1st IEEE International Challenge in Design Methods for Power Electronics

2023 PELS-Google-Tesla-Princeton MagNet Challenge

MagNet 2023

Kickoff Meeting, April 7, 2023

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MagNet challenge

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"It's time to upgrade the Steinmetz Equation"
– in 100-year honor of Prof. Charles P. Steinmetz (1865-1923)

- Do you like Steinmetz Equation?

$$P_v = k \times f^a \times B^b$$

  - Perhaps the **weakest** link in power electronics.
  - Not much physics, not accurate.
  - No waveform, temperature, dc-bias, etc.
  - Better first-principle physical models?
  - More accurate, capable data-driven models?

Charles Steinmetz
(1865-1923)

- If not, how can we improve/upgrade it?
  - **Improve - Stay within the Steinmetz framework?**
    - ✓ Leverage all the existing explanation and carry the historical understanding / data / knowledge about core loss.
  - **Upgrade - Jump outside of the Steinmetz framework?**
    - ✓ Try machine learning or other more advanced signal processing methods for modeling magnetics.
  - **Data is ready / tools are ready / need a clever mind**

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Strategy to win the competition?

- **Understand physics and understand data**
  - Model / method should be reasonably explainable
  - Balancing model generality and model accuracy
- **Understand materials and understand design**
  - What manufacturers provide? – modeling framework
  - What designers need? – software engineering
- **Respect legacy and challenge legacy**
  - Understand what has been done
  - Challenge existing understanding
  - Leverage modern methods and tools
- **Winning team structure:**

Data Science

Power Electronics

Software Engineering

Magnetics

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MagNet 2023 Team

MagNet 2023 Chair:

- Minjie Chen, Princeton, USA

Competition Organizing Committee:

- Haoran Li, Princeton, USA
- Thomas Guillod, Dartmouth, USA
- Diego Serrano, Wolfspeed, USA
- Shukai Wang, Princeton, USA
- Ping Wang, Princeton, USA
- Youssef Elasser, Princeton, USA

Academic Advisory Committee:

- Charles Sullivan, Dartmouth, USA
- David Perreault, MIT, USA
- Johann Kolar, ETH Zurich, Switzerland
- Dragan Maksimovic, CU Boulder, USA
- SY Ron Hui, NTU, Singapore

Industry Advisory Committee:

- Chee Chung, Google, USA
- Houle Gan, Google, USA
- Qin Lei, Tesla, USA
- Jizheng Qiu, Tesla, USA
- Shuai Jiang, Google, USA

Ad Hoc Consulting Committee:

- Maeve Duffy, U. Galway, Ireland
- Matt Wilkowski, EnaChip, USA
- George Slama, Wurth Elektronik, USA
- Edward Herbert, PSMA, USA
- Jens Schweickhardt, PE-Systems, Germany
- Ziwei Ouyang, DTU, Denmark
- Alex Hanson, UT Austin, USA

PELS TC10 Steering Committee:

- Kevin Hermanns, PE-Systems, Germany
- Shirley Pei, University of Bath, UK
- Subham Sahoo, Aalborg, Denmark
- Miroslav Vasic, UPM, Spain

PELS Signee:

- Pat Wheeler – PELS VP
- Mario Pacas – PELS VP
- Dehong Xu – PELS VP
- Frede Blaabjerg - President
- Liucheng Chang - President

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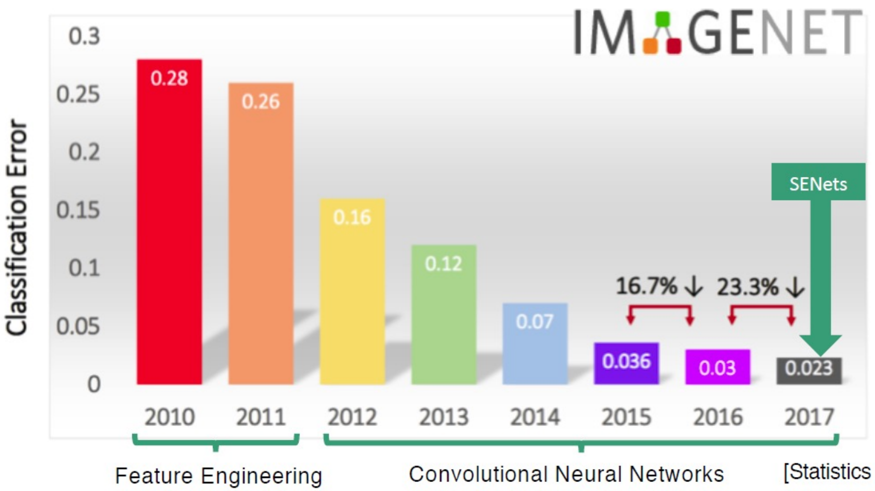
Open-Source Database and Innovation

IMAGENET
Challenge



[Statistics provided by ILSVRC]

Image Recognition Error Trend (2010-2017)

https://www.image-net.org/challenges/LSVRC/

- **An opportunity to make friends and learn from each other.**

pels MagNet challenge

- Open
- Transparent
- Inclusive
- Forward-looking
- Community
- Education
- Research
- Industry
- Fun
- Rewarding

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IEEE International Challenge in Design Methods for Power Electronics

- **IEEE PELS Hardware Design Challenge**

  http://energychallenge.weebly.com/ifec-2022.html

  IEEE International Future Energy Challenge

- **IEEE PELS Software Design Challenge**
  - **Very low entry bar**
    - A computer with internet access (Python/Matlab)
    - Magnetics + power electronics+ data science
  - **Very high potential impact**
    - The next Steinmetz's equation ???
    - Software/method foundation for Magnet-GPT or Power-GPT
    - Prompt – "Tell me a bit about N87 material under dc-bias at 100 kHz?"
  - **Realistic goals for 2023**
    - A few software packages to replace the Steinmetz equation (callable functions)
    - Manufacturers start to publish better data in more interactive way
    - Apply similar techniques to magnetics, capacitors, batteries, piezoelectric, etc …

Motivation for MagNet Challenge

- Steinmetz equations need an upgrade.
- **Imprecise material ↔ imprecise model ↔ imprecise design.**
- Unnecessary design margins (thermal, B_{sat}, batch-to-batch variation, …).
- Future chips, vehicles, and robotics need miniaturization and precision.
- Opportunities to reduce the size of all magnetics by 20%~50%?
- Need a better way to document, compress, and share information.
- Help the manufacturers to improve repeatability, control the quality, and share better data in better ways.

Charles Steinmetz
(1865-1923)

$$P_v = k \times f^a \times B^b$$

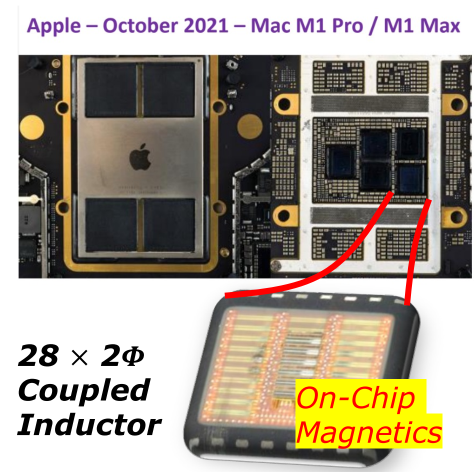
Possibly improve with MagNet 2023:

- Waveform
- Temperature

Remaining Challenges:

- Dc-bias
- Geometry impact
- HF magnetics characterization methods

On-Chip Magnetics



Every mm³ matters!!!

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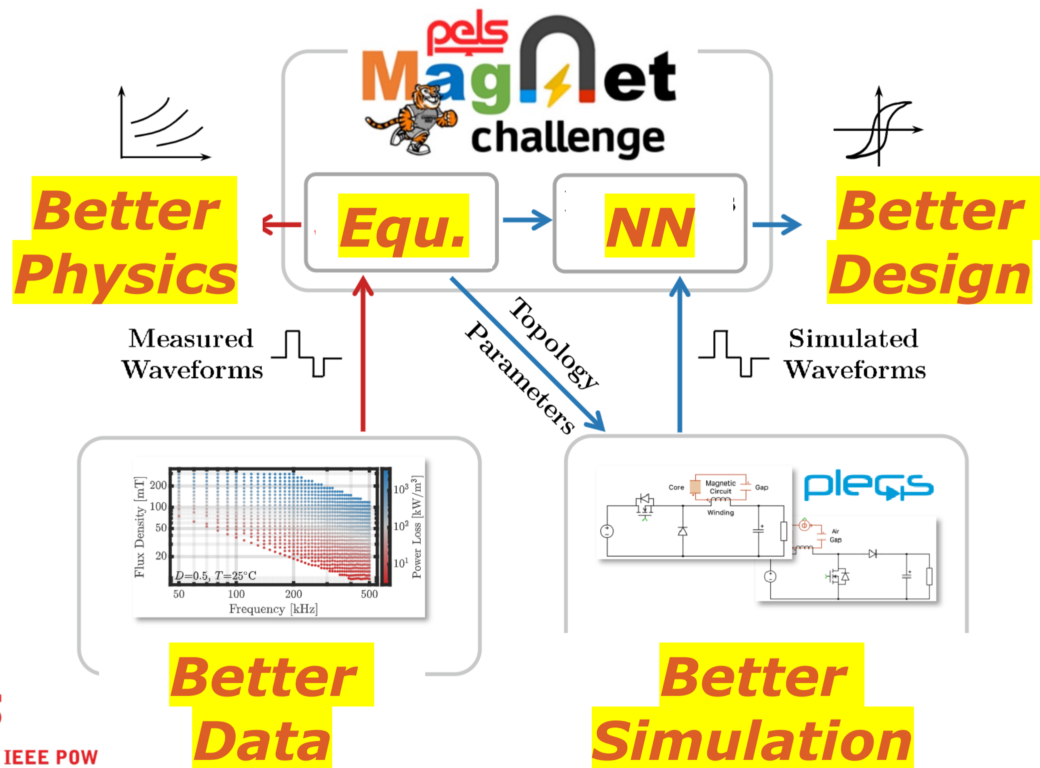
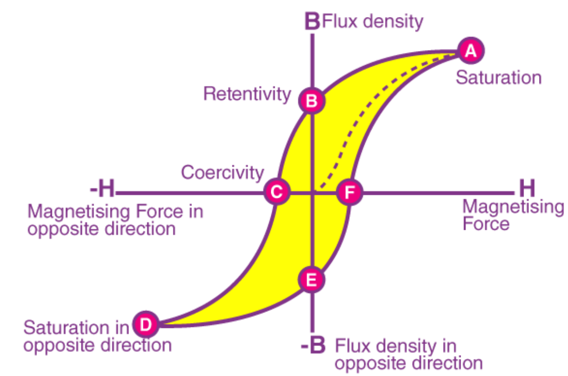
Outcomes of MagNet Challenge

- Better understandings about power magnetics.
- Better tools for power magnetics design.
- Better ways of sharing information (digital/interactive datasheet).
- Cultivate an open-source community.
- Models for other complex materials (capacitors, PZT, etc.)





- Hysteresis loop exists for almost all energy materials
- Magnetics, capacitors, piezoelectric, batteries, etc.

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Competition Focus of MagNet Challenge

- MagNet 2023 focus: understand the core loss dependency on waveform, temperature and frequency, and ***systematically*** develop a callable Python/MATLAB function for each material as the "digital" datasheet (like SPICE model for MOSFETs).

$$P_v = function\ (waveform, frequency, temperature)$$

Input Information

$B(t)$: *Single-cycle 1024-step waveform*	*in mT*
f: *Excitation frequency*	*in kHz*
T: *Operating temperature*	*in °C*

Output Information

P_v: *Volumetric Core Loss*

by integrating B-H loop

- Note: the modeling framework for different materials can be different. They don't need to be the same, e.g., ferrite and powdered iron can naturally have different models.
- **Classification + regression?**

Balance Between Generality and Accuracy

- **Steinmetz Equation (SE), 1890s** — 3 parameters

$$P_V = k \cdot f^{\alpha} \cdot \hat{B}^{\beta}$$

- **Improved Generalized Steinmetz Equation (iGSE), 2000s** — 3 parameters

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

- **Improved-improved GSE (i^2GSE), 2010s** — 8 parameters

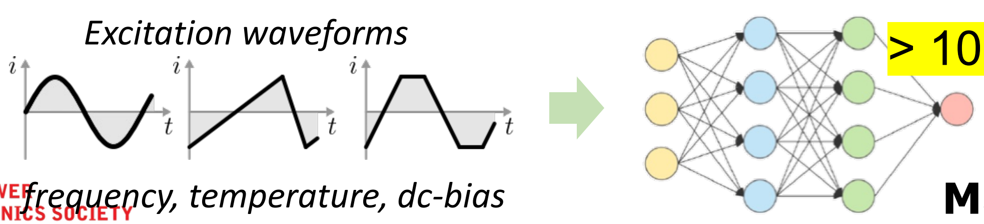
$$P_V = \frac{1}{T}\int_0^T k_i \cdot \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} \cdot (\Delta B)^{\beta}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{rl} \cdot P_{rl}$$

- **Other Parameterized Methods, 2010s** — 10~100 parameters

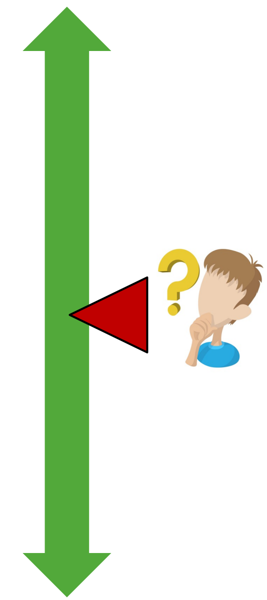
MagNet Competition Space

- Model Structure
  - simpler better
- Model Parameter
  - fewer better

- **Baseline Neural Network Models, 2020s** — > 10,000 parameters



Explainable
General
Not accurate



Not Explainable
Specialized
Accurate

MagNet Tutorial

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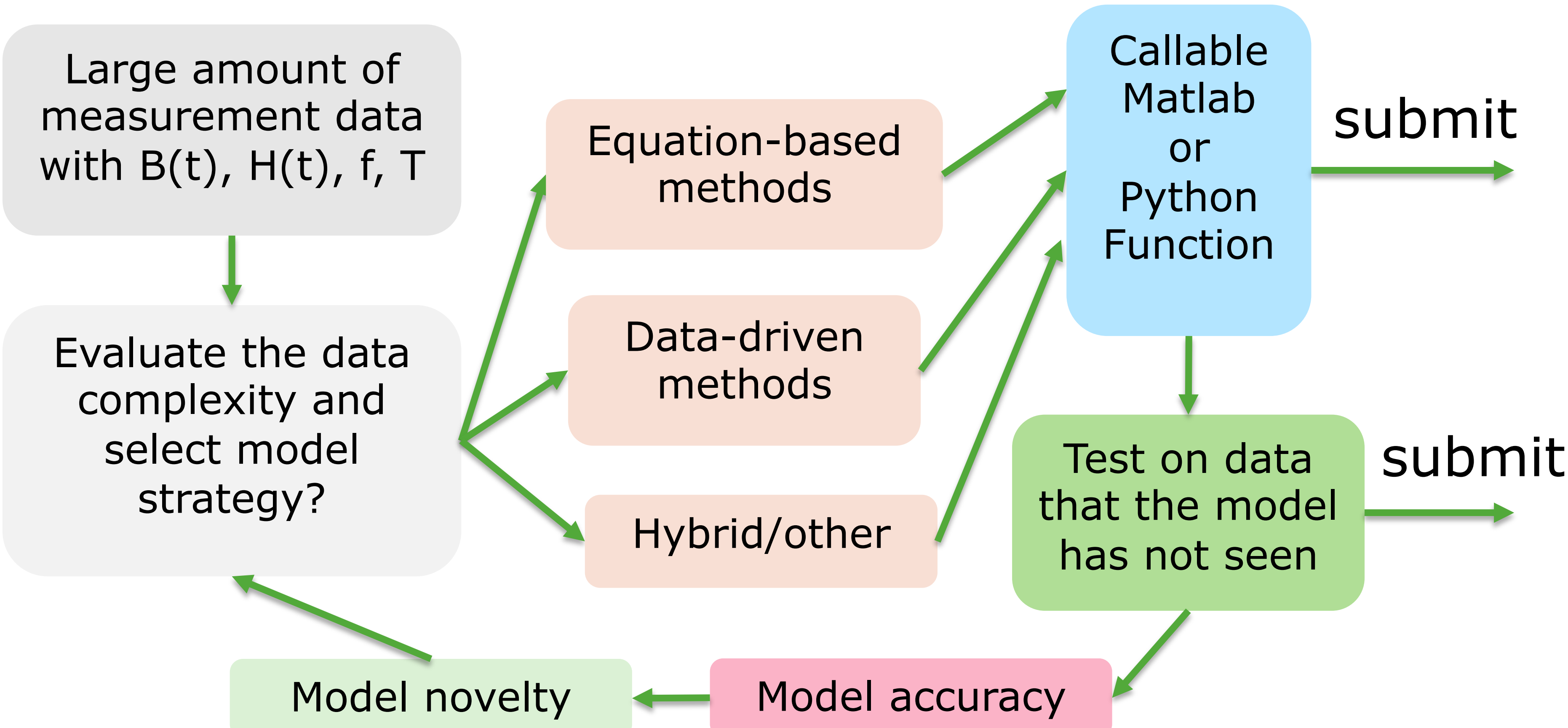
Information Flow of MagNet Challenge

$$P_v = function\,(waveform, frequency, temperature)$$



Timeline of MagNet Challenge

Feb 1st, 2023	Initial Call for Participation Announcement
April 7th, 2023	**Online Q&A Session and Official Announcement**
May 1st, 2023	1-Page Letter of Intent Due with Signature [Attached]
June 1st, 2023	2-Page Proposal Due for Eligibility Check [TPEL Format]
July 1st, 2023	Notification of Acceptance [Eligibility Check]
Nov 1st, 2023	Preliminary Submission Due, Finalists Selected
Dec 24th, 2023	Final Submission Due
March 1st, 2024	Winner Announcement and Presentation

April 1st - Large amount of data for 10 materials released

May 1st – 1-Page letter of intent due

June 1st – 2-Page proposal due

July 1st – All participating teams confirmed

Nov 1st – Callable models for 10 materials due

Nov 1st – Release small training data for 3 new materials

Dec 24th – Callable models and predicted core loss (Pv) for 10+3 materials under a variety of {B(t), f, T} conditions, and a 5-page TPEL format report due

March 1st , 2024 – Winner Announcement

MagNet Methodology
- Develop methods on **old** materials
- Test methods on **new** materials
- Train models with **small** datasets
- Test models with **large** datasets

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Student Team Eligibility

- **University Eligibility Limit: Each university's geographical campus is limited to support ONE student team (TWO?).** To confirm eligibility, potential participating schools must submit a Letter of INTENT (attached) by **May 1st, 2023**, to pelsmagnet@gmail.com, for better coordination.
- For each team, the minimum student number is **three (3)** and the maximum student number is **five (5)** to qualify for the competition. Each team should consist of between **one (1) to two (2)** undergraduate students (B.S. or equivalent), between **two (2) to three (3)** graduate students (M.S./Ph.D. or equivalent), and at least **one (1)** faculty advisor and optionally **one (1)** industry mentor. Interdisciplinary and diversified teams are highly encouraged.
- Note: We will try to host as many teams as possible. We can perhaps host **2-3 teams per university** depending on the final total participating team numbers and the quality of the proposals.
- Members of the judging committee will be replaced if there is a conflict from the same university. Student teams will NOT be judged by experts with conflicts of interest.

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Evaluation Criteria

- **Winning solution: a simple, robust, and trustworthy method to**
  - **(1) accurately predict power magnetic core loss**
  - **(2) efficiently use the training data**
  - **(3) provide useful design insights**
  - **(4) advance understanding about power magnetics**
  - **(5) other novel contributions to the field**

- **Model performance:** 95th percentile error on core loss prediction.
- **Model size:** number of material-specific parameters that need to be kept in the model. Jointly evaluated by submitted package size and code review.
- **Model novelty:** new insights and new methods in physical understanding, data processing, model development, and anything else related to power magnetics.
- **Model generality:** extending the developed model to different materials.

Final Winners selected by the Academic Advisory Committee:

- Charles Sullivan, Dartmouth, USA
- David Perreault, MIT, USA
- Johann Kolar, ETH Zurich, Switzerland
- SY Ron Hui, NTU, Singapore
- Dragan Maksimovic, UC Boulder, USA

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Award Structure

Tesla Award for Model Performance 1^{st} Place \$10,000	Google Award for Model Novelty 1^{st} Place \$10,000	Princeton CSML Award for Outstanding Software Engineering \$5,000
PELS Award for Model Performance 2^{nd} Place \$5,000	PELS Award for Model Novelty 2^{nd} Place \$5,000	PELS Honorable Mentions \$1,000 x multiple

- Performance
- Model size

- Novelty
- Model generality

- Software implementation
- Other contributions

Intellectual Property

- MagNet Challenge has no restrictions on intellectual property.
- We encourage open-source culture and open-source licenses.
- Presenting the models to MagNet team is considered as public disclosure.
- Student teams should take actions before disclosure if IP protection is needed.

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Extended Reading

- **iGSE** - K. Venkatachalam, C. R. Sullivan, T. Abdallah and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," Proc. IEEE Workshop Comput. Power Electron., pp. 36-41, 2002.
- **iGSE** - Matlab Implementation https://www.mathworks.com/matlabcentral/fileexchange/39995-magnetic-core-loss-evaluation-for-arbitrary-flux-waveforms
- **i2GSE** - J. Muhlethaler, J. Biela, J. W. Kolar and A. Ecklebe, "Improved Core-Loss Calculation for Magnetic Components Employed in Power Electronic Systems," in IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 964-973, Feb. 2012.
- **iGSE-CD** - D. Menzi et al., "iGSE-CD—An Electric-/Displacement-Field Related Steinmetz Model for Class II Multilayer Ceramic Capacitors Under Low-Frequency Large-Signal Excitation," in IEEE Open Journal of Power Electronics, vol. 4, pp. 107-116, 2023.
- **Stenglein Model -** E. Stenglein and T. Dürbaum, "Core Loss Model for Arbitrary Excitations With DC Bias Covering a Wide Frequency Range," in IEEE Trans. on Magnetics, vol. 57, no. 6, pp. 1-10, June 2021.
- **IGCC -** T. Guillod, J. S. Lee, H. Li, S. Wang, M. Chen, C. R. Sullivan, "Calculation of Ferrite Core Losses with Arbitrary Waveforms Using the Composite Waveform Hypothesis," IEEE Applied Power Electronics Conference (APEC), 2023.
- **How MagNet -** H. Li et al., "How MagNet: Machine Learning Framework for Modeling Power Magnetic Material Characteristics," TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.21340998.v3.
- **Why MagNet -** D. Serrano et al., "Why MagNet: Quantifying the Complexity of Modeling Power Magnetic Material Characteristics," TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.21340989.v3.
- **Transformer -** H. Li, D. Serrano, S. Wang, T. Guillod, M. Luo , M. Chen, "Predicting the B-H Loops of Power Magnetics with Transformer-Based Encoder-Projector-Decoder Neural Network Architecture," IEEE Applied Power Electronics Conference (APEC), 2023.