Optimizing Magnetics for Inverters

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Core losses vs. winding losses

- **Winding** losses:
  - Material properties: Linear and well known.
  - Loss prediction: analytical or FEA solutions.
  - Many variables to optimize—design opportunity!

- **Core** losses:
  - Material properties: nonlinear; not well understood.
  - Loss prediction: generalization of empirical measurements.
  - Few variables: material choice and flux density.
Winding losses: Skin Effect

Well known effect, but not the full story.

Skin depth

\[ \delta = \sqrt{\frac{\rho}{\pi \mu f}} \]

Original drawing from Snelling
Naïve idea to overcome skin effect

- Use diameter no bigger than ~2 skin depths...

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>60 Hz</th>
<th>20 kHz</th>
<th>200 kHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG 0</td>
<td>8.5 mm</td>
<td>0.467 mm</td>
<td>0.148 mm</td>
<td>66 μm</td>
<td>21 μm</td>
</tr>
<tr>
<td>AWG 24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWG 35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWG 42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWG 51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$2\delta$</th>
<th>60 Hz</th>
<th>20 kHz</th>
<th>200 kHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG 7/0</td>
<td>17 mm</td>
<td>0.93 mm</td>
<td>0.30 mm</td>
<td>132 μm</td>
<td>42 μm</td>
</tr>
<tr>
<td>AWG 18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWG 29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWG 36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWG 45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example transformer geometry
Diameter = 2 skin depths

200 kHz
d = 0.3 mm

Rac/Rdc = 1.36

Rac/Rdc = 27.7
Diameter = skin depth

50 kHz
d = 0.3 mm

Rac/Rdc = 1.03

Rac/Rdc = 3.01
Proximity Effect

Maybe a misnomer: effect of external field, including the effect of other wires and the effect of the core.
Litz wire

- Reduce ac resistance—skin and proximity effects.
- Invention: 1888, Sebastian de Ferranti.
- Analysis 1917 Howe; 1926 Butterworth.
- Two main parameters to choose number of strands and their diameter.
- Double jeopardy: can have high cost *and high loss*
Litz-wire design options

Full-bobbin design—double the loss of cheaper design.

Cheaper and lower loss

Good design requires optimization

Relative Loss

Relative Cost....~ amount of Cu

Normalized Cost

10
-1
10
0
10
1
10
2
10
0
10
1
32
34
36
38
40
42
44
46
48
50

power.thayer.dartmouth
Simple litz optimization (APEC 2014)
see http://bit.do/simplitz

- Target number of strands:
  \[ n_e = k \frac{\delta^2 b}{N_s} \]

  \( n_e \) - Number of turns per winding section
  \( k \) - Skin depth
  \( \delta \) - Window breadth
  \( b \) - AWG strand size
  \( N_s \) - Target number of strands

<table>
<thead>
<tr>
<th>AWG strand size</th>
<th>32</th>
<th>34</th>
<th>36</th>
<th>38</th>
<th>40</th>
<th>42</th>
<th>44</th>
<th>46</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k ) (mm(^3))</td>
<td>114</td>
<td>280</td>
<td>694</td>
<td>1.73k</td>
<td>4.29k</td>
<td>10.6k</td>
<td>25.5k</td>
<td>56.5k</td>
<td>118k</td>
</tr>
</tbody>
</table>

- Example: 200 kHz, 48 turns in 3 mm width (vs. 0.3 mm wire):

<table>
<thead>
<tr>
<th>AWG</th>
<th>36</th>
<th>38</th>
<th>40</th>
<th>42</th>
<th>44</th>
<th>46</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strands</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>15</td>
<td>35</td>
<td>77</td>
<td>162</td>
</tr>
<tr>
<td>% Rac</td>
<td>23.3%</td>
<td>15.9%</td>
<td>10.8%</td>
<td>7.8%</td>
<td>5.7%</td>
<td>4.4%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>
Litz wire construction details

- Full model now available to predict effect of construction.
- Simple rules to avoid problems are in the 2014 simple litz paper.
Inductor for a dc-dc converter:
DC current plus HF ripple

- Use a combination of a solid-wire winding (copper color) and a litz winding (blue).
- DC distributes to minimize loss (mostly in solid wire).
- Leakage inductance forces most HF current through the litz winding.
- Spacing from gap keeps wire out of intense field.
Foil winding with circular cutout

Very low dc resistance with good ac resistance
Inductor for an inverter: LF AC current plus HF ripple

- Same structure with litz wire and solid wire.
- Challenge: keep LF out of litz winding.
- Solution: series capacitor for litz winding only.
- Can now use a small inductor value: high ripple no longer leads to high loss.
### Other metals?

<table>
<thead>
<tr>
<th>Metal</th>
<th>Resistivity $\rho$ (conductor grade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver (Ag)</td>
<td>1.59 $\mu\Omega\cdot\text{cm}$</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>1.72 $\mu\Omega\cdot\text{cm}$</td>
</tr>
<tr>
<td>Gold (Au)</td>
<td>2.44 $\mu\Omega\cdot\text{cm}$</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>2.83 $\mu\Omega\cdot\text{cm}$</td>
</tr>
</tbody>
</table>

- Note units: cm not kg
- Price per kg is not the right metric: consider price per volume.
Costs: Cu vs. Al
(old numbers, but ratios are still the same)

- Mass:
  $9.20/kg vs. $2.40/kg (wrong metric)

- Volume:
  8.2 ¢/cm³ vs. 0.65 ¢/cm³ 12X

- Resistance:
  $14 \frac{\mu\Omega}{m^2}$ vs. $1.8 \frac{\mu\Omega}{m^2}$ 7.7X

- Actual Al magnet wire prices aren’t that good, but even at the same price per kg, Al would be ½ the price for the same resistance!
Can AI work at high frequency?
Measured transformer ac resistance

- 29 turns of 0.5 mm (AWG 24) wire.
- Two layers on EE19 core.

Rac

- Al 64% worse (61% measured)
- Al no worse
- Al 28% worse (30% measured)

Frequency

1 kHz 10 kHz 100 kHz 1 MHz
Cost and loss of Al vs. Cu

- For same dc resistance, Al is >7X cheaper (commodity price).
- Advantages at high frequency are even greater than at low frequency.
- Only reasons for Cu:
  - Where compact size is more important than efficiency, cost, temperature or weight.
  - If termination cost difference exceeds wire cost difference.
Conclusions

- Litz wire is ideal for high-power, high-frequency windings, e.g. in transformers.
  - Without explicit design calculations, litz wire can make loss worse at high cost.
- For DC-DC converter inductors, shaped foil and dual-winding designs can provide low AC and DC resistance.
- Inverter output inductors are trickier, but it’s possible to use dual-winding inductors with a capacitor added.
- Consider aluminum if you care about cost or weight.