DESIGN HIGH PF HIGH EFFICIENCY
PSR FLYBACK LED DRIVER

Name: Roy Mi

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Outline

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- Flyback Converter for LED Lighting Application
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  - Discontinues Conduction Mode
  - Boundary Conduction Mode
  - Hybrid (Partial BCM) Mode
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- Design Procedure for PSR Flyback
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LED Driver Design Challenges

- Cost
LED Driver Design Challenges

- Cost
- Standard & Agency Requirements
- Design Complexity
  - Power Factor Correction
  - Safety and Protection
  - Constant Current Control accuracy
- Thermal / Efficiency
- Reliability & Lifetime
# LED Driver Design Challenges

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<tr>
<th>Agency</th>
<th>Location</th>
<th>Voluntary vs. Mandatory</th>
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<tr>
<td>Energy Star - US</td>
<td>United States</td>
<td>Voluntary</td>
</tr>
<tr>
<td>California Energy Commission</td>
<td>United States - California</td>
<td>Mandatory</td>
</tr>
<tr>
<td>European Commission ErP Ecodesign Directive</td>
<td>Europe</td>
<td>Mandatory</td>
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<tr>
<th>Item</th>
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<tr>
<td>Power Factor (PF)</td>
<td>Energy Star Program Requirements for Integral LED Lamps Version 1.1</td>
<td>≥ 0.7 for &gt;5W</td>
</tr>
<tr>
<td></td>
<td>(Amended – Mar. 22, 2010)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0, (Effective date: Oct 1, 2011)</td>
<td>Residential ≥ 0.7 for &gt;5W Commercial ≥ 0.9 for &gt;5W ≥ 0.5 for ≤5W</td>
</tr>
<tr>
<td>Total Harmonic Distortion (THD)</td>
<td>EN(IEC)61000-3-2 Class C (Lighting)</td>
<td>Class C (&gt;25W) ≤ 30%THD</td>
</tr>
<tr>
<td></td>
<td>KS C7651/2/3 (IEC61000-3-2)</td>
<td>Class D (≤25W)</td>
</tr>
<tr>
<td>Dimming</td>
<td>Energy Star Program Requirements Product Specifications for Luminaires (Light Fixtures) Version 1.0, (Effective date: Oct 1, 2011)</td>
<td>Continuous dimming from 35% to 100% of total light output</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>NEMA SSL 1-2010</td>
<td>120, 127, 208, 220, 230, 240, 277, 347, 480 V&lt;sub&gt;AC&lt;/sub&gt; at 50 or 60 Hz, 12 or 24V&lt;sub&gt;AC&lt;/sub&gt; or V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
Why Flyback For low Wattage LED application:

Pro: Cost and Size
Why Flyback For low Wattage LED application:

Pro: Cost and Size

Con:
1. Huge output current ripple & output capacitor
3. Not best for Triac Dimming application
4. Inferior electrical characteristics for LED applications, i.e., THD, Efficiency…
DCM Flyback

- Duty cycle and $f_s$ are constant during a half-wave.
- Converter is in deep DCM when $V_{\text{in}}(t)$ is low, and operates close to BCM at the $V_{\text{in}}(t)$ peak.
- Excellent PF $\geq 0.9$
- Theoretically THD < 10% with universal input.

Input current is sinusoidal!

\[
I_{\text{IN}} = I_{\text{P\_AVG}} = \frac{T_{\text{ON}} \cdot (V_{\text{IN}}/L_m) \cdot T_{\text{ON}}}{2T} \propto V_{\text{IN}}
\]

- Realistically, THD close to 25% at High Input due to circuit parasitic parameters and small switching duty cycle.
BCM FLYBACK

\[ V_{in}(t) = V_{in}^{\text{Peak}} \cdot \sin(\theta) \quad I_{Q1}(t) = I_{Q1}^{\text{Peak}} \cdot \sin(\theta) \quad \text{(envelope of MOSFET current is sinusoidal)} \]

\[ I_{D1}(t) = n \cdot I_{Q1}(t) \quad \text{(envelope of diode current is sinusoidal)} \quad \quad n = \text{transformer turns ratio} \]

\[ T_{On} = \frac{L_p \cdot I_{Q1}(\theta)}{V_{in}(\theta)} = \frac{L_p \cdot I_{Q1}^{\text{Peak}}}{V_{in}^{\text{Peak}}} = \text{const.} \quad T_{Off} = \frac{L_s \cdot I_{D1}(\theta)}{V_{Out} + V_f} = \frac{L_p \cdot n \cdot I_{Q1}(\theta)}{n \cdot (V_{Out} + V_f)} \]

\[ f_s = \frac{1}{T_{On} + T_{Off}} = \frac{V_{in}^{\text{Peak}}}{L_p \cdot I_{Q1}^{\text{Peak}}} \left( 1 + \frac{V_{in}^{\text{Peak}}}{V_{R}} \cdot |\sin(\theta)| \right)^{-1} \]

\[ V_R = n \cdot (V_{Out} + V_f) \quad \text{"Reflected Voltage"} \]

Ref: Michael Weirich, Fairchild Semiconductor Inc. “A High Power Factor Flyback with Constant Current Output for LED Lighting Application”.
Input Current with BCM Flyback

Input current = averaged (filtered) MOSFET current

\[ I_{in}(t) = \frac{d}{2} \cdot I_{Q1}(\theta) = \frac{d}{2} I_{Q1}^{peak} \cdot |\sin(\theta)| \]

(average of triangular current times the momentary duty cycle)

Define: \[ R_{VR} = \frac{V_{in}^{peak}}{V_{R}} \]

\[ d = \frac{1}{1 + R_{VR} \cdot |\sin(\theta)|} \]

\[ I_{in}(t) = \frac{I_{Q1}^{peak} \cdot |\sin(\theta)|}{2 \cdot (1 + R_{VR} \cdot |\sin(\theta)|)} \]

Input current is not sinusoidal!
Hybrid (partial BCM) Operation Mode

\[ I_{in}(\theta) = \frac{T_{on}}{2L_m} V_{AC} \left\{ \begin{array}{ll} D \cdot |\sin(\theta)|, & \theta_1 < \theta \text{ or } \theta > \pi - \theta_1 \\ \frac{|\sin(\theta)|}{1 + \frac{V_{Peak}^{AC} \cdot |\sin(\theta_1)|}{V_R}}, & \theta_1 \leq \theta \leq \pi - \theta_1 \end{array} \right. \]
PSR Flyback Principle

\[ V_{EAI}(\theta) = \text{Gain}_{IC} \times V_{CS}(\theta) \times t_{\text{dis}}(\theta) \times f_s(\theta) \]

\[ \frac{1}{\pi} \int_{0}^{\pi} \text{Gain}_{IC} \times V_{CS}(\theta) \times t_{\text{dis}}(\theta) \times f_s(\theta) \, d\theta = V_{\text{ref}} \]

\[ I_{out} = \frac{1}{2\pi} \int_{0}^{\pi} \frac{V_{CS}(\theta)}{R_s} \times n_{ps} \times t_{\text{dis}}(\theta) \times f_s(\theta) \times d\theta \]
PSR Flyback Principle

\[ I_{out} = \frac{V_{ref}}{2G\text{ain}_{\text{IC}}} \times \frac{n_{ps}}{R_S} \]
Single Stage PFC PSR Flyback

- Accurate constant-current: <±3%
- Power Factor Correction: >0.9
- Excellent THD: <10% at universal line
- High-Voltage circuit for fast startup
- Cycle-by-Cycle current limit
- LED Short Protection
- LED Open Protection
- Sensing Resister Short/Open Protection
- Output Diode Short Protection
- Overshoot Suppression
A practical approach to design a PSR Flyback with PFC can start from the determination of the transformer primary to secondary winding turns ratio.

The selection of the turns ratio has to be based on the consideration of following factors:

- MOSFET voltage rating.
- Maximum switching duty cycle.
- Flyback converter operation mode.
- Flyback Transformer preliminary side magnetizing inductance.
- Power Factor and THD requirement.
Design Procedure: Turns Ratio & Inductance

Max Transformer Turns Ratio

$$\eta_{ps}^{\text{max}} = \frac{80\% \times BV_{DSS} - V_{ACmax}^{\text{Peak}}}{1.5 \times (V_{out_{max}} + V_{d}^{Fwd})}$$

Max Transformer Magnetizing Inductance for DCM

$$I_{rms_{in}} = \frac{V_{out} \times I_{out}}{\eta \times V_{AC}^{rms}}$$

$$I_{Lm}^{\text{Peak}} = \frac{t_{on} \times V_{ACmin}^{\text{Peak}}}{L_{m}}$$

$$D \leq \frac{V_{R}}{V_{ACmin}^{\text{Peak}} + V_{R}}$$

$$L_{m} \leq \frac{\eta}{4V_{out} \times I_{out} \times f_{s}} \times \left[ \frac{V_{ACmin}^{\text{Peak}} \times \eta_{ps_{DCM}}^{\text{max}} (V_{out} + V_{d}^{Fwd})}{V_{ACmin}^{\text{Peak}} + \eta_{ps_{DCM}}^{\text{max}} (V_{out} + V_{d}^{Fwd})} \right]^{2}$$
Design Procedure: Min & Max Inductance

**Min Magnetizing Inductance:**
For Flyback driver operating in DCM, we have

\[
\frac{1}{\pi} \int_{0}^{\pi} \frac{1}{2} L_m \left( \frac{V_{cs}(\theta)}{R_s} \right)^2 f_s \, d\theta \geq \frac{I_{out} \cdot V_{out}}{\eta}
\]

\[
V_{cs}(\theta) = V_{CS}^{Peak} \cdot \sin(\theta)
\]

\[
L_m \geq \frac{4 \cdot I_{out} \cdot V_{out} \cdot R_s}{\eta \cdot V_{CS}^{Peak^2} \cdot f_s}
\]

**Max Magnetizing Inductance:**
For a PSR Flyback driver running in Hybrid mode, its Max operation duty cycle can be determined based on when it enters into BCM mode

\[
L_m = \frac{V_{ref}}{2 \cdot Gain_{IC}} \cdot \frac{t_{on} \cdot V_{ACmin} \cdot n_{ps}^{max}}{I_{out} \cdot V_{CS}^{Peak}}
\]

\[
D_{max} \leq \frac{V_R}{V_{ACmin} \cdot \sin(\theta_1) + V_R}
\]

\[
L_m \leq \frac{V_{ref}}{2 \cdot Gain_{IC}} \cdot \frac{V_{Peak}^{ACmin} \cdot n_{ps}^{max}}{I_{out} \cdot V_{CS}^{Peak} \cdot f_s} \cdot \frac{V_R}{V_{ACmin} \cdot \sin(\theta_1) + V_R}
\]

Targeting \( \theta_1 = \pi/4 \) is a good choice.
A. Design Specification
   Mains voltage range: Vac=90V to 305V rms
   Mains frequency: 60Hz
   Max DC Output voltage Vout =25V
   Output Constant Current: Iout=0.7A

B. Pre-Design Choices:
   Controller: FL7733A
   Switching Frequency: 70kHz
   Selected peak Vol. of current sensor $V_{CS}^{Peak}$ : 0.85V
   MOSFET Voltage Rating: FQP6N80C (800V/5.5A)
Transformer One: (for DCM operation only)
Primary winding: 51 turns, 28AWG wire
Secondary winding: 19 turns, 4X28AWG wire
Core: PC40RM8Z from TDK
Primary winding inductance: 460uH
With the selected turn ratio: A 300V/3A fast recovery diode is used for output rectifier (EGP30F).

Transformer Two: (Hybrid operation)
Primary winding: 65 turns, 28AWG wire
Secondary winding: 19 turns, 4X28AWG wire
Core: PC40RM8Z from TDK
Primary winding inductance: 720uH
With the selected turn ratio: A 200V/3A schottky diode is used for output rectifier (S320).

<table>
<thead>
<tr>
<th>Loss Analysis (@Vin=90V)</th>
<th>Design 1 (DCM)</th>
<th>Design 2 (Hybrid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>1.058</td>
<td>0.83</td>
</tr>
<tr>
<td>Output Diode</td>
<td>0.798</td>
<td>0.588</td>
</tr>
<tr>
<td>Transformer</td>
<td>0.674</td>
<td>0.642</td>
</tr>
<tr>
<td>Bridge Rectifier</td>
<td>0.409</td>
<td>0.409</td>
</tr>
<tr>
<td>Snubber</td>
<td>0.535</td>
<td>0.483</td>
</tr>
<tr>
<td>others</td>
<td>0.151</td>
<td>0.151</td>
</tr>
<tr>
<td><strong>Total Loss (W)</strong></td>
<td><strong>3.625</strong></td>
<td><strong>3.103</strong></td>
</tr>
<tr>
<td><strong>Driver Efficiency</strong></td>
<td><strong>82.61%</strong></td>
<td><strong>84.73%</strong></td>
</tr>
</tbody>
</table>

Loss comparison of DCM and Hybrid operation
Count in the Efficiency in the Design Equations

Max Transformer Turns Ratio

$$n_{ps}^{max} = \frac{80\% \times BV_{DSS} - V_{AC_{max}}^{Peak}}{1.5 \times (V_{out\_max} + V_{d_{Fwd}})}$$

Max Transformer Magnetizing Inductance for DCM

$$L_m \leq \frac{\eta}{4V_{out} \times I_{out} \times f_s} \times \left[ \frac{V_{AC_{min}} \times n_{ps\_DCM}^{max} (V_{out} + V_{d_{Fwd}})}{\sqrt{\eta} \times V_{AC_{min}}^{Peak} + n_{ps\_DCM}^{max} \times (V_{out} + V_{d_{Fwd}})} \right]^2$$

$$D \leq \frac{V_R}{\sqrt{\eta} \times V_{AC_{min}}^{Peak} + V_R}$$

Min Magnetizing Inductance:

$$L_m \geq \frac{4 \times I_{out} \times V_{out} \times R_S}{\eta \times V_{CS}^{Peak} \times f_s}$$

$$I_{out} = \frac{V_{ref}}{2Gain_{IC} \times R_S} \times n_{ps}$$

Max Magnetizing Inductance:

$$L_m \leq \frac{V_{ref}}{2Gain_{IC}} \times \frac{V_{AC_{min}}^{Peak} \times n_{ps}^{max}}{I_{out} \times V_{CS}^{Peak} \times f_s} \times \frac{V_R}{\sqrt{\eta} \times V_{AC_{min}}^{Peak} \times Sin(\theta_1) + V_R}$$
Design Example

To learn more about Flyback LED Driver design, please visit
www.fairchildsemi.com/powersupplywebdesigner
THANK YOU