ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Power Electronic Systems Laboratory

Core Loss Modeling of Inductive Components

– Effects with Considerable Impact on Core Losses –

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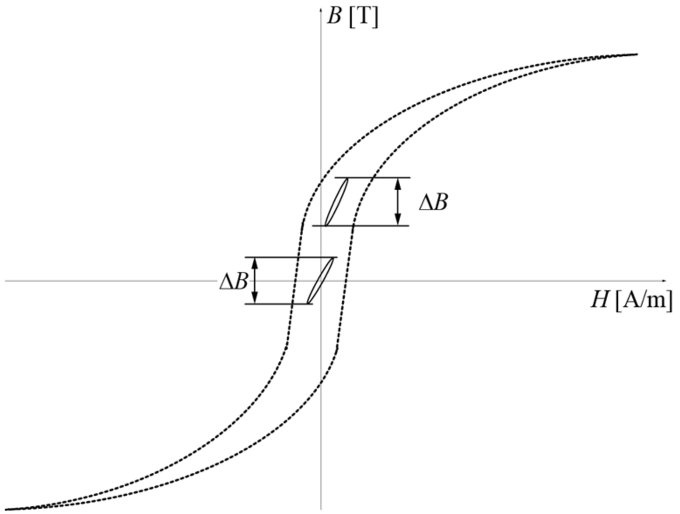
Agenda

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

Core Losses under DC Bias Condition
Motivation

BH Loop



iGSE [5]

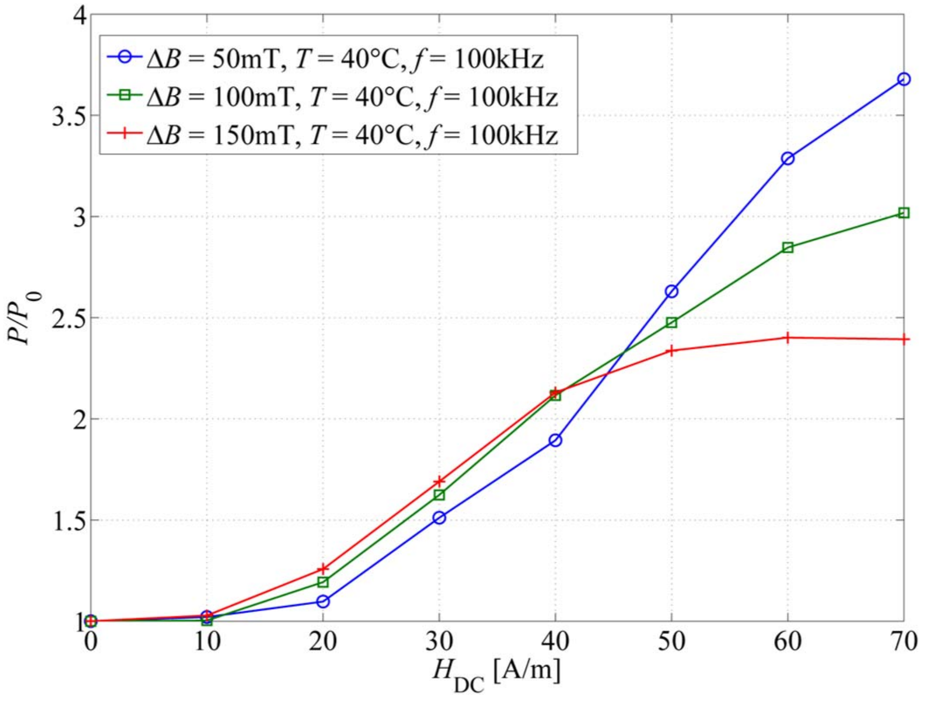
$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha} \,\mathrm{d}t$$

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

Core Losses under DC Bias Condition
Measurement Results

Results

Ferrite EPCOS N87



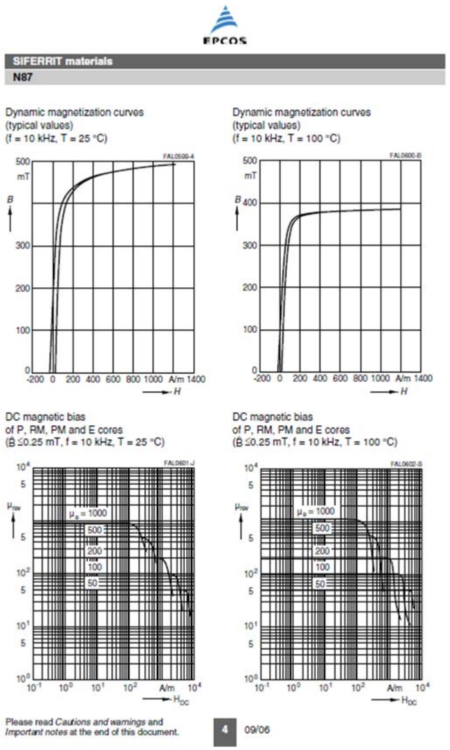
… the losses increase with an increase of H_{DC}!

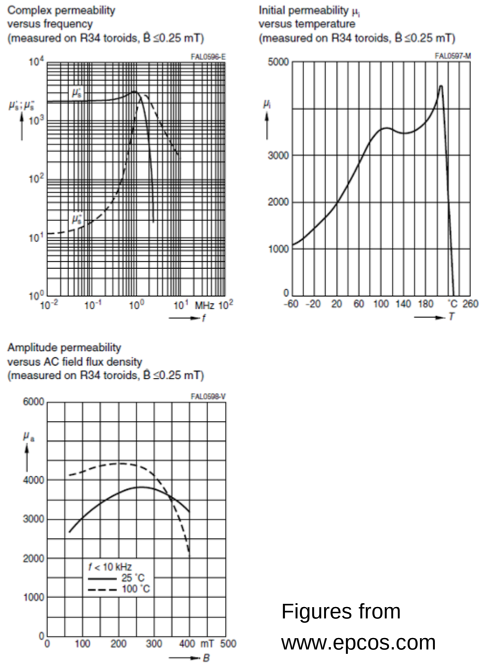
Core Losses under DC Bias Condition

Model Derivation (1) : Motivation

Copy from Data Sheet

EPCOS N87





Figures from
www.epcos.com

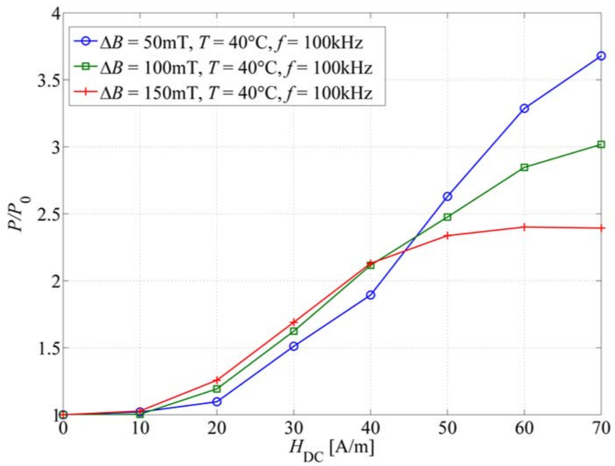
How could the effect of a DC bias be described in a data sheet?

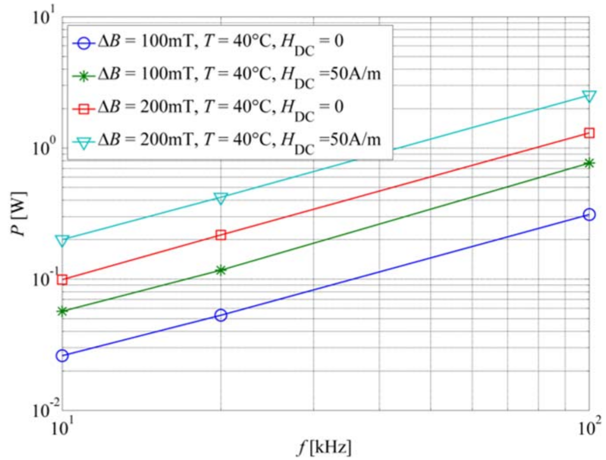
Idea: Steinmetz parameters could be published as a function of the premagnetization H_{DC}

Core Losses under DC Bias Condition

Model Derivation (2)

Measurement Results **(symmetric triangular flux waveforms)**





iGSE

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

$$= k_i (2f)^{\alpha}\,\Delta B^{\beta}$$ **(for symmetric triangular flux waveforms)**

k_{i} depends on H_{DC}

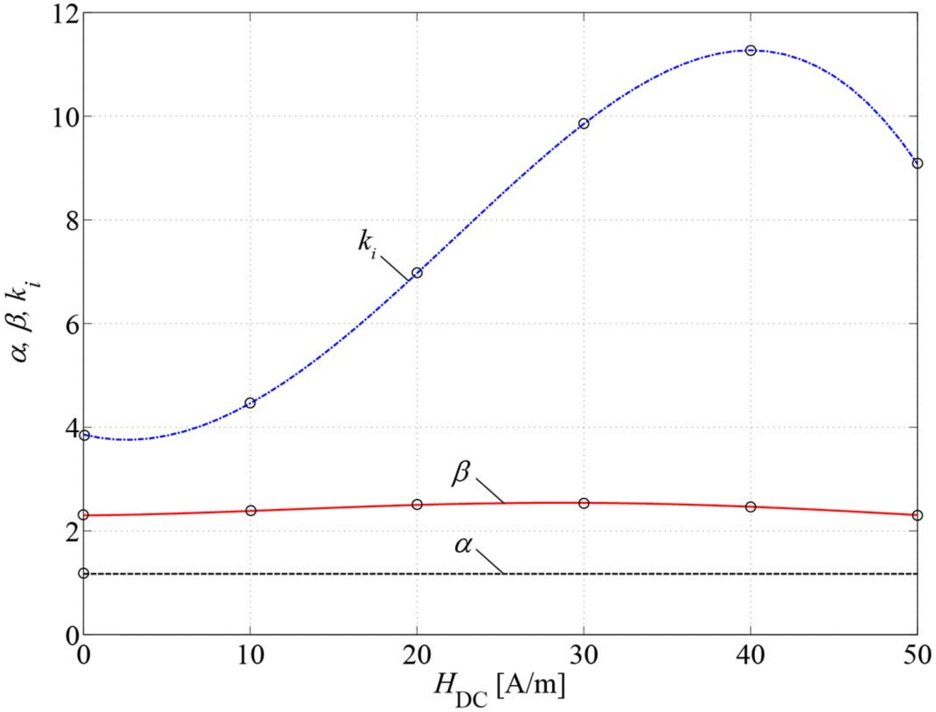
β depends on H_{DC}.

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

α is independent of H_{DC}

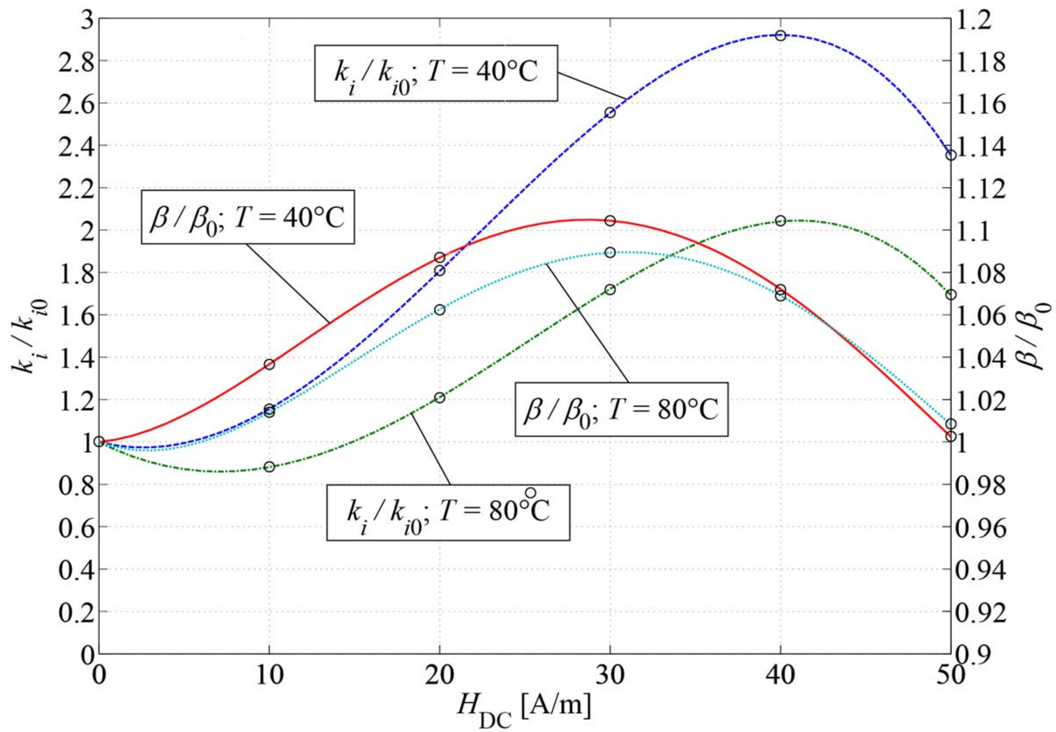
Core Losses under DC Bias Condition

Model Derivation (3) : Steinmetz Parameters as a Function of H_{DC}



Core Losses under DC Bias Condition

The Steinmetz Premagnetization Graph (SPG) [1]

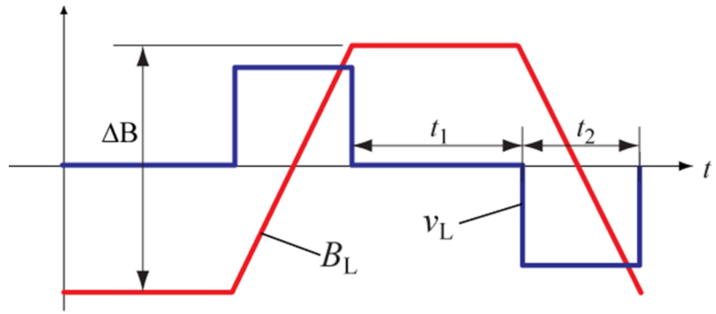


Agenda

- **Core Losses under DC Bias Conditions**
- **Relaxation Effects in Magnetic Materials**
- **Losses in Gapped Tape Wound Cores**

Relaxation effect
Motivation (1)

Waveform



iGSE [5]

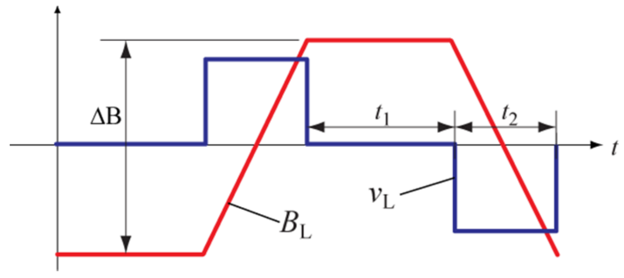
$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt$$

Conclusion

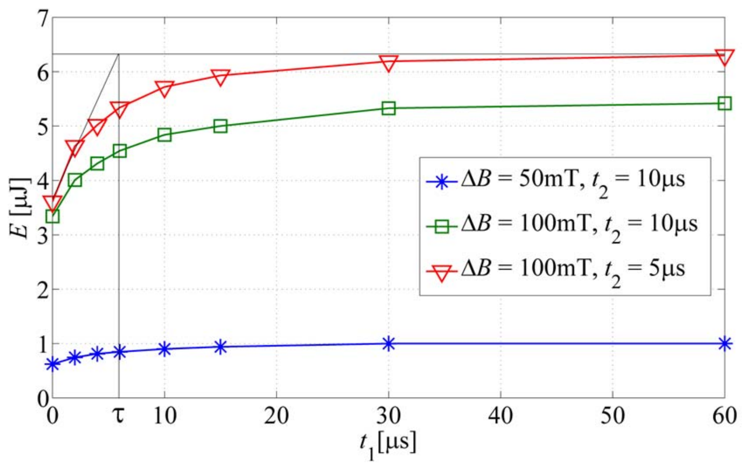
No losses occur in the phase of constant flux! True?

Relaxation effect
Motivation (2)

Waveform



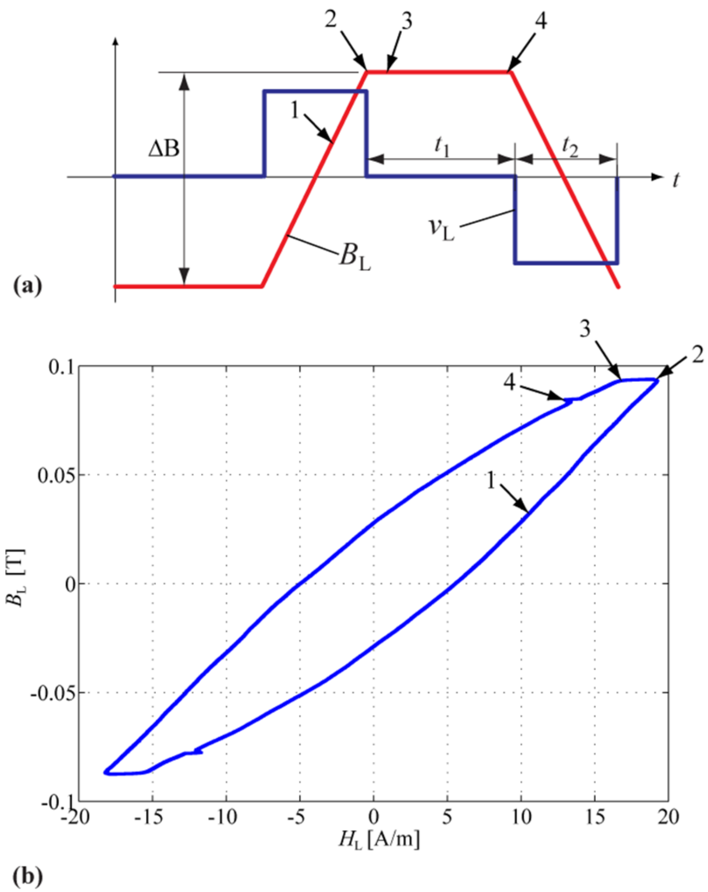
Results



Conclusion

~~No~~ <u>Losses</u> occur in the phase of constant flux!

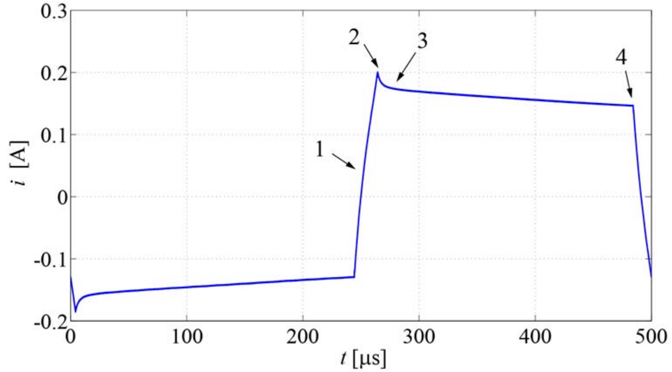
Relaxation effect
Theory



Relaxation Losses

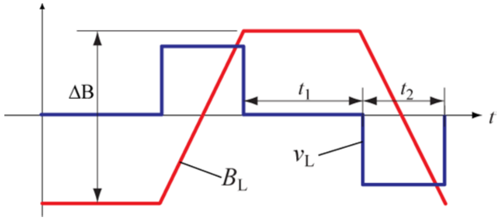
- Rate-dependent *BH* Loop.
- Reestablishment of a thermal equilibrium is governed by relaxation processes.
- Restricted domain wall motion.

Current Waveform

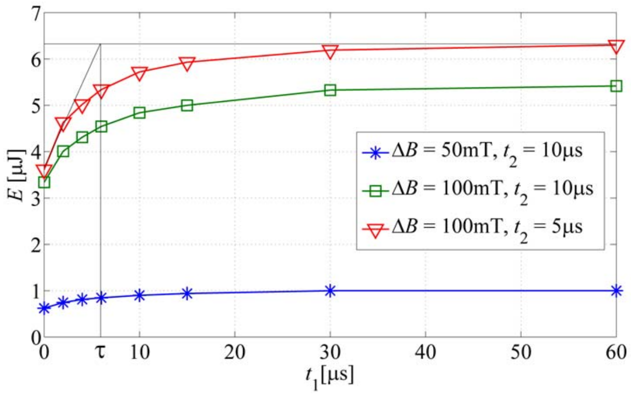


Relaxation effect
Model Derivation 1 (1)

Waveform



Loss Energy per Cycle



Derivation (1)

Relaxation loss energy can be described with

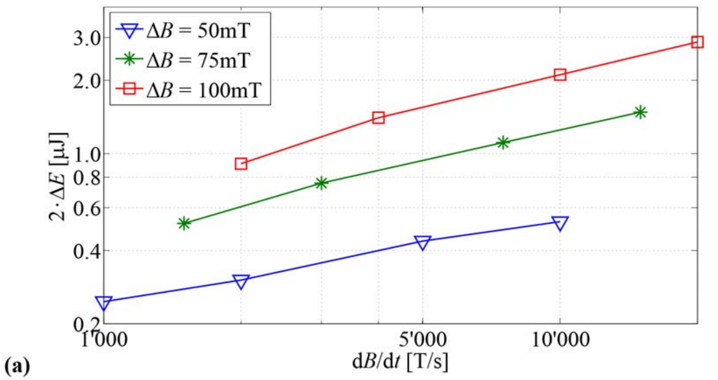
$$E = \Delta E \left(1 - e^{-\frac{t_1}{\tau}} \right)$$

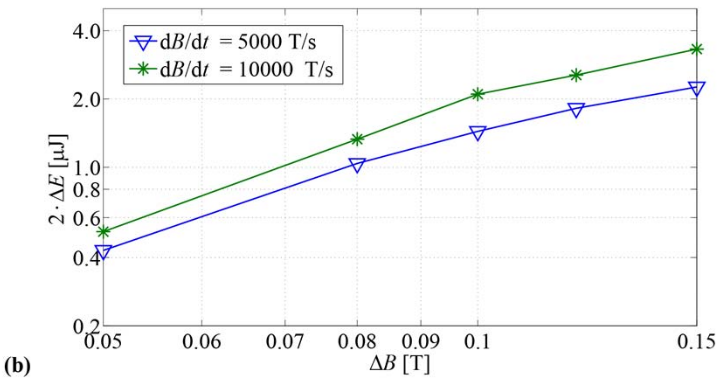
τ is independent of operating point.

How to determine ΔE?

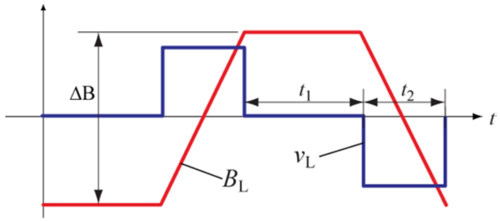
Relaxation effect
Model Derivation 1 (2)

ΔE – Measurements



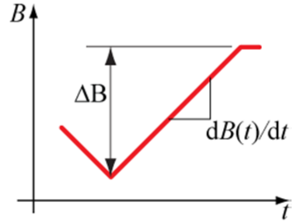


Waveform



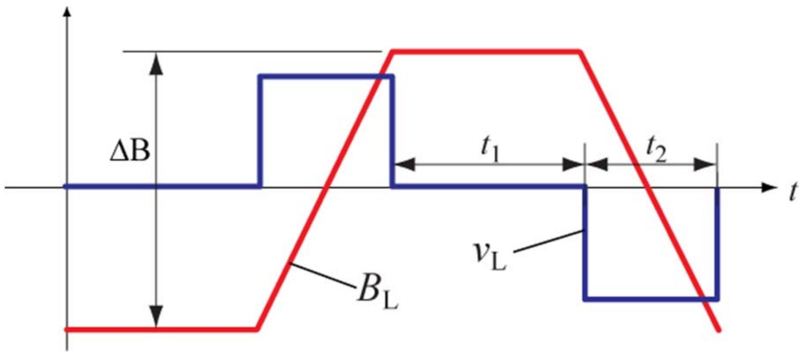
Conclusion

→ 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

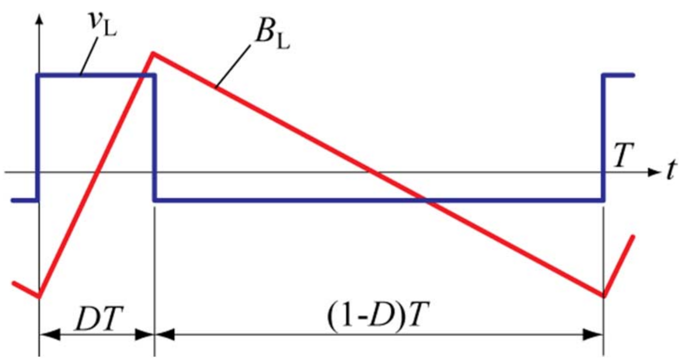
$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} P_{rl}$$

$$P_{rl} = \frac{1}{T} k_r \left|\frac{\mathrm{d}}{\mathrm{d}t} B(t)\right|^{\alpha_r} (\Delta B)^{\beta_r} \left(1 - e^{-\frac{t_1}{\tau}}\right)$$

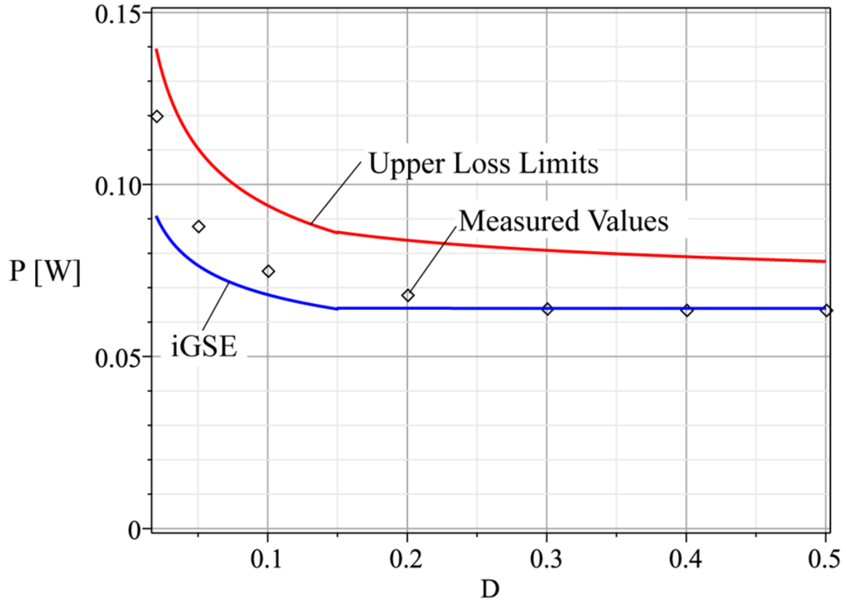
Relaxation effect

Model Derivation 2 (1)

Waveform



Power Loss

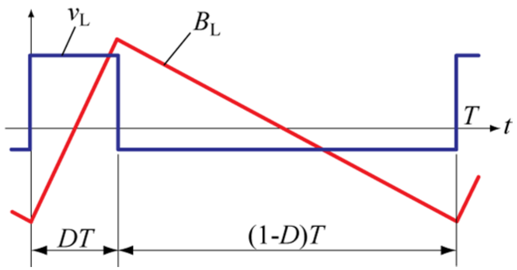


Explanation

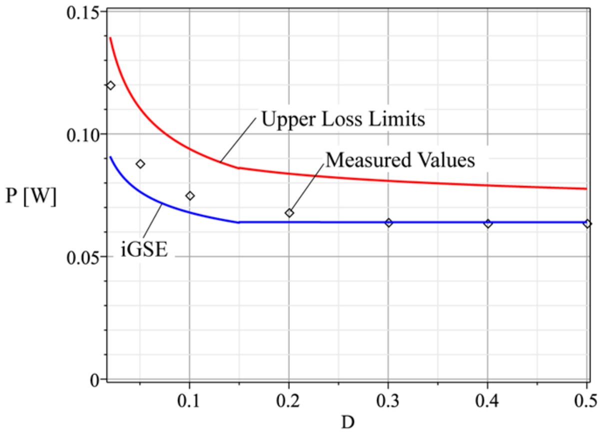
1) For values of *D* close to 0.5 the iGSE is expected to be accurate.
2) For values of *D* close to 0 or close to 1 a loss underestimation is expected when calculating losses with iGSE (no relaxation losses included).
3) Hence, adding the relaxation term leads to the upper loss limit, while the iGSE 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 $D = 0$

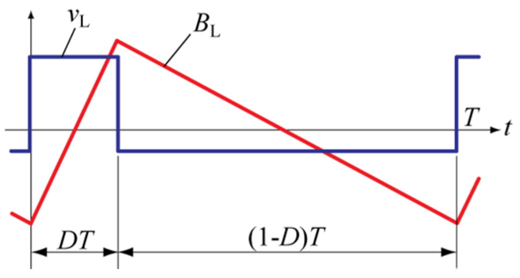
Q_{rl} should be 0 for $D = 0.5$

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

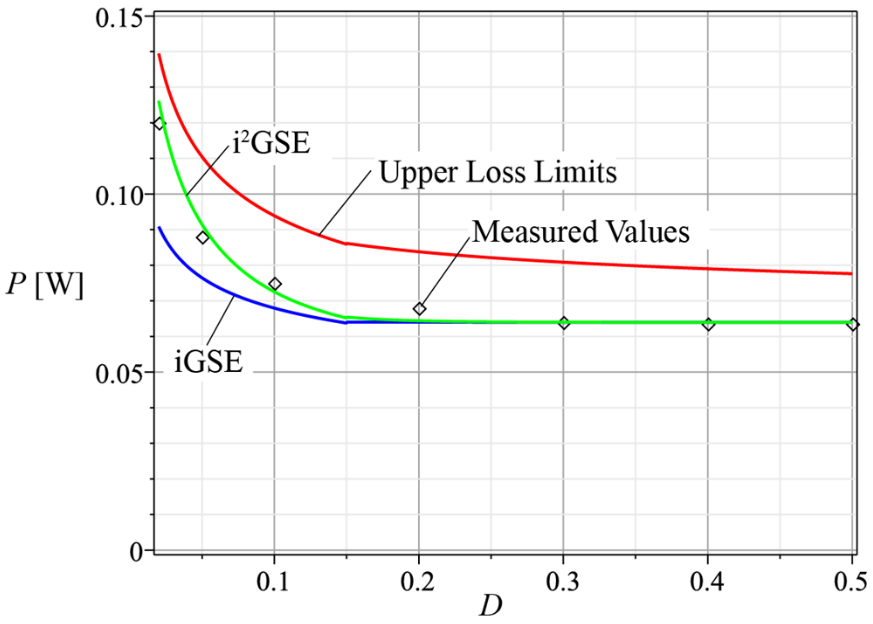
$$Q_{rl} = e^{-q_r \left|\frac{dB(t+)/dt}{dB(t-)/dt}\right|} \left(= e^{-q_r \frac{D}{1-D}} \right)$$

Relaxation effect
Model Derivation 2 (3)

Waveform



Power Loss



Relaxation effect
New Core Loss Model

The improved-improved Generalized Steinmetz Equation (i²GSE)

Evaluated for each piecewise-linear flux segment

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

Evaluated for each voltage step, i.e. for each corner point in a piecewise-linear flux waveform.

with

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

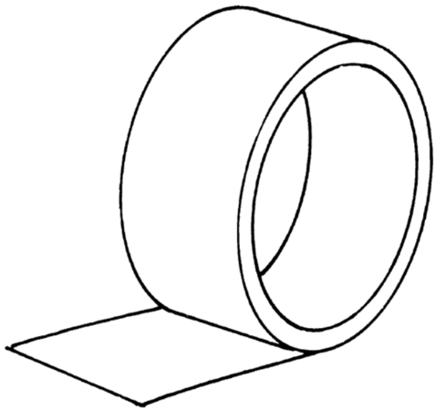
and

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

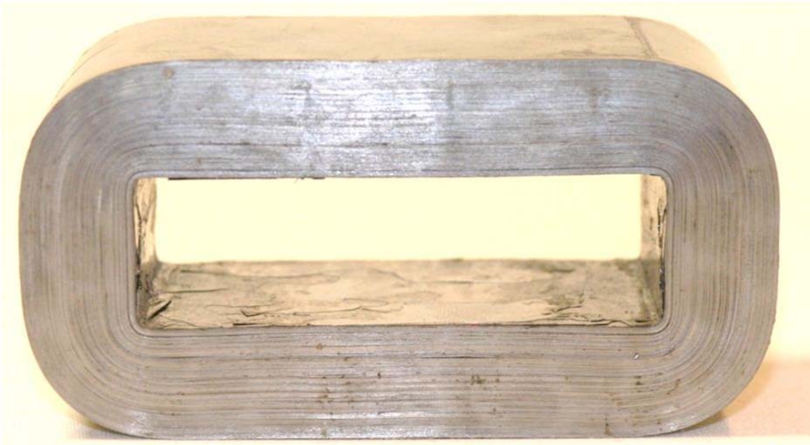
Agenda

- **Core Losses under DC Bias Conditions**
- **Relaxation Effects in Magnetic Materials**
- **Losses in Gapped Tape Wound Cores**

Losses in Gapped Tape Wound Cores
Tape Wound Cores



www.vacuumschmelze.de



Thin ribbons (approx. 20 μm)

Wound as toroid or as double C core.

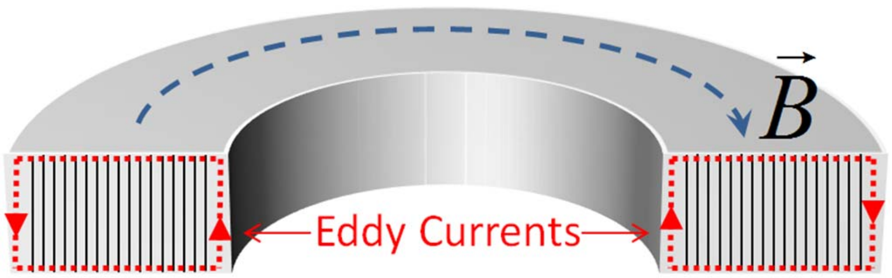
Amorphous or nanocrystalline materials.

Losses in gapped tape wound cores higher than expected!

Losses in Gapped Tape Wound Cores
Cause 1: Interlamination Short Circuits

Machining process

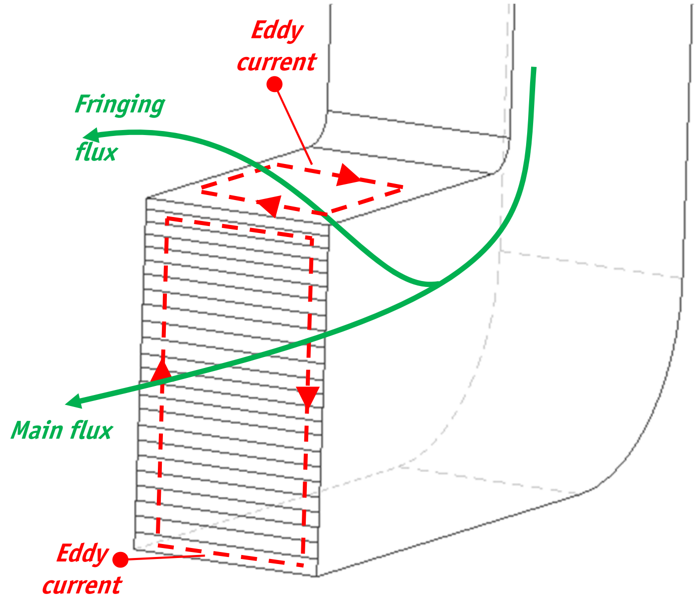
Surface short circuits introduced by machining
(particular a problem in in-house production).



After treatment may reduce this effect. At ETH, a core was put in an 40% ferric chloride $FeCl_3$ solution after cutting, which substantially (more than 50%) decreased the core losses.

Losses in Gapped Tape Wound Cores

Cause 2: Orthogonal Flux Lines

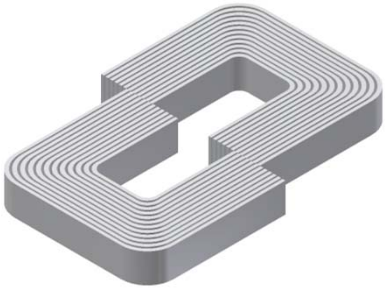


A flux orthogonal to the ribbons leads to very high eddy current losses!

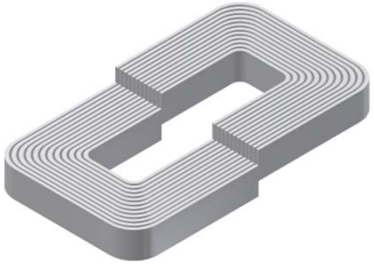
Losses in Gapped Tape Wound Cores
Orthogonal Flux Lines – Illustrative Experiment

An experiment that illustrates well the loss increase due to an orthogonal flux is given here.

Displacements

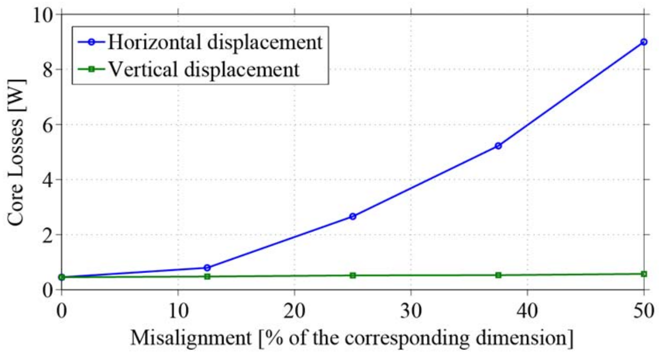


Horizontal Displacement



Vertical Displacement

Core Loss Results

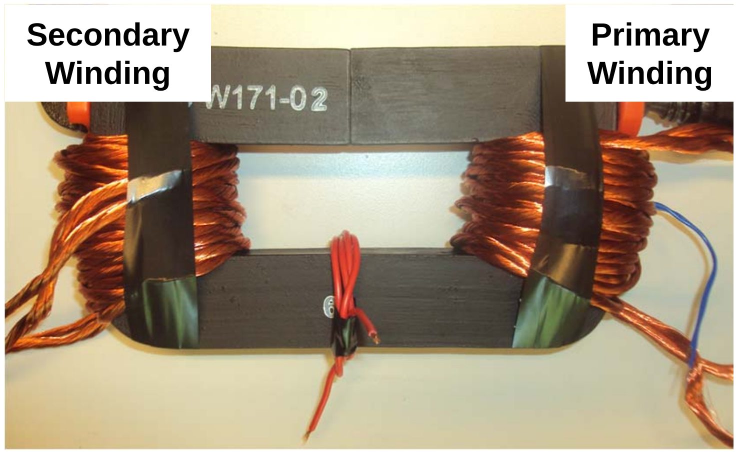


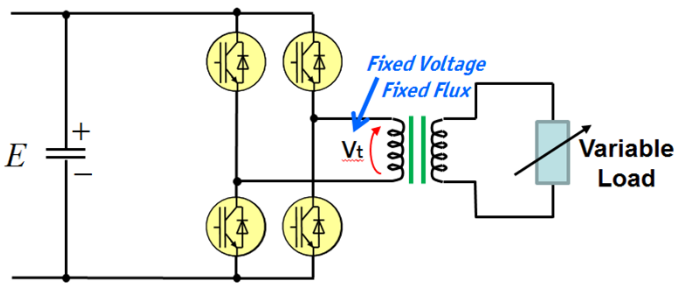
Losses in Gapped Tape Wound Cores

Orthogonal Flux Lines – Transformer Leakage Flux

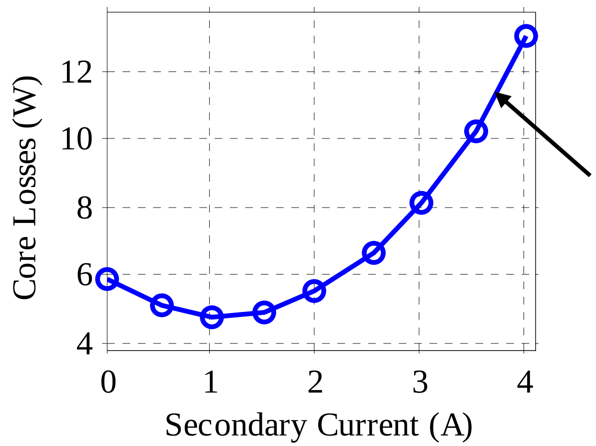
Core loss increase due to leakage flux in transformers.

Measurement Set Up



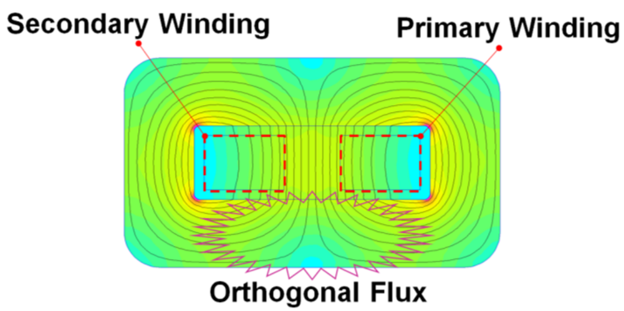


Results



A higher load current leads to higher orthogonal flux!

FEM



Losses in Gapped Tape Wound Cores

Orthogonal Flux Lines – Air Gap Length

In [10] a core loss increase with increasing air gap length has been observed.

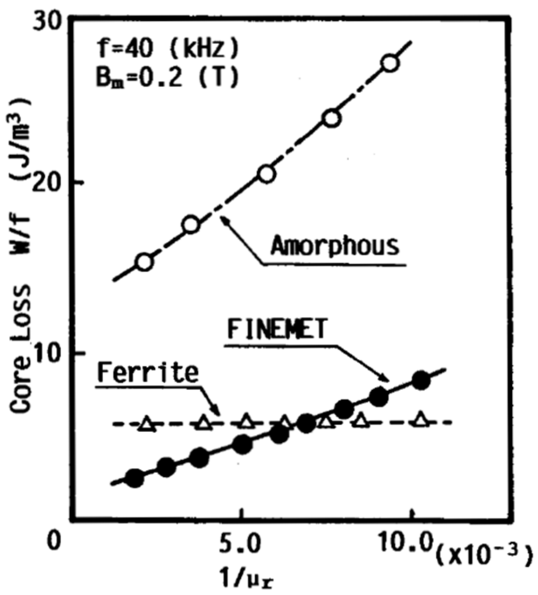


Fig.1 Core loss per cycle W/f in FINEMET, Fe-based amorphous, and ferrite cut cores as a function of inverse of the effective permeability μ_r.

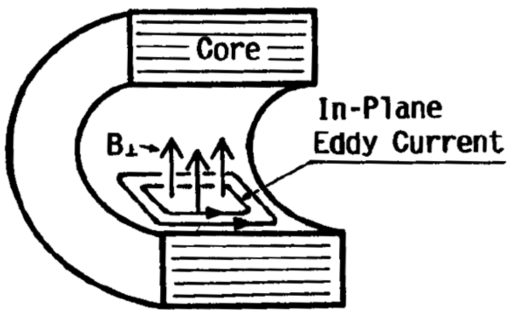


Fig.2 Schematic representation of in-plane eddy current generated by leakage flux normal to ribbon surfaces.

Figures from [10]

[10] 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.

Conclusion & Outlook

The following effects have been discussed:

Core Losses under DC Bias Condition [1]

Relaxation Effects in Magnetic Materials [2]

Losses of Gapped Tape Wound Cores [3,4]

Thank you !

Do you have any questions ?

References

[1] J. Mühlethaler, J. Biela, J. W. Kolar, A. Ecklebe, “Core Losses Under the DC Bias Condition Based on Steinmetz Parameters“, IEEE Transactions on Power Electronics, Vol. 27, No. 2, February 2012.

[2] J. Mühlethaler, J. Biela, J. W. Kolar, A. Ecklebe, “Improved Core-Loss Calculation for Magnetic Components Employed in Power Electronic Systems“, IEEE Transactions on Power Electronics, Vol. 27, No. 2, February 2012.

[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.