2nd IEEE International Challenge in Design Methods for Power Electronics

2025 PELS MagNet Challenge

MagNet Challenge 2

"From Steady-State to Transient Models!"

Kickoff Meeting, January 5, 2025

Shukai Wang, Hyukjae Kwon, Haoran Li, Thomas Guillod, Minjie Chen, Charles R. Sullivan

MagNet 2025 Organizing Team
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A Very Successful MagNet Challenge 1

MagNet Challenge for Data-Driven Power Magnetics Modeling

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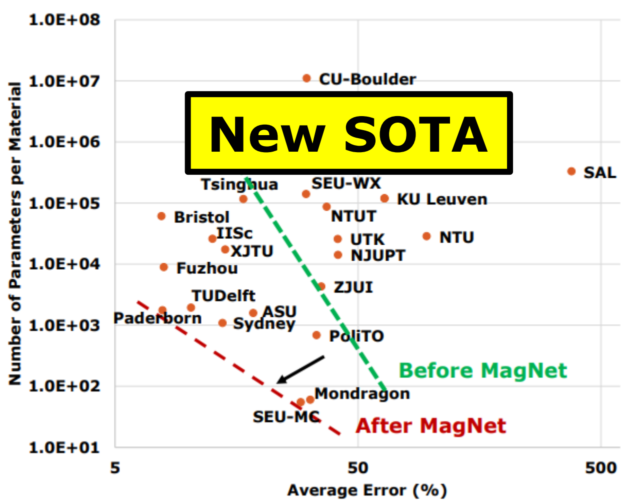
133 co-authors

Charles Steinmetz (1865-1923)



- Arizona, USA
- Fuzhou, China
- Hangzhou, China
- Bangalore, India
- Leuven, Belgium
- Hernani, Spain
- Nanjing, China
- Cambridge, USA
- Singapore, Singapore
- Taipei, Taiwan
- Hong Kong, China
- Paderborn, Germany
- Princeton, USA
- Hanover, USA
- Piscataway, USA
- Torino, …
- Graz, A…
- Lalitpu…
- Beijing…
- Fremont, USA
- D…
- B…
- Z…
- B…
- Santa Clara, USA
- Manchester, UK
- Sydney, Australia
- Knoxville, USA
- Xi'an, China
- Mountain View, USA

24 teams

Many theses

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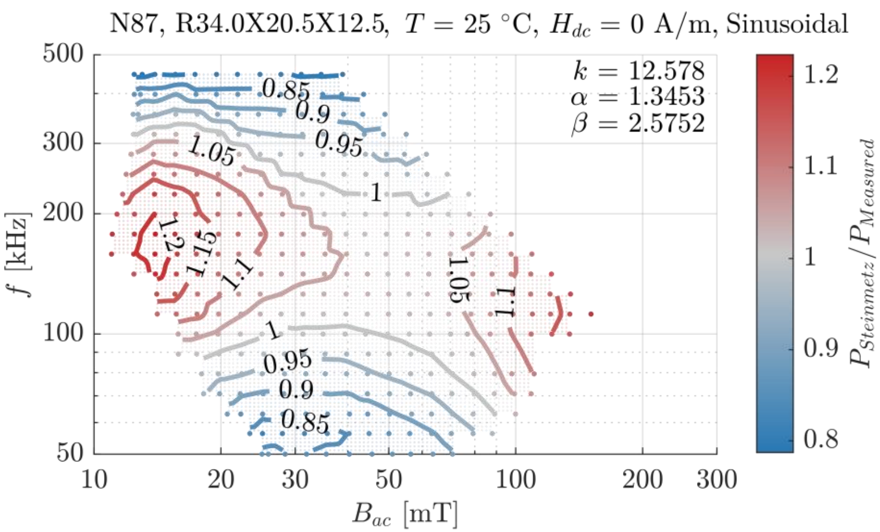
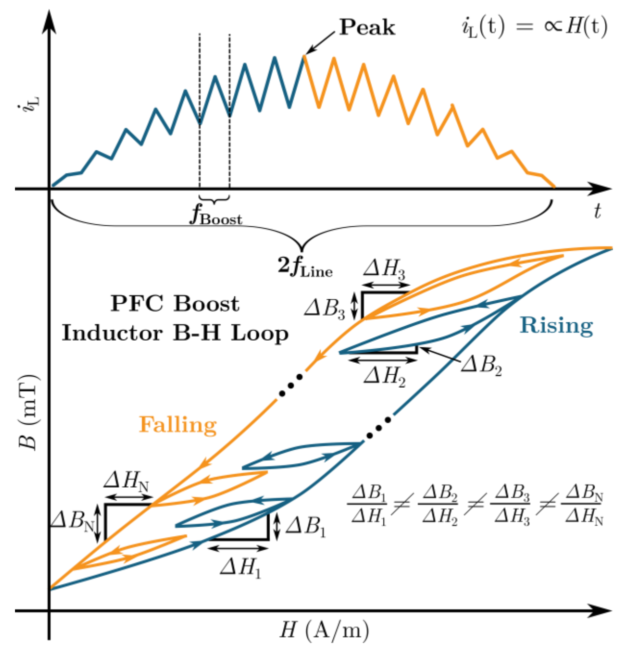
MagNet 2025 – A Transient Challenge



Steinmetz Equation
(1890s)



Preisach Model & J-A Model
(1930s) & (1980s)

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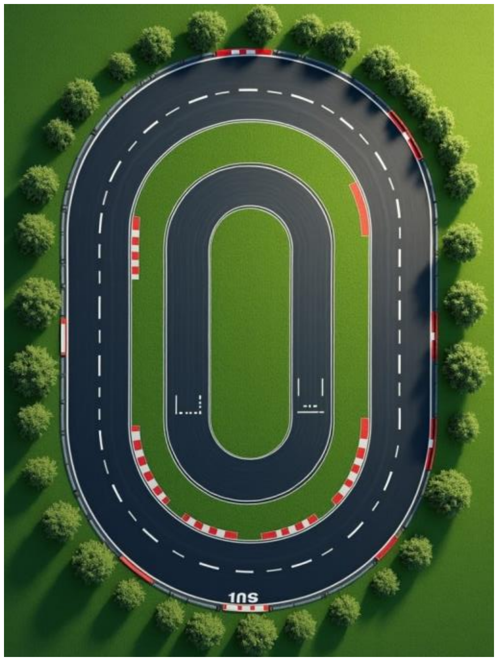
2025: from Racetrack to Open Path

Periodic Steady State Excitations

Non-Periodic Excitations



pels MagNet challenge

IEEE pels MagNetX Challenge 2

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Foundation Model for Power Magnetics

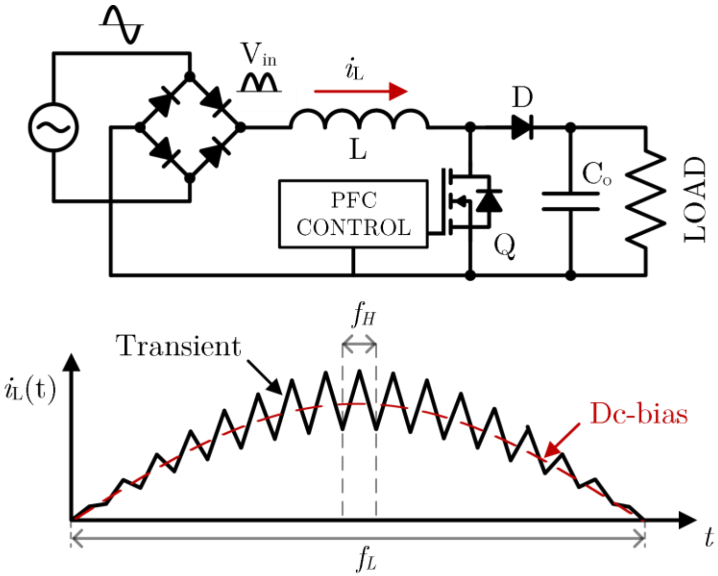
- **Foundation Model for Magnetic Materials?**
  - Frequency agnostic (non-steady-state)
  - Universal time step (long- or short-time steps)
  - Finite memory system (damping all initial impacts)
  - Long term convergence (long term converging)
  - …

- **A Rigorous Mathematical Framework?**
  - A compact and efficient, hopefully explainable modeling framework which will converge over time to the material's steady state condition

Motivation for the MagNet Challenge 2

- No good method to design magnetics in transient.
- **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.

An example PFC converter



Make every AC-DC adapters 30% smaller?

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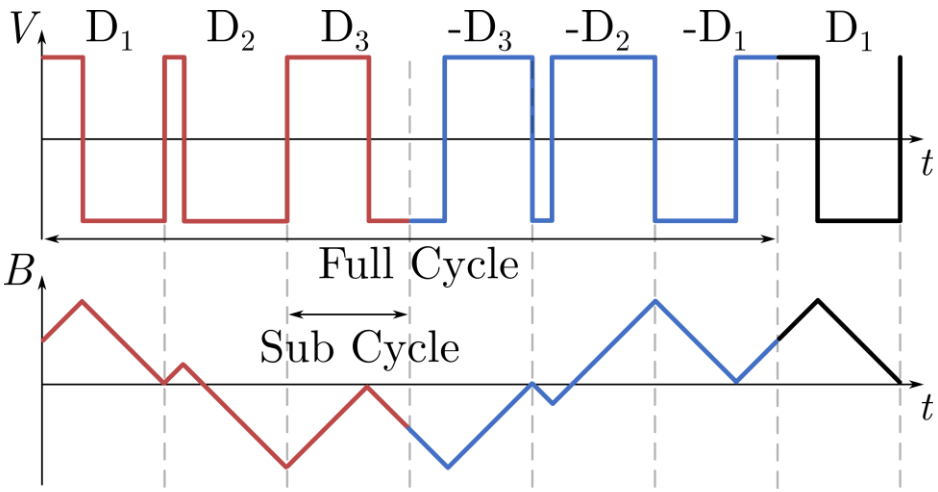
New MagNetX Dataset for Transient Dynamics

- Duty cycle step changes D = 0.2~0.8, min step size = 0.1
- Fixed frequency sequences f = 50kHz~800kHz, 7 frequency levels
- Three temperatures: 25°C, 50°C, 70°C
- ~7 voltage levels
- 100 subcycles per sequence

Example symmetric magnetizing and demagnetizing sequences



Symmetric magnetizing and demagnetizing sequences

15 ferrite materials

>5,000 sequences per material

Fixed sampling frequency: 16 MHz

50 kHz: 320 steps per subcycle

500 kHz: 32 steps per subcycle

- Hyukjae Kwon, Shukai Wang, Haoran Li, et al. "**MagNetX: Extending the MagNet Database for Modeling Power Magnetics in Transient**," *TechRxiv*. December 11, 2024. Accepted to APEC 2025.

Data Structure

For Training

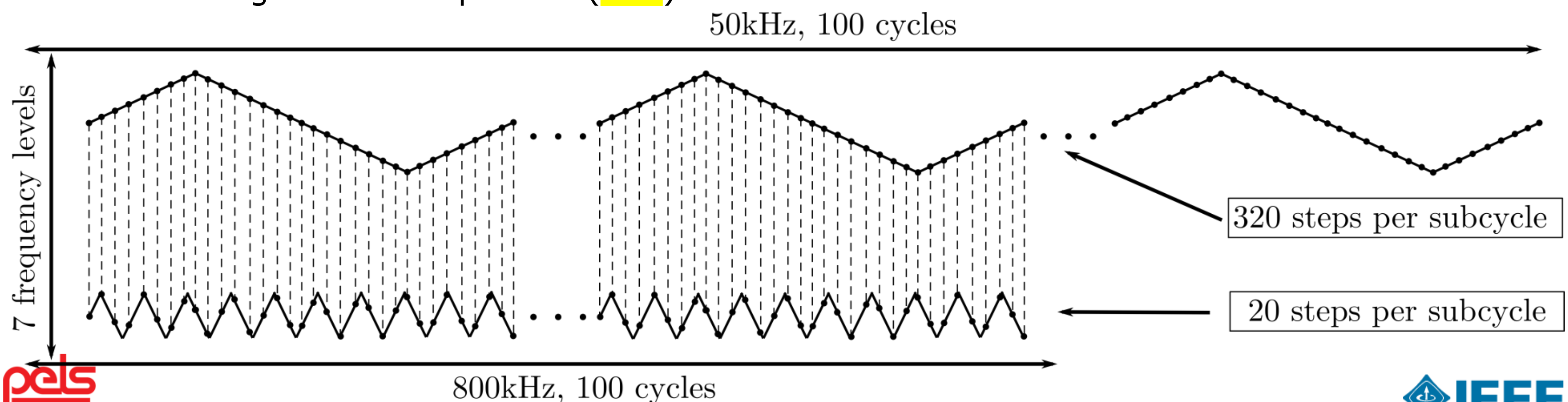
- Material format:
  - 7 sets of B(t), H(t), T for each material
  - Frequency information not provided
- Sampling frequency for all sequences: 16MHz
  - 50kHz: 32016 steps
  - 80kHz: 20016 steps
  - 125kHz: 12816 steps
  - 200kHz: 8015 steps
  - 320kHz: 4975 steps
  - 500kHz: 3216 steps
  - 800kHz: 1967 steps

Testing

- Same length for all sequences (TBA)

Material Folder: 3C90

3C90_1_B	3C90_3_H	3C90_5_T
3C90_1_H	3C90_3_T	3C90_6_B
3C90_1_T	3C90_4_B	3C90_6_H
3C90_2_B	3C90_4_H	3C90_6_T
3C90_2_H	3C90_4_T	3C90_7_B
3C90_2_T	3C90_5_B	3C90_7_H
3C90_3_B	3C90_5_H	3C90_7_T



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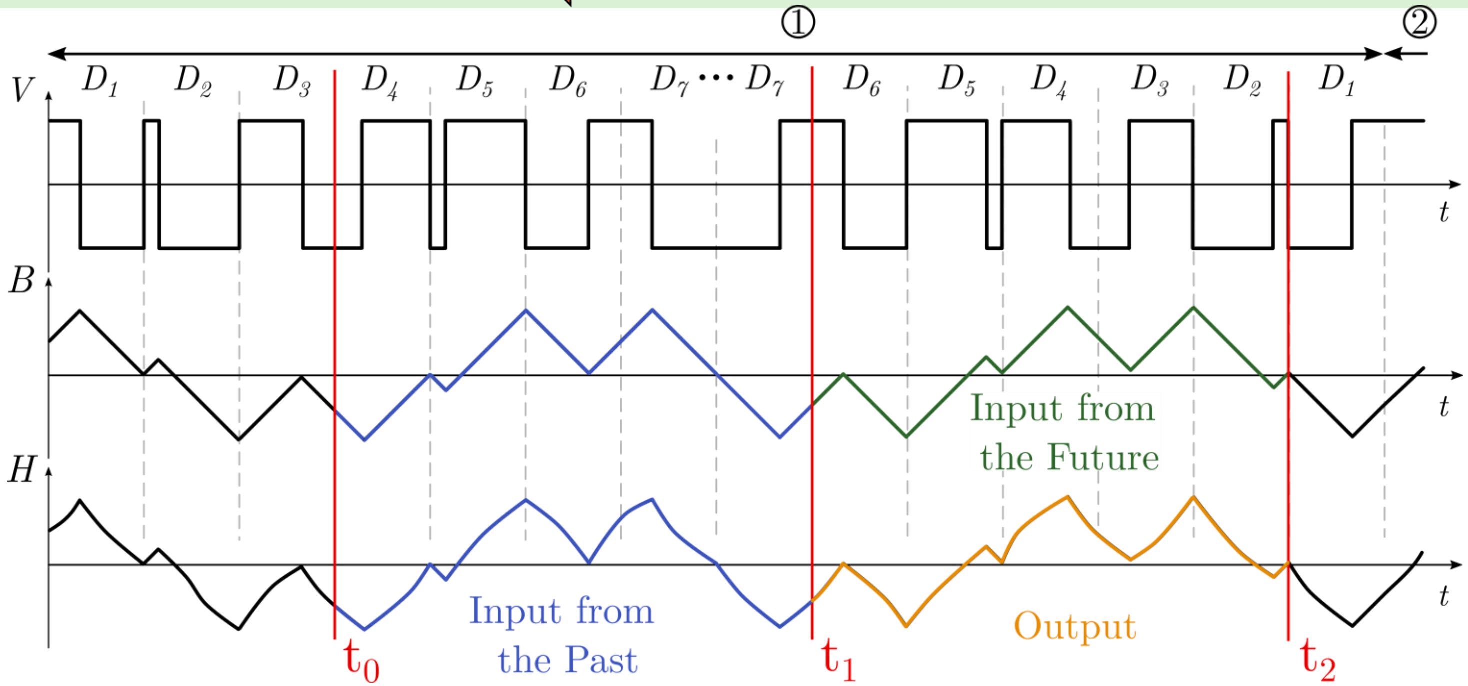
Training data:
- 10 training materials
- Lots of long B(t)-H(t) pairs
- Temperature

Evaluate:
- Total core loss from t_1 to t_2
- H(t) RMS error from t_1 to t_2
- Model size (# of parameters)

Testing data:
- 5 new materials
- Temperature
- Practicing: plenty of long B(t) and H(t) pairs
- Testing:
  - B(t) and H(t) pairs from t_0 to t_1
  - B(t) from t_1 to t_2

Output:
  - H(t) from t_1 to t_2



- Hyukjae Kwon, Shukai Wang, Haoran Li, et al. "**MagNetX: Extending the MagNet Database for Modeling Power Magnetics in Transient**," *TechRxiv*. December 11, 2024. Accepted to APEC 2025.

Strategies to win the Challenge?

- **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

MagNet 2025 – A Transient Challenge

MagNet 2025 Organizing Committee:

- **Shukai Wang**, Princeton, USA
- **Hyukjae Kwon**, Princeton, USA
- **Haoran Li**, Princeton, USA
- **Minjie Chen**, Princeton, USA
- **Charles Sullivan**, Dartmouth, USA
- **Thomas Guillod**, Dartmouth, USA

Judge Committee:

- **Charles Sullivan**, Dartmouth, USA
- **David Perreault**, MIT, USA
- **Jürgen Biela**, ETH Zurich, Switzerland
- **Dragan Maksimovic**, CU Boulder, USA
- **SY Ron Hui**, CUHK, Hong Kong

Liaison Committee:

- **Han Cui**, Tianjin, China
- **Sinan Li**, Sydney, Australia
- **Oliver Wallscheid**, Paderborn, Germany

Advisory Committee:

- **Gerard Hurley**, National University of Ireland, Ireland
- **Maeve Duffy**, National University of Ireland, Ireland
- **Brad Lehman**, Northeastern University, USA
- **Matt Wilkowski**, Wurth Electronics, USA
- **Mike Ranjram**, Arizona State University, USA
- **Alex Hanson**, UT Austin, USA

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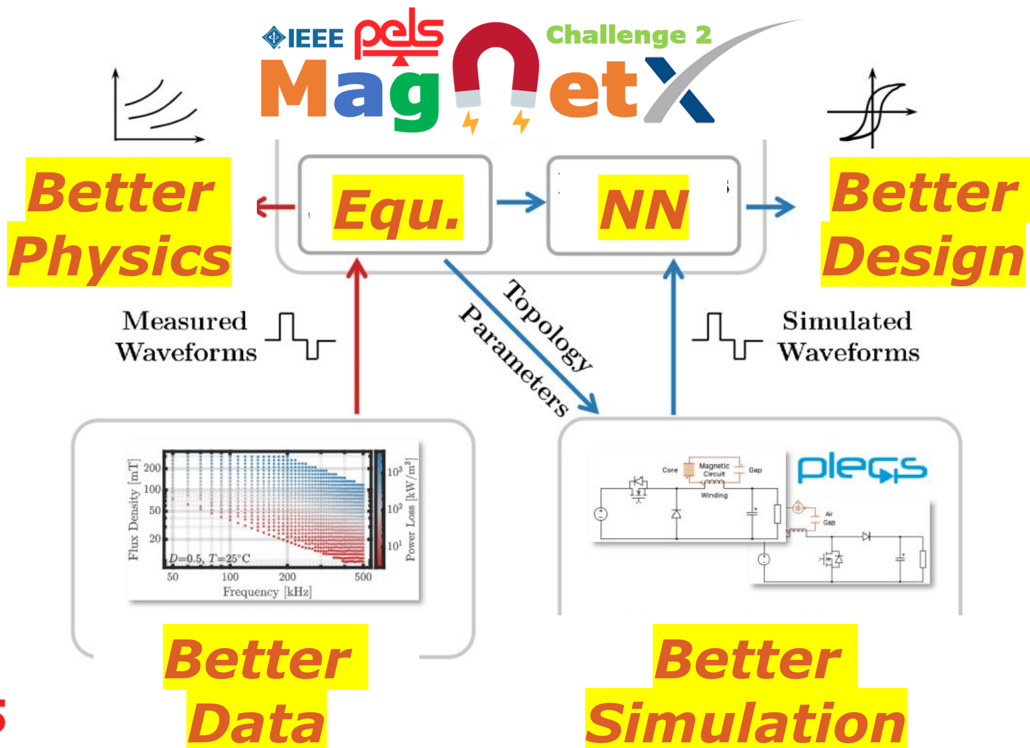
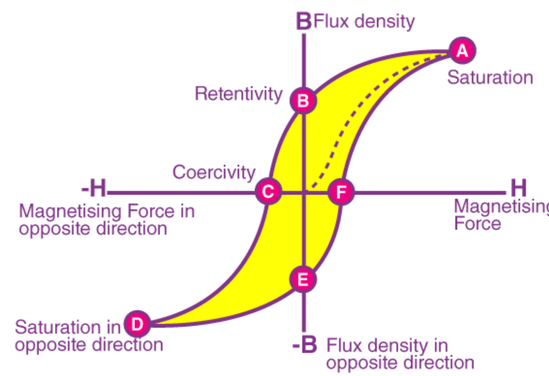
Outcomes of the MagNet Challenge 2

- Better understandings about power magnetics.
- Better tools for power magnetics design.
- Better ways of sharing information (digital/interactive datasheet).
- Cultivate an open-source community.
- Better impact on practical design.





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

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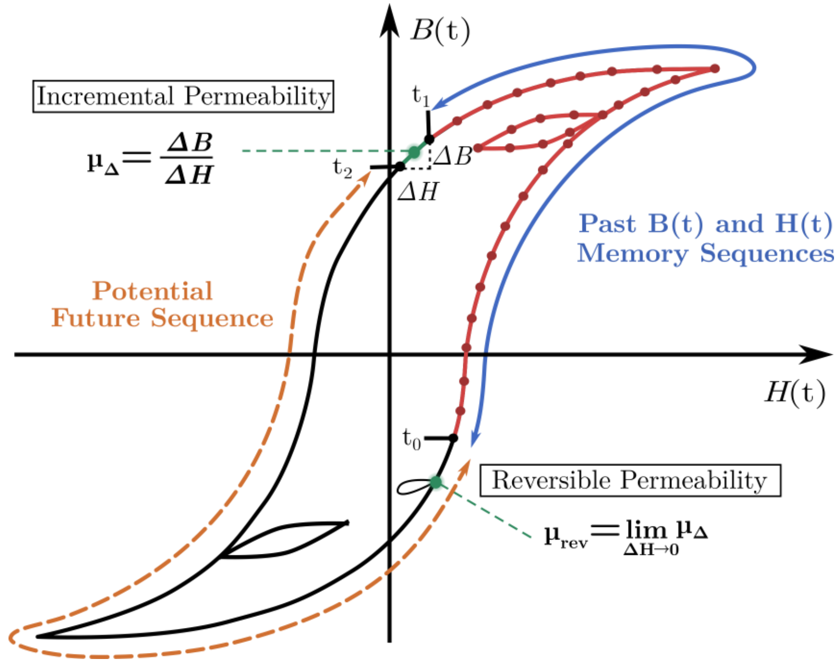
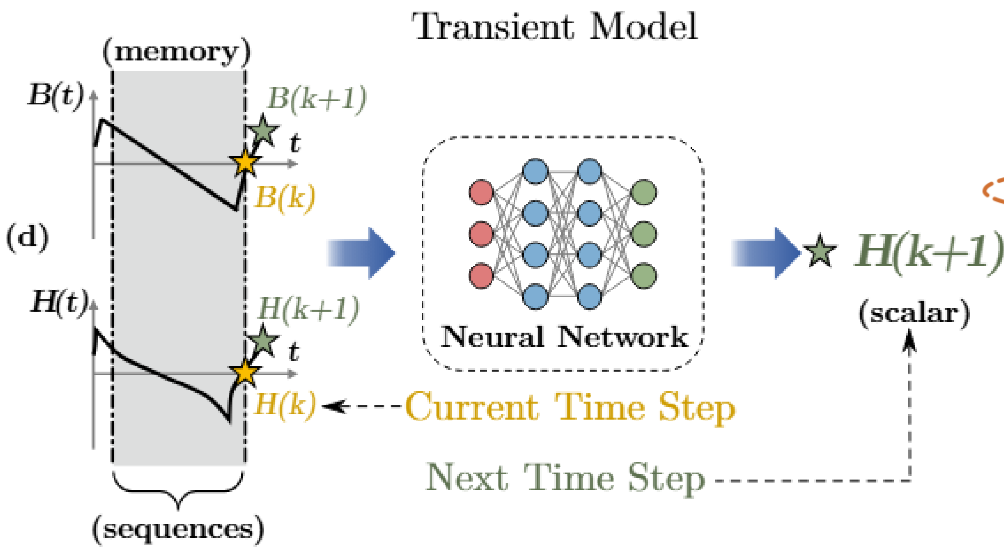
A Miniaturized Model for the Next Step

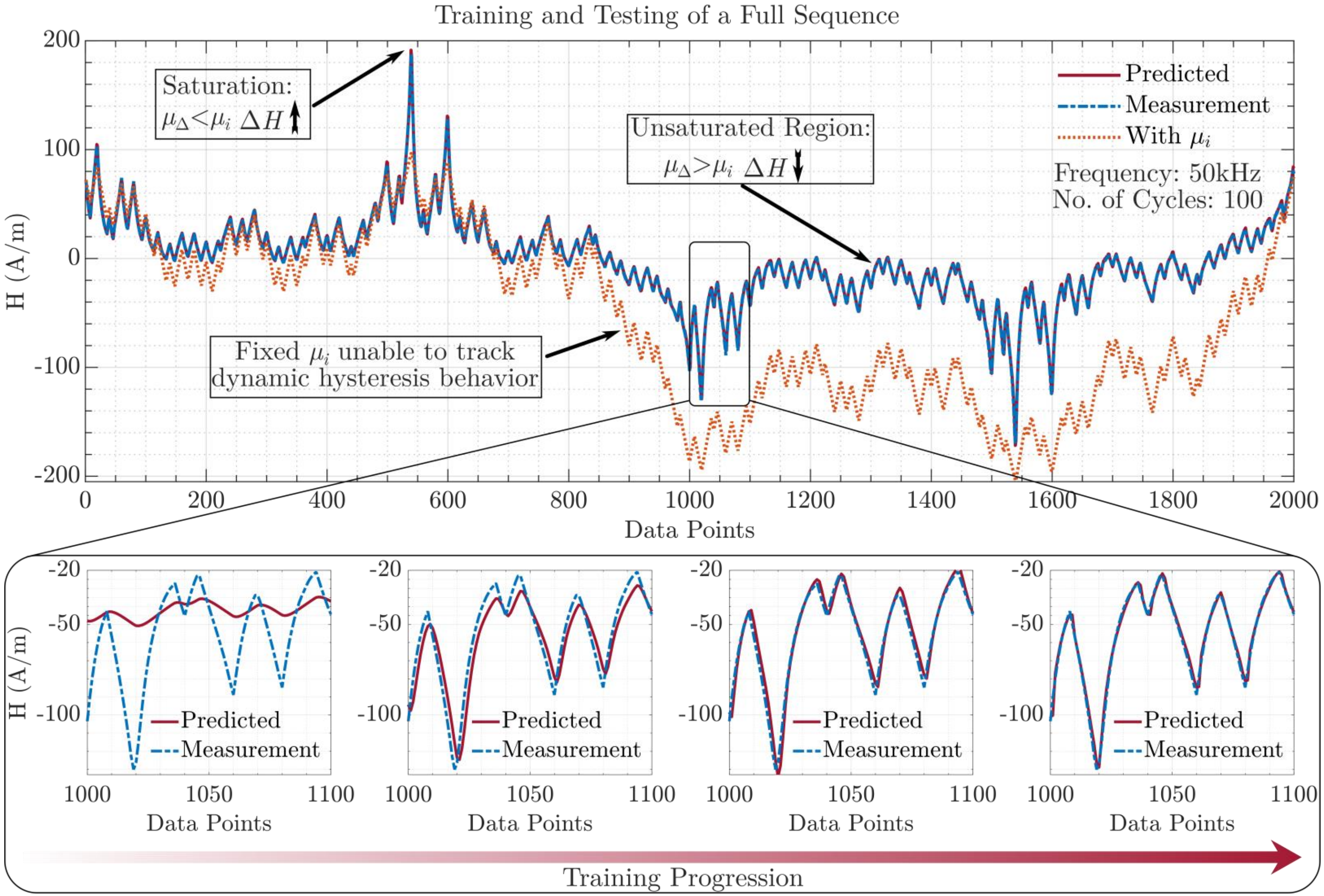
Input: B(t) in the past 80 steps
H(t) in the past 80 steps
future B(t) from t_1 to t_2
Output: future H(t) from t_1 to t_2





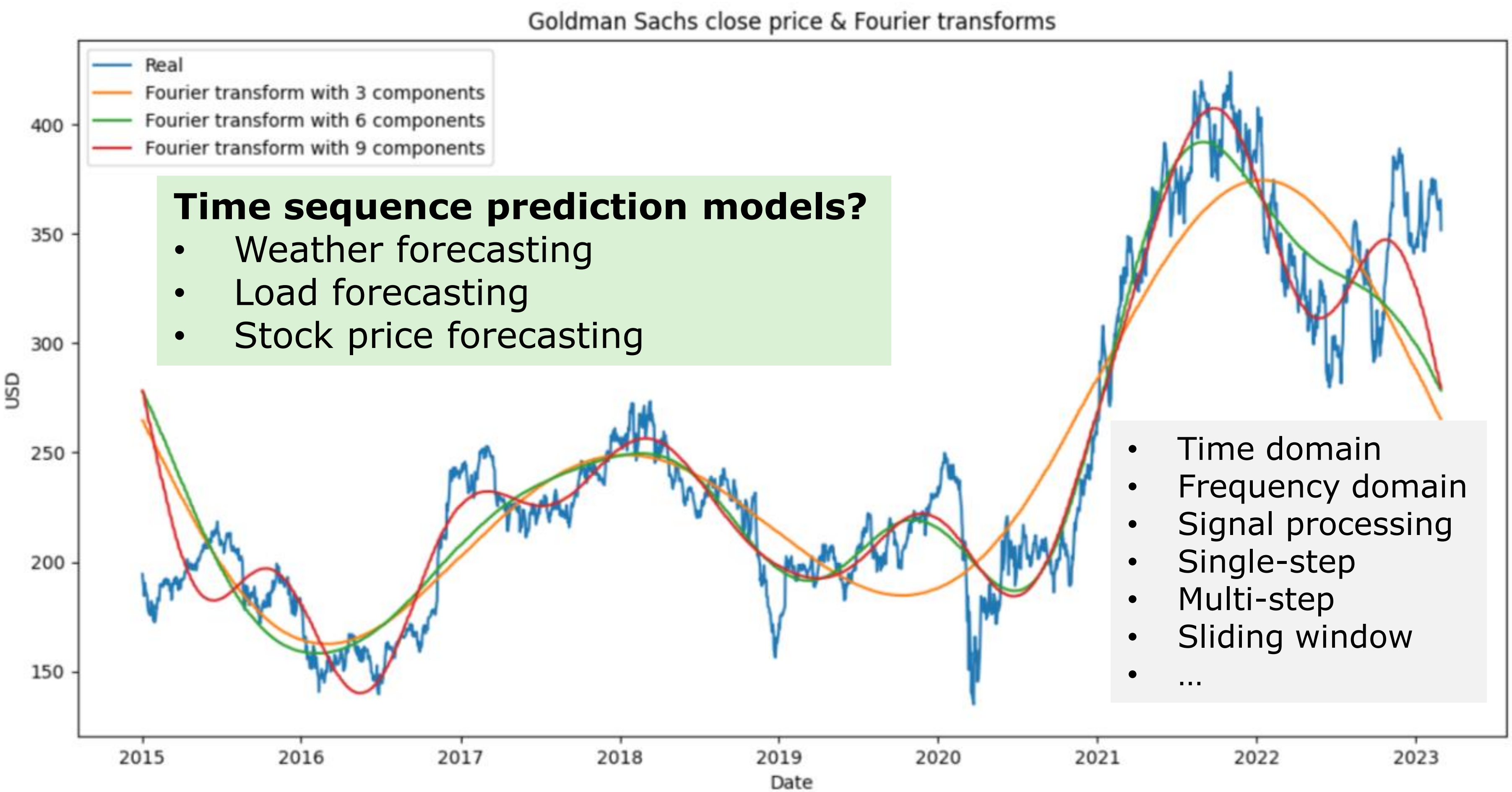
- Shukai Wang, Hyukjae Kwon, Haoran Li, et al. ”**MagNetX: Foundation Neural Network Models for Simulating Power Magnetics in Transient**.” *TechRxiv*. December 11, 2024. Accepted to APEC 2025.

A Large Model for the Long Sequences



Goal: Autoregressive Prediction

Separate Fast Details and Slow Trends



Time sequence prediction models?

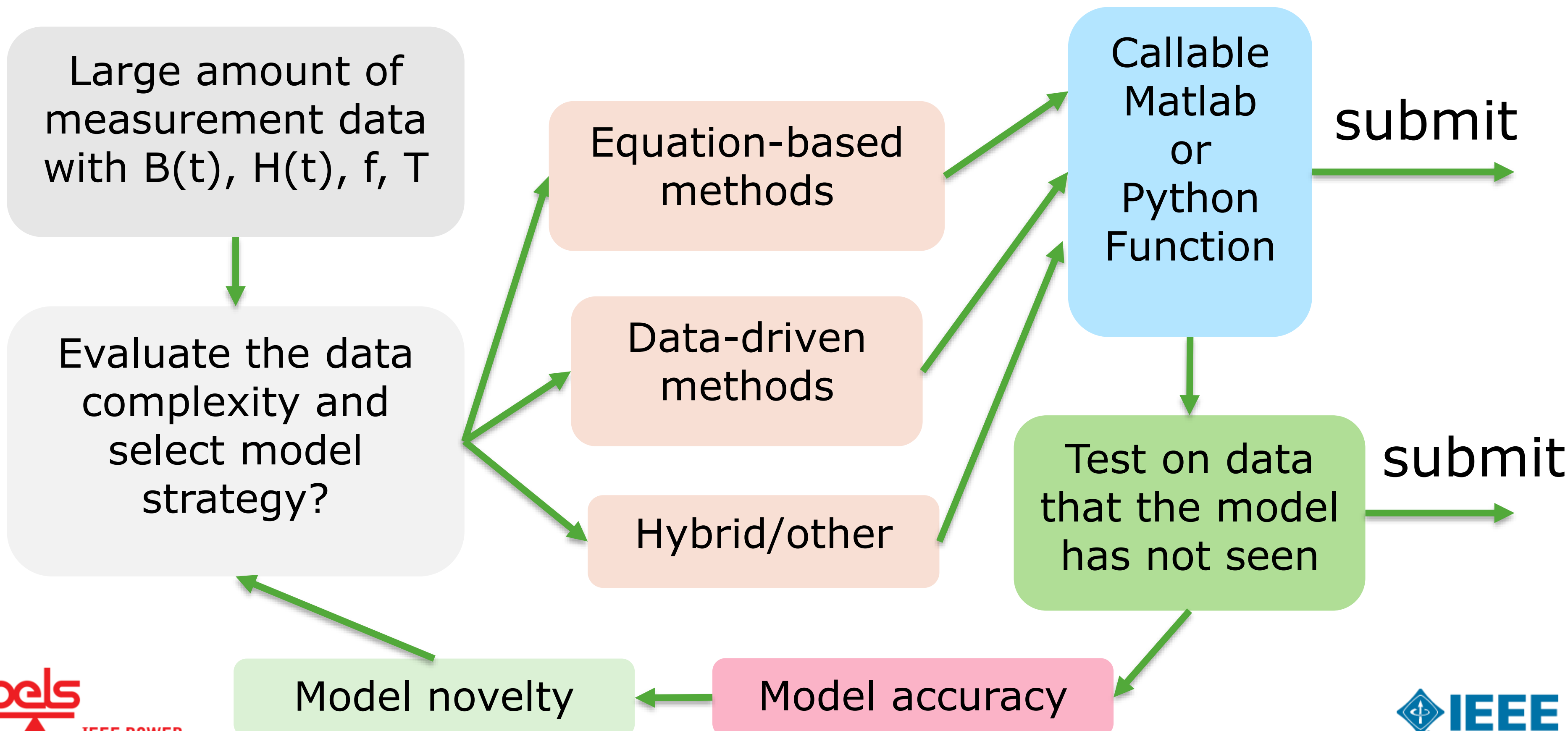
- Weather forecasting
- Load forecasting
- Stock price forecasting

- Time domain
- Frequency domain
- Signal processing
- Single-step
- Multi-step
- Sliding window
- …

Information Flow of MagNet Challenge 2

Next step: $H_{t+1} = function\,(B(t), H(t), B_{t+1}, T)$

Long cycle: $H_{t_1 \to t_2} = function\,(B(t), H(t), B_{t_1 \to t_2}, T)$



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Evaluation Criteria

- **Winning solution: a simple, robust, and trustworthy method to**
  - **(1) accurately predict power magnetic behaviors**
  - **(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 RMS error in B-H sequence.
- **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
- Jürgen Biela, ETH Zurich, Switzerland
- SY Ron Hui, NTU, Singapore
- Dragan Maksimovic, UC Boulder, USA

Timeline of the MagNet Challenge 2

Feb 10st, 2025	Initial Call for Participation Announcement
March 18th, 2025	APEC Official Announcement
April 1st, 2025	Online Q&A Session
May 1st, 2025	1-Page Letter of Intent Due with Signature [Attached]
June 1st, 2025	2-Page Proposal Due for Eligibility Check [TPEL Format]
July 1st, 2025	Notification of Acceptance [Eligibility Check]
Nov 1st, 2025	Preliminary Submission Due, Finalists Selected
Dec 24th, 2025	Final Submission Due
March 1st, 2026	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 5 new materials

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

March 1st , 2026 – 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

- **Eligibility:** To confirm eligibility, potential participating schools must submit a Letter of INTENT (attached) by **May 1st, 2025**, 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.
- We will invite **20-30 prominent researchers** from academia and industry as scientific advisors to student teams.

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Award Structure (TBD)

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

- Performance
- Model size

- Novelty
- Model generality

- Software implementation
- Other contributions

Intellectual Property

- MagNet Challenge 2 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.

Extended Reading – MagNet Challenge 2

- **J-A Model –** D. Jiles and D. Atherton, “Theory of ferromagnetic hysteresis,” Journal of Magnetism and Magnetic Materials, vol. 61, no. 1, pp. 48–60, 1986.
- **Preisach Model –** F. Preisach, “Uber die magnetische Nachwirkung,” Zeitschrift fur Physik,vol. 94, no. 5-6, pp. 277–302, May 1935.
- **LLG Model –** H. H. Cui, S. Dulal, S. B. Sohid, G. Gu, and L. M. Tolbert, “Unveilingthe microworld inside magnetic materials via circuit models,” IEEEPower Electronics Magazine, vol. 10, no. 3, pp. 14–22, 2023.
- **iGSE-PFC –** M. J. Jacoboski, A. de Bastiani Lange and M. L. Heldwein, “Closed-Form Solution for Core Loss Calculation in Single-Phase Bridgeless PFC Rectifiers Based on the iGSE Method,” in IEEE Transactions on Power Electronics, vol. 33, no. 6, pp. 4599-4604, June 2018.
- **Why MagNet –** D. Serrano et al., “Why MagNet: Quantifying the Complexity of Modeling Power Magnetic Material Characteristics,” in IEEE Transactions on Power Electronics, vol. 38, no. 11, pp. 14292-14316, Nov. 2023.
- **How MagNet –** H. Li et al., “How MagNet: Machine Learning Framework for Modeling Power Magnetic Material Characteristics,” in IEEE Transactions on Power Electronics, vol. 38, no. 12, pp. 15829-15853, Dec. 2023.
- **MagNet-AI –** H. Li, D. Serrano, S. Wang and M. Chen, “MagNet-AI: Neural Network as Datasheet for Magnetics Modeling and Material Recommendation,” in IEEE Transactions on Power Electronics, vol. 38, no. 12, pp. 15854-15869, Dec. 2023.
- **MagNet Challenge –** M. Chen et al., “MagNet Challenge for Data-Driven Power Magnetics Modeling,” in IEEE Open Journal of Power Electronics, accepted.

Extended Reading – MagNet Challenge 2

- **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.
- **MagNetX Models -** S. Wang, H. Kwon, H. Li, et al. “MagNetX: Foundation Neural Network Models for Simulating Power Magnetics in Transient,” TechRxiv. December 11, 2024.
- **MagNetX Database -** H. Kwon, S. Wang, H. Li, et al. “MagNetX: Extending the MagNet Database for Modeling Power Magnetics in Transient,” TechRxiv. December 11, 2024.