Survey of Winding Techniques Used in Power Magnetic Components

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Considerations

- Winding loss
  - DC
  - High-frequency
- Cost and manufacturing.
  - Repeatability.
- Thermal performance
- Capacitance
- Voltage breakdown and corona

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## Conductors

- Wire
  - Solid: ● and ■
  - Litz and stranded.
  - Cu and Al
- Rectangular strip and foil
- Planar/PCB/etched/stamped
- 3-D printed or cast shapes.

## Configurations

- Simple
- Orthocyclic
- Multifilar and transposed (Roebel)
- Sectioned
- Interleaved
- Shaped for fringing fields
- Edge wound (strips)
- Combinations

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Conductors .... Configurations

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High-frequency loss effects

- Fundamental issue: eddy currents
- Extra current means extra loss.

\[
\oint E \cdot d\ell = -\frac{d\Phi}{dt}, \quad J = \frac{E}{\rho}
\]

\( dB/dt \geq 0 \)

Conductor
Two results of eddy currents

- Skin effect: Current near the surface in a skin depth
  \[ \delta = \sqrt{\frac{\rho}{\pi \mu f}} \]

- Proximity effect: Fields from the winding and core induce losses in the winding.

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Single-layer vs. multilayer windings

Single layer: mostly skin effect.

Multi-layer: mostly proximity effect

\( \frac{R_{ac}}{R_{dc}} = 1.36 \)

200 kHz
\( d = 0.3 \text{ mm} = 2\delta \)

\( \frac{R_{ac}}{R_{dc}} = 27.7 \)
Single-layer winding:
Skin effect vs. thickness

- Making it thicker than a skin depth doesn’t help, but doesn’t hurt either.
Single-layer winding:
Skin effect vs. frequency and thickness

- Making it thicker than a skin depth doesn’t help, but doesn’t hurt either.
- Degradation at higher frequency is gradual: resistance and loss go as $\sqrt{f}$
Multi-layer winding (9-layer example): Proximity effect vs. freq. and thickness

- Very sensitive to thickness!
  - Want to nail the optimum.
  - Minimum be much lower than single-layer winding.
- Degradation at higher frequency is rapid: resistance and loss go as $f^2$.
- Issues start even when it’s smaller than a skin depth.

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Single layer vs. Multilayer

- Forgiving: gets worse only slowly at high frequency.
- Uses very little of the winding window for high frequency current.
- Can have very low dc resistance: no penalty for very thick conductors.

- Can achieve lower ac resistance.
- Choose thickness carefully
- Needs very thin conductors if it uses many layers.

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Winding types:

**Single layer** vs. **Multilayer**

- **Simple wire**
- **Edge wound**
- **Foil**
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http://coilws.com
http://mpsind.com
Winding types: **Litz?**

**Single layer** vs. **Multilayer**

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**Litz:** always multilayer (layers of strands)
Winding types: PCB?

Single layer vs. Multilayer

- Edge wound
- Foil

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Winding types: PCB?

Single layer vs. Multilayer

Edge wound

Side-by-side makes it single-layer

Stacked windings makes it multilayer

Foil

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Winding types:
Single layer vs. Multilayer

Simple wire
Edge wound
PCB

Simple wire
Foil
PCB

Litz
Litz

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Comparing single-layer and multi-layer

- If layers are very thin compared to a skin depth, multi-layer has lower ac resistance.
- With a fixed number of layers, $p$, and optimized thickness reduce loss by $\frac{1}{\sqrt{p}}$.
- Single-layer can use thick copper with no penalty: better for low dc resistance.

For more, see [7]
Layers and Interleaving

- Interleaving used to make all designs function as single-layer designs.  
  *(how to count)*

- **Limits:**
  - Capacitance
  - Complexity

- **Solutions:**
  - PCB winding allows complexity.
  - Circuit designs with low voltage swing per winding.

*Count from the interface to a zero field region.*

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If you interleave, do it right.

- One layer, two interfaces.
- Note symmetry.

- One layer, three interfaces.
- Just as good Rac, but
  - More capacitance
  - More complex construction
Inductors

- Interleaving doesn’t apply.
- Low $R_{dc}$ is often useful ... single layer?
  - Single-layer counting from the gap or low-perm core.

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Improving window utilization in gapped inductors

- If there’s substantial dc current, add a parallel winding to reduce $R_{dc}$.

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

- Improve $R_{ac}$ by using litz for the high-frequency winding.

- Can also use multiple gaps... see 2018 workshop presentation.

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Winding shape optimization

- Shape winding configuration to work with curved gap field.
- Applies to round wire and litz wire, not foil.
- Can actually work better than a distributed gap!
- Ad-hoc approach common, but full optimization is available [16].

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Thermal Performance

- Copper is a great heat conductor
  - Parallel to layers and along wires.
  - 2 good directions for foil and planar vs. 1 good direction for wire.

- Surface area for cooling by convection (and radiation) or by conduction.

http://dartgo.org/PMIC  http://www.ikes.16mb.com/
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http://mpsind.com
Capacitance and voltage withstand

- Separate wires that have big voltage differences.
- Interleaving increases capacitance.

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Conclusions

- No one winding type is superior for all parameters.
- Don’t be discouraged by red regions: none are show stoppers.
- Multiple layers can help or hurt. With $p$ layers you can reduce $R_{ac}$ by $\frac{1}{\sqrt{p}}$ using the optimal thickness.
- Litz wire is always multilayer: think in terms of number of strands and diameter of strands.

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Thank you!

PMIC Power Management Integration Center
Open to new company members: http://dartgo.org/pmic

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Description of key references

Key references in high-frequency power magnetics with an emphasis on publications from our group and a focus on discrete components rather than chip-scale microfabricated components; for our perspective on the latter see [1].

For windings, Zimmanck’s method can efficiently generate frequency dependent winding loss matrices for any geometry, 1D, 2D, or 3D, and use them to predict loss for different nonsinusoidal waveforms in any number of [2]. This method applies very generally, including to coupled inductors, wireless power transfer coils, etc. References cited in [2] provide more detailed background, including [26,27]. See also [28]. A systematic approach to generating full models for loss and simulation for 1D geometry is provided in [3]. To use 2D models effectively for 3D geometries such as E-cores, the strategy in [25] can reduce the error involved by a factor of 5.

Although the Dowell model is reasonably accurate, see the appendix of [9] for a simple correction that can enhance the accuracy. Also useful in the appendix of [9] is a simple effective frequency approach to address winding loss with non-sinusoidal windings.

Strategies to reduce proximity effect loss, using multiple thin layers or avoiding multiple layers, are compared in [6, 7, 8], considering different types of optimization constraints. An overview of the most common implementation of thin layers to reduce proximity effect loss, litz wire, is provided in [9]. A practical guide to using it is provided in [10], and the most complete model including effects of details of twisting construction, is in [11]. Approaches for using thin foil layers beyond frequencies where litz is practical are discussed in [12]. An implementation of these concepts for a resonant coil for applications such as wireless power transfer is described in [13]. For other applications, thin foil layers can have capacitance issues; circuits designs that reduce the voltage swing on the windings (e.g., [14]) can help reduce the impact of the capacitance.

The impacts of gap fringing and the quasi-distributed gap technique for reducing these problems are discussed in [15]. This reference includes data showing that a small gap is not effective for reducing the impact of fringing. With round-wire or litz-wire windings, shaping the winding can allow excellent performance with a standard gap [16].

In inductors with substantial dc resistance, two windings in parallel can be a good choice for good dc and ac resistance[17]. It is possible to extend this approach to applications in which the inductor carries a combination of line frequency ac current and high-frequency switching ripple, using, if needed, a capacitor to prevent low-frequency current from flowing through the high-frequency winding [18]. A foil winding with a semi-circular cutout region near the gap [19, 20, 21] can also be used to achieve a favorable ac/dc resistance combination.

Although copper windings are most common, aluminum can offer advantages if cost or weight are important [22, 23].

Performance factor for magnetic materials is described and extended in [24], and data on performance factor is provided for many materials in the MHz range. For core loss with non-sinusoidal waveforms, the iGSE model remains the standard method [4], although some of its limitations are now known, as discussed in [5].
References, p. 1 of 2


