Optimal Design of Highly Efficient and Highly Compact PCB Winding Inductors

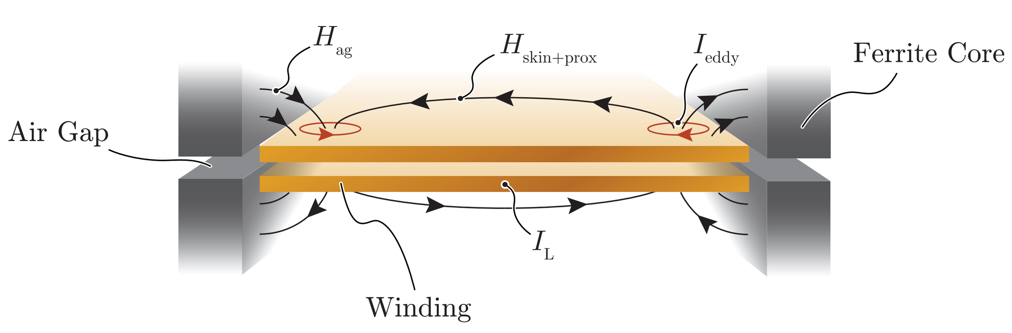
Jannik Schäfer, Dominik Bortis and Johann W. Kolar
Power Electronic Systems Laboratory (PES), ETH Zürich, Switzerland
{schaefer,bortis,kolar}@lem.ee.ethz.ch

Power Electronic Systems Laboratory

ETH zürich

I. CHALLENGES

- Minimize the AC resistance of the inductor winding for efficient high-frequency (HF) operation
- Avoid parasitic HF magnetic fields in the winding



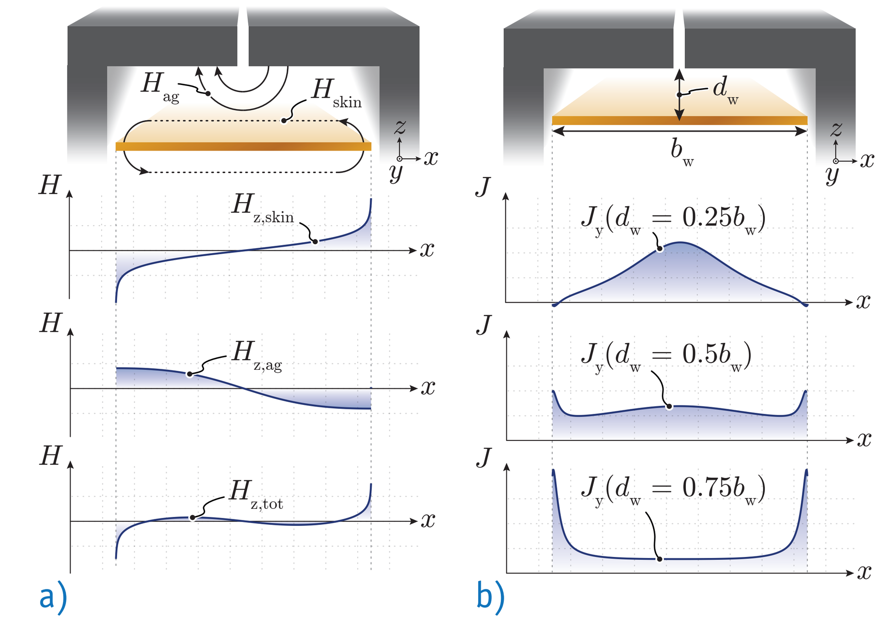
▲ Parasitic magnetic skin field H_{skin}, proximity field H_{prox} and fringing field H_{ag} around the air gap

II. METHODS

- Place air gap above the conductor
- Use fringing field H_{ag} to compensate the magnetic fields H_{skin} and H_{prox}
- Find optimal distance d_w between air gap and conductor

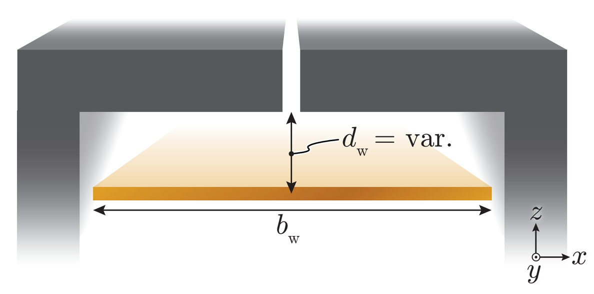
$$\frac{R_{AC}}{R_{DC}} = F_R = f(d_w) \xrightarrow{\text{minimize}} F_R = 1$$

$$P_{cond} = R_{DC} F_R I_{rms}^2 = \int_V \frac{J(x,y,z)^2}{\sigma} dV$$



▲ a) Magnetic field components perpendicular to the conductor surface and b) current densities J_y for different d_w

III. STRAIGHT CONDUCTOR

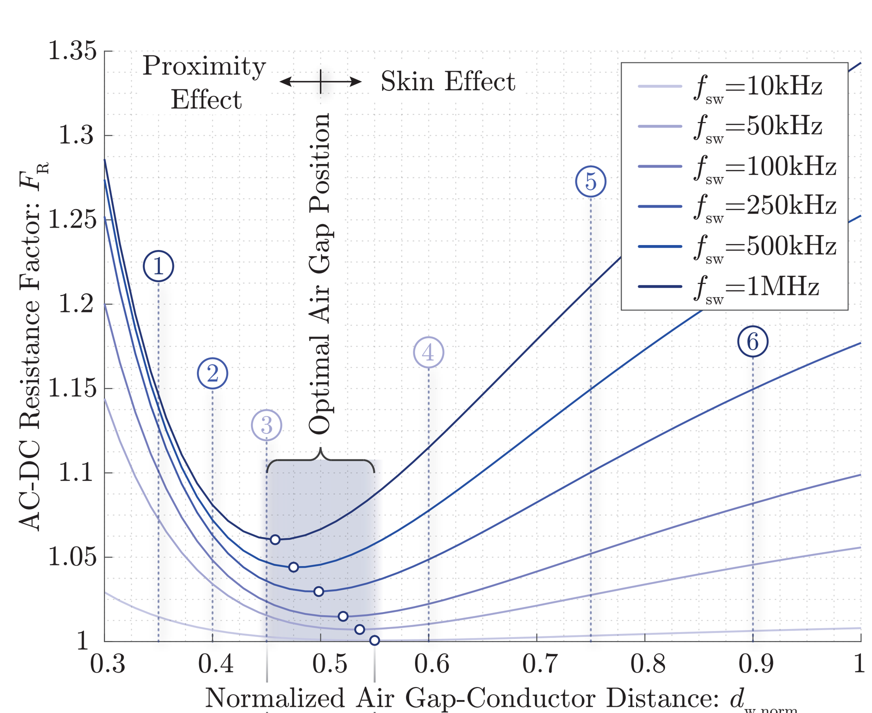


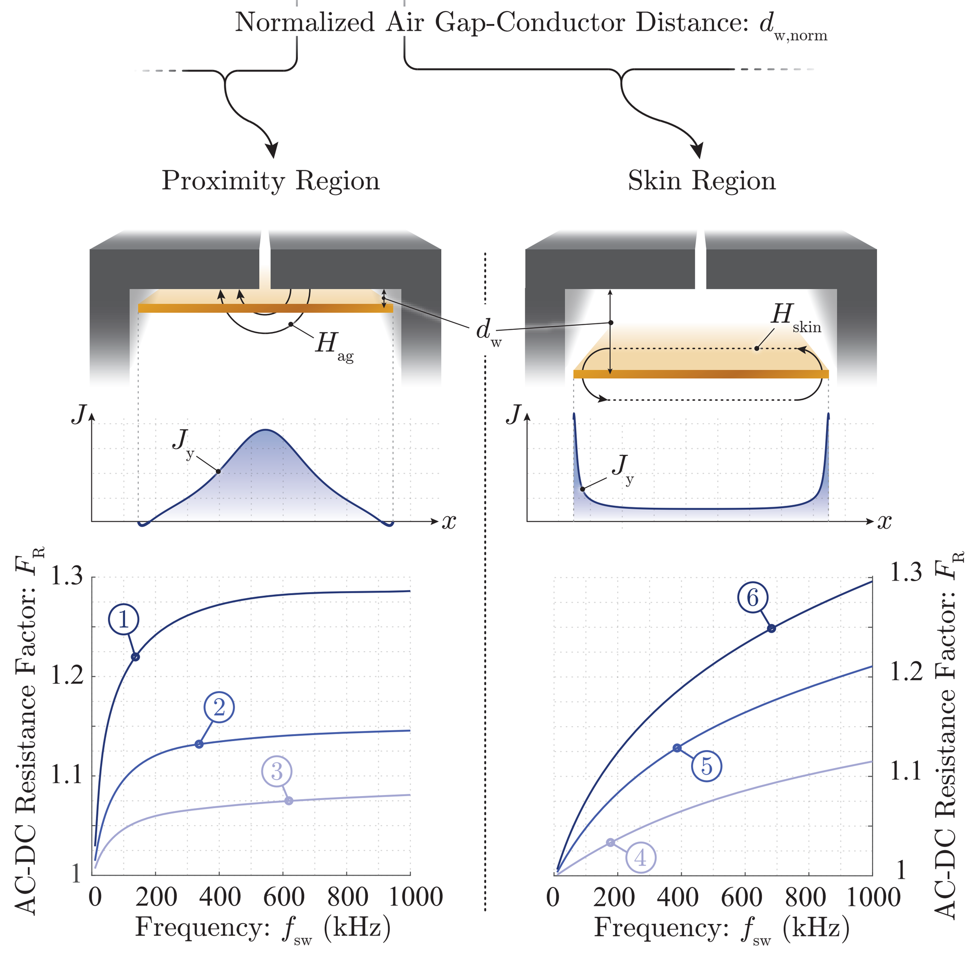
▲ Straight conductor with single air gap orthogonal to the conductor surface

- Design guideline for optimal air gap to conductor distance d_w based on simplified field calculations:

$$\frac{\partial}{\partial d_w} F_R(d_w) \overset{!}{=} 0 \longrightarrow d_{w,opt} = \frac{b_w}{2} \qquad (1)$$

▼ F_R values for different normalized distances $d_{w,norm} = \frac{d_w}{b_w}$ and different frequencies f_{sw}



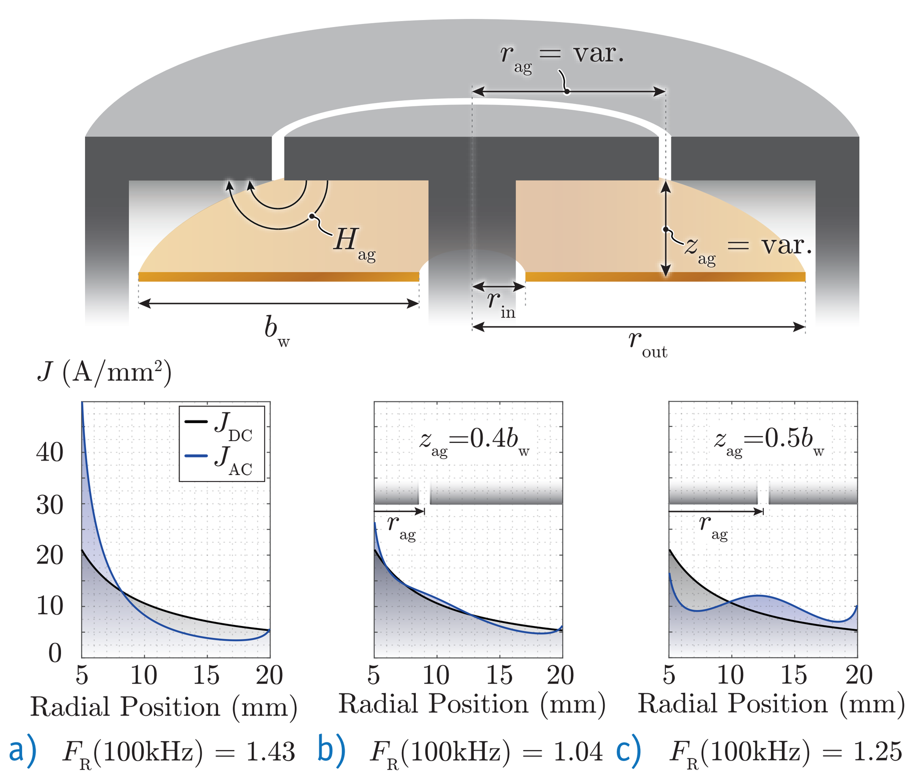


▲ F_R values in the region with dominating proximity effect

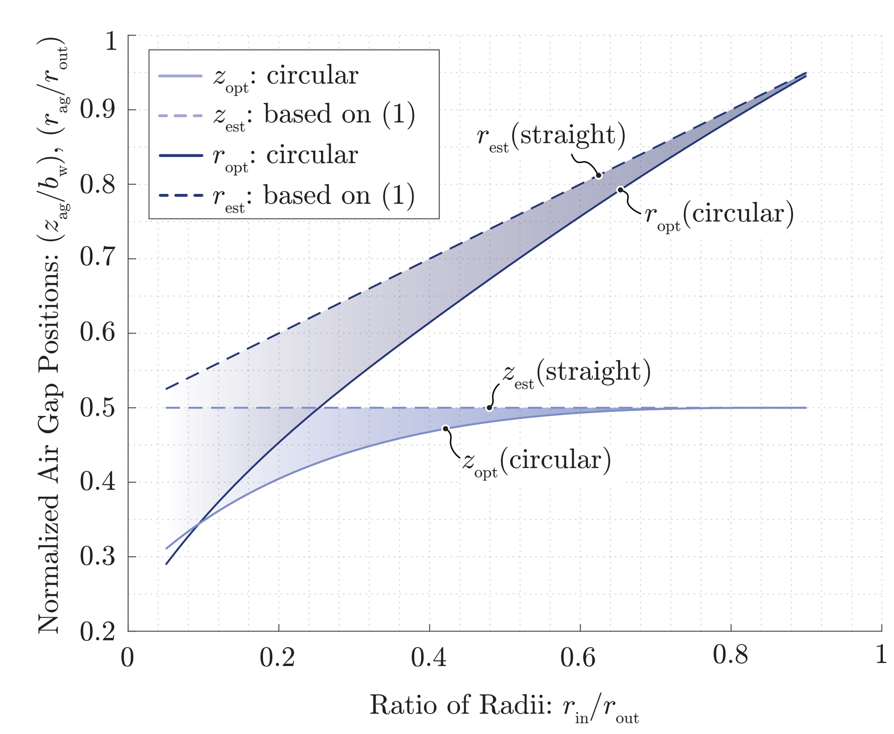
▲ F_R values in the region with dominating skin effect

IV. CIRCULAR CONDUCTOR

- The DC current density J_{DC} in a circular conductor is not homogeneous as in a straight conductor ⟶ Find optimal air gap position (z_{ag},r_{ag}), where J_{AC} matches J_{DC}



▲ Currend densities in a circular conductor with r_{in} = 5mm and r_{out} = 20mm for a) without an air gap, b) an air gap placed in the optimal position and c) an air gap positioned as in a straight conductor

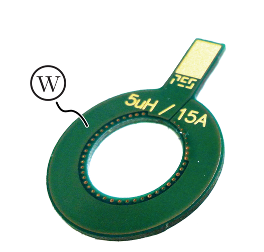


▲ Optimal air gap positions for a circular PCB winding and different ratios of radii r_{in}/r_{out}

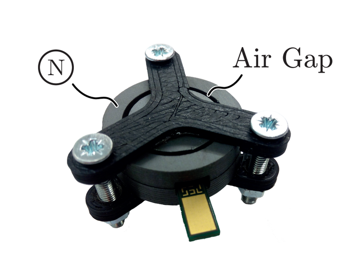
V. EXPERIMENTAL RESULTS

- Practical implementation of the design concept

Specifications: N_{layer} = 6, I_{sat} = 30A, L_{nom} = 5μH

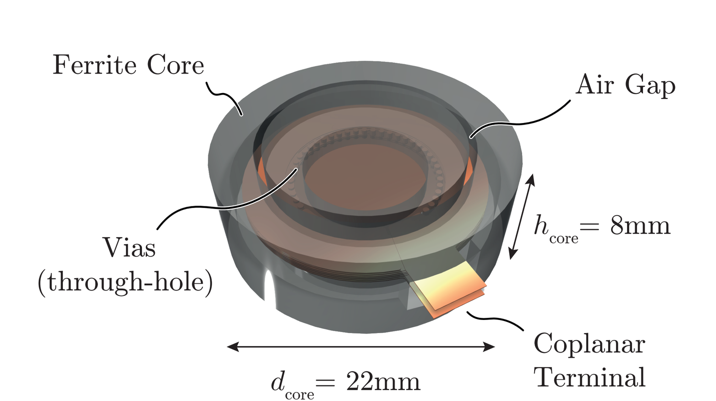


▲ PCB winding only (L = 500nH)

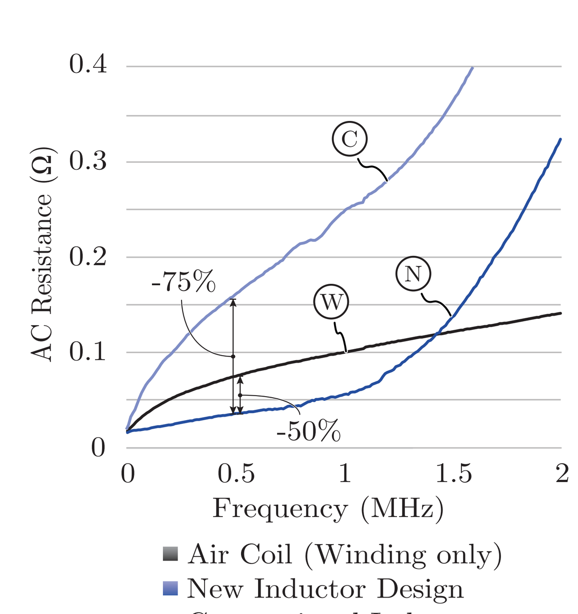


▲ PCB inductor using new design approach (L = 5μH)

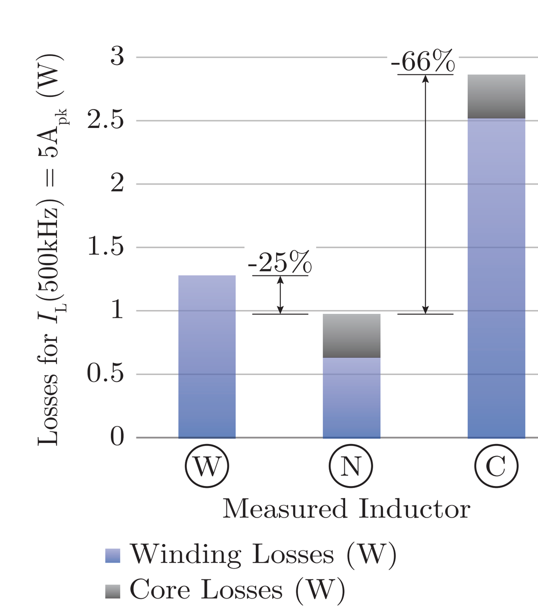
▲ Conventional PCB inductor (L = 5μH)



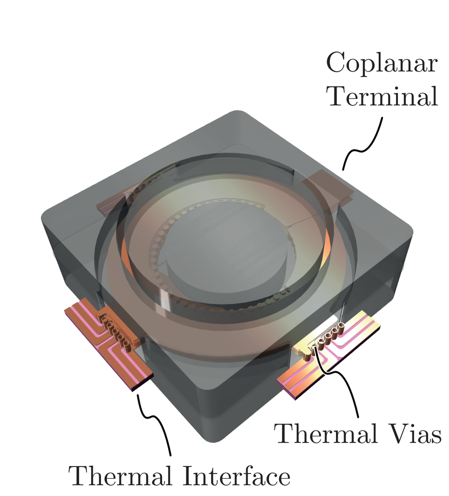
▲ Practical implementation of the proposed inductor design concept



▲ Measured AC resistance values using an impedance analyzer



▲ Calorimetric measurements of the total inductor losses



▲ Thermally enhanced PCB inductor design