Power Electronic Drivers’ Influence on LED Light Flicker

Brad Lehman
Northeastern University
lehman@ece.neu.edu

Collaborators: Arnold Wilkins, University of Essex; Anindita Bhattacharya; Semtech, Dustin Rand, Northern Power; Jennifer Veitch, NRC of Canada, Anatoly Shteynberg, Dialog Semiconductor; Michael Poplawski and Naomi Miller, PNNL
Disclaimer

- The views and opinions of this presentation do not represent views of the IEEE or IEEE PAR 1789 working group, but only reflect opinions of the presenter.
Presentation outline

• Introduction LED Lighting
• Flicker in Lighting
• LED drivers and flicker
• Conclusions
Introduction to LED Lighting

<table>
<thead>
<tr>
<th>Incandescent</th>
<th>60 watts</th>
<th>850 lumens</th>
<th>1000 hour life</th>
<th>$0.50/lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25,000 hour life-cycle cost</td>
<td>$12.50 (cost of 25 lamps)</td>
<td>$240.00 (energy cost)</td>
<td>$252.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CFL</th>
<th>13 watts</th>
<th>840 lumens</th>
<th>12,000 hour life</th>
<th>$4.47/lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25,000 hour life-cycle cost</td>
<td>$9.31 (cost of 2.1 lamps)</td>
<td>$52.00 (energy cost)</td>
<td>$61.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Philips LED</th>
<th>10.5 watts</th>
<th>800 lumens</th>
<th>20,000 hour life</th>
<th>$10.97/lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25,000 hour life-cycle cost</td>
<td>$13.71 (cost of 1.25 lamps)</td>
<td>$42.00 (energy cost)</td>
<td>$55.71</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cree LED</th>
<th>9.5 watts</th>
<th>800 lumens</th>
<th>25,000 hour life</th>
<th>$12.97/lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25,000 hour life-cycle cost</td>
<td>$12.97 (cost of 1 lamp)</td>
<td>$38.00 (energy cost)</td>
<td>$50.97</td>
</tr>
</tbody>
</table>

Source: US Green Building Council, Massachusetts chapter (June 2013)
http://usgbcma.blogspot.com/2013/06/say-goodbye-to-incandescent-lamp-and.html
Applications of HB-LEDs

Illumination
-- Local Illumination
-- General Lighting

Ref: www.lumileds.com
www.colorkinetics.com
Motivation

People LOVE light quality from LEDs!

Brad Lehman lit by CFL

Brad lit by incandescent

Brad lit by LEDs
Why High Brightness LEDs?

- LEDs have an incredibly long life, lasting ~50,000 hours (depends on operating temperature). A fluorescent tube lasts 7,500 hours and a normal incandescent bulb lasts only 1,000 hours.

- LED bulbs are environmentally friendly and no mercury to dispose of as in some fluorescent lamps.

- Lower maintenance cost as LEDs have long lifetimes. For the same reason replacement costs are also reduced.

- High-levels of brightness and intensity as combinations of Red, Green and Blue produce various colors.

- Can be easily controlled and programmed.
Predictions

- According to statistics published by Optoelectronics Industry Development Association (OIDA), replacement of one 60 Watt bulb with an equivalent lumens LED white light bulb will
  - Save over **1800 pounds** of coal.
  - Reduce carbon dioxide emissions by **3000 pounds**
  - Reduce Sulphur dioxide emissions by **12 pounds**
  - Creates **no mercury** emissions

- DOE estimates that Solid State Lighting could potentially reduce the US electricity used for illumination up to **50% by 2025**.
  - Alleviate the need of more than **40** power stations of **1000MW**.
## Power Conversion for “White” Light Sources

<table>
<thead>
<tr>
<th></th>
<th>Incandescent† (60W)</th>
<th>Fluorescent† (Typical linear CW)</th>
<th>Metal Halide‡</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Light</td>
<td>8 %</td>
<td>21 %</td>
<td>27 %</td>
<td>15-25 %</td>
</tr>
<tr>
<td>Infrared</td>
<td>73 %</td>
<td>37 %</td>
<td>17 %</td>
<td>~ 0 %</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>0 %</td>
<td>0 %</td>
<td>19 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Total Radiant Energy</td>
<td>81 %</td>
<td>58 %</td>
<td>63 %</td>
<td>15-25 %</td>
</tr>
<tr>
<td>Heat (Conduction + Convection)</td>
<td>19 %</td>
<td>42 %</td>
<td>37 %</td>
<td>75-85 %</td>
</tr>
<tr>
<td>Total</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

† IESNA Lighting Handbook – 9th Ed.
‡ Osram Sylvania
Comic strips go green.

I don’t care if you are a cartoon. Anytime you have an idea, I want to see and LED coming from your head and not an incandescent!!!
Flicker in Lighting

- Flicker, flutter, shimmer
  - Repetitive change in magnitude over time, or modulation, of the luminous flux or luminance of a light source
  - Light output modulation

- Visible vs. invisible, sensation vs. perception
  - Visible flicker = Light output modulation is sensed and perceived (<60Hz~90Hz)
  - Invisible flicker = Light output modulation is sensed, but not perceived (>90Hz)
  - Sensation: external conditions are detected and neurons respond
  - Perception: the brain detects AND the mouth can report it sees
Light source modulation

60W A19

T12

A19 CFL

A-lamp/G-lamp

R30/P AR30

R38/P AR38
Even battery powered flashlights can be programmed to flicker

1. High brightness
   145Hz (long duty cycle)
2. Low brightness
   57Hz (double pulse)
3. Flickering
   10Hz
Eye Saccade

- Eye in motion from (e.g. left to right) more sensitive to flicker
- Experiment: CRT with flickering bar (vs.) constant illuminating bar
  - Above what frequency is image same?
  - Implication to LED tail-lights (worst case scenario here)
  - Experiment designed by Jane Roberts and A. Wilkins, Univ. Essex, gives worst case upper bound of perceptible flicker
Driving at night

Do any of you find this annoying?
Strobing LED car tail lights
The "phantom array"

Saccade:

Flashing Light:

Appearance:

Figure 1. If you shift your gaze saccadically from the left to the right of a point light source in a darkened room, blinking on and off at 120 Hz, you will see phi movement to the left within a phantom array that is displaced to the right. From “Saccadic Eye Movements and the Perception of Visual Direction,” by W. [A.] Hershberger, 1987, *Perception & Psychophysics*, 41, p. 39. Copyright 1987 by Psychonomic Society, Inc. Reprinted with permission.
Experimental Setup

Participants view flickering line in the dark and make eye saccade

Which do you see?

Roberts and A. Wilkins (2013), Lehman et al (2011)
Two-interval force choice

Roberts and A. Wilkins (2013),
Roberts and A. Wilkins (2013),

Mean of individual thresholds = 1.98kHz (SD 1.13kHz)
Stroboscopic Effect:
Flickering light on a moving object
• What is max value of flicker that a viewer can detect stroboscopic effects?
  \[ \% \text{flicker} < 0.16 \times (\text{flicker_freq}) - 5.6 \]

Example: \(\text{flicker_freq}=120\text{Hz}\)
\[ \% \text{flicker} < (0.16)\times120-5.6 = 13.6\% \]

Where \(\% \text{flicker} = (\text{Max} - \text{Min})/(\text{Max}+\text{Min})\)
Flicker: Potential Health Effects

• Photosensitive epilepsy
  – Short exposure to 3 – 70 Hz flicker (i.e., visible modulation) may cause seizures in sensitive people
  – 1 in ~20,000 people

• Malaise: headache and eyestrain
  – Slower onset to frequencies in range of 100-120Hz have been published
  – Exact population frequency is not known (not everyone affected)

A double-masked study of headache and eye-strain

Compared conventional ("flickering") lighting (100Hz) with high-frequency ("non-flickering") lighting (>20kHz)

Seminal study by A. Wilkins (1989)
Timers measured hours lamp was turned on

Hidden in casing

Showed HF lights left on for longer

A. Wilkins (1989)
Headaches and lighting: over twice the occurrence of headaches when magnetic ballasts with 120Hz

A. Wilkins (1989)
Table 2 Risk Levels

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>Color code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Green</td>
</tr>
<tr>
<td>Medium</td>
<td>Orange</td>
</tr>
<tr>
<td>Serious</td>
<td>Yellow</td>
</tr>
<tr>
<td>High</td>
<td>Red</td>
</tr>
</tbody>
</table>

Figure 1 Risk Matrix by Hazard. Greater opacity corresponds to greater certainty

G, Ryder, R. Altkorn, X. Chen, JA Veitch, M. Poplawski, Safety 2012, the 11th World Conference on Injury Prevention and Safety Promotion
LED Drivers and Flicker

What makes LEDs different? Why the concern about flicker?
Methods of Driving LEDs – Basic Circuit

- Basic Circuit Advantages
  - Simple and low cost

- Basic Circuit Disadvantages
  - Lower efficiency due to resistor R
  - Uneven light intensity due to Vf variations from temperature (+/- 20%)
  - Reliability impacted by Vf variations due to temperature – higher temperature causes increase in current causing higher junction temperature of LED
1 Strings of LEDs with 1 Source

Series combination of LEDs with a voltage source (left), with a current source (right)

- Operate the source as a current source instead of voltage source and regulate string current
- Regulating current = regulating luminous intensity (if temperature is constant)
Basic Concept for LEDs

Light Output (luminance) is roughly proportional to the LED current.
LED Drivers and Flicker: The Concern?

AC Powered LED Lighting System

- SOURCE
- LED DRIVER
  - AC-DC Converter
- STRINGS OF LEDS
- LIGHT FIXTURE
- LIGHT

AC-DC converters often have 120Hz harmonics (flicker) in their current. How much is acceptable? (120Hz = twice the line frequency, which would be 100Hz in Europe.)

AC LEDs: It is possible to eliminate AC-DC converter using a few special techniques: Reduce costs, eliminate capacitors, smaller size, increased lifetime. But this gives 100Hz/120Hz flicker.
**AC LEDs**

1. Rectify AC and send to LED string

![Rectify AC and send to LED string diagram]

Directly power two LED strings with opposite Anode/Cathode connections

![Directly power two LED strings diagram]

Luminous Flux (periodic every 1/120 sec) is proportional to LED current

Or a capacitor

![Luminous Flux graph]

LED Current vs. Time

- 0.05 to 0.105 seconds
- 0 to 0.5 A LED Current (amps)
Failures may cause 60 Hz flicker: Open circuit in rectifier or in LED string

- Rectify AC and send to LED string

- Directly power two LED strings with opposite Anode/Cathode connections

(c) Simulation of current through HB LEDs. Luminance is proportional to current, causing lamp to flicker at the AC mains line frequency (shown periodic every 1/60 sec)
What About Power Electronic Drivers?

- **SOURCE**
  - *AC source*

- **LED DRIVER**
  - *AC-DC Converter*

Single Stage: Has Power Factor Correction (PFC) but produces high (up to 100%) flicker at twice line frequency

Two Stages: Has PFC and the ability to reduce the 120 Hz flicker
Flyback converter is able to keep input current in phase with AC voltage for PFC
Output LED current has substantial flicker at 120 Hz (unless peripheral circuits added for cancellation—Fang(2013), Hu(2012))
Typical Single-Stage LED driver

AC source input current in phase with the voltage

Fang(2013), IEEE TPEL

Output LED current has large flicker at 120 Hz
Typical Dual-Stage LED driver
It is possible to eliminate flicker completely.

DC/DC or AC/DC converter acts as pre-regulator to create Vo above the required highest string voltage (voltage imbalance among strings!).

Linear regulators can keep current constant and the same in each string.

PWM dimming (series) can be added to the Linear current regulator. Adjust Vo according to Vmin so Vo adapts to which strings are on/off.

---

From: IEEE TRANSACTIONS ON POWER ELECTRONICS, NOVEMBER 2008
Driver With Self-Adaptive Drive Voltage”, Yuequan Hu and Milan M. Jovanovi´c,

DC/DC or AC/DC converter acts as pre-regulator to create Vo above the required highest string voltage (voltage imbalance among strings!).

Linear regulators can keep current constant and the same in each string.

PWM dimming (series) can be added to the Linear current regulator. Adjust Vo according to Vmin so Vo adapts to which strings are on/off.
Power Factor Correction (PFC)

Architecture Trade-Off

Dual-stage PFC
- Near perfect PFC possible
- With proper control and component design, flicker can also be kept minimal
- BUT: Boost stage adds components and cost

Single-Stage with PFC
- Modulating the input impedance improves PF
- BUT: Higher %Flicker at twice line frequency usually remains
- (Some have proposed combining passive pfc with single stage power converter… to impact both pf and flicker.)

It Comes Down to Flicker vs. cost vs. Performance
Triac Phase Modulate Dimmers
PWM Dimming

Used with either AC Mains or DC power as source
Can increase or induce flicker

Few LED lamps will visually flicker on AC wall dimmers (3Hz~25Hz) because they fail to work properly.
Triac Dimmer

Dimmer malfunctions during light load with current less than minimum latching and holding currents, as is often the case with single LED lamps (Rand et al, PESC 2007).

- **Solution**: Add resistor or active load to the LED lamp: When dimming on triac, there is a forced power sink wasting energy to keep the triac on. (not great...)

Require a large hold-up capacitor to keep current in LEDs during off-time of the dimmer (not realistic in size, cost, lifespan, etc.)
The Concern?

A few LED lamps will visually flicker on AC wall dimmers (3Hz~25Hz) because they fail to work properly.

Commercial LED lamp flickers at 3.15Hz when connected to typical residential dimmer switch.
Solution: holdup capacitor – LM3445

- Vcc receives power at all times
- Triac off – the capacitive valley fill circuit still powers the buck converter’s input voltage
- Dimming level corresponds to the on-time of the Triac
- Add Passive PFC

Many LED driver manufacturers now keep DC voltage across LEDs at all times, even during triac off-time
LED PWM Dimming Example

Switch

100% dimmer

~75% dimmer

~50% dimmer

~25% dimmer

~0% dimmer
Conclusions

- Various level of 120 Hz flicker appear in all lighting
- The driving method for LED lamps influences the amount and shape of the flicker
- IEEE PAR1789 Standard Committee intends to provide a recommended practice for how to apply this information

http://grouper.ieee.org/groups/1789/
IEEE PAR 1789 - PURPOSE

Vision: Bring together a community of lighting environmental psychologists, medical researchers, lamp designers, LED driver designers, and LED lamp users to openly discuss concerns for LED lighting.

• There is a need to create a community where experts among the above different fields can communicate.
• Suggest a recommended practice, not a standard. Representation on IEEE P1789 from ENERGY STAR, CIE and NEMA may later incorporate findings into standards if deemed necessary.
• IEEE Standards Association has a unique open process that MUST involve all interest groups including academics, national labs, industry, customers… (current membership is ~50 with around 25% academics, 25% government labs, 50% industry/consulting)
• International participation from members and from standards groups
IEEE PAR 1789 - PURPOSE

• Describe some possible health risks, such as headaches, eye strain and epileptic seizure, associated with low frequency modulation of High Brightness LEDs in different applications.

• Provide recommended practices to aid design of LED driving systems to modulate at safe frequencies for their particular applications in order to protect against the described health risks.

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