Boost Inductors:
Optimal Winding Design

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President and CEO
West Coast Magnetics

ISO9001:2008 Registered
Topics

Will discuss:

Winding design for inductors operating at SMPS frequencies of 10 kHz and higher.

Applicable to inductors with HF AC ripple and DC or low frequency AC fundamental.
Components of Inductor Loss

**dc loss**

\[
P_{dc} = I_{dc}^2 R_{dc}
\]

Winding only

**ac loss**

\[
P_{ac} = I_{ac,rms}^2 R_{ac}
\]

Core and winding
Skin Effect

- An isolated conductor carrying high-frequency current which generates a field in itself that forces the current to flow near the surface of the conductor.
- Skin depth is the distance below the surface of an infinitely thick plane conductor where the field magnitude and current density decrease to $1/e$ of those at the surface.

Skin depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$
**Proximity Effect**

- An isolated conductor is placed in an uniform external field.
- External field results from other wires and windings near the conductor and from the field present in a gapped core.

Original drawing from Snelling
Comparison of Solid Wire, Litz Wire and Foil

**FOIL**
- DCR = very low
- ACR = medium

**SOLID WIRE**
- DCR = low
- ACR = high

**50/40 awg LITZ WIRE**
- DCR = medium/high
- ACR = low
Total Winding Loss vs. Ripple Current 10 kHz, Single Gap, Center Leg
Total Winding Loss vs. Ripple Current 100 kHz, Single Gap Center Leg
Core gaps have traditionally been thought of as creating winding loss. They can also be used to steer AC and DC current into different sections of the windings or into different windings to reduce overall copper losses!
WHAT IS THE OPTIMAL SOLUTION OF WINDING PLACEMENT FOR A LITZ WIRE WINDING IN A GAPPED CORE

Simulation from Shapeopt Software developed by the Thayer School of Engineering at Dartmouth.
SHAPE OPT EXPERIMENT: HOLD ALL THE DESIGN PARAMETERS CONSTANT
AND VARY THE GAUGE OF THE INDIVIDUAL LITZ STRANDS
10 uH, 4 amp, 250 kHz INDUCTOR

<table>
<thead>
<tr>
<th>Wire Gauge</th>
<th>Number of Strands</th>
<th>DCR (mOhms)</th>
<th>AC Loss (watts)</th>
<th>DC loss (watts)</th>
<th>Total Loss (watts)</th>
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</thead>
<tbody>
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<td>30</td>
<td>5</td>
<td>36.80</td>
<td>0.53</td>
<td>0.54</td>
<td>1.07</td>
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<tr>
<td>32</td>
<td>9</td>
<td>30.50</td>
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<td>34</td>
<td>17</td>
<td>25.70</td>
<td>0.31</td>
<td>0.40</td>
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<tr>
<td>36</td>
<td>32</td>
<td>21.30</td>
<td>0.25</td>
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<td>0.59</td>
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<tr>
<td>38</td>
<td>55</td>
<td>19.10</td>
<td>0.19</td>
<td>0.31</td>
<td>0.50</td>
</tr>
<tr>
<td>40</td>
<td>109</td>
<td>16.60</td>
<td>0.14</td>
<td>0.27</td>
<td>0.41</td>
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<tr>
<td>42</td>
<td>181</td>
<td>15.30</td>
<td>0.11</td>
<td>0.24</td>
<td>0.35</td>
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<tr>
<td>44</td>
<td>314</td>
<td>14.00</td>
<td>0.09</td>
<td>0.22</td>
<td>0.31</td>
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<tr>
<td>46</td>
<td>527</td>
<td>13.00</td>
<td>0.07</td>
<td>0.21</td>
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<tr>
<td>48</td>
<td>918</td>
<td>12.50</td>
<td>0.05</td>
<td>0.20</td>
<td>0.25</td>
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<tr>
<td>50</td>
<td>1465</td>
<td>12.00</td>
<td>0.04</td>
<td>0.19</td>
<td>0.23</td>
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OPTIMAL WINDING SHAPE: 10 uH, 4 amp, 250 kHz
Inductor

5 strands 30 AWG
Optimal shape of the winding (wire placement in green) - gap at (0, bw/2)

314 strands 44 AWG
Optimal shape of the winding (wire placement in green) - gap at (0, bw/2)
Current Distribution: Ungapped E-Core and Gapped E-Core

Full Foil: Ungapped Core

AC current evenly distributed on surface of foil across full width of foil.

Shaped Foil: Gapped Core

AC current pulled to small copper cross section in the vicinity of the gap.

Shaped Foil is a patented technology developed by Professor Charles Sullivan and Dr. Jennifer Pollock at Dartmouth College.
Experiment: What is the Loss/Cost Tradeoff for the Different Windings?

- **Step 1: Define the Inductor**
  - Inductance: 70 uH
  - Current: 40 Adc
  - Core: E70/33/32 Ferroxcube 3C90 material
  - Gap: 2.64 mm (1.32 mm each center leg)
  - Turns: 16

- **Step 2: Wind inductors with conventional windings using best practices**
  - Full window
  - Single layer

- **Step 3: Determine winding losses for each inductor as a function of ripple magnitude**
Winding Cross Sections

- **DCR 2.44 mOhms**: 420/36 litz
- **DCR 3.46 mOhms**: Solid Wire
- **DCR 2.75 mOhms**: 1050/44 litz
- **DCR 8.12 mOhms**: 420/36 litz
- **DCR 4.38 mOhms**: Solid Wire
- **DCR 7.88 mOhms**: 1050/44 litz
SINGLE GAP CENTER LEG

Total Winding Loss vs. Ripple Current 100 kHz

Litz 1
Litz 2
Solid Wire
Shaped Foil 1
Shaped Foil 2
New Technology
Full Foil
New Technology
# Winding Cost Comparison

<table>
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<tr>
<th></th>
<th>12 awg</th>
<th>1050/44</th>
<th>400/38</th>
<th>full foil</th>
<th>0.4 cut out</th>
<th>new technology</th>
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<td>$/LB</td>
<td>$5.061</td>
<td>$49.74</td>
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<td>$/LB regained</td>
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<td>$4.00</td>
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<tr>
<td>Bobbin</td>
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<tr>
<td>Tape 3M56 for 1000 parts</td>
<td>$100.00</td>
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<td>Cost 3M Tufquin for 1000 parts</td>
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<td>weight with bobbin</td>
<td>0.50766</td>
<td>0.35805</td>
<td>0.37</td>
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<tr>
<td>without bobbin</td>
<td>0.48802</td>
<td>0.33841</td>
<td>0.35036</td>
<td>1.14248</td>
<td>1.14248</td>
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<td>LBs for 1000 parts</td>
<td>488.02</td>
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<td>350.36</td>
<td>1142.48</td>
<td>1142.48</td>
<td>737.083871</td>
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<td>Cost for 1000 parts (copper)</td>
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<tr>
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Thank you for your time

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