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 and 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 ~3-~70Hz;
2. Health concerns due to invisible (not perceivable) flicker at frequencies below ~165Hz 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 by primary authors; 3) Presentation and editing of the report in a subcommittee composed of experts in lighting health and flicker; 4) Approval of draft report of the subcommittee to be presented to all members of P1789; 5) Presentation of report to all members of P1789 by telecom and web board discussions; 6) Soliciting of comments and edits from all members of IEEE P1789; 7) Revision of report to include members comments; 8) Posting of the report on the IEEE P1789 public website for comments from the public.

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

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

http://grouper.ieee.org/groups/1789/public.html

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

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

Assumptions in the Report:

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

3. Flicker refers to the modulation of luminous intensity in a lamp (see definition below). However, at times, this report 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-a-versa. (Thus we are not considering operating the LED in its nonlinear saturation regions above rated currents.)
4. The discussion in Section I discusses *possible* health concerns due to flicker. Actual health risks from flicker are dependent on frequency, modulation depth, brightness, lighting application, and several other factors. Further, it is understood that some of the risks in Section I pertain to small minority of a population. These topics are not discussed in any detail and will be dealt with in future reports.

Basic Definitions:

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

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

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

Visible Flicker: Flicker that is perceivable by human viewer.

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

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

I. Introduction to Hazards of Flicker

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

A. Photosensitive Epilepsy

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

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

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

- **Brightness**. Stimulation in the scotopic or low mesopic range (below about 1 cd/m^2) has a low risk and the risk increases monotonically with log luminance in the high mesopic and photopic range.
- **Contrast** with background lighting. Contrasts above 10% are potentially a risk.
- **Distance** between the viewer and the light source, which determines
- the total **area** of the retina receiving stimulation. The likelihood of seizures increases according to the representation of the visual field within the visual cortex of the brain. The cortical representation of central vision is greater than that of the visual periphery, and so
- the **location** of stimulation within the visual field is important: stimuli presented in central vision pose more of a risk than those that are viewed in the periphery, even though flicker in the periphery may be more noticeable.
- **wavelength** of the light. Deep red flicker and alternating red and blue flashes may be particularly hazardous.
- whether a person’s **eyes** are **open** or **closed**. Bright flicker can be more hazardous when the eyes are closed, partly because the entire retina is then stimulated. However, if flickering light is prevented from reaching the retina of one eye by placing the palm of a hand over that eye, the effects of the flicker are very greatly reduced in most patients.

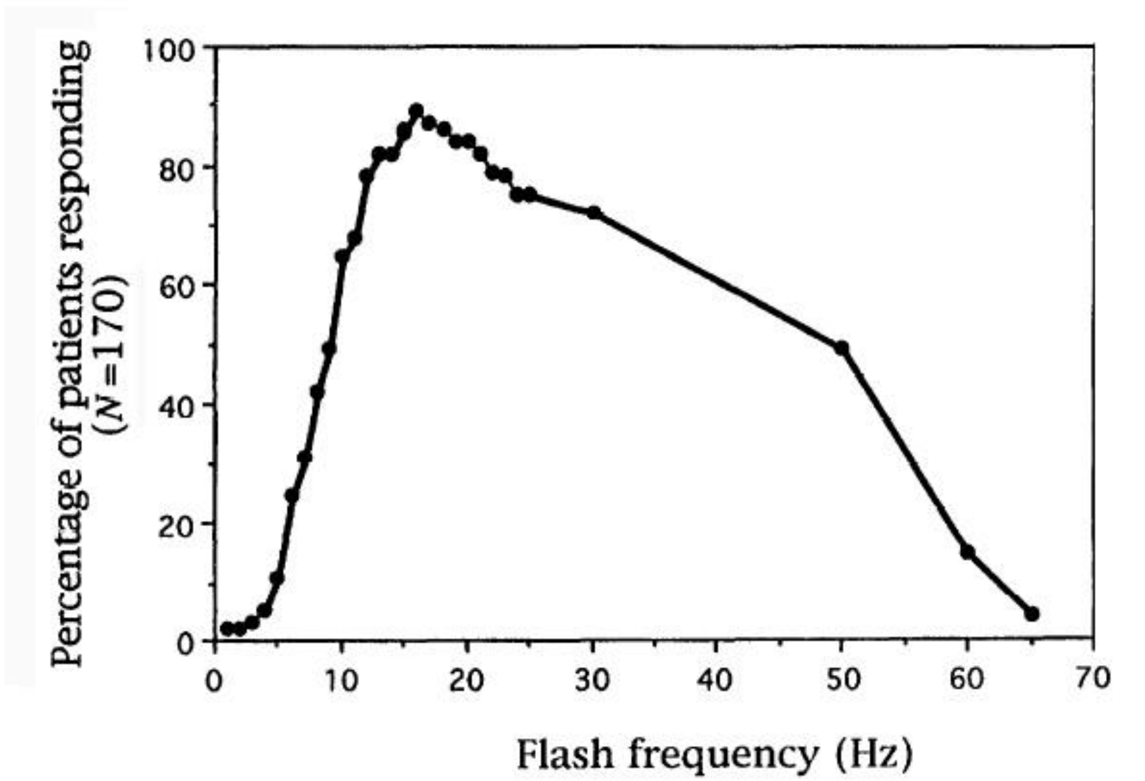


Figure 1. Percentage of patients with photosensitive epilepsy exhibiting epileptiform EEG responses to the flicker from a xenon gas discharge lamp shown as a function of flash frequency. After Harding and Jeavons (Harding and Jeavons, 1994).

Figure 2. Escalator stair tread

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.

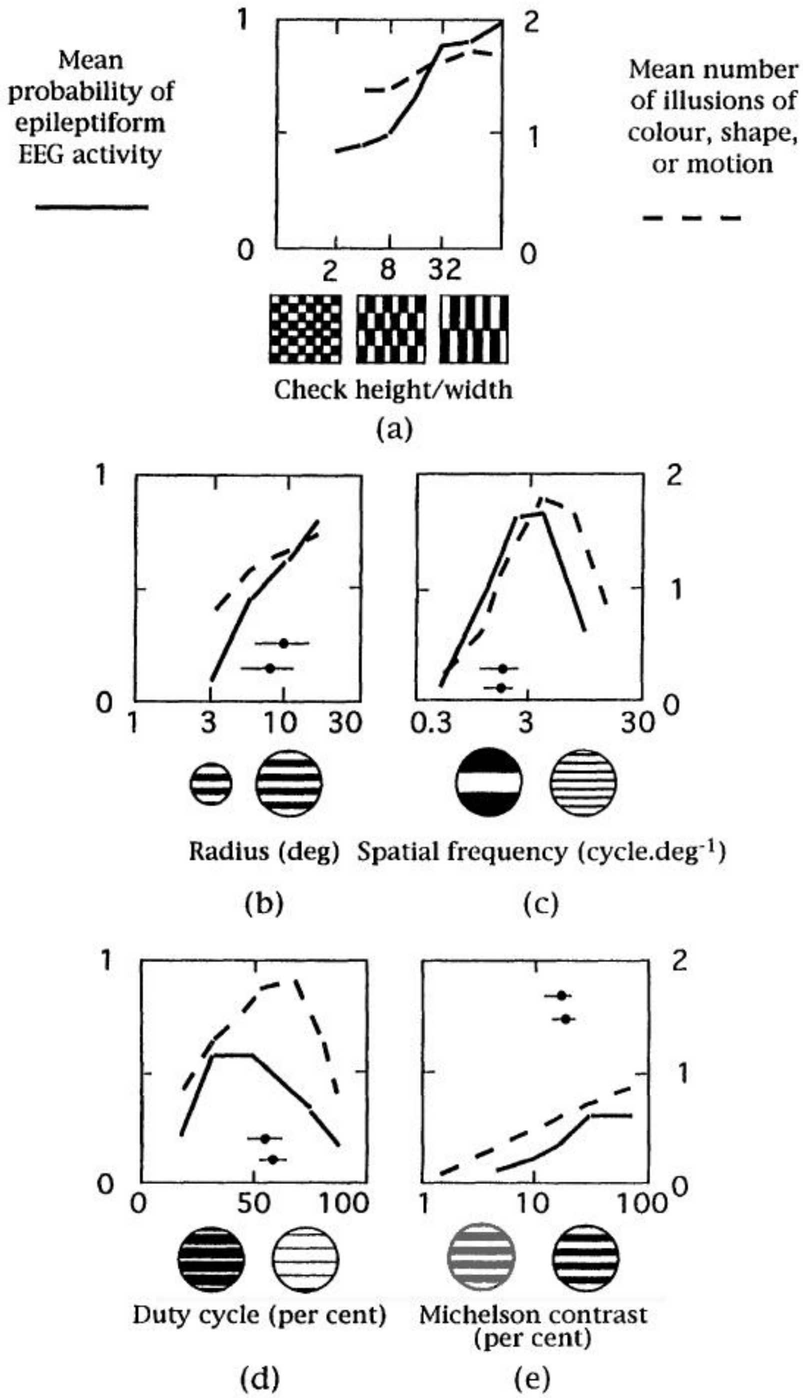


Figure 3. Mean probability of epileptiform EEG activity in patients with photosensitive epilepsy when viewing geometric patterns of checks or stripes, shown as a function of various parameters. Variation in the pattern parameters is represented schematically beneath the abscissae. Perceptual distortions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

B. Covert hazards of invisible (imperceivable) flicker

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

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

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

Computer monitors and backlights

When making a rapid jerk (saccade), for example when reading, the eyes move at a velocity of about 180 degrees per second. As a result, any intermittently lit contour is displaced at a succession of retinal positions during the flight of the eye and can sometimes be seen as a set of repetitive targets. The LED rear lamps of motor vehicles can produce such an effect. Some displays on netbook computers have LED backlights and exhibit significant flicker at 60Hz. Their flicker also results in the perception of multiple images during a saccade. It is possible that this effect is responsible for the known disturbance of ocular motor control by high frequency flicker, a disturbance which, in its turn, may be responsible for the known impairments in visual performance.

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

C. Summary of Risks to Health

The obvious risks to health occur

- from flicker that is visible;
- immediately.

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

The less obvious risks to health occur

- from flicker that is invisible[1];
- after exposure of more than about 20 minutes.

[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.

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

As noted in the table below, much of the literature might suggest that ~160Hz – ~200Hz may be a sufficient limit for flicker to have negligible biological effects in some lighting applications, but note that none of the literature considers the eyes in motion across a high spatial contrast.

Finally, it is important to mention that the fact that there is "biological effect" (ERG or notice of visual flicker in special circumstances) does not necessarily imply health risk to viewers. For example, flickering light at ~200Hz may theoretically be annoying to spectators of tennis or ping-pong games, but may not pose any health risks (Rea and Ouellette, 1988).

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

Table 1. Sources of flicker, their frequency range and biological effects, and 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)

A few general implications for practice

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

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

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

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

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

II. Typical LED Driving Methods in Low Flicker Frequency Range

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

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

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

(1) 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 waveform shape similar to a scaled absolute value of a sine wave. That is, the rectified sine wave may be of the form $|V_p \sin(\omega t)|$, 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 Fig. 4 below shows. In a first approximation, the LED current is equal to a scaled rectified voltage, with the additional deadtime (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, which in North America leads to 120Hz modulation and in Europe leads to 100 Hz modulation. As Fig. 4(a) shows, often a resistor is added in series with the LED string for current limiting protection.

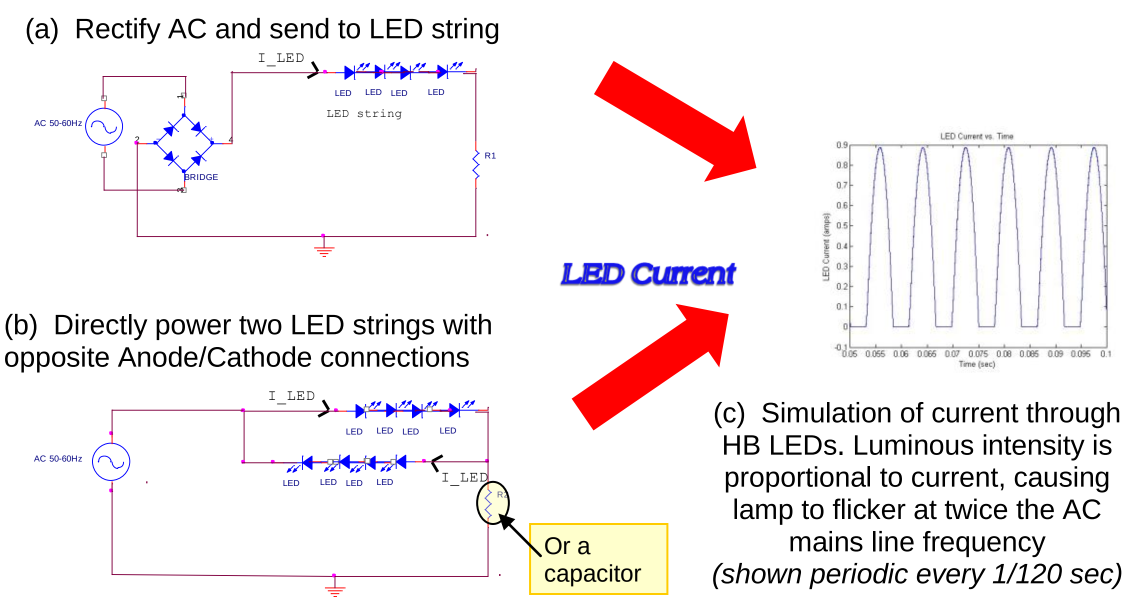


Figure 4. Two methods to drive LEDs at twice line frequency: (a) Full bridge rectification, (b) Opposite connected parallel strings, and (c) Current/Luminous Output in the LEDs for both approaches.

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

A second LED driving method that doubles line frequency is shown in Fig. 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 Fig. 4, the LED current modulates at twice the line frequency. Since the intensity of the LEDs is proportional to the current through the LEDs, this causes the LEDs to flicker at frequency equal to twice the AC line frequency, i.e. 100Hz~120Hz.

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

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

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

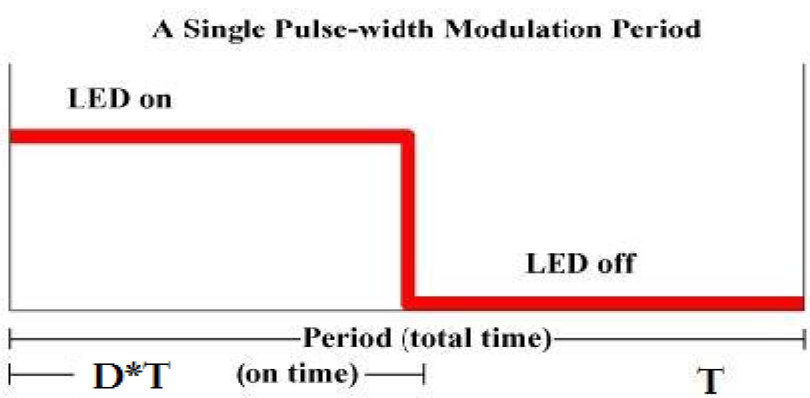


Figure 5. Pulse Width Modulated Dimming

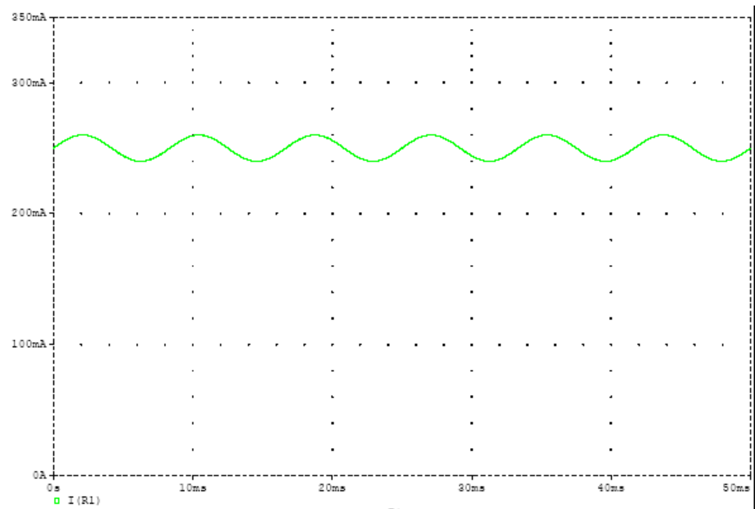
By adjusting the length of time that the LED current is High or Low (zero) in Fig. 5, the luminous intensity of the LED is adjusted. Frequency, by definition is equal to 1/T, where T is the period of the signal. Thus, PWM dimming circuits may be designed to operate at any frequency, whether the input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

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 brightness is dimmed. This approach does not use flicker to adjust brightness and therefore, should not induce flicker related health risks.

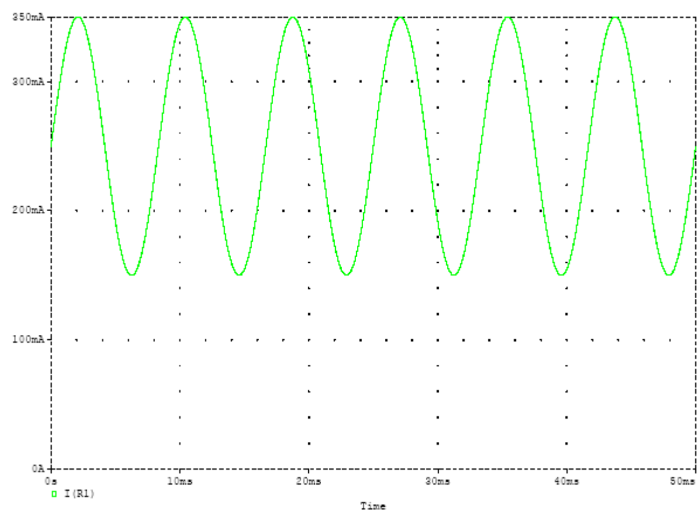
(4) Power Factor Correction Circuitry

Even when sophisticated high frequency switching power supplies with power factor correction circuits are used to drive LEDs from AC mains, 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 (Fig. 6(a)) and unnoticeable to being significant in magnitude (Fig. 6(b)). The simulations illustrate the current through a string of LEDs. This current is approximately proportional to luminous intensity. There is a DC current through the LEDs but also a 120Hz modulated signal. Referring to Fig. 6(b), the LED current has average value of 250 mA, yet the 120 Hz signal superimposed upon the DC value has peak-to-peak value of 100mA (40% the average LED current). The ripple in Fig. 6(a) is only 10mA peak to peak (4% of the average LED current of 250mA). Using the definition of modulation in the beginning of this report, this implies that Fig. 6(a) has 2% Percent Flicker and Fig. 6(b) has 20% Percent Flicker. (Modulation/percent flicker will be half the peak-to-peak percent ripple value.)



(a)



(b)

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

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

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

In either of the two methods described in Section II.A, 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. 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 circuits prevent current flow, and therefore, the LED modulation frequency may change. As Fig. 7 shows, this single diode failure in the rectifier will cause the output voltage for the full wave rectifier to become the input voltage for half the AC line cycle, and then 0 volts for the remaining half line cycle. This means that if the AC Mains frequency is f and the period is T=1/f, then non-zero voltage is applied to the LEDs for 0.5*T seconds and then is zero for the next 0.5*T seconds, causing the LED current to modulate at line frequency.

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

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

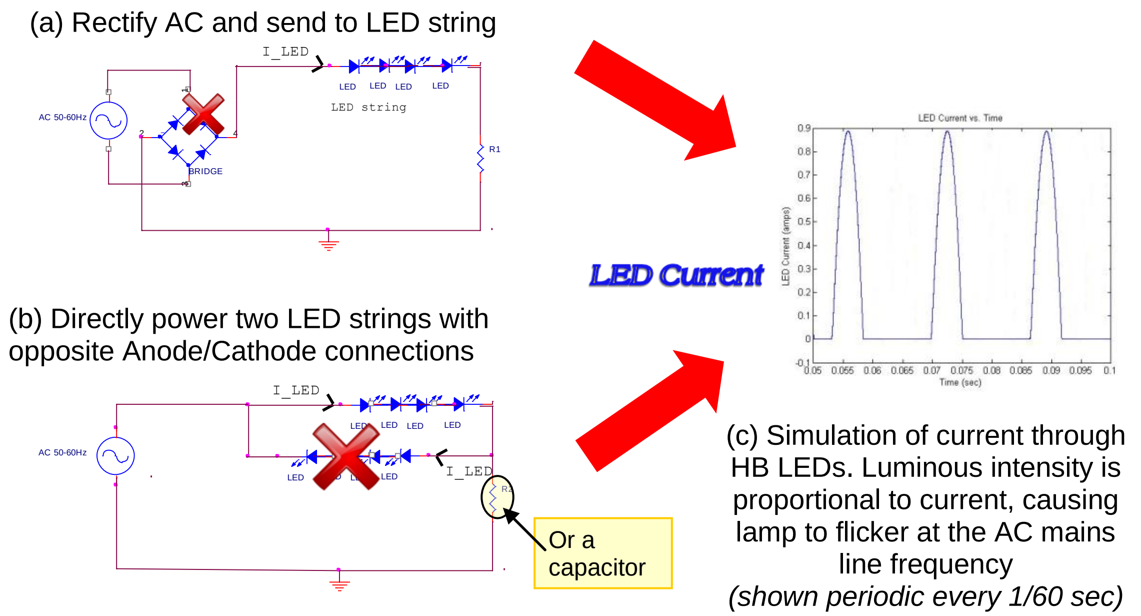


Figure 7. Diode failure(a) or LED failure(b) may cause low frequency flicker (c) at line frequency through strings of LEDs.

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

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

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

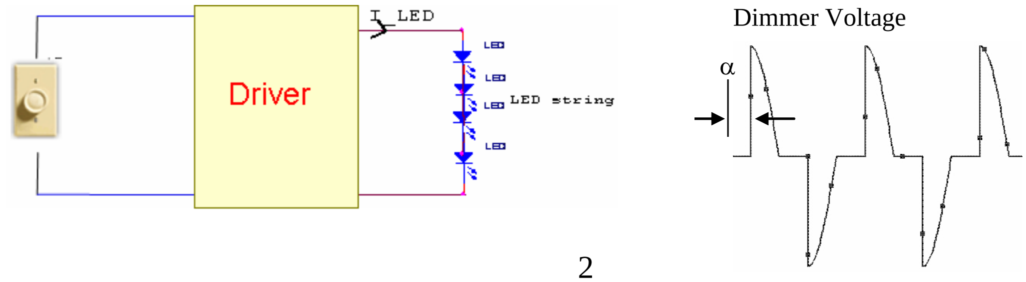


Figure 8. Residential dimmer and its output voltage sent to the driver (Rand et al., 2007).

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

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

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

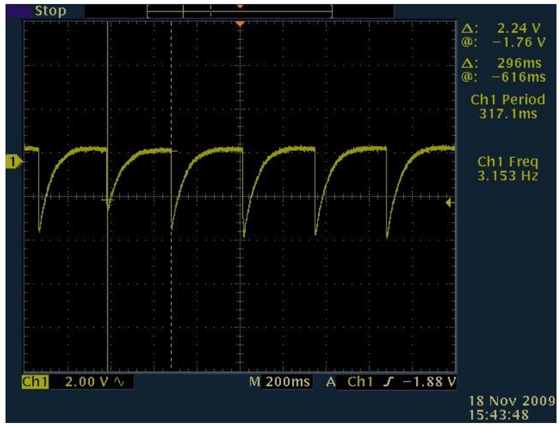


Figure 9. Commercial LED lamp flickers at 3.15Hz when connected to typical residential dimmer switch.

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

Full Wave Rectifier with Capacitor:

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

DC/DC Converters for LED Drivers with Residential Dimmers:

Often, LED lamps utilize DC/DC converters after the full wave rectification and capacitive filter. These LED Edison socket bulbs may not utilize power factor correction, since their wattage is so small and there are (at the time of writing) no regulations requiring them to be implemented. Thus, simple buck derived (step-down power converters), low cost, systems are sometimes utilized after the rectification. As experimentally shown in (Rand et al., 2007; Rand, 2005), many of these systems typically have difficulty with residential dimmer switches. For example, even when the triac dimmer is off, it sometimes has finite leakage current. This sometimes results in enough voltage across the input of the driver IC to turn the LED lamp briefly on and then off again. Hence, the LED lamp flickers and never fully turns off. This is just one type of failure that has been reported. The flicker frequency reported in (Rand et al., 2007) was at 15Hz for sample LED lamps, typical of waveforms shown in the oscilloscope plot above. Thus, these driving techniques may cause flicker frequency in the range of 3Hz-60Hz, which is in a range of frequencies that is at risk to induce photosensitive seizures.

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

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

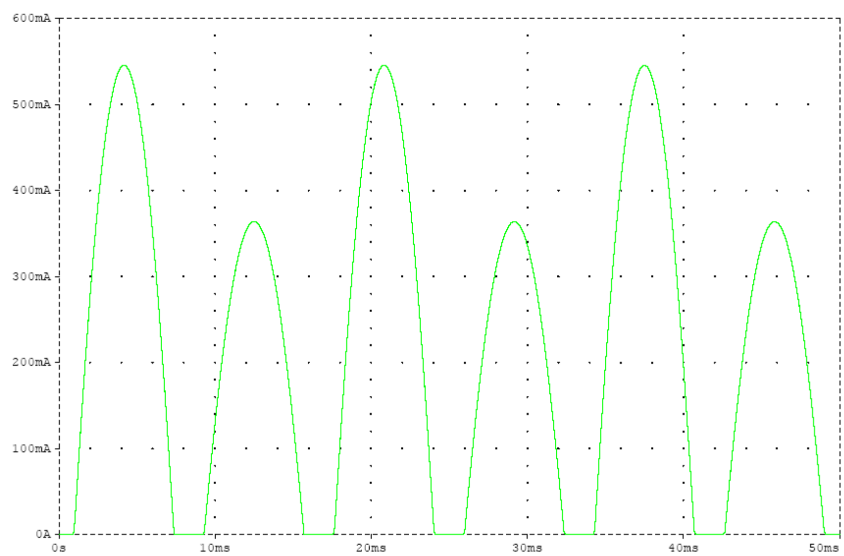


Figure 10. Unbalanced LED Current in Each String of LEDs Using Driving Method in Fig. 4(b). The unbalanced driving will cause uneven luminous output in the lamp and low frequency flicker.

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

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

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

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

Primary References for This Report

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

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IEEE Approved Scope of PAR1789

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

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