Designing the Power Train of a 200W Power Supply with PFC

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Global Power Resource Center, Europe
Design issues for 200W PSU

System Specification
- AC Input Voltage: 85 – 265 Vrms
- Power-Factor: > 0.95
- Total Output Power: 200W
- Three DC Outputs:
  - 5V/0.3A (standby)
  - 12V/6A
  - 24V/5A
- Height limit: 25mm

Target application: LCD TV

Design Issues
- System partitioning
- Low profile boost inductor
- PFC MOSFET dissipation
- Using single switch forward tools to design two-switch forward converters
- Two-switch forward drive
- Second post-regulated output for a forward converter
- Auxiliary power supply
- Layout
Control Component Overview

- PFC/two switch forward circuit
  - FAN4800 combined CCM PFC and current mode controller
  - FAN7382 dual high and low side driver
- Post regulation circuit
  - Low cost MC34063A controller with external MOSFET
- Auxiliary power supply
  - FSD210 Fairchild Power Switch
System Partitioning

85V – 265VAC input

1. Rectifier
2. PFC Stage
3. Two Switch Forward Primary Side
4. Forward Transformer
5. Forward Output
6. PFC/PWM Combo controller
7. Bias Power
8. Flyback Auxiliary Primary Side
9. Flyback Transformer
10. Flyback Output
11. Buck Post-regulation

Isolation Boundary

24V, 6A
24V, 2.5A
12V, 5A
5V, 0.3A
Rectifier dimensioning and tips

Output power
Output power is 200W
Efficiency assumptions:
   PFC stage: 90%
   Forward converter: 90%
Maximum input current (rms) is 2.9A

Bridge rectifier
Rectifiers with larger current ratings typically have lower forward voltages
We chose GBU6K (6A/800V): Vf=0.45V
Estimate the equivalent resistance from the datasheet: Rs=0.03 ohm

Conclusion
4.7W dissipation
21°C/W heatsink needed

\[
P_{\text{In}} = \frac{200W}{0.9 \cdot 0.9} = \frac{247W}{85V} = 2.9A
\]

\[
P_{\text{Loss, BR1}} = 4 \cdot (I_{AVG, D} \cdot V_{F, D} + I_{RMS, D}^2 \cdot R_{S, D}) = 4 \cdot (I_{In, RMS} \cdot 0.45 \cdot 0.8V) + \left(\frac{I_{In, RMS}}{\sqrt{2}}\right)^2 \cdot 0.03\Omega)
= 4.7W
\]

\[
R_{\Theta, BR1} = \frac{T_{J, \text{max}} - T_{A, \text{max}}}{P_{\text{Loss, BR1}}} = \frac{150°C - 50°C}{4.7W} = 0.75°C/W
\approx 21°C/W
\]
PFC inductor dimensioning

Pin = 247W, Input rms current = 2.9A

Inductor inductance value
FAN4800 PFC set to switch at 100kHz
\( dI \), the percentage current ripple is set to 20%

Inductor peak current
The peak value of the input rms current is added to half of the ripple current

Conclusion
1mH inductor
4.5A peak current

\[
L_1 = \left( \frac{V_{Out} - \sqrt{2} \cdot V_{In,min}}{V_{Out} \cdot f_S \cdot dI \cdot P_{In}} \right) \cdot V_{In,min}^2
\]

\[
= \left( \frac{(400V - 85V \cdot \sqrt{2}) \cdot 85V^2}{400V \cdot 100kHz \cdot 20% \cdot 247W} \right)
= 1.08mH
\]

\[
I_{Peak,L1} = I_{In,RMS} \cdot \sqrt{2} + \frac{I_{Ripple}}{2}
\]

\[
= I_{In,RMS} \cdot \sqrt{2} + 0.2 \cdot I_{In,RMS} \cdot \sqrt{2} / 2
\]

\[
= I_{In,RMS} \cdot \sqrt{2} \cdot 1.1
\]

\[
= 4.5A
\]
PFC inductor design (1)

Input rms current = 2.9A, peak = 4.5A

**Wire thickness**
Copper wire: 5A/mm$^2$ for rms current
0.58mm$^2$ copper wire area (ACu)
Three or four strands required: skin effect
Design used three strands of 0.5mm wire

**Core size**
Use the area product $A_P$ to estimate core size from $A_e$ (magnetic cross section) and $A_w$ (winding cross section)
$B_{peak}$ is 0.35 Tesla for standard ferrite core

**Conclusion**
Area product is 14914 mm$^4$

Skin depth:
$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_0 \cdot \mu_r \cdot \sigma}}$$

Proximity effect: useful area of a conductor is reduced due to magnetic field generated by adjacent layers

$$A_P = A_e \cdot A_w = \frac{L \cdot I_{peak} \cdot A_{Cu}}{B_{peak} \cdot f_{Cu}}$$

$$A_P = 14914 \text{ mm}^4$$
PFC inductor design (2)

Area product is 14914 mm^4

General selection
Normally Ae and Aw are equal, so as a starting point, select Ae as 122mm^2
>> no 25mm height bobbins available

Specific selection
Look for cores meeting area product and size requirements:
EER3542 core (Ae=107mm^2, Aw=154mm^2)

Turns
Aw is 154mm^2, ACu is 0.58mm^2
Assuming a fill factor of 50%, we can get 130 turns.

Gap
A gap is needed to get the required Inductance. AL = 1mH/130^2

\[ s \approx 0.4 \cdot \pi \cdot A_e \cdot \left( \frac{1}{A_L} - \frac{1}{A_{L,0}} \right) \]

s is the gap size, AL,0 is the AL value for an ungapped core

Adjust the turns to get a standard gap size

Conclusion
Gap is 2mm, 124 turns, 1mH inductance

\[ B_{max} = \frac{1mH \cdot 4.5A}{124 \cdot 107mm^2} = 0.34T \]
Low Profile Boost Inductor Specification

PFC Choke

Winding Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Pins (Start → End)</th>
<th>Layers</th>
<th>Strands x Wire ø</th>
<th>Turns</th>
<th>Construction</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>8 → 16</td>
<td>6</td>
<td>3 x 0.5 mm</td>
<td>124</td>
<td>perfect solenoid</td>
<td>CuLL</td>
</tr>
</tbody>
</table>

Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pins</th>
<th>Specification</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>8 → 16</td>
<td>1000 uH +/- 5%</td>
<td>10kHz, 100mV</td>
</tr>
</tbody>
</table>

Core and Bobbin

Core: EER3542
Material: PC40 (TDK) or equivalent
Bobbin: EER3542 / 16 Pin / Horizontal e.g. Pin Shine P-3508
Gap in center leg: approx. 2.0 mm for an $A_L$ of 65 nH/Turns$^2$
PFC MOSFET Selection

Voltage and current ratings
500V MOSFET needs external surge protection
600V MOSFET preferred
Peak current same as inductor (4.5A)

Power dissipation and heatsink
FCP16N60 chosen:
RDSon=0.45ohm,
Coss,eff=110pF
Cext=150pF, (estimated parasitic capacitance)

Conclusions
Power dissipation: 9W
10ºC/W heatsink needed

\[
I_{\text{RMS},Q1} = I_{\text{in,RMS}} \cdot \frac{\sqrt{1 - \frac{8 \cdot \sqrt{2} \cdot V_{\text{in,Min}}}{3 \cdot V_{\text{out}}}}}{V_{\text{out}}}
\]

\[
= 2.94 \cdot \sqrt{1 - \frac{8 \cdot \sqrt{2} \cdot 85V}{3 \cdot \pi \cdot 400V}}
\]

\[
= 2.5A
\]

\[
P_{\text{Loss,Cond}}^{\text{Cond}} = I_{\text{RMS},Q1}^2 \cdot R_{\text{DSON,max,Q1}}
\]

\[
= 2.8W
\]

\[
P_{\text{Loss,Cap}}^{\text{Cap}} \approx 0.5 \cdot (C_{\text{OSS,eff}} + C_{\text{ext}}) \cdot V_{\text{out}}^2 \cdot f_S
\]

\[
= 0.5 \cdot 260 \text{pF} \cdot 400 \text{V}^2 \cdot 100 \text{kHz}
\]

\[
= 2.1W
\]

\[
P_{\text{Loss,Cross}}^{\text{Cross}} \approx 0.9 \cdot I_{\text{in,RMS}} \cdot V_{\text{out}} \cdot \frac{1}{6} \cdot t_{\text{crossover}} \cdot f_S
\]

\[
= 0.9 \cdot 2.9A \cdot 400V \cdot 0.5 \cdot 50\text{ns} \cdot 100\text{kHz}
\]

\[
= 2.6W
\]

\[
P_{\text{Loss,rr}}^{\text{rr}} \approx 2W
\]
Two-switch forward design with PFC front-end

- Use the forward design spreadsheet
  - Enter 284V to emulate PFC input
  - Use a very large DC link capacitor to account for the PFC stage
  - Set the maximum duty cycle to 0.45 to ensure demagnetisation
  - The ratio Np/Nr can be ignored as there is no need for a reset winding

- A single switch forward would need 803V rating without any safety factor
  - two-switch forward designs need half of this

<table>
<thead>
<tr>
<th>For forward converter with reset winding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blue cell</strong></td>
</tr>
<tr>
<td>is the input parameters</td>
</tr>
</tbody>
</table>

### 1. Define specifications of the SMPS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Line voltage (V, line min)</td>
<td>284 V.rms</td>
</tr>
<tr>
<td>Maximum Line voltage (V, line max)</td>
<td>284 V.rms</td>
</tr>
<tr>
<td>Line frequency (fL)</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

### 2. Determine DC link capacitor and the DC voltage range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC link capacitor</td>
<td>1000 uF</td>
</tr>
<tr>
<td>DC link voltage ripple</td>
<td>4 V</td>
</tr>
<tr>
<td>Minimum DC link voltage</td>
<td>397 V</td>
</tr>
<tr>
<td>Maximum DC link voltage</td>
<td>402 V</td>
</tr>
</tbody>
</table>

### 3. Determine the maximum duty ratio (Dmax)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum duty ratio</td>
<td>0.45</td>
</tr>
<tr>
<td>Turns ratio (Np/Nr)</td>
<td>1 &gt; 0.82</td>
</tr>
<tr>
<td>Maximum nominal MOSFET voltage</td>
<td>803 V</td>
</tr>
</tbody>
</table>
Two Switch Forward Output Inductor

Output Inductor Design

- Current ripple should be small as possible to reduce the RMS and peak values of the primary and secondary currents.
- Small current ripple results in large inductors
- Design compromise:
  - Current ripple is set to 42% (Note KRF used in spreadsheet is half of the current ripple)
  - Output inductance 40uH
- The calculated windings will fill an EER2828 core completely.

Choke 40uH / 9A (L5)

Winding Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Pins (Start → End)</th>
<th>Layers</th>
<th>Strands x Wire ø</th>
<th>Turns</th>
<th>Construction</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>1,2,3,4,5 → 8,9,10,11,12</td>
<td>6</td>
<td>5 x 0.71 mm</td>
<td>15</td>
<td>perfect solenoid</td>
<td>CuL</td>
</tr>
</tbody>
</table>

Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pins</th>
<th>Specification</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>1 → 5</td>
<td>40 uH +/- 5%</td>
<td>10kHz, 100mV</td>
</tr>
</tbody>
</table>
Two Switch Forward Transformer

Main Transformer Specification

Winding Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Pins (Start → End)</th>
<th>Layers</th>
<th>Strands x Wire Ø</th>
<th>Turns</th>
<th>Construction</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1a</td>
<td>6 → 3</td>
<td>1</td>
<td>1 x 0.5 mm</td>
<td>39</td>
<td>perfect solenoid</td>
<td>CuLL</td>
</tr>
<tr>
<td>W3</td>
<td>10,11,12 → 7,8,9</td>
<td>2</td>
<td>3 x 0.7 mm</td>
<td>11</td>
<td>perfect solenoid</td>
<td>Triple insulated</td>
</tr>
<tr>
<td>W1b</td>
<td>3 → 1</td>
<td>1</td>
<td>1 x 0.5 mm</td>
<td>38</td>
<td>perfect solenoid</td>
<td>CuLL</td>
</tr>
</tbody>
</table>

Layers not to scale!

Schematic

Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pins</th>
<th>Specification</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Inductance</td>
<td>1 → 6</td>
<td>13 mH +/- 30%</td>
<td>10kHz, 100mV, all secondaries open</td>
</tr>
<tr>
<td>Leakage Inductance</td>
<td>1 → 3</td>
<td>500 uH maximum</td>
<td>10kHz, 100mV, all secondaries short</td>
</tr>
</tbody>
</table>

Core and Bobbin

Core: EER2834
Material: PC40 (TDK) or equivalent
Bobbin: EER2834 / 12 Pin / Horizontal e.g. Pin Shine P-2809
Gap in center leg: 0 mm
From forward calculation spreadsheet:
Peak current is 1.6A
RMS current is 0.9A

Voltage and current ratings
600V MOSFET preferred
Peak current same as inductor (1.6A)

Power dissipation and heatsink
FCP7N60 chosen:
Rdson=1.1ohm, 100ºC
Coss,eff=60pF
Cext=60pF, (estimated)
As tr=120ns and tf=75ns in datasheet
are measured at 7A scale by 1.6A/7A

Conclusions
Power dissipation: 3.7W
20ºC/W heatsink needed

\[
P_{\text{Loss,Sw}}^{\text{Cond}} = I_{\text{RMS,Sw1}}^2 \cdot R_{\text{DSON,max,Sw}}
\]
\[
= 0.9A^2 \cdot 1.1\Omega
\]
\[
= 0.9W
\]

\[
P_{\text{Loss,Q205}}^{\text{Cap}} \approx 0.5 \cdot \left(C_{\text{OSS,eff}} + C_{\text{ext}}\right) \cdot V_{\text{Out}}^2 \cdot f_s
\]
\[
= 0.5 \cdot 120\, \text{pF} \cdot 400V^2 \cdot 100kHz
\]
\[
= 1.2W
\]

\[
P_{\text{Cross, Q205}}^{\text{Loss}} \approx I_{\text{Peak,Q205}} \cdot V_{\text{Out}} \cdot \frac{t_r + t_f}{2} \cdot f_s
\]
\[
= 1.6A \cdot 400V \cdot \frac{120 + 75}{2} \cdot 1.6 \cdot 100kHz
\]
\[
= 1.4W
\]

\[
P_{\text{Loss,Q205}}^{\text{Tot}} \approx 3.7W
\]
Waveforms for low side switch and output diode

Low side switch voltage and current

Output diode voltage and current
Rectifier diodes

From forward calculation spreadsheet:
Diode reverse output voltage is 57V
Output current is 8.5A

Voltage and current ratings
100V Schottky diode used: FYP2010DN
Average current: 4.7A

Power dissipation and heatsink
Rs=0.04ohm (from datasheet curves)
Vf=0.25V

Snubber network
Schottky diodes switch fast causing oscillations
RC snubber network needed to damp these

Conclusions
Power dissipation: 2.5W
20°C/W heatsink needed
Snubber network needed

\[ I_{Avg,\,rect} = I_{Out} \cdot (1 - D_{max}) \]
\[ = 8.5A \cdot 0.55 \]
\[ = 4.7A \]

\[ P_{Loss,\,rect} \approx I_{Avg,\,rect} \cdot V_{F,\,Rect} + I_{RMS,\,rect}^2 \cdot R_{S,\,Rect} \]
\[ = 4.7A \cdot 0.25V + 5.7A^2 \cdot 0.04\Omega \]
\[ = 2.5W \]
MC34063A Post-regulation Circuit

Hysteretic buck control (or ripple regulator)
Choke 100μH / 6A (L6)

Winding Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Pins (Start →End)</th>
<th>Layers</th>
<th>Strands x Wire ø</th>
<th>Turns</th>
<th>Construction</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>1,2,3,4,5 → 8,9,10,11,12</td>
<td>5 x 0.56mm</td>
<td>25</td>
<td></td>
<td>perfect solenoid</td>
<td>CuL</td>
</tr>
</tbody>
</table>

Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pins</th>
<th>Specification</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>1 → 5</td>
<td>100 μH +/- 5%</td>
<td>10kHz, 100mV</td>
</tr>
</tbody>
</table>

Core and Bobbin
Core: EER2828
Material: PC40 (TDK) or equivalent
Bobbin: EER2828 / 12 Pin / Horizontal e.g. Pin Shine P-2816
Gap in center leg: approx. 0.45 mm for an \( L_c \) of 205nH/Turns²
Auxiliary Power Supply using FSD210
Standby Transformer Specification

Winding Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Pins (Start → End)</th>
<th># of Layers</th>
<th>Strands x Wire Ø</th>
<th>Turns</th>
<th>Construction</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1a</td>
<td>3 → 2</td>
<td>2</td>
<td>1 x 0.15 mm</td>
<td>91</td>
<td>spaced winding</td>
<td>Cu.LL</td>
</tr>
<tr>
<td>W3</td>
<td>8 → 6</td>
<td>1</td>
<td>1 x 0.5 mm</td>
<td>8</td>
<td>spaced winding</td>
<td>Triple insulated</td>
</tr>
<tr>
<td>W1b</td>
<td>2 → 1</td>
<td>2</td>
<td>1 x 0.15 mm</td>
<td>91</td>
<td>spaced winding</td>
<td>Cu.LL</td>
</tr>
<tr>
<td>W2</td>
<td>4 → 5</td>
<td>1</td>
<td>1 x 0.15 mm</td>
<td>24</td>
<td>spaced winding</td>
<td>Cu.LL</td>
</tr>
</tbody>
</table>

Schematic of construction

Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pins</th>
<th>Specification</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Inductance</td>
<td>1 → 3</td>
<td>5.85 mH +/- 5%</td>
<td>10kHz, 100mV, all secondaries open</td>
</tr>
<tr>
<td>Leakage Inductance</td>
<td>1 → 3</td>
<td>290 uH maximum</td>
<td>10kHz, 100mV, all secondaries short</td>
</tr>
</tbody>
</table>

Core and Bobbin

Core: EF 20
Material: FI325 (Vogt) or equivalent
Bobbin: EF20 / 10 Pin / Horizontal / Increased creepage
Gap in center leg: approx. 0.2 mm for $A_c$ of 177 nH/Turns²
Layout and Heatsink

• General Power Supply Layout Rules
  • the enclosed area of loops with high di/dt must be as small as possible
  • the copper area of nodes with high dv/dt must be as small as possible.
  • avoid common impedance coupling by using star connections to ground

• These rules conflict with other requirements
  • Heatsink construction at the edge of a board
  • Star connection of all ground lines would enlarge the PCB
  • Low cost solutions require single sided PCB’s which result in longer traces

• Compromise
  • Critical signals are routed to the shortest path
  • Less critical signals give way to the large ground plane which emulates star-like connection

• Heatsink
  • All devices except Q1 are connected to a simple heatsink made of 2mm aluminium bent into the form of a U
  • Q1 dissipates more power so needs an additional heatsink
Layout and photo of finished board

Dimensions: 170mm x 156mm x 25mm (L x W x H)
Standby power and efficiency

Less than 0.5W standby power for 195V-265V

Overall efficiency target of 81% (90%×90%) met
Summary

Design Issues
• System partitioning
• Low profile boost inductor
• PFC MOSFET dissipation
• Using single switch forward tools to design two-switch forward converters
• Two-switch forward drive
• Second output for a forward converter
• Auxiliary power supply
• Layout
• Performance