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Designing to Mitigate the Effects of Flicker in LED Lighting

Reducing risks to health and safety

by Brad Lehman and Arnold J. Wilkins

How often has this scenario happened? You are driving at night behind a car that has bright light-emitting diode (LED) taillights. When looking directly at the taillights, the light is not blurry, but when glancing at other objects, a trail of lights appears, known as a *phantom array*. The reason for this trail of lights might not be what you expected: it is not due to glare, degradation of eyesight, or astigmatism. The culprit may be the flickering of the LED lights caused by pulse-

width modulating (PWM) drive circuitry. Actually, many LED taillights flicker on and off at frequencies between 200 and 500 Hz, which is too fast to notice when the eye is not in rapid motion. However, during a rapid eye movement (saccade), the images of the LED lights appear in different positions on the retina, causing a trail of images to be perceived (Figure 1). This disturbance of vision may not occur with all LED taillights because some taillights keep a constant current through the LEDs. However, when there is a PWM current through the LEDs, the biological effect of the light flicker may become noticeable during the eye saccade.

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Human Biological Effects of Light Flicker

Flicker can be defined as a rapid repetitive change in brightness [1]. At a minimum, flicker is a distraction. However, it can also become a hazard to health, provoking an increased incidence of headaches [2], [3] and even epileptic seizures [4]–[6]. The hazard depends on the area of retina exposed to the flicker and the way in which the light changes with time (frequency and modulation depth), among other factors. When flicker occurs at frequencies between 3 and 70 Hz with a sufficient peak-to-peak amplitude, the dangers can be the most catastrophic: a small percentage of the population may suffer an epileptic seizure [4]–[6].

Fortunately, almost all flicker in lighting occurs at or above a frequency twice that of the ac input power line: 100 Hz in Europe and 120 Hz in North America [2]. So in normal operation, commercial lighting may not increase the incidence of photosensitive seizures. Indeed, flicker cannot usually be seen when its frequency is greater than the so-called critical flicker fusion frequency (CFF), which is usually between ~60 and 90 Hz, although the frequency varies with the characteristics of the light and the observer. Above the CFF, the light appears continuous, but this does not mean that it is innocuous. In fact, the flicker can still be seen under certain circumstances, as in the case of the LED taillights. Even when

it cannot be seen, however, flicker can remain hazardous to humans [2]. We know this because of experience with fluorescent lighting. When fluorescent lamps are controlled by line-frequency magnetic ballasts, a discharge occurs twice with each cycle of the electricity supply. The flicker cannot usually be seen, but it doubles the average incidence of headaches in office workers [3], triggers migraines in some individuals [7], [8], and impairs the performance of visual tasks [9]. The twofold increase in headache incidence is due to a small proportion of the population who experience relatively frequent headaches [3], [10].

An increased hazard also occurs in fluorescent lamps with low-frequency magnetic ballasts as they age. Sometimes, the discharge may be brighter when the ac flows in one direction more efficiently than in the other, resulting in brightness variation at the frequency of electricity supply. The flicker can then sometimes be seen, and, generally speaking, when flicker can be seen, there is a risk of seizures.

When the lamp is operating normally, however, and the flicker cannot be seen, there may be little risk of seizures, but the possibility of other neurological consequences, such as headaches, remains. There are important lessons to be learned from fluorescent lighting, e.g., the negative health effects from flicker should be mitigated in all possible life cycle operations for any lamp technology.

When looking directly at the taillights, the light is not blurry, but when glancing at other objects, a trail of lights appears, known as a phantom array.





FIG 1 When a person's eyes move quickly from side to side, multiple images are observed in some LED car taillights.

The eye is continually in motion, moving the retinal image in a succession of drifts and jerks (saccades), even when we gaze directly at something [10]. These movements are necessary for vision for, without them, the image fades. When the gaze is redirected from one point of regard to another, the eyes make a large saccade, and the flight of the eye during such a saccade can be extremely rapid, reaching more than 400°/s for the largest saccades. Although the eyes are open and the retinal cells are functional, we are usually unaware of what we see during a saccade. This lack of awareness, called *saccadic suppression*, arises partly because what we see before and after the rapid eye movements are relatively stable images, which mask the moving image that occurs during the saccade. When the image is illuminated intermittently by flickering light, the image during the flight of the eye is not a moving image but a succession of discrete images, and these can get confused with the images before and after the flight of the eye. You become aware of flickering LED taillights because each saccade is accompanied by a disconcerting trail of images [11]–[13]. At night, there is nothing to see before and after the saccade to mask the intrasaccadic image. The frequency of flicker at which such intrasaccadic images are visible can be as high as 2 kHz [14]. During a saccade, the image on the eye is moved as the eye moves. On the other hand, when the eye is relatively stable and the objects themselves move rapidly, we may again notice a similar succession of images. This is known as the *stroboscopic effect*, and it occurs at frequencies that are similarly high [15].

Driving LED Lamps May Lead to Flicker

Figure 2 shows the light output of typical commercially available LED Edison socket bulbs with A19 size, all of which are marketed as 60-W incandescent replacement bulbs and have about 800 lumens of light output. Most LED bulbs will demonstrate modulating light output that is periodic at twice the line frequency, which, in this case, is 120 Hz. However, as can be seen from one bulb, it is possible to design a driver that exhibits virtually no flicker. High-frequency measurement noise may be ignored because it is due to the low-cost Texas Instruments OPT101 photodiode and transimpedance amplifier. To eliminate the measurement noise, the more elaborate experimental measurement setup described in [2] and [16] may be utilized. The flickering levels of the LED bulbs depend on the type of driving method that is utilized to convert the ac input to the required dc through the LED.

Incandescent bulbs do not require these power electronic drivers since it is possible to send the positive and negative cycle current directly through their tungsten filaments. The thermal time response for the filament is so slow that the flicker is naturally filtered to a lower level. On the other hand, LEDs are unidirectional devices and require ac–dc conversion. The response time for LEDs is almost instantaneous, and it is commonly assumed that the luminous intensity of an LED is approximately linearly proportional to the current through the LED. As a result, LED current ripple instantaneously becomes light flicker ripple. This has caused flicker to reemerge as an important issue in the design process, even giving rise to new standards groups such as IEEE PARI789 that study safe levels [17].

From the experimental plots of luminous intensity in Figure 2, it is possible to define [2], [18]

$$\text{Percent Flicker or Mod\%} = 100 (\text{Max} - \text{Min}) / (\text{Max} + \text{Min}),$$

where Max/Min represent the maximum/minimum measured light intensity from the lamp. It is interesting to note that there is no dependence on flicker frequency in this definition, although it is known to be an important parameter in human safety for lighting. From the definition, it can be seen that Mod% will always be a value between 0% and 100%. A summary of the Mod% of the tested commercially available A19 LED Edison socket bulbs is presented in Table 1. For reference, compact fluorescent lamps with high-frequency ballasts normally have a Mod% of less than 10%, while that of fluorescent lamps with magnetic ballasts is 25–50% [2], [16]. Outdoor lighting with high- or low-pressure sodium lamps may have up to 100% modulation.

In the following sections, we present a few of the basic methods to create the required dc whereby unwanted flicker may be introduced in LED lighting [2], [19]. There are many variations of the presented methods.

Full-Wave Rectifier Connected to LED String

In this approach, shown in Figure 3(a), 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

Table 1. Philips and Maxlite are within the measurement error of the flicker.

LED Bulbs	Mod%
60-W incandescent	7.62%
Cree	21.27%
Philips	~1%
Utilitech	48.39%
Ecosmart	16.96%
GE	19.63%
MaxLite	~1%
Sylvania	29.41%

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 form $|V_p \sin(\omega t)|$, where V_p is the amplitude of the sine wave, ω is the angular frequency in radians $\omega = 2\pi f_{ac}$, and f_{ac} is the ac mains power line frequency. Similarly, it is possible to use the so-called ac-LED approach, as shown in Figure 3(b). Two strings of LEDs are powered in parallel, with the 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 a current through it. The combined LED current would, therefore, in both cases have a shape as in Figure 3(c), which has $\text{Mod}\% = 100\%$ with flicker frequency f_{Flicker} equal to twice the ac mains frequency, i.e., $f_{\text{Flicker}} = 120 \text{ Hz}$ (North America) or $f_{\text{Flicker}} = 100 \text{ Hz}$ (Europe).

The benefits of the ac-LED approach are the minimal part count and the elimination of high-frequency power electronic drivers, but this comes at a cost of extremely high ripple—much higher than in line-frequency magnetic ballast for fluorescent lamps. Alterations on the ac-LED approach may include ac stacking, which varies the number of conducting LEDs depending on the voltage level of the input source [19]–[21]. Then, it may be possible to add holdup capacitors of reasonable size to subsequently provide energy to the LEDs, even when the input voltage becomes low. Such approaches can partially reduce the flicker modulation percentage [22].

Simple Dimming PWM Circuits

It is common to dim LEDs by pulsing the current through them, as shown in Figure 4. The average luminous intensity of the LED can be adjusted by varying the length of time that the LED current is high and low. Thus, PWM dimming circuits may be designed to operate at any frequency. This is true whether the input source is ac or dc power, although Figure 4 assumes a dc input source, perhaps coming from a prior ac–dc conversion. In Figure 4(a), the switch is in series so that when it is on, the current will flow through the LED. When the switch is off, no current flows through the LEDs. In Figure 4(b), the current flows through the

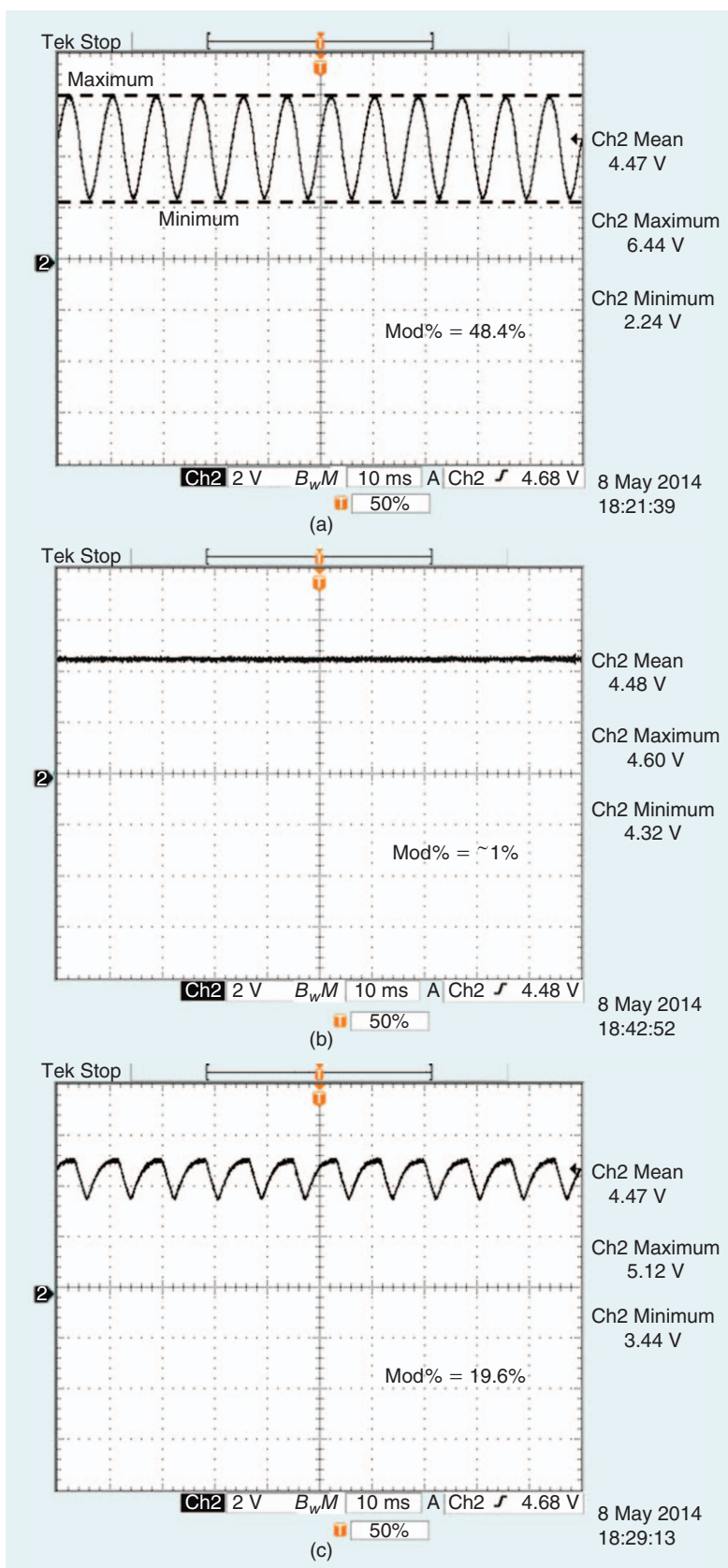


FIG 2 The typical plots of luminance light flicker in commercial LED A19 bulbs (60-W incandescent replacement bulbs). $\text{Mod}\% = (\text{Max luminance} - \text{Min luminance}) / (\text{Max luminance} + \text{Min luminance})$. $\text{Mod}\%$ for the three bulbs are (a) Utilitech, 48.4%; (b) Philips, <1%; and (c) GE, 19.6%.

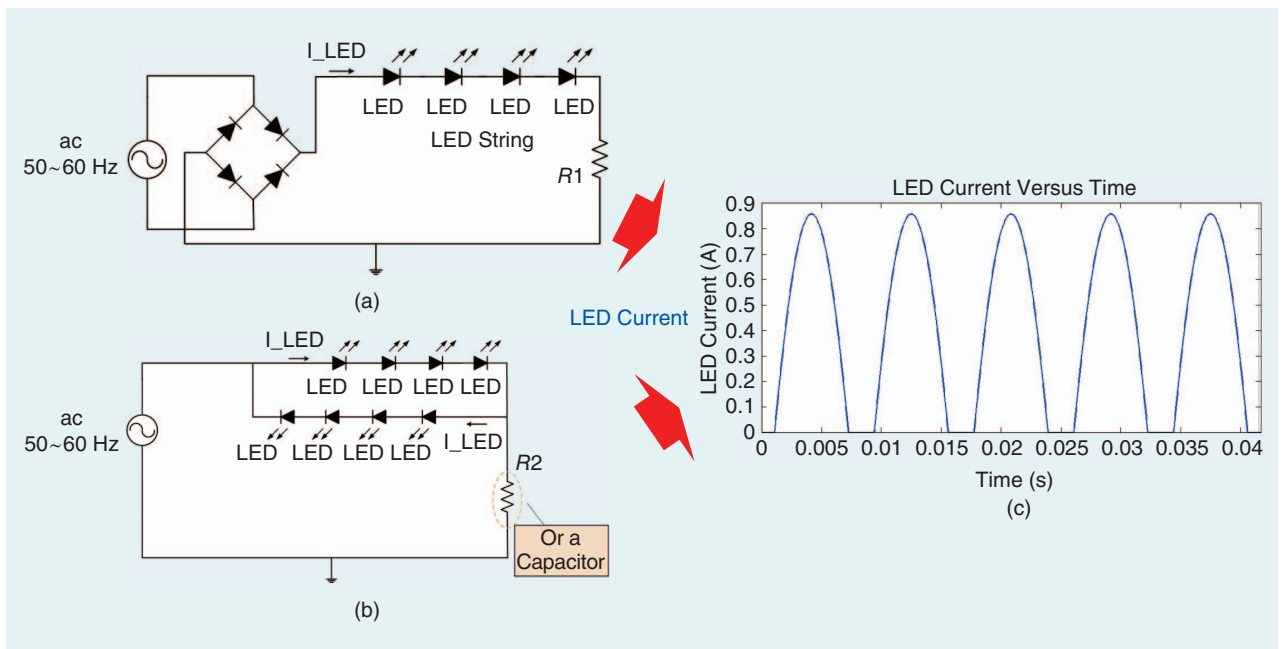


FIG 3 The two methods to drive LEDs at twice the line frequency. (a) A full-bridge rectification: rectify ac and send to the LED string. (b) The opposite connected parallel strings: directly power two LED strings with opposite anode/cathode connections. (c) The current/luminous output in the LEDs for both approaches: simulation of current through HB LEDs. The luminous intensity is proportional to the current, causing the lamp to flicker at twice the line frequency (shown periodically every 1/120 s) [2].

LEDs when the switch is off, while there is no current in the LED when the switch is on. In either case, the LED current looks similar to Figure 4(c) and has a flicker frequency of $f = 1/T$, where T is the period of the PWM. The flicker frequency for PWM dimming in commercial LED lamps typically varies from 120 to 480 Hz [16], but it is also possible to perform high-frequency dimming [23].

It should be mentioned that there are alternative approaches to dimming, such as amplitude dimming, in which the current through the LED is continuous and not pulsing. By reducing the value of this continuous current (amplitude), the luminance is dimmed. This approach can avoid flicker.

Power Factor Correction Circuitry

Even when more sophisticated high-frequency switching power supplies with power factor correction (PFC) circuits

are used to drive LEDs from ac mains, such as in Figure 5, there is often flicker 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 significant in magnitude. The percent flicker depends on the controller design, the circuitry being used, and filter component values, among other factors.

Figure 5 shows a typical circuitry that may be used in driving the LEDs in a bulb. A two-stage approach [19], [24]–[26] is illustrated because this can have a reduced flicker Mod%. The first stage may be used to achieve PFC to meet typical requirements, such as a power factor greater than 0.7 given by EnergyStar requirements [27]. The second stage can be used to reduce the percent flicker. An energy buffer, such as a dc-link reservoir capacitor, is usually used to absorb the ripple between

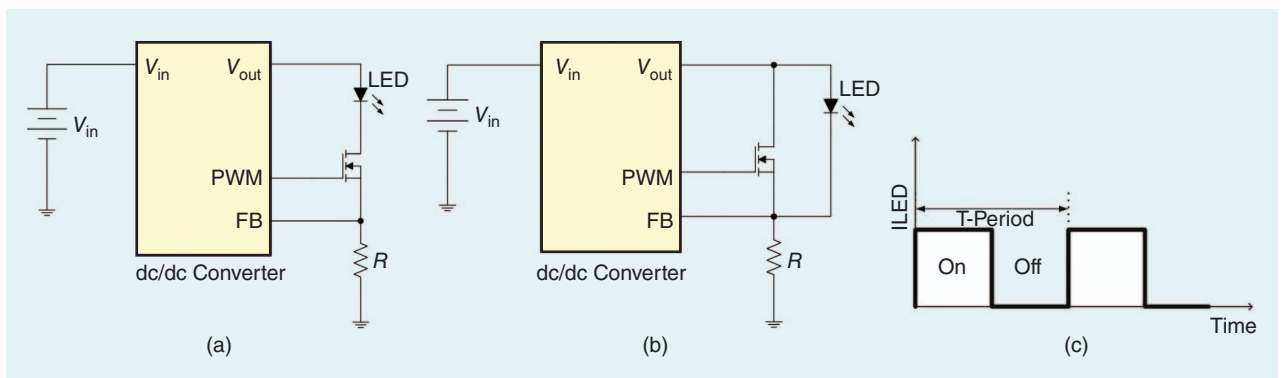


FIG 4 Sending a PWM current through LEDs: (a) series PWM dimming, (b) parallel PWM dimming, and (c) the PWM current through the LED in either method.

the two stages. To reduce the value of the dc-link capacitance, some designs sacrifice the performance. On the other hand, some vendors may utilize only a single-stage ac-dc approach and only keep the PFC portion of Figure 5 [28]–[31]. In this case, it is likely that the percent flicker may significantly increase, but there is a benefit of lower cost as a result of the lower parts count. A compromise between the two- and single-stage approaches is the single switch converters that integrate two topologies [32]. Finally, it should be mentioned that linear regulators may be inserted in series with the LEDs to regulate constant dc so that no flicker appears [33]. This comes at the disadvantage of additional power loss.

Developing Levels of Flicker That Have Minimal Human Biological Effects

This section presents flicker criteria that can mitigate the human biological effects. The focus of the results concerns flicker at frequencies above 90 Hz since this is the dominant location of flicker for commercial LED driving methods. However, it is important to mention the following known criterion to prevent photosensitive epileptic seizures: to reduce the risk of seizures to individuals susceptible to photosensitive epilepsy, all flicker at frequencies below 90 Hz must satisfy $\text{Mod}\% \leq 5\%$.

There is a significant amount of research from medical and vision science to support the necessity for keeping flicker below 5% modulation for flicker frequencies below 90 Hz [4]–[6]. It seems reasonable to avoid designing drivers that cause flicker below 90 Hz. This would, in effect, forbid the half-bridge rectified ac power line from being directly used to drive LED strings, but it would also mean that the bulb should not flicker in this low frequency even when connected to a dimmer switch. It has already been well

documented that some LED bulbs fail on residential dimmer switches, and these flicker at low frequencies that may induce photosensitive seizures in some individuals [34].

Note that the 5% modulation criterion does not prevent discomfort from flicker but only implies that it would not induce photosensitive seizures. In fact, it is well understood that in the 1–35-Hz range, a 5% modulation may be detected by observers since the eye is sensitive to flicker in the very low frequency range [35]–[39]. IEEE PAR1789 Standards Working Group [17], as well as other groups [27], [35], [36], may shortly provide recommended practices to limit the detectability of flicker below the CFF in these lower frequency ranges below 90 Hz. However, these flicker frequencies would occur because of poor power line harmonics rather than the LED driving method. Instead, this research considers the more common flicker frequencies observed in LED lighting that occur at or above twice the ac line frequency. For flicker frequencies, f_{Flicker} , above 90 Hz, $\text{Mod}\%$ should satisfy the following:

- low-risk level: $\text{Mod}\% \leq 0.08 * f_{\text{Flicker}}$ will mitigate any distractions or negative biological effects caused from flicker
 - no-observable-effect level: $\text{Mod}\% \leq 0.0333 * f_{\text{Flicker}}$.
- Note that the $\text{Mod}\%$ has a maximum of 100%.

Example Calculations

Normally, in lighting, the flicker frequency will have a fundamental component at twice the ac line frequency, i.e., $f_{\text{Flicker}} = 2 * f_{\text{ac}}$ and that $f_{\text{Flicker}} > \text{CFF}$.

- Example 1: In the United States, $f_{\text{ac}} = 60 \text{ Hz}$
 - The low-risk level leads to $\text{Mod}\% < 0.08 * 120 \text{ Hz} = 10\%$ (rounded to the nearest percent).
 - The no-effect level leads to $\text{Mod}\% < 0.0333 * 120 \text{ Hz} = 4\%$ (rounded to the nearest percent).

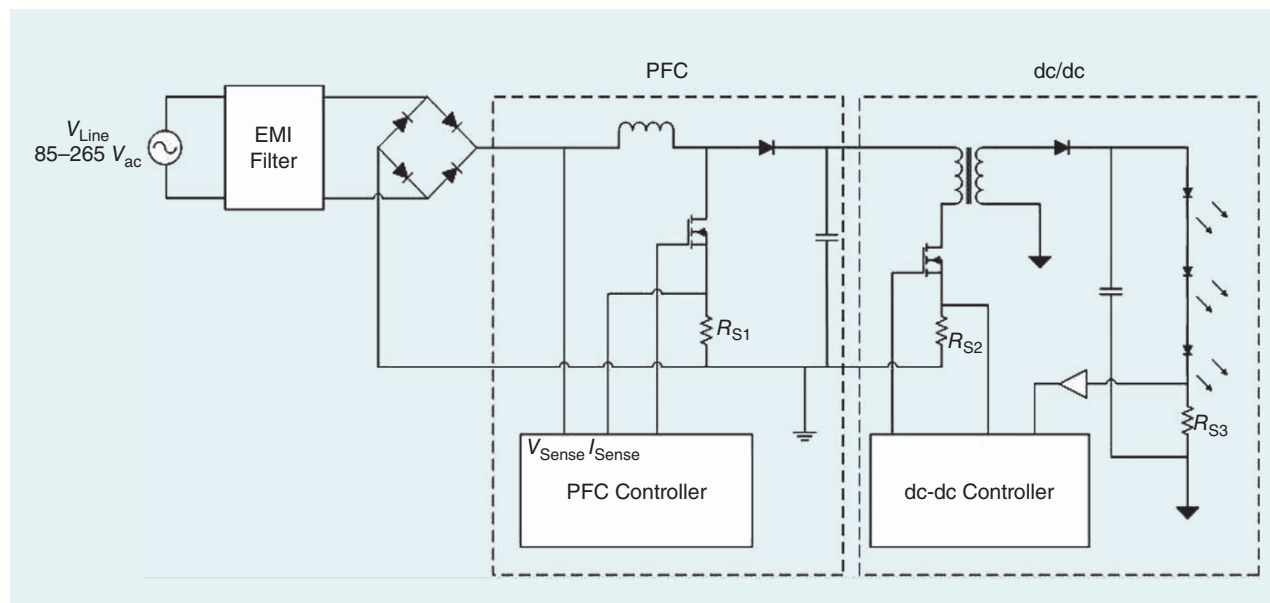


FIG 5 The typical active PFC circuitry for an ac line input will normally have some flicker frequency at twice the ac line frequency.

- Similarly, in Europe, $f_{ac} = 50$ Hz. The low-risk level leads to $\text{Mod}\% < 0.08 \cdot 100 \text{ Hz} = 8\%$ (rounded to the nearest percent), and no-effect level leads to $\text{Mod}\% < 0.0333 \cdot 100 \text{ Hz} = 3\%$ (rounded to the nearest percent).
- Example 2: PWM dimming
- The low-risk level for PWM dimming at 100% modulation can be derived by solving $100\% = 0.08 \cdot f_{\text{Flicker}}$. This means that keeping $f_{\text{Flicker}} > 1.25$ kHz would minimize the visual distractions such as the phantom array effects. The no-observable-effect level flicker is $f_{\text{Flicker}} > 3$ kHz, which can be derived by solving $100\% = 0.0333 \cdot f_{\text{Flicker}}$.

Remembering that the maximum value of $\text{Mod}\% = 100\%$, Example 2 implies that flicker above 1.25 kHz is low risk and flicker above 3 kHz can be considered to have no human biological effects, independent of the $\text{Mod}\%$.

How Were the Low-Risk and No-Effect Regions Derived?

The derivation of the low-risk and no-observable-effect level can be seen from Figure 6. Data from several independent lab studies on flicker are superimposed to first derive the no-observable-effect line $\text{Mod}\% = 0.0333 \cdot f_{\text{Flicker}}$. The low-risk region $\text{Mod}\% \leq 0.08 \cdot f_{\text{Flicker}}$ is then derived by multiplying the no-effect line by a factor of 2.5 and then comparing it with the data from [40], incandescent lighting experiments [14], and the results of a U.S. Department of Energy/Pacific Northwest National Laboratory (DOE/PNNL) case study, as we discuss next.

Roberts and Wilkins [14] (the triangles in Figure 6) measured the ability to see a flickering light during a sac-

cade. They showed that during a saccade, the flicker could be seen as a trail of lights even when the frequency of the flicker was as high as 2 kHz. The data from [14] were obtained when making horizontal saccades across a vertical bar that was either steady or intermittently illuminated (time-averaged luminance $150 \text{ cd}\cdot\text{m}^{-2}$) in an otherwise dark room (< 1 lux). On the basis of their perception of a phantom array, participants were forced to choose on which of the two immediately successive trials the vertical bar was intermittently illuminated. The forced-choice procedure ensured veridical limits on perception that were not contaminated by a predisposition to report flicker when none was visible.

The data from [14] were then combined with those from other independent studies in which flicker was detected not as a direct result of eye movement but from the movement of a target—the so-called stroboscopic effect. First, the data from [14] and [15] (the squares in Figure 6) are combined to provide data to create the no-observable-effect limit. In [15], participants were asked to report the stroboscopic perception of a white rod that they held in their hand and waved. The data in Figure 6 show the frequency at which flicker was reported on 50% of occasions. A 50% criterion was used because there was no control for the reporting of flicker when none was visible. The participants had the ability to alter the speed of the white rod that they waved until they noticed any flicker (if ever). This freedom to change the speed of the wand motion suggests a worst-case analysis suitable for no-effect levels. The data from [14] and [15] are curve fit to create a line $\text{Mod}\%$ of approximately $0.0333 \cdot f_{\text{Flicker}}$ and are shown in Figure 6 on log-log axes.

The low-risk region $\text{Mod}\% < 0.08 \cdot f_{\text{Flicker}}$ is then derived by multiplying the no-effect line by a factor of 2.5. This is further validated by noticing that the line curve fits the data from [40], which collected data for noticing stroboscopic effect, more suitable for the low-risk region. Specifically, the data from [40] (circular points) relate to the perception of the stroboscopic flicker of a white dot on a black rotating turntable, rotating at a certain fixed speed quickly enough to make saccadic eye movements likely. The data were those from the third experiment in [40, Figure 5]. The observer reported the presence or the absence of the stroboscopic effect, and a 50% threshold was obtained by increasing the frequency in interleaved staircases within the initial dc standard for comparison. The lower limits of the thresholds were given (shown in Figure 6). The threshold data excluded outliers (a substantial proportion of the data). Because outlier data have been excluded, the experiments are taken as suggesting a low-risk level but not a no-effect level.

Roberts and Wilkins [14] also measured the modulation depth at which the flicker could be seen when the frequency was 120 Hz. They showed that the flicker became visible at modulation depths greater than 9% and suggested that this might explain the tolerance of incandescent lighting, which

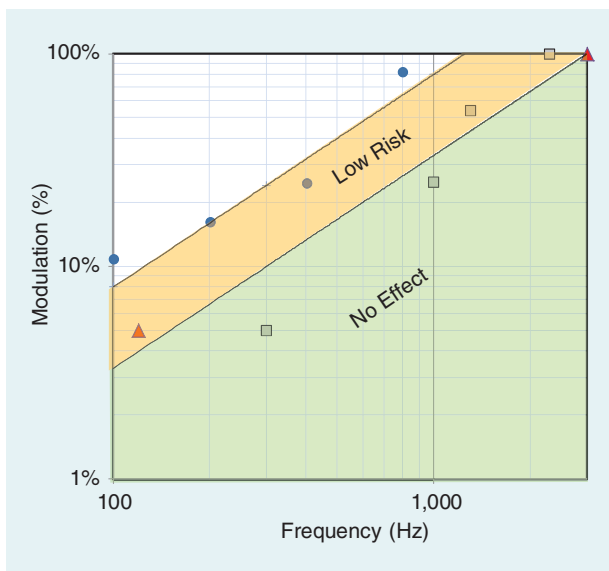


FIG 6 The low-risk (orange) and no-observable-effect (green) regions for flicker as a function of the frequency and modulation percentage. The line $\text{Mod}\% = 0.0333 \cdot f_{\text{Flicker}}$ separates the no-observable-effect and low-risk regions, and the upper margin of the low-risk region is given by the line $\text{Mod}\% = 0.08 \cdot f_{\text{Flicker}}$. (Data taken from Figure 3 of [14] and [15].)

has a modulation that is usually less than this, versus the intolerance of gas-discharge lighting, which can often have a modulation greater than 9%. Their observations are consistent with creating a low-effect level line that multiplies the no-observable-effect line by a factor of 2.5 to obtain $\text{Mod}\% < 0.08 \cdot f_{\text{Flicker}}$.

The conservativeness of the low-risk level line $\text{Mod}\% \leq 0.08 \cdot f_{\text{Flicker}}$ can be examined by comparing it with data from a study by the U.S. DOE/PNNL, which measured the detection of flicker in LED troffers in real-world lighting situations [41]. The LED lamps tested by the U.S. government lab had a flicker frequency ranging from 120 to 480 Hz. At full output, none of the observers was able to reliably detect flicker, even when the percent modulation reached ~24%. However, when dimmed, some of the lamps had flicker that was noticeable either by the stroboscopic effect produced by hand motion or pencil movement in the troffer area, or, in some cases, several observers detected flicker with normal eye motion only. The study introduces a numerical perceived flicker rating on a scale from 1 to 5. Flicker “scores” below ~2.6 might lead to observer distractions.

Several items should be noted from the DOE/PNNL study [41].

- Each of the seven luminaires with a flicker score below 2.6 would violate the condition that $\text{Mod}\% < 0.08 \cdot f_{\text{Flicker}}$.
- All 21 luminaires tested by PNNL that satisfied the condition $\text{Mod}\% \leq 0.08 \cdot f_{\text{Flicker}}$ had satisfactory flicker ratings, whether dimmed or not.
- Two LED luminaires at full output and one at dimmed level did not satisfy the condition that $\text{Mod}\% \leq 0.08 \cdot f_{\text{Flicker}}$, but they had flicker ratings above 2.6, which suggested that, in the conditions tested, the flicker was not regularly detected.

It can be inferred, therefore, that for flicker frequencies above 90 Hz, $\text{Mod}\% < 0.08 \cdot f_{\text{Flicker}}$ should contain the low-risk level, but with proper design of specific lighting circumstances (glare, brightness, spectral content, etc.), it may be possible to operate outside the region and still be acceptable. In any case, the DOE/PNNL experiments suggest that the low-risk region $\text{Mod}\% < 0.08 \cdot f_{\text{Flicker}}$ is not overly conservative.

Conclusions

This article presents criteria that can mitigate the biological effects of light flicker. The results were derived for LED lighting, but they can be applied to all general illumination technologies. LED lighting, however, has been the focus of more attention recently because its driving methods may introduce more flicker than other lamp technologies. The flicker depends on the drivers selected for the LED bulb, as described in this article. In addition, flicker health risks

depend upon a variety of lighting applications and exposure factors. For example, outdoor lighting with high-pressure sodium lamps on magnetic ballasts and low-pressure sodium lamps sometimes has nearly 100% modulation. They are often used without health incident, perhaps because the light is not being used for prolonged reading, studying, or

other more difficult visual tasks. According to DOE/PNNL researchers [16], a lighting situation may determine the case-by-case tolerance of flicker. They conjecture that flicker matters most in 1) general lighting, 2) spaces where children or susceptible populations spend time (e.g., hospitals), 3) task lighting, and 4) industrial spaces with moving machinery. Even in other lighting applications, prudence should be used when designing the amount of light flicker. This article creates generalized low-risk and no-

effect flicker regions that would be both task and lighting application independent.

A low-risk criterion of $\text{Mod}\% \leq 0.08 \cdot f_{\text{Flicker}}$ for flicker frequencies above 90 Hz may be a reasonable target for flicker design for LED bulb manufacturers. Some bulb manufacturers have already met the criterion, while others are close to meeting it. In fact, two of the seven tested LED bulbs actually satisfy the no-effect level criteria, $\text{Mod}\% \leq 0.0333 \cdot f_{\text{Flicker}}$. It, therefore, seems possible that commercial LED luminaires may be able to reduce their $\text{Mod}\%$ with small changes in their controllers or software, or even by changing a few filter component values (perhaps without altering the package size) if they desire to meet the low-risk level criterion for flicker.

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