LED Lighting

LED Lighting Basics

Contents

• Why Led?
• Common LED lighting terms
  – Efficiency
  – Efficacy
  – Power factor
• Frequently encountered electrical terms
• LED configuration
• Isolated/Non-isolated
• Dimming
• TRAIC in lighting dimmers
• TI LED driver summary
Why LED?

Incandescent Lamp

- First, we had the incandescent bulb (optimized, but not invented by, Mr. Edison):
  - Instant on and off
  - Near perfect color rendering
  - Easy to dim
  - Cheap to manufacture
- But, it had two “minor” issues:
  - It only lasts about 2,000 hours
  - It is horribly inefficient: only ~8% of the energy comes out as visible light
Discharge Lamp

- Next, we had low and high intensity discharge lamps, like fluorescent and high pressure sodium, respectively:
  - Lasted much longer
  - Much more efficient – 300-400% as efficient as incandescent

- But, they too have some issues:
  - Contain mercury, a neurotoxin
  - Can’t be turned on and off quickly
  - Difficult and costly to dim
  - Color rendering ranges from very poor to acceptable

Solid State Lamp

- It turned out, it was more efficient and cost effective to install discharge lamps and leave them on all night than to modulate incandescent and replace them all every 6 months!

- But… what if we had the best of all worlds?

<table>
<thead>
<tr>
<th>Power Conversion for “White” Light Sources</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Visible Light</td>
</tr>
<tr>
<td>IR</td>
</tr>
<tr>
<td>Total Radiant Energy</td>
</tr>
<tr>
<td>Total (Continuous)</td>
</tr>
</tbody>
</table>

1. EEMAC Handbook
2. Cherevits
3. Note: depending on LED efficacy, this range represents the currently available technology in color temperature from warm to cool. EEMAC, Indoor Task Categories (May 2004) cite the maximum efficiency difference to more than 50% to 122.
Common Lighting Terms

• Key Driver Attributes
  – Dimming
    Analog Dimming, PWM Dimming
  – Efficiency
  – Total Harmonic Distortion (THD) & Power Factor Correction (PFC)
  – LED Current
    Ripple
  – Reliability & Lifetime

• General Lighting & System Terms
  – Light Output Terms
    • Luminous Flux (Lumens)
    • Lux
    • Candela
  – Light Effects
    • Stroboscopic Effect
    • LED Flicker
  – Input and Output Voltage

Key Driver Attributes

Dimming Interfaces

These are the different types of dimming devices that the driver is expected to work with.

Most common interfaces are leading-edge (TRIAC) and trailing-edge (IGBT) dimmers and 0-10V.

Efficiency

Efficiency is the measurement of how good the power supply converts input power to output power and is measured in %.

Efficacy

Efficacy is the measurement of how good the luminaire is at converting electrical power to light and is measured in lm/W.

PFC / THD

Power Factor of an AC electric power system is defined as the ratio of the real power flowing to the load over the apparent power in the circuit.

Total Harmonic Distortion is the amount of harmonics that the driver creates and pushes back on to the AC line.

LED Current

LED Ripple is the amount of ripple current present on the output of the LEDs. This can cause flickering and is very common in single-stage PFC controller and typically needs large output capacitor to filter out the ripple.

Good PFC does not always mean good THD.

Reliability/Lifetime

Reliability is frequently luminaries are expected to fail during their operational life.

Lifetime describes how long luminaries can be expected to operate on average.

LED Term
Review of Dimmer Concepts

- **Leading Edge Dimmers**
  - Otherwise known as TRIAC dimmer
  - >70% of current dimmers are leading edge
  - Holding current required for EU or US

- **Trailing Edge Dimmers**
  - Mainly used in newer infrastructure
  - Does not impose holding current requirements
  - Needs some minimum impedance for dimmer to function properly.

- **0-10V Dimming**
  - Typically used for commercial applications
  - One of the earliest and simplest electronic lighting control signaling systems
  - Requires additional wiring

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**Review of Efficiency**

\[
\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}}
\]

- **Power FET**
  - Conduction Losses (I^2R)
  - Switching Losses (F*CV^2)

- **Inductor**
  - Conduction Losses (I^2R)

- **Freewheeling Diode**
  - Conduction Losses (IV)

**Simple BUCK Regulator (V_{out} < V_{in})**
Lighting Efficiency

- The simple answer: Light, only when we need it, only where we need it, and only how much we need, not more.

- Overall efficacy has many elements:
  - Source efficacy
  - Power supply efficiency
  - Fixture efficacy
  - Light distribution efficiency
  - Light provided vs. light needed efficiency

Source Efficacy

<table>
<thead>
<tr>
<th>Year</th>
<th>2009</th>
<th>2010</th>
<th>2012</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Efficacy (lm/W)</td>
<td>113</td>
<td>134</td>
<td>173</td>
<td>215</td>
<td>243</td>
</tr>
</tbody>
</table>

Review of Power Factor

- **Power Factor** is the Ratio of Real Power (Watts) to Apparent Power (RMS Volt-Ampere product)

  \[ PF = \frac{\text{Real Power (W)}}{\text{Apparent Power (VA)}} \]

- **Power Factor** has two components –
  - Displacement Factor (DispF) \( \text{DispF} = \cos \phi \)
  - Distortion Factor (DF) \( DF = \frac{I_d}{I_{rms}} = \frac{1}{\sqrt{1 + \text{THD}^2}} \)

- **Power Factor** PF is the product of DF and DispF

  \[ PF = \frac{1}{\sqrt{1 + \text{THD}^2}} \cdot \cos \phi \]

PWM vs. Analog Dimming (1)

**Analog Dimming**
- Linearly
- Pulsating

**PWM Dimming**
- VOLTAGE REGULATOR (LINEAR OR SWITCHING)
- LED
- \( V_{FB} \)
- \( R_{SW} \)
- \( I_F \) Changes

**PWM Dimming**
- VOLTAGE REGULATOR (LINEAR OR SWITCHING)
- LED
- \( V_{FB} \)
- \( R_{SW} \)
PWM vs. Analog Dimming (2)

- Analog dimming consists of changing the constant current through the LED by adjusting the sense voltage.
  - Quiet, does not generate additional noise in the system.
  - The dominant wavelength varies with LED current however, so the color will change using this method.

- PWM dimming consists of setting a desired LED current and turning the LED on and off at speeds faster than the human eye can detect.
  - Noisier. The input supply must be filtered properly to accommodate the high input current transients.
  - The dominant wavelength does not change so color can be well controlled. This is usually the preferred method of dimming high current LEDs.

Analog Dimming – Why Not?

- CCT provides the basis for “cool” white (more blue) and “warm” white (more red) - CCT shifts with \( I_F \) as well.
- Most white LEDs are made off blue LEDs with yellowish phosphor coating.
- CCT shifts are much easier to see than with colored LEDs (more yellow at low \( I_F \) and more blue at high \( I_F \)).
Analog vs. PWM Dimming (3)

More Yellow

1W LED driven at 50 mA continuous

More Blue

Same 1W LED driven at 300 mA with 1/6th duty cycle (500Hz)

PWM Dimming Schemes

Enable Dimming

- \( I_f \) On/OFF through Enable/Disable
- Simple implementation
- Slow current transitions

Series Dimming

- \( I_f \) On/OFF through the series FET
- OK current transitions
- Vout overshoots, complex implementation

Shunt Dimming

- \( I_f \) In/Out through the shunt FET
- Super-fast current transitions
- High-power dissipation in the shunt FET
Review of Reliability/Lifetime

- Every component limits lifetime – to some degree
- 3 types of components usually have the largest influence on ultimate lifetime
  - Non-solid electrolytic capacitors (e-Caps)
  - Solder joints
  - Optical isolation devices (opto-couplers)

LED Configuration
**All in Series**

- **Pros:**
  - Guaranteed current matching
  - Continues to operate if LEDs fail short circuit
- **Cons:**
  - Highest output voltage
    - Component selection thins as voltages go up
    - Safety standards get more strict
  - No more light if an LED fails open circuit

**Series-Parallel**

- **Pros:**
  - Lower $V_O$
    - Staying within safety limits
  - Continues to operate (poorly) if LEDs fail short circuit
- **Cons:**
  - No current matching
    - $V_F$ varies from LEDs, even LEDs from same wafer
    - $V_F$ drops with $T_J$, potential positive feedback loop
Pitfall of Series-Parallel #1

- Ballast resistors work well with a voltage source and a low current LED
- The old way:

\[ I_F = \frac{V_O - n \times V_F}{R_{BALLAST}} \]

- The tolerance of \( I_F \) improves:
  - As \( I_F \) decreases
  - As \( R_{BALLAST} \) increases
  - As \( V_{BALLAST} \) increases

Low Frequency ( < 1 kHz)

- General and automotive applications
- More efficient: less transitions
- Duty cycle requirements not as strict: 10% to 90% is typical
- Usually achievable by using the DIM or EN pins
High Frequency ( > 10 kHz)

- Technical requirements force the users to high frequency
- High speed PWM dimming can be desirable in order to avoid certain frequency bands, such as audio
- Generation of white light from RGB in backlights, video projectors
- Loss of efficiency due to the transitions
- Some big questions…
  - How do we do this when LED current is very high?
  - How do we do this with various topologies?

Current Sensing
Low-Side Sensing

• Easier to implement, easier to amplify
• With a controller, $V_{O-MAX}$ can be 100V+
• $I_F = \frac{V_{REF}}{R_{SNS}}$
Isolated or Non-isolated

Safety of Lighting System

• 4KVac High Pot Test between Chassis & Terminals is required to meet safety standard in lighting system (EN60968/9)
Non-Isolated Solution

The LED drivers & heatsink of LEDs is fully encapsulated by the plastic case.

Like the conventional CFL light bulb, the plastic enclosure as the insulator, the heatsink/metal & electronic devices are non-accessible by Human Finger.

Can simply employ Non-isolated LED driver to pass 4KVAC test.

Non-Isolated Solution (II)

Heatsink for thermal management of LEDs

Plastic enclosure
Why need Isolated Solution?

For higher power GI applications, such as downlights, the IMS (insulated metal substrate) Board is directly attached to the metal casing of fixture for optimizing the thermal management of LED.

Metal/Heatsink can be accessible by Human.

And, the insulated layer is only relied on the thermal conductive insulated substrate of Metal Core Board.

Why need Isolated Solution? (II)

Potential leakage current path

Isolation is only rely on thermal conductive insulation substrate of Metal Core

→ May not reliable
Isolated AC/DC LED Driver

How can we meet safety requirement for non-isolated driver in LED light bulb /w metal enclosure?
What is Triac Dimmer?

The Basics of Triac

Three general methods are available to switch Thyristors to on-state condition:

1. Applying Proper Gate Signal
2. Exceeding Thyristor dv/dt characteristics
3. Exceeding voltage break-down point

In the below discussion, we are focus on (1)
Triac Dimmer Characteristics

- Triac requires a resistive load to fire
  - Drip current of 10-15mA
  - Once Triac fires, drip current can be removed to increase efficiency

- Output is a sampled segment of the offline AC waveform
  - Based on the firing angle set by the Triac dimmer

Triac Dimming Circuit
Switch-On the Thyristor by Proper Gate Signal

• To turn on the Thyristor, Gate signal must exceed IGT and VGT requirements of the Thyristor used.

• Triac (bilateral device) can be turned on with gate signal of either polarity; however, different polarities have different requirements of IGT and VGT which must be satisfied.

Latchining Current of the Triac

• Latching current (IL) is the minimum principal current required to maintain the Thyristor in the on state immediately after the switching from off state to on state has occurred and the triggering signal has been removed.

• Latching current can best be understood by relating to the “pick-up” or “pull-in” level of a mechanical relay.
Holding Current of Triac

- Holding current (IH) is the minimum principal current required to maintain the Thyristor in the on state.
- Holding current can best be understood by relating it to the “dropout” or “must release” level of a mechanical relay.

What is Holding Current?

- Example:
  - Suppose Triac Dimmer uses BTA06-TW

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Quadrant</th>
<th>BTA06 / BTB06</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{GT}$ (1)</td>
<td>$V_D = 12 , \text{V}$, $R_L = 30 , \Omega$</td>
<td>I - II - III</td>
<td>MAX.</td>
<td>\begin{tabular}{c</td>
</tr>
<tr>
<td>$V_{GT}$</td>
<td></td>
<td>I - II - III</td>
<td>MAX.</td>
<td>1.3</td>
</tr>
<tr>
<td>$V_{GD}$</td>
<td>$V_D = V_{GBU}$, $R_L = 3.3 , \text{k}\Omega$, $T_j = 125^\circ \text{C}$</td>
<td>I - II - III</td>
<td>MIN.</td>
<td>0.2</td>
</tr>
<tr>
<td>$I_H$ (2)</td>
<td>$I_T = 100 , \text{mA}$</td>
<td>MAX.</td>
<td>10 &amp; 15 &amp; 35 &amp; 50</td>
<td>mA</td>
</tr>
<tr>
<td>$I_L$</td>
<td>$I_G = 1.2 , I_{GT}$</td>
<td>I - III</td>
<td>MAX.</td>
<td>10 &amp; 25 &amp; 50 &amp; 70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
<td></td>
<td>15 &amp; 30 &amp; 60 &amp; 80</td>
</tr>
</tbody>
</table>

Max. holding current $I_H = 10 \, \text{mA}$
Common Problem with Triac Dimmer

- If holding current does not flow through the triac continuously, the triac will re-fire at the same conduction period.

Summary of Triac Operation

1) To turn on the Triac, Gate signal must exceed specified IGT and VGT requirements.

2) Latching current (IL) is required to maintain the Triac in the on state immediately after the switching from off state to on state has occurred and the triggering signal has been removed.

3) Then, Holding current (IH) is the required to maintain (hold) the Thyristor in the on state.

4) As the cathode to anode current of Triac is less than specified holding current, the Triac is switched to off-state.
Why flickers?

- As mentioned before, not just holding current, the input EMI filter interact with different types of triac dimmers also could misfire the triac....

Proof it by removing by X CAPs
TI Lighting Power Products at a Glance

Light Bulbs & Low Power Luminaries
- B10, GU10, A19, PAR20-38
- LM3445/8
- TPS92010
- TPS92012
- TPS92010
- TPS92210
- MR16, AR111
- LM3401
- LM3444
- LM3492
- TPS40211
- Architectural, Wall Washers, Sconces, Downlights
- LM3402/4/5/5A/6/7
- LM3430/31
- LM3410
- LM3421/3/4/9
- TPS40211
- Linear

High Power Wide Area Luminaries
- Street Light, High Bay, Parking, Parkway, Troffers
- UCC28810/1
- TPS92020
- TPS92210
- LM3450A
- LM3401/9
- LM3433/34
- LM3402/4/5/5A/6/7
- LM3414
- LM3420/1
- LM3410
- LM3421/2/4/9
- TPS40211
- LM3432
- LM3492
- LM3464
- LM3486
- LM3463

Automotive
- Exterior, Interior & Infotainment backlighting
- LM3424Q
- LM3421G/23D/29Q
- LM3406Q
- LM3410Q
- LM3431Q

Q & A?