Accurate Estimation of Losses of Power Inductor in Power Electronics Applications

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Introduction

- Applications of Power Inductor in Power Electronics & the necessity to estimate losses accurately

**Storage Inductor**

![Storage Inductor Diagram](image)

**Coupled Inductor**

![Coupled Inductor Diagram](image)

**Filter Inductor**

![Filter Inductor Diagram](image)
Losses

- Loss in Magnetic components
  - Ohmic copper Loss
  - Winding loss due to AC & DC current
  - Core Loss – Hysteresis & Eddy current loss

- Hysteresis loss $\propto f \cdot (B_m)^\alpha$
- Eddy Current loss $\propto f^2 \cdot (B_m)^2$

Fig 4: Typical B-H Curve of a magnetic material with Sine-wave excitation
Estimation of Losses

- Copper Ohmic loss: $I_{rms}^2 \cdot R_{DC}$
- Winding Loss due to AC current – Skin effect, Proximity effect → Finite Element Analysis

- Hysteresis & Eddy Current Loss due to AC flux in the core
  - Steinmetz Equation(SE): $P_v = K_1 \cdot f^\alpha \cdot \Delta B^\beta$
  - Modified Steinmetz Equation(MSE): $P_v = K_1 \cdot f_{eq}^\alpha \cdot \Delta B^\beta f$
  - Separation of Eddy Current & Hysteresis loss
  - Core manufacturer models, etc.

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Estimation of Losses

Empirical Data & Test Setup:

![Figure 5: Typical Core Loss graph plotted against peak flux density at different frequencies](image)

![Figure 6: Classical Core loss measurement test set up](image)
Disadvantages

- Low accuracy with Pulsating and triangular waveforms
- Mostly applicable for 50% duty cycle
- Limitations over frequency range
- Dependent on Core Manufacturer’s empirical data
- Inaccuracy with Iron powder materials & Metal alloys
- Omission of AC losses in the winding
- No estimation of losses in the component which has more than one material
- Complexity of the set up to produce empirical data
Würth Elektronik AC loss Model

- **Description & Set up:**

  ![Diagram](image)

  Fig 7 & 8: Practical DC-DC converter set-up & resulting scope shots

- A pulsating input voltage is applied over the Inductor
- \((P_{\text{in}} - P_{\text{out}})\) is the power loss in the Inductor
- Divide losses of the Inductor in to AC & DC loss
Würth Elektronik AC loss Model

- DC Loss: Ohmic loss in copper
- AC Loss: Loss due to AC flux swing in the core & windings
- This process is repeated over wide range of parameters to produce our own empirical data

- This empirical data is then used to plot a AC loss graph & create an equation to calculate AC loss as shown in figure 10

\[ P_{AC} = f(V, F_{sw}, k1, k2, ...) \]

Fig 10: AC loss plotted against Switching frequency
Würth Elektronik AC loss Model

- **Point of Operation Approach**

Fig 11: Typical approach for extracting core loss data

Fig 12: Würth Elektronik’s Point of Operation approach
Experimental results

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Input - 12V
Switching Frequency - 500KHz
Topology - Buck
Output Current - 5A
Inductance - 3.3uH

Core/AC Loss (mW) vs Duty Cycle

Core/AC Loss (mW) vs Switching Frequency (KHz)
Experimental results

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- AC/Core Loss - Iron Powder Material
  - Input: 12V
  - Switching Frequency: 500KHz
  - Topology: Buck
  - Inductance: 3.3uH

- Core/AC Loss MnZn Material
  - Input: 12V
  - Output: 5V, 5A
  - Topology: Buck
  - Inductance: 3.3uH
Advantages & Disadvantages

Würth AC Loss Model

- multiple materials supported
  - i.e. NiZn, MnZn, iron powder, metal alloy, etc.

Steinmetz Models

- only single material,
  - mainly for NiZn, MnZn
  - Not applicable for iron powder & metal alloy
Advantages & Disadvantages

**Würth AC Loss Model**
- real core shapes
- losses due to air gap (fringing effects)
- winding structure
- Considers even small change in core material and winding structure

**Steinmetz Models**
- ring cores only
Advantages & Disadvantages

Advantages:
- Accurate calculation of losses for any given Duty Cycle
- Accurate over wide range of frequency
- Estimation of temperature rise
- Includes AC winding losses
- Constantly improving and adding the new data based on the customer feedback

Disadvantages:
- Cannot separate Core loss & AC winding losses
Implementation in **REDEXPERT**

www.we-online.com/redexpert
Future Work & Conclusion

- Model for Coupled Inductors
- Estimating loss of Inductors in Inverters (Averaged Sine wave)
- Verify the performance in DCM mode

Conclusion:
Application based extraction of empirical is way forward to estimate losses for efficient design(s).
Questions

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