Inductor loss model in system-level Power integrity analysis and optimization

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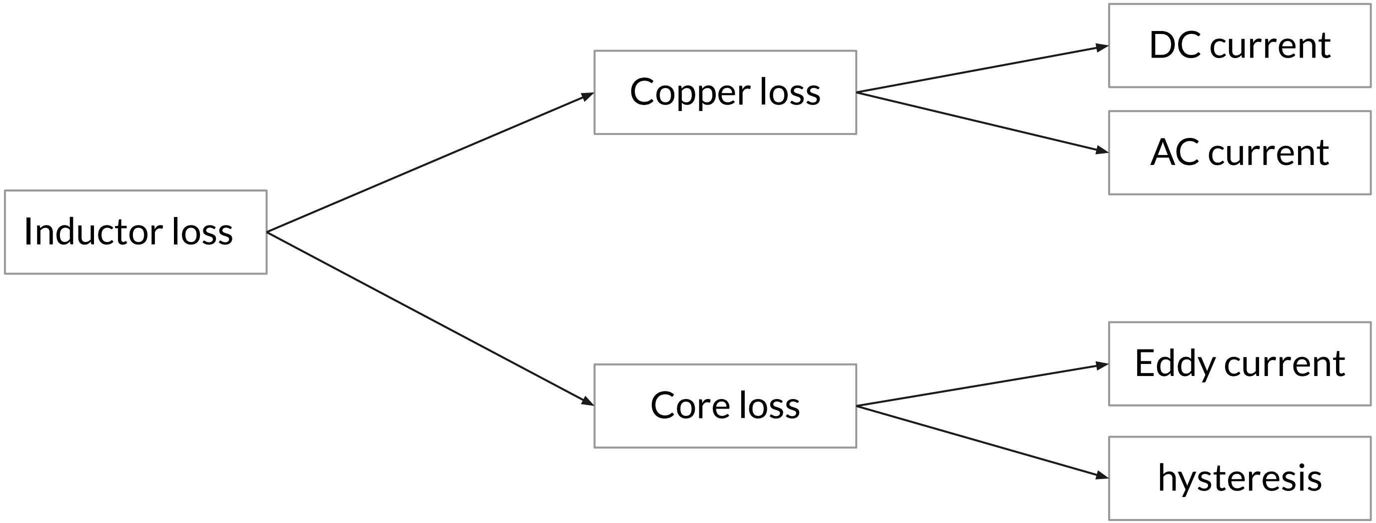
Inductor loss types



Steinmetz Equation for core loss [1]

Coefficients

$$P_{core} = kB_{max}^{\beta} f^{\alpha}$$

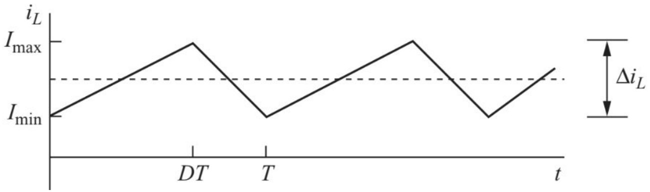
Peak flux density

Frequency

This Steinmetz equation is only valid for sinusoidal current.
Improved general form:

$$P_{core} = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} \Delta B^{\beta-\alpha} dt$$

Inductor core loss of DC-DC converter



$$\Delta B = \frac{\mu_0 N}{\sum_i \frac{l_i}{\mu_{ri}}} \Delta i_L$$

Number of turns

H field path segments

Relative permeability

Substituting this into generalized Steinmetz Equation gives:

$$P_{core} = K_1[D(1-D)]^{1-\alpha} \Delta i_L^{\beta} f^{\alpha}$$

- In practice, α is larger than 1, and β is larger than 2 (depending on material).
- D close to 0.5 is desired to reduce core loss.

Inductor core loss of DC-DC converter

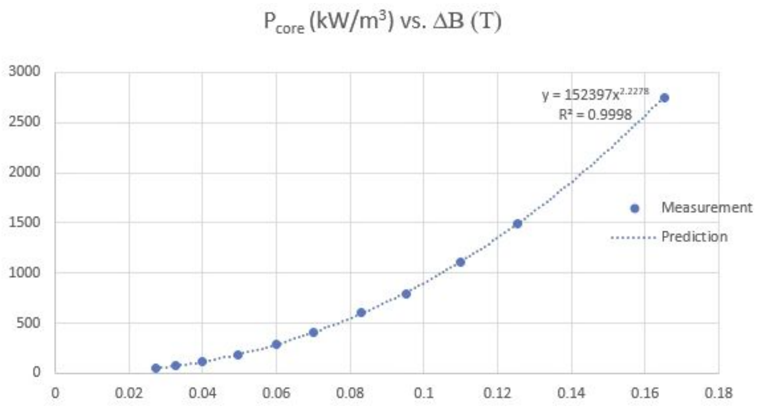
According to the ripple current calculation:

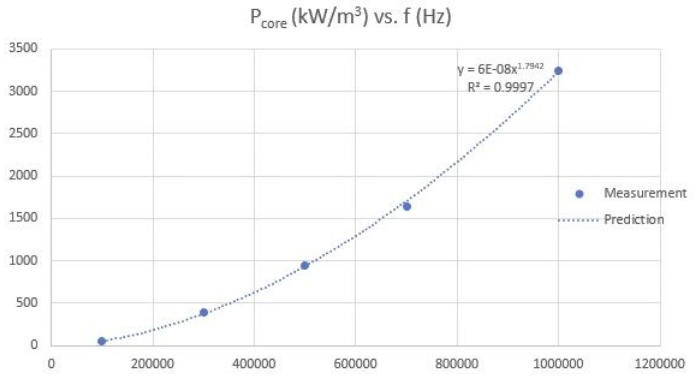
$$\Delta i_L = V_{in} \frac{D(1-D)}{fL}$$

Finally we have:

$$P_{core} = K_1 V_{in}^{\beta} L^{-\beta} [D(1-D)]^{\beta-\alpha+1} f^{\alpha-\beta}$$

Formula vs. Measurement





NP7: α = 1.7942, β = 2.2278, K_1 = 0.120

Inductor copper loss in AC [2]

- Skin effect:

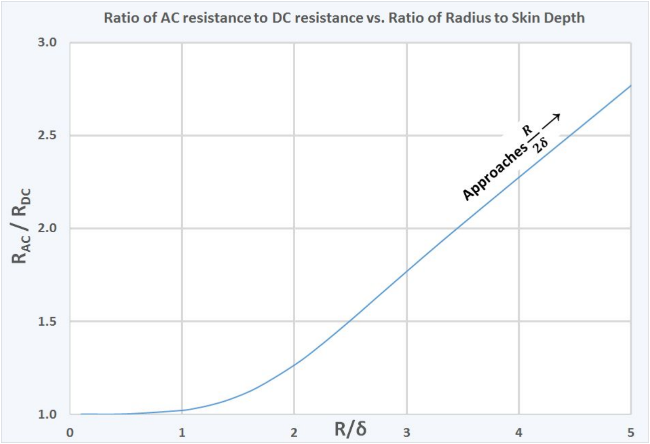
Skin depth: $$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

ρ: Resistivity

μ: Permeability

- AC resistance will be larger than DC resistance
    - Assuming round copper coil with R = 0.5mm, f = 500kHz:
        - δ = 0.0923mm
        - R_{ac}/R_{dc} = 2.6
    - $R_{ac}/R_{dc} \propto$ sqrt(f) for f close or larger than 500kHz.
- Proximity effect $R_{ac} \propto f^2$
- Summary: $R_{ac} = R_{dc}[k_2 \text{ sqrt}(f) + k_3 f^2]$. For the current waveform on slide 4: $P_{ac} = R_{ac}(\Delta i_L/12)^2$

R_{ac}/R_{dc} vs. R/δ [3]



Inductor copper loss in AC

- Summary: $R_{ac} = R_{dc}[k_2 \text{ sqrt}(f) + k_3 f^2]$. For the current waveform on slide 4: $P_{ac} = R_{ac} \Delta i_L^2 /12$
- Substituting:

$$\Delta i_L = V_{in} \frac{D(1-D)}{fL}$$

Finally we got

$$P_{ac} = R_{dc} V_{in}^2 L^{-2} [D(1-D)]^2 \left(K_2 f^{-1.5} + K_3\right)$$

Summary

The overall inductor loss can be expressed as:

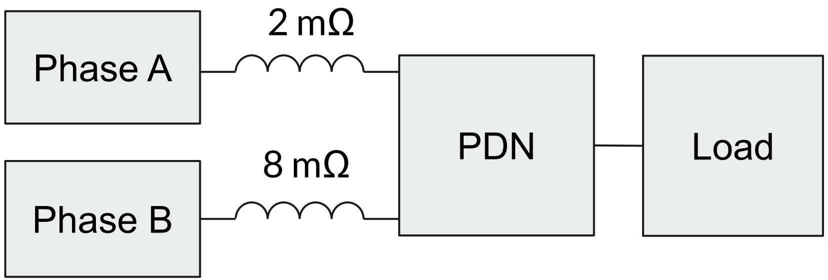
$$P_{ind} = P_{core} + P_{ac} + P_{dc}$$
$$= K_1(\bar{i}_L)V_{in}^{\beta}L^{-\beta}[D(1-D)]^{\beta-\alpha+1}f^{\alpha-\beta} + R_{dc}V_{in}^2L^{-2}[D(1-D)]^2\left(K_2f^{-1.5}+K_3\right) + R_{dc}\bar{i}_L^2$$

Note: K_1 is dependent on DC bias, and K_2, K_3 are not.

Conclusion:

- When switching frequency ↗️, Core loss ↘️, AC copper loss ↘️, VR loss↗️.
- In DC/IR drop simulation, inductor can be modeled as DCR + core loss equivalent R
- In system-level simulation, trade-off between VR loss and inductor core loss should be considered.
- Inductor vendor should be able to provide K_1, K_2, K_3, α and β.

Application Example



Due to geometry limitation, phase B inductor has much more core loss and DCR

Balanced I:

VRM Name	Output Nominal Voltage (V)	Actual Current (A)
VRM_VNNA	0.826104	23
VRM_VNNB	0.966691	23

41.23W

Unbalanced ratio 1.5:

VRM Name	Output Nominal Voltage (V)	Actual Current (A)
VRM_VNNA	0.83691	27.6
VRM_VNNB	0.927768	18.4

40.17W, ~2.6% power loss reduction

Reference

[1] J. Muhlethaler, J. Biela, J. W. Kolar and A. Ecklebe, "Core Losses Under the DC Bias Condition Based on Steinmetz Parameters," in IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 953-963, Feb. 2012, doi: 10.1109/TPEL.2011.2160971.

[2] Sudhoff, Scott D. Power magnetic devices: a multi-objective design approach. John Wiley & Sons, 2014.

[3] https://en.wikipedia.org/wiki/Skin_effect