APEC 2025

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Georgia World Congress Center

Core Evaluation Kit Initiative for the comparison of core loss measurement

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Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

UNI KASSEL VERSITÄT

KU LEUVEN

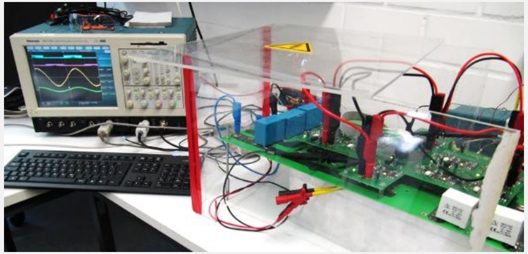
IS24.1

Introduction

KDEE-EVS/LE

- Founded in 2009, cooperation of four chairs
- Former head of the Institute: Prof. Dr.-Ing. habil. Peter Zacharias
- Future focus currently under development

Laboratories (KDEE-EVS/LE)



Jens Friebe

2004-2017
- **SMA Solar Technology**
- WBG, Magnetics, Power Electronics Packaging <20kW

2018-02/2023
- **Leibniz University Hannover**
- Passives in Power Electronics
- WBG-focus on GaN(Systems)

Since 03/2023
- **University of Kassel**
- Power Electronics

Core Evaluation Kit – What is it?

- Initiative of different scientific and industrial partners for core losses
- Comparison of
  - Measurement setups
  - Analytical methods
  - Numerical methods
- Goals
  - Better understanding of core losses
  - Better possibilities for comparison of datasheets of different manufactures
- Composition of a set of cores to minimize the effects at measurements of the material, core size, etc.

  → Core-Evaluation-Kit

Core Evaluation Kit – What is it?

- 6 Kits, each with 18 different toroid cores
  - 9 nanocrystalline cores
  - 6 powder cores
  - 3 ferrite cores

Content of one Core-Evaluation-Kit					
			Core dimensions		
Manufacturer	**Material**	**A_L @10 kHz [µH]**	**OD [mm]**	**ID [mm]**	**h [mm]**
VAC Vacuumschmelze GmbH & Co. KG	ZINA	-	16	10	6
	VP500F	43			
	VP500F	10.5			
	VP500F	67	25	16	10
	VP500F	10.5 – 24.6			
	VP550HF	69.9			
	VP712F	8.6			
	VP500F	45	50	40	20
	VP500F	18			
Magnetics Inc.	High Flux 060	-	16	10	6
			25	16	10
			50	30	15
	Kool Mu 060	-	16	10	6
			25	16	10
			16	10	6
Sumida AG	Fi335	-	16	10	6
			25	16	10
			50	30	15

Core Evaluation Kit – Guidelines

- <u>**Power density:**</u>
  - Limited to a maximum of **300mW/cm^3**
- <u>**Frequency**</u>:
  - Range of **10 kHz - 200 kHz**
  - Step Size: 10 kHz, 20 kHz, 50 kHz, 100 kHz, 200 kHz
- <u>**Current shape:**</u>
  - **Sinusoidal** or **triangular**
- <u>**Flux density**</u>:
  - Starting point: **10 mT**
  - Final point: corresponding to the setup and the other maximum defined values.
  - **10 different points**
- <u>**Temperature:**</u>
  - Maximal **temperature rise** of **5K** during the measurement.
  - **Ambient** temperature of **25°C.**
  - **Temperature** shall be **logged.**
- <u>**Measurement time**</u>:
  - **As short as possible** to minimize the rise of temperature.
- <u>**Documentation**</u>:
  - .csv-format
  - Measurement time and date shall be documented.
- Measurement setup shall be documented.

<u>**Restrictions**</u>

- No oil cooling allowed.
- No machine winding allowed.
- Identification of the core shall be maintained throughout the whole process.

Measurement Setups - Norm

- International Norm IEC 62044-3

  Cores made of soft magnetic materials – Measuring methods

  Part 3: Magnetic properties at high excitation level

  - Multiplicating-method
    - V-A-W – measurement setup analog
      - Voltage-Ampere-Watt -> $P = \overline{(v \cdot i)}$
    - Impedance-analysator
      - $P = \frac{V_{rms}^2}{R_p}$
    - V-A-W – measurement setup digital
      - Voltage-Ampere-Watt -> $P = \frac{1}{n} \cdot \sum_{i=1}^{n} (V_i \cdot I_i)$
    - Vector spectrometer technique
      - $P = \sum_k (V_k \cdot I_k) \cdot \cos(\varphi_k)$
      - k: k-th harmonic U: RMS-value I: RMS-value
    - Cross-Power-method
      - FFT of u(t) and i(t)
      - Calculation of the RMS-values for the fundamental frequency and the harmonics
      - Same Calculation as for the vector spectrometer technique

DIN EN IEC 62044-3, “Cores made of soft magnetic materials – Measuring methods – Part 3: Magnetic properties at high excitation level”, August 2024

Measurement Setups - Norm

- International Norm IEC 62044-3

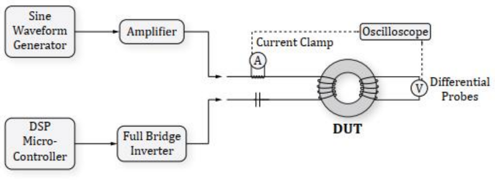
  Cores made of soft magnetic materials – Measuring methods

  Part 3: Magnetic properties at high excitation level

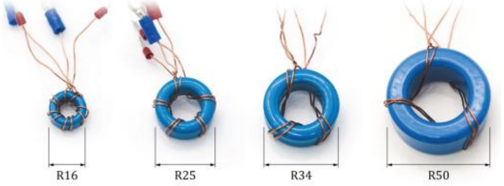
  - RMS-method
    - Method with True RMS-measuring devices
  - Reflection-method
    - Measurement with network-analysator
    - Based on the difference of radiated power and reflected power
    - Suitable for frequencies over 500 kHz
  - Calorimetric measurement setup
    - Based on temperature differences in consequence of increased or decreased power loss of the DUT

DIN EN IEC 62044-3, “Cores made of soft magnetic materials – Measuring methods – Part 3: Magnetic properties at high excitation level”, August 2024

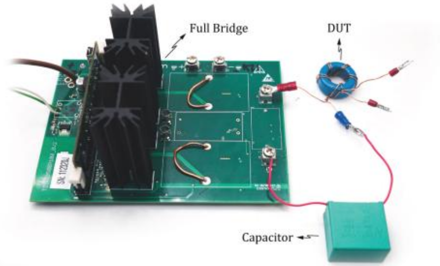
Iron Loss Characterization – KU Leuven



(a)

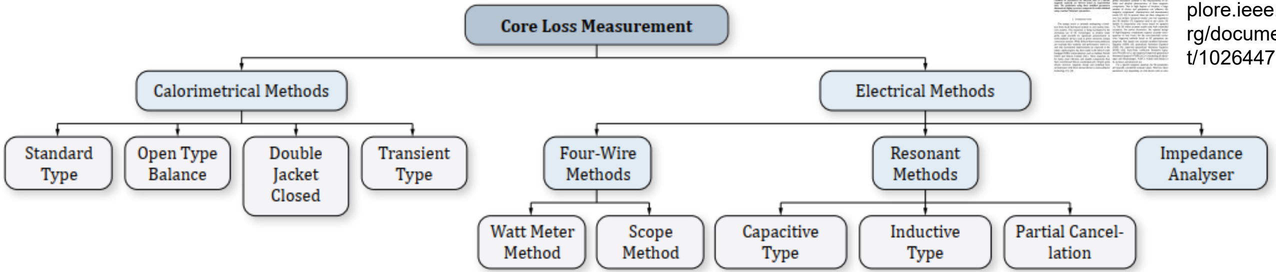


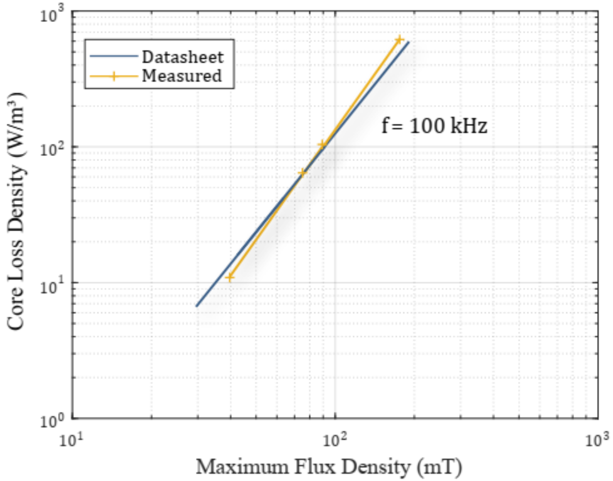
(b)

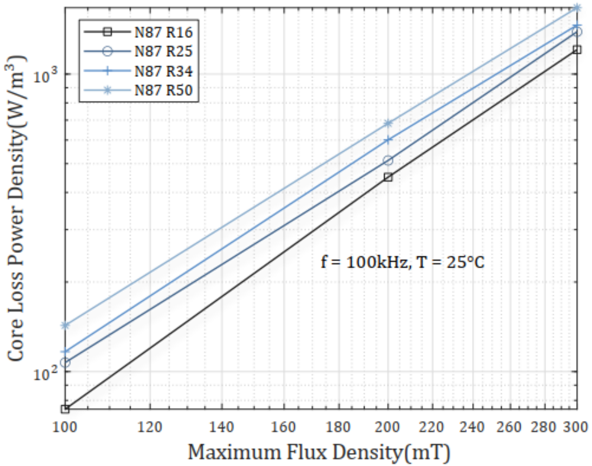


$$P_{loss\_density} = \frac{N_1}{N_2 T V_e} \cdot \int_0^T i(t) \cdot v(t)$$

Overview of core loss measurements in practice







Paper IEEE

https://ieeexplore.ieee.org/document/10264477

Xiaobing Shen, Hans Wouters, Wilmar Martinez. "Improving Steinmetz Parameters for Iron Loss Characterization with a Magnetic Measurement Kit", 2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe), Aalborg, Denmark, doi: 10.23919/EPE23ECCEEurope58414.2023.10264477

Comparison of Core Losses – KU Leuven

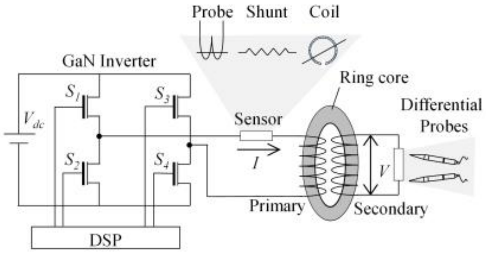
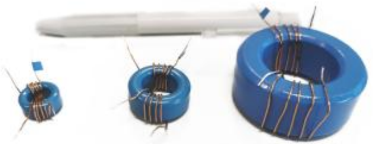
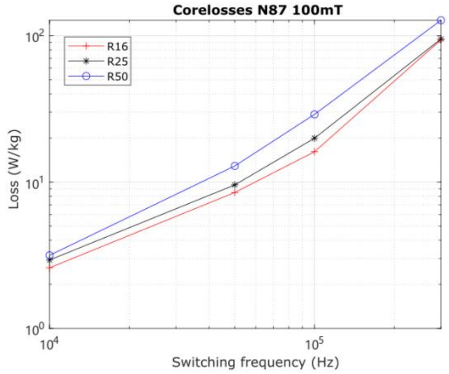


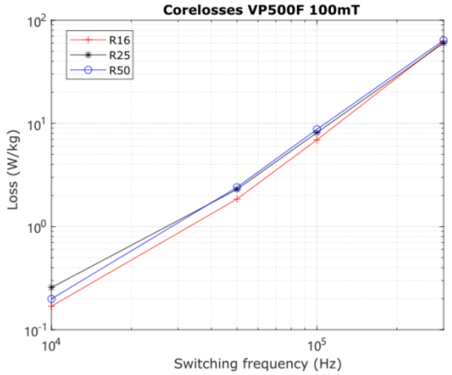
Fig. 2: Measurement circuit

Fig. 3: GaN Inverter Setup



$$P_{Fe} = \frac{N_1}{N_2 T \rho V_e} \cdot \int_0^T i(t) \cdot v(t)$$



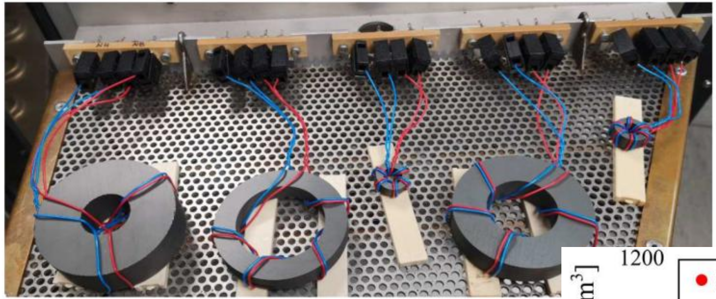


Paper IEEE

https://ieeexplore.ieee.org/document/9907561

Wilmar Martinez, Xiaobing Shen, Siqi Lin, Jens Friebe. "Magnetic Core Evaluation Kit for the Comparison of Core Losses", 2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe), Hanover, Germany

Investigation of core-loss - SUMIDA

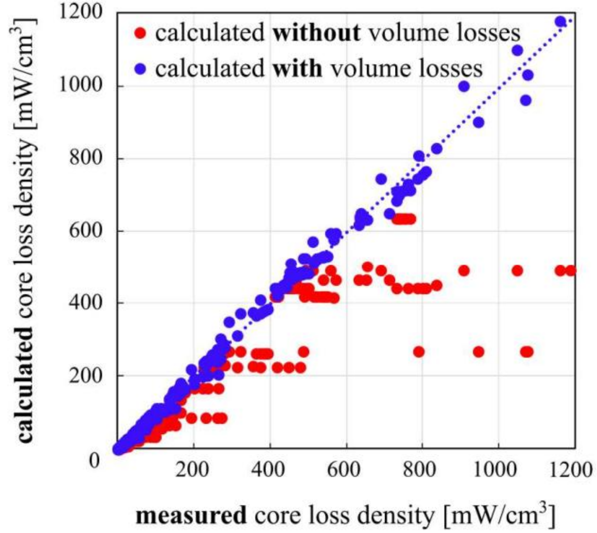


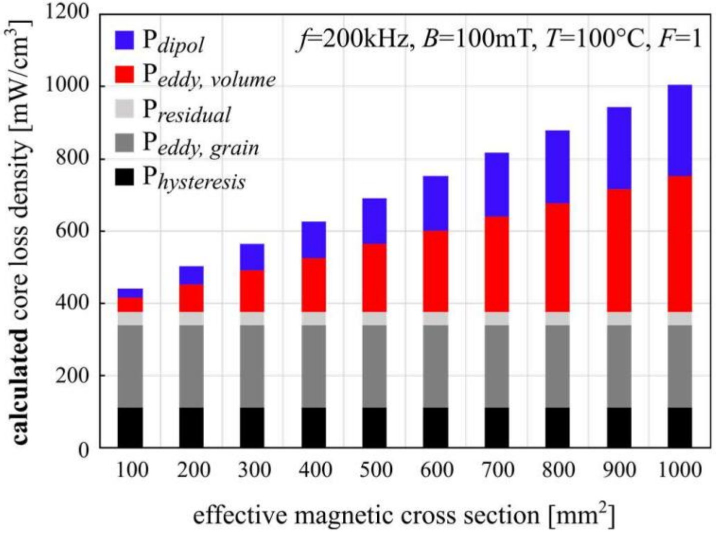
$$P_{core} = P_{hyst} + P_{edddy,grain} + P_{res} + P_{dielectric}$$

Paper IEEE

https://ieeexplore.ieee.org/document/9907281

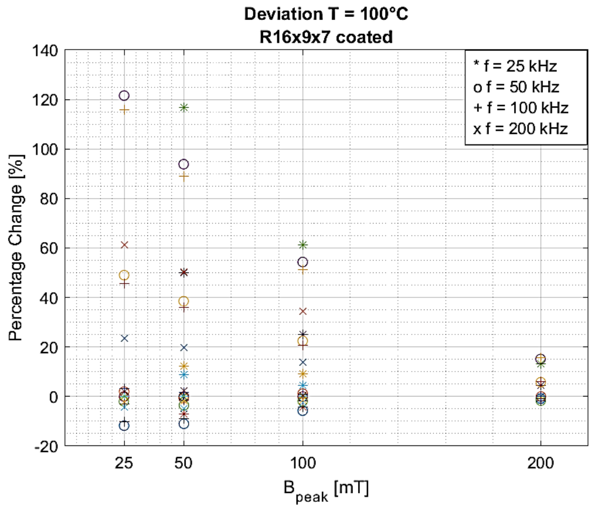
- Comparison of calculated and measured core-losses with (blue) and without (red) dielectric losses
- Each point represents either a toroidal core or a U-core with different cross sections and produced of different ferrite materials

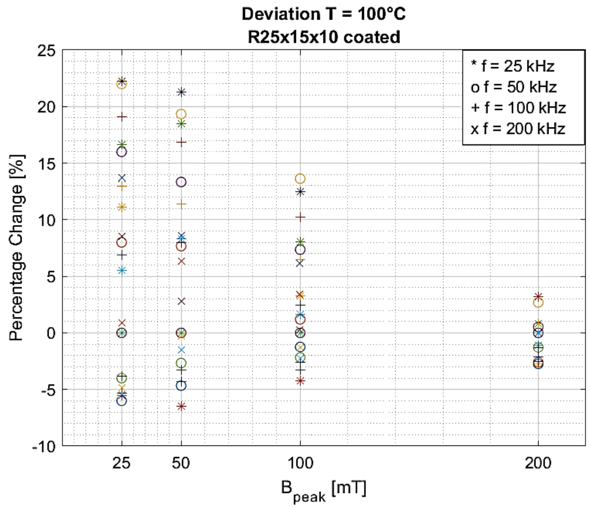


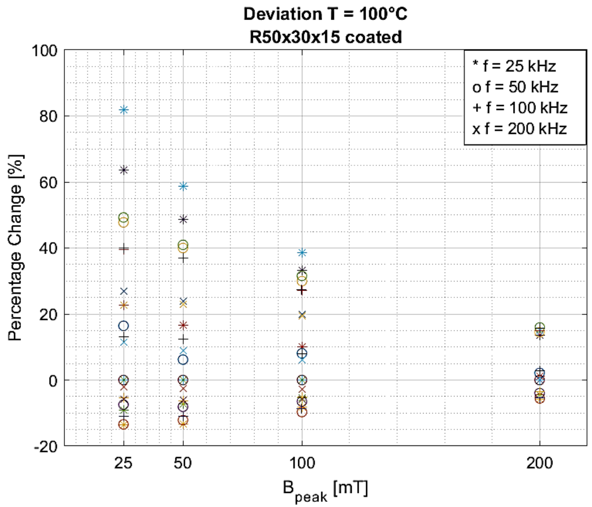


Michael Baumann, Christoph Drexler, Jonas Pfeiffer, Jens Schueltzke, Erwin Lorenz, Michael Schmidhuber. "Investigation of core-loss mechanisms in large scale ferrite cores for high frequency applications", 2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe), Hanover, Germany

Difference between the Kits







$$Kit\ (x): Kit\ (1), Kit(2), Kit(3), Kit(4), Kit(5)\ or\ Kit(6)$$

$$temp: Temperature$$

$$dev[\%] = \frac{p_v(Kit\ (x), temp) - p_v(Kit\ 1, temp)}{p_v(Kit\ 1, temp)} \cdot 100$$

Map of current Core-Evaluation-Kit members

Scientific members

- Germany:
  - University of Kassel
    - Calorimetric Setup and Resonant measurement setup
  - TH Cologne – University of Applied Sciences
    - Measurement Setup for coupled inductors
  - University of Paderborn
    - Setup under development
- Belgium
  - KU Leuven – Energyville
    - GaN full-bridge inverter
- USA
  - University of Texas at Austin
    - Setup under development
- United Kingdom
  - University of Bristol
    - Triple Pulse Test

Industrial members

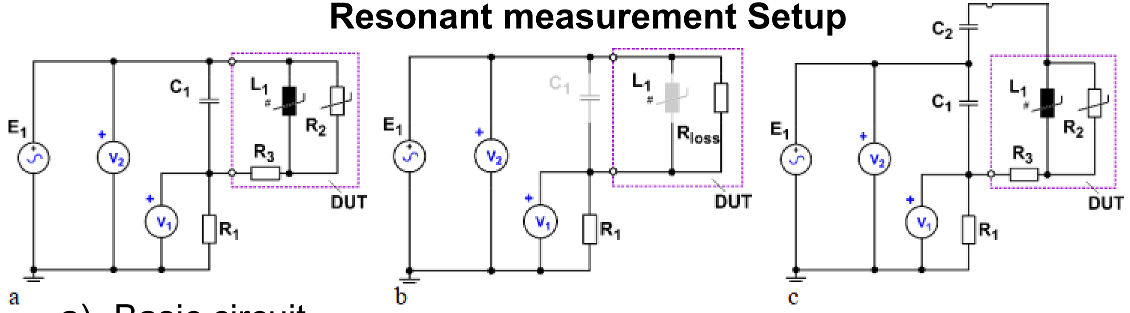
- Germany:
  - SUMIDA AG
- Poland
  - SMA Magnetics

Measurement Setups - University of Kassel

Peter Zacharias, Alejandro Aganza-Torres. “Measurement method for simple determination of sinusoidal large signal losses in inductive components”, 2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe), Hanover, Germany

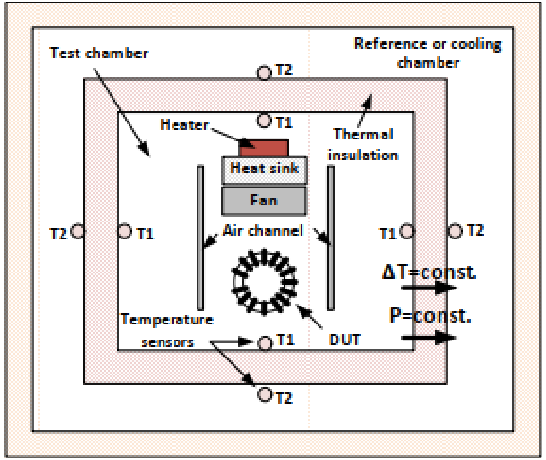
https://ieeexplore.ieee.org/document/9907263

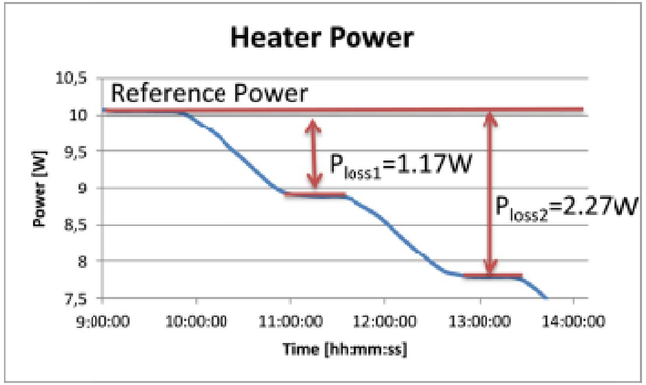
Resonant measurement Setup



a) Basic circuit
b) Remaining structure in the resonance case
c) Extension of the ciruit to achieve higher voltages at the DUT

Calorimetric Setup

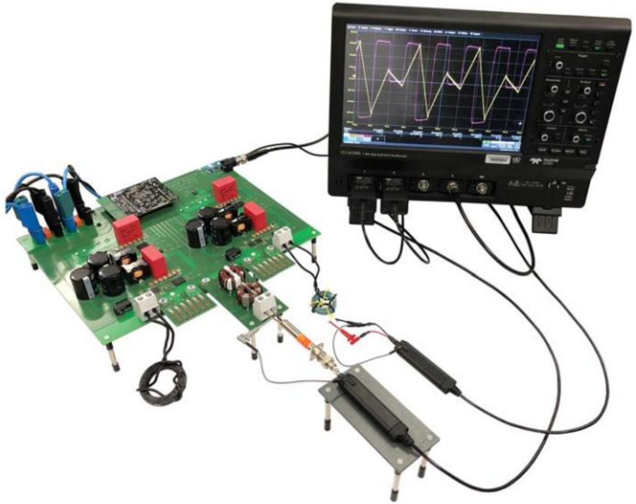




Thiemo Kleeb, Benjamin Dombert, Samuel Araujo, Peter Zacharias ."Loss measurement of magnetic components under real application conditions”, 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, France

https://ieeexplore.ieee.org/document/6631895

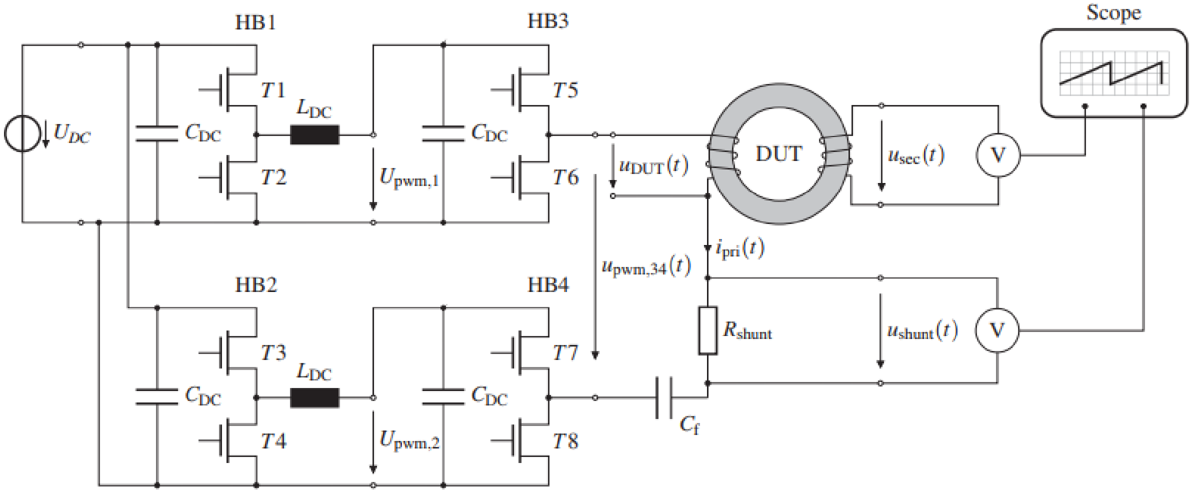
Measurement Setups - TH Cologne



Special Measurement Setups for Core-Loss – Measurement Setup for Coupled Inductors

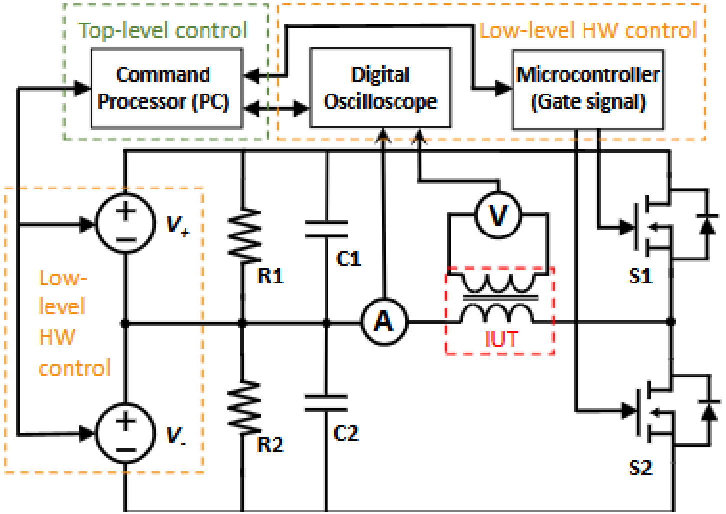
Paper IEEE

https://ieeexplore.ieee.org/document/9907479

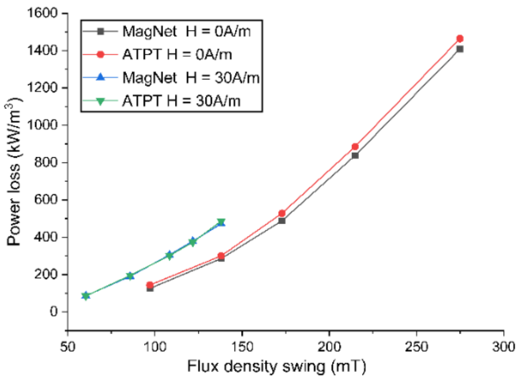


David Bohne, Valentin Wagner, Patrick Deck, Christian Dick. "Loss characterization for soft magnetic nano-crystalline tape materials in coupled inductors", 2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe), Hanover, Germany

Measurement Setups - University of Bristol



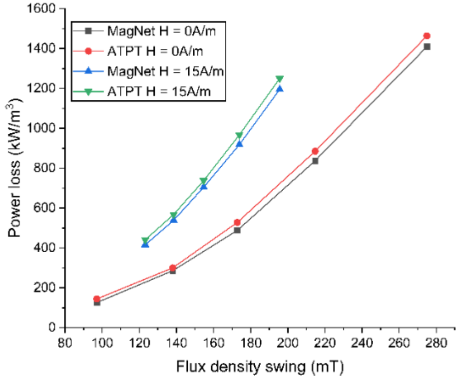
Automated Triple Pulse Testbed



Paper IEEE

https://ieeexplore.ieee.org/document/10567424

Core: N87 R34



Core: 3C90 TX25-15-10

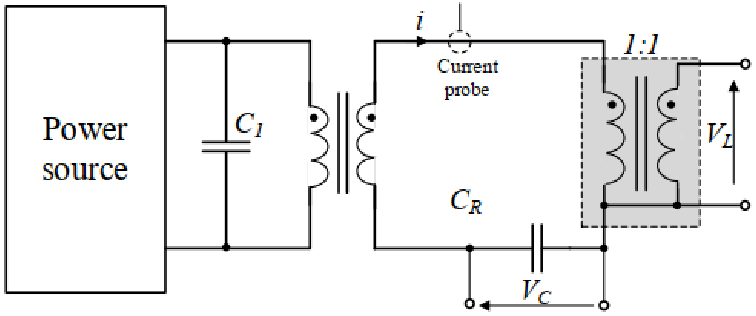
Binyu Cui, Jun Wang, Xibo Yuan, juan Aguarón, Alfonso Martinez, Francisco Cabaleiro. "Automated Triple Pulse Testbed (ATPT) 1.0 – Large-Signal Hardware-in-the-loop Characterization Platform for Power Magnetics". 2024 IEEE 10th International Power Electronics and Motion Control Conference (IPEMC2024-ECCE Asia). Chengdu. China. doi: 10.1109/IPEMC-ECCEAsia60879.2024.10567424

Measurement Setups – SMA Magnetics

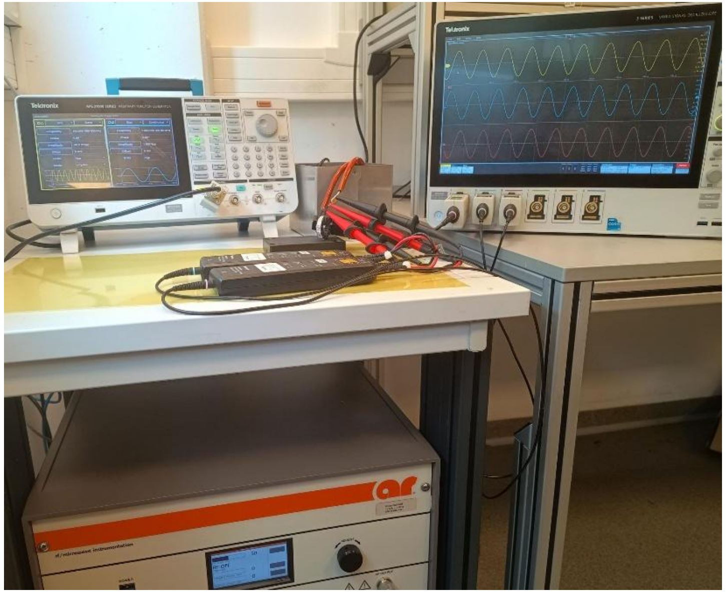
- Requires coarse resonant capacitor selection
  - reduced inherent parasitic loops
- Does not required resonance
- Need for high quality capacitors with outstanding frequency characteristics
- Cancellation achieved by waveform postprocessing
- Inductice version for non-sinusoidal waveforms

Paper IEEE

https://ieeexplore.ieee.org/document/7479554

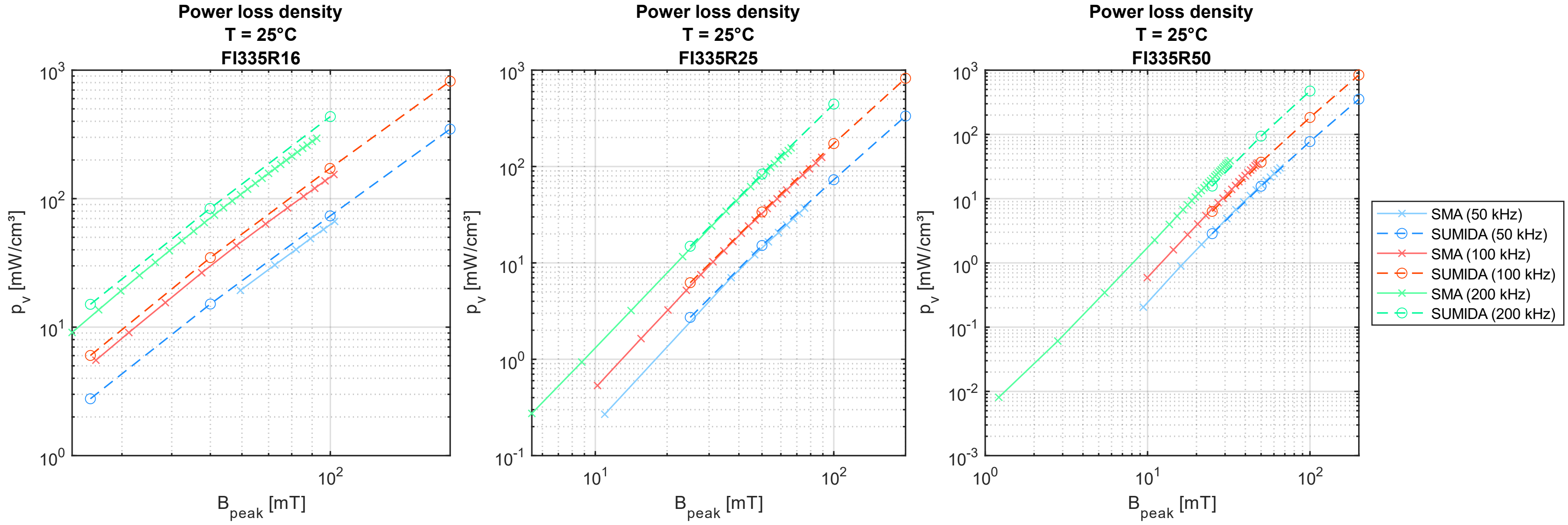


Partial cancellation concept



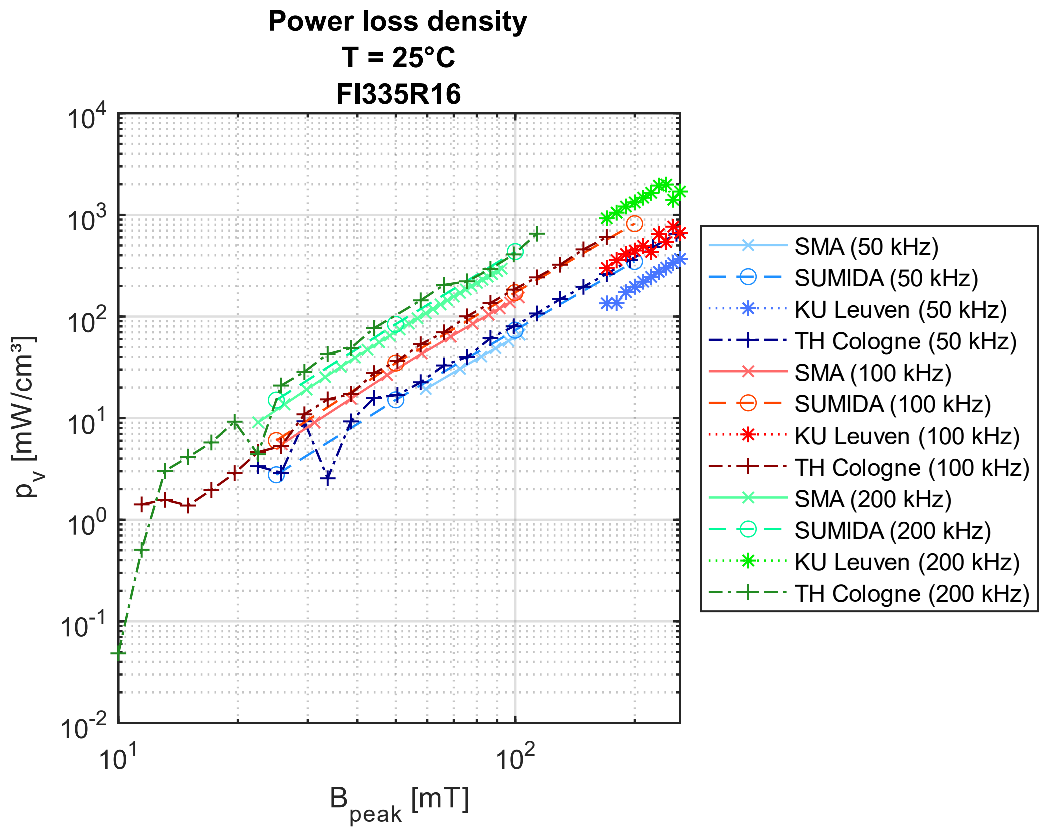
Comparison - SMA Magnetics and SUMIDA

Sinusoidal voltage / Ferrite cores / Same kit



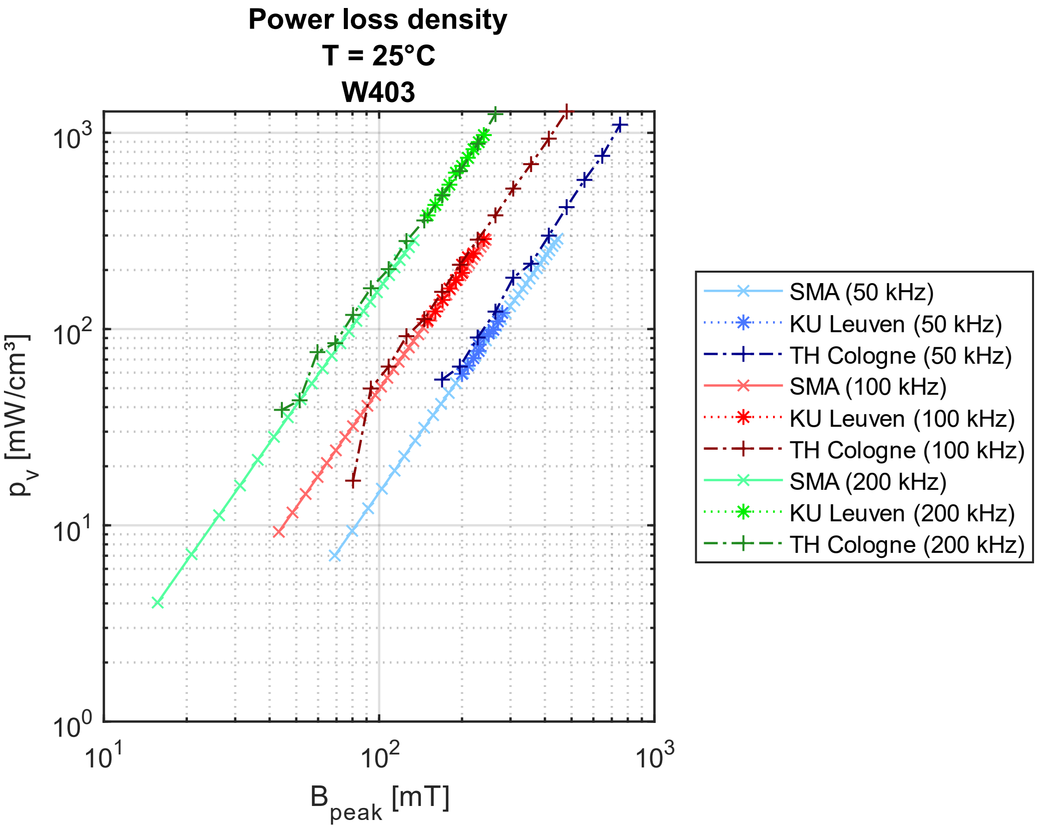
Excerpt of the Results - Ferrite

- SMA Magnetics
  - Sinusoidal voltage
  - Kit 3
- SUMIDA
  - Sinusoidal voltage
  - Kit 3
- TH Cologne
  - Rectangular voltage
  - Kit 3
- KU Leuven
  - Rectangular voltage
  - Kit 1



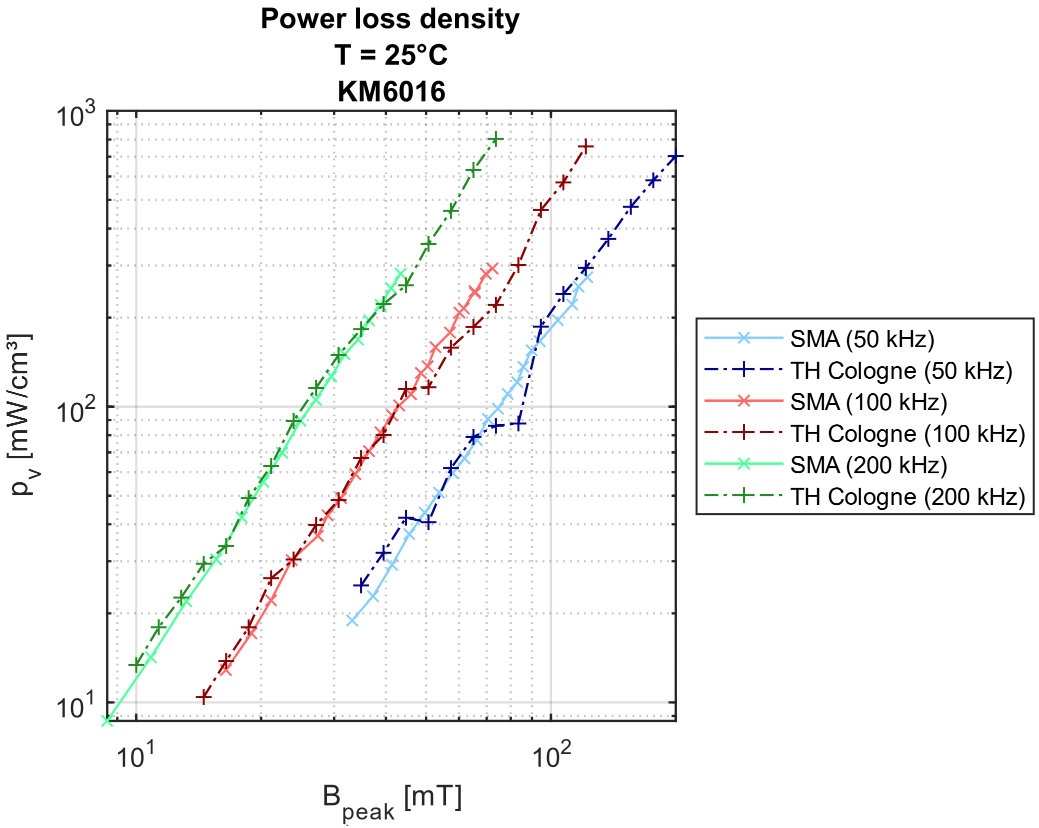
Excerpt of the Results - Nanocrystalline

- SMA Magnetics
  - Sinusoidal voltage
  - Kit 3
- TH Cologne
  - Rectangular voltage
  - Kit 3
- KU Leuven
  - Rectangular voltage
  - Kit 1



Excerpt of the Results - Powder

- SMA Magnetics
  - Sinusoidal voltage
  - Kit 3
- TH Cologne
  - Rectangular voltage
  - Kit 3



Map of current Core-Evaluation-Kit members

Scientific members

- Germany:
  - University of Kassel
  - TH Cologne – University of Applied Sciences
  - University of Paderborn
- Belgium
  - KU Leuven – Energyville
- USA
  - University of Texas at Austin
- United Kingdom
  - University of Bristol

Industrial members

- Germany:
  - SUMIDA AG
- Poland
  - SMA Magnetics

If you are interested participating, please contact us.

Jens Friebe - University of Kassel

Wilmar Martinez – KU Leuven EnergyVille

Pierre Küster - University of Kassel

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