by the fluorescent lamp and the illuminance were measured. As was shown in figure 3.7, the lamp tube voltage is a square waveform instead of a sinusoidal waveform. The fundamental RMS values (50Hz) of the lamp voltage have been calculated using FFT analysis, which are given in column 2 of table A.2. The corresponding resistance of the lamp tube has been calculated as well. The results are shown in table A.2. As explained in section 3.3.2, these results are different from those of the incandescent lamp because of the different working principle of the fluorescent lamp.

A.1.3 Compact fluorescent lamp (CFL) with electromagnetic ballast

The same measurement as for the fluorescent lamp was made for a 9W CFL with electromagnetic ballast. The results are shown in table A.3. As expected, the results show the similar load characteristics as of the fluorescent lamp.

A.2 Lamp illuminance measurements

Lamp illuminance measurements were also made in the PQ lab of TU/e. In section 3.3.3, the instantaneous illuminance waveforms of a 60W incandescent lamp and a 11W energy saving lamp were presented and compared. As additional information, the measured instantaneous illuminance waveforms of the 15W fluorescent lamp and 3.4W LED lamp are shown in figure A.1 and A.2. These illuminance waveforms are different from the incandescent lamp. This is caused by the characteristics of the extra components that are in series with the lamp tube, e.g. the ballast of the fluorescent lamp and the rectifier in the LED lamp.

Table A.1 The lamp load characteristics measurement results of a 230V 60W incandescent lamp

Input Voltage (preset) (V)	Lamp Voltage (measured) (V)	Lamp Current (A)	Consumed Active Power (W)	Illuminance (lux)	Lamp resistance (Ω)
130	129.54	0.19	24.97	420	671.95
135	134.58	0.20	26.47	500	684.23
140	139.65	0.20	27.98	620	696.94
145	144.63	0.20	29.52	730	708.62
150	149.72	0.21	31.12	840	720.32
155	154.69	0.21	32.72	950	731.22
160	159.79	0.22	34.38	1080	742.70
165	164.82	0.22	36.03	1210	753.86
170	169.78	0.22	37.73	1360	764.03
175	174.87	0.23	39.48	1520	774.53
180	179.87	0.23	41.18	1680	785.73
185	184.90	0.23	42.96	1860	795.80
190	189.94	0.24	44.73	2060	806.47
195	194.94	0.24	46.57	2290	815.95
200	199.88	0.24	48.39	2520	825.66
205	204.90	0.25	50.23	2770	835.78
210	209.91	0.25	52.08	3030	846.09
215	214.92	0.25	54.02	3320	854.99
220	219.92	0.25	55.96	3620	864.21
225	224.93	0.26	57.97	3930	872.80
230	229.90	0.26	59.87	4270	882.82
235	235.01	0.26	62.03	4620	890.41
240	239.95	0.27	64.01	5000	899.54
245	245.02	0.27	66.13	5380	907.81
250	250.07	0.27	68.18	5790	917.19

Table A.2 The lamp load characteristics measurement results of a 230V 15W fluorescent lamp

Input Voltage (preset) (V)	Lamp Voltage (fundamental RMS) (V)	Lamp Current (A)	Consumed Active Power(W)	Illuminance (lux)	Lamp resistance (Ω)
90	63.45	0.06	3.51	790	1146.22
95	61.83	0.07	4.19	930	911.69
100	60.68	0.08	4.77	1060	772.53
105	60.01	0.09	5.26	1170	684.28
110	59.03	0.10	5.73	1280	608.27
115	58.12	0.11	6.16	1380	548.76
120	57.41	0.11	6.57	1470	501.34
125	56.67	0.12	6.99	1560	459.51
130	56.03	0.13	7.37	1650	426.22
135	55.44	0.14	7.79	1730	394.66
140	54.94	0.15	8.08	1810	373.55
145	54.45	0.16	8.47	1890	349.97
150	53.97	0.16	8.85	1960	329.04
155	53.43	0.17	9.12	2030	313.06
160	53.05	0.18	9.47	2100	297.16
165	52.51	0.19	9.83	2160	280.48
170	52.05	0.19	10.13	2220	267.40
175	51.56	0.20	10.44	2290	254.62
180	51.10	0.21	10.75	2350	242.84
185	50.70	0.22	10.99	2410	233.89
190	50.20	0.23	11.33	2470	222.49
195	49.86	0.23	11.63	2530	213.83
200	49.40	0.24	11.89	2580	205.26
205	49.13	0.25	12.16	2630	198.57
210	48.66	0.26	12.44	2690	190.30
215	48.38	0.26	12.78	2750	183.14
220	48.03	0.27	13.06	2800	176.55
225	47.96	0.28	13.41	2860	171.54
230	47.57	0.29	13.69	2910	165.32
235	47.23	0.30	13.99	2970	159.45
240	47.01	0.30	14.31	3030	154.46
245	46.83	0.31	14.64	3090	149.77
250	46.60	0.32	14.99	3160	144.90
255	46.43	0.33	15.43	3220	139.77
260	46.43	0.34	15.85	3290	136.00

Table A.3 The lamp load characteristics measurement results of a 230V 9W CFL with electromagnetic ballast

Input Voltage (preset) (V)	Lamp Voltage (fundamental RMS) (V)	Lamp Current (A)	Consumed Active Power (W)	Illuminance (lux)	Lamp Resistance (Ω)
90.0	0.05	33.01	1.67	0	0
95.0	63.31	0.03	2.26	1420	2116.36
100.0	62.22	0.04	2.75	1810	1543.73
105.0	61.04	0.05	3.14	2090	1278.05
110.0	60.59	0.06	3.49	2310	1110.44
115.0	59.23	0.06	3.78	2510	985.31
120.0	58.99	0.07	4.08	2690	899.70
125.0	58.41	0.07	4.42	2850	794.60
130.0	57.69	0.08	4.64	3000	749.08
135.0	57.34	0.09	5.01	3150	681.46
140.0	56.61	0.09	5.22	3280	637.64
145.0	56.43	0.10	5.45	3410	603.52
150.0	55.91	0.10	5.69	3520	563.06
155.0	55.12	0.11	5.93	3630	536.80
160.0	55.04	0.11	6.14	3730	509.09
165.0	54.48	0.12	6.42	3820	473.38
170.0	54.19	0.12	6.66	3890	454.64
175.0	53.48	0.13	6.91	3980	429.58
180.0	53.00	0.13	7.06	4060	415.71
185.0	52.62	0.14	7.30	4150	391.55
190.0	52.07	0.14	7.51	4230	374.23
195.0	51.57	0.15	7.72	4300	358.56
200.0	51.23	0.15	7.95	4380	338.67
205.0	50.92	0.16	8.20	4450	324.43
210.0	50.73	0.16	8.35	4530	312.10
215.0	50.26	0.17	8.59	4620	294.63
220.0	49.99	0.18	8.75	4700	278.22
225.0	49.65	0.19	8.63	4800	249.86
230.0	48.99	0.19	9.59	4910	268.52
235.0	48.36	0.20	9.91	5040	255.26
240.0	47.94	0.21	10.20	5190	242.32
245.0	47.26	0.22	10.59	5370	226.02
250.0	46.21	0.23	10.96	5550	214.12
255.0	63.31	0.24	11.43	6230	198.83
260.0	62.22	0.25	11.74	6420	181.82

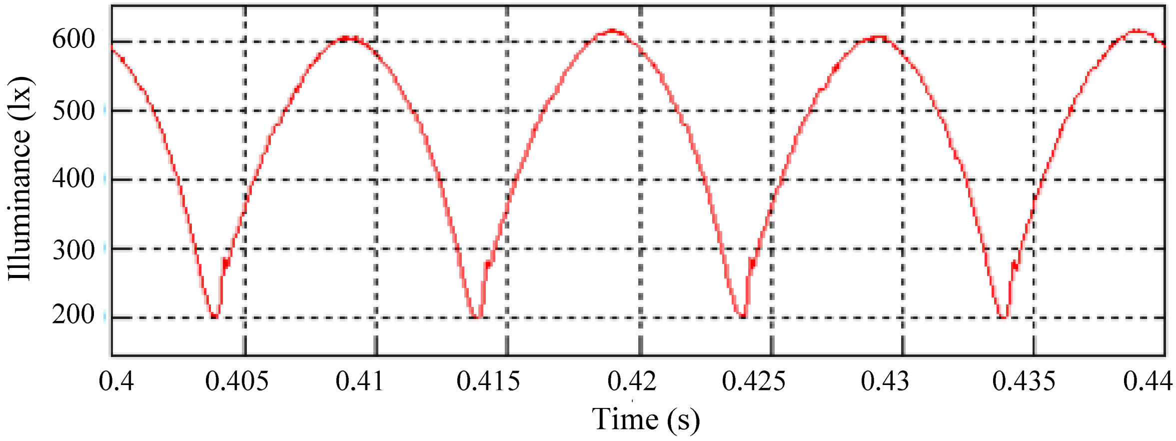

Figure A.1 The instantaneous illuminance of a 15W fluorescent lamp

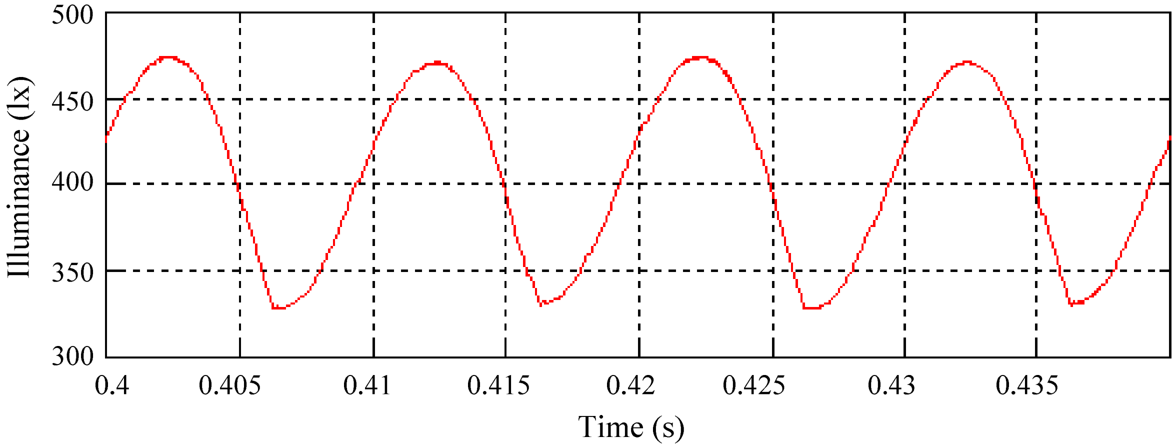

Figure A.2 The instantaneous illuminance of a 3.4W LED lamp

Appendix B

Lamp Flicker Response Measurements with Rectangular Voltage Fluctuations

B.1 Introduction

In section 3.4, the lamp flicker response measurement results with sinusoidal voltage fluctuations are shown and discussed. In a real network, there are also lots of rectangular voltage fluctuations or fluctuations with a similar waveform shape, e.g. the voltage profile when a motor starts. In IEC 61000-4-15, a different table (table 2 of [31]) is given for the testing of the performance of the flickermeter with rectangular voltage fluctuations.

The lamp flicker response measurements of various lamp types with rectangular voltage fluctuations were also carried out in the PQ lab of TU/e. The measurement set-up is the same as the one described in section 3.2. The tested lamp types are:

- The 60W glass incandescent lamp
- The 40W halogen lamp
- The 15W fluorescent lamp
- The 11W energy saving lamp
- The 3.4W LED lamp

The rectangular voltage fluctuation waveforms were generated by the programmable power source. The measurement results of the lamp flicker response to the rectangular voltage fluctuations are presented in this appendix.

Figure B.1 shows a measured rectangular voltage fluctuation waveform with 3% modulating voltage amplitude (based on a 230V system) and 4Hz modulating voltage frequency.

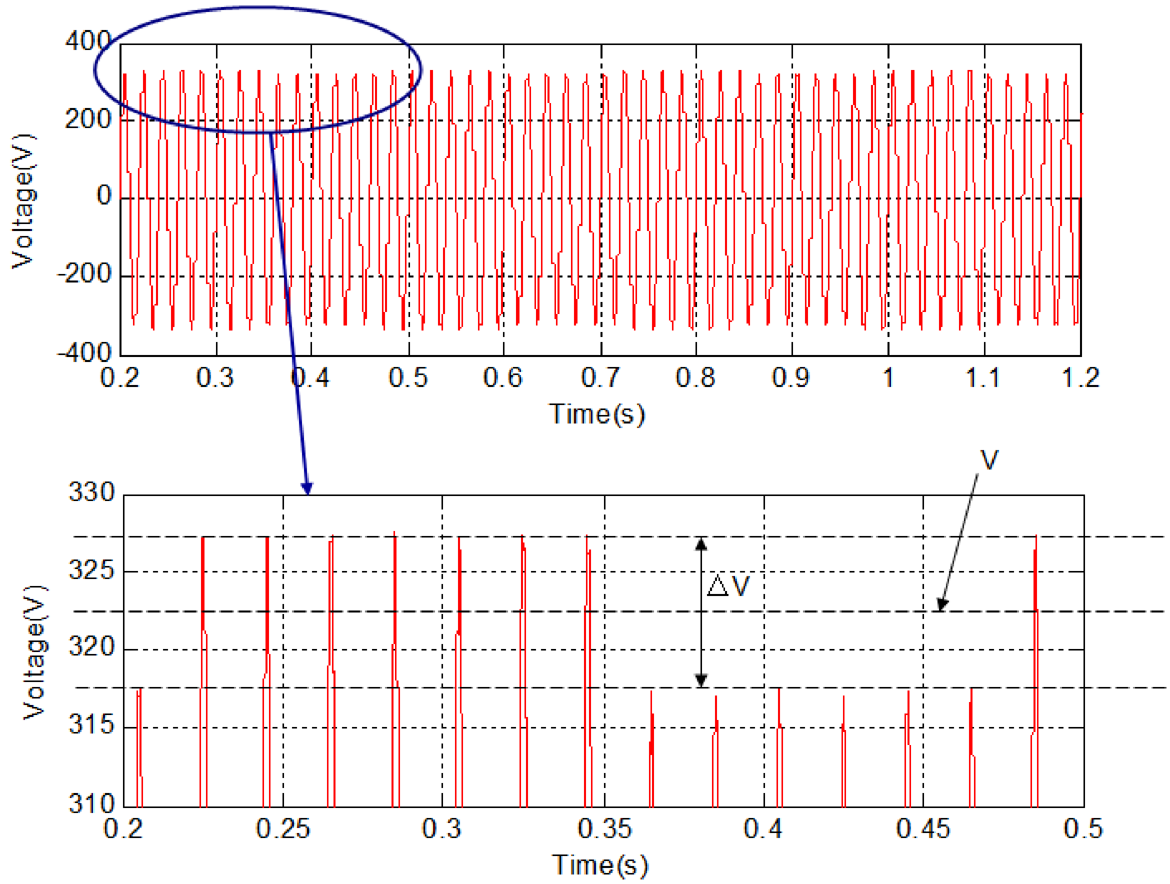

Figure B.1 The measured rectangular voltage fluctuation waveform (modulating voltage amplitude is 3% and the modulating voltage frequency is 4Hz) The figure below is the enlarged figure of a part of the waveform in the figure above

The lamp illuminance is a sinusoidal amplitude modulation waveform when the lamp is fed by a sinusoidal voltage fluctuation. However, it becomes a distorted amplitude (non-rectangular and non-sinusoidal) modulation waveform when the lamp input voltage is a rectangular voltage fluctuation. The illuminance waveform resembles a rectangular amplitude modulation waveform if the modulating voltage frequency is lower. Otherwise, the illuminance is more like a sinusoidal amplitude modulation waveform. This is due to the fact that the lamp illuminance cannot exactly follow the rectangular voltage fluctuations because of the time constant of the thermal emission of the filament or the discharge between the electrodes. Figure B.2 shows the illuminance of a 60W incandescent lamp subject to a rectangular voltage fluctuation, whose modulating frequency is 4Hz and the modulating amplitude is 3%.

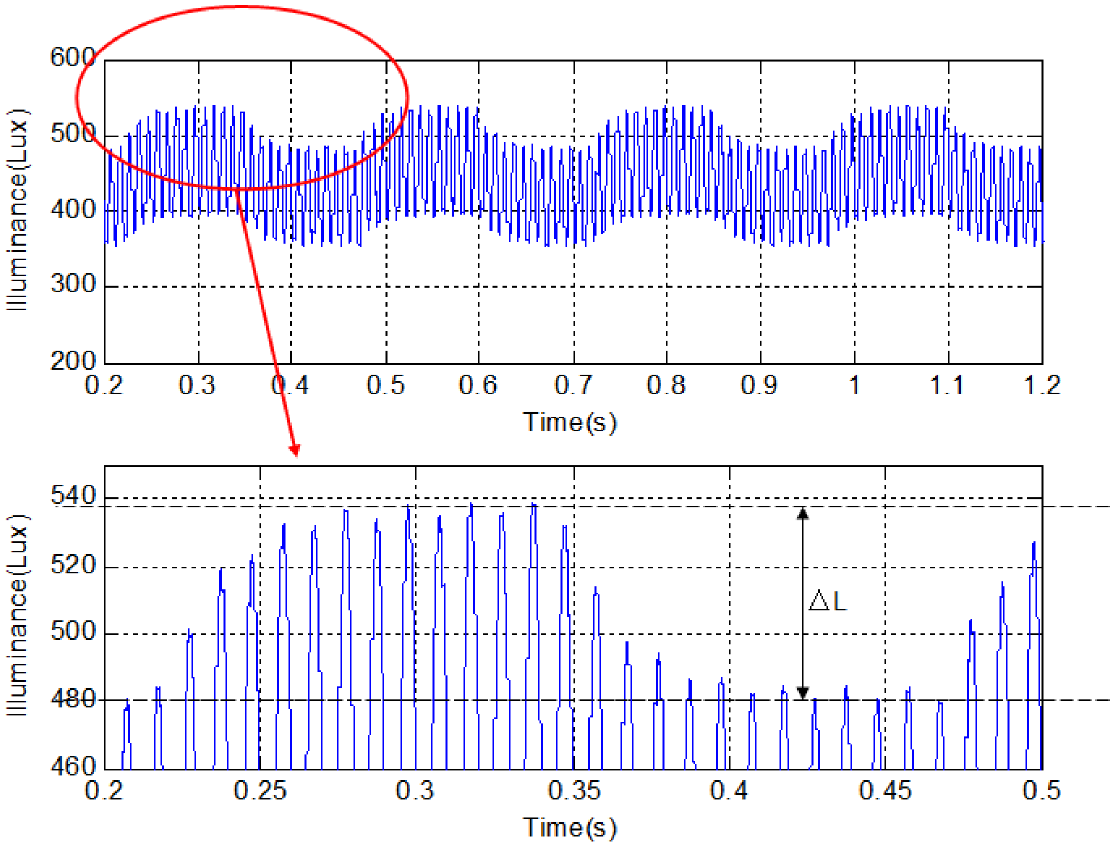

Figure B.2 The illuminance of a 60W incandescent lamp under rectangular voltage fluctuation (modulating voltage amplitude is 3% and the modulating voltage frequency is 4Hz) The figure below is the enlarged figure of a part of the waveform in the figure above

Since the illuminance is an irregular amplitude modulation waveform if the lamp is fed by a rectangular voltage fluctuation, the illuminance variation is defined in this thesis as the difference between the maximum and minimum peak instantaneous illuminance (i.e. $\triangle L$ in figure B.2). In order to compare the illuminance variation of different lamp types, the relative illuminance variation is used since the average illuminnace of different lamp types is different. The relative illuminance variation is:

$$L_r = \frac{\Delta L}{L_{av}} \cdot 100 \qquad \text{(B.1)}$$

Where: L_r is the relative illuminance variation of different lamp types

$\triangle L$ is the absolute illuminance variation of different lamp types

L_{av} is the average illuminance of different lamp types measured by a luxmeter

Analog to the analysis of sinusoidal voltage fluctuations, the per unit value of the relative illuminance variation for different lamp types is used to show the different flicker responses of the various lamp types. As mentioned in section 3.4.1, the relative illuminance variations of the incandescent lamp for different modulating voltage frequencies are selected as the base value L_b since it is used as a reference in the standard [31]. The relative illuminance variation per unit value is calculated by:

$$L_{unit} = \frac{L_r}{L_b} \tag{B.2}$$

Where: L_{unit} is the relative illuminance variation per unit value

B.2 Measurement Results

To test the lamp flicker response to rectangular voltage fluctuations, two types of measurements were made: one is the measurement using the modulating voltage amplitude of the IEC standard; another is the measurement using a constant modulating voltage amplitude. These measurement results are shown and discussed in section B.2.1 and B.2.2 respectively.

B.2.1 The standard modulating voltage amplitude

To compare the flicker response of different lamp types, a first measurement was made using the modulating voltage amplitudes of the IEC standard, which are shown in table B.1. Since the relative voltage fluctuation values are obtained from table 2 of the standard IEC61000-4-15, these modulating voltage amplitudes are called 'the standard modulating voltage amplitude'. The modulating voltage amplitudes shown in table B.1 can generate the maximum instantaneous flicker sensation of 1, i.e. $P_{inst,max} = 1$.

All 36 different modulated voltages with the corresponding modulating voltage amplitude and frequency were fed to the tested lamp by the programmable power source. The modulated voltage and the instantaneous illuminance were recorded. The relative illuminance variation of the tested lamps for each modulating voltage frequency was calculated by equation (B.1). As mentioned in section B.1, the relative illuminance variation per unit value is calculated using equation (B.2). The relationship between the relative luminance variation per unit value L_{unit} and the modulating voltage frequency for different lamp types is shown in figure B.3. The curves are smoothed by a 6^{th} order polynomial fitting method.

Table B.1 Standard rectangular modulating voltage amplitudes for the maximum instantaneous flicker sensation $P_{inst,max} = 1$

Frequency (Hz)	Voltage Fluctuation (230V lamp 50Hz system)		Frequency (Hz)	Voltage Fluctuation (230V lamp 50Hz system)	
	Relative Voltage Fluctuation ($\Delta V/V$) (%) (From standard [1])	Modulating Voltage Amplitude (ΔV) (Volts) (Calculated value)		Relative Voltage Fluctuation ($\Delta V/V$) (%) (From standard [1])	Modulating Voltage Amplitude (ΔV) (Volts) (Calculated value)
0.5	0.514	0.591	10.0	0.205	0.236
1.0	0.471	0.542	10.5	0.213	0.245
1.5	0.432	0.497	11.0	0.223	0.257
2.0	0.401	0.461	11.5	0.234	0.270
2.5	0.374	0.430	12.0	0.246	0.283
3.0	0.355	0.408	13.0	0.275	0.316
3.5	0.345	0.397	14.0	0.308	0.354
4.0	0.333	0.383	15.0	0.344	0.397
4.5	0.316	0.363	16.0	0.376	0.432
5.0	0.293	0.337	17.0	0.413	0.475
5.5	0.269	0.309	18.0	0.452	0.520
6.0	0.249	0.286	19.0	0.498	0.573
6.5	0.231	0.266	20.0	0.546	0.628
7.0	0.217	0.250	21.0	0.586	0.674
7.5	0.207	0.238	22.0	0.604	0.695
8.0	0.201	0.231	23.0	0.680	0.782
8.8	0.199	0.229	24.0	0.743	0.855
9.5	0.200	0.230	33.33	1.67	1.921

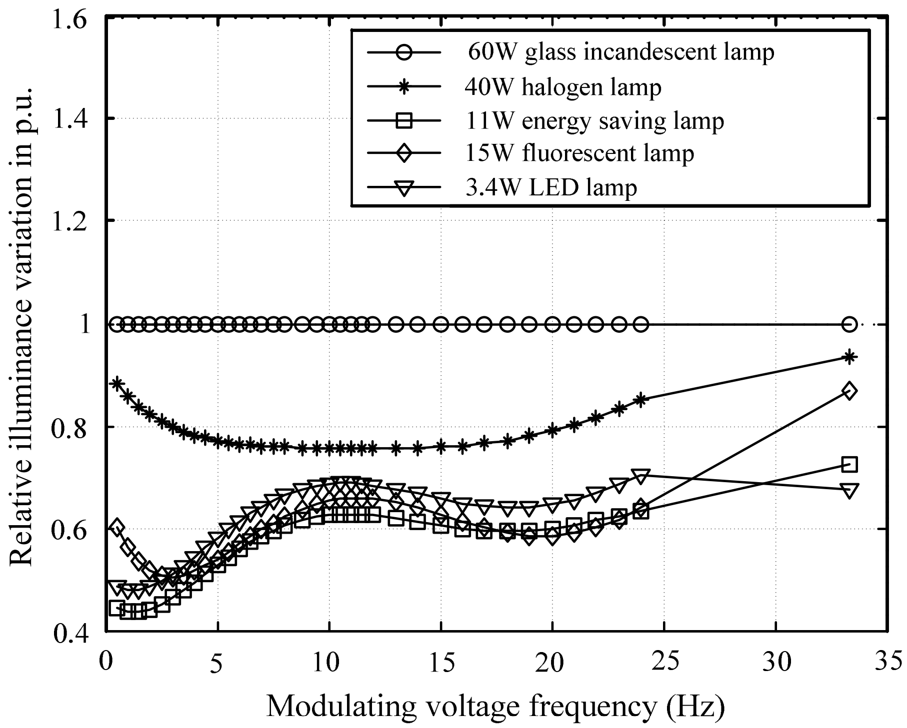

Figure B.3 The flicker response of different lamp types to rectangular voltage fluctuations (with modulating voltage amplitude for $P_{inst,max}=1$)

Since the relative illuminance variation of the incandescent lamp is selected as the base value to calculate the relative illuminance variation per unit value, the per unit values of the incandescent lamp are always equal to one for each modulating voltage frequency. As mentioned earlier, the relative illuminance variation represents the lamp flicker response to the rectangular voltage fluctuation. A lamp is more sensitive to the flicker if the relative illuminance variation per unit value is higher. Thus, it can be concluded from figure B.3 that the incandescent lamp is most sensitive to rectangular voltage fluctuations. Figure B.3 also shows that the halogen lamp is more sensitive to rectangular voltage fluctuations than other lamp types. The energy saving lamp is the most insensitive to rectangular voltage fluctuations. This is due to the fact that the electronic ballast in the energy saving lamp can help to maintain the lamp tube voltage under flicker conditions. These conclusions are similar to those drawn from the lamp flicker response to sinusoidal voltage fluctuations.

B.2.2 Constant modulating voltage amplitude

The second type of measurements was carried out using a constant rectangular modulating voltage amplitude with various modulating voltage frequencies (totally 36 frequencies). This is a similar measurement as the one described in section 3.4.2.4. For all tested lamps, modulating voltage amplitudes of 1%, 2% and 3% (based on 230V) were examined. The modulated voltage and the instantaneous illuminance were recorded in the measurements. The relative illuminance variations of each tested lamp are calculated using equation (B.1). The results of the relative illuminance variations versus the modulating voltage frequencies for different types of lamps are shown in figure B.4 – B.8.

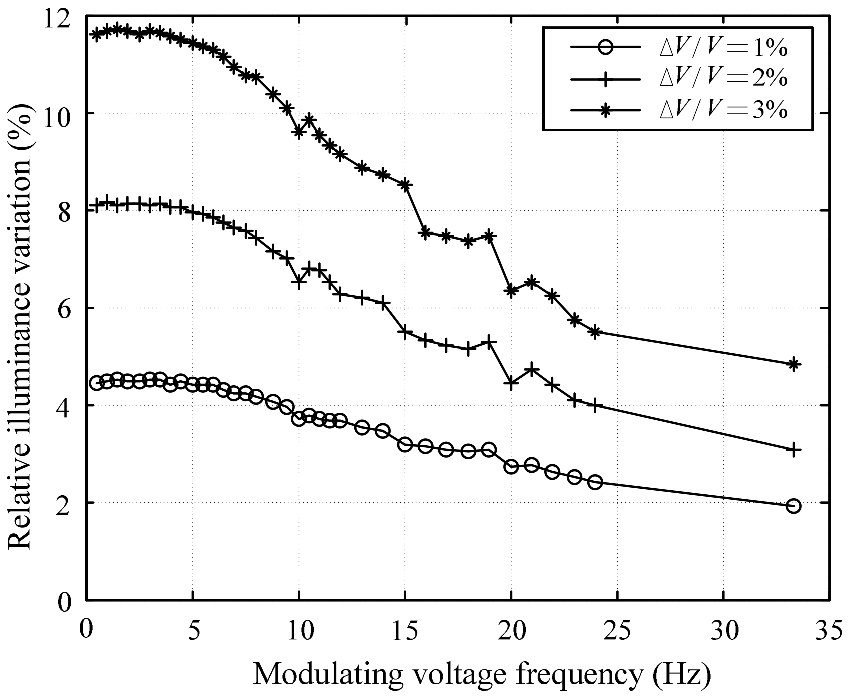

Figure B.4 Relative illuminance variation of a 60W glass incandescent lamp versus the modulating voltage frequency

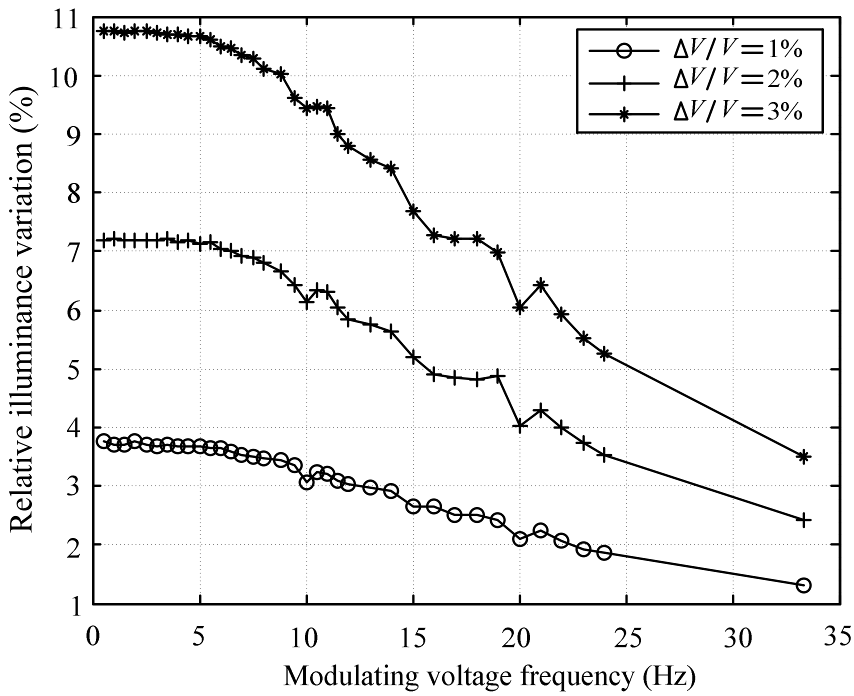

Figure B.5 Relative illuminance variation of a 40W halogen lamp versus the modulating voltage frequency

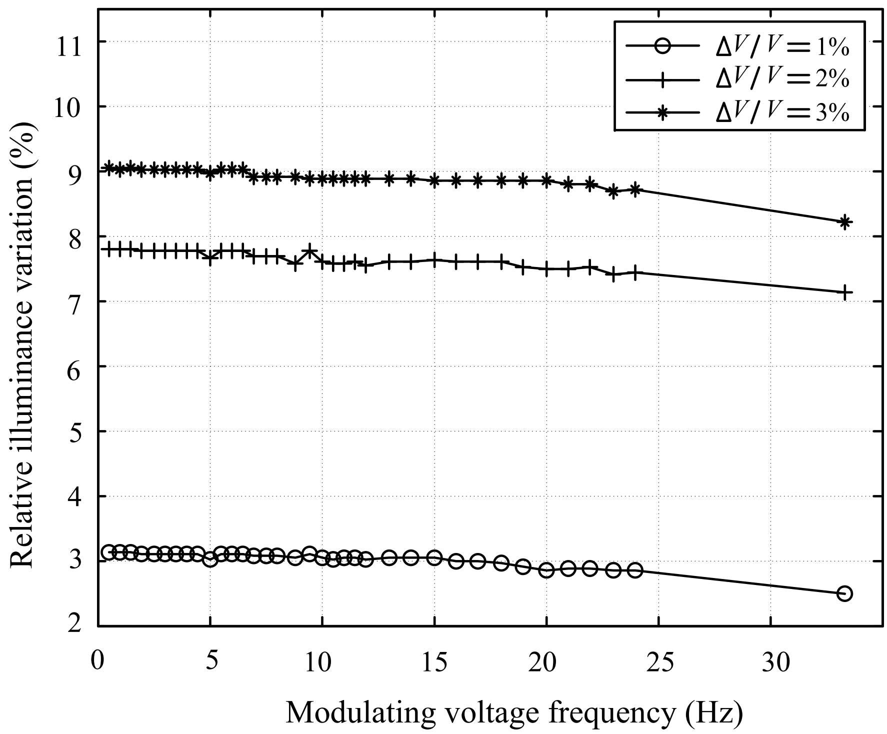

Figure B.6 Relative illuminance variation of a 15W fluorescent lamp versus the modulating voltage frequency

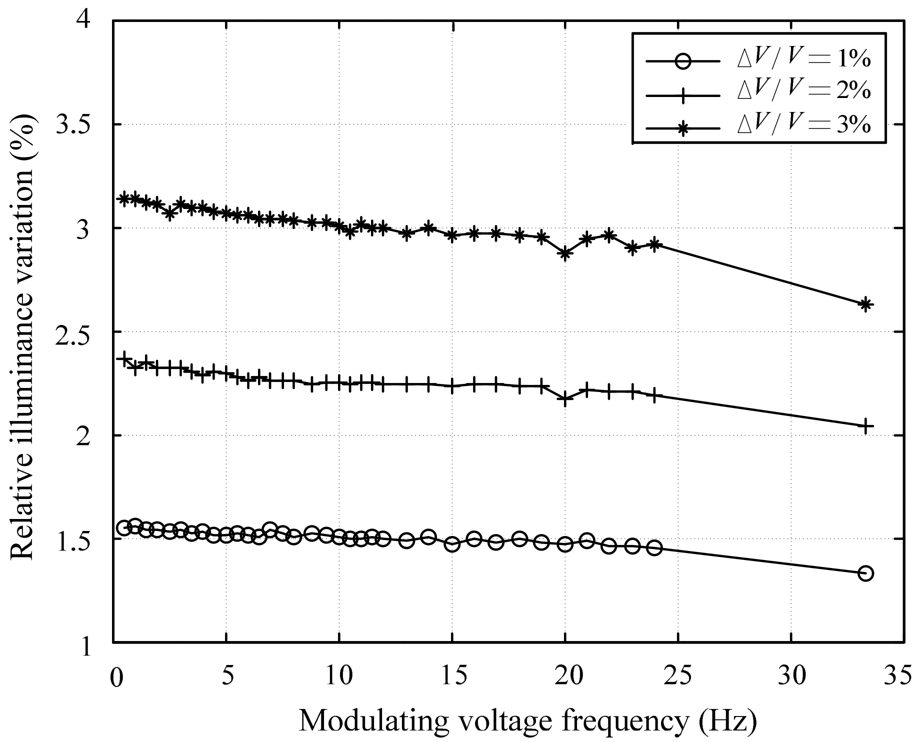

Figure B.7 Relative illuminance variation of a 11W energy saving lamp versus the modulating voltage frequency

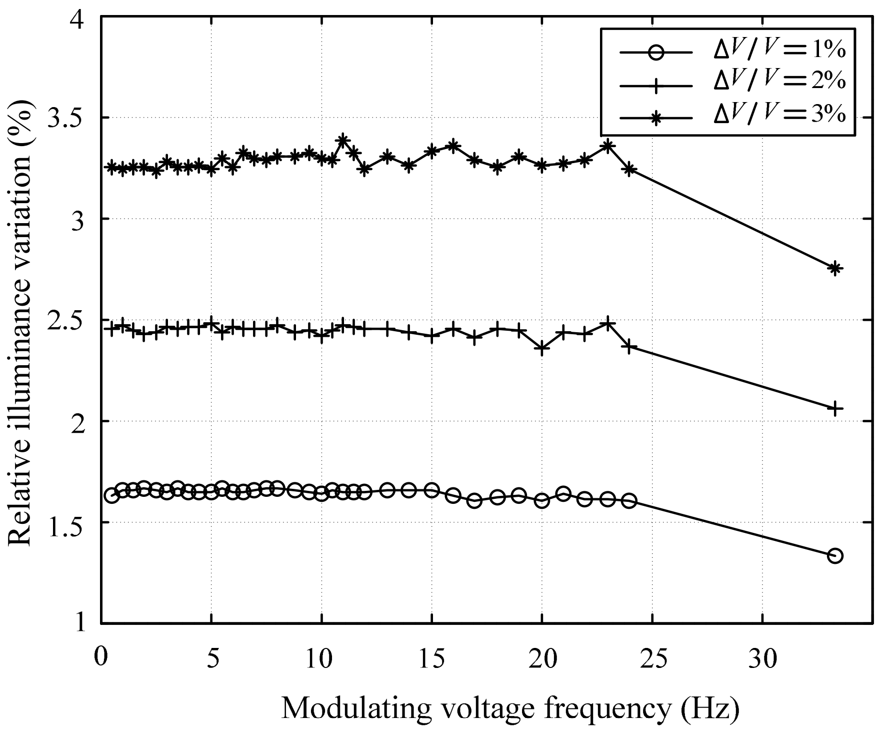

Figure B.8 Relative illuminance variation of a 3.4W LED lamp versus the modulating voltage frequency

Some relative illuminance variation curves shown in figure B.4 – B.8 are not exactly smooth. This is caused by the same reason as mentioned in section 3.4.2.4 (inaccuracies and disturbances during the measurement). The deviations are within a range of $\pm 5\%$. Such deviation is accepted in this thesis since the same deviation range is used in standard IEC 61000-4-15.

The curves in figure B.4 - B.8 show that the relative illuminance variation of all tested lamp types decreases with increasing modulating voltage frequency. Furthermore, the relative illuminance variation of all lamp types increases with the modulating voltage amplitude for the same modulating voltage frequency. The same conclusions have also been drawn from the lamp flicker response to sinusoidal voltage fluctuations. The relative illuminance variation of the tested lamp types does not vary proportional to the corresponding modulating voltage amplitude of the rectangular voltage fluctuation. The relative illuminance variation of the energy saving lamp increases for instance 1.49 times when the corresponding modulating voltage increases 2 times. The relative illuminance variations were proportional to the corresponding modulating voltage amplitudes for sinusoidal voltage fluctuations.

Appendix C

Human Being Flicker Response

C.1 Introduction

The short-term flicker indicator P_{st} equal to one is used as one of the important requirements for the design of an electricity network. The meaning of $P_{st} = 1$ is that 50% of the people who are exposed to the related voltage fluctuation will not feel flicker. The current weighting filter of the UIE/IEC flickermeter is based on the measurements of De Lange [29]. However his data seem to be based on only two test persons. To obtain more knowledge about the human being flicker response, e.g. the effect of different ages and different genders, own experiments have been set-up. The measurements were made in the PQ lab of TU/e and the results are presented in section C.2.

For simplicity, the assumption that the human being has the same flicker feeling for the same illuminance variation of different lamp types is made in this thesis. This is not obvious since different lamp types have a different spectral output. To verify this assumption human being flicker response measurements have been made for the incandescent lamp and the energy saving lamp. These measurement results are presented in section C.3.

C.2 Human Being Flicker Response with the Incandescent Lamp

Eleven observers, called A – K respectively, were selected in this experiment with different age and gender. The detailed information about the observers is shown in table C.1.

Table C.1 The age and gender information of the observers

Age	20 - 29		30 - 39		> 40	
Gender	Male	Female	Male	Female	Male	Female
Number of observers	3	2	2	2	1	1

To simulate the flicker effect as good as possible, the observers were sitting inside a small dark room (approximately 2.5 m^2). The only light source was a 60W incandescent lamp, which was fed with the sinusoidal voltage fluctuation via the programmable power source. The incandescent lamp was put towards one wall, where the observer looked at. The distance between the lamp and the wall is 1.5 meters, which is the same distance between the observer and the wall. In total 37 modulating voltage frequencies were tested. The measurements were made following the next steps:

1. A voltage fluctuation with the modulating frequency and the corresponding modulating voltage amplitude (i.e. the voltage fluctuation where $P_{inst,max}$ reaches one), obtained from the table 1 of IEC 61000-4-15, was supplied to the lamp in the test room by the programmable source. The voltage fluctuation was kept for 15 seconds.
2. If the observer can see the flicker, the modulating voltage amplitude and frequency were recorded.
3. The step 1 was repeated with another modulating voltage frequency.
4. If the observer can not see the flicker, the modulating voltage amplitude was increased with a 0.1V step until the observer can see the flicker.

The measurement results of the eleven observers are presented in the next sub-sections.

C.2.1 Flicker responses of different people

The modulating voltage amplitudes that lead to the flicker feeling of the observer are plotted against the modulating voltage frequency for each observer. The results are presented in figure C.1. The modulating voltage amplitude shown is the percentage value calculated on a 230V base. The modulating voltage amplitudes, which can cause one unit of the maximum instantaneous flicker sensation (i.e. $P_{inst,max} = 1$) are also given in figure C.1. As mentioned in section 2.4.4, the ratio between the short-term flicker indicator and the maximum instantaneous flicker sensation is approximately 0.68. It is assumed that the ratio between P_{st} and $P_{inst,max}$ is the same as the ratio between the corresponding for modulating voltage amplitudes. In this way, the modulating voltage amplitudes, which can cause the one unit of P_{st}, are calculated and presented in figure C.1.

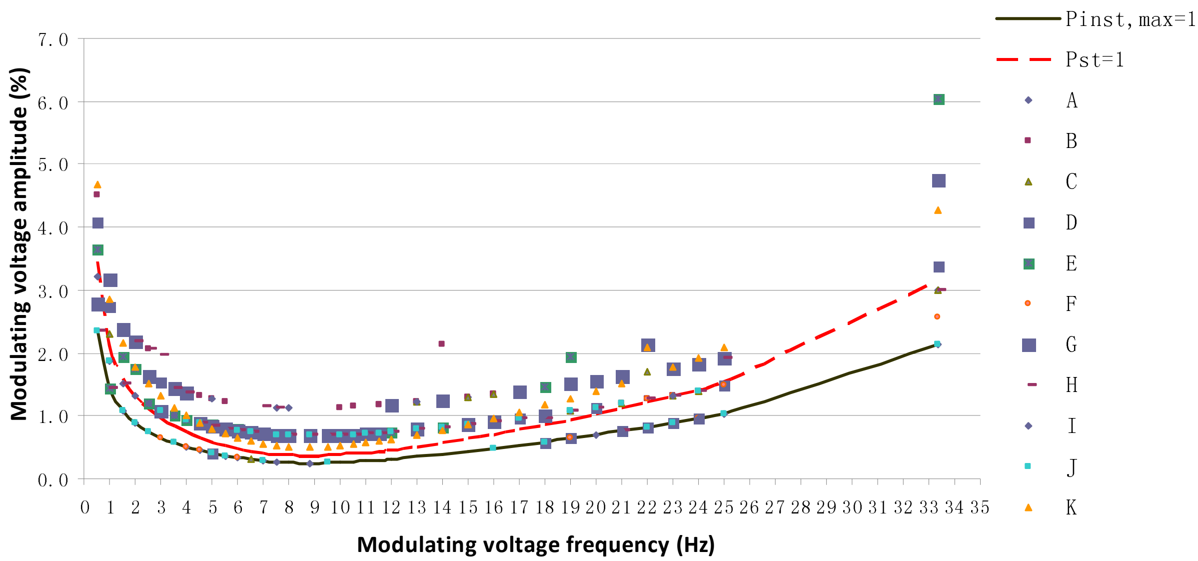

Figure C.1 The modulating voltage amplitude values seen by different observers

Figure C.1 shows that all observers are the most sensitive to the modulating voltage frequency of 8.8Hz, as stated in the standard IEC 61000-4-15. None of the observers can see all flickers within the whole tested modulating voltage frequency range (0.5Hz – 33.33Hz) when the modulating voltage amplitudes for one unit of P_{st} were supplied to the lamp. For some specific modulating voltage frequencies, the observers F, J and I can see the flicker with a modulating voltage amplitude that is even lower than the one which can cause one unit of P_{st}.

The average modulating voltage amplitude of all observers has been calculated. The plot of the average modulating voltage amplitude versus the modulating voltage frequency is shown in figure C.2. The plots in figure C.2 show that all observers are the most sensitive to the modulating voltage frequency of 7Hz, 8.8Hz and 9.5Hz. The difference in the modulating voltage amplitude between the average value of the observers and the value of one unit of P_{st} is smaller (less than 0.2%) for the lower frequencies (e.g. 0.5Hz – 1.5Hz) and the higher frequencies (e.g. 20Hz – 25Hz). And, these differences are bigger (bigger than 0.3%) for other tested modulating voltage frequencies.

As a general conclusion it can be stated that the results of our observers are rather consistent with the voltage fluctuation values which are used in the current standard.

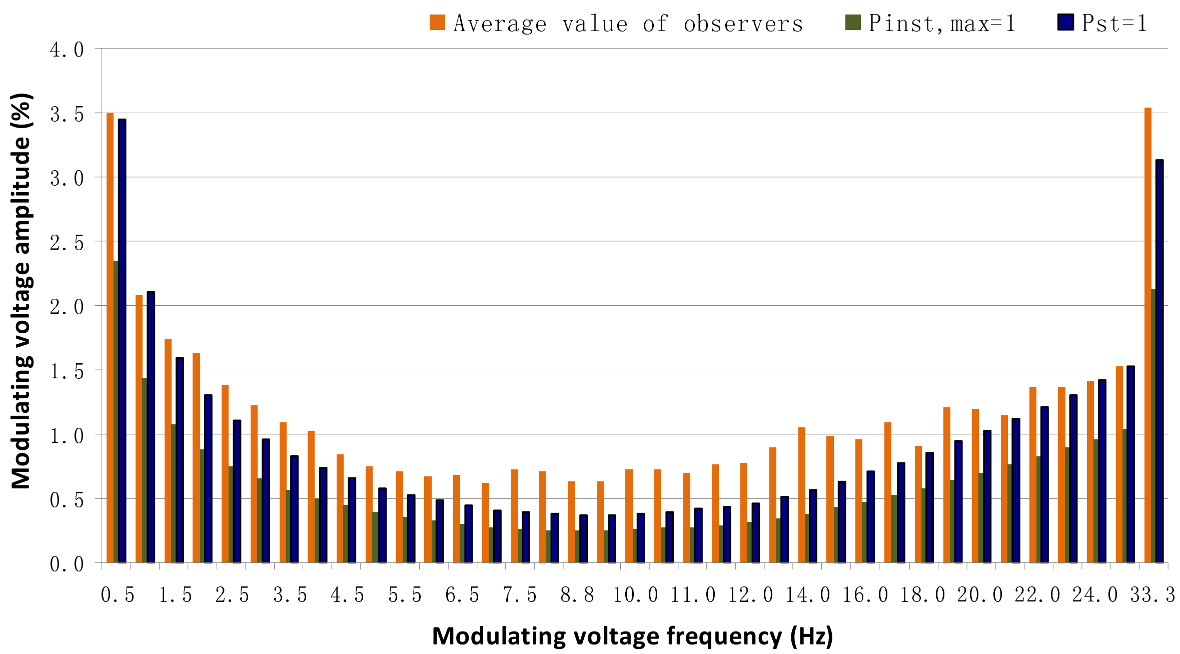

Figure C.2 The average modulating voltage amplitude seen by all tested observers

C.2.2 Human being flicker response of different ages

To study the human being flicker response difference between ages, the observers are separated in three age groups: the 20 – 29 group, the 30 – 39 group and the older than 40 group. The average modulating voltage amplitudes have been calculated for each age group. The average modulating voltage amplitudes of the three age groups versus the modulating voltage frequency are plotted in figure C.3. It can be concluded from figure C.3 that the age group of 30 – 39 is the least sensitive to flicker. The observers who are older than 40 years are the most sensitive to the flicker.

C.2.3 Human being flicker response of different genders

The human being flicker responses have also been compared between different genders. The average modulating voltage amplitudes have been calculated using the values of the male observers and the female observers respectively. The average modulating voltage amplitudes versus the modulating voltage frequency are presented in figure C.4. The plot shows that the female observers are more sensitive to the flicker if the modulating voltage frequency is lower than 18Hz. However, the male observers become more sensitive to flicker if the modulating voltage frequency is higher than 18Hz.

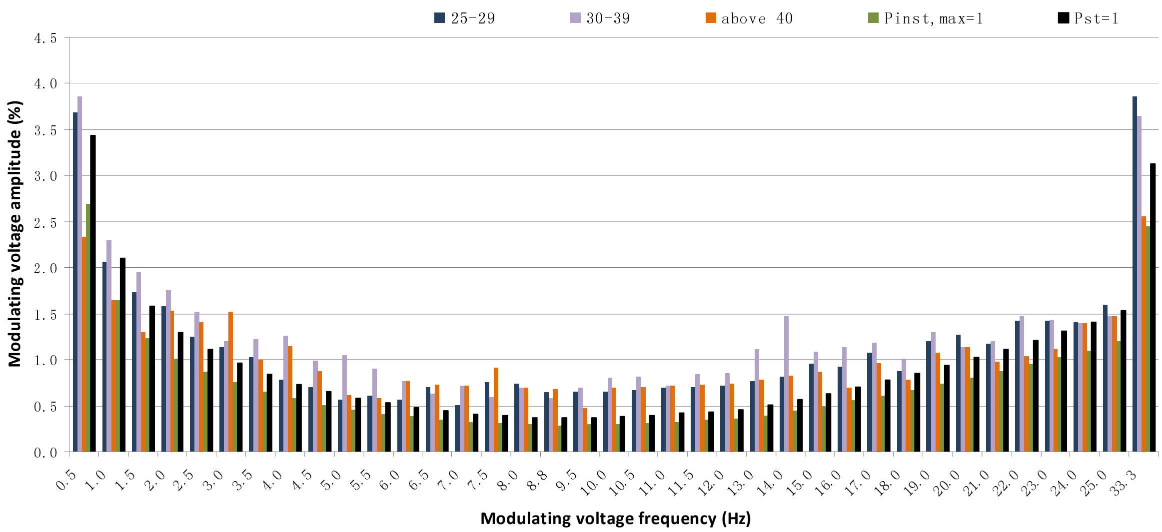

Figure C.3 The average modulating voltage amplitudes of different age groups

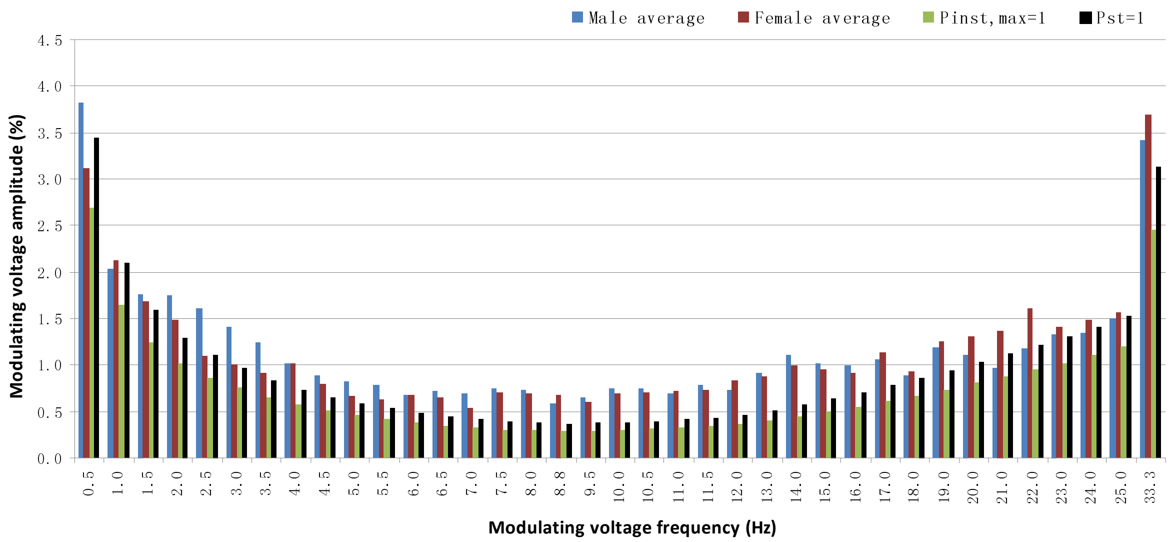

Figure C.4 The average modulating voltage amplitudes of different genders

C.3 Human Being Flicker Response for Different Lamp Types

In order to test if the human being has the same flicker feeling when the relative illuminance variation generated by different lamp types is the same, ten observers were selected for such a measurement. This measurement was made for both a 60W incandescent lamp and a 11W energy saving lamp. The measurement environment and methods are the same as for the experiments described in section C.2. For each observer, the relative illuminance variation value was recorded for different modulating voltage frequencies (0.5Hz – 25Hz) when the observer feels flicker. The average relative illuminance variation value of these ten observers was calculated for the different modulating voltage frequencies. The results are shown in figure C.5.

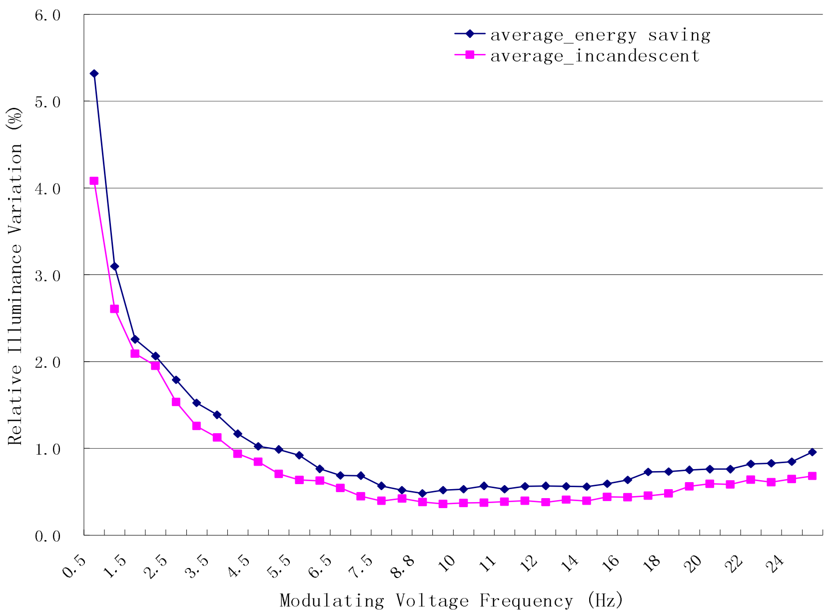

Figure C.5 The average relative illuminance variation of the incandescent and the energy saving lamp for different modulating voltage frequencies when the observer feels flicker

The curves in figure C.5 did not show exactly the same flicker feeling for the same illuminance variation of the incandescent lamp and the energy saving lamp. The tested person feels flicker when the relative illuminance variation of the energy saving lamp is higher than the incandescent lamp. However, the results show that there is not a big difference of relative illuminance variation between the incandescent lamp and the energy saving lamp when the tested person feels flicker from these two lamp types. The highest difference of the illuminance variation between the incandescent lamp and the energy saving lamp is 1.23% at 0.5Hz. The average difference of the illuminance variation between the two lamp types is 0.2295%. Normally the difference is smaller than 0.3%.

Since the difference of the relative illuminance variation between the incandescent lamp and the energy saving lamp is quite small for all observers, it can be concluded that no obvious difference in the relative illuminance variation between the incandescent lamp and the energy saving lamp exists when the observers feel flicker from these two lamp types. In other words, the observers have the similar flicker feeling for the same illuminance variation of the incandescent lamp and the energy saving lamp. These results confirm the validity of the assumption in this thesis that the eye-brain response is the same for different lamp types.

Appendix D

Additional Simulation Results of the Improved Flickermeter Model

Section 4.4.2 presents the simulation results of the improved flickermeter model for the energy saving lamp. In this appendix, the simulation results of the improved flickermeter model for other lamp types (halogen lamp, fluorescent lamp and LED lamp) are presented.

As mentioned in section 4.4.2, the assumption, that a human being has the same flicker feeling for different lamp types if the relative illuminance variation of these lamp types is the same, is used in the research presented in this thesis. By using this assumption, the modulating voltage amplitude values of different lamp types, which can cause the maximum instantaneous flicker sensation of one, can be obtained from the measurements made in the PQ lab of TU/e. These values are presented in column 2 of table D.1 – D.3. The expected maximum instantaneous flicker sensation should be 1. The simulation results of the improved flickermeter model for the other lamp types are presented in the column 3 of table D.1 – D.3. The errors between the simulation and the expected maximum instantaneous flicker sensation are shown in the column 4 of table D.1 – D.3.

Table D.1 Performance test results of the halogen lamp flickermeter model

Modulating Voltage Frequency (Hz)	Relative Voltage Fluctuation (%)	$P_{inst,max}$	Error (%)
0.5	2.57	1.0172	1.72
1.0	1.58	1.0235	2.35
1.5	1.22	0.9823	-1.77
2.0	1.09	0.9654	-3.46
2.5	1.04	0.9927	-0.73
3.0	1.00	0.9736	-2.64
3.5	0.93	0.9875	-1.25
4.0	0.68	0.9829	-1.71
4.5	0.59	0.9754	-2.46
5.0	0.61	0.9731	-2.69
5.5	0.51	0.9815	-1.85
6.0	0.49	0.971	-2.90
6.5	0.44	0.9651	-3.49
7.0	0.43	0.9682	-3.18
7.5	0.41	0.9753	-2.47
8.0	0.42	0.9635	-3.65
8.8	0.42	0.9518	-4.82
9.5	0.46	0.9529	-4.71
10.0	0.48	0.9723	-2.77
10.5	0.48	0.9841	-1.59
11.0	0.48	0.9926	-0.74
11.5	0.53	0.9848	-1.52
12.0	0.68	0.9614	-3.86
13.0	0.68	0.9788	-2.12
14.0	0.72	0.9632	-3.68
15.0	0.95	0.9813	-1.87
16.0	1.08	0.9624	-3.76
17.0	1.07	0.9756	-2.44
18.0	1.28	0.9621	-3.79
19.0	1.23	0.9538	-4.62
20.0	1.46	0.9611	-3.89
21.0	1.47	0.9523	-4.77
22.0	1.58	0.9642	-3.58
23.0	1.63	0.9675	-3.25
24.0	1.78	0.9519	-4.81
25.0	1.92	0.9629	-3.71

TableD.2 Performance test results of the fluorescent lamp flickermeter model

Modulating Voltage Frequency (Hz)	Relative Voltage Fluctuation (%)	$P_{inst,max}$	Error (%)
0.5	10.09	1.0372	3.72
1.0	5.83	1.0133	1.33
1.5	4.52	0.9985	-0.15
2.0	3.57	0.9701	-2.99
2.5	3.22	0.9835	-1.65
3.0	2.78	0.9783	-2.17
3.5	2.17	0.9872	-1.28
4.0	2.09	0.9945	-0.55
4.5	1.74	0.9931	-0.69
5.0	1.30	0.9826	-1.74
5.5	1.22	0.9715	-2.85
6.0	1.13	0.9974	-0.26
6.5	1.04	0.9725	-2.75
7.0	0.85	0.9838	-1.62
7.5	0.83	0.9621	-3.79
8.0	0.81	0.9843	-1.57
8.8	0.79	1.0152	1.52
9.5	0.80	0.9737	-2.63
10.0	0.87	0.9839	-1.61
10.5	0.96	0.9621	-3.79
11.0	1.04	0.9532	-4.68
11.5	1.04	0.9578	-4.22
12.0	1.04	0.9573	-4.27
13.0	1.13	0.9763	-2.37
14.0	1.13	0.9503	-4.97
15.0	1.22	0.9608	-3.92
16.0	1.30	0.968	-3.2
17.0	1.48	0.9623	-3.77
18.0	1.57	0.9853	-1.47
19.0	1.57	0.9831	-1.69
20.0	1.65	0.9816	-1.84
21.0	1.65	0.9824	-1.76
22.0	1.65	0.9857	-1.43
23.0	1.72	0.9539	-4.61
24.0	1.73	0.9927	-0.73
25.0	1.89	0.9837	-1.63

Table D.3 Performance test results of the LED lamp flickermeter model

Modulating Voltage Frequency (Hz)	Relative Voltage Fluctuation (%)	$P_{inst,max}$	Error (%)
0.5	14.36	1.0378	3.78
1.0	8.27	1.0126	1.26
1.5	6.03	0.9873	-1.27
2.0	5.04	0.9946	-0.54
2.5	4.37	0.9742	-2.58
3.0	3.90	0.9768	-2.32
3.5	3.42	0.9831	-1.69
4.0	2.92	0.9721	-2.79
4.5	2.31	0.9635	-3.65
5.0	2.35	0.9617	-3.83
5.5	1.85	0.9744	-2.56
6.0	1.76	0.9615	-3.85
6.5	1.38	0.9523	-4.77
7.0	1.36	0.9612	-3.88
7.5	1.35	0.9525	-4.75
8.0	1.33	0.9519	-4.81
8.8	1.23	0.9502	-4.98
9.5	1.57	0.9583	-4.17
10.0	1.66	0.9619	-3.81
10.5	1.67	0.9724	-2.76
11.0	1.67	0.9739	-2.61
11.5	1.69	0.9628	-3.72
12.0	1.85	0.9582	-4.18
13.0	1.85	0.9726	-2.74
14.0	1.88	0.9815	-1.85
15.0	2.35	0.9772	-2.28
16.0	2.96	0.9658	-3.42
17.0	2.97	0.9711	-2.89
18.0	3.64	0.963	-3.7
19.0	3.96	0.9716	-2.84
20.0	4.82	0.9512	-4.88
21.0	5.79	0.9589	-4.11
22.0	6.11	0.9513	-4.87
23.0	6.44	0.9647	-3.53
24.0	7.19	0.9534	-4.66
25.0	8.01	0.9521	-4.79

Appendix E

The Characteristics Plots of the Derived Lamp Flicker Response Models

Flicker response identification models for five different lamps have been presented in section 4.2. To show more characteristics of these models, the plots of the correlation functions, the zero-poles and the frequency response of the models are shown in this appendix (see figure E.1 – E.12). The plots of the incandescent lamp flicker response identification model are presented in section 4.2.

Figure E.1, E.4, E.7 and E.10 show the correlation functions of the different lamp type flicker response identification models, which are the OE models described in section 4.2. For all figures, the cross correlation of the model input and the model output residues lies within the confidence region. This indicates that the output residues are independent of the model input. Therefore, these models can be applied for other inputs. The autocorrelation of the residues for the model output shown in all figures is more or less slightly out of the confidence region. This indicates that the derived identification model can be improved by using a higher order. But, the autocorrelation of the residues for the model output does not significantly affect the performance of the identification model in an open-loop system, as which the lamp flicker response identification model presents. By balancing the fitting rate and the autocorrelation functions, these identification models are accepted in this thesis. The residues of these models are not caused by the measurement noise since the estimation and validation data of the model are rebuilt data without measurement noise. As for the incandescent lamp flicker response model, these residues are generated by the model error.

The zero-pole plots of the identification models for different lamp types are shown in figure E.2, E.5, E.8 and E.11. As can be seen in the figures, all poles of the lamp flicker response identification models are located inside the unit circle. Therefore, these models are stable. For the identification model of the halogen lamp and the LED lamp, there are two zero-points on the unit circle. This can be accepted in a discrete-time system. These zero-points will not affect the stability of the models.

Figure E.3, E.6, E.9 and E.12 show the frequency response of the identification models. It should be noted that the models are developed for a frequency range up to 25Hz. Furthermore, as mentioned for the incandescent identification model in section 4.2, the phase response is not of concern in this thesis because the lamp flicker response identification model only focuses on the amplitude response.

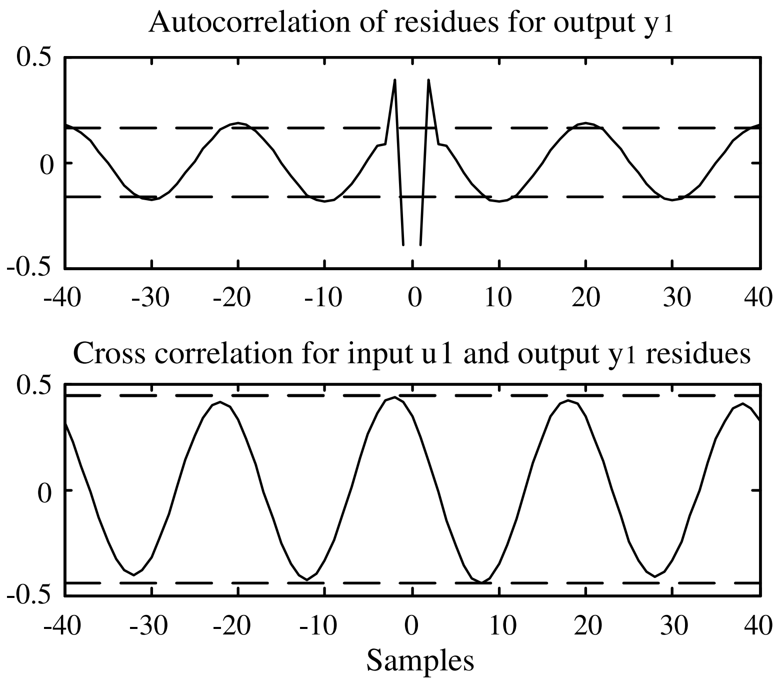

Figure E.1 The residual analysis of the5th order fluorescent lamp flicker response identification model for the 10Hz voltage modulating frequency. The solid line is the correlation function; the dashed line is the 99.9% confidence interval

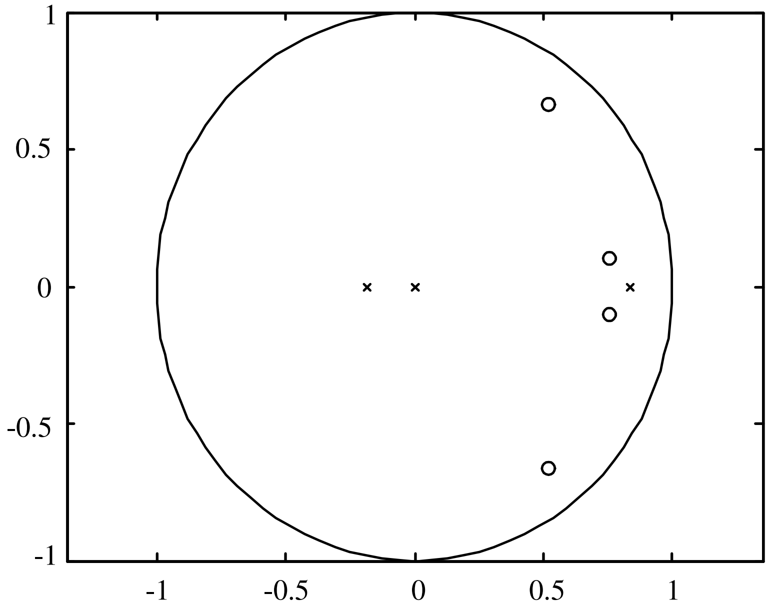

Figure E.2 The zero-pole plot of the 5^{th} order fluorescent lamp flicker response identification model

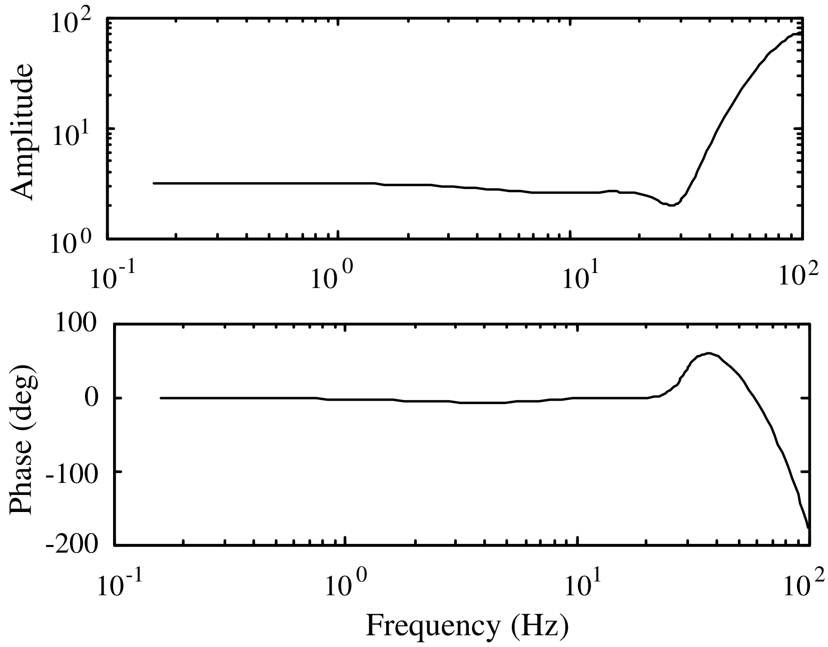

Figure E.3 The frequency response of the 5^{th} order fluorescent lamp flicker response identification model

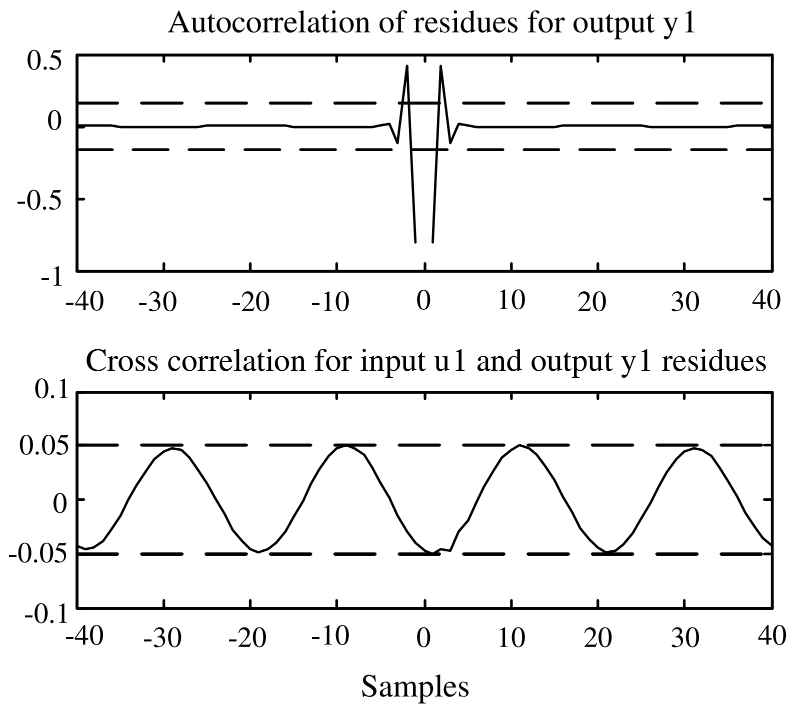

Figure E.4 The residual analysis of the 6th order energy saving lamp flicker response identification model for the 10Hz voltage modulating frequency. The solid line is the correlation functions; the dashed line is the 99.9% confidence interval

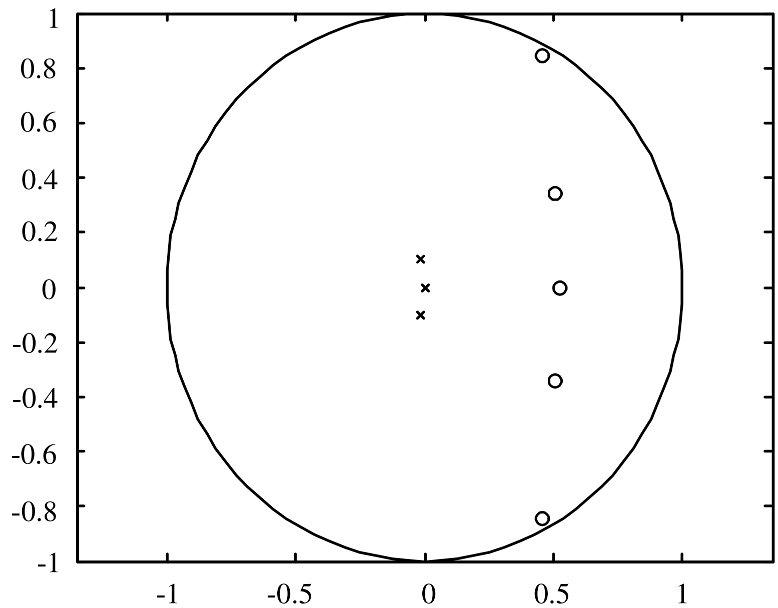

Figure E.5 The zero-pole plot of the 6th order energy saving lamp flicker response identification model. Poles: x*; zeros:* o

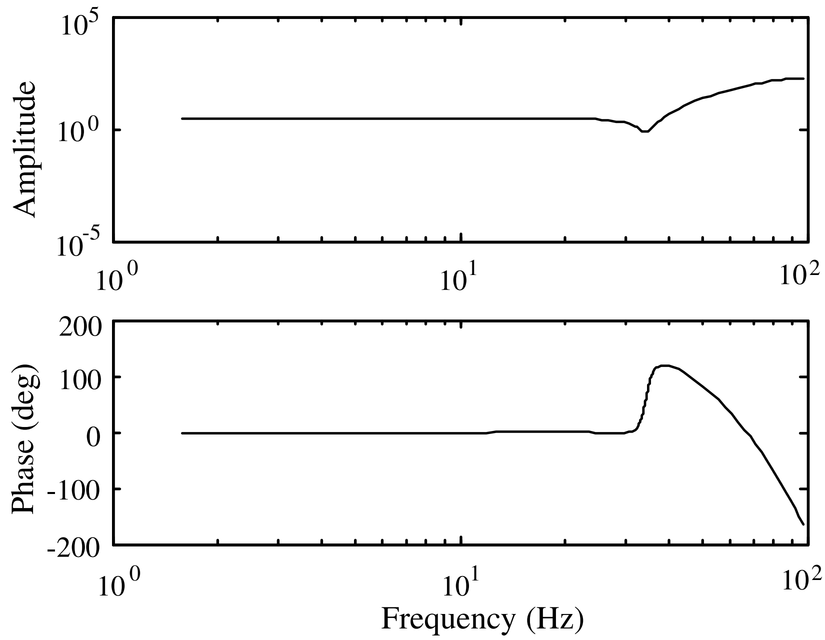

Figure E.6 The frequency response of the 6th order energy saving lamp flicker response identification model

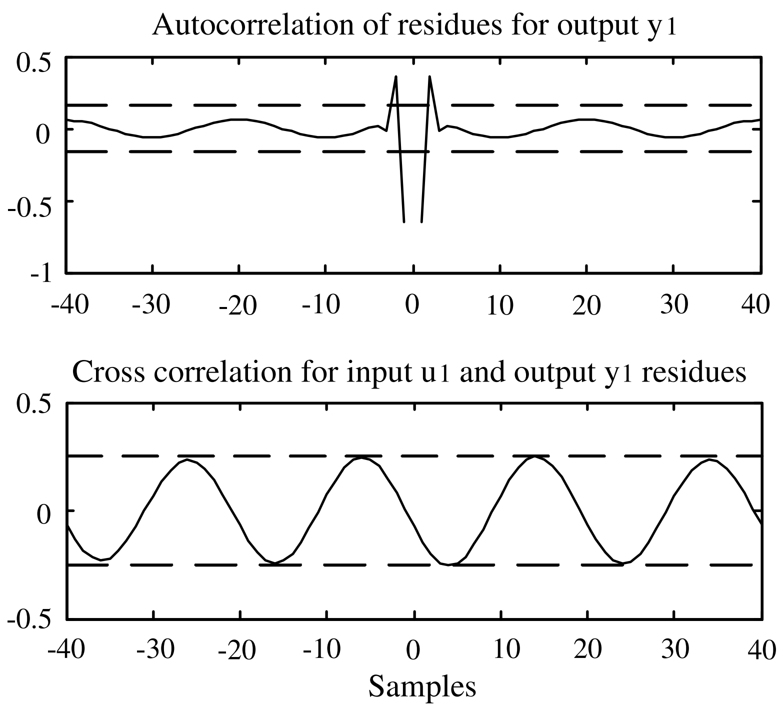

Figure E.7 The residual analysis of the 6th order halogen lamp flicker response identification model for the 10Hz voltage modulating frequency. The solid line is the correlation function; the dashed line is the 99.9% confidence interval

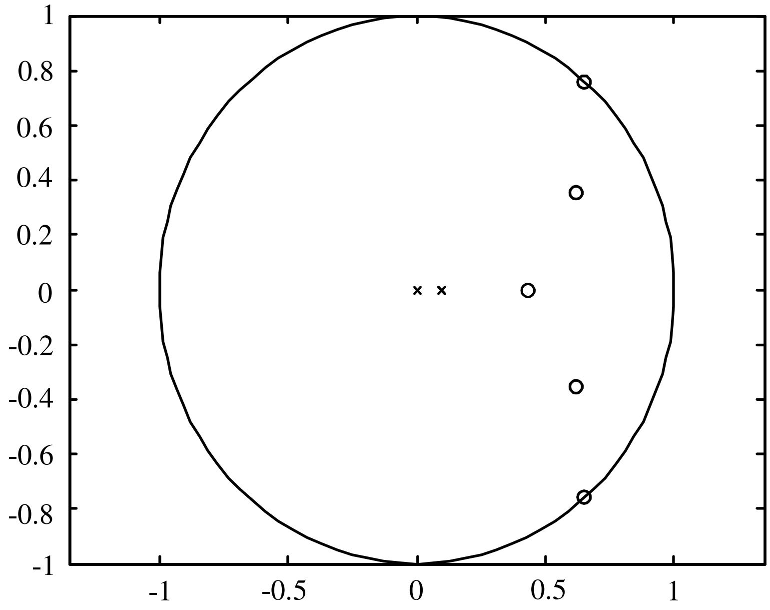

Figure E.8 The zero-pole plot of the 6th order halogen lamp flicker response identification model. Poles: x*; zeros:* o

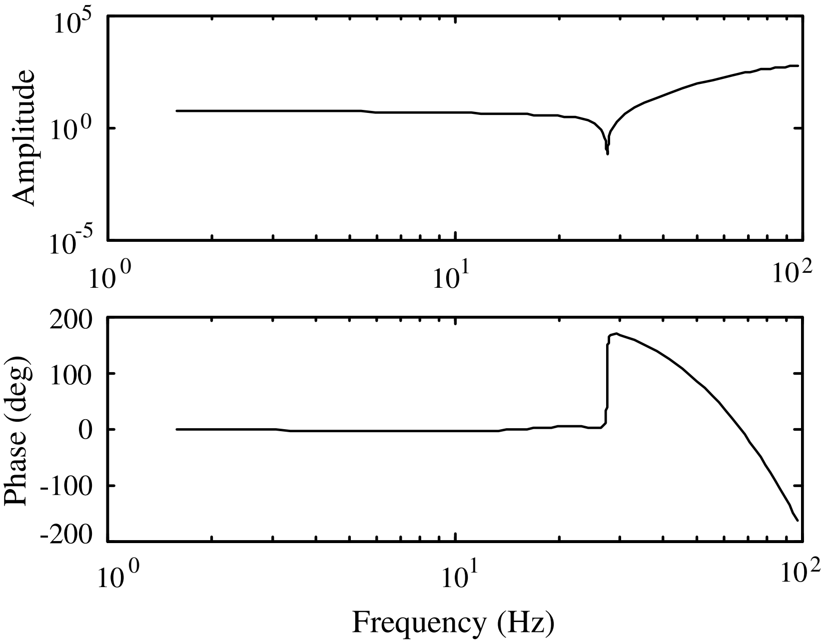

Figure E.9 The frequency response of the 6th order halogen lamp flicker response identification model

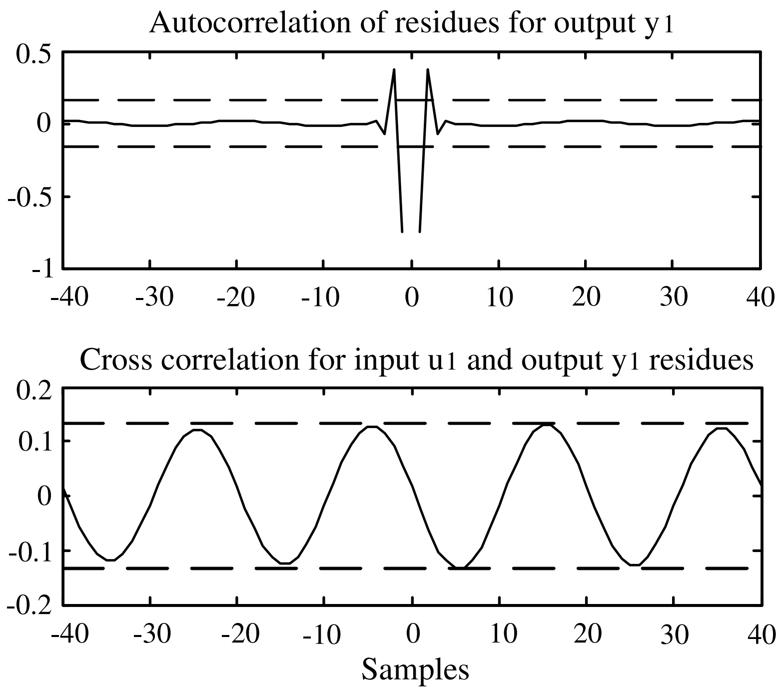

Figure E.10 The residual analysis of the 6th order LED lamp flicker response identification model for the 10Hz voltage modulating frequency. The solid line is the correlation function; the dashed line is the 99.9% confidence interval

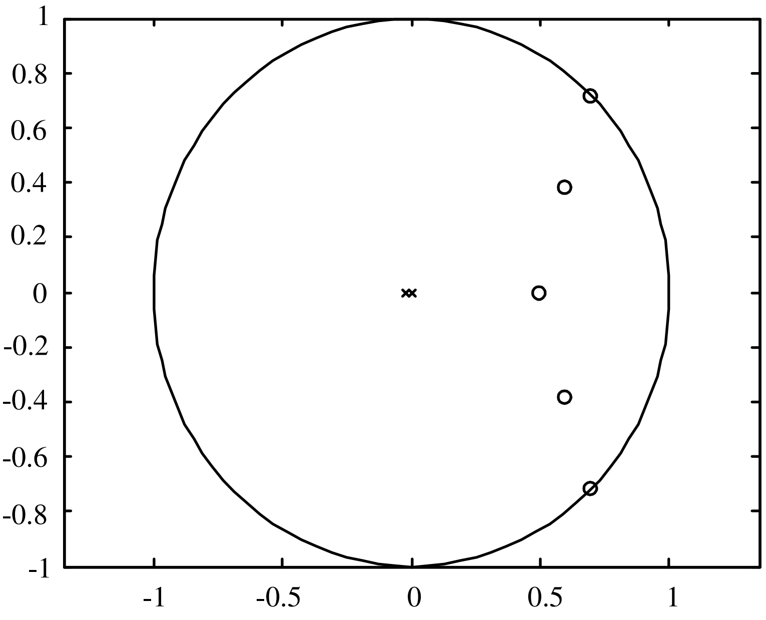

Figure E.11 The zero-pole plot of the 6th order LED lamp flicker response identification model. Poles: x; *zeros*: o

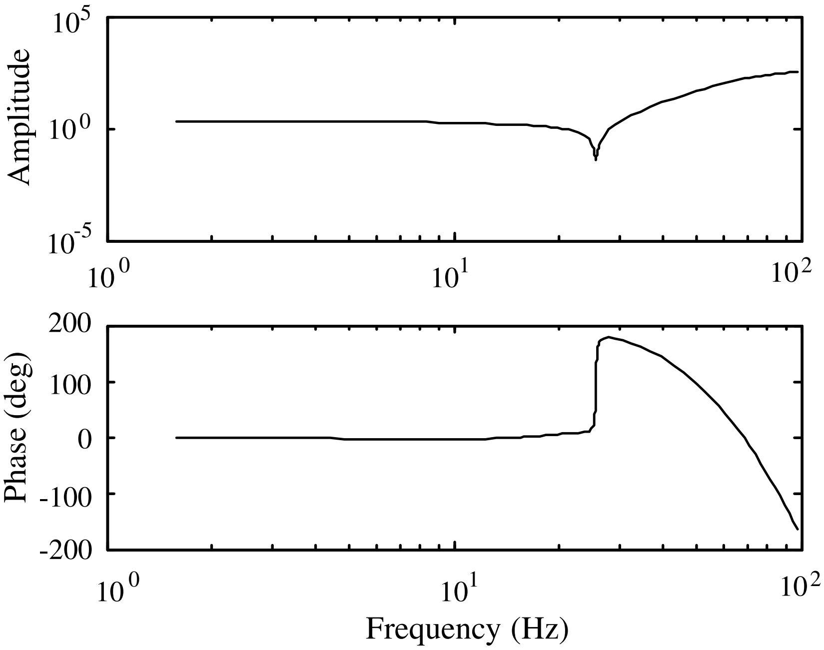

Figure E.12 The frequency response of the 6th order LED lamp flicker response identification model

Appendix F

Measurement Instruments

The pictures of the measurement equipment and instruments mentioned in this thesis are presented in this appendix. Due to the limitation of the digital camera, the complete measurement set-up cannot be captured by the camera. The schemes of these set-ups are shown in figure 3.1, 5.1 and 6.7.

The accuracies of the apparatus are:

Power source (MX45-3Pi):	0.1V
Current probe (Fluke 80i-110s):	±3% (100mV/A setting)
Voltage probe (TT-SI9002):	±2%
Handyscope (HS3):	0.3%±1LSB (Least Significant Bit)
Luxmeter (Hagner E4-x):	±3%
Spectrometer (HR2000+):	75photons/count at 400nm and 41photons/count at 600nm

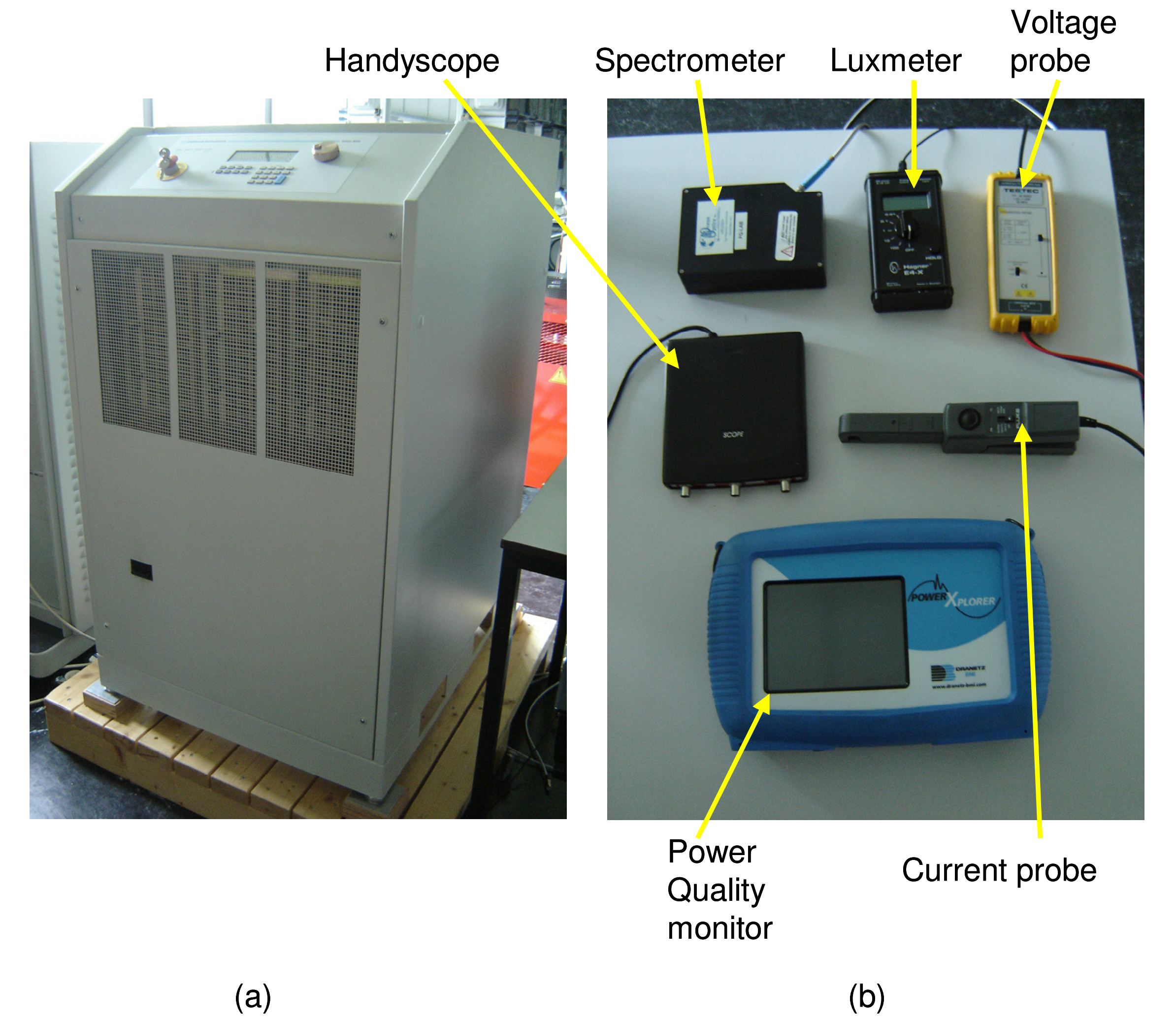

Figure F.1 Picture of the power source (a) and some measurement instruments (b)

Figure F.2 Picture of the white box (a) and inside of the white box (b)

Appendix G

Glossary, List of Symbols and Abbreviations

G.1 Glossary

- **Radiant flux** is equal to the total power in watts of electromagnetic radiation emitted or received. It may include both visible and non-visible components.

- **Luminous flux** is a measure of the power of visible light.

- **Lumen (lm)** is the photometric equivalent of the watt, weighted to match the eye response of the 'standard observer'.
  1W = 683 lm at 555nm.

- **Illuminance** is the luminance flux per unit area falling on a surface.

- **Illumination** or **Illumination level** is the same meaning as the illuminance.

G.2 List of Symbols

Table G.1 List of physical quantities and corresponding SI units [67]

Physical quantity	SI unit		
	Name	Symbol	Expressed in term of other SI units
Energy	joule	J	N·m
Radiant flux	watt	W	J/s
Luminous flux	lumen	lm	cd[a]
Illuminance	lux	lx[b]	lm/m^2 or cd/m^2

(a) 1lm = 1/(4π) cd (only if isotropic)

(b) $1lm/m^2 = 1lx$

P_{st} - short-term flicker indicator [-]
P_{lt} - long-term flicker indicator [-]
THD - total harmonic distortion [-]
$P_{inst,max}$ - maximum instantaneous flicker sensation [-]
f_c - critical modulating voltage frequency [Hz]
ΔV - modulating voltage amplitude [V]
$\Delta V/V$ - relative voltage fluctuation [%]
f_m - modulating voltage frequency [Hz]
ΔL - illuminance variation [lx]
L_r - relative illuminance variation [%]
L_{fm} - absolute illuminance of f_m component [lx]
L_{av} - average illuminance [lx]
L_{unit} - relative illuminance variation per unit value [-]
L_b - relative illuminance variation base value [%]
$W(f_m)$ - weighting factor of the modulating voltage frequency f_m [-]
k_l - linearity ratio [-]

G.3 List of abbreviations

AC - Alternating Current
ARX - Auto-Regressive with eXogenous
ARMAX - Auto-Regressive Moving Average with eXogenous

BJ	-	Box-Jenkins
CFL	-	Compact Fluorescent Lamp
CIE	-	Commission Internationale de l’Eclairage (International Committee on Illumination)
CIGRE	-	Conseil International des Grands Réseaux Électriques (International Council on Large Electric Systems)
DC	-	Direct Current
EDF	-	Electricité de France
EN	-	European Norm
ERA	-	Electrical Research Association
FGH	-	Forschungsgemeinschaft für Hochspannungs und Hochstromtechnik
FFT	-	Fast Fourier Transform
ICT	-	Information and Communication Technology
IEC	-	International Electrotechnical Committee
IEEE	-	Institute for Electrotechnical and Electronic Engineers
IGBT	-	Insulated Gate Bipolar Transistor
IOP	-	Innovation Oriented research Program
LED	-	Light-emitting diode
MOSFET	-	Metal-Oxide Semiconductor Field-Effect Transistor
OE	-	Output Error
PQ	-	Power Quality
rms	-	root mean square
THD	-	Total Harmonic Distortion
TU/e	-	Eindhoven University of Technology
TRIAC	-	Triod for Alternating Current
UIE	-	International Union for Electricity Applications

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List of Publications

1. Cai Rong, “Analysis of STATCOM for Voltage Dip Mitigation”, Master thesis, ISSN 140-6184, Gothenburg, Sweden, December 2004
2. Rong Cai, Massimo Bongiorno and Ambra Sannino, “Control of D-STATCOM for Voltage Dip Mitigation”, FPS 2005 Conference, 16-18 November 2005
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8. C. Rong, J.H. Blom, J.M.A. Myrzik and W.L. Kling, “New Flicker Weighting Curves for Different Lamp Types Based on the Lamp Light Spectrum”, 13th International Conference on Harmonics and Quality of Power (ICHQP 2008), Wollongong, Australia, 28 September - 1 October 2008

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She has been working for 6 years in the electrical engineering industry in China. From 1997 to 2000, she worked in China Hua Tai Transformer Co., Ltd as a design engineer. She was a key designer of dry type transformers for several important projects, e.g. Beijing Metro Fu-Ba line. She joined GE Beijing Hua Lun Medical System Co., Ltd as a system staging engineer in 2000. From 2001 to 2003, she worked in ABB Beijing Drive System Co., Ltd as a product engineer. She was responsible for the transfer of the production of the ACS400 series frequency converter.

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