Robert Bosch Center for Power Electronics
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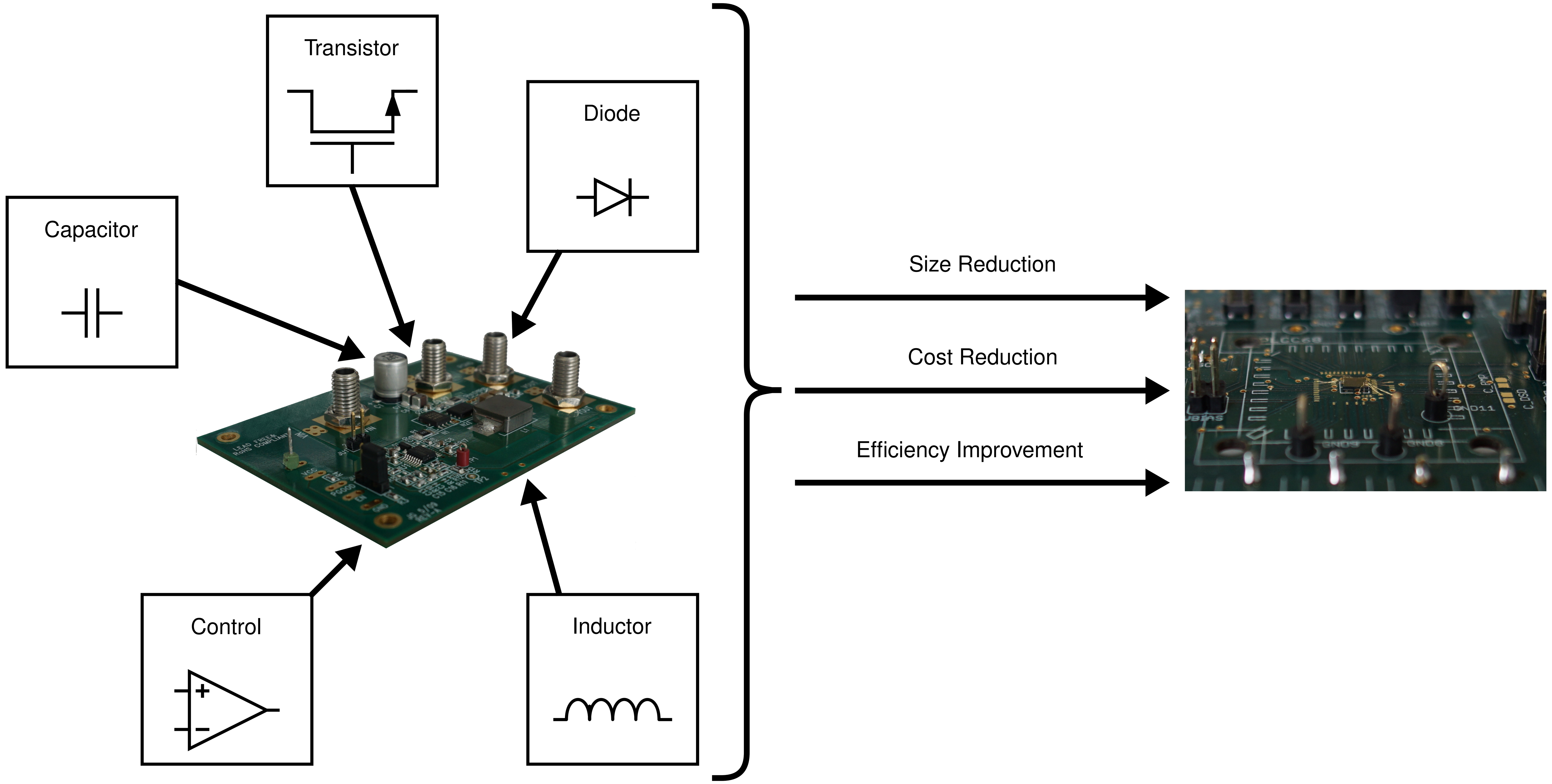
Loss Reduction in Air-Cored Inductors Used in Multi-MHz Power Converters

Christoph Rindfleisch, Bernhard Wicht

Motivation

Goal: Optimization of Size, Cost and Efficiency



Optimization Approach

State of the Art

- Use of air-cored inductors instead of inductors with magnetic core material to reduce losses and material cost
- Increase of the switching frequency to reduce the inductor size

Improvement Presented in this Study

Optimized use of air-cored inductors by investigating the loss behaviour at switching frequencies close to and beyond the cut-off frequency of the inductor, allowing:

- ... the reduction of inductor AC losses
- ... the reduction of the inductor size
- ... cost reduction due to savings in material

Realization possibilities:

a) Optimization of the transfer function of the inductor for a given converter setup
b) Optimization of the converter parameters for a given inductor

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Calculation Approach

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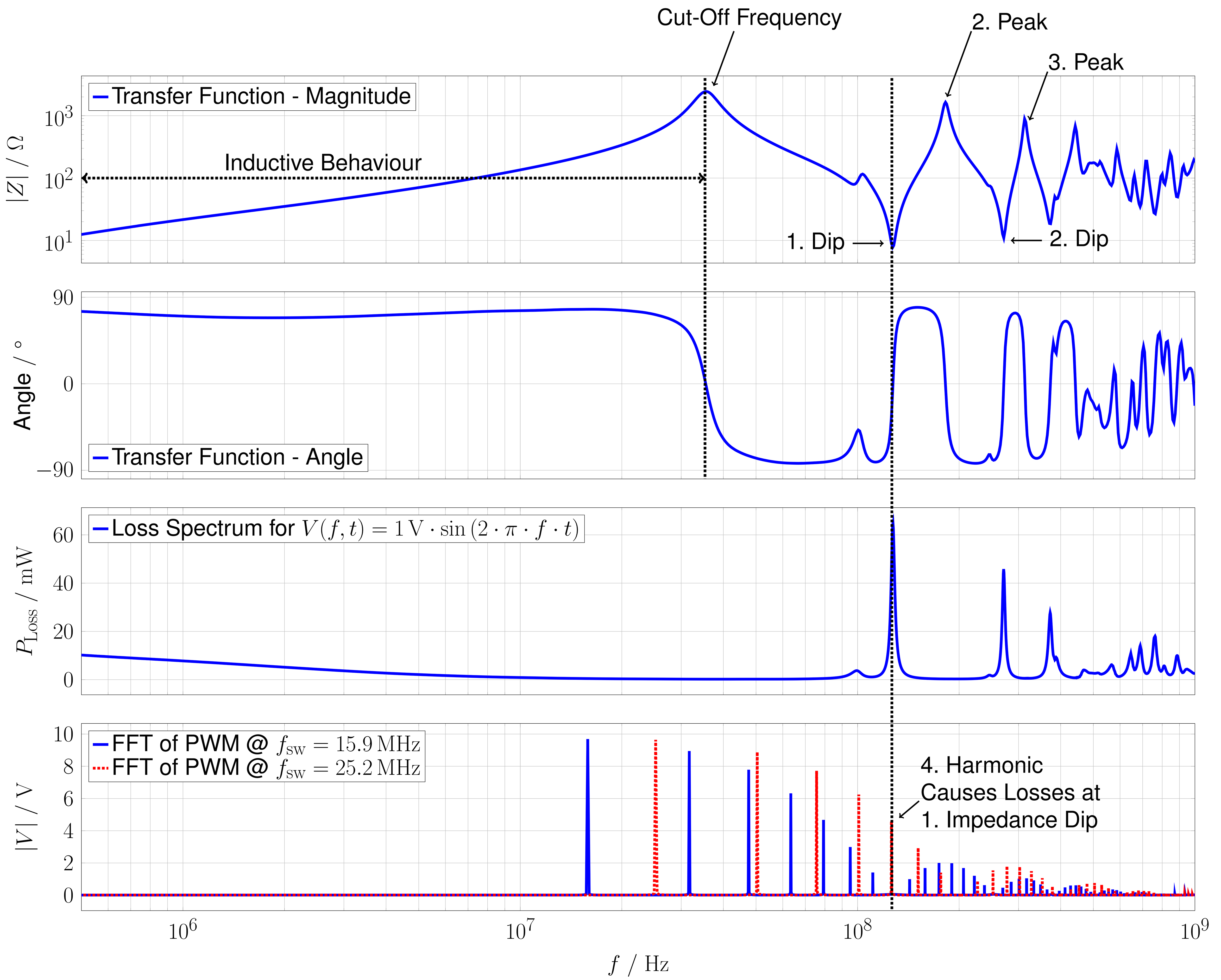
Results

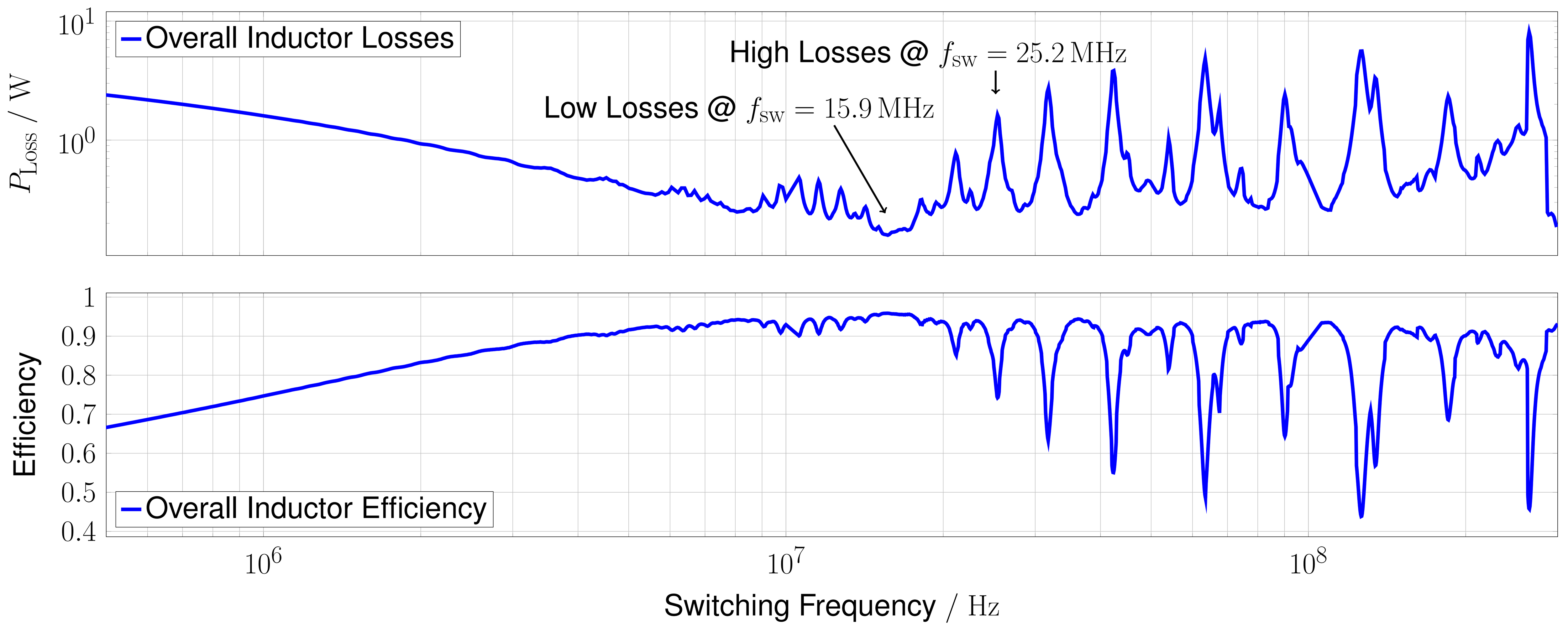
Transfer Function and Loss Behaviour of an Inductor



Characteristics

- Inductor losses depend on the inductor voltage (V) and the frequency dependent impedance of the inductor ($Z(f) = R(f) + iX(f)$): $P_{\mathrm{Loss}}(f) = V(f)^2 \frac{R(f)}{R(f)^2+X(f)^2}$
- At high frequencies, inductor losses behave inversely proportional to the square of the inductor impedance
- Low losses are achieved at impedance peaks (e.g. the cut-off frequency)
- High losses occur at low frequencies and at impedance dips
- For PWM voltages, the sum of the losses caused by the fundamental frequency and each harmonic determines the overall AC losses of an inductor
- Due to the harmonics of the switching frequency, loss peaks already occur at switching frequencies ten times below the cut-off frequency of the inductor
- Finding the switching frequency with the lowest losses is possible by calculating and summing up the losses of the fundamental frequency and each harmonic for all switching frequencies of interest (realized by the presented calculation approach and depicted for an example inductor in the graph below)

Switching Frequency Dependent Loss Behaviour of an Inductor



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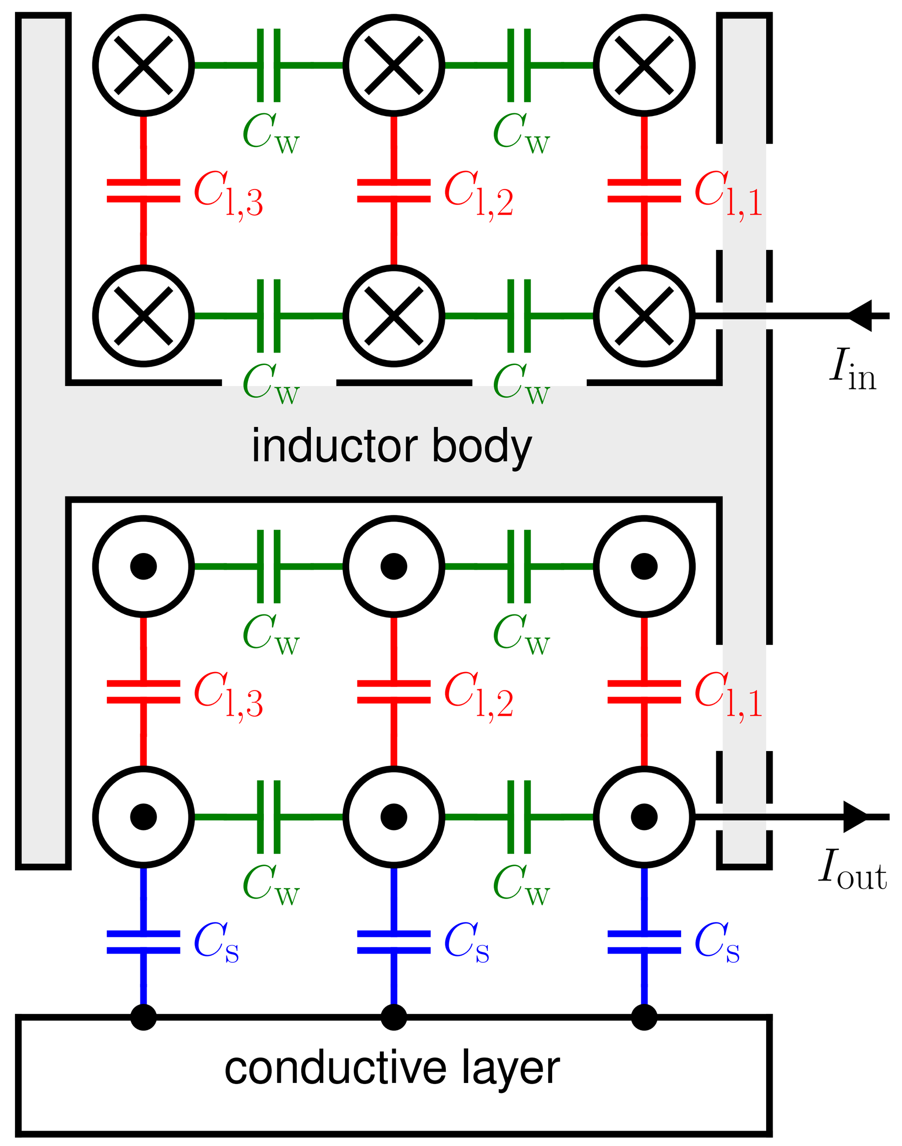
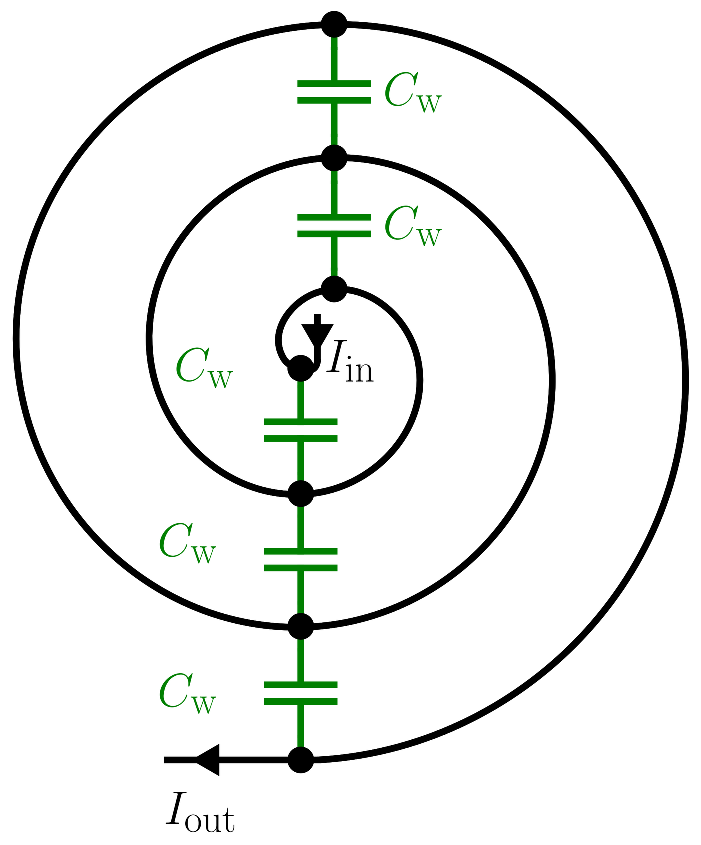
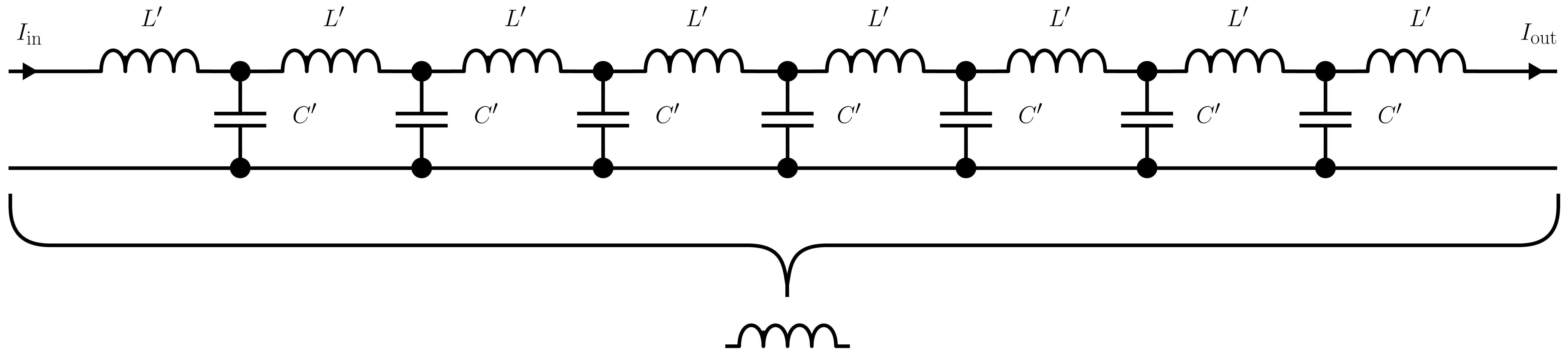
Optimization Potential - Parasitic Effects

Cross Section of Different Solenoids

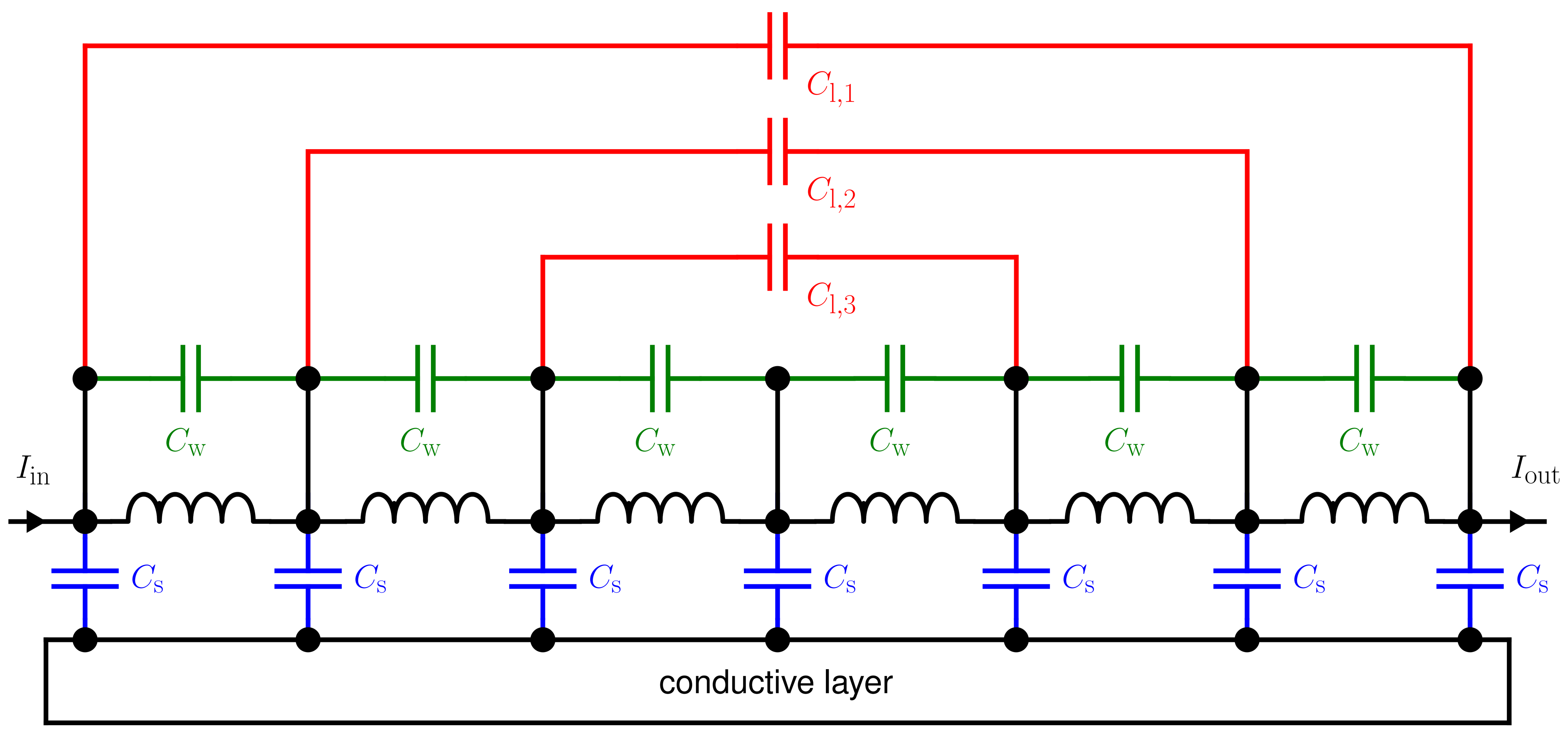




Equivalent Circuit - Transmission-Line Model



Equivalent Circuit - Parasitic Caps



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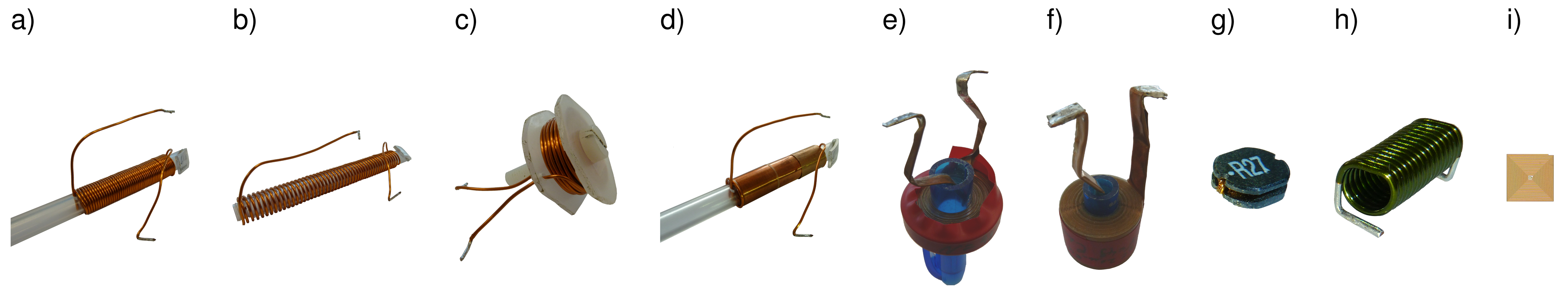
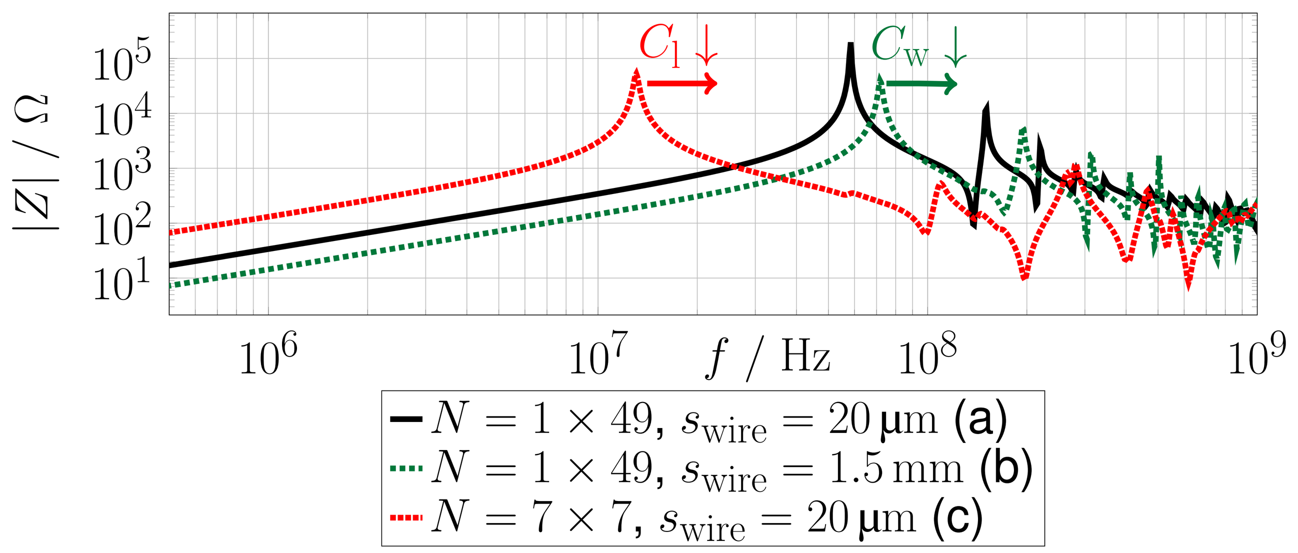
Optimization Potential - Influence of Parasitic Elements

Investigated Inductors



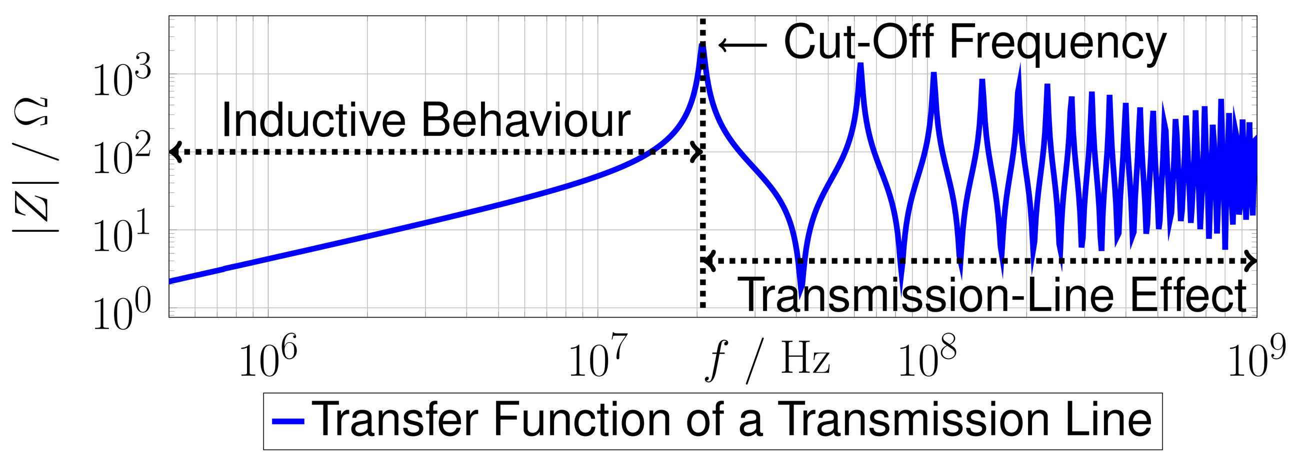
Influence of Parasitic Caps Between Windings and Layers of Solenoids

- C_w and C_l short circuiting the inductance, resulting in an additional cut-off frequency superimposed to the transmission-line effect
- A higher distance between windings results in a smaller C_w and thus in a higher cut-off frequency
- C_l can be reduced by reducing the number of layers, which, however, reduces the inductance
- C_l shows a much higher optimization potential than C_w, since e.g. $C_{\mathrm{l},1}$ shortens the whole inductor and each C_w just a part of it



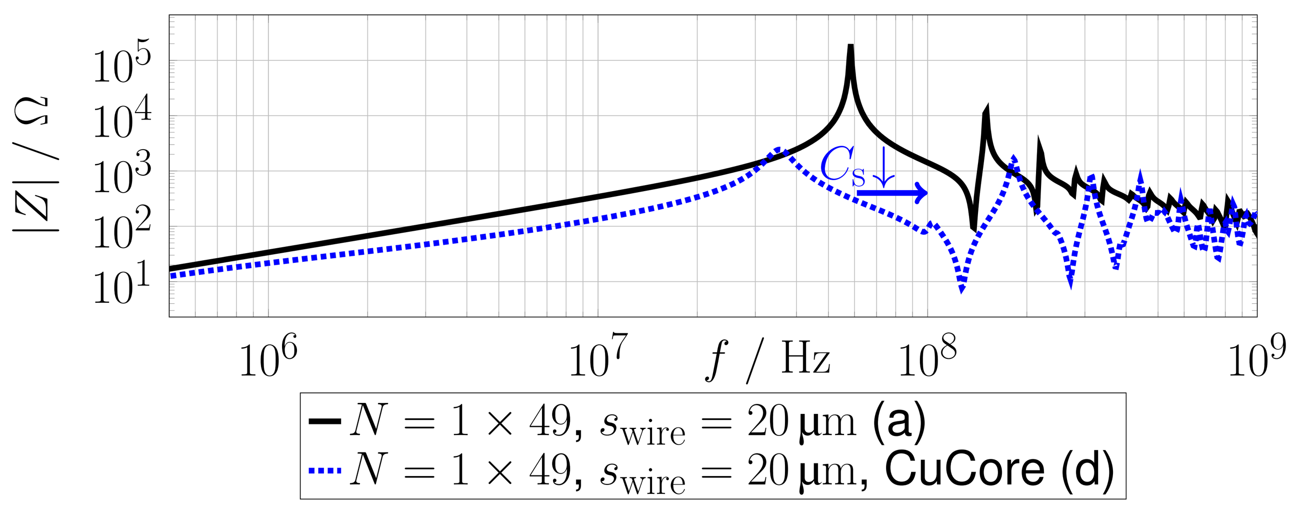
Characteristics of the Transmission-Line Effect

- Dominates in air-cored inductors with small discrete parasitic caps
- Transforms the output impedance (buck converter: C_out = short @ high frequencies) periodically in a short or an open at the input
- Influenced by the wire length (l_wire) and the equally distributed capacitance (C') and inductance (L')
- Estimation of cut-off frequency with: $f_\mathrm{cut,TL} \approx \frac{v_0}{4 \cdot l_\mathrm{wire}} = \frac{1}{4 \cdot l_\mathrm{wire} \cdot \sqrt{L' \cdot C'}}$



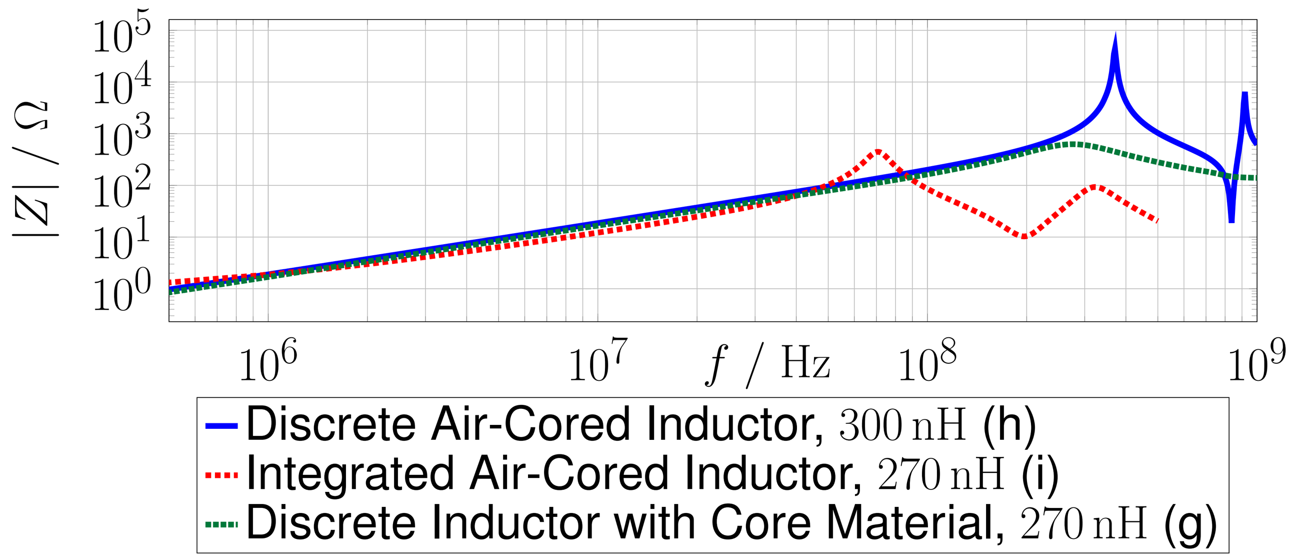
Influence of Parasitic Caps Between Windings and Conducting Layers

- C_s capacitively connects the windings of an inductor to a conducting layer, and thus shortens the inductance across this conducting layer
- The larger the distance between the conducting layer and the windings, the smaller C_s and the higher the cut-off frequency
- C_s can be caused by e.g. PCB metal layers, on-chip metal layers, the substrate of a chip or a shield



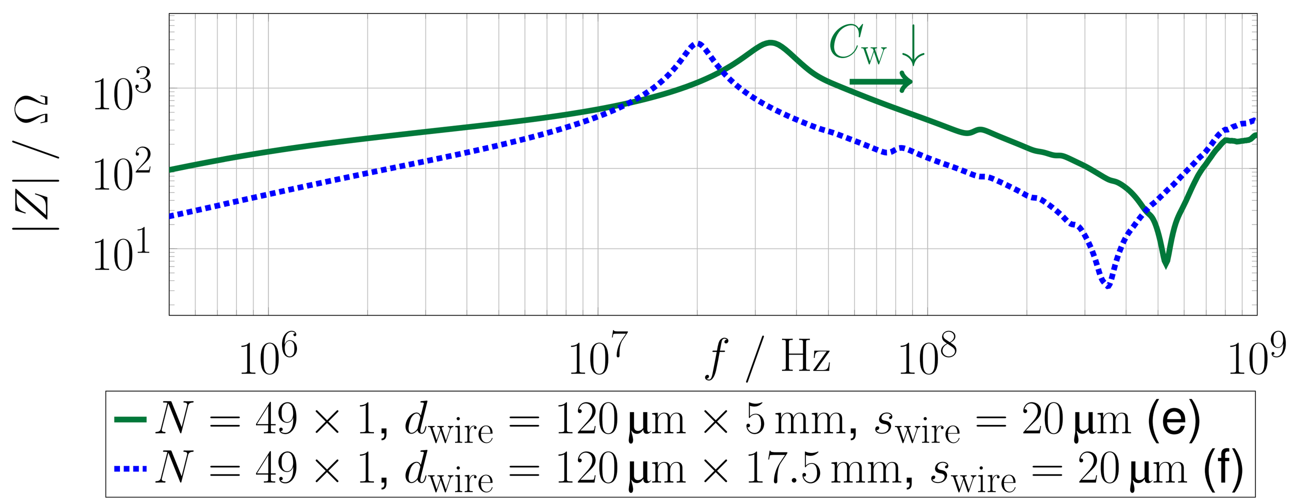
Benefit - Transfer Function of Three Inductors with the Same Inductance but Different Shapes

- Without optimizing the switching frequency, large and expensive discrete inductors must be used for switching frequencies beyond $10\,\mathrm{MHz}$
- Calculation of switching frequency dependent losses allows power efficient usage of small and cheap integrated inductors beyond switching frequencies of $10\,\mathrm{MHz}$



Influence of Parasitic Caps Between Windings of Foil Air-Cored Inductors

- Due to the large conductor surface between adjacent windings, C_w is much higher compared to solenoids
- The narrower the foil, the smaller the conductor surface and thus C_w, resulting in a higher cut-off frequency
- Similar structure to recently published promising approaches for integrated power inductors



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