Minimum Loss Operation of High Frequency Inductors

Presentation
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Motivation / Scientific contribution
System-level approach

**Specs:**
- DC/DC
- $V_{in} = 400V$
- $V_{out} = 200V$
- $P = 2kW$
- EMI Class B

**Topology**

**System DOF**
- Switch. Freq $f_{sw}$
- Current ripple $r$
- In capacit. $C_{in}$
- Out capacit. $C_{out}$
- Filter Induct $L$
- etc

**Component DOF**
- IGBT, MOSFET
- Chip area
- E-core, ETD-core
- Ferrite, Iron
- Round, Litz
- etc

**ETH Zürich**
Motivation / Scientific contribution
System-level approach

- **Choosing the remaining DOF**
  - System DOF
  - Component DOF

- **Component level difficulties**
  - Design/Performance space diversity
  - Complex interactions between components
  - Large number of design variables

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*Multi-objective Optimization*

[Diagram of DC/DC Buck converter]

- **DC/DC Buck converter**

*Graphs showing Design Space and Performance Space with Pareto Frontier*

- **Pareto Frontier**
Motivation / Scientific contribution
State-of-the-art characterization of magnetic components

- Performance factor: \( PF = B_{pk}f \)
- Performance factor incl. winding losses: \( PF_w = B_{pk}f^w \)
- Performance factor incl. dc bias: \( PF_{dc} = \sqrt{fB_{ac}B_{dc}} \)

What is missing?
- Effect of **fringing field** on the copper losses (air-gap)
- **Temperature** sensitivities (core & coil)
- **DC-bias** effect on the core losses
- Winding turns’ packing

Optimal operating condition of filter inductor?

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Motivation / Scientific contribution
Component-level approach

- DC/DC Buck converter

Specifications:
- \( V_{\text{in}} = 400 \text{ V} \)
- \( V_{\text{out}} = 200 \text{ V} \)
- \( d = 50 \% \)
- \( P = 2 \text{ kW} \)

- Power Inductor losses investigation
- Concept can be extended to more complex topologies

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Motivation / Scientific contribution

Component-level approach

- **Design space** (System DOF)
  - Switching frequency ($f$)
  - Current ripple ($r$)

- **Elimination of further influences by considering:**
  - Constant magnetic core: E55/28/21 – Ferrite N87
  - Constant type of coil: Litz wire – 100μm
  - Sinusoidal HF excitation + DC bias
  - Constant power, i.e., constant power density
Motivation / Scientific contribution
Component-level approach

- Different models employed
  - Simplified analytic model
  - Employment of an Electromagnetic – Thermal (EMT) coupled model

- Investigation of the following matters:
  - Optimal switching frequency
  - Reasonable range of operation
  - Important influencing parameters

In other words:
Provided a core, what are the best operating conditions of the component?
Brief Outline

- Scaling laws / simplified evaluation
- Electromagnetic-thermal coupled model (EMT)
- Analysis of identified losses
- Experimental verification
- Identified bottleneck & extension to advanced HF materials
- Practical design guidelines
Investigation based on analytic models

- **Core losses**
  (General Steinmetz Equation)
  \[ P_{\text{core}} = \text{Vol} \times k \times f_{\text{sine}} \times B_{\text{ac}}^\beta \]

- **Coil losses**
  (dc + skin/proximity effect ac losses)
  \[ P_{\text{coil}} = R_{\text{dc}} \times i_{\text{dc}}^2 + R_{\text{dc}}(F_R i_{\text{ac,pk}}^2 + N_{\text{str}}^2 G_R H_{s,rms,pk}^2) \]

- **Simplified H-field calculation**
- **Constant Steinmetz parameters**
- **Temperature dependency disregarded**

\[ f_{\text{sine}} = 50 \text{ kHz} \]

\[ f_{\text{sine}} = 500 \text{ kHz} \]

\[ P_{\text{tot}} - P_{\text{coil}} - P_{\text{core}} \]

Optimum ripple (i.e., \( L_{\text{opt}} \)) @\( N_{\text{opt}} \approx N_{\text{sat}} \)
Investigation based on analytic models

- With increasing $f \uparrow \rightarrow i_{\text{opt}} \downarrow$
- With increasing $f \uparrow \rightarrow P_{\text{tot}} \downarrow$
- From analytical calculations:
  \[ L_{\text{opt}} \propto f_{\text{sine}}^{\frac{\alpha-\beta}{2+\beta}} \]
  
  With increasing $f \uparrow \rightarrow \alpha \uparrow$
**ElectroMagnetic – Thermal (EMT) Model**

- Implemented in MATLAB

**Core losses calculation:**
  - General Steinmetz Equation – GSE
  - Premeasured/Tabulated Steinmetz coefficients considering the effects of $B_{ac}$, $B_{dc}$, $f$, $T$

**Winding losses calculation:**
  - Ferreira – Bessel functions
  - H-field estimation using the mirroring method

**Reluctance model**
  - Accurate airgap and flux DC-bias definition
  - 3D airgap reluctance calculation

**Detailed thermal model**

- EMT coupling iteratively until temperature convergence
Analysis of identified losses

Analytic approach

- **Specifications**
  - \( V_{\text{in}} = 400 \text{ V} \)
  - \( V_{\text{out}} = 200 \text{ V} \)
  - \( d = 50 \% \)
  - \( P = 2 \text{ kW} \)

- **Semi-numeric approach using EMT model**
  - Considered ripple and frequency ranges:
    - Switching frequency \((f)\): \(50\text{kHz} \ldots 1\text{MHz}\)
    - Current ripple pk-pk \((r)\): \(2\% \ldots 200\%\)

\[ r = \frac{I_{\text{AC},\text{pk-pk}}}{I_{\text{dc}}} \]

\( r \) Current ripple definition

- For each \( r - f \) pair \( L \) is defined from:
  \[
  L(f, r) = \frac{1}{fr} \frac{(1 - D)DU_{\text{in}}}{I_{\text{dc}}}
  \]

- Remaining DOF the **number of turns** \((N)\)
- Local optimization wrt \( N \)

\( U_{\text{in}} = 400 \text{ V} \)
\( V_{\text{out}} = 200 \text{ V} \)
\( d = 50 \% \)
\( P = 2 \text{ kW} \)
Analysis of identified losses

Analytic approach

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  - $V_{in} = 400$ V
  - $V_{out} = 200$ V
  - $d = 50\%$
  - $P = 2$ kW

- **Semi-numeric approach using EMT model**
  - Considered ripple and frequency ranges:
    - Switching frequency ($f$): $50$ kHz ... $1$ MHz
    - Current ripple pk-pk ($r$): $2\%$ ... $200\%$
  
  \[ r = \frac{I_{AC,pk-pk}}{I_{dc}} \]
  
  ▲ Current ripple definition

- **Current ripple definition**
  - $r : 85\%$
  - $f : 80$ kHz
  
  ▲ Current ripple definition

- $r : 8\%$
  - $f : 500$ kHz
Analysis of identified losses
Local optimization of individual operating points (E55/28/21, N87 – $d_{\text{strand}} = 100\mu m$)

$r : 85 \, \%$, $f : 80 \, \text{kHz}$
$L = 147\mu H$

$r : 8 \, \%$, $f : 500 \, \text{kHz}$
$L = 250\mu H$
Analysis of identified losses
Local optimization of individual operating points (E55/28/21, N87 – $d_{\text{strand}} = 100\mu\text{m}$)

$r : 85 \% , f : 80 \text{ kHz}$
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Analysis of identified losses

Local optimization of individual operating points (E55/28/21, N87 – $d_{\text{strand}} = 100\mu$m)

\[ r : 85\% , \; f : 80\; \text{kHz} \]

\[ L = 147\mu\text{H} \]

\[ r : 8\% , \; f : 500\; \text{kHz} \]

\[ L = 250\mu\text{H} \]

\[ P_{\text{tot}} (N) \approx P_{\text{coil}, 25} \left( \frac{N}{25} \right)^2 + P_{\text{core}, 25} \left( \frac{N}{25} \right)^{-\beta} , \text{ where } P_{\text{coil}, 25} \approx P_{\text{core}, 25} \approx \frac{P_{\text{tot}, 25}}{2} \]
Analysis of identified losses
Complete f-r domain investigation (E55/28/21, N87 – d_{strand} = 100\mu m)

- **Regions identified:**
  1. Optimal design region
  2. Thermally valid – suboptimal designs
  3. Exceedingly high HF losses
  4. Exceedingly high LF losses

- **$P_2 \approx 30\% P_1$**

- **Trajectories of interest:**
  1. $r_a$: optimal $r, f$ pairs
     \[ r_a(f) \approx \frac{1}{f \left(\frac{50\text{kHz}}{f}\right)} \]
     
     *Constant Inductance*

  2. $r_b$: constant frequency, ripple sensitivity
Analysis of identified losses
Optimal trajectory $r_a$

- **Constant $L$**
- **Flat behavior for** $f \in [300, 750]$ kHz
- **Basic scaling laws**
  \[ P_{\text{core}} \propto f^{\alpha - \beta} \]
  \[ P_{\text{coil, HF}} \propto R_{dc} G_R H_{P_k, HF}^2 \left[ f^{-2} \right] \propto 1 \]
  With $f \uparrow \Rightarrow \begin{cases} N \downarrow, & \text{if } \alpha < \beta \\ N \uparrow, & \text{if } \alpha \geq \beta \end{cases}$ such that:
  \[ P_{\text{core}} \approx P_{\text{coil}} \]
- **Global opt** @ $f = 500$ kHz, where $\alpha \approx \beta$
- **Summary regarding opt. designs:**
  - Balanced copper/core losses
  - $B_{pk}$ close to $B_{\text{sat}}$
Analysis of identified losses

\( f = 500 \text{ kHz trajectory } r_b \)

- **3 distinct Regions**
  - **Region 1 \( (r < 8\%) \)**
    - High \( L \rightarrow \) High \( N \rightarrow \) High \( J \)
    - \( B_{p,k} \) limited by \( B_{\text{sat}} \)
    - High DC copper losses
  - **Region 3 \( (20\% \geq r) \)**
    - Increasing AC losses
  - **Region 2 \( (8\% \leq r < 20\%) \)**
    - Flat behavior!
    - Further details → P. Papamanolis, APEC 2018
Experimental verification
Measurement setup

Operating principle
► Step 1: DUT disabled
  @ steady state (i.e. \( T_{\text{in,amb}} = T_{\text{set}} \)). \[ P_{\text{heater}} = P_0 \]
► Step 2: DUT enabled. Controller adapts
  \[ P_{\text{heater}} = P_1 \] to preserve constant \( T_{\text{in}} \).
► \( P_{\text{DUT}} = P_0 - P_1 \)

Properties of measurement method
+ No calibration required
+ High accuracy at low loss measurements
+ Measurement at desired “ambient” temperature
- Large time constants because of the DUT
- Increased complexity

Calorimetric meas. setup [Kleeb 2013]

Simplified schematic

Measurement example
Experimental verification

DUT considered

- Single inductor design
  - Core: E55/28/21
  - Litz wire – 900x100µm
  - L = 167 µH
  - N = 16 (2 layers x 8 turns)
  - Total air-gap: 800µm (400µm per leg)
  - Resonance freq @ 2.5 MHz

- Compromise between optimal designs for $f_c$[200kHz, 750kHz]
**Experimental verification**

**Measurements**

- **Same trend**
- **Underestimation** observed, up to 0.5 Watts (error below 25%), reasons:
  - Core-loss data interpolation for $f > 270$ kHz
  - Conductor close to air-gap → intense fringing field losses

According to prev. **scaling laws** for $N = \text{const.}$

- $P_{\text{core}} \propto f^{\alpha - \beta}$
- $P_{\text{coil,HF}} \propto R_{dc}G_{R_{p}k_{HF}}H_{2}^{2} \propto f^{-2}$

**Minimum @ $\alpha \approx \beta$**

- $\Delta$ Model evaluation VS Measurement
Extension to further materials

Measurements

- Main limitation is where $\alpha = \beta$ (This corresponds to the peak of the PF)

  $$GSE: \ p = k \ f^\alpha B^\beta \Rightarrow B = \left(\frac{p}{k}\right)^\beta f^{-\frac{\alpha}{\beta}}, \quad PF = Bf = \left(\frac{p}{k}\right)^\beta f^{\frac{\beta-\alpha}{\beta}} = \text{const.} \ f^{\frac{\beta-\alpha}{\beta}}$$

- Using existing performance factor data, together with the proposed guideline, allows for estimation of the optimal operating points $(r_{opt}, f_{opt})$.

  - Data from TDK-EPCOS
  - $T = 100 \, ^\circ C$
  - $P_L = 300 \, \text{kW/m}^3$

- Need of materials with better PF $\rightarrow$ Typically achieved at higher frequencies $\rightarrow$
  At these frequencies GaN semiconductors achieve great performance

- Existing electrical methods limited, due to parasitics, intensive calibration and post-process requirements and need for expensive equipment
Acquirement of new data using newly proposed transient calorimetric method from PES ETH-Zurich (presented at APEC 20’ – New Orleans)

Accurate measurement within some tens of seconds

Knowledge of the cores thermal capacitance required, since:

\[ P_{\text{core}} = C_{\text{th,core}} \frac{dT_{\text{meas}}}{dt} \]

Proposed methods:
- Differential Scanning Calorimetry (DSC)
- DC current injection through core block
Extension to further materials

Measurements

► Concept verification through coupled Magnetic and Heat transfer FEM simulations

► Further verification using high accuracy IR thermal imaging

▲ Flux density
▲ Loss density
▲ Temperature distribution
▲ Stored energy distribution

▲ $T_{\text{core}} = 30^\circ\text{C}$
▲ $T_{\text{core}} = 34^\circ\text{C}$
▲ $T_{\text{core}} = 36^\circ\text{C}$
Extension to further materials

Measurements

► Application on MnZn ferrite TDK-EPCOS N87/N49 – Comparison to electrical measurements

► Application on NiZn ferrite Fair-Rite 67 [5 – 50 MHz]
Conclusions
Conclusion (1) / Practical Guidelines

- Provided **magnetic core** → $f_{\text{opt}}$ exists @ $\alpha \approx \beta$
  $f > f_{\text{opt}}$ → Increases losses

- Provided $f_{\text{opt}}$, choose $N_{\text{opt}}$ and $r_{\text{opt}}$ such that:
  - Balanced copper/core losses
  - $B_{\text{pk}}$ close to $B_{\text{sat}}$

- **Minimum losses** correspond to approx. constant $L_{\text{opt}}$

  $$L_{\text{opt}} = \frac{1}{f_{\text{opt}} r_{\text{opt}}} \frac{(1 - D)D U_{\text{in}}}{I_{dc}}$$

- For any frequency the **optimal current ripple** equals:

  $$r_{\text{subopt}}(f) = \frac{1}{f L_{\text{opt}}} \frac{(1 - D)D U_{\text{in}}}{I_{dc}}$$
Conclusion (2) / Observations and Future steps

Useful Observations

- 3 different flat-optima regions of interest (N87 E55/28/21 – 100μm):
  - Provided f & r with respect to N. e.g. \( N \in [19, 31] \) @ \( f = 80 \text{ kHz}, r = 85\% \)
  - Provided \( L \) with respect to \( f \). e.g. \( f \in [300 \text{ kHz}, 750 \text{ kHz}] \) @ \( L = 167 \mu\text{H} \)
  - Provided \( f \) with respect to \( r \). e.g. \( r \in [8\%, 20\%] \) @ \( f = 500 \text{ kHz} \)

Experimental Verification

- **Total losses** measurement using **steady-state calorimeter**
- Measurement of **core-losses** and **PF** evaluation using **transient calorimetric measurement**
  (Further details at APEC 2020 – New Orleans)

Useful Observations

- Total losses measurement using steady-state calorimeter
- Measurement of core-losses and PF evaluation using transient calorimetric measurement
  (Further details at APEC 2020 – New Orleans)
Discussion...
Analysis of identified losses

Further application

Different litz wire strand diameter
- 200μm: \(d_{\text{strand}} \uparrow \rightarrow F_R, G_R \uparrow \rightarrow P_{\text{Cu,ac}} \uparrow\)
- 71μm: \(d_{\text{strand}} \downarrow \rightarrow F_R, G_R \downarrow \rightarrow P_{\text{Cu,ac}} \downarrow\)
- \(P_{\text{Cu,dc}} \rightarrow \text{const. due to similar fill factor (}k\text{)}\)

Different core: E42/21/20
- Area of valid designs narrower
- Operation @\(f_{\text{low}}\) thermally invalid
Experimental verification

Measurement setup

- Calorimeter consists of 2 boxes
  - Inner enclosure (temp. sensors, heater, DUT)
  - Outer enclosure (reference chamber)
- Heater control unit (preserve temperature)
- DUT excitation circuit
- Operating principle
  - Step 1: DUT disabled
    @ steady state (i.e. $T_{in,amb} = T_{set}$). [$P_{heater} = P_0$]
  - Step 2: DUT enabled. Controller adapts
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  - $P_{DUT} = P_0 - P_1$

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