Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Power Electronic Systems Laboratory

Vernachlässigte Effekte mit erheblichem Einfluss auf die Verluste von Induktivitäten

Jonas Mühlethaler, Johann W. Kolar

Power Electronic Systems Laboratory, ETH Zurich

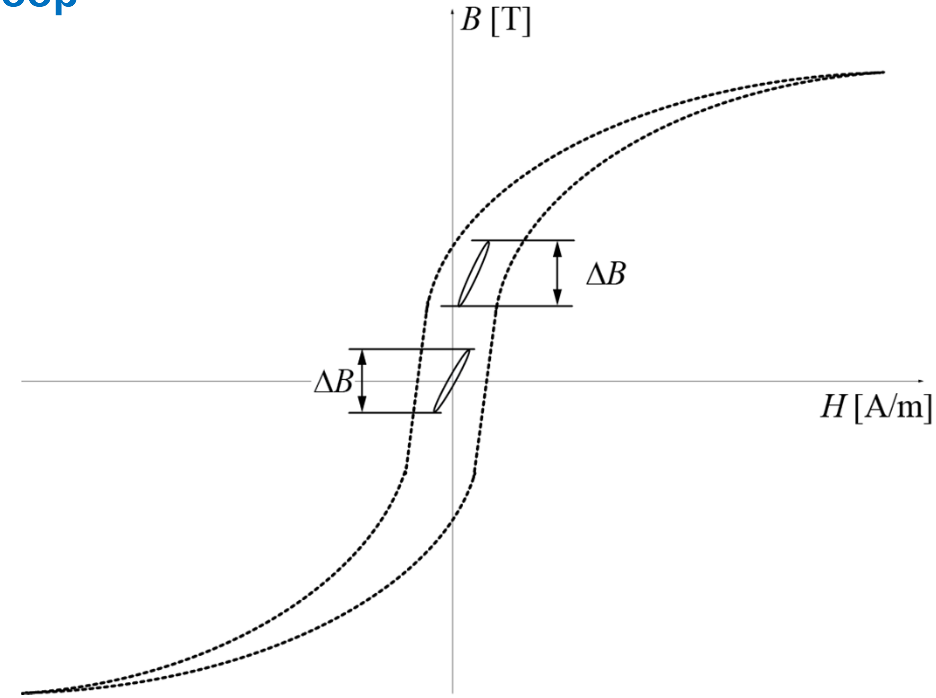
Agenda

- Core Losses under DC Bias Condition
- Relaxation Effects in Magnetic Materials
- Losses of Gapped Tape Wound Cores

Core Losses under DC Bias Condition

Motivation

BH Loop



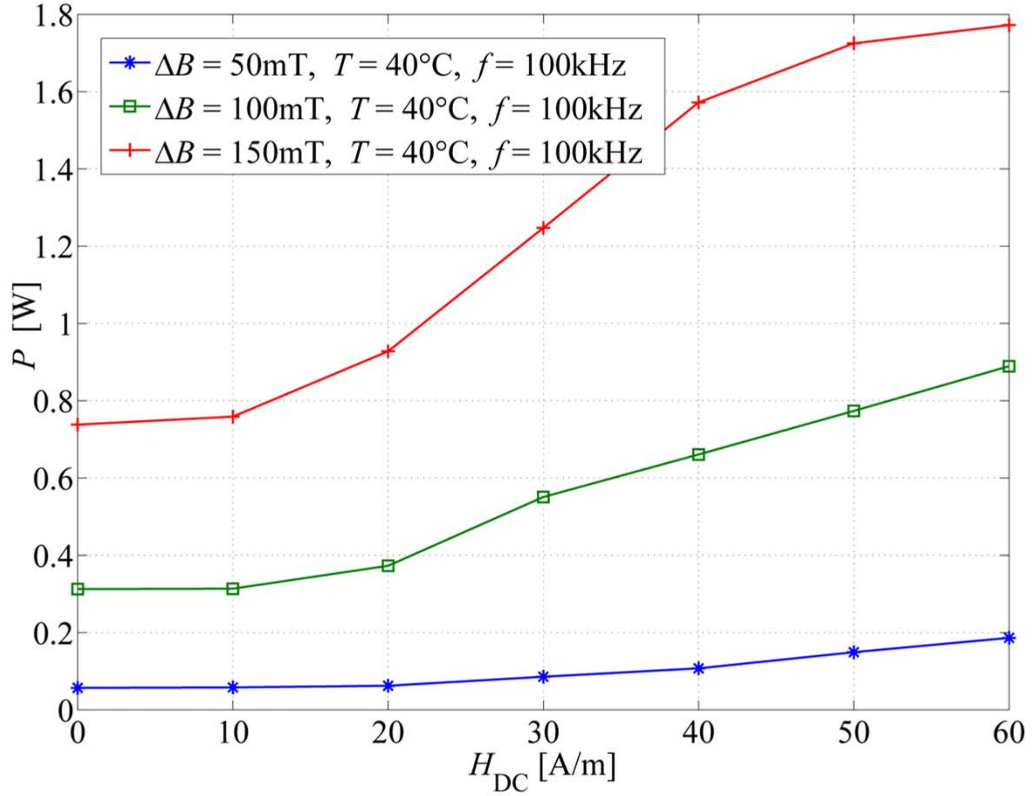
Steinmetz Equation

$$P = k\, f^{\alpha} B^{\beta}$$

According to the Steinmetz Equation core losses should be the same for both loops, but …

Core Losses under DC Bias Condition
Measurement Results (1)

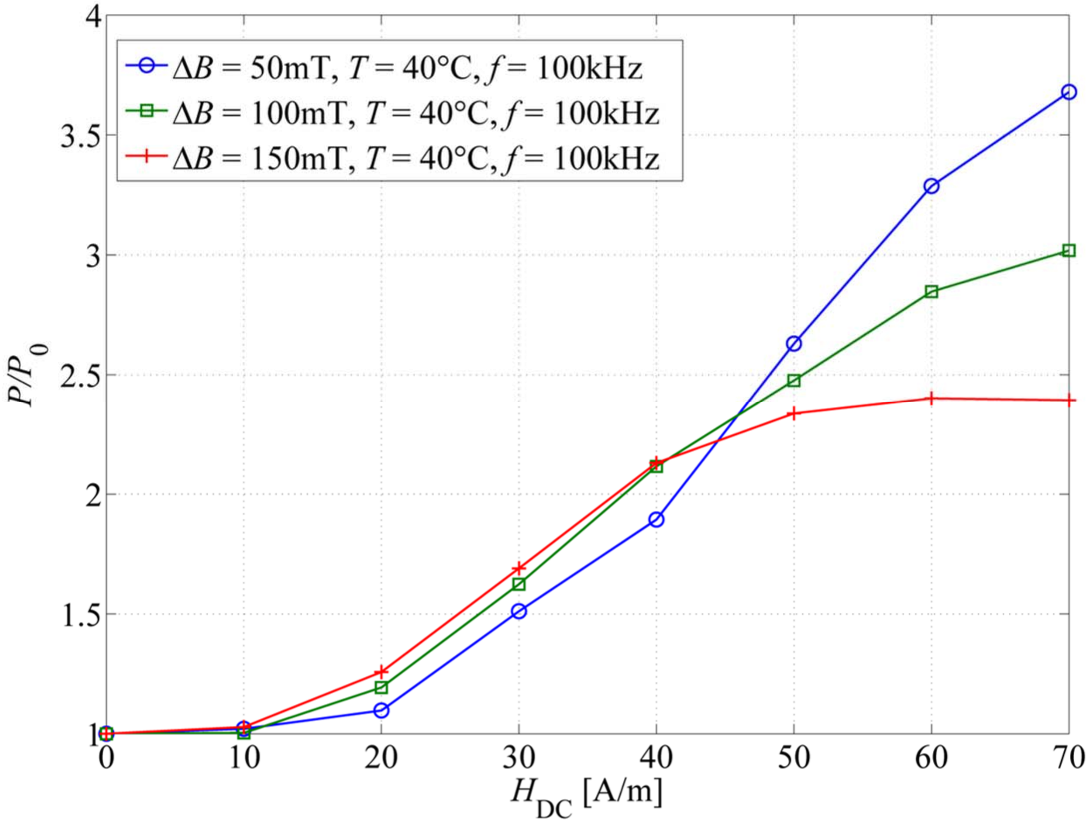
Results
Ferrite EPCOS N87



Core Losses under DC Bias Condition
Measurement Results (2)

Results

Ferrite EPCOS N87

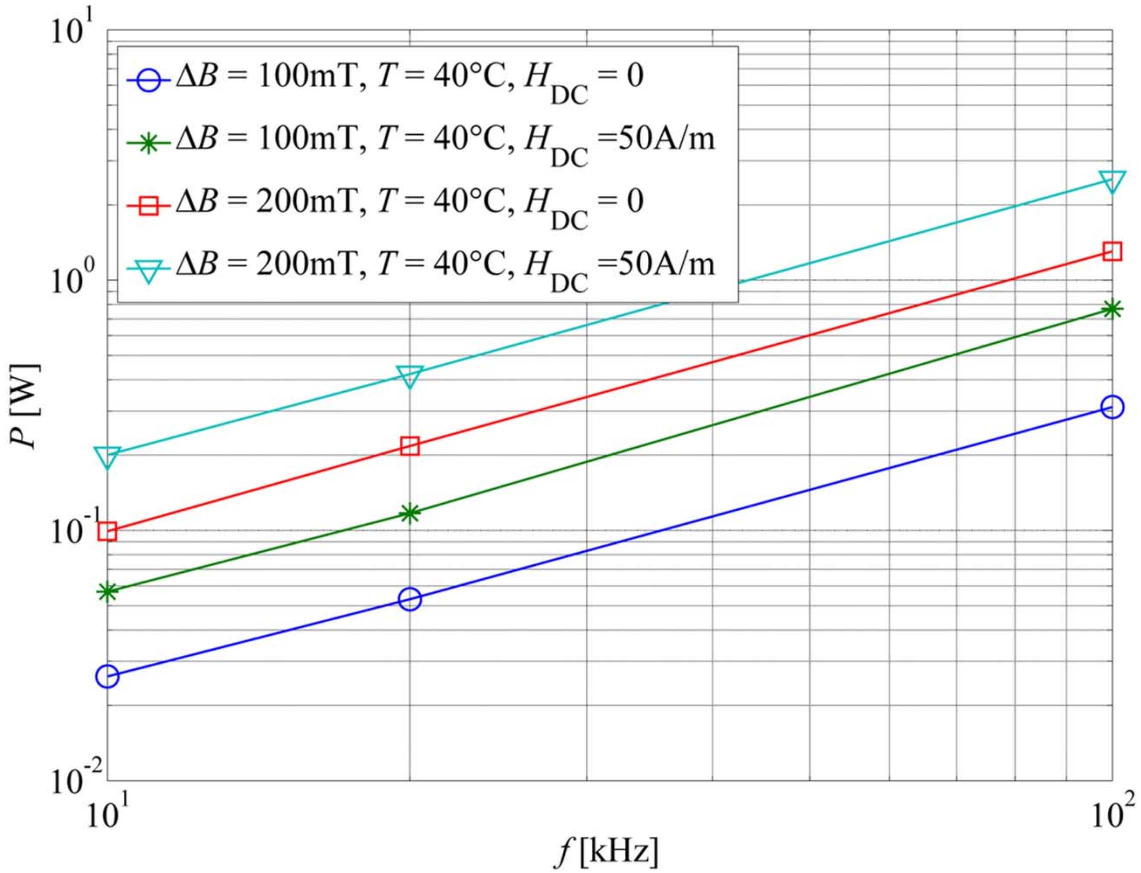


Core Losses under DC Bias Condition

Measurement Results (3)

Results

Ferrite EPCOS N87

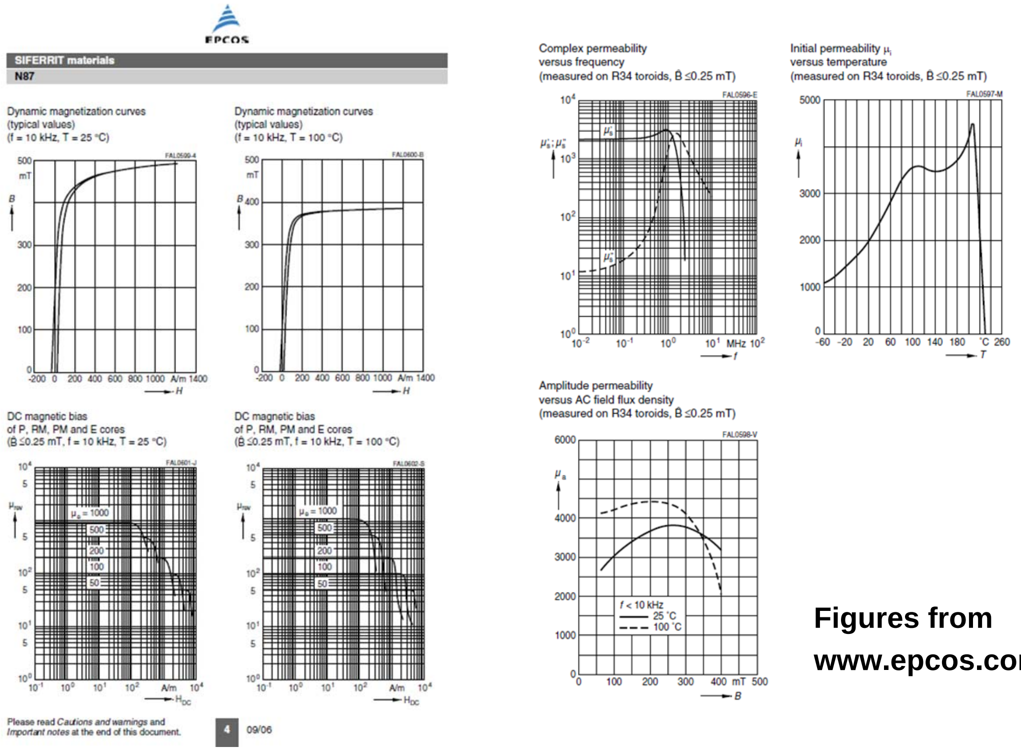


Core Losses under DC Bias Condition

Model Derivation (1) : Motivation

Copy from Data Sheet

EPCOS N87



Figures from www.epcos.com

How could the effect of a DC bias be described in a data sheet?

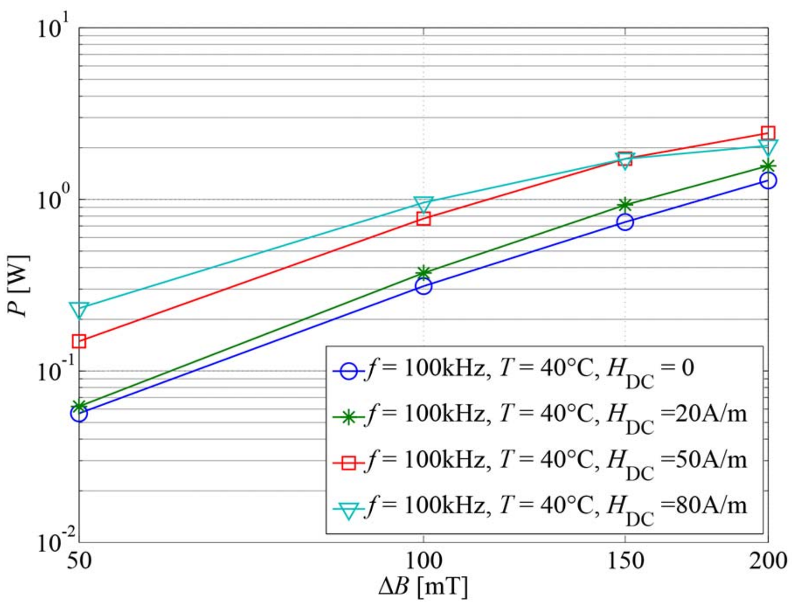
Idea: **to publish Steinmetz parameters as a function of the premagnetization H_{DC}**

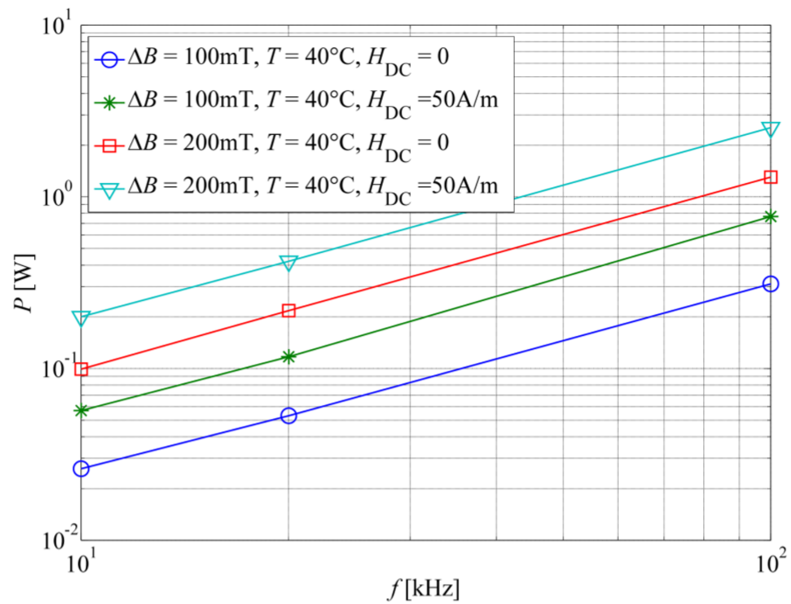
Core Losses under DC Bias Condition

Model Derivation (2) : Power Law?

Can core losses under DC Bias condition still be described by a power law (Potenzgesetz)?

Measurement Results

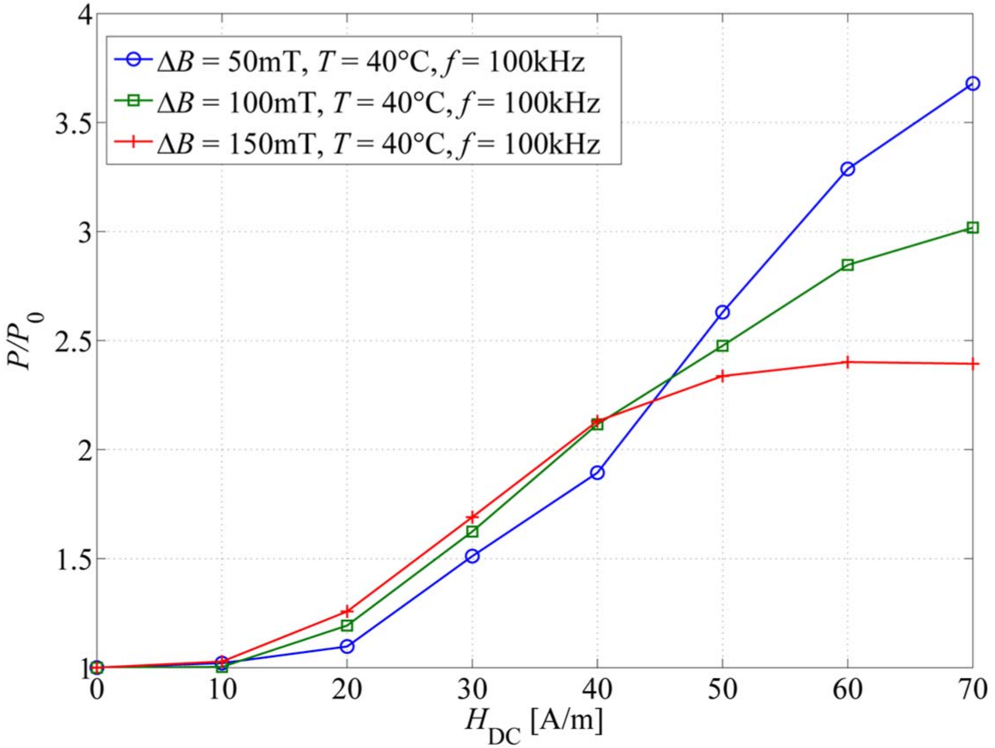




Steinmetz Equation $P = k\, f^{\alpha} B^{\beta}$

Core Losses under DC Bias Condition

Model Derivation (3) : What Parameters Depend on H_{DC}



Steinmetz Equation

$$P = k\, f^{\alpha}\, B^{\beta}$$

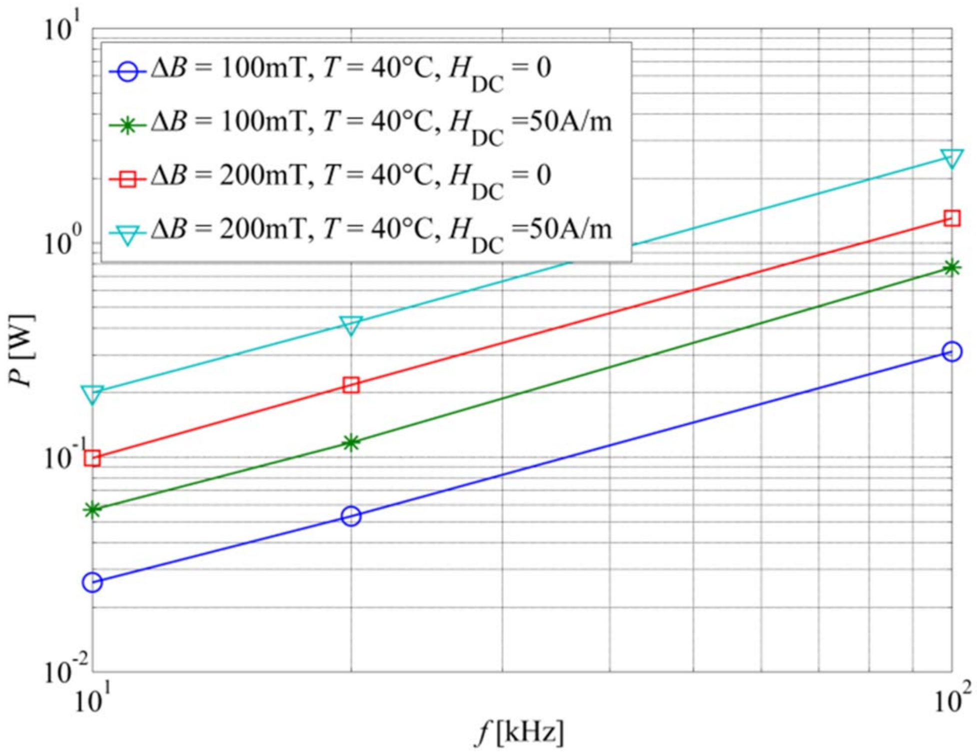
k **depends on** H_{DC}

β **depends on** H_{DC}**.**

$$\frac{P}{P_0} = f(\Delta B)$$

Core Losses under DC Bias Condition

Model Derivation (4) : What Parameters Depend on H_{DC}



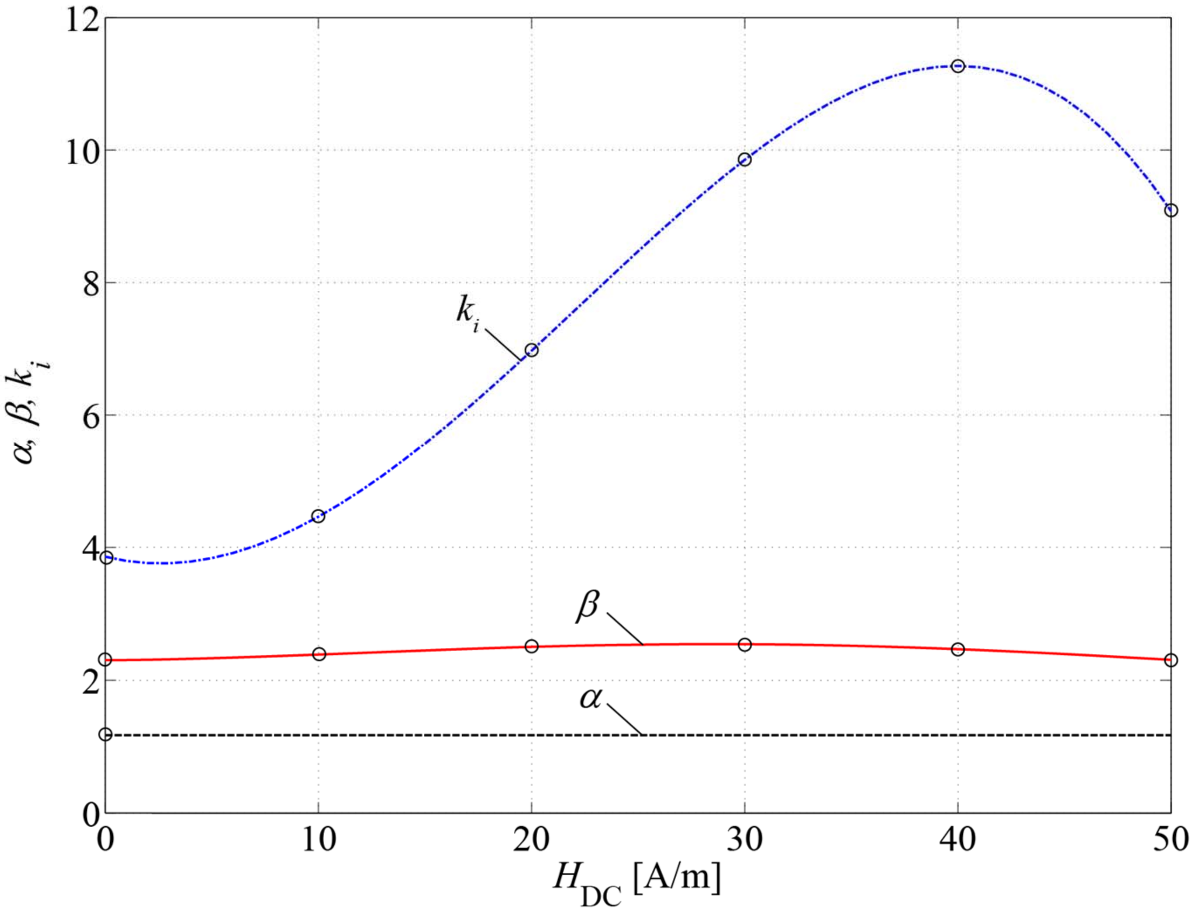
Steinmetz Equation

$$P = k\, f^{\alpha}\, B^{\beta}$$

α **is independent of** H_{DC}

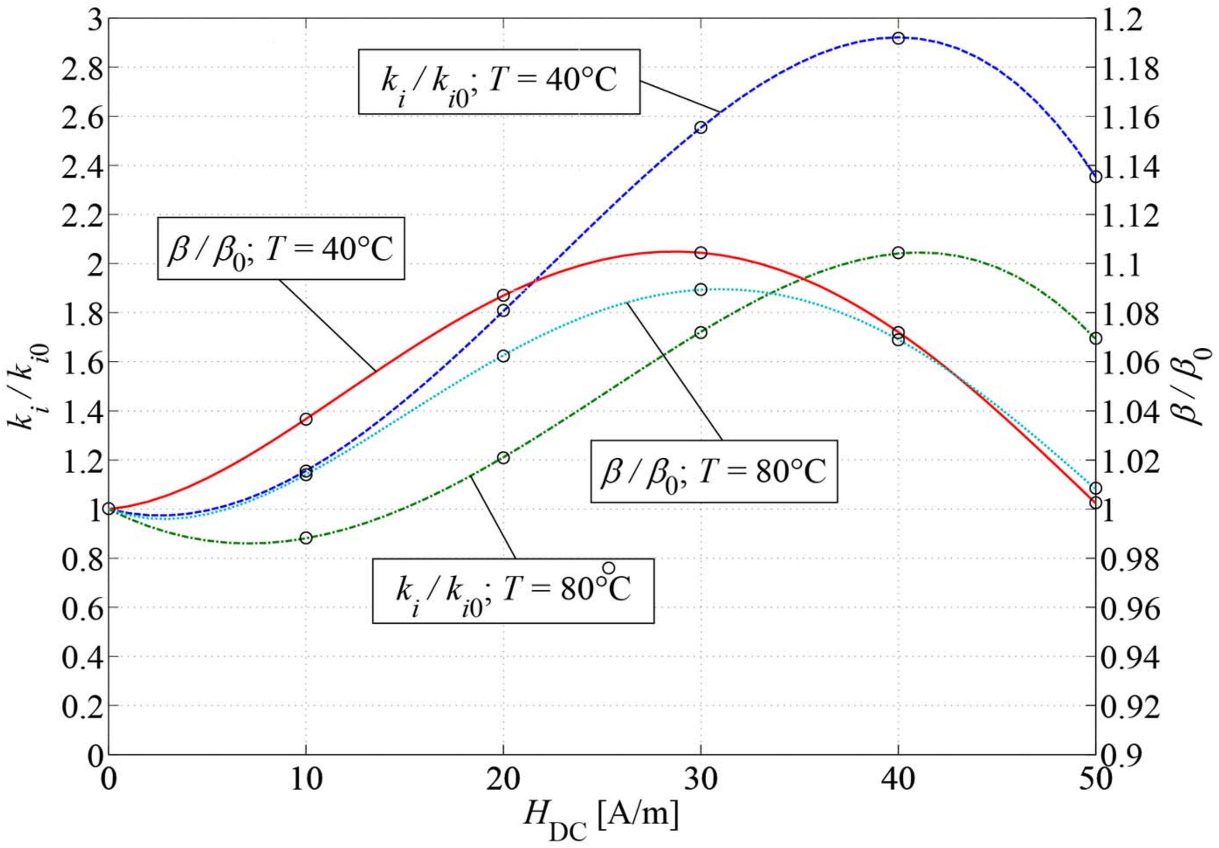
Core Losses under DC Bias Condition

Model Derivation (5) : Steinmetz Parameters as a Function of H_{DC}



Core Losses under DC Bias Condition

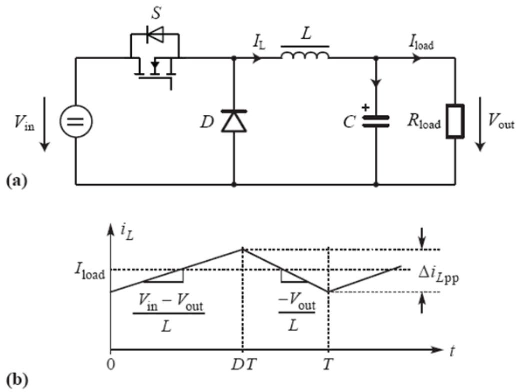
The Steinmetz Premagnetization Graph (SPG)



Core Losses under DC Bias Condition

SPG – An Example

Buck Converter



V_{in} / V_{out}	12 V / 6 V
f	100 kHz
P	2 W
I_{load}	0.33 A
L	150 μH (EPCOS N87; R25; N=8) (core part number: B64290L618X87 [19])

Steps towards accurate core losses:

- Calculate magnetic operating point: H_{DC} = 44 A/m / ΔB = 73 mT.
- Extract Steinmetz parameters: α = 1.25, β = 2.46, k = 15.9
- Calculate k_i (iGSE)
- Adjust k_i and β according to the SPG: β = 2.56, k_i = 3.28
- Calculate core losses with the iGSE.

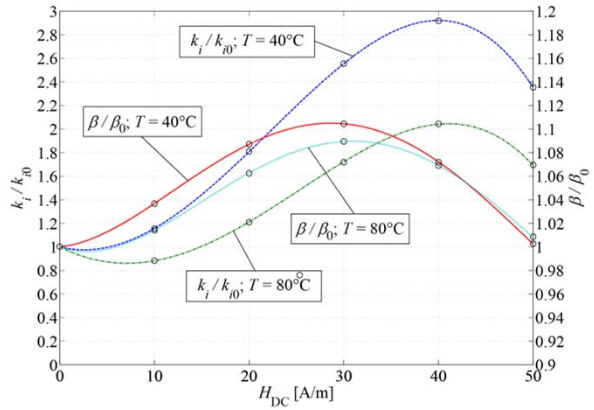
Tools

iGSE [5]:

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

$$k_i = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi} |\cos\theta|^{\alpha}\, 2^{\beta-\alpha}\, d\theta}$$

SPG [1]:

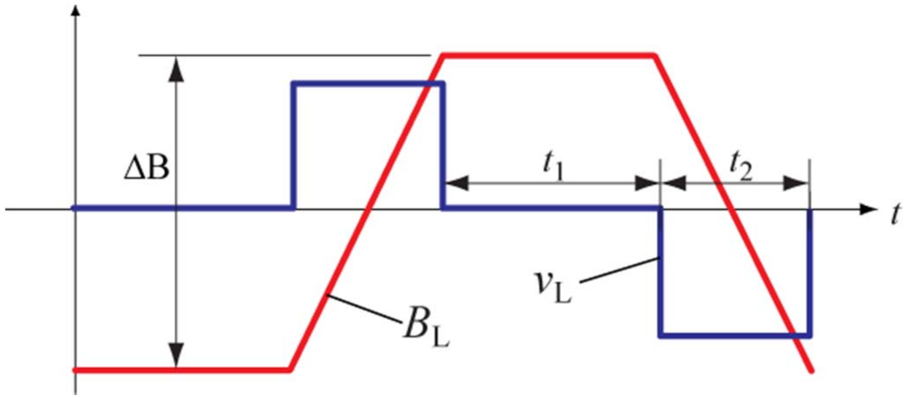


Agenda

- Core Losses under DC Bias Condition
- Relaxation Effects in Magnetic Materials
- Losses of Gapped Tape Wound Cores

Relaxation effect
Motivation (1)

Waveform



iGSE [5]

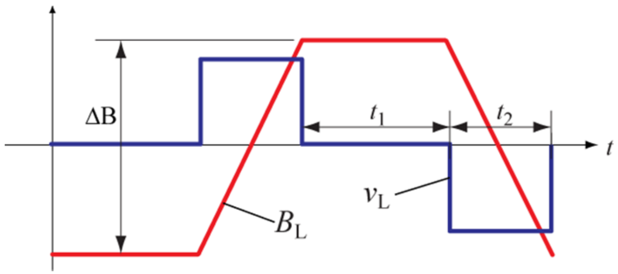
$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt$$

Conclusion

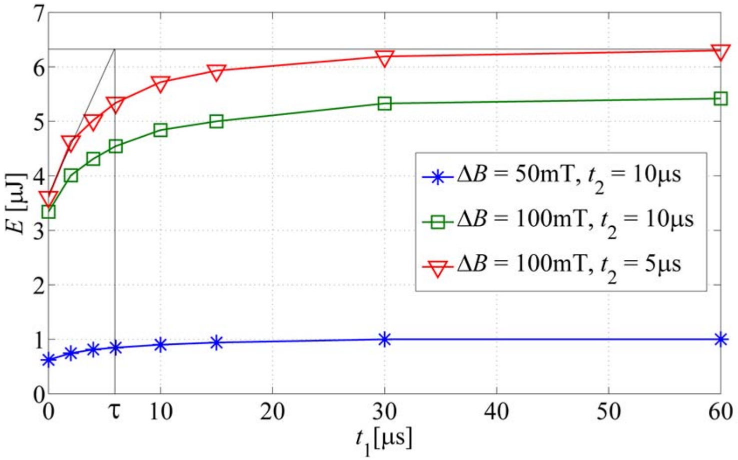
No losses in the phase of constant flux! True?

Relaxation effect
Motivation (2)

Waveform



Results

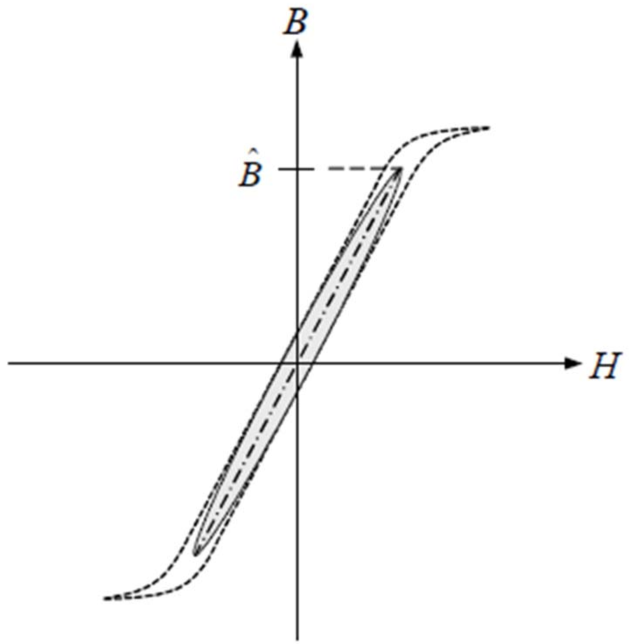


Conclusion

~~No~~ **<u>losses</u> in the phase of constant flux!**

Relaxation effect
Theory

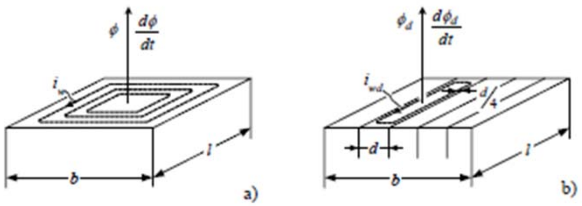
- **(Static) hysteresis loss**
  - **Rate-independent BH Loop.**
  - **Loss energy per cycle is constant.**
  - **Irreversible changes each within a small region of the lattice (Barkhausen jumps).**
  - **These rapid, irreversible changes are produced by relatively strong local fields within the material.**



- **Eddy current losses**
- **Residual Losses – Relaxation losses**

Relaxation effect
Theory

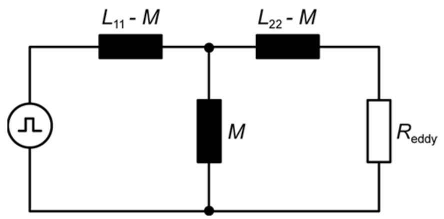
- (Static) hysteresis loss
- Eddy current losses
  - Depending on material conductivity and core shape.
  - Very low in ferrites.
  - Affect BH loop.
- Residual Losses – Relaxation losses



Equivalent circuit

$L_{11} - M \approx 0$

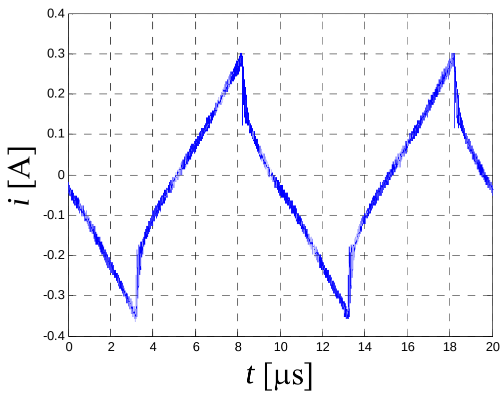
$L_{22} - M = 0$



→ Eddy Currents may be discontinuous

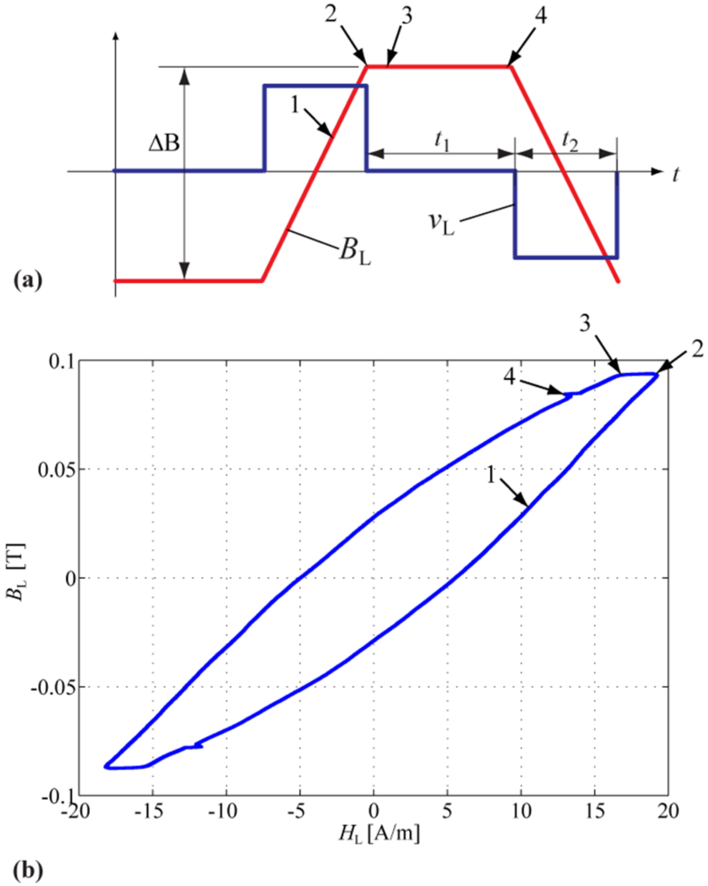
Measurements

VITROPERM 500F



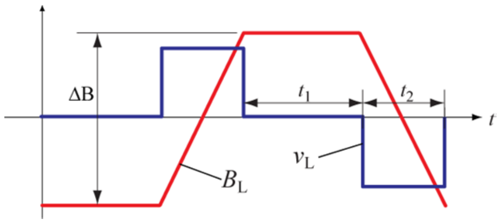
Relaxation effect
Theory

- (Static) hysteresis loss
- Eddy current losses
- Residual Losses – Relaxation losses
  - Reestablishment of a thermal equilibrium is governed by relaxation processes.
  - Restricted domain wall motion.

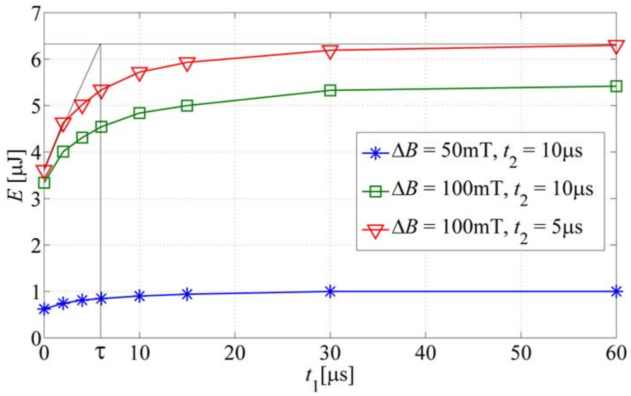


Relaxation effect
Model Derivation 1 (1)

Waveform



Loss Energy per Cycle



Derivation (1)

Relaxation loss energy can be described with

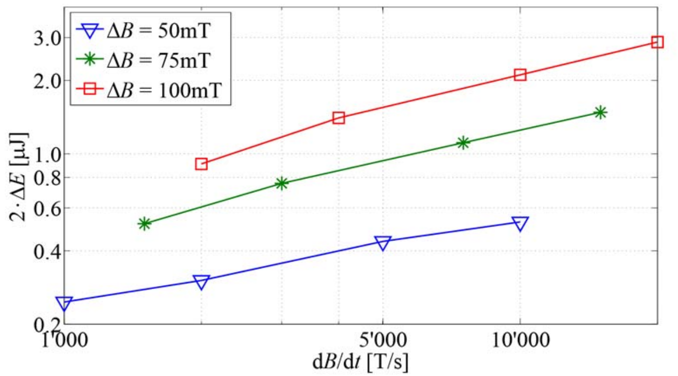
$$E = \Delta E\left(1 - e^{-\frac{t_1}{\tau}}\right)$$

τ **is independent of operating point.**

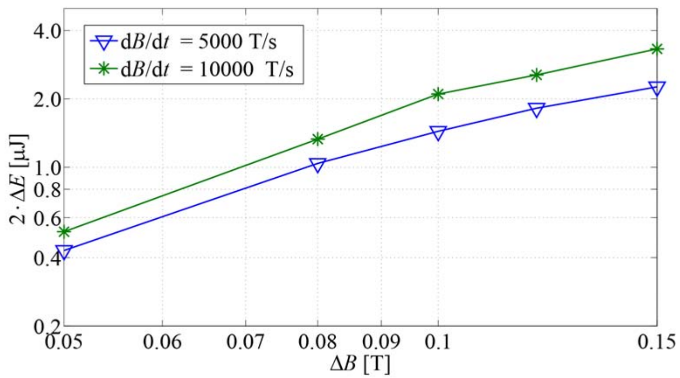
How to determine ΔE?

Relaxation effect
Model Derivation 1 (2)

ΔE – Measurements

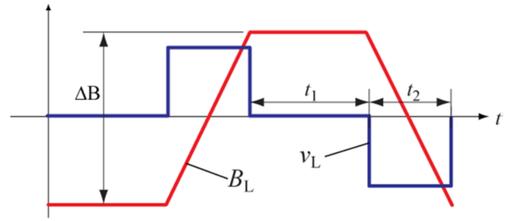


(a)



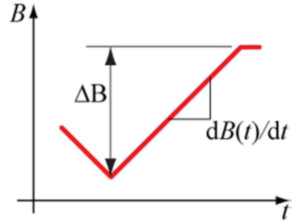
(b)

Waveform



Conclusion

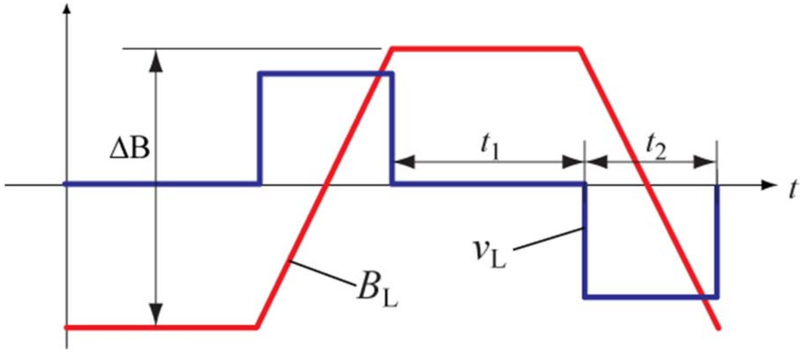
→ **ΔE follows a power function!**



$$\Delta E = k_r \left| \frac{d}{dt} B(t) \right|^{\alpha_r} (\Delta B)^{\beta_r}$$

Relaxation effect

Model Derivation 1 (3)



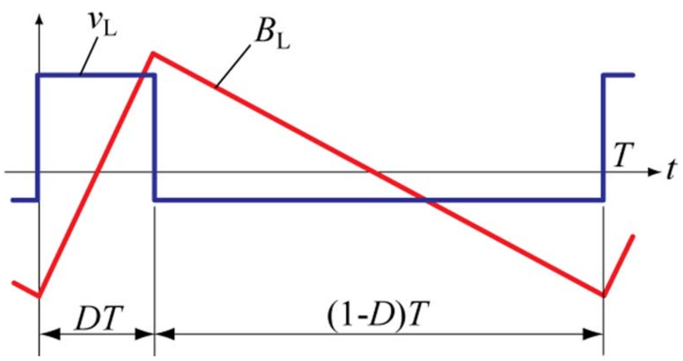
Model Part 1

$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} P_{\mathrm{r}l}$$

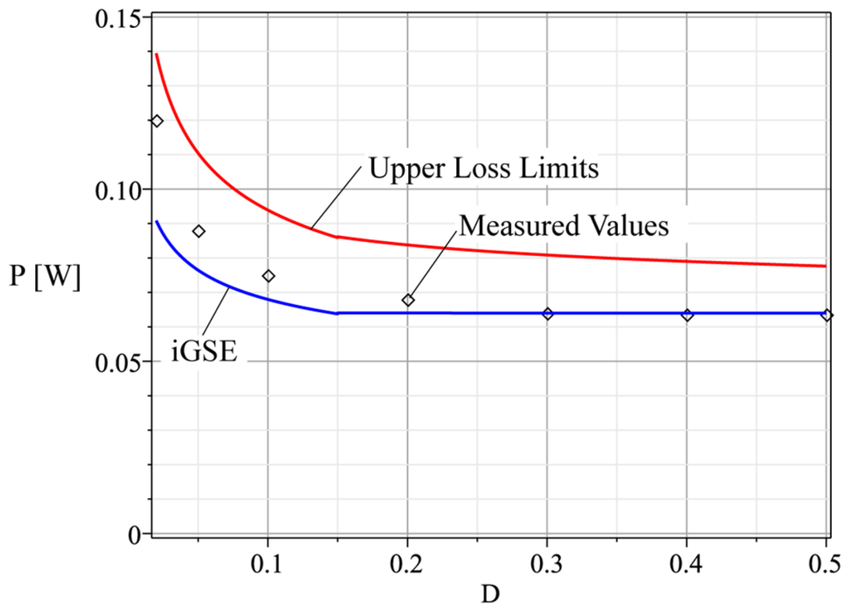
$$P_{\mathrm{r}l} = \frac{1}{T} k_{\mathrm{r}} \left|\frac{\mathrm{d}}{\mathrm{d}t} B(t)\right|^{\alpha_{\mathrm{r}}} (\Delta B)^{\beta_{\mathrm{r}}} \left(1 - \mathrm{e}^{-\frac{t_1}{\tau}}\right)$$

Relaxation effect
Model Derivation 2 (1)

Waveform



Power Loss



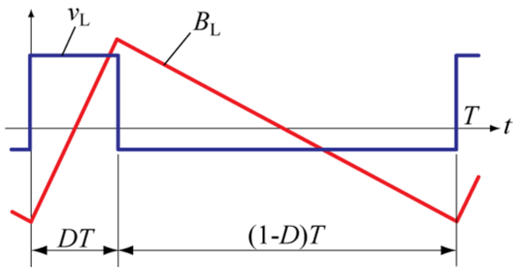
Explanation

1) **For values of *D* close to 0 or close to 1 a loss underestimation is expected when calculating losses with iGSE (no relaxation losses included).**
2) **For values of *D* close to 0.5 the iGSE is expected to be accurate.**
3) **Hence, adding the relaxation term leads to the upper loss limit, while the iGSE represents the lower loss limit.**
4) **Losses are expected to be in between the two limits, as has been confirmed with measurements.**

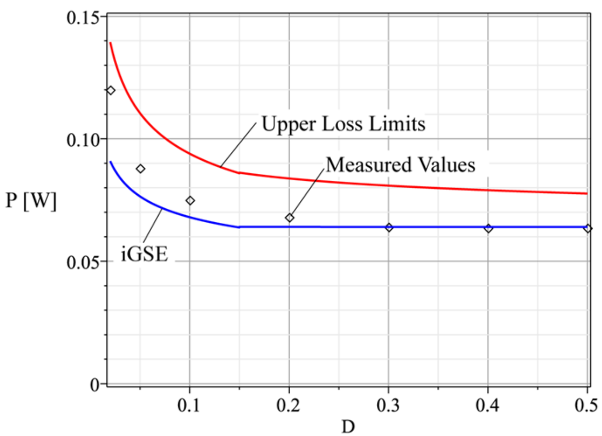
Relaxation effect

Model Derivation 2 (2)

Waveform



Power Loss



Model Adaption

$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt + \sum_{l=1}^{n} Q_{rl} P_{rl}$$

Q_{rl} should be 1 for $D = 0$

Q_{rl} should be 0 for $D = 0.5$

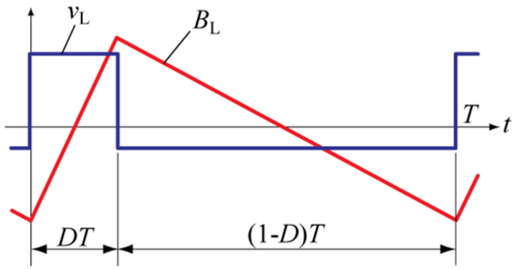
Q_{rl} should be such that calculation fits a triangular waveform measurement.

$$Q_{rl} = e^{-q_r \left|\frac{dB(t+)/dt}{dB(t-)/dt}\right|} \left(= e^{-q_r \frac{D}{1-D}} \right)$$

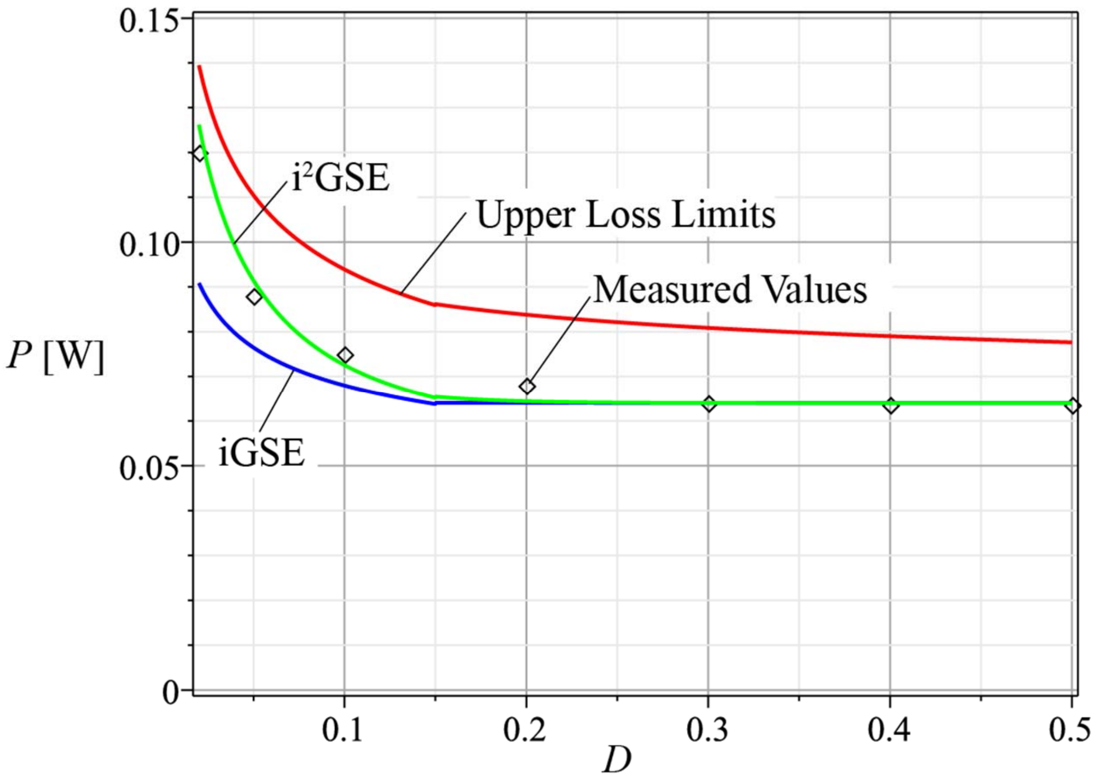
Relaxation effect

Model Derivation 2 (3)

Waveform



Power Loss



Relaxation effect

New Core Loss Model

The improved-improved Generalized Steinmetz Equation (i²GSE)

$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{\mathrm{r}l} P_{\mathrm{r}l}$$

with

$$P_{\mathrm{r}l} = \frac{1}{T} k_{\mathrm{r}} \left|\frac{\mathrm{d}}{\mathrm{d}t} B(t)\right|^{\alpha_{\mathrm{r}}} (\Delta B)^{\beta_{\mathrm{r}}} \left(1 - \mathrm{e}^{-\frac{t_1}{\tau}}\right)$$

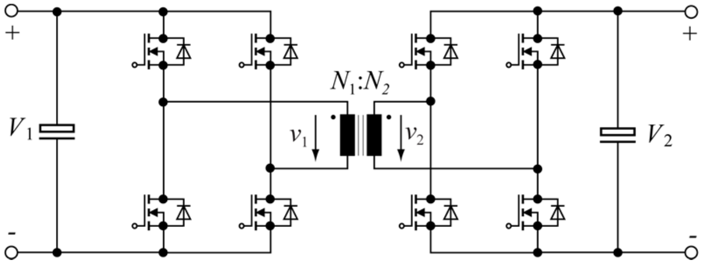
and

$$Q_{\mathrm{r}l} = \mathrm{e}^{-q_{\mathrm{r}} \left|\frac{\mathrm{d}B(t+)/\mathrm{d}t}{\mathrm{d}B(t-)/\mathrm{d}t}\right|}$$

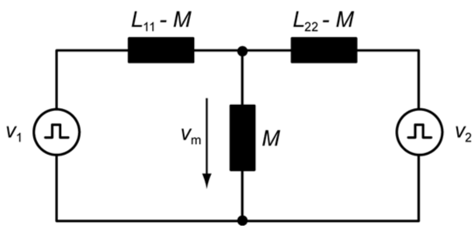
Relaxation effect

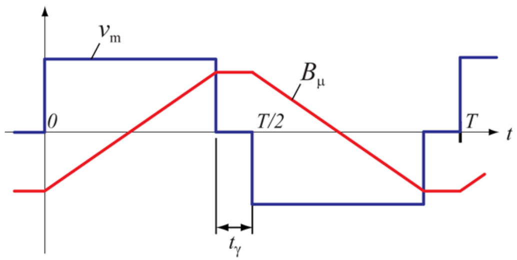
Example: Dual Active Bridge

Schematic

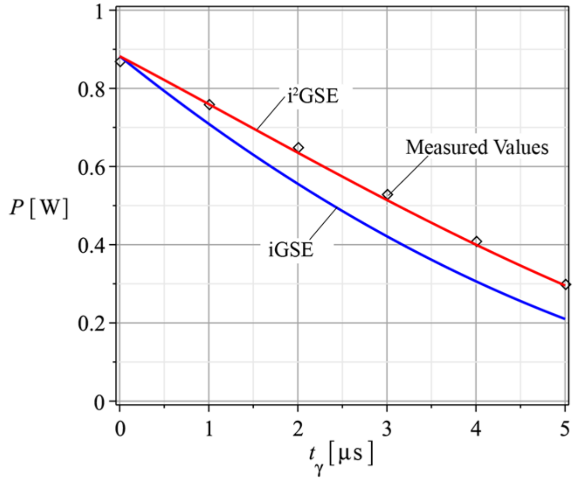


Waveform & Model



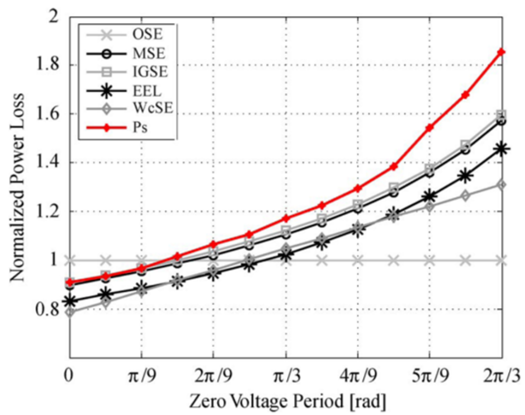


i²GSE Results



Results from [6]

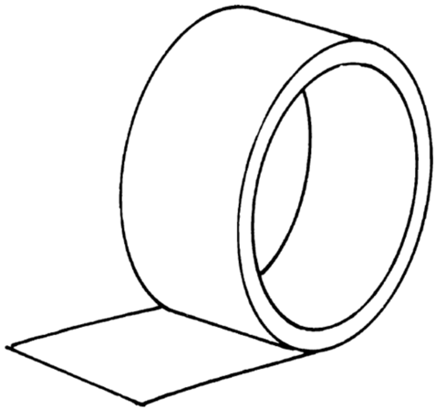
In [6] a very similar example has been calculated. For increasing zero voltage periods, the calculated core losses start deviating from the measured core losses. The reason becomes clear with the new approach i²GSE and the calculation can be improved. In Figure on the right the losses are normalized to calculation with original Steinmetz Equation (OSE).

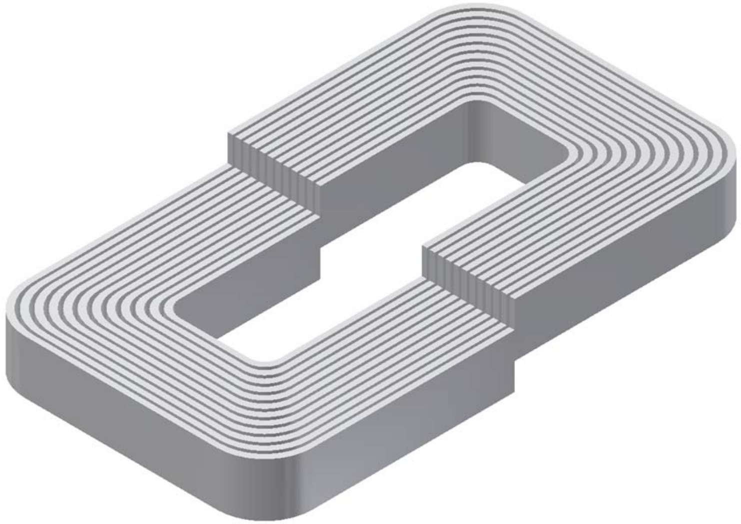


Agenda

- Core Losses under DC Bias Condition
- Relaxation Effects in Magnetic Materials
- Losses of Gapped Tape Wound Cores

Losses of Gapped Tape Wound Cores
Motivation





Losses in gapped tape wound cores higher than expected!

(gapped tape wound cores such as amorphous or nanocrystalline iron materials).

Left figure from www.vacuumschmelze.de

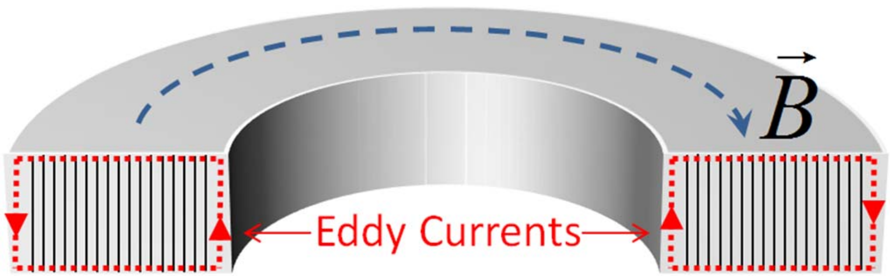
Losses of Gapped Tape Wound Cores

Cause 1 : Interlamination Short Circuits

Machining process

Surface short circuits introduced by machining.

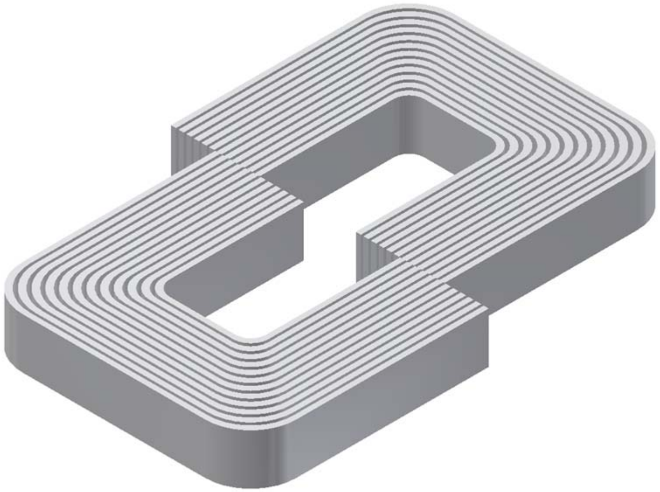
Particular a problem in in-house production.



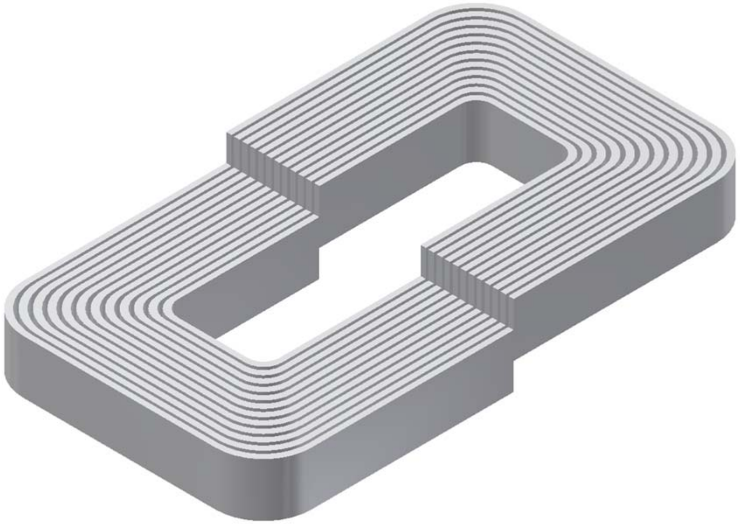
After treatment may reduce this effect. At ETH, a core was put in an 40% ferric chloride (Eisenchlorid $FeCl_3$) solution after cutting, which substantially decreased the core losses [3].

Losses of Gapped Tape Wound Cores
Cause 2 : Orthogonal Flux Lines (1)

Experiment that illustrates well the loss increase due to a flux that is orthogonal to the lamination layers (1).



Horizontal Displacement

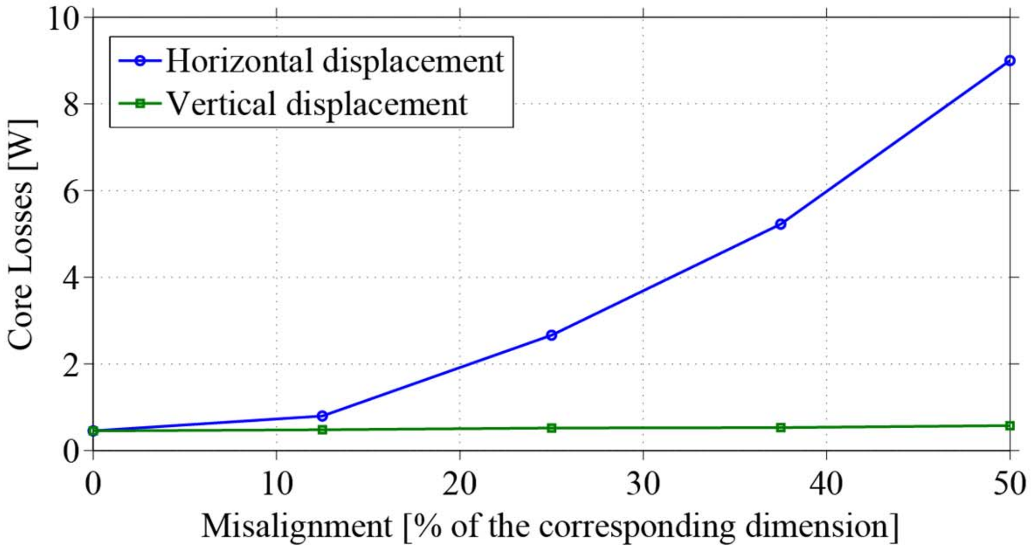


Vertical Displacement

Losses of Gapped Tape Wound Cores
Cause 2 : Orthogonal Flux Lines (2)

Experiment that illustrates well the loss increase due to a flux that is orthogonal to the lamination layers (2).

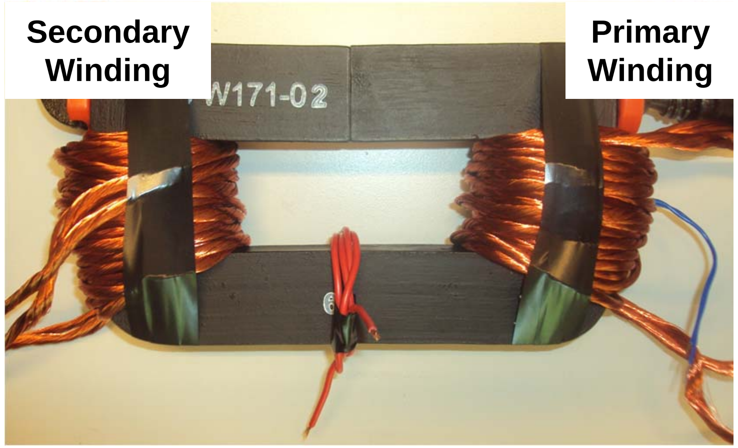
Core Loss Results



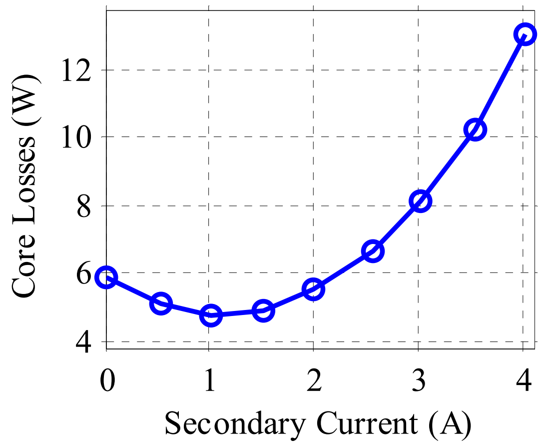
Losses of Gapped Tape Wound Cores
Cause 2 : Orthogonal Flux Lines (3)

Core loss increase due to leakage flux in transformers.

Measurement Set Up



Results



Losses of Gapped Tape Wound Cores

Cause 2 : Orthogonal Flux Lines (4)

In [4] a core loss increase with increasing air gap length has been observed.

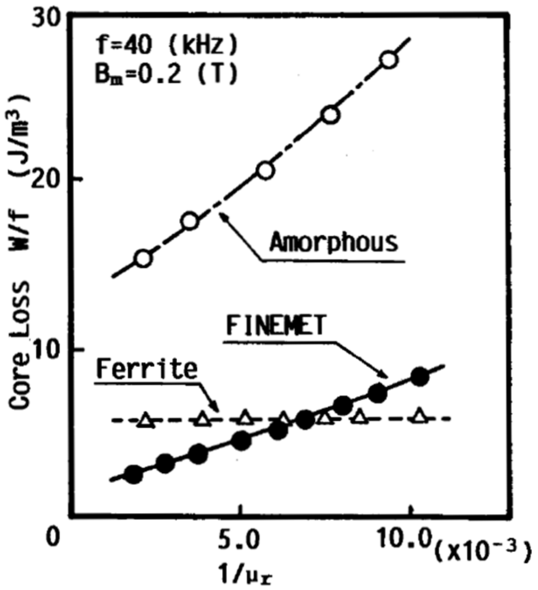


Fig.1 Core loss per cycle W/f in FINEMET, Fe-based amorphous, and ferrite cut cores as a function of inverse of the effective permeability μ_r.

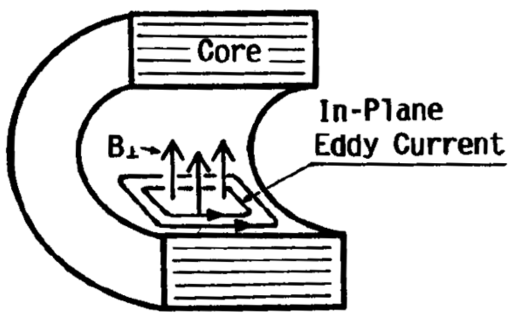


Fig.2 Schematic representation of in-plane eddy current generated by leakage flux normal to ribbon surfaces.

Figures from [4].

Conclusion & Outlook

The following effects have been discussed:

Core Losses under DC Bias Condition [1]

Until core manufacturers provide data about losses under DC bias condition, measuring core losses is indispensable.

Relaxation Effects in Magnetic Materials [2]

The model i^2GSE takes such effects into account.

Losses of Gapped Tape Wound Cores [3,4]

To the speaker's knowledge, there exists no approach which allows to analytically describe the presented effects.

Thank you !

Do you have any questions ?

References

[1] J. Mühlethaler, J. Biela, J.W. Kolar, and A. Ecklebe, "Core Losses under DC Bias Condition based on Steinmetz Parameters", in *Proc. of the IPEC - ECCE Asia*, Sapporo, Japan, 2010.

[2] J. Mühlethaler, J. Biela, J.W. Kolar, and A. Ecklebe, "Improved Core Loss Calculation for Magnetic Components Employed in Power Electronic Systems", in *Proc. of the APEC*, Ft. Worth, TX, USA, 2011.

[3] B. Cougo, A. Tüysüz, J. Mühlethaler, J.W. Kolar, "Increase of Tape Wound Core Losses Due to Interlamination Short Circuits and Orthogonal Flux Components", in *Proc. of the IECON, Melbourne,* 2011.

[4] H. Fukunaga, T. Eguchi, K. Koga, Y. Ohta, and H. Kakehashi, "High Performance Cut Cores Prepared From Crystallized Fe-Based Amorphous Ribbon", in IEEE Transactions on Magnetics, vol. 26, no. 5, 1990.

[5] K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca , "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters", in Proc. of IEEE Workshop on Computers in Power Electronics, pages 36–41, 2002.

[6] I. Villar, U. Viscarret, I. Etxeberria-Otadui, A. Rufer, "Global Loss Evaluation Methods for Nonsinusoidally Fed Medium-Frequency Power Transformers", IEEE Transactions on Industrial Electronics, vol. 56, pages 4132-4140, 2009.