LED Lighting Flicker and Potential Health Concerns: IEEE Standard PAR1789 Update

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***Abstract* -- The IEEE Standards Working Group, IEEE PAR1789 "Recommending practices for modulating current in High Brightness LEDs for mitigating health risks to viewers" has been formed to advise the lighting industry, ANSI/NEMA, IEC, EnergyStar and other standards groups about the emerging concern of flicker in LED lighting. This paper introduces power electronic designers for LED lighting to health concerns relating to flicker, demonstrates that existing technologies in LED lighting sometimes provide flicker at frequencies that may induce biological human response, and discusses a few methods to consider when trying to mitigate unintentional biological effects of LED lighting. The paper represents on-going work in IEEE PAR1789 that is vital to designing safe LED lamp drivers.**

***Index Terms*-- LED, health risk, flicker, lighting, power electronics, ergonomics, drivers, headache, seizure, standards**

I. Nomenclature

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 refers to modulation as variation in luminance as a proportion of the average luminance (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:

Modulation = (Lmax - Lmin) / (Lmax + Lmin) (Lighting Design Glossary)

Visible Flicker: Flicker that is consciously perceivable by a human viewer.

Invisible or Imperceptible Flicker: Flicker that is not consciously 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.

II. Introduction

This paper summarizes a public report created by the IEEE Standards PAR1789 group on LED lighting that is examining biological effects of flicker in emerging LED lighting technologies. (The full length version of the report can be found at http://grouper.ieee.org/groups/1789/) The intention of this document is to provide an objective summary of the effects on human health for both visible and invisible flicker and to draw attention to implications for the design of LED lighting. Specifically, contributions of this paper include making the reader aware of

1. Risks of seizures due to flicker at frequencies within the range ~3- ~70Hz;
2. Human biological effects due to invisible flicker at frequencies below ~165Hz;
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 possible health implications of flicker. By bringing these issues to the power electronic and lamp designers now, it will permit better ethical discussions and decisions to be made on development of future LED lamps as the market continues to have explosive growth. This report endorses no technology for driving LED lamps. Specifically, Section III of the report gives tutorial surveys on health effects of flicker. Section IV introduces a few typical LED driving methods that introduce flicker in frequency ranges of interest.

III. 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 less obvious 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). Human biological effects 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] may combine to affect the likelihood of seizures including:

- **Flash Frequency**. Any repetitive change in a visual stimulus within the frequency range 3 Hz to 70 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/m2) 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 and its location which determine
- **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
- **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.
- **Open or closed eyes**. 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.

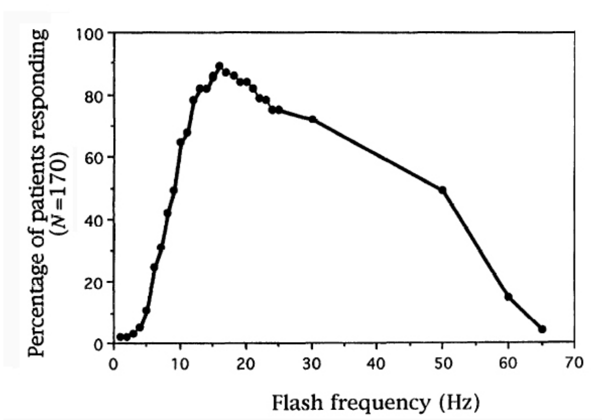


Figure 1. Percentage of patients with photosensitive epilepsy exhibiting epileptiform EEG responses to the flicker from a xenon gas discharge lamp shown as a function of flash frequency. After Harding and Jeavons (1994).

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.

B. Imperceptible 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 (Binnie et al., 1979). Nevertheless some photosensitive patients do complain of normally functioning (older) fluorescent lighting (with magnetic ballasts).

Measurements of the electroretinogram have indicated that modulation of light in the frequency range 100-160Hz and even up to 200 Hz is resolved by the human retina although the flicker is too rapid to be seen (Burns et al. 1992, 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 (see work of

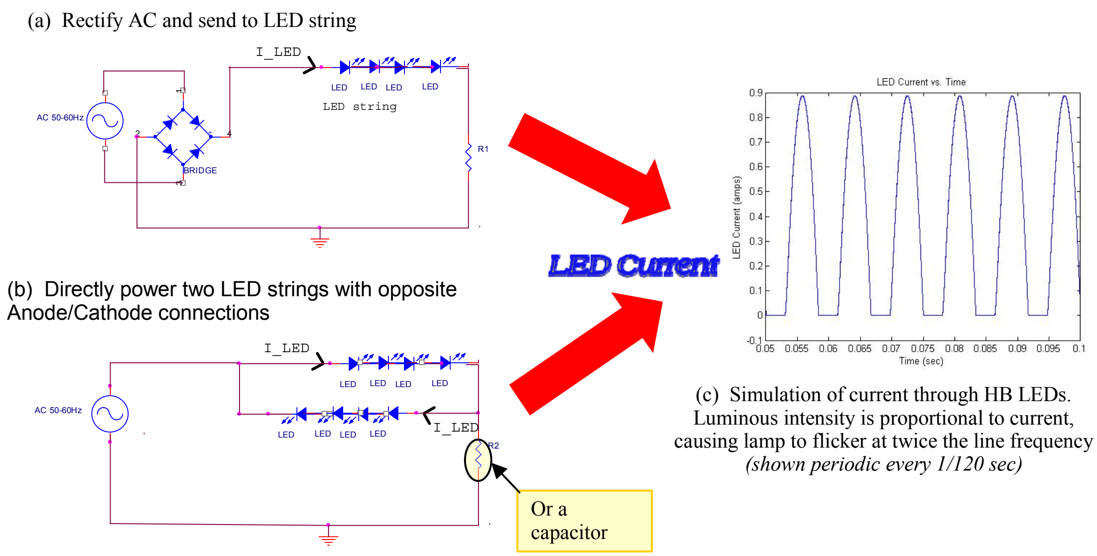


Figure 3. Two methods to drive LEDs at twice line frequency: (a) Full bridge rectification, (b) Opposite connected parallel strings, and (c) Current/Luminous Output in

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 effects 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 normal observers 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 imperceptible flicker the effects of different waveforms have not been studied in detail. The peak-trough modulation depth of the 100-120Hz flicker from older fluorescent lamps with magnetic ballasts 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). The IEEE Standards PAR1789 working group is developing new measures/definitions of flicker that rely on Fourier series of the flicker. The present definitions for modulation do not distinguish the difference between low frequency and high frequency modulation. But for sufficiently high flicker frequencies, there are limited human biological effects.

C. Summary of Biological Effects

The obvious biological effects occur: 1) immediately from 2) flicker that is visible. The risks include seizures, and less specific neurological symptoms including malaise and headache. Seizures can be triggered by flicker in individuals with no previous history or diagnosis of epilepsy.

The less obvious biological effects occur: 1) from flicker that is invisible 2) after exposure of several minutes. Invisible flicker health effects have been reported to include headaches and eye-strain.

The table in the Appendix summarizes and categorizes the types of flicker and the biological effects they cause.

D. A Few General Implications for Practice

Visual flicker is an undesirable attribute of any lighting system. The Appendix Table summarizes research suggesting 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 and can be a potential health hazard. Any hazard will, however, 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 paper and will be covered in future IEEE PAR1789 documents. However, it is possible to make general comments about the research cited in the Appendix Table:

1. **Frequency.** Normally functioning fluorescent lighting controlled by magnetic ballasts 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 the Appendix Table 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).

IV. 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 been reported (Rand et al., 2007; Rand, 2005) to malfunction and produce visual flicker in the 15Hz range when connected to a conventional residential dimmer.

Below, we present only a few driving approaches 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 a waveform shape similar to a scaled absolute value of a sine wave. That is, the rectified sine wave may be of the $|V_p \sin(\omega t)|$ form, where Vp is the amplitude of the sine wave and ω is the angular frequency in radians ω = 2*π*f. In this case, the LED current is of similar shape, as Fig. 3 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. 3(a) shows, often a resistor is added in series with the LED string for current limiting protection.

(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. 3(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. 3, the LED current modulates at twice the line frequency. Since the intensity of the LEDs is (ideally) proportional to the current through the LEDs, this causes the LEDs to flicker at frequency equal to twice the AC line frequency, i.e. 100Hz~120Hz. There are many variations of the approach in Fig. 3 that are not shown here.

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

It is common to dim LEDs by pulsing the current through them intentionally.The luminous intensity of the LED can be adjusted by varying the length of time that the LED current is High or Low,. Thus, PWM dimming circuits may be designed to operate at any frequency, whether the input is DC or AC. (It should be noted that it is not uncommon for LED drivers using AC residential phase modulated dimmer circuits to attempt to "emulate" PWM type signals with frequency 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 and unnoticeable to being significant in magnitude.

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

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

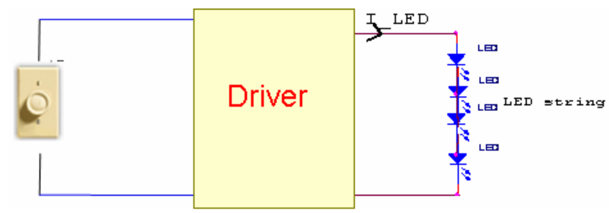
In either of the two methods of Fig. 3, there is risk of failure that can cause LED current modulation at AC line frequency, thereby entering the range of frequencies that may induce photosensitive epilepsy. For example, if one of the legs of the full wave rectifier bridge fails, then it is common that the leg becomes an open circuit. Open circuits prevent current flow, and therefore, the LED modulation frequency may change. 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 line 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 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.

(2) Residential Dimmer Switches Can Cause Low Frequency Flicker (~3Hz – 70Hz)

Residential dimmers for incandescent bulbs primarily utilize phase modulating dimming through triac switches to control the power sent to the bulb. These dimmers 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.4. 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. 4, less power goes to the incandescent bulb and brightness is reduced

Some LED lamps and their associated drivers may 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. Rand's work (Rand et al., 2007; Rand, 2005) explains the causes of these failures and shows that low frequency flicker may occur.



Dimmer Voltage

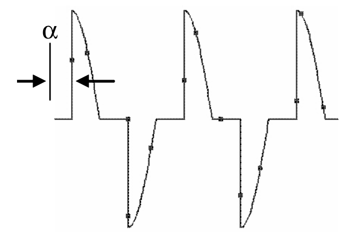


Figure 4. Residential dimmer and its output voltage sent to the driver (Rand et al., 2007).

Fig. 5 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 by Rand et al., 2007; 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, some typical lamps may have parallel strings of many Red, Blue, Green 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.

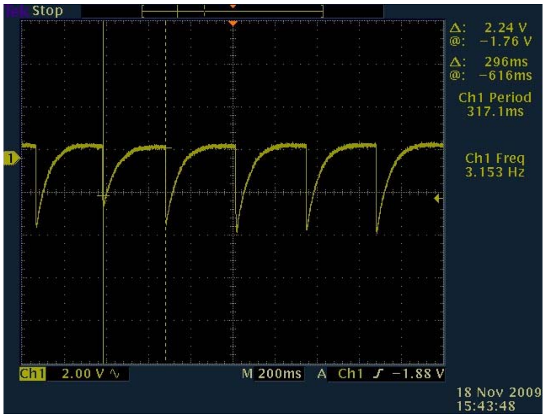


Figure 5. Commercial LED lamp flickers at 3.15Hz when connected to typical residential dimmer switch.

The experimental data in Fig. 5 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. 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 Fig. 5 is typical of *a few* 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.

The reasons that the dimmer switch may fail when connected to LED lamp bulbs are given in (Rand et al., 2007; 2005).

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

Consider the circuit in Fig. 3(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.

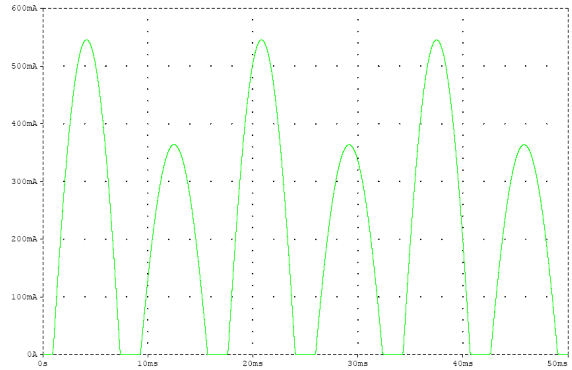


Figure 6. Unbalanced LED Current in Each String of LEDs Using Driving Method in Fig. 3(b). The unbalanced driving will cause uneven luminous output in the lamp and low frequency flicker.

For example, suppose over time, aging causes degradation of one of the two strings in Fig. 3(b) such that its string resistance increases by 50%. This could also be caused by improper design of each string in Fig. 3(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.6.

For example, the effective DC LED current in the numerical simulation of Fig. 6 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 typical analysis above 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.

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.

V. Conclusions

The purpose of this paper is to make lamp and power electronic designers aware of biological effects of flicker and to introduce the reader to a few LED driving methods that will have flicker. The LED driving approaches described in this paper are not exhaustive and are only meant to introduce the reader to a few common approaches. 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.

This paper assigns no health risk to the biological effects of flicker in the various LED lamps. The hope is that by discussing the issue of flicker within the power electronic community, it will be possible to decide as a community whether or not standards or recommended practices are necessary. We do not attempt to do so here. However, we do offer simple suggestions as to what should be considered when designing lamps, such as flicker frequency, angle of viewing, task being performed, spatial distribution, AC dimmer flicker, etc. Further, it is not difficult to create shut-down or other safety prevention circuits that prevent flickering in the 3Hz-70Hz range when the lamp is in failure mode. This is the flicker range that has risk of photosensitive epilepsy for small minority of the population.

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APPENDIX

TABLE I
FLICKER AND BIOLOGICAL EFFECTS

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 (Wilkins et al 1989)
Normally functioning fluorescent lighting (50Hz ballast)	32% modulation	Reduced speed of visual search	Two masked studies (Jaen et al., 2005)
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)