Planar Magnetics for Auxiliary Power Supplies – A Case Study

Vladimir Alexiev

Power Magnetics - High Frequency Workshop
APEC 2022
Houston, Texas – March 19, 2022
Vladimir Alexiev has a B.Sc. in Industrial Electronics and Electrical Engineering and is a Senior Staff Applications Engineer for Power Integrations. Vladimir has more than 30 years of experience in researching and developing AC-DC and DC-DC power supplies, their control, magnetics, EMI compliance, simulation and modelling. Prior to joining Power Integrations, Vladimir worked in R&D and engineering roles at Cambridge Semiconductors, SAFT Power Systems and Duvine Developments. He also worked as a Senior Lecturer and Researcher at the Technical University of Gabrovo.
Introduction

- On-board, low-power auxiliary power supplies provide operating power for a variety of electronic and industrial equipment
  - Appliances
  - Instruments
  - Metering
- Typical low-power AC-DC switching power supplies
  - Use integrated power supply controllers
    - Reduced component count
  - Use wire wound ferrite core transformers
  - Operating frequencies <150 kHz
Planar Magnetics for Auxiliary Power Supplies

- Planar magnetics – an advanced solution for auxiliary power supplies
- Limited adoption so far due to perception
  - Complex to design
  - High tooling costs
- Provide benefits for low- and high-volume designs
  - Dramatically simplify the transformer manufacturing process
  - Provide consistent electrical performance
  - Enable transformer manufacturing in the same flow as PCB assembly
Advantages/Disadvantages of Wound Magnetics

- Disadvantages
  - For low-volume design
  - Expensive manual labor
  - High parameter tolerances
  - Higher leakage due to limited splitting options (pins and connections)

- Advantages
  - Allows larger number of turns
  - Smaller inter-winding capacitance
  - Samples for testing quickly available
Advantages of Planar Magnetics

- Higher surface-to-volume ratio – more effective at conducting heat
- Height of planar magnetic device is typically 25% to 50% less than wire-wound
- Unrivalled parametric repeatability
- Easy interleaving
  - Allows reduction of leakage inductance
  - Reduces high-frequency winding losses
- Modularity
Planar magnetics have become much more cost competitive
PCB manufacturers are embracing PCB-based technology
Simple rules ensure easy availability and low cost
- Limit PCBs to four layers
- \( \leq 3 \)-ounce copper
- Uniform dielectric thickness throughout the stack
- Use standard core or prepreg thickness options available from the PCB manufacturer
- Minimize blind and buried vias
Case Study: Analysis, Considerations & Approach

- Evaluation of 10 W auxiliary switch mode power supply (SMPS) using planar magnetics
- Four different transformers compared for this study
- One wire wound transformer used for reference
- Three different transformer constructions tested for planar
Design Example – Technical Specification

- Prototype specification and controller
  - Output: 5 V / 2 A
  - Input: 85 VAC to 265 VAC
  - 65 - 75 kHz operation

- InnoSwitch™3-CE INN3163C IC from Power Integrations
  - Flyback circuit switcher
  - Integrated 650 V MOSFET
  - Synchronous rectification
  - $I_{P(MAX)} = 550$ mA
Schematic for 5 V / 2 A PSU Used in Case Study
Magnetics Design – Wound Transformer
Design of Planar Transformer

- Safety requirement for reinforced insulation
  - Minimum internal distance through isolation (DTI)
    \[ DTI_{min} = 0.4 \text{ mm} \quad \text{and} \quad DTI_{Air\,min} = 6.4 \text{ mm} \]

- Tracks width – from current density
  - For boundary operation, assume initial current density is
    \[ CD_{init} = 8.5 \frac{A}{mm^2} \quad (230CMA) \]
    and track thickness for 3 ounces is \( TT_{30Zcopp} = 108 \mu m \)
  - Secondary: For \( IRMS_{sec} = 4 A \)
    \[ TW_{sec} = \frac{IRMS_{sec}}{CD_{init} TT_{30Zcopp}} = 4.53 \text{ mm} \]
  - Considering single track in a layer, horizontal space of required is
    \[ BW_{min} = TW_{sec} + 2 \times DTI_{min} = 5.4 \text{ mm} \]
  - Primary: For \( IRMS_{prm} = 0.25 A \) single primary track width is \( TW_{prm} = 0.29 \text{ mm} \)
  - Assuming the same BW, the maximum primary turns in layer (TIL) possible are
    \[ TIL_{prm} = 11 \] (with 0.2mm reserved between turns and core)

Primary AC factors
\[ \varphi_{AC} = \frac{TT_{30Zcopp}}{\sqrt{\frac{TIL_{prm} TW_{sec}}{BW_{min}} D_{skin\,75kHz}}} = 0.31 \quad ; \quad \varphi_{prox2L} = 1.5 \quad ; \quad \varphi_{prox4L} = 3 \]
Planar Design – Core Selection E22/6/16

- Check for the minimum required bobbin width
  \[ BW_{\text{min}} = 5.45 \text{ mm} \]
  \[ BW_{\text{E22}} = \frac{B_{\text{min}} - C_{\text{max}}}{2} = 5.65 \text{ mm} \]

- Primary inductance is
  \[ L_p = \frac{V_{\text{in min}}}{I_p F_{\text{nop}}} = 1.3 \text{ mH} \]

- 44 turns are required for
  \[ B_m = 0.32 \text{ T} \]
  - With \( TILprm = 11 \) turns, four layers are needed to complete the primary winding
Split Primary Planar Transformer – Design Constraints

- Split primary construction
  - PCB1: Two layers 22 turns – first half primary winding
  - PCB2: Screen, two layers secondary, bias
  - PCB3: Two layers 22 turns – second half primary winding

Winding cross-section illustration

Gerbers snapshot

Construction and dimension overview
Solution – Transformer Construction

- All transformers have four windings as shown in the electrical diagram.
- Differences are:
  1. Core
  2. Winding technology
  3. Stack organization
  4. Number of turns

<table>
<thead>
<tr>
<th>TRF</th>
<th>Core</th>
<th>NP</th>
<th>Primary Conductor</th>
<th>Primary Construction</th>
<th>NS</th>
<th>Secondary Conductor</th>
<th>Winding Technology</th>
<th>N_BIAS</th>
<th>N SCREEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM7</td>
<td>2xRM7</td>
<td>66</td>
<td>1x32AWG</td>
<td>None-split</td>
<td>5</td>
<td>1x20AWG</td>
<td>Wire Wound</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>E22 v1</td>
<td>2xE22/6/16</td>
<td>44</td>
<td>0.274mm 3OZ</td>
<td>None-split</td>
<td>2</td>
<td>4.48mm 3OZ</td>
<td>Planar</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>E22 v2</td>
<td>2xE22/6/16</td>
<td>44</td>
<td>0.274mm 3OZ</td>
<td>Split</td>
<td>2</td>
<td>4.48mm 3OZ</td>
<td>Planar</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>E22 v3</td>
<td>2xE22/6/16</td>
<td>44</td>
<td>0.274mm 3OZ</td>
<td>None-split</td>
<td>4</td>
<td>4.48mm 3OZ</td>
<td>Planar</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

* Shield treated as separate winding
Comparison of Transformers in Case Study

1. Conventionally wound transformer

2. Planar transformer none-split primary configuration, two turns secondary

3. Planar transformer with split primary configuration, two turns secondary

4. Planar transformer none-split primary configuration, four turns secondary
PCB Comparison

- Planar and wire wound transformer PCBs
Prototypes Used for Study

Prototype with RM7 Wound Transformer Used as Baseline

Prototype with Planar Transformer
Efficiency Comparison at 85 VAC & 115 VAC
Efficiency Comparison – 230 VAC & 265 VAC
Solution – Transformer Windings Results

Winding parameter simulation results

<table>
<thead>
<tr>
<th>Core/ Ver.</th>
<th>( R_{DC} ) [Ω]</th>
<th>( R_{AC} ) 75 kHz [Ω]</th>
<th>( R_{AC}/R_{DC} ) 75 kHz</th>
<th>( L_{MA} ) [mH]</th>
<th>( L_{lk} ) [µH]</th>
<th>Self Cap [pF]</th>
<th>Prim-Sec Cap [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIMARY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM7</td>
<td>1.03</td>
<td>11.1</td>
<td>10.73</td>
<td>1.30</td>
<td>8.60</td>
<td>7.29</td>
<td>3.79</td>
</tr>
<tr>
<td>E22v1</td>
<td>2.22</td>
<td>6.29</td>
<td>2.84</td>
<td>1.23</td>
<td>17.0</td>
<td>7.90</td>
<td>26.5</td>
</tr>
<tr>
<td>E22v2</td>
<td>2.22</td>
<td>8.17</td>
<td>3.69</td>
<td>1.22</td>
<td>8.59</td>
<td>7.11</td>
<td>26.7</td>
</tr>
<tr>
<td>E22v3</td>
<td>2.22</td>
<td>7.53</td>
<td>3.40</td>
<td>1.22</td>
<td>17.4</td>
<td>7.78</td>
<td>27.7</td>
</tr>
<tr>
<td>SECONDARY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM7</td>
<td>503 E-3</td>
<td>505 E-3</td>
<td>1.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E22v1</td>
<td>5.6 E-3</td>
<td>13.6 E-3</td>
<td>2.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E22v2</td>
<td>5.6 E-3</td>
<td>17.4 E-3</td>
<td>3.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E22v3</td>
<td>11.1 E-3</td>
<td>62.7 E-3</td>
<td>5.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Solution – Transformer Windings Results

- **Winding parameters**
  - Comparison of simulated and measured values

<table>
<thead>
<tr>
<th>Core /Ver.</th>
<th>$[R_p] R_{DC}$, $[\Omega]$</th>
<th>$[R_p] R_{AC}$ @75 kHz</th>
<th>$[R_p] R_{AC}/R_{DC}$</th>
<th>$L_M$ [mH]</th>
<th>$L_{L1}[L_{L1}]$, [uH]</th>
<th>$[C_{11}]$ Self Capacitance (pF)</th>
<th>$[C_{12}]$ Prim-Secondary Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM7</td>
<td>0.86 1.03</td>
<td>11.1 10.7</td>
<td>1.30 1.30</td>
<td>18.6</td>
<td>8.60</td>
<td>12.1</td>
<td>10.1</td>
</tr>
<tr>
<td>E22v1</td>
<td>2.40 2.22</td>
<td>6.29 2.84</td>
<td>1.21 1.23</td>
<td>56.3</td>
<td>17.0</td>
<td>13.7</td>
<td>36.2</td>
</tr>
<tr>
<td>E22v2</td>
<td>2.76 2.22</td>
<td>8.17 3.69</td>
<td>1.20 1.22</td>
<td>24.0</td>
<td>8.59</td>
<td>11.5</td>
<td>31.4</td>
</tr>
<tr>
<td>E22v3</td>
<td>2.53 2.22</td>
<td>7.53 3.40</td>
<td>1.27 1.22</td>
<td>42.9</td>
<td>17.4</td>
<td>13.3</td>
<td>29.9</td>
</tr>
</tbody>
</table>

![Diagram of a transformer with labels for $R_p$, $C_{11}$, $C_{12}$, $L_1$, $L_2$, $R_{DC}$, $R_{AC}$, $R_{AC}/R_{DC}$, $L_M$, $L_{L1}$, and $L_{L1}$].
Questions Remaining & Other Issues to Address

- Effects of self-capacitance and construction techniques to reduce it
  - Minimizing overlapping of top and bottom side traces
    - Results in poor space utilization
- Effects of inter-winding capacitance and construction techniques to reduce it
  - Shielding is effective
- Reducing the voltage gradient between overlapping turns
  - Requires construction complexity and simplifies interlayer connections
- Interleaving with shielding is often impractical
  - Increases losses
- Passive cancellation (noise-balancing techniques)
Planar magnetics for auxiliary power supplies simplifies manufacturing
- Simplifies supply chain for transformers
- Enables use of PCB assembly infrastructure for transformer build

Suitable for low- and high-volume designs

No significant performance disadvantage compared to wound transformers

Important to understand process limitations of PCB vendors

Limit designs to four layers and 3-ounce copper for easy availability
Thank you for your interest.

Email: vladimir.alexiev@power.com
Power Magnetics - High Frequency Workshop