

IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers

IEEE Power Electronics Society

Sponsored by the
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IEEE
3 Park Avenue
New York, NY 10016-5997
USA

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IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers

Sponsor

Standards Committee
of the
IEEE Power Electronics Society

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Abstract: This document includes a definition of the concept of modulation frequencies for light-emitting diodes (LEDs), a discussion on their applications to LED lighting, a description of LED lighting applications in which modulation frequencies pose possible health risks to users, a discussion of the dimming of LEDs by modulating the frequency of driving currents/voltage, and recommendations for modulation frequencies (flicker) for LED lighting and dimming applications to help protect against known potential adverse health effects.

Keywords: flicker, headaches, health, IEEE 1789™, LED lighting, migraines, modulation, perception, power electronic drivers, seizure, stroboscopic

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Participants

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Brad Lehman, *Chair*
Michael Poplawski, *Vice Chair*
Howard Wolfman, *Secretary*

Robert Altkorn
David Bannister
Sam Berman
Anindita Bhattacharya
Scott Brown
Xiao Chen
Pei-Ting Chou
Henry S.-H. Chung
Jon Connell
James Dakin
Montu Doshi
Jiri Drapela
Yuan Fu

Zdenko Grajcar
Steve Hayes
Jiao Jianzhong
Faisal Khan
Susan Larson
James Lazar
Peng Li
Yan-Fei Liu
Jonathan McHugh
Naomi Miller
David Neal
Brandon Oakes

Yoshi Ohno
Radu Pitigoi-Aron
Gene Rider
Scott Riesebosch
Anatoly Shteynberg
Michael Shur
David Sliney
Jennifer A. Veitch
Ingrid Vogels
Arnold Wilkins
Peter Wilson
Liang Yan
Regan Zane

The following members of the individual balloting committee voted on this recommended practices document. Balloters may have voted for approval, disapproval, or abstention.

Robert Altkorn
David Bannister
Sam Berman
Bill Brown
Liuchen Chang
Xiao Chen
Henry S.-H. Chung
James Dakin
Sourav Dutta
Randall Groves

Brad Lehman
Peng Li
Yan-Fei Liu
Homer Alan Mantooth
William McBride
Jonathan McHugh
Naomi Miller
Dorin Neacsu
Charles Ngethe
Michael Poplawski
Gene Rider

Bartien Sayogo
Su Sheng
Eugene Stoudenmire
Jennifer A. Veitch
John Vergis
Ingrid Vogels
Arnold Wilkins
Peter Wilson
Howard Wolfman
Liang Yan

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Introduction

This introduction is not part of IEEE Std 1789-2015, IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers.

The IEEE P1789 Working Group was formed in December 2008. Prior that time, the impact of flicker in light-emitting diode (LED) lighting was not being discussed. New technologies were being developed in LED lamps that introduced high levels of flicker. Occasionally, under special circumstances, some lamps would fail and cause flicker that could introduce seizures in the small percentage of the population that suffers from photosensitive epilepsy. One of the initial reasons to form the working group was to bring together a diverse community of experts to discuss the effects of flicker: members from the medical community, lighting community, photobiologists, electrical engineers, and many more. Without a community discussing the issue of flicker, it would not be possible for developers of LED lighting to fully understand any health effects that might be related to their design. The intent of this document is to explain what is known about flicker in LED lighting and to provide recommended practices that can help mitigate possible adverse biological effects of light flicker, when such mitigation is desired.

This document was written through the following procedure:

- a) Creation of an outline of topics using teleconferences and web board discussions;
- b) Drafting of various publications and other working documents by primary authors;
- c) Presentation and editing of the working documents by subcommittees composed of experts in lighting, health, and flicker;
- d) Approval of the working documents of the subcommittees to be presented to all members of the working group;
- e) Presentation of the working documents to all members of the working group by teleconferences and electronic media;
- f) Solicitation of comments and edits from all members of working group;
- g) Revision of the working documents to include member comments;
- h) Merging of all the working documents into this formal recommended practices document;
- i) Inclusion of additional material into the merged document, written by primary authors and necessary to make the recommended practices more complete;
- j) Obtaining of comments and edits from subcommittees on the recommended practices;
- k) Revision of the recommended practices document according to subcommittee comments;
- l) Submission of the recommended practices document for comments to all members of the working group;
- m) Revision of the recommended practices document according to the comments from working group members; and
- n) Submission of the recommended practices document for ballot, following the official IEEE standards balloting process for approval (not described here).

The IEEE P1789 Working Group effort is an open process. All official comments or proposed edits from working group members for this document were formally entered onto a comment form. Regardless of whether a comment was fully accepted, partially accepted, or rejected, the reasons for the decision were also entered on the form. As a matter of transparency and ethics, only comments submitted through comment forms or in official working group meetings/teleconferences were reviewed by working group members.

The process to develop this document took longer than initially anticipated. While the material in Clause 5 and Clause 6 was developed by the working group carefully and in a timely fashion, the group wanted to carefully weigh all the available scientific data in an objective and fair manner before it developed any recommended practice. It was decided that the working group members should develop a hazard and risk analysis for flicker using a formal process. The development of the material in Clause 7 was led by the same authors that developed the European Union Commission's policy on consumer product recall. That is, the material in Clause 7 was carefully developed over a one- to two-year period by experts in hazard

analysis who accumulated research data and scientific references and flew around the world (at their own expense) to interview experts in flicker, LED lighting, and human vision—all to prepare the material in Clause 7.

Similarly, the philosophy of the working group was to recruit experts in diverse research fields whenever necessary to help develop material. To create a comprehensive and precise set of recommended practices, it was necessary to include in the working group research experts in the fields of power electronic drivers, risk analysis, photobiology, vision, lamp design, psychology, LEDs, and many other areas. The result was a diverse field of experts, able to interpret scientific studies in medical fields, vision, electrical engineering, hazard analysis, and lighting. Many of the authors of the original scientific studies that are discussed in this document also contributed to, and authored text in, this document; this collaboration leads to a strong confidence in the scientific accuracy of IEEE Std 1789.

Each clause was developed by separate subcommittees, and then input and comments were received from the entire IEEE 1789 community about the individual clauses. Brad Lehman, chair, served as editor-in-chief of the entire document, but he also served as editor of Clause 1–Clause 3 and Clause 5 and co-editor of Clause 6 and Clause 8. Jennifer Veitch served as editor of Clause 4. Clause 7 had three co-editors: Bob Altkorn, Xiao Chen, and Gene Rider. Additionally, Arnold Wilkins served as co-editor of Clause 6 and Clause 8. Dozens of IEEE members contributed technically to the document, but major writing contributions of this document were performed by Sam Berman, Faisal Khan, Naomi Miller, and Michael Poplawski in addition to the previously listed editors.

A goal of this working group and recommended practices document is to aid all standards groups that want to develop suitable standards or certification processes about flicker in LED lighting. Observers from various agencies were included in the working group (ENERGY STAR, NEMA, IEC, CIE, OSHA, and many others). The working group plans to continue to work with these agencies and remain a resource for them in their processes (see <http://grouper.ieee.org/groups/1789/>).

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IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers

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1. Overview

1.1 Scope

The scope of this recommended practices document is to

- Define the concept of modulation frequencies for light-emitting diodes (LEDs) and discuss their applications to LED lighting.
- Describe LED lighting applications in which modulation frequencies pose possible health risks to users.
- Discuss the dimming of LEDs by modulating the frequency of driving currents/voltage.
- Present recommendations for modulation frequencies (flicker) for LED lighting and dimming applications to help protect against known potential adverse health effects.

1.2 Purpose

Presently, there are no standards on safe modulating frequencies for high-brightness LEDs. Vendors suggest various driving frequencies—some at low frequencies and others at high frequencies. In the late 1980s and early 1990s, studies showed that office fluorescent lighting with magnetic ballasts modulating at twice the ac line frequency increased the incidence of health-related problems, such as headaches, eyestrain, and, when the lamps were in failure, epileptic seizures. The detrimental effects depend on factors such as brightness, angle of viewing, wavelength, and depth of modulation, among others. The purpose of this document is to describe some possible health risks associated with low-frequency modulation of

high-brightness LEDs and provide recommended practices to aid the design of LED driving systems to modulate at benign frequencies in order to help protect against the described health risks.

1.3 How to use this document

This document is divided into eight clauses. Clause 1 provides the scope of this guide and its context with respect to other IEEE standards and other standards that are related to the subject of flicker. (Clause 2 is reserved for future normative references.) Clause 3 lists relevant acronyms and abbreviations. Note that no new definitions have been generated for this document; however, for the convenience of the reader, important definitions already in existence are cited in the glossary (Annex A). Clause 4 introduces the concept of flicker and its metrics for lighting applications. Clause 5 describes how the various methods used in the power electronic drivers for LED lights will have different effects on the light flicker that is produced in the LED luminaire. Clause 6 gives a summary of the biological effects of flicker that have appeared in the literature cited in this document (see the bibliography in Annex B). Clause 7 presents formal risk analysis for flicker in LED lighting. Clause 8 presents three recommended practices relating flicker to modulation depth and frequency. It should be mentioned that operating outside the low-risk recommended practice regions presented in Clause 8 does not necessarily imply high risk. However, following the recommended practices would lead to high confidence that there is low risk of health problems to viewers due to flicker. This issue is further discussed in Clause 8.

This document also contains two annexes. Annex A presents basic definitions used in vision and lighting with which a typical power electronics designer may not be familiar. Annex B is a bibliography of materials cited in this document.

This document attempts to provide information to the reader (e.g., ballast designers, other standards, or certification organizations), using the best knowledge available at the present time, on how to help mitigate the risk of distractions and possible adverse biological effects caused by flicker in LED lighting. At minimum, designers may decide to use this information to help design the output filters or switching frequency of their driving methods for LED lamps. The authors of this document recognize, also, for example, that it is common in the video game industry to put warning labels in their products/manuals to alert photosensitive people about their products if they believe flicker is a concern. Without the information in this document, designers could be unaware of how their lighting design decisions may impact human biological responses. This document should therefore be a valuable informational resource to the entire lighting industry, LED IC driver manufacturers, LED manufacturers, and even to the broader designers of luminaires other than LEDs (since much of what is described in this document is applicable to all types of lighting).

As the use of LED lighting proliferates in the consumer sector, it is vital for the lighting design community and other standards organizations to determine how to best use the information in this document. The recommended practices presented in Clause 8 describe how to help mitigate the risk of possible adverse biological effects of LED lighting. They may be, at times, conservative for specific lighting applications. This issue is thoroughly and openly discussed in Clause 8. However, following the guidelines presented should lead to minimal biological effects of the flicker in the LED luminaires. The recommended practices represent recommended low-risk operating regions of flicker. Operating outside these recommended low-risk regions does not necessarily imply high risk, however. Instead, the purpose of the recommended practices is to present potentially lower risk regions that, for many LED driver approaches, are not difficult to achieve.

One of the strengths of this document is that Clause 7 adapts a rigorous risk assessment framework formally used by government agencies and consumer protection agencies for product safety evaluation. This risk assessment follows the method developed by the Eurosafe Working Group on Risk Assessment (Rider et al. [B90]) and is similar in form to the SCENIHR “Scientific opinion on light sensitivity” [B95].¹ This formal analysis procedure is able to separate the discussions on severity of the biological effect,

¹ Numbers in brackets correspond to the numbers in the bibliography in Annex B.

probability of occurrence, and confidence level of the scientific data on which the conclusions are based. This approach was adopted so that areas that have limited experimental data can be discussed openly within the lighting community. In fact, an additional purpose of this document is to urge industry and research laboratories to continue to critically evaluate data from research and from field experience and make additional recommendations when supported by data. The risk analysis discussion in Clause 7 should allow research entities to identify areas of valuable research topics that could further the understanding of the human biological effects of light flicker.

The purpose of this subclause is to assist the reader in applying the recommendations of this document to particular cases of interest in LED lighting. LEDs as a light source do not inherently flicker. Nevertheless, when coupled with their driving electronics, some (but not all) LED lighting products will exhibit more pronounced flicker than current fluorescent and incandescent lamps, even as high as high-pressure sodium (HPS) lamps. This study was undertaken to collect what is known about potential undesirable health effects of flicker—especially urgent because government and industry studies project that LED lighting products will account for as much as 50% of the lighting market by the year 2020.

It is important to mention that, when determining the most suitable light source for a specific application, flicker is only one condition that must be considered, along with factors such as luminous intensity and color metrics, power factor, electromagnetic fields of the driver circuitry, audio noise of chokes, total harmonic distortion metrics, reliability and life metrics, energy saving, cost, lighting application, etc. The scope of this document, though, is to emphasize flicker performance. It is beyond the scope of IEEE Std 1789 to explain many of these other design aspects, but they may also be important in making lighting decisions.

This document provides recommended practices that can help mitigate the risk of possible adverse biological effects of flicker in LED lighting. The recommended practices are suitable for all LED lighting in general illumination. In other words, this document does not separate the discussion into different lighting applications and then create recommended practices for each of the lighting application circumstances. The reasons for this approach are extensively discussed in Clause 7 and Clause 8. However, it could be the next step for other organizations to develop lighting-application-specific recommended practices. This may be within the scope of other certification and standards groups, such as CIE, IEA 4E Solid State Lighting group, ISO TC 274, ENERGY STAR, CALiPER, etc. A logical next step would be for these bodies to use this IEEE document to help develop particular standards that may include lighting-specific applications, weighing such matters as adaptation luminance, color, tasks, etc. The end of Clause 8 further clarifies this idea and urges the lighting community to continue to expand guidelines for flicker in LED lighting.

1.4 Context and contents

This recommended practices document is divided into seven subsequent clauses.

- Clause 2 (the clause traditionally reserved by IEEE to list other standards that are integral to implementing the IEEE document) is included only to point out that no other standards are necessary to implement this document.
- Clause 3 (the clause traditionally reserved by IEEE to define relevant terms) is included only to point out that no new definitions have been created for this document. For the convenience of the reader, some existing definitions are provided in the glossary (see Annex A) and Clause 4, and other definitions can be found in the *IEEE Standards Dictionary Online*.
- Clause 4 describes and presents the need for creating recommended practices pertaining to flicker.
- Clause 5 explains how flicker is introduced when utilizing power electronic drivers for LED lighting. The material is divided into four subsections:
 - LED driving methods, which typically produce flicker at twice the ac power line frequency, are discussed. Only a brief introduction is presented, and the methods are sometimes simplified so that the basic concepts of the driving approaches can be understood.

- Failure modes for LED driving methods that may cause flicker to have frequency between 3 Hz and 70 Hz are presented. This frequency range is of particular concern because it may cause seizures in people that are susceptible to photosensitive epilepsy.
- The topic of dimming is presented, and its relation to flicker frequency is discussed.
- Various experimental waveforms of flickering light sources are presented.
- Clause 6 presents an overview of the various reported biological effects of light flicker.
- Clause 7 gives a formal risk assessment of flicker in LED lighting. For the major enumerated potential health risks, the clause covers epidemiology, severity, susceptible subgroups, and values of influential parameters. A discussion of Low-Risk Levels based on the evaluated risk analysis parameters is introduced to provide background to the recommended practices presented in Clause 8. Clause 7 presents the following material:
 - A brief introduction to this risk assessment presents the assumptions and then illustrates the risk assessment results in figures.
 - The methodology of the risk assessment strategy is presented. It follows the method developed by the Eurosafe Working Group on Risk Assessment (Rider et al. [B90]) and is similar in form to the SCENIHR “Scientific opinion on light sensitivity” [B95]. A strength of this approach is that it categorizes confidence levels of the data used in the analysis.
 - The probability levels and severity levels used in the risk assessment are explained.
 - Risk assessment of different possible biological effects of flicker is presented. The topics discussed include photosensitive seizure, stroboscopic effect, migraine, aggravation of autistic behaviors, performance asthenopia/eyestrain, and headaches as well as a mention of anxiety and vertigo-related issues. The hazard level, probability of occurrence, and confidence level of the research are discussed for the different biological effects.
- Clause 8 presents the recommended practices. The recommended practices give guidelines on the relation between flicker frequency and modulation percentage that can be maintained in order to help mitigate the risk of possible biological effects of flicker. Clause 8 is divided as follows:
 - Three recommended practices are presented, and then examples are given on how the recommended practices may be applied.
 - Justification about deriving a recommended practice for general lighting applications instead of separate recommended practices for different lighting applications is presented.
 - A more in-depth justification of the derivation of the recommended practices is given. The recommended practices are validated by multiple independent research studies as well as small-scale real-world lighting applications. The conservativeness of the recommended practices is discussed.
 - The issue of subharmonics is presented. The recommended practices have made the assumption that there is no power line flicker and that the flicker in the LED lamps is produced due to the driving method only. It is possible that this assumption is not the case and a method is proposed, but is not part of any recommended practice, which may be used to adapt a recommended practice to the case of subharmonic flicker.
 - Final comments are given.
- Annex A gives basic definitions used in vision and lighting with which a typical power electronics designer may not be familiar.
- Annex B is a bibliography of materials cited in this document.

2. Normative references

There are no other documents that are indispensable for the application of the recommended practices outlined in this document.

NOTE 1—Related IEEE documents are referred to in the text and are helpful to understand the voltage flicker issue for incandescent bulbs. These documents explain how power line harmonics influence incandescent flicker, and Clause 8 utilizes these documents (and other scientific documents) to help validate the recommended practices (see IEC 61000-3-3:2013 [B56] and IEC 61000-4-15:2010 [B57]).²

² Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

NOTE 2—Peripherally related lighting standards exist. In Europe, high-brightness LEDs are often held to similar optical standards as Class 1 lasers, EN60825, but this practice has not been the case for the United States. These standards for lasers are concerned primarily with optical radiation. Furthermore, documents exist for best working practices for indoor lighting, but do not cover health effects of flicker (see ANSI/IES RP-1-04 [B1], ISO/CIE 8995-1:2002 [B60], IEC 62471:2006 [B58], and IEC 60825-1:2007 [B55]).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. No new definitions have been generated while developing this document. However, for the convenience of the reader and for tutorial purposes, Annex A presents some basic definitions in the fields of lighting science. Clause 4 also introduces some basic definitions on flicker as well as their associated metrics.³

3.2 Acronyms and abbreviations

CFF	critical flicker fusion frequency
CFL	compact fluorescent lamp
EEG	electroencephalograph or electroencephalogram
f	frequency
HID	high-intensity discharge
HPS	high-pressure sodium
LED	light-emitting diode
MH	metal halide
<i>Mod%</i>	Modulation (%)
LPS	low-pressure sodium
NOEL	no observable effect level
PFC	power factor correction
PWM	pulse width modulation or modulated
rms	root-mean-square
SSL	solid-state lighting

4. Flicker

4.1 What is flicker?

Light modulation has many names, including flicker, flutter, and shimmer. The Illuminating Engineering Society's (IES) *Lighting Handbook* [B28] defines *flicker*—the most commonly used term—as “variations of luminance in time” (see also CIE S 017/E:2011 [B21]).⁴ Here, IEEE Std 1789 is concerned with flicker

³ *IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

⁴ Photometric flicker should not be confused with electrical flicker, which refers to noise on ac distribution lines that can directly create additional (light) modulation on resistive (incandescent) loads. In cases of electrical flicker, the ac line is the source of the modulation, rather than characteristics of the light source design and construction.

as a characteristic of the light source design and construction. (See Annex A for formal definitions of flicker.)

All light sources modulate light, or flicker, to some degree, usually as a consequence of their drawing power from ac mains sources (i.e., 60 Hz ac in North America). The flicker created by electrically powered light sources is typically periodic. A periodic waveform can be characterized by at least four parameters: its amplitude modulation (i.e., a variation in amplitude over a periodic cycle), its average value over a periodic cycle (also called the *dc component*), its shape or duty cycle (in this recommended practices document, *duty cycle* normally refers to the percentage of time spent at maximum value in pulse width modulated (PWM) square waves), and its periodic frequency. The viewer's response to a flickering light depends on all these characteristics; of these, frequency has been the most studied and is better understood.

Throughout this document, reference is made to variation in light intensity associated with flickering light. Several metrics have been developed and used to quantify this intensity variation. These existing metrics are defined below. Where documentation exists, the specific metric used in cited studies is noted.

- Flicker index, introduced by Eastman and Campbell [B30], is defined by Lehman et al. [B72] as the area above the line of average light divided by the total area of the light output curve for a single cycle. Referring to Figure 1,

$$\text{Flicker Index} = (\text{Area 1}) / (\text{Area 1} + \text{Area 2})$$

- Percent flicker, also known as peak-to-peak contrast, Michelson contrast, Modulation (%), or modulation depth (Lehman et al. [B72]). Referring to Figure 1, percent flicker is defined as

$$\begin{aligned} \text{Percent Flicker or equivalently Modulation (\%)} \\ \text{Mod\%} = 100 (\text{Max} - \text{Min}) / (\text{Max} + \text{Min}) = 100 (A - B) / (A + B) \end{aligned}$$

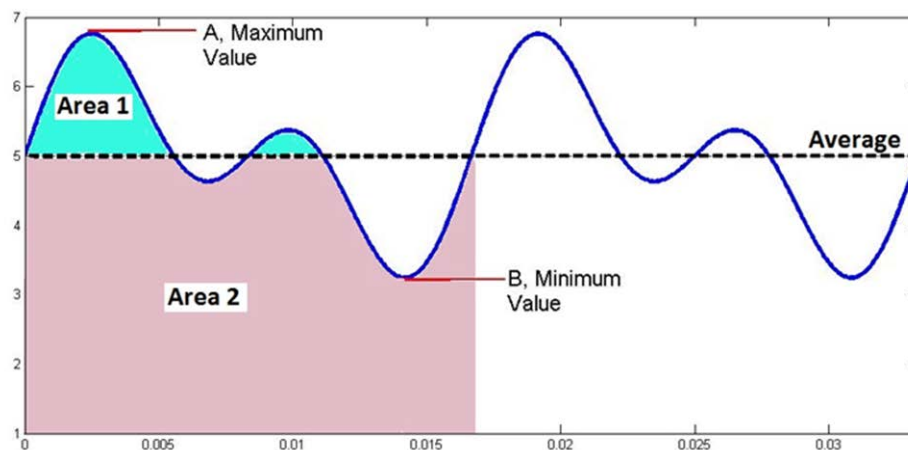


Figure 1—Diagram for definition of flicker index and percent flicker

For example, flicker exists in most light sources, but with varying levels. This is true for the different types of lighting technologies such as incandescent, fluorescent, and solid-state lighting (SSL). In particular, SSL flicker is dependent on the method that is used to convert the input electric signal from a typical ac input to the desired dc output that the LEDs utilize. This is further explained in Clause 5.

Flicker refers to the modulation of luminous intensity in a lamp. However, Clause 5 refers to the modulation of LED current through the lamp. The assumption is that LED current is approximately proportional to the luminous flux output of the LED. Therefore, reference to LED current is meant to infer

reference to LED luminous intensity and vice versa. (Thus no consideration is being given to operating the LED in its nonlinear saturation regions above rated currents.) This implies, for example, that a Modulation (%) of 100% in flicker is equivalent to a Modulation (%) of 100% in LED current.

In LED power electronic drivers, typical design specifications in application notes might include specifications on peak-to-peak LED ripple current% or root-mean-square (rms) LED ripple current. Peak-to-peak LED current% = $100 \times (ILED_{max} - ILED_{min})/ILED_{avg}$, where $ILED$ represents the current through the LED. For the special symmetric cases when $ILED_{avg} = 0.5 \times (ILED_{max} + ILED_{min})$, then the peak-to-peak LED ripple current% is equal to twice the Modulation (%). This may be typical of triangular wave periodic flicker or sinusoidal wave flicker in LED currents that are commonly produced in LED drivers. Relating rms of the ripple current to Modulation (%), however, is more complicated. This depends on the shape of the LED current, even if it is symmetric.

Examples of flicker in lighting can be seen in Figure 2 for incandescent bulbs and in Figure 3 for LED lighting. The luminous flux is normalized on the vertical axis so that the maximum value equals 1. Therefore, the percent flicker simplifies to $100 \times (1 - Min)/(1 + Min)$, where the minimum value is specified in each figure. Figure 2 and Figure 3 represent only sample flickering outputs in luminaires. Extensive testing and measurements of flicker in LED and other lamps can be found in Lehman et al. [B72] and in several U.S. Department of Energy (DOE) and Pacific Northwest National Laboratory (PNNL) publications (Poplawski et al. [B84], Poplawski and Miller [B83], Poplawski [B85], and Miller et al. [B77]).

For the human observer, flicker can be broken into categories, based on detection (sensation) and perception (Wilkins et al. [B117]) (see Annex A for more precise definitions).

- Sensation: The eye/brain/neurological system detects the modulation of light output over time in the external conditions, and neurons respond.
- Visible flicker: The luminous modulation is sensed and consciously perceived.
- Invisible flicker: The luminous modulation is sensed, but not consciously perceived (unless it is appreciated in terms of effects on spatial perception, such as the phantom array or the stroboscopic effect).

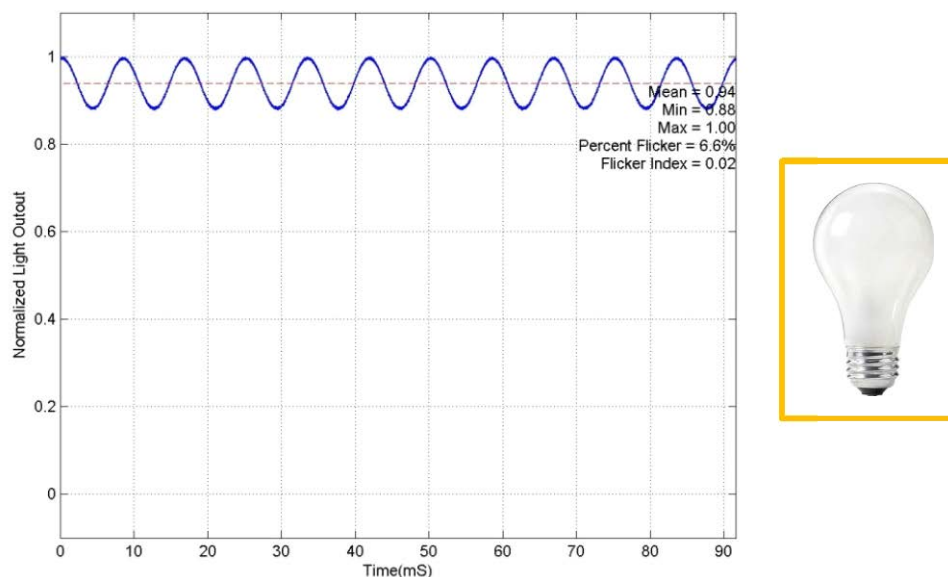


Figure 2—Typical incandescent lamp flicker of ~6.6% (Lehman et al. [B71])

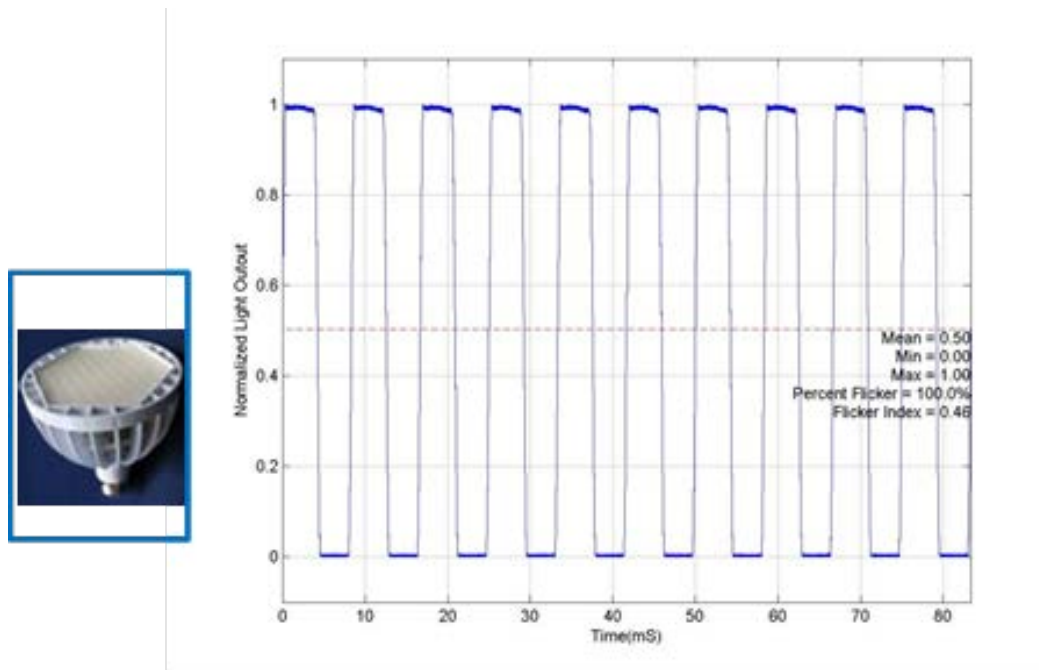


Figure 3—Example SSL flicker at 100% (Lehman et al. [B71])

For most people, flicker that occurs with a frequency of less than 60 Hz is visible. The frequency at which a flickering light source fuses into an apparently constant source varies for individuals and depends on the modulation amplitude, adaptation luminance, and visual field size of the source. However, this critical flicker fusion frequency (CFF) occurs generally in the range of 60 Hz to 100 Hz (Kelly [B65]). Invisible flicker, occurring at a rate greater than the CFF, may nonetheless have physiological effects even though the individual normally cannot report the conscious perception of flicker (see Clause 6).

Flicker was an issue when magnetically ballasted fluorescent lamps were common, before the mid-1990s. Research at that time identified flicker of the light source to be related to migraines, headaches, reduced visual performance and comfort, and other possible neurological health issues (see Clause 7). When high-frequency electronic ballasts were introduced for energy efficiency, the negative effects of flicker were reported less frequently and largely disappeared from public discourse. In the meantime, magnetically ballasted high-intensity discharge (HID) lamps have been continuously used for outdoor light with relatively few complaints despite their high modulation depth.

With the introduction of SSL products to the marketplace, flicker has re-emerged as a consideration, partly because the modulation of light-emitting diode (DOE [B106]) light output has been frequently observed to be greater than the modulation seen with fluorescent or HID sources (Poplawski et al. [B84]). For LED sources, flicker is primarily determined by the driver. Some driver designs produce little to no detectable flicker at full or dimmed outputs; others flicker noticeably at both full and dimmed output; still others produce little to no flicker at full output, but flicker objectionably when dimmed. Some LED products produce flutter or light level instabilities while the dimming level changes from one level to another. The flutter or light level instabilities disappear when the dimming level remains constant.

4.2 The need for recommended practices specifically for LED lighting

SSL is widely recognized as revolutionary, and the technology offers the promise of dramatically reducing lighting energy use. Reports produced for the DOE project that the adoption of LEDs for general lighting could result in savings on the order of 19% less electricity used for lighting by 2020, and 46% by 2030 (DOE [B106]). Such a reduction would deliver substantial savings for building owners and operators

(including households) and has the potential to deliver important societal benefits in the form of reduced greenhouse gas emissions and the release of electrical generating capacity for other uses.

These projected energy savings are based on assumptions about the adoption of this new technology; if these assumptions are not met, the savings will not occur. The path to adoption of any new technology should take into account lessons learned from the introduction of previous technologies. In the case of LED lighting, the comparator case is the introduction of compact fluorescent lamps (CFLs) in the early- to mid-1990s. It is widely accepted that the uptake of CFLs was much slower than had been anticipated, and the projected energy savings did not materialize (Sandahl et al. [B94]). Equipment performance was among the problems that hindered adoption, and one of the key lessons derived from the CFL experience was “Don’t launch a product until performance issues are ironed out” (Sandahl et al. [B94]).

Among the performance issues that contributed to slow CFL uptake was the perception that fluorescent lighting can cause adverse health effects. Flicker had long been among the complaints made about fluorescent lighting (Stone [B103]), when Beckstead and Boyce [B4] found that the belief that fluorescent lighting could cause negative effects on people predicted the likelihood that people would use fluorescent lighting at home. As the lighting industry strives not to repeat the CFL experience, these findings underpin the need for recommended practices concerning LED flicker.

Other clauses of this document summarize what is known concerning the effects of flicker on human health and well-being (see Clause 6) and the variety of flicker rates that LED lighting systems can exhibit (see Clause 5). Possible adverse health effects can occur under flicker conditions that lie outside the visible range (see Clause 7); the nervous system can detect and respond to these conditions without their being accessible to conscious reports of the perception. This sets the stage for learned associations between LED lighting and potential adverse health effects from the specific product to the general class of LED products.

Given the wide variety of flicker patterns detected in LED products already on the market (Poplawski et al. [B84]), some of which may lie in the region where potential health risks exist, it is possible that the public will associate this new technology with negative health outcomes. However, the lighting industry has the opportunity through product design to reduce the occurrence of flicker conditions that could cause potential adverse health and well-being effects and thereby help avoid a future in which the public associates LEDs with these outcomes. A recommended practice for LED lighting flicker can make a valuable contribution to the speedy adoption of LED technology and the achievement of energy efficiency targets by defining, based on science and consensus, the flicker conditions that may best be avoided.

Prior to the IEEE P1789 Working Group, there were no formal entities that were allowing designers, health experts, and engineers to discuss the best guidelines flicker in SSL. This vacuum left engineers to design their power electronic drivers without knowledge of possible health effects to the public. The scope of this document is to

- Define the concept of modulation frequencies for LEDs and give discussion on their applications to LED lighting.
- Describe LED lighting applications in which modulation frequencies pose possible health risks to users.
- Discuss the concept of dimming of LEDs by modulating the frequency of driving currents/voltage.
- Present recommendations and design guidelines that can help enable a designer to select, with more knowledge, appropriate power electronic drivers to desirably modulate frequencies for LED lighting and dimming applications to help protect against possible adverse health effects.

At minimum, this document can help educate the community about the need to create desirable LED lighting to help reduce flicker conditions.

5. Explanation of flicker in LED lighting: Power electronic drivers⁵

Several common methods used to drive LEDs can operate with frequency of modulation in the areas of discussion in this recommended practices document, ranging from 3 Hz to ~1 kHz. Some produce visible flicker that may be of concern, while others do not. For example, commercially available LED lamps have been reported (Rand et al. [B86]) to malfunction and produce visual flicker in the 15 Hz range when connected to a conventional residential dimmer.

Below, only a few driving approaches that modulate in various frequency ranges are presented. The list is not exhaustive, and the discussions are meant only to demonstrate typical driving LED currents with frequencies in this range. In this clause, it is helpful to make the following assumptions:

- a) The flicker described below is self-generated/device-inherent flicker. There is no power line flicker, and the flicker in the LED lamps is produced due to the driving method only.
- b) Only a few sample methods of LED driving are considered. Many variations of the presented methods and several other driving approaches that produce flicker are not presented.
- c) Flicker refers to the modulation of luminous intensity in a lamp (see Clause 4). However, this clause refers to the modulation of LED current through the lamp. The assumption is that LED current is approximately proportional to the luminous flux output of the LED.

5.1 LED driving current frequencies in the range of ~100 Hz to 120 Hz

LED driving current frequencies in range are described as follows:

- a) Full-wave rectifier connected to LED string.

In this approach, the ac input source is sent into a full-wave rectifier, causing the (approximate) absolute value of the input voltage to be sent to the load. In this case, the current through the LEDs has a waveform shape similar to a scaled absolute value of a sine wave. That is, the rectified sine wave may be approximately equal $|V_p \sin(\omega t)|$, where V_p is the amplitude of the sine wave and ω is the angular frequency in radians $\omega = 2\pi f$. In this case, the LED current is of similar shape, as Figure 4 shows. In a first approximation, the LED current is equal to a scaled rectified voltage, with the additional dead time (zero current) caused by the LED bias voltage. Thus, when properly functioning, the direct full-wave rectifier driving approach modulates the LEDs at twice the line frequency; this result in North America leads to 120 Hz modulation and in Europe leads to 100 Hz modulation. As Figure 4(a) shows, often a resistor is added in series with the LED string for current limiting protection.

- b) Directly driving two parallel LED strings with opposite anode/cathode connections.

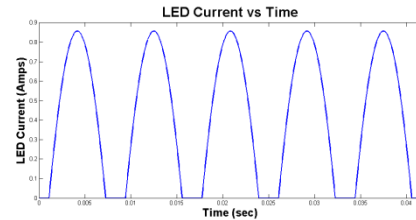
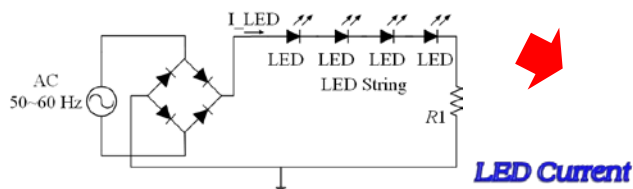
A second LED driving method that doubles line frequency is shown in Figure 4(b). Two strings of LEDs are powered in parallel, with anode of one paralleled string connected to the cathode of the other parallel string. When the ac line voltage is positive, energy drives one of the LED strings. When the ac line voltage is negative, the other paralleled LED string is driven. At most, one of the LED strings has current through it. The net effect is that the effective LED driving current is modulating at 120 Hz in North America or 100 Hz in Europe.

Thus, for both driving methods illustrated in Figure 4, the LED current modulates at twice the line frequency. Since the intensity of the LEDs is (ideally) proportional to the current through the LEDs, this causes the LEDs to flicker at frequency equal to twice the ac line frequency, i.e., 100 Hz to ~120 Hz. Many variations of the approach in Figure 4 are not shown here. The more

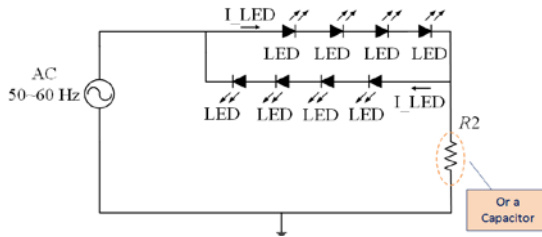
⁵ Material in this clause, especially 5.1, 5.2, and 5.3 (including Figure 4, Figure 7, and Figure 8), is taken from Wilkins et al. [B117].

modern approaches generally reduce flicker and harmonic distortion (Shteynberg et al. [B99], Noge and Itoh [B79], and Texas Instruments [B105]).

(a) Rectify ac mains and send to LED string



(b) Directly power two LED strings with opposite Anode/Cathode connections



(c) Simulation of current through HB LEDs. Luminous intensity is proportional to current, causing lamp to flicker at twice the line frequency (shown periodically every 1/120 sec)

Figure 4—Two methods to drive LEDs at twice line frequency:
(a) Full bridge rectification and (b) Opposite connection parallel strings
with (c) Current/Luminous output in the LEDs for both approaches
(Lehman and Wilkins [B73])

c) Simple dimming pulse width modulated (PWM) circuits.

It is common to dim LEDs by pulsing the current through them intentionally. The luminous intensity of the LED can be adjusted by varying the length of time that the LED current is High or Low. Thus, PWM dimming circuits may be designed to operate at any frequency, whether the input is dc or ac. (It should be noted that it is not uncommon for LED drivers using ac residential phase modulated dimmer circuits to attempt to “emulate” PWM type signals with frequency 120 Hz. That is, when the ac dimmer shuts off, no current is sent to the LEDs.) Figure 5 illustrates two methods to create PWM current through LEDs. In Figure 5(a) the switch is in series so that when it is ON, the current will flow through the LED. When the switch is off, no current flows through the LEDs. In Figure 5(b), the current flows through the LEDs when the switch is off, while there is no current in the LED when the switch is ON. In either case, the LED current looks similar to Figure 5(c) and has flicker frequency $f = 1/T$, where T is the period of the signal.

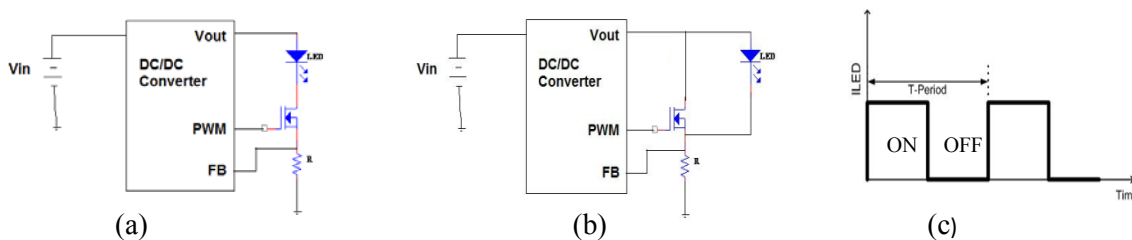


Figure 5—Sending PWM current through LEDs:
(a) Series PWM dimming and (b) Parallel PWM dimming
with (c) PWM current through the LED in either method (Wilkins et al. [B117])

It should be mentioned that there are alternative approaches to dimming, such as amplitude dimming, in which the current through the LED is continuous and not pulsing. By reducing the

value of this continuous current (amplitude), the luminance is dimmed. This approach does not use PWM to adjust luminance; therefore, flickering does not exist, and flicker-related health effects should not be induced.

d) Power factor correction (PFC) circuitry.

Even when sophisticated high-frequency switching power supplies with PFC circuits are used to drive LEDs from ac mains, such as in Figure 6, there is commonly a frequency component in the current (and luminous intensity) of the LEDs at twice the line frequency. Depending on the design of the circuitry, the harmonic content of this flicker may vary from being small and unnoticeable to being significant in magnitude. The modulation depth of the flicker depends on controller design, circuitry being used, and filter component values, among other factors.

Figure 6 shows typical circuitry that may be used in driving the LEDs in a bulb. A two-stage approach (Chen et al. [B18], Arias et al. [B2], Zhang et al. [B121], and Gu et al. [B41]) is illustrated because this can have reduced flicker Modulation (%). A first stage may be used to achieve PFC to meet typical requirements, such as *power factor* > 0.7 given by ENERGY STAR requirements [B31]. The second stage can be used to reduce the percent flicker. On the other hand, some vendors may utilize only a single stage ac-dc approach and keep only the PFC portion of Figure 6 (see Hu et al. [B54], Xie et al. [B119], Chou et al. [B20], and Cheng et al. [B19]). In this case, it is likely that the percent flicker may significantly increase, but there is a benefit of lower cost from lower parts count. Finally, it should be mentioned that linear regulators may be inserted in series with the LEDs to regulate constant dc current so no flicker appears (Hu and Jovanovic [B53]). This comes at the disadvantage of additional power loss.

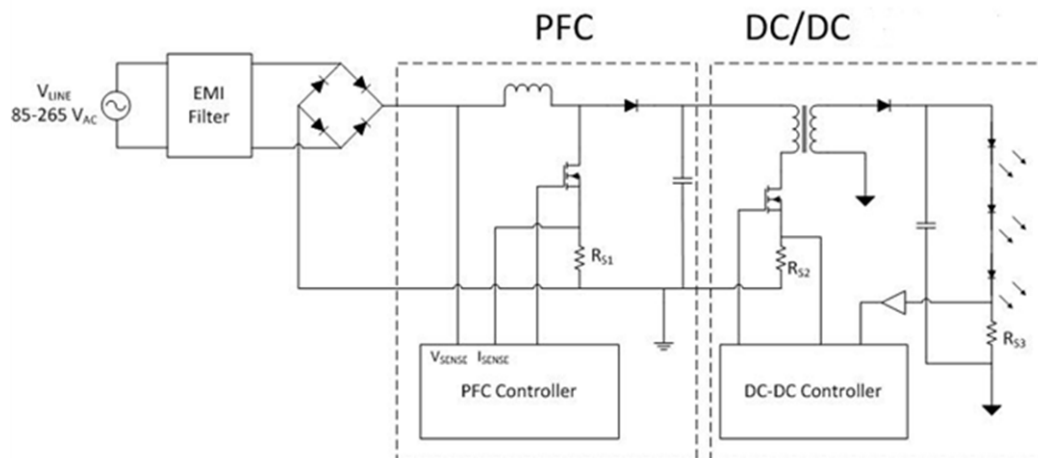


**Figure 6—Typical active PFC circuitry:
some flicker frequency at twice the ac line frequency may remain
(Lehman and Wilkins [B73])**

5.2 LED driving current frequencies in the range of 3 Hz to 70 Hz

LED driving current frequencies in range are described as follows:

a) Failures in rectification or LED strings: 50 Hz to ~60 Hz modulation.

In either of the two methods of Figure 4, there is risk of failure that can cause LED current modulation at ac line frequency, thereby entering the range of frequencies that may induce photosensitive epilepsy that is discussed in Clause 6 and Clause 7. For example, if one of the legs of the full-wave rectifier bridge fails, then it is common that the leg becomes an open circuit. Open