Windings for High Frequency

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The Issue

- The best-available technology for low-loss windings up to ~ 3 MHz is litz wire.
- At higher frequencies, litz wire has little benefit.

This Talk:

- What limits litz wire above 3 MHz?
- What else can be done above 3 MHz?
- Litz wire and other approaches for < 3 MHz
Naïve idea to overcome skin effect

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

<table>
<thead>
<tr>
<th>f</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>δ</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></td>
<td>AWG 0</td>
<td>AWG 24</td>
<td>AWG 35</td>
<td>AWG 42</td>
<td>AWG 51</td>
</tr>
<tr>
<td>2δ</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></td>
<td>AWG 7/0</td>
<td>AWG 18</td>
<td>AWG 29</td>
<td>AWG 36</td>
<td>AWG 45</td>
</tr>
</tbody>
</table>
Diameter = 2 skin depths

200 kHz
d = 0.3 mm

Rac/Rdc = 1.36

Rac/Rdc = 27.7
Issue: Proximity Effect (field impinging on wire)
Design Criterion with Proximity Effect

- Effect of using many layers. (Simplified 1-D analysis)
  - For $p$ layers, the layer thickness for minimum ac resistance is $t = \frac{1.3\delta}{\sqrt{p}}$
  - Achievable ac resistance is proportional to $\frac{1}{\sqrt{p}}$

- We’d like wire diameter of $\frac{\delta}{10}$, for example, but at 1 MHz, $\frac{\delta}{10} = 6.6 \mu m$, about $\frac{1}{4}$ the smallest available.

- Consider the case of constrained wire diameter.
Litz > 1 MHz

- Available improvement vs. single-layer solid wire:
  \[ \frac{P_{\text{litz}}}{P_{\text{solid}}} \approx 0.58 \frac{d}{\delta} \]

<table>
<thead>
<tr>
<th>f</th>
<th>300 kHz</th>
<th>1 MHz</th>
<th>3 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta)</td>
<td>0.148 (\mu m)</td>
<td>66 (\mu m)</td>
<td>38 (\mu m)</td>
<td>21 (\mu m)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strand size</th>
<th>Loss reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG44 51 (\mu m)</td>
<td>80% 55% 22% None</td>
</tr>
<tr>
<td>AWG46 40 (\mu m)</td>
<td>84% 65% 39% None</td>
</tr>
<tr>
<td>AWG48 32 (\mu m)</td>
<td>87% 72.7% 51% 11%</td>
</tr>
</tbody>
</table>

- For 3 MHz and higher need \(d < < 32 \(\mu m\)
Low AC resistance > 3 MHz

Options:

- Single-layer windings
  OR
- Winding dimensions < 20 μm
  - Wire is too expensive.
  - Foil is cheap.
  - Microfabrication with photolithography also an option.
Single-layer transformer designs

Two layer

Simple single layer

1X interleaving

Double interleaving
Interleaving limitations

- Each level of interleaving adds capacitance.
- Also adds fabrication complexity.
- Not possible with inductors.
Single-layer inductors

- Gapped high-perm
- Low-perm core
- Air core

- All have low window utilization.

- Toroids: can reduce end-to-end capacitance with split winding (Qiu, Hanson and Sullivan COMPEL 2013)
Improving window utilization in inductors

- If there’s substantial dc current, add a parallel winding to reduce Rdc.

- Simpler construction for the same net effect: Shaped foil windings. (available from West Coast Magnetics)

- Improving Rac further requires a multilayer winding.
Multi-layer foil windings: $N = p$

- Compared to single-layer winding, AC resistance ideally reduced by $\frac{1}{\sqrt{p}}$ for $p$ layers, if the layer thickness is $t = 1.3 \delta / \sqrt{p}$.

- Simplest option: barrel-wound foil where the number of turns $N$ is equal to the number of layers $p$.

- Two challenges:
  - Keeping the field parallel to the foil (esp. in gapped L)
  - Terminations
Solutions for multilayer foil inductors:

I. Field Parallel to Foil

- Quasi-distributed gap, designed right, produces parallel field in winding region.
  - Sullivan et. al., “Inductor Design for Low Loss with Dual Foil,” ECCE 2013
Solutions for multilayer foil inductors: 
II. Terminations

- Counter-wound Z-foil keeps terminations away from inner high-field region.

Same reference:
Sullivan et. al., “Inductor Design for Low Loss with Dual Foil,” ECCE 2013
Paralleling foil layers

- Simple paralleling has little benefit. Current flows in surface layer(s).

- One solution: interchange layers to achieve equal flux linkage.
  - Option 1: use many regularly spaced interchanges (like litz); hope for flux to average out.
Options for Making Foil Winding Interchanges

- Vias in PCB technology
  - E.g., paper 16.3 yesterday, Lope, Carretero, Acero, et al.

- Folding
  - E.g., Glaser and de Rooij, PESC 2006

- Interlinked slits
Options for Making Foil Winding Interchanges:

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Current sharing between layers without interchanges: I. Spacing*

- With balanced MMF, it is possible to achieve balanced flux linkage just by adjusting spacing between layers.

- “Unwound” diagram showing relative flux densities in each inter-layer region.

<table>
<thead>
<tr>
<th>Turn number</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>12</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>-4</td>
<td>-8</td>
</tr>
<tr>
<td>Layer 2</td>
<td>11</td>
<td>7</td>
<td>3</td>
<td>-1</td>
<td>-5</td>
<td>-9</td>
</tr>
<tr>
<td>Layer 3</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>-2</td>
<td>-6</td>
<td>-10</td>
</tr>
<tr>
<td>Layer 4</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>-3</td>
<td>-7</td>
<td>-11</td>
</tr>
</tbody>
</table>

- In this case, with equal turn lengths, the net flux between any two layers is zero when $h_1 = 1.4 \ h_0$
Current sharing without interchanges:

II. Current balancing transformer*

Overall concept:
add balancing transformer:

Magnetic topology of balancing transformer:

One implementation for foil layers.

*patent pending
Current sharing without interchanges:

III. Capacitive ballasting*

- Use overlapping insulated layers to create a different tuned series capacitance for each layer.

- Capacitance can be chosen for exact current sharing at one frequency or approximate current sharing over a wider range.
One application/implementation of current sharing by capacitive ballasting

- Resonant coil for wireless power or nanoparticle cancer treatment.
- Resonant capacitor = ballasting capacitors for hundreds of layers of 12 μm foil.
Below 3 MHz

- Foil options are still attractive for low cost and high packing factor. Al foil is especially economical.
- Litz wire also viable.
  - Essential to do careful design—otherwise can have higher loss than a single-layer winding and much higher cost.
- LitzOpt online or MATLAB:
  - Updated/upgraded this year.
  - But not commercial software—no support.
Winding loss analysis: methods for wide frequency range and 2D shapes

- Hybridized Nan’s method (Zimmanck, 2010)
- Homogenization with complex permeability (Nan 2009, Meeker, 2012)
Summary and Conclusions

- For lowest loss: need dimensions not just smaller than a skin depth but much smaller.
- Wire fine enough to help much at > 3 MHz is not economical, but foil down ~ 6 μm is inexpensive.
- The challenge with foil is getting current to share equally with many layers...but there are many possible ways to do this.
- There may be no “silver bullet” magnetic material...but there’s a lot that can be done to make better windings.
  - Better windings -> can use more turns -> lower flux density -> lower core loss.
References and notes for simple round-wire loss formulas

The simplest formulations are valid for wire diameter smaller than about two skin depths. Good designs will use wire that small, except when the winding is optimized primarily for one frequency and you are interested in analyzing loss at a higher frequency.


References for windings with multiple frequencies


References for windings with multiple frequencies and 2D fields

12. D. R. Zimmanck and C. R. Sullivan, “Efficient Calculation of Winding Loss Resistance Matrices for Magnetic Components,” Twelfth IEEE Workshop on Control and Modeling for Power Electronics (COMPEL), June, 2010. In some cases this is slightly less accurate than the following two, but the FEA computation is dramatically less: rather than using one FEA simulation at each frequency of interest, it uses one dc (static) simulation and can then predict losses for any frequency.


More References:


- Sullivan, Charles R; Beghou, Lotfi; “Design methodology for a high-Q self-resonant coil for medical and wireless-power applications,” IEEE 14th Workshop on Control and Modeling for Power Electronics (COMPEL), 2013. [http://dx.doi.org/10.1109/COMPEL.2013.6626460](http://dx.doi.org/10.1109/COMPEL.2013.6626460)
