Introduction of the CFFC-Compensating Fringing Field Concept and its Application in PCB Winding Inductors

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Brief Outline

- Challenges in Conventional PCB Winding Inductor Designs
- Derivation of the CFFC
- Experimental Verification
- Thermally Improved Inductor Design
Conventional PCB Winding Inductors

Challenges in the Design of PCB Winding Inductors

- Limited available copper
  Can only be increased by increasing the winding width $b_w$ (2D $\rightarrow$ poor power density)
  
- High frequency conduction losses
  $\rightarrow$ Large copper planes are prone to eddy current induction

$H_{\text{ext}}$  

$\rightarrow$ Efficient utilization of the available copper inevitable!
Conventional PCB Winding Inductors

- Air Coil – PCB Winding without Core
  Assumption: One turn per layer
  - High frequency conduction losses
    - Magnetic skin and proximity fields push the current towards the edges of the PCB winding
  - AC to DC resistance ratio of ≈ 2.1 @ 500kHz
Conventional PCB Winding Inductors

- Same PCB Winding with Two ELP Cores
  Assumption: One turn per layer
  - High frequency conduction losses
    → Magnetic skin and proximity fields push the current towards the edges of the PCB winding
    → Additionally, fringing field around the air gap exacerbates the current displacement
  → AC to DC resistance ratio of ≈ 8.2 @ 500kHz
**Conventional PCB Winding Inductors**

- **Same PCB Winding with ELP+I Cores**
  
  Assumption: One turn per layer
  
  - High frequency conduction losses
    - Magnetic skin and proximity fields push the current towards the edges of the PCB winding
    - Fringing field around the air gap still exacerbates the current displacement
    - AC to DC resistance ratio of ≈ 5.1 @ 500kHz
Conventional PCB Winding Inductors

■ Special Challenges in the Design of PCB Winding Inductors
  • Conventional Inductor Designs
    → Fringing field around the air gap is heading in the same direction as the skin and proximity fields
  • Possible Alternative?
    → Relocate the air gap, such that the fringing field counteracts the parasitic skin and proximity fields

► Air Coil
► ELP Cores
► ELP+I Cores

► Customized Core with Perpendicular Air Gap
Proposed PCB Winding Inductor Design

- Same PCB Winding with a Customized Core
  Assumption: One turn per layer
  - High frequency conduction losses
    - Magnetic skin/proximity fields and the fringing fields around the air gaps are heading in opposite direction
    - Mutual partial compensation of the fields
    - AC to DC resistance ratio < 1.1 @ 500kHz
Compensating Fringing Field Concept (CFFC)

- Simplified Analytical Derivation
- Power Density Improvement by Utilizing Multiple Air Gaps
- Effectivity of the CFFC for Multilayer PCB Windings
Compensating Fringing Field Concept

Analytical Derivation of the Magnetic Fields

- **Skin/Proximity Field**
  Skin/proximity field for a homogeneous current distribution within the conductor

\[ H_{\text{prox,y}}(x) = \frac{l_L}{2 \pi b_w} \ln \left( \frac{b_w - 2x}{-b_w - 2x} \right) \]

- **Fringing Field Around the Air Gap**
  Fringing field for different distances between the air gap and the conductor [1]

\[ H_{\text{fringe,y}}(x, d_{ag}) = \frac{H_g}{2 \pi} \ln \left( \frac{x^2 + (d_{ag} - l_{ag})^2}{x^2 + (d_{ag} + l_{ag})^2} \right) \]

Effect of Vertical Magnetic Fields

- Increase of the conduction losses:

\[ P_{\text{AC}} = R_{\text{DC}} \left( 2F_{\text{RMS}}^2 + 2G_{\text{F}} H_{\text{vert},\text{RMS}}^2 \right) \]

\[ H_{\text{vert,RMS}} = H_{\text{prox,y}} + H_{\text{fringe,y}} \]

Compensating Fringing Field Concept

Analytical Derivation of the Magnetic Fields

- Skin/Proximity Field
  Skin/proximity field for a homogeneous current distribution within the conductor
  \[ H_{\text{prox},y}(x) = \frac{I_L}{2\pi b_w} \ln\left( \frac{b_w - 2x}{-b_w - 2x} \right) \]

- Fringing Field Around the Air Gap
  Fringing field for different distances between the air gap and the conductor [1]
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Partial Mutual Compensation of the Fields

- Quality of the compensation depends on the distance \( d_{ag} \) between the air gap and the conductor
  \[ H_{\text{tot},y}(x) = H_{\text{fringe},y}(x, d_{ag}) + H_{\text{prox},y}(x) \]

Optimal Distance Between the Air Gap and the Conductor

- Conduction Loss Estimation based on $H_{\text{tot,y}}$
  
  In a first approximation, the local AC conduction losses are proportional to $H_{\text{tot,y}}^2$

\[ P_{\text{cond}}(d_{ag}) \propto \int H_{\text{tot,y}}^2 \, dx \]

- First Design Guideline

\[ d_{ag \text{opt}} = \frac{b_w}{2} \]

Far away from the air gap is not always ideal!

CFFC: Use fringing field in a beneficial way!
Compensating Fringing Field Concept

Utilization of Multiple Air Gaps to Reduce $d_{ag,\text{opt}}$

- Magnetic Field Compensation of Multiple Air Gaps

The quality of the field compensation improves with the number of air gaps

$$P_{\text{cond}}(d_{ag}) \propto \int H_{\text{tot},y}^2 dx$$
Compensating Fringing Field Concept

Utilization of Multiple Air Gaps to Reduce $d_{ag,\text{opt}}$

- Magnetic Field Compensation of Multiple Air Gaps
  The quality of the field compensation improves with the number of air gaps
  $$P_{\text{cond}}(d_{ag}) \propto \int H_{\text{tot}}^2 dx$$

- Second Design Guideline
  $$d_{ag,\text{opt}} = \frac{b_w}{2 \cdot N_{ag}}$$

FEM-Simulated Normalized Conduction Losses

$$d_{ag}, o_{\text{opt}} = \frac{b_w}{2 \cdot N_{ag}}$$

Magnetic Fields

Customized Core
**Compensating Fringing Field Concept**

- **Multilayer PCB Winding**
  - How effective is the CFFC for multilayer PCB windings?
  - Quality of compensation only slightly decreases with increasing the number of layers

**FEM Simulated Current Densities**

- Simulated Air Coil ($R_{AC/DC} = 2.54$)
- Simulated with Single Air Gap ($R_{AC/DC} = 1.34$)
- Simulated with Dual Air Gap ($R_{AC/DC} = 1.18$)
Experimental Verification

- Design of the PCB Winding
- AC-Resistance Measurements
- Calorimetric Measurements
Practical Implementation of the CFFC

- **Design of the PCB Winding**
  - Circular shape to minimize winding length
  - Use through-hole vias to minimize costs
  - Vertically aligned termination to minimize losses

- **Design of the Ferrite Core**
  - Circular air gap above and beneath the winding
  - Customized CNC-milled core shape

Assembly of the PCB winding inductor (core diameter = 20mm)

Design of a circular PCB inductor winding
Experimental Verification

AC-Resistance Measurements
- Measurements have been performed using an impedance analyzer
  - 45% less conduction losses at high frequencies

Assembly of the PCB winding inductor (core diameter = 20mm)

Experimentally measured AC-resistance of the PCB winding
Experimental Verification

AC-Resistance Measurements
- Measurements have been performed using an impedance analyzer
  → **45%** less conduction losses at high frequencies

Calorimetric Measurements
- Even though the inductance of B is 10x larger than the inductance of A
  → **25%** less losses

Assembly of the PCB winding inductor (core diameter = 20mm)

Thermally limited to $I_{\text{rms}} < 7\text{A}$ ($T_{\text{PCB}} < 150^\circ$)
Thermally Improved PCB Winding Inductor

- Derivation of the Thermal Model of a Circular PCB Winding
- Improving the Thermal Performance by Utilization of Additional Thermal Interfaces
- Experimental Verification
Thermally Improved PCB Winding Inductor

Thermal Modelling of PCB Windings

- Equivalent thermal conductivity of a PCB
  \[ \lambda_{\text{eff}} = r_{\text{PCB}} \lambda_{\text{Cu}} + (1 - r_{\text{PCB}}) \lambda_{\text{FR4}} \]

- Thermal resistance of a rectangular piece of PCB
  \[ R_{\text{th}} = \frac{l_w}{\lambda_{\text{eff}} \cdot b_w \cdot h_{\text{PCB}}} \]

Simplified drawing of an 8 layer PCB

Thermal resistance of a sample piece of an 8 layer 70um PCB
Thermally Improved PCB Winding Inductor

Thermal Model of a Circular PCB Winding

- Thermal “per-length” resistance
  \[ r_{th,W} = \frac{1}{2\pi} \left( \frac{2r_W \pi}{\lambda_{eff} \cdot b_W \cdot h_{PCB}} \right) \]
- “Per-length” conduction losses
  \[ q_W = \frac{P_W}{2\pi} \]

Simulated and calculated temperature distribution within the winding for \( P_W = 6W \) and a heat sink temperature of \( T_A = 25°C \)

Thermally Improved PCB Winding Inductor

Thermal Bottleneck

Simulated and calculated temperature distribution within the winding for \( P_W = 6W \) and a heat sink temperature of \( T_A = 25°C \)
Thermally Improved PCB Winding Inductor

Thermally Improved PCB Winding

- Thermal “per-length” resistance
  \[ r_{\text{th,W}} = \frac{1}{2\pi} \left( \frac{2r_w \pi}{\lambda_{\text{eff}} \cdot b_w \cdot h_{\text{PCB}}} \right) \]
- “Per-length” conduction losses
  \[ q_w = \frac{P_w}{2\pi} \]

Thermally Improved PCB Winding Inductor

\[ T_W(\varphi) = T_A + R_{\text{th,T}} \cdot \frac{P_w}{4} + q_w \cdot \frac{r_{\text{th,W}}}{4} \cdot \varphi \cdot (\pi - 2\varphi) \]

Thermal model of a thermally improved PCB winding with four thermal interfaces

Simulated and calculated temperature distribution within the winding for \( P_w = 6W \) and a heat sink temperature of \( T_A = 25°C \)
**Thermally Improved PCB Winding Inductor**

- **Experimental Verification of the Thermal Model**
  - Measurement of the temperature distribution within two identical PCB windings with either 1 or 4 thermal interfaces
  - The rectangular aluminum heat sink was screwed on a water-cooled \( T_A = 25°C \) base plate

- Calculated and measured temperature distribution within the winding for a constant loss of 3.5W and \( T_A = 25°C \)

- **Experimental setup for the temperature measurement of two sample inductor windings**
Thermally Improved PCB Winding Inductor

Adapted Inductor Core Design
- Circular core → Rectangular core
- Homogeneous flux density in the inner and outer core limbs required [2]

Core Holder for Improved Mechanical Stability
- 3D-printed core holder ensures homogeneous air gap and the ideal distance between air gap and winding
- Customized core can be used as conventional E cores

Exemplary PCB-Winding Inductor

Series Resonant Inductor for 3kW DC/DC Converters

- Specifications:
  - $L_{\text{res}} = 6.8 \ \mu\text{H}$
  - $I_{\text{pk}} = 25 \ \text{A}$
  - $I_{\text{rms}} = 16.2 \ \text{A}$

- FEM-simulated resistance and current distribution of the 6.8$\mu$H inductor prototype (Measured AC to DC resistance ratio @ 300kHz: 1.49)

- Exemplary PCB-Winding Inductor

- Simplified resonant converter topology for a 500V-12V DC/DC converter

- FEM-simulated resistance and current distribution of the 6.8$\mu$H inductor prototype (Measured AC to DC resistance ratio @ 300kHz: 1.49)
Exemplary PCB-Winding Inductor

Output Inductors of a Phase-Shifted Full-Bridge Converter

- Specifications:
  - $L_0 = 250 \text{ nH}$
  - $I_{pk} = 210 \text{ A}$
  - $I_{rms} = 118 \text{ A}$

3.6kW 500V/12V three-port DC/DC converter for automotive applications
Conclusions

- Fringing field around air gaps can be used in a variety of applications for minimizing HF conduction losses.
- CFFC can be used for shaping the current distribution in the conductor arbitrarily.
- Good thermal design → Very high current densities can be allowed.
- Customized cores are necessary to fully utilize the benefits of the CFFC.

It is possible to design highly efficient and compact PCB winding inductors.

Questions?
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Thank You!
Compensating Fringing Field Concept

Utilization of Multiple Air Gaps to Reduce $d_{ag,\text{opt}}$

- Magnetic Field Compensation of Multiple Air Gaps
  The quality of the field compensation improves with the number of air gaps
  \[ P_{\text{cond}}(d_{ag}) \propto \int H_{\text{tot}}^2 \, dx \]

- Second Design Guideline
  \[ d_{ag,\text{opt}} = \frac{b_w}{2 \cdot N_{ag}} \]

Circular Inductor Arrangements
- Design guidelines are also valid for circular inductor arrangements with $r_{\text{out}} < 2 \cdot r_{\text{in}}$
Compensating Fringing Field Concept

Multilayer PCB Winding
- How effective is the CFFC for multilayer PCB windings?
- Quality of compensation only slightly decreases with increasing the number of layers

FEM Simulated Current Densities

- Simulated Air Coil ($R_{AC/DC} = 2.54$)
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PCB Winding Inductor

Inductor Design Concept
- Integrate the inductor winding into the PCB in order to reduce the manufacturing costs

Idea
- Use the usually adverse fringing field of the air gap to mitigate the parasitic skin and proximity fields in the winding
- Relocate the air gap perpendicular to the winding

Design Variation

AC/DC-Resistance Ratio

Circular Conductors
- The optimal position of the air gap does not change significantly for circular conductors
Practical Implementation of the Inductor

- Implemented in a 8 Layer PCB
  - Coplanar termination → Efficient due to homogeneous current density
  - Through-hole vias only → Cheap manufacturing
  - 7 turns (8th layer used for termination and layer transitions)
- Current densities > 100 A/mm² possible
- Fast and effective heat extraction
  - Important due to the poor thermal conductivity of a PCB

PCB Inductor Assembly

Current flow
Layer transition
Heat extraction
Terminals

PCB Inductor Winding

FEM Simulated Current Density

J (A/mm²)

0
100
200
300

Terminal
Layer transition
Practical Implementation of the Inductor

Thermal Management of the Inductor
- PCB winding attached to aluminum heat sink through thermal interface material (TIM)
- Provides 4 paths for heat extraction
  - Hot spot temperature of 79°C for forced convection
  - Temperature gradient within the PCB winding of $\Delta T = 35°C$

FEM Simulated Temperature (Forced Convection)
Motivation: Conventional PCB Winding Inductors

- Challenges in Conventional PCB Winding Inductor Designs
- Magnetic Field Distributions