Power Factor and Lighting

Requirements for power factor and harmonic currents for AC driven LED lamps.

Paul de Vries, Staf Field Application Engineer
Will these Lamps pass regulations in the EU?

- CFL Lamp, 15 W, PF = 0.44
- LED Lamp, 12 W, PF = 0.77
- LED Lamp, 28W, PF = 0.97
What is the Power Factor

- Power Factor (PF) is a measure of the quality of the current
- \( PF \neq \cos(\phi) \)
- \( PF = \frac{\text{Real Power (W)}}{\text{Apparent Power (VA)}} \)

\[
PF = \frac{P}{S}
\]
IEC61000-3-2  
Lamps Class C: Harmonic Currents

- **Input Power > 25W**
  - relative limits in Table-2
- **Input Power ≤ 25W**
  - Table 3, column 2
  - Or an exception: see next slide
- -> No PF requirement
  - Only Harmonic Currents
  - However high PF means low harmonics
  - Low harmonics can still have low PF due to phase shift!

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Max harmonic current, % of fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>30 * PF</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>11 ≤ n ≤39 (odd only)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2: Input Power > 25W

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Max harmonic current per Watt, mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.4</td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
</tr>
<tr>
<td>9</td>
<td>0.35</td>
</tr>
<tr>
<td>11 ≤ n ≤39 (odd only)</td>
<td>3.85 / n</td>
</tr>
</tbody>
</table>

Table 3: Input Power ≤ 25W
IEC61000-3-2 LED Lamps Class C
Input Power ≤ 25W Exception

- $3^{\text{rd}}$ harmonic < 86% of fundamental
- $5^{\text{th}}$ harmonic < 61% of fundamental
- Current flow starts ≤ 60°
  and last peak ≤ 65°
  and does not stop flowing before 90°
EU Regulation: Directive 2009/125/EC

- Power Factor (PF) for lamps with integrated control gear: (since September 1st 2013)

<table>
<thead>
<tr>
<th>Input Power</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 2 W</td>
<td>no requirement</td>
</tr>
<tr>
<td>2 W &lt; P ≤ 5 W</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>5 W &lt; P ≤ 25 W</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>P &gt; 25 W</td>
<td>&gt; 0.9</td>
</tr>
</tbody>
</table>

Source: Table 5, Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment
Ways to get an higher PF

• Passive Power Factor Correction

• Active Power Factor Correction
Passive PFC

- Filter
  - Would require huge coils -> not practical
  - Not universal mains

passive PFC 250W supply
Passive PFC

- Valley Fill Circuit
- PF > 0.7 easy to reach
- Current not much like a sine wave -> large amount of harmonic currents!
- Exception does not apply, as last peak not before 65 °
Harmonic currents in valley fill passive PFC

- A LED driver with a passive PFC, the so called Valley Fill will not pass the IEC61000-3-2 requirements

![Harmonics currents versus Limits graph](chart.png)
Harmonic currents with active PFC

- A LED driver with active PFC can normally easily pass the IEC61000-3-2
Will these Lamps pass regulations in the EU?

- CFL Lamp, 15 W, PF = 0.44
- LED Lamp, 12 W, PF = 0.77
- LED Lamp, 28W, PF = 0.97
Will these Lamps pass regulations in the EU?

- **CFL Lamp, 15 W, PF = 0.44** -> Not any more
  - It did pass when it was sold
  - Now the PF is too low, should be above 0.5 for P > 5 W

- **LED Lamp, 12 W, PF = 0.77** -> No
  - it uses Valley Fill, harmonic currents are too high

- **LED Lamp, 28W, PF = 0.97** -> Yes, is above 0.9
  - but PF is not only criteria. The harmonic currents are important and do pass as well
Active PFC

• Most PFC are Boost converters

• Min Output voltage > SQR(2) * VAC(max)
  – to have PFC operation at highest mains voltages

• Many operating mode to make boost work as PFC
  – CCM / CrM / DCM / mixed form

• Buck can also be used as PFC
• Can get very high PF: > 0.99
• Harmonic currents will be low as well, often expressed in THDI:
  Total Harmonic Distortion in the Current(I)
THDI

• Total Harmonic Distortion in the current

\[ THDI = \sqrt{I_2^2 + I_3^2 + \ldots I_n^2} \frac{100}{I_1} \%
\]

• THDI is not a regulation but a Lighting Marketing Requirement

• Currently: **THDI ≤ 10%** at full power at nominal input voltage range for professional Lighting

• When THDI < 30% you most likely already pass the IEC61000-3-2
ON Semiconductor PFC portfolio

Power Factor Controllers

Fixed Frequency
- Continuous Mode
  - NCP1650
  - NCP1653
  - NCP1654
- Single Stage PFC
  - NCP1652

Variable Frequency
- Critical Conduction Mode
  - NCP1607
  - NCP1608
  - NCL30000
  - NCL30060
- Freq. Clamp Critical Mode
  - NCP1605*
- Current Control Freq. Foldback
  - NCP1611
  - NCP1612
  - NCP1615*
- Interleaved PFC
  - NCP1631

* Parts in Green bold features HV Start-up

ISOLATED SINGLE STAGE LED DRIVERS
Using a Flyback with PFC
Single Stage Power factor corrected Flyback

• A flyback is very similar to a boost
  – Add a secondary winding to the boost coil
  – and third ‘aux’ winding to get power for VCC
• In the beginning pure PFC controllers were used
• However Lighting has different requirements than PFC in power supplies.
• NCL30060 LED lighting optimized driver
NCL30060 Features

- Built-In High Voltage Start-up Circuit
- Quasi-Resonant Switching
- Wide Vcc range with Gate Drive voltage clamp
- Direct Opto-coupler Feedback Connection
- Precision Constant On Time Programming
- Frequency Jittering for reduced EMI profile
- Robust Fault Protection
  - Over-current, Over-voltage, Short Winding, Shorted Output Rectifier
  - Output open and short circuit protection
- Auto-recoverable and latched fault handling options
- 1 second timer for low power dissipation for auto-recoverable faults
- Thermal Shutdown Function
- Enable/Disable Function
- Support external circuit bias during Disable for Smart μP Based Drivers
NCL30060 typical application diagram
PRIMARY SIDE CONTROLLED LED DRIVERS
Classical Offline LED Driver Feedback Control

- **Primary Side**
  - AC Input
  - Flyback Controller
  - Current/Voltage Sense
- **Secondary Side**
  - Power Conversion
  - Feedback Control
Primary Side Control Block Diagram

Advantages
- Reduces Parts Count
- Simplifies PCB Layout
- Saves Space
- Increases Efficiency
- Simplifies Safety Analysis

CCCV Loop Components
- Dual Op Amp
- TL431 or Zener Reference
- Bias for Opto-coupler
- Bias Regulator for Op Amp
- Current Sense Resistor
- Voltage Sense Sense for OVP
Challenges of Primary Side Control

- Control algorithm must deal with many variables
  - LED string voltage and input line voltage variation
  - Component variation (transformers, FET, IC, resistors)

- Target is to precisely regulate current over Wide $V_{fw}$ support
  - LED forward voltage changes with temperature and lot-to-lot
  - No need to bin LEDs to get tight $V_{fw}$
  - One driver design can be used for a range of products (optics/LED etc) simplifying design and reducing engineering cost
  - Future proof designs so as LEDs improve, same driver can be used

- NCL3008x PSC family was designed to achieve best-in-class performance using Quasi-Resonant Approach
Flyback Primary and Secondary Currents

- \( t_{\text{demag}} \) is the primary inductor reset time.
- \( I_{L,pk} \) is the controlled magnitude in a current mode circuit:
  \[ I_{L,pk} = \frac{V_{CS}}{R_{\text{sense}}} \]

The controller measures \( t_{\text{demag}} \) and controls \( I_{L,pk} \) to maintain \( I_{out} \) constant:

\[
I_{out} = \langle I_{\text{sec}}(t) \rangle_{T_{SW}} = f(t_{\text{demag}}, T_{SW}, I_{L,PK})
\]

- Unfortunately Flyback transformer is not ideal
Flyback current with Leakage inductor

- $t_1$ is the reset time of the leakage inductor.
- $t_{demag}$ is the primary inductor reset time.
- $I_{L,pk}$ is the controlled magnitude in a current mode circuit: $I_{L,pk} = V_{CS} / R_{sense}$

- Most controller measures $t_{demag}$ and control $I_{L,pk}$ to maintain $I_{out}$ constant.
- As $t1$ is small but not negligible, the error in output current can be a few percent.

$$I_{out} = \left< I_{sec}(t) \right>_{T_{SW}} = f \left( t_1, t_{demag}, T_{SW}, I_{L,PK} \right)$$
Flyback current with Leakage inductor: ON Semiconductor solution

- $t_1$ is the reset time of the leakage inductor.
- $t_{demag}$ is the primary inductor reset time.
- $I_{L, pk}$ is the controlled magnitude in a current mode circuit: $I_{L, pk} = V_{CS} / R_{sense}$

The NCL3008x measures $t_{demag}$ and $t_1$ and control $I_{L, pk}$ to maintain $I_{out}$ constant:

$$I_{out} = \left\langle I_{sec}(t) \right\rangle_{T_{SW}} = f\left(t_1, t_{demag}, T_{SW}, I_{L, PK}\right) = \frac{V_{ref}}{C N_{sp} R_{sense}}$$
NCL30088 Primary Side Controller
(High Power Factor Flyback Implementation)

(1) Wide Vcc Range with built in OVP Protection

(2) Negative Temperature Resistor for Thermal Foldback Protection

(3) Programmable OVP Protection (optional)

Input Line Sensing and Brownout Detection

Leakage Inductance Monitoring
**NCL30085 Series Hi-PF PSR Family**

- Combines precise primary side quasi-resonant current control of NCL30080 series with active power factor correction, typical 0.98+
- Applications can range up to 60 W, **typical 8-25 W**
- <10% THD can be achieved for single line range
- Supports isolated flyback or non-isolated buck-boost topologies
- SOIC8/10 packaging platform (same body size)
- User programmable thermal fold-back with external NTC
- Non-dimmable, Analog/Digital and Step Dimming versions
- Robust Protection Suite

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Package</th>
<th>Thermal Fold back</th>
<th>Target Applications</th>
<th>Analog &amp; Digital Dimming</th>
<th>Step Dimming</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCL30085</td>
<td>SOIC8</td>
<td>Yes</td>
<td>Retrofit Bulbs and Drivers</td>
<td>No</td>
<td>Yes -3 levels</td>
</tr>
<tr>
<td>NCL30086</td>
<td>SOIC10</td>
<td>Yes</td>
<td>Smart Lighting</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NCL30088</td>
<td>SOIC8</td>
<td>Yes</td>
<td>Retrofit Bulbs &amp; Tubes / Drivers</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

1 mm Lead Pitch In SOIC8 Body
ISOLATED DUAL STAGE LED DRIVERS
## Single versus Dual stage

### Single Stage

- **Advantages**
  - Direct current drive
  - Single switch and magnetic

- **Disadvantages**
  - 100 / 120 Hz ripple
  - Higher MOSFET stress
  - Wider Duty Cycle Range
  - Typically limited < 60W

### Dual Stage

- **Advantages**
  - Primary energy storage means low output ripple
  - Easy to scale in power/size
  - Easy to provide secondary bias power

- **Disadvantages**
  - Two magnetics, at least 2 power switches
Dual Stage Design Idea: NCP16xx+NCL30082

- PFC + Isolated PSR Flyback Controller
- Low THDI, high PF, high Efficiency over dimming range
- Tight output current control < ±1%
- Analog and Digital Dimming (can do both at same time)
- Thermal Foldback

NCP1607 / NCP1611

NCL30082
Combo Devices
Dual stage Boost + Buck

PFC NCP16xx

NCL30161 Buck LED Driver

MCU for Dimming and Control

ZLL

(2x) … Two strings to implement white LED color control

(3x) … Three strings to implement RGB LED color control

Whole Room Light
40-80 W
100 lm/W
Boost LED Drivers

• For driving very long strings / very high forward voltages
Non-Dimmable <10 W HiPF Boost
NCP1075 Switcher and +/- 2% accurate NCP4328A CCCV Controller

- Off-the-shelf inductor, >91% efficient driving $V_f$ string of 220V @ 30 mA (6.6 W)
- Typical PF > 0.96 and THD of <20% at 120 Vac
- < 20 msec typical startup time
- Perfect for High Voltage LEDs like CREE 48Vx5 XT-E or Philips Luxeon 200 V

Actual Size: 24.1 x 34.7 mm
QUESTIONS?