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A SPICE Model of Inductors Considering Hysteresis Properties

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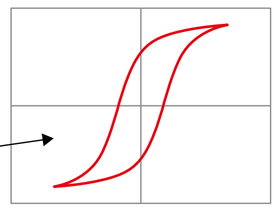
Motivation and Purpose

- Magnetic components in power circuits are one of the most important elements to achieve high efficiency.

Coil
- DC Loss
- Eddy Current Loss due to skin and proximity effects

Magnetic Material
- Eddy Current Loss
- **Hysteresis Loss**



Problems

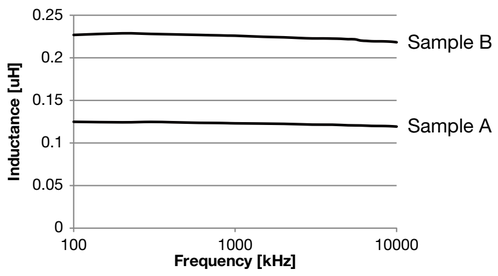
1. We cannot accurately compute the hysteresis loss.
2. We usually ignore the hysteresis property for design of power circuit.
3. A SPICE model for magnetic components considering the hysteresis loss has not been proposed.

- **We propose a novel method to synthesize an equivalent circuit of magnetic component considering the hysteresis loss from measured inductor loss.**

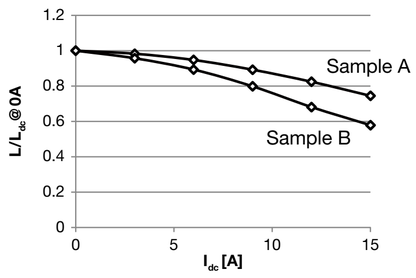
Inductor Benchmark

	Inductance (nH)	Dimension (mm)			RDC (mΩ)	Isat (A)
Sample A	100	2.5	2.0	1.2	5.0	14.0
Sample B	220	2.5	2.0	1.2	7.0	10.5

Inductance-*f* Characteristics



Inductance-Idc Characteristics



Mathematical Model (Sinusoidal Model without DC Bias)

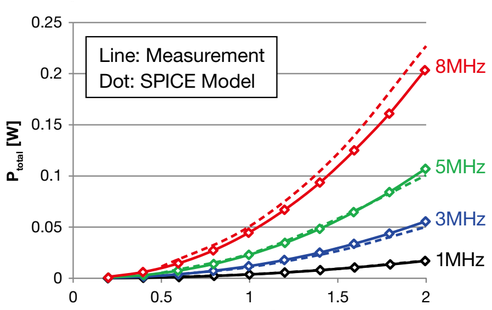
$$P_{total} = \underbrace{R_{dc} I_{dc}^2}_{\text{DC Loss}} + \underbrace{R_{ac}(f)\left(\frac{I_{acp\text{-}p}}{2\sqrt{2}}\right)^2}_{\text{Eddy current (Coil) + Eddy current (Core)}} + \underbrace{Kf^{\alpha}\left(\frac{I_{acp\text{-}p}}{2\sqrt{2}}\right)^{\beta}}_{\text{Hysteresis loss (Core) + Others}}$$

- $R_{ac}(f)$, K, α, β are optimized from **inductor loss data** with Genetic Algorithm(GA).

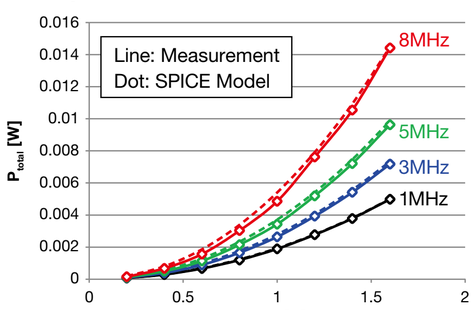
Objective function of GA

$$error = \sum_i \sum_j \frac{\left| P_{total}(f_i, I_{acp\text{-}p\_j}) - P_{measure}(f_i, I_{acp\text{-}p\_j}) \right|}{P_{measure}(f_i, I_{acp\text{-}p\_j})} \rightarrow \min.$$

Sample A



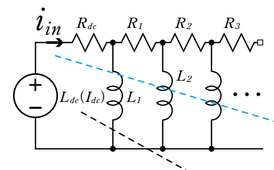
Sample B



SPICE Model (Arbitrary Model)

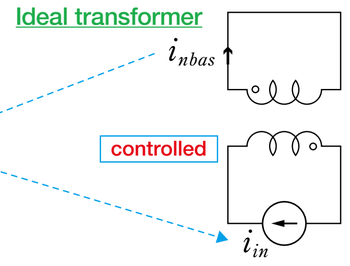
From mathematical model, the following circuit can be synthesized.

1st & 2nd Term

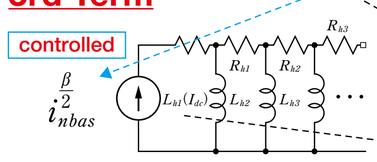


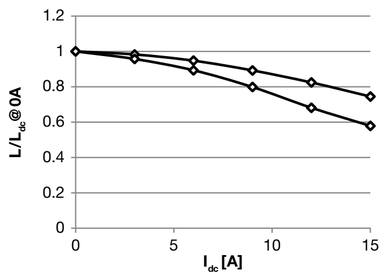
Bias blocker

Ideal transformer



3rd Term





Loss computation

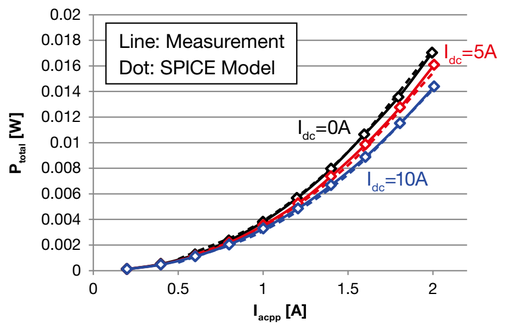
$$P_{total} = \frac{1}{T}\int_0^t \left(R_{dc} I_{in}^2 + \sum_j^{q_1} R_j i_j^2 + \sum_j^{q_2} R_{hj} i_{hj}^2 \right) dt$$

Advantage

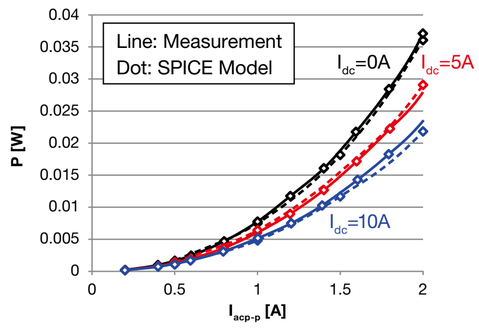
- This SPICE model can consider not only eddy current loss but also hysteresis loss.
- We can estimate the loss under the arbitrary excitation
- We can easily import it into SPICE to analyze the whole system including the hysteresis loss.

Sinusoidal Excitation with Bias @1MHz

Sample A



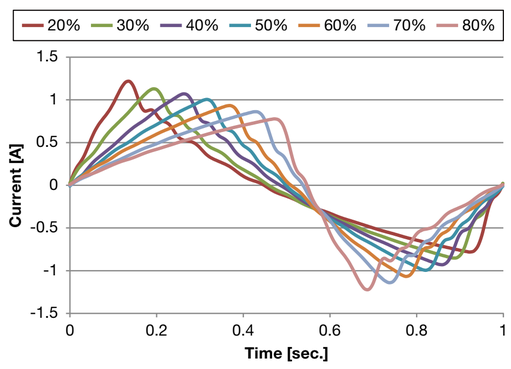
Sample B



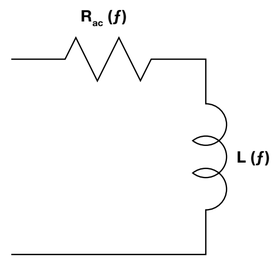
Triangular Excitation

Excitation Waveform (Different duty factor)

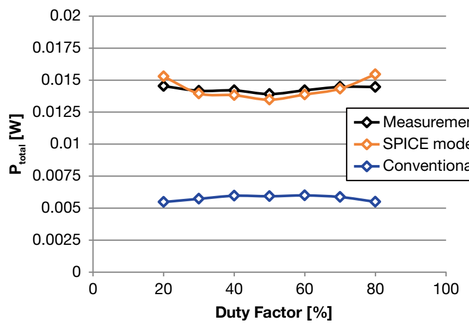
Excitation Conditions: 1MHz, $I_{acp\text{-}p}$ = 2A



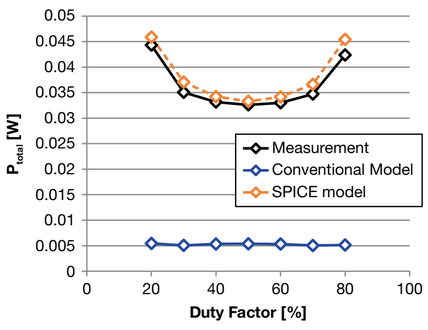
Conventional Circuit



Sample A



Sample B



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