

A Review of the Literature on Light Flicker: Ergonomics, Biological Attributes, Potential Health Effects, and Methods in Which Some LED Lighting May Introduce Flicker

2/26/10

IEEE Standard P1789

<http://grouper.ieee.org/groups/1789/>

Abstract: This report is intended to be a draft sub-section of the final report from the IEEE Standards Working Group, IEEE PAR1789 *"Recommending practices for modulating current in High Brightness LEDs for mitigating health risks to viewers."* The final recommended practice report aims to be completed and be approved at the end of 2010. This document intends to explain some potential health consequences of flicker in LED lighting and demonstrate that existing technologies for LED driving may flicker at frequencies that may have health effects.

Purpose of Report: The goal of this report is to perform an objective summary of the effects on human health for both visible and invisible flicker with attention drawn to implications for the design of LED lighting. Specifically, contributions of this report include making the reader aware of

1. Risks of seizures due to flicker in frequencies within the range $\sim 3\text{-}70\text{Hz}$;
2. Health concerns due to invisible (not perceivable) flicker at frequencies below $\sim 165\text{Hz}$ including, but not limited to, headaches, migraines, impaired ocular motor control, and impaired visual performance;
3. The differences between "visible" flicker and "invisible" flicker and any relation to health risks;
4. A few, typical driving approaches in LED lighting that may produce flicker.

This report does not attempt to make recommendations on safe flicker frequencies or modulation depths for LED lighting. Its purpose is to describe health implications of flicker. (Separate IEEE P1789 documents will describe recommended practices.) Specifically, Section I of the report gives tutorial surveys on health effects of flicker. Section II of the report introduces a few typical LED driving methods that introduce flicker in frequency ranges of interest.

Methodology in Writing Report: IEEE P1789 was formed December 2008 for the purpose to bring together experts in photobiology, power electronic LED drivers, lighting health, lamp design, and LEDs together to discuss health effects of flicker in LED lighting. Writing this report followed the following procedure: 1) initial telecons and web board discussions to create an outline of topics to be included into the report; 2) Drafting of report

1 by primary authors; 3) Presentation and editing of the report in a
2 subcommittee composed of experts in lighting health and flicker; 4) Approval
3 of draft report of the subcommittee to be presented to all members of
4 P1789; 5) Presentation of report to all members of P1789 by telecom and
5 web board discussions; 6) Soliciting of comments and edits from all members
6 of IEEE P1789; 7) Revision of report to include members comments; 8)
7 Posting of the report on the IEEE P1789 public website for comments from
8 the public.

9
10 In general, the IEEE Standards P1789 committee has agreed upon the
11 following general strategy (see meeting minutes 1/15/10 on IEEE P1789
12 website): 1) Continue to update this report regularly and post newer versions
13 on the public website. The report represents a survey of the health effects of
14 flicker, and it is important for people to be aware of known research results
15 in flicker. 2) Help define metrics in modulation depths of flicker that are
16 suitable to be used to create standards and recommended practices in LED
17 lighting to mitigate health risks (if necessary), and 3) If necessary, create
18 recommendations in frequencies limits and/or modulation depths based on
19 the flicker metrics being proposed. In order to do this fairly, IEEE Standards
20 P1789 may use tools similar to risk matrix analysis to guide the assessment
21 of severity of the risk, confidence level, and probability of occurrence of a
22 health hazard.

23
24 IEEE P1789 is an open process. Further, a goal is to aid all standards groups
25 that want to develop suitable standards. Observers from various agencies
26 participate already and guide directions of the committee (EnergyStar,
27 NEMA, IEC, CIE, and others). If there are any corrections, missing citations,
28 or suggestions to this report, the reader is requested to submit them on the
29 web entry form of the IEEE Standards P1789 website:

30 <http://grouper.ieee.org/groups/1789/public.html>

31 As a matter of transparency and ethics, only comments submitted through
32 the web site will be reviewed by IEEE P1789 members. We encourage the
33 reader to submit any suggestions to improving the document through the
34 website.

35
36 This report will be continually updated and improved. New versions of the
37 report will be time stamped and placed on the IEEE P1789 public website.

38 **Assumptions in the Report:**

- 39 1. The flicker described in Section II is self generated/device inherent
40 flicker. The report assumes that there is no power line flicker and that
41 the flicker in the LED lamps is produced due to the driving method
42 only.
- 43 2. In Section II of this report, only a few, typical (sample) methods of
44 LED driving are considered. There are many variations of the
45 presented methods and several other driving approaches that produce
46 flicker that are not presented.
47

- 1 3. Flicker refers to the modulation of luminous intensity in a lamp (see
 2 definition below). However, at times, this report refers to the
 3 modulation of LED current through the lamp. The assumption is that
 4 LED current is approximately proportional to the luminous flux output
 5 of the LED. Therefore, reference to LED current is meant to infer
 6 reference to LED luminous intensity and vice-a-versa. (Thus we are
 7 not considering operating the LED in its nonlinear saturation regions
 8 above rated currents.)
- 9 4. The discussion in Section I discusses *possible* health concerns due to
 10 flicker. Actual health risks from flicker are dependent on frequency,
 11 modulation depth, brightness, lighting application, and several other
 12 factors. Further, it is understood that some of the risks in Section I
 13 pertain to small minority of a population. These topics are not
 14 discussed in any detail and will be dealt with in future reports.

17 **Basic Definitions:**

18 Flicker: a rapid and repeated change over time in the brightness of
 19 light.

20 Modulation : a measure of light variation that is often applied to periodic
 21 oscillations. This report specifically refers to modulation as the relation
 22 between the spread and the sum of the two luminances (commonly
 23 referred to as Percent Flicker, Peak-to-Peak Contrast, Michelson
 24 Contrast, or Depth of Modulation). For a time-varying luminance with
 25 maximum and minimum values:

$$26 \quad \text{Modulation} = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min}) \quad (\text{Lighting Design Glossary})$$

27 Visible Flicker: Flicker that is perceivable by human viewer.

28 Invisible Flicker: Flicker that is not perceivable by a human viewer.

29 The effects of flicker can range from decreased visual performance to
 30 non-specific malaise to the onset of some forms of epilepsy.

32 **I. Introduction to Hazards of Flicker**

33 The health effects of flicker can be divided into those that are the immediate
 34 result of a few seconds' exposure, such as epileptic seizures, and those that
 35 are the insidious result of long-term exposure, such as malaise, headaches
 36 and impaired visual performance. The former are associated with visible
 37 flicker, typically within the range ~ 3 - ~ 70 Hz, and the latter with invisible
 38 modulation of light at frequencies above those at which flicker is perceptible
 39 (invisible flicker). Health risks are a function of flicker frequency, modulation
 40 depth, brightness, lighting application, and several other factors.

1

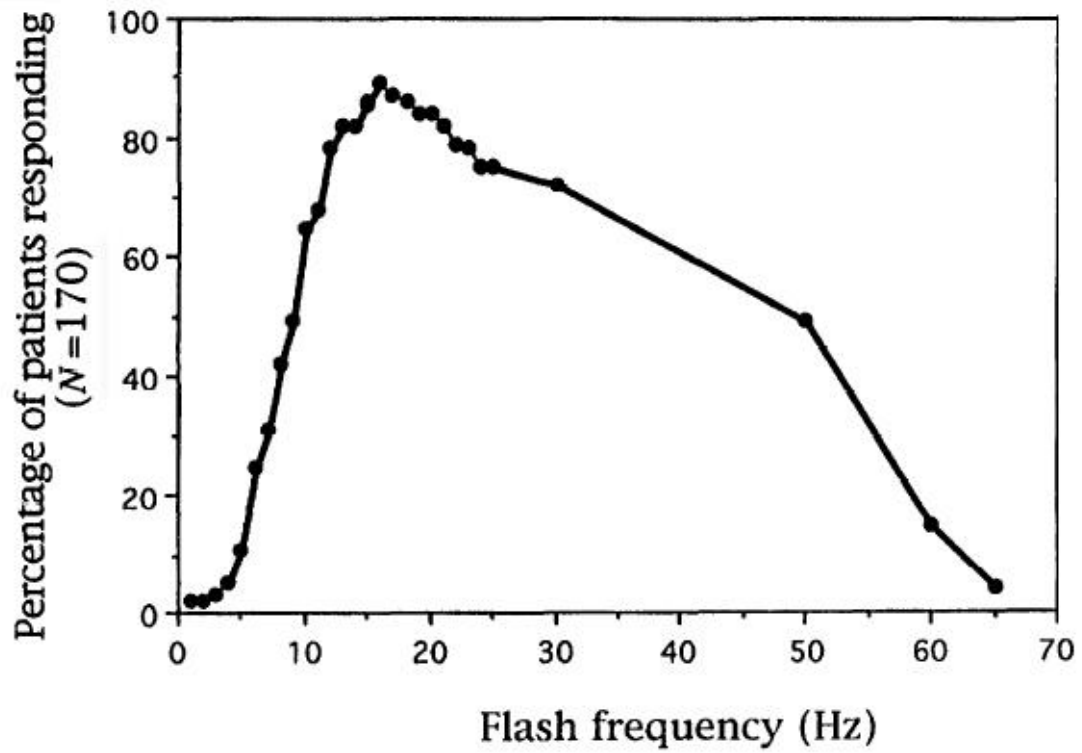
2 **A. Photosensitive Epilepsy**

3 About one in 4000 individuals is recognized as having photosensitive
4 epilepsy. Repetitive flashing lights and static repetitive geometric patterns
5 may induce seizures in these individuals, and in perhaps as many again who
6 have not been diagnosed and may be unaware that they are at risk.

7 The seizures reflect the transient abnormal synchronized activity of brain
8 cells, affecting consciousness, body movements and/or sensation. The onset
9 of photosensitive epilepsy occurs typically at around the time of puberty; in
10 the age group 7 to 20 years the condition is five times as common as in the
11 general population. Three quarters of patients remain photosensitive for life
12 (Harding and Jeavons, 1994; Wilkins, 1995; Fisher et al. 2005). Many factors
13 [see Fisher et al., 2005 for extensive reference list and survey of the factors]
14 may combine to affect the likelihood of seizures including:

15 how quickly the light is flashing (**flash frequency**). Any repetitive change
16 in a visual stimulus within the frequency range 3 Hz to 65 Hz, is
17 potentially a risk and the greatest likelihood of seizures is for frequencies
18 in the range 15 Hz to 20 Hz, see Fig. 1. The flashes do not have to be
19 rhythmic.

- 20 • **Brightness**. Stimulation in the scotopic or low mesopic range (below
21 about 1 cd/m²) has a low risk and the risk increases monotonically
22 with log luminance in the high mesopic and photopic range.
- 23 • **Contrast** with background lighting. Contrasts above 10% are
24 potentially a risk.
- 25 • **Distance** between the viewer and the light source, which determines
26 the total **area** of the retina receiving stimulation. The likelihood of
27 seizures increases according to the representation of the visual field
28 within the visual cortex of the brain. The cortical representation of
29 central vision is greater than that of the visual periphery, and so
30 the **location** of stimulation within the visual field is important: stimuli
31 presented in central vision pose more of a risk than those that are
32 viewed in the periphery, even though flicker in the periphery may be
33 more noticeable.
- 34 • **wavelength** of the light. Deep red flicker and alternating red and blue
35 flashes may be particularly hazardous.
- 36 • whether a person's **eyes** are **open** or **closed**. Bright flicker can be
37 more hazardous when the eyes are closed, partly because the entire
38 retina is then stimulated. However, if flickering light is prevented from
39 reaching the retina of one eye by placing the palm of a hand over that
40 eye, the effects of the flicker are very greatly reduced in most
41 patients.



1

2 Figure 1. Percentage of patients with photosensitive epilepsy exhibiting epileptiform EEG
3 responses to the flicker from a xenon gas discharge lamp shown as a function of flash
4 frequency. After Harding and Jeavons (Harding and Jeavons, 1994).

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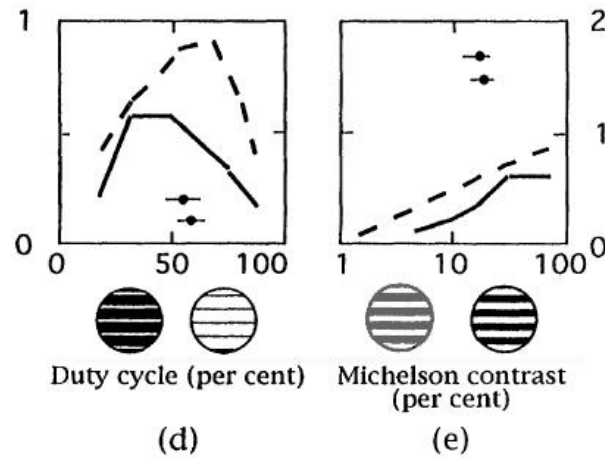
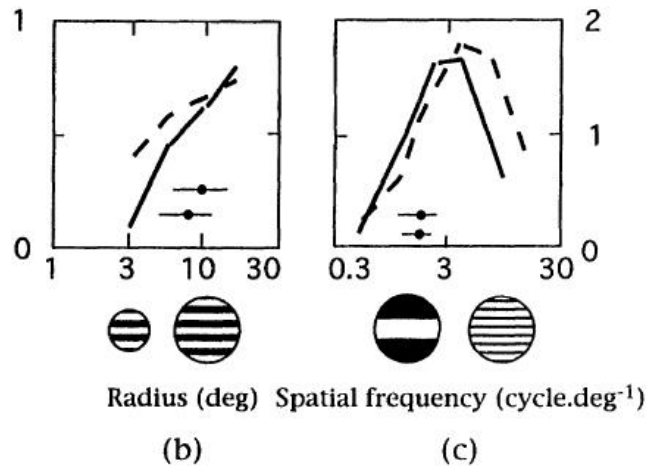
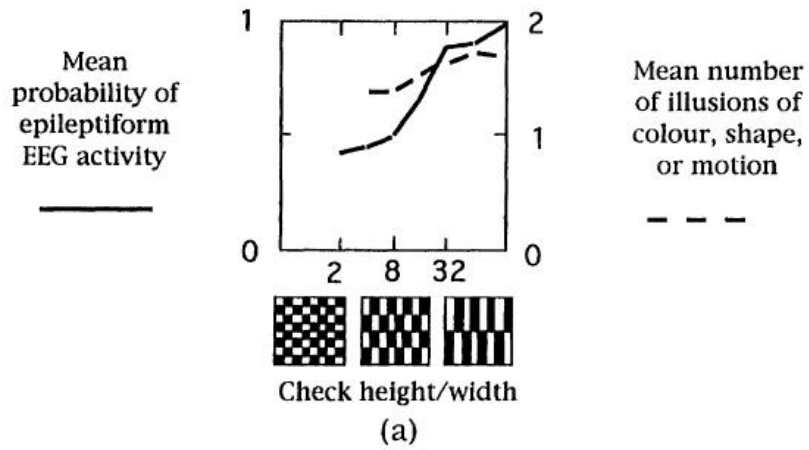


Figure 2. Escalator stair tread

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In addition, a substantial minority of patients (usually those who are sensitive to flicker) are sensitive also to **spatial patterns**, see Fig. 2 for an example. About one third of patients are sensitive to patterns even when there is no flicker, and most are more sensitive to flicker if it is patterned (Harding and Jeavons, 1994; Wilkins, 1995; Fisher et al., 2005; Wilkins et al. 1979). The worst patterns are those of stripes in which one cycle of the pattern (one pair of stripes) subtends at the eye an angle of about 15 minutes of arc, see Fig. 3. The stair tread on escalators provides an example of such a pattern

As with flicker, the effects of such patterns are greater the brighter they are, the higher their contrast, and the larger the area of retina stimulated.



1
 2 Figure 3. Mean probability of epileptiform EEG activity in patients with photosensitive epilepsy
 3 when viewing geometric patterns of checks or stripes, shown as a function of various
 4 parameters. Variation in the pattern parameters is represented schematically beneath the
 5 abscissae. Perceptual distortions reported by normal observers (broken lines) are similarly
 6 affected. After Wilkins (Wilkins, 1995) Figure 3.1.

7
 8

1 **B. Covert hazards of invisible (imperceptible) flicker**

2
3 The frequency of the alternating current electricity supply is 60Hz in America
4 and 50Hz in Europe; in Japan, both 50Hz and 60Hz are used in different
5 regions. The circuitry in older fluorescent lamps with magnetic ballasts
6 operate so as to flash the lamps at twice the supply frequency (100Hz or
7 120Hz). However, as the lamps age, the flashes that occur with one direction
8 of current may not equal those that occur with the other direction, and the
9 lamps may emit flicker with components at the frequency of the electricity
10 supply. It has been determined that photosensitive seizures should not occur
11 if fluorescent lamps are operating properly. However, when the lamps
12 malfunction giving flicker below 70Hz, electroencephalographic recordings
13 indicate a risk of seizures. Nevertheless some photosensitive patients do
14 complain of normally functioning (older) fluorescent lighting (Binnie et al.,
15 1979)(with magnetic ballasts).

16
17 Measurements of the electroretinogram have indicated that modulation of
18 light in the frequency range 100-160Hz is resolved by the human retina even
19 though the flicker is too rapid to be seen (Burns et al. 1992) and even up to
20 200 Hz in (Berman et al., 1991). In an animal (cat), 100Hz and 120Hz
21 modulation of light from fluorescent lamps has been shown to cause the
22 phase-locked firing of cells in the lateral geniculate nucleus of the thalamus,
23 part of the brain with short neural chains to the superior colliculus, a body
24 that controls eye movements (Eysel and Burandt, 1984). There are several
25 studies showing that the characteristics of human eye movements across
26 text are affected by modulation from fluorescent lamps and cathode ray tube
27 displays (e.g. Wilkins,1986; Kennedy and Murray, 1991), and two studies
28 have shown impairment of visual performance in tasks involving visual
29 search as a result of flicker from fluorescent lamps (e.g. Jaen et al., 2005).
30 Under double-masked conditions the 100Hz modulation of light from
31 fluorescent lamps has been shown to double the average incidence of
32 headaches in office workers, although this effect is attributable to a minority
33 that is particularly affected (Wilkins et al., 1989).

34
35 Sensitivity affects due to flicker at frequencies above perception have also
36 been observed in normal people with good vision and health. A substantial
37 decrement in sensitivity to visible flicker at 30 Hz, used as a testing
38 condition, occurs in those people when there is a prior exposure of only 2
39 minutes duration with flicker frequencies about 20% above the observers
40 critical fusion frequency (CFF) (Shady et al. 2004).

41 **Computer monitors and backlights**

42
43 When making a rapid jerk (saccade), for example when reading, the eyes
44 move at a velocity of about 180 degrees per second. As a result, any
45 intermittently lit contour is displaced at a succession of retinal positions
46 during the flight of the eye and can sometimes be seen as a set of repetitive
47 targets. The LED rear lamps of motor vehicles can produce such an effect.
48 Some displays on netbook computers have LED backlights and exhibit

1 significant flicker at 60Hz. Their flicker also results in the perception of
2 multiple images during a saccade. It is possible that this effect is responsible
3 for the known disturbance of ocular motor control by high frequency flicker, a
4 disturbance which, in its turn, may be responsible for the known impairments
5 in visual performance.

6 7 **Modulation depth and the Fourier fundamental.**

8 The effects of flicker depend not only on the frequency of the flicker but also
9 on the modulation depth. For visible flicker, the amplitude of the Fourier
10 fundamental predicts flicker fusion (de Lange Dzn, 1961). For flicker that is
11 not visible the effects of different waveforms have not been studied in detail.
12 The peak-trough modulation depth of the 100-120Hz flicker from fluorescent
13 lamps varies with the component phosphors, some of which exhibit
14 persistence, varying the chromaticity of the light through its cycle (Wilkins
15 and Clark, 1990). The peak-trough modulation depth known to induce
16 headaches from fluorescent lighting at 100Hz is about 35% (Wilkins et al.,
17 1989).

18 19 **C. Summary of Risks to Health**

20 The obvious risks to health occur

- 21 • from flicker that is visible;
- 22 • immediately.

23 The risks include seizures, and less specific neurological symptoms including
24 headache, dizziness and general malaise. Seizures can be triggered by flicker
25 in individuals with no previous history or diagnosis of epilepsy. (It is not
26 known whether seizure occurrence carries an increased risk of further
27 occurrence.) The chances of seizures are greatest with flicker from lighting
28 (e.g. strobe lamps) because of the brightness and the large area of retina
29 stimulated.

30
31 The less obvious risks to health occur

- 32 • from flicker that is invisible¹;
- 33 • after exposure of more than about 20 minutes.

34
¹ The upper frequency limit above which high frequency flicker ceases to have biological effects is not known. However, IEEE Standard P1789 speculates (not based on experimental evidence) that a conservative estimate can be obtained as follows. Spatial modulation of high contrast boundaries is visible below about 30cycles/degree. The eyes move at a velocity of about 180degrees per second during a saccade. This would suggest that modulation of light is unlikely to affect vision or ocular motor control at frequencies above 30cycles/degree x 180degrees/second =5.4kHz. When the light illuminates rapidly moving objects these considerations may not apply. Further the actual upper limit on frequency may be lower and depends on many factors, including but not limited to size/brightness of light, eye cone chemistry, modulation, etc. (This is conservative estimate and need not in any way be interpreted as a recommendation on flicker frequencies). It should be noted that this discussion is based on visual health effects only. There may be audio effects between 20Hz and 20kHz, maximal at 2-3kHz. The above 5.4kHz conservative limit takes no account of "saccadic suppression", the reduced perception of spatial contrast during the flight of the eye, due in part to the stronger contrast images seen before and after the saccade.

1 The risks include headaches and eye-strain. The risks are subtle and
2 insidious but should not be ignored. (Migraine headache is covertly disabling,
3 a major economic burden, and carries an increased risk of stroke.) The
4 sources of high frequency flicker associated with headache include lighting
5 (formerly principally lighting from gas discharge lamps) and computer
6 screens (formerly cathode ray tube displays, now LED back-lights).

7
8 As noted in the table below, much of the literature might suggest that
9 $\sim 160\text{Hz}$ – $\sim 200\text{Hz}$ may be a sufficient limit for flicker to have negligible
10 biological effects in some lighting applications, but note that none of the
11 literature considers the eyes in motion across a high spatial contrast.

12
13 Finally, it is important to mention that the fact that there is “biological effect”
14 (ERG or notice of visual flicker in special circumstances) does not necessarily
15 imply health risk to viewers. For example, flickering light at $\sim 200\text{Hz}$ may
16 theoretically be annoying to spectators of tennis or ping-pong games, but
17 may not pose any health risks (Rea and Ouellette, 1988).

18
19 The table below summarizes and categorizes the types of flicker and the
20 biological effects they cause. The first five rows relate to obvious health risks
21 and the remainder to those that are less obvious. The reference list is not all-
22 inclusive, but is only meant to be an indicator for typical frequency ranges
23 relevant to LED flicker health risks. The table and this report do not address
24 the modeling, estimation, or measuring of critical flicker-frequency (CFF)
25 (Kelly, 1969; Kelly, 1971; Halpin et al, 2003). The topic of CFF and
26 determining when time varying light stimulus is no longer perceptual under
27 normal observers and circumstances is covered by the separate IEEE
28 standards groups IEEE P519 and IEC 61000. The IEEE Standard P1789 will
29 refer to these documents as needed. However, this report tries to summarize
30 not the perception of flicker but its health effects, both when the flicker is
31 visible and when it is imperceptible.

32

1 Table 1. Sources of flicker, their frequency range and biological effects, and
 2 references to the evidence.

Source of flicker	Frequency range	Biological effect	Evidence
Sunlight through roadside trees or reflected from waves	Various	Seizures	Clinical histories (Harding and Jeavons, 1994)
Xenon gas discharge photo-stimulator	3-60Hz	Epileptiform EEG in patients with photosensitive epilepsy	Many clinical EEG studies e.g (Harding and Jeavons, 1994)
Malfunctioning Fluorescent lighting	Large 50Hz component	Epileptiform EEG in patients with photosensitive epilepsy	(Binnie et al., 1979)
Television	50Hz and 60Hz (discounting 25Hz component)	Epileptiform EEG in patients with photosensitive epilepsy	Many studies eg (Harding and Harding, 2008; Funatsuka et al., 2003)
Flashing televised cartoon	~10Hz	Seizures in children with no previous diagnosis of epilepsy	Major incident (Okumura et al, 2004)
Normally functioning fluorescent lighting (50Hz ballast)	100Hz (small 50Hz component)	Headache and eye strain	Many anecdotes.
Normally functioning fluorescent lighting (50Hz ballast)	100Hz (small 50Hz component)	Headache and eye strain	Double-masked study (de Lange Dzn, 1961)
Normally functioning fluorescent lighting (50Hz ballast)	32% modulation	Reduced speed of visual search	Two masked studies (Jaen et al., 2005; Veitch and McColl, 1995)
Normally functioning fluorescent lighting (60Hz ballast)	120Hz	Reduced visual performance	(Veitch and McColl, 1995)
Normally functioning fluorescent lighting (50Hz ballast)	100Hz (minimal 50Hz component)	Increased heart rate in agoraphobic individuals	(Hazell and Wilkins, 1990)
Normally functioning fluorescent lighting (50Hz ballast)	100Hz	Enlarged saccades over text	(Wilkins, 1986)
Visual display terminals	70-110Hz raster	Changes in saccade size	(Kennedy et al., 1998)
Visual display terminals	~70Hz Raster		Many anecdotal reports of prolonged photophobia
Normally functioning fluorescent lighting	100Hz and 120Hz	Phase-locked firing of LGN neurons in cats	(Eysel and Burandt, 1984)
Various	Up to 162Hz	Human electroretinogram signals at light frequency	(Berman et al., 1991; Burns et al 1992)
Normally functioning fluorescent lighting (50Hz ballast)	100Hz	Inconsistent changes in plasma corticosterone levels in captive starlings	(Maddocks et al., 2001)
Normally functioning fluorescent lighting (50Hz ballast)	100Hz	Mate choice in captive starlings	(Evans et al., 2006)

1 **A few general implications for practice**

2 Visual flicker is an undesirable attribute to any lighting system. The above
3 Table 1 summarizes research suggests that, for both visible and invisible
4 flicker (in the mentioned frequency ranges), there may be a special at-risk
5 population for which flicker is more than just annoying in that it could be a
6 potential health hazard. This, however, will depend on modulation depth,
7 ergonomics, flicker parameters and their relation to perception and the ability
8 to measure/determine the influence of these parameters with human
9 diagnostics. These topics are beyond the scope of this report and will be
10 covered in future IEEE P1789 documents. However, it is possible to make
11 general comments about the research citations listed in Table 1:

12
13 1. *Frequency.* Normally functioning fluorescent lighting controlled by
14 magnetic ballast has been associated with headaches due to the flicker
15 produced. LEDs driven so that they flicker at a frequency twice that of the AC
16 supply may have a depth of modulation greater than that from most
17 fluorescent lamps. The effects of the flicker are therefore likely to be more
18 pronounced in these cases.

19
20 2. *Field of view.* Point sources of light are less likely to induce seizures and
21 headaches than a diffuse source of light that covers most of a person's field
22 of vision. Flicker from LEDs used for general lighting is therefore more likely
23 to be a health hazard than that from LEDs used in instrument panels.

24
25 3. *Visual task.* The invisible flicker described in Table 1 is more likely to cause
26 problems when the visual task demands precise positioning of the eyes, as
27 when reading.

28
29 4. *Spatial distribution of point sources of light.* Spatial arrays of continuously
30 illuminated point sources of light have the potential to induce seizures in
31 patients with photosensitive epilepsy when the field of view is large and when
32 the arrays provide a spatial frequency close to 3 cycles/degree (e.g. large
33 LED public display boards viewed from close proximity).

34 35 **II. Typical LED Driving Methods in Low Flicker Frequency Range**

36
37 There are several common methods that are used to drive LEDs that can
38 operate with frequency of modulation in the ranges discussed in the above
39 table (below 120Hz, including frequencies in the vicinity of 15Hz.) For
40 example, commercially available LED lamps have reported (Rand et al.,
41 2007; Rand, 2005) to produce visual flicker in the 15Hz range when
42 connected to a conventional residential dimmer. The present report
43 summarizes this effect only, and deep technical explanation (theory,
44 experiments, and simulations) can be found in (Rand et al., 2007).

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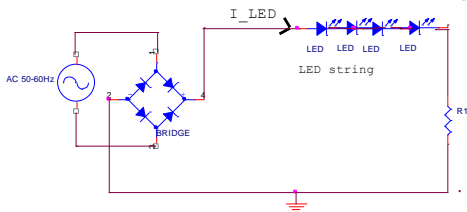
1 Below, we present only a few driving approaches for that modulate in
 2 frequency ranges from zero to 120Hz. The list is not exhaustive, and the
 3 discussions are only meant to demonstrate typical driving LED currents with
 4 frequencies in this range.

5 **A. LED Driving Current Frequencies in Range: ~100Hz–120Hz**

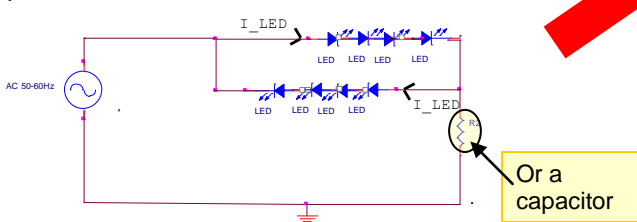
7 (1) *Full Wave Rectifier Connected to LED String*

8 In this approach, the AC input source is sent into a full wave rectifier,
 9 causing the (approximate) absolute value of the input voltage to be sent to
 10 the load. In this case, the current through the LEDs has waveform shape
 11 similar to a scaled absolute value of a sine wave. That is, the rectified sine
 12 wave may be of the form $|V_p \sin(\omega t)|$, where V_p is the amplitude of the sine
 13 wave and ω is the angular frequency in radians $\omega = 2*\pi*f$. In this case, the
 14 LED current is of similar shape, as Fig. 4 below shows. In a first
 15 approximation, the LED current is equal to a scaled rectified voltage, with the
 16 additional deadtime (zero current) caused by the LED bias voltage. Thus,
 17 when properly functioning, the direct full wave rectifier driving approach
 18 modulates the LEDs at twice the line frequency, which in North America leads
 19 to 120Hz modulation and in Europe leads to 100 Hz modulation. As Fig. 4(a)
 20 shows, often a resistor is added in series with the LED string for current
 21 limiting protection.

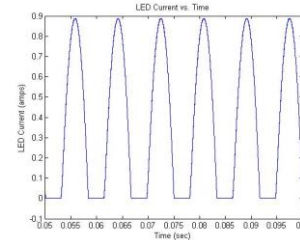
(a) Rectify AC and send to LED string



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



LED Current



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

22

23 Figure 4. Two methods to drive LEDs at twice line frequency: (a) Full bridge
 24 rectification, (b) Opposite connected parallel strings, and (c)
 25 Current/Luminous Output in the LEDs for both approaches.

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2

3 (2) *Directly Drive Two Parallel LED Strings with Opposite Anode/Cathode*
 4 *Connections*

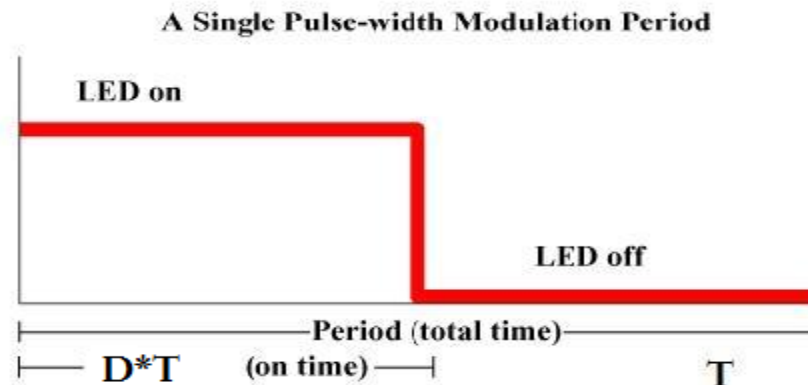
5 A second LED driving method that doubles line frequency is shown in Fig.
 6 4(b). Two strings of LEDs are powered in parallel, with anode of one
 7 paralleled string connected to the cathode of the other parallel string. When
 8 the AC line voltage is positive, energy drives one of the LED strings. When
 9 the AC line voltage is negative, the other paralleled LED string is driven. At
 10 most, one of the LED strings has current through it. The net effect is that the
 11 effective LED driving current is modulating at 120 Hz in North America or 100
 12 Hz in Europe.

13 Thus, for both driving methods illustrated in Fig. 4, the LED current
 14 modulates at twice the line frequency. Since the intensity of the LEDs is
 15 proportional to the current through the LEDs, this causes the LEDs to flicker
 16 at frequency equal to twice the AC line frequency, i.e. 100Hz~120Hz.

17 There are many variations of the approach in Fig. 4 that are not shown. They
 18 utilize different circuitry but rely on the fact that in the positive AC line cycle,
 19 current flows through sets of LED strings and during the negative line cycle,
 20 current flow through different sets of LED strings. The net effect is commonly
 21 to produce 120Hz flicker harmonic at twice the line frequency.

22 (3) *Simple Dimming Pulse Width Modulated (PWM) Circuits*

23 As discussed in the previous section on LED driving methods (Give reference
 24 to this section), it is common to dim LEDs by pulsing the current through
 25 them intentionally. The simplest waveform that does this is the PWM signals
 26 shown in Fig. 5.



27

28

Figure 5. Pulse Width Modulated Dimming

1 By adjusting the length of time that the LED current is High or Low (zero) in
2 Fig. 5, the luminous intensity of the LED is adjusted. Frequency, by definition
3 is equal to $1/T$, where T is the period of the signal. Thus, PWM dimming
4 circuits may be designed to operate at any frequency, whether the input is
5 DC or AC. (It should be noted that it is not uncommon for LED drivers using
6 AC residential phase modulated dimmer circuits, described below to attempt
7 to emulate the above signal with frequency 120Hz. That is, when the AC
8 dimmer shuts off, no current is sent to the LEDs.)

9 It should be mentioned that there are alternative approaches to dimming,
10 such as amplitude dimming, in which the current through the LED is
11 continuous and not pulsing. By reducing the value of this continuous current
12 (amplitude), the brightness is dimmed. This approach does not use flicker to
13 adjust brightness and therefore, should not induce flicker related health
14 risks.

15 (4) *Power Factor Correction Circuitry*

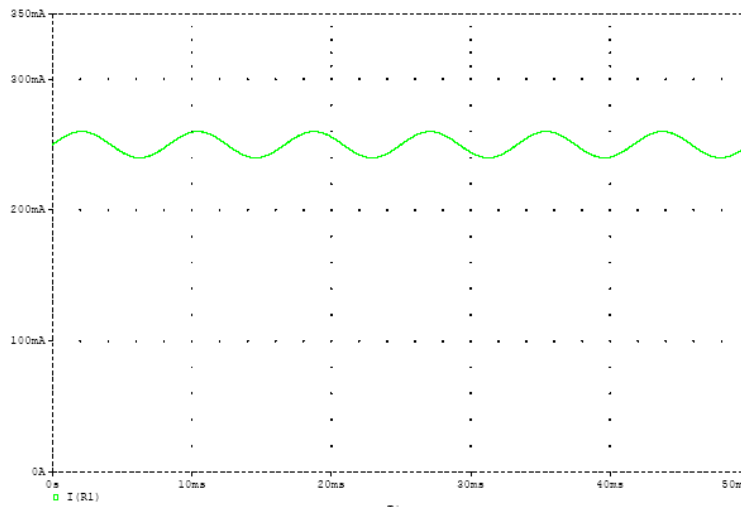
16 Even when sophisticated high frequency switching power supplies with power
17 factor correction circuits are used to drive LEDs from AC mains, there is
18 commonly a frequency component in the current (and luminous intensity) of
19 the LEDs at twice the line frequency.

20 Depending on the design of the circuitry, the harmonic content of this flicker
21 may vary from being small (Fig. 6(a)) and unnoticeable to being significant in
22 magnitude (Fig. 6(b)). The simulations illustrate the current through a string
23 of LEDs. This current is approximately proportional to luminous intensity.
24 There is a DC current through the LEDs but also a 120Hz modulated signal.
25 Referring to Fig. 6(b), the LED current has average value of 250 mA, yet the
26 120 Hz signal superimposed upon the DC value has peak-to-peak value of
27 100mA (40% the average LED current). The ripple in Fig. 6(a) is only 10mA
28 peak to peak (4% of the average LED current of 250mA). Using the definition
29 of modulation in the beginning of this report, this implies that Fig. 6(a) has
30 2% Percent Flicker and Fig. 6(b) has 20% Percent Flicker.
31 (Modulation/percent flicker will be half the peak-to-peak percent ripple
32 value.)

33

34

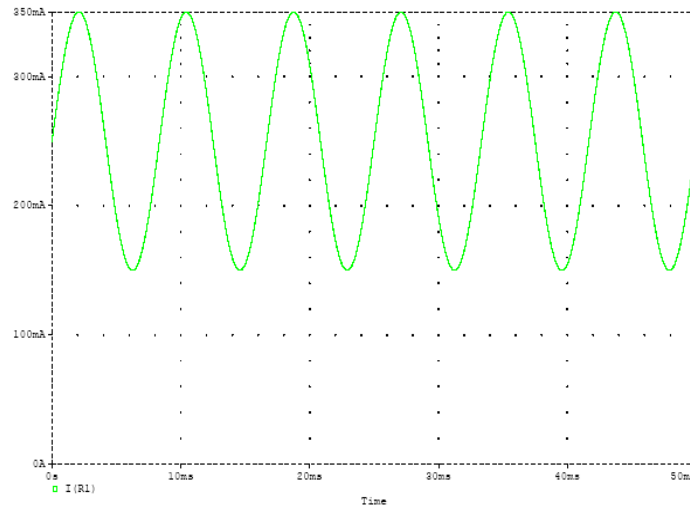
35



1

2

(a)



3

4

(b)

5 Figure 6. Typical LED current being driven by PFC circuitry, each having
 6 120Hz component at twice the AC mains line frequency. Fig. 6(a) has small
 7 ripple, while Fig. 6(b) has high 120Hz harmonic content. Luminous intensity
 8 is proportional to the current in the LED. Therefore Fig. 6(a) has flicker with
 9 small modulation and Fig. 6(b) has higher flicker modulation, each at 120Hz.

10 B. LED Driving Current Frequencies in Range: 3Hz~70Hz

11

12 (1) Failures in rectification or LED strings: 50Hz ~ 60 Hz Modulation

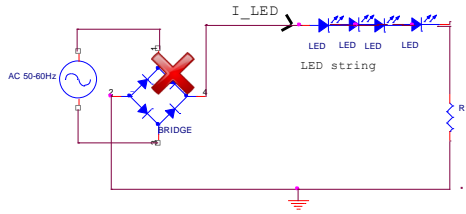
13 In either of the two methods described in Section II.A, there is risk of failure
 14 that can cause LED current modulation at AC line frequency, thereby entering

1 the range of frequencies that may induce photosensitive epilepsy. For
2 example, if one of the legs of the full wave rectifier bridge fails, then it is
3 common that the leg becomes an open circuit. Open circuits prevent current
4 flow, and therefore, the LED modulation frequency may change. As Fig. 7
5 shows, this single diode failure in the rectifier will cause the output voltage
6 for the full wave rectifier to become the input voltage for half the AC line
7 cycle, and then 0 volts for the remaining half line cycle. This means that if
8 the AC Mains frequency is f and the period is $T=1/f$, then non-zero voltage is
9 applied to the LEDs for $0.5 \cdot T$ seconds and then is zero for the next $0.5 \cdot T$
10 seconds, causing the LED current to modulate at line frequency.

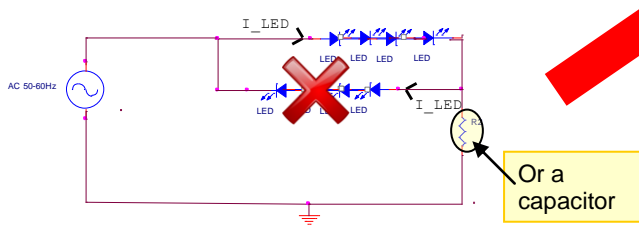
11 Similarly, when the two strings of LEDs are connected in parallel with
12 opposite anodes and cathodes in each string, a failure in one string of the
13 LEDs may cause an open circuit to occur in that string. The net effect is the
14 same as before: the current is modulating at line frequency, i.e. 50Hz ~
15 60Hz. This is shown in Fig. 7, where an 'X' is used to indicate open circuit.

16 For example, the LED current waveform in Fig. 7(c) assumes 60Hz line
17 frequency. Compared with the effective LED driving current in Fig. 4(c)
18 (when the driving is properly functioning), there is zero current each half line
19 cycle. That is, the source energy is being used to drive the LEDs from $0 \text{ sec} <$
20 $t < 1/120 \text{ sec}$ (although the LEDs may not be driven that entire time
21 duration). Then there is no current through any of the LEDs from $1/120 \text{ sec} <$
22 $t < 1/60 \text{ sec}$. The periodic cycle repeats itself, thus leading to 60 Hz
23 modulation of the LEDs. Similarly, in Europe, these failures may lead to
24 50 Hz modulation. This low frequency driving current leads to brightness
25 flicker in the LEDs at 50Hz~60Hz, since the current in the LEDs is
26 proportional to their intensity. This is in a range of frequencies that are at
27 risk of causing photosensitive epilepsy.

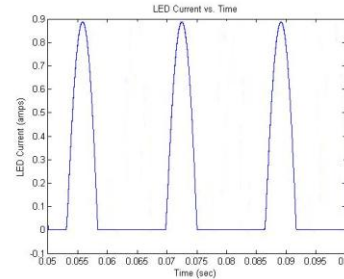
(a) Rectify AC and send to LED string



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



LED Current



(c) Simulation of current through HB LEDs. Luminous intensity is proportional to current, causing lamp to flicker at the AC mains line frequency (shown periodic every 1/60 sec)

1

2 Figure 7. Diode failure(a) or LED failure(b) may cause low frequency flicker
3 (c) at line frequency through strings of LEDs.

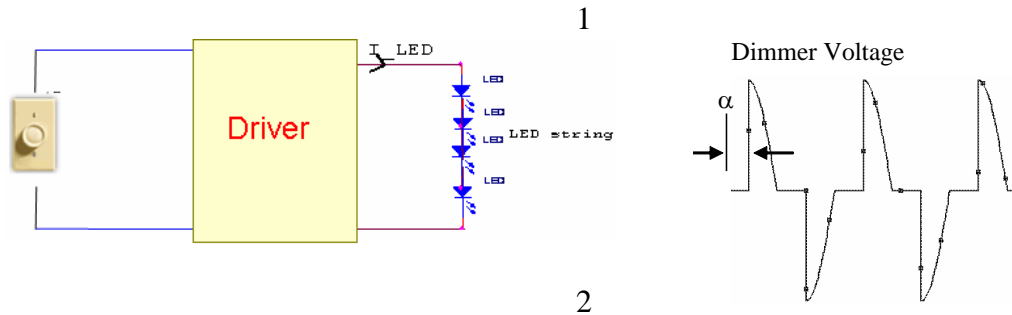
4

5 (2) Residential Dimmer Switches Can Cause Low Frequency Flicker (~3Hz – 70Hz)
6 (see (Rand et al., 2007; Rand, 2005) for technical details of discussion
7 below)

8 Residential dimmers for incandescent bulbs primarily utilize phase
9 modulating dimming through triac switches to control the power sent to the
10 bulb. These dimmers actually control the RMS voltage applied to the bulb by
11 suppressing part of the AC line voltage using a triac. The effect is a chopped
12 sine wave as shown in Fig. 8. Thus, as the dimmer switch is manually
13 adjusted, the value of the off-time, α (often referred to as the phase delay)
14 changes. As α is increased in Fig. 8, less power goes to the incandescent bulb
15 and brightness is reduced

16 Many LED lamps and their associated drivers do not perform properly with
17 residential phase modulated dimmers. Often on the LED bulb application
18 notes or on the lamp’s manufacturer web sites, there are warnings to the
19 user that their bulbs may not work properly when used with residential
20 dimmer switches. The work of (Rand et al., 2007; Rand, 2005) explains the
21 causes of these failures and shows that low frequency flicker may occur.

22



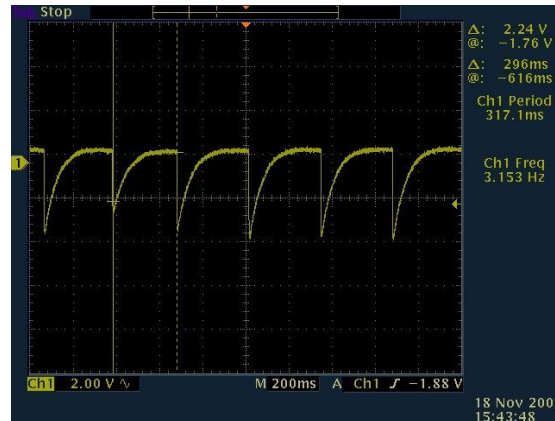
3
4 Figure 8. Residential dimmer and its output voltage sent to the driver (Rand
5 et al., 2007).

6
7
8 Fig. 9 illustrates how one type of commercially available LED lamp flickers in
9 the noticeable visual range when connected to a dimmer switch. The
10 particular lamp involved has a common LED driver configuration (further
11 discussed below) of a full bridge rectifier with capacitor filter within their
12 Edison Socket, described in more detail in (Rand et al., 2007; Rand, 2005).
13 The results presented in the figure may be typical of similar driving
14 configurations. The circuit will continuously peak charge the filter capacitor to
15 the peak voltage of the input waveform, i.e. 169Vdc for standard 120Vac line
16 voltage. This high level DC voltage may then be fed into a large string of
17 LEDs in series. For example, typical lamps may have parallel strings of 50 or
18 more (perhaps Red, Green and Blue, averaging 2.6V at 90mA) LEDs in series
19 attached through a current limiting resistor to the high level DC voltage. The
20 particular lamp tested utilized a combination of 64 Red, Green and Blue LEDs
21 to produce white light.

22 The **experimental data** in the Fig. 9 represents the voltage of a photo-
23 sensor placed directly underneath the LED lamp. Specifically, a photoresistor
24 circuit is used to generate a voltage proportional to the light intensity shining
25 on it. As the experimental voltage shows, the bulb malfunctions when
26 connected to (phase modulated) residential dimmer switch. It produces a
27 noticeable visual flicker frequency. In particular, the flicker varies between
28 around 3.0Hz and 3.3Hz, with average over many cycles of 3.153Hz. This
29 frequency is in the range that has been shown to be a risk for causing
30 photosensitive epileptic seizures.

31 The flicker illustrated in this above scope plot is typical of several LED lamps
32 on the market when connected to a dimmer. However, the precise flicker
33 frequency is hard to predict, as it may either be higher or lower depending
34 on various factors such as number of lamps on the dimmer, position of the
35 dimmer switch (the value of desired off-time α), and/or internal
36 characteristics of the lamp. However, as the experimental oscilloscope plot
37 shows, the flicker frequency may be in the range that induces photosensitive
38 seizures.

1



2

3 Figure 9. Commercial LED lamp flickers at 3.15Hz when connected to typical
4 residential dimmer switch.

5 The reasons that the dimmer switch may fail when connected to LED lamp
6 bulbs is explained in (Rand et al., 2007; Rand, 2005) for two cases of typical
7 LED driving circuits: full wave capacitor rectifiers and rectifiers with DC/DC
8 converters, which are now summarized:

9 **Full Wave Rectifier with Capacitor:**

10 Since the dimmer has a triac switch internally, it needs to charge an internal
11 capacitor to generate a high enough voltage to turn on the internal triac to
12 send energy to the lamp. However, this charging cannot occur properly due
13 to the filter capacitor in the LED driving circuit. Essentially the additional filter
14 capacitor in the LED lamp is causing a high impedance path and slows down
15 charging needed in the dimmer. Thus, it takes several cycles to charge the
16 triac's capacitor within the dimmer to turn the dimmer on and let energy flow
17 to the lamp. Thus, the dimmer would desire to turn on and off twice per AC
18 line cycle, i.e. every 120Hz in USA. But the capacitor filter slows down the
19 internal charging within the dimmer to occur at much lower frequencies.
20

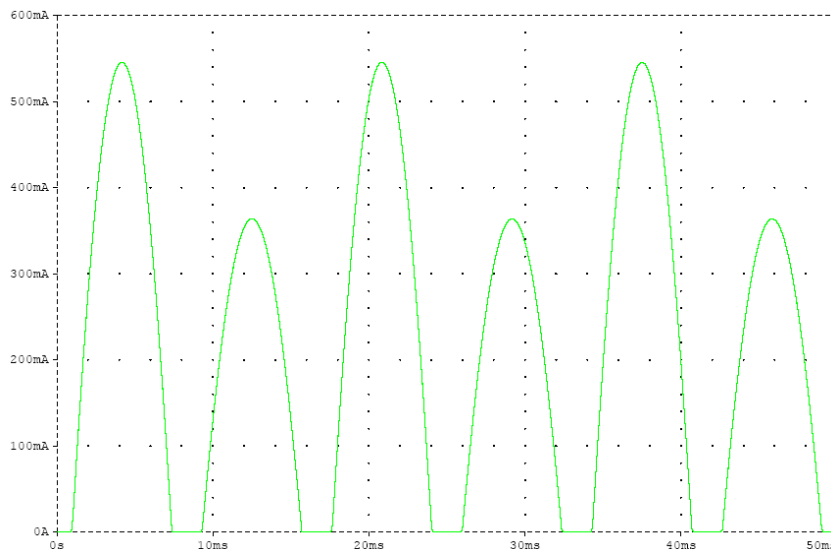
21 **DC/DC Converters for LED Drivers with Residential Dimmers:**

22 Often, LED lamps utilize DC/DC converters after the full wave rectification
23 and capacitive filter. These LED Edison socket bulbs may not utilize power
24 factor correction, since their wattage is so small and there are (at the time of
25 writing) no regulations requiring them to be implemented. Thus, simple buck
26 derived (step-down power converters), low cost, systems are sometimes
27 utilized after the rectification. As experimentally shown in (Rand et al., 2007;
28 Rand, 2005), many of these systems typically have difficulty with residential
29 dimmer switches. For example, even when the triac dimmer is off, it
30 sometimes has finite leakage current. This sometimes results in enough
31 voltage across the input of the driver IC to turn the LED lamp briefly on and

1 then off again. Hence, the LED lamp flickers and never fully turns off. This is
 2 just one type of failure that has been reported. The flicker frequency
 3 reported in (Rand et al., 2007) was at 15Hz for sample LED lamps, typical of
 4 waveforms shown in the oscilloscope plot above. Thus, these driving
 5 techniques may cause flicker frequency in the range of 3Hz-60Hz, which is in
 6 a range of frequencies that is at risk to induce photosensitive seizures.

7 *(3) Uneven Brightness in Different LED Strings When Connected as in Fig.*
 8 *4(b)- With Strings Having Opposite Anode/Cathode Connections*

9
 10 Consider the circuit in Fig. 4(b). Notice that each LED must have the same
 11 dynamic characteristics (forward voltage and dynamic resistance) in order for
 12 the current to be perfectly balanced in each alternating illuminated string. If
 13 for some reason this does not occur (aging, temperature gradients, poor
 14 design), then the current through the strings will not be identical each cycle.
 15 For example, suppose over time, aging causes degradation of one of the two
 16 strings in Fig. 4(b) such that its string resistance increases by 50%. This
 17 could also be caused by improper design of each string in Fig. 4(b) so that
 18 the current in each string is not balanced. This is quite possible since LEDs
 19 are binned by different voltages, and further, each string may be composed
 20 of different color LEDs that have different nominal voltage drops for the same
 21 current. Then, the effective LED current through the bulb will look as in Fig.
 22 10.
 23



24
 25 **Figure 10. Unbalanced LED Current in Each String of LEDs Using**
 26 **Driving Method in Fig. 4(b). The unbalanced driving will cause uneven**
 27 **luminous output in the lamp and low frequency flicker.**

28
 29 For example, the effective DC LED current in Fig. 10 has average value of
 30 around 233mA. However, the Fourier component at 60 Hz (taking FFT) is
 31 80mA and the Fourier component at 120Hz is nearly 240mA. Thus, in this
 32 example the low frequency component of 60Hz represents over 33% of the

1 DC component, while the 120 Hz component represents 100% of the DC
2 current. Higher frequency components of the LED current in the above figure
3 are also present in multiples of 60Hz. However, the above typical analysis
4 indicates that LED lamps may demonstrate flicker frequency at line
5 frequency, similar to older fluorescent lamps (previously discussed) that aged
6 unevenly: the flashes/brightness with one direction of line current may not
7 equal those that occur in the other direction of line current.

8
9 The above example also illustrates that it is possible for flicker in a lamp to
10 have harmonics with multiple low frequency components, here at both 60Hz
11 and 120Hz.

12
13
14
15
16 *Final Comments:* The driving approaches described above are not exhaustive
17 and are only meant to introduce the reader to a few common approaches in
18 which LEDs have flicker. Other approaches/applications of LED lighting that
19 may also have flicker include, but are not limited to, pulse amplitude
20 modulation driving, triangle wave currents through LEDs, using LED flicker
21 for wireless communication (see IEEE Standard 802), beat frequencies
22 created through the interaction of different lamp flicker frequencies, etc.

23
24

1 **Primary References for This Report**

2 (Please refer to the IEEE P1789 website for additional references
3 <http://grouper.ieee.org/groups/1789/> that were also used. The web
4 site will continuously be updated.)

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14 **IEEE Approved Scope of PAR1789**

15
16 *The scope of this standard is to: 1) Define the concept of modulation frequencies*
17 *for LEDs and give discussion on their applications to LED lighting, 2) Describe*
18 *LED lighting applications in which modulation frequencies pose possible health*
19 *risks to users, 3) Discuss the concept of dimming of LEDs by modulating the*
20 *frequency of driving currents/voltage 4) Present recommendations for modulation*
21 *frequencies for LED lighting and dimming applications to protect against known*
22 *adverse health effects.*

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33 The report was assembled with input from many members of P1789.

34 35 **Members of the P1789 committee at the time of the report being** 36 **written (including observers):**

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