U.S. DEPARTMENT OF
ENERGY
Office of Electricity

Establishment of a Medium Voltage (MV) Core Loss Test System (CLTS) and Application Relevant Characterization of MV Dielectric / Insulation Materials

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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- Broader impact

Project Overview

Project Summary :

- Establishment of a low voltage (LV) core loss test system (CLTS)
- Development of medium voltage (MV) core loss test system (CLTS) and insulation/dielectric material characterization system (ICS)
- Publications of advanced data sheets on various commercially available and custom developed soft magnetic materials and insulation materials (including detailed information required for component optimization)

Total value of award : ~$550k over 3 years

Period of performance : 4/1/2017 – 3/31/2020

Project lead and partners : NETL (lead on overall subtask), NCSU, U. Pitt.

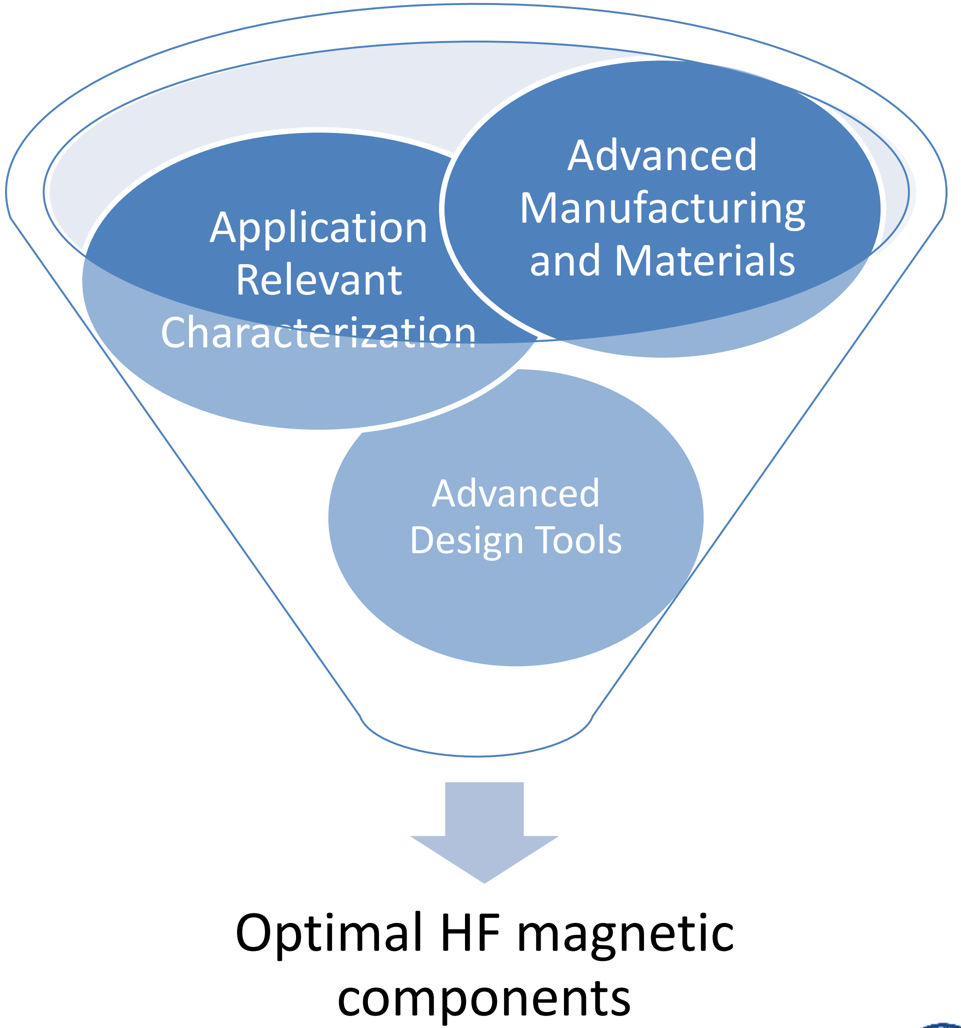
The Problem Being Addressed : Research Motivation

What tools are needed to design high frequency magnetic components?

1. Advanced Manufacturing Processes and Materials

2. Application Relevant Core / Component Characterization – Publication of Data Sheets

3. Advanced Design Tools
   – Multi-Objective Optimization
   – Co-Simulation Methods



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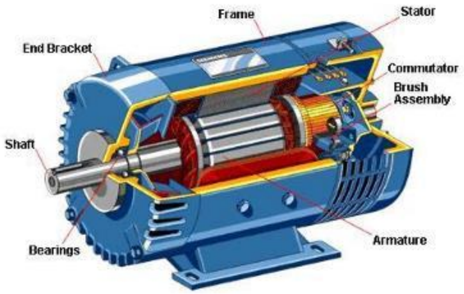
The need for advanced core / material data sheets

- Soft magnetic materials and insulation materials are foundational in power electronics, e.g. inductors, transformers, and electric machines including generators.

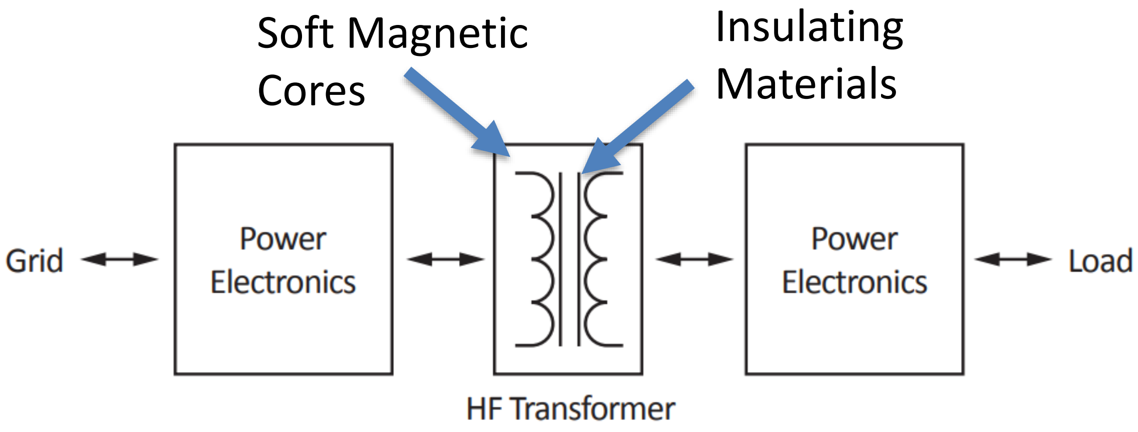
- Material characteristics information in existing manufacturer data sheets is often insufficient for detailed magnetic designs
  - Biased to provide "best possible" properties
  - Does not consider details of excitation waveforms
  - Lack of standardization in testing and presentation

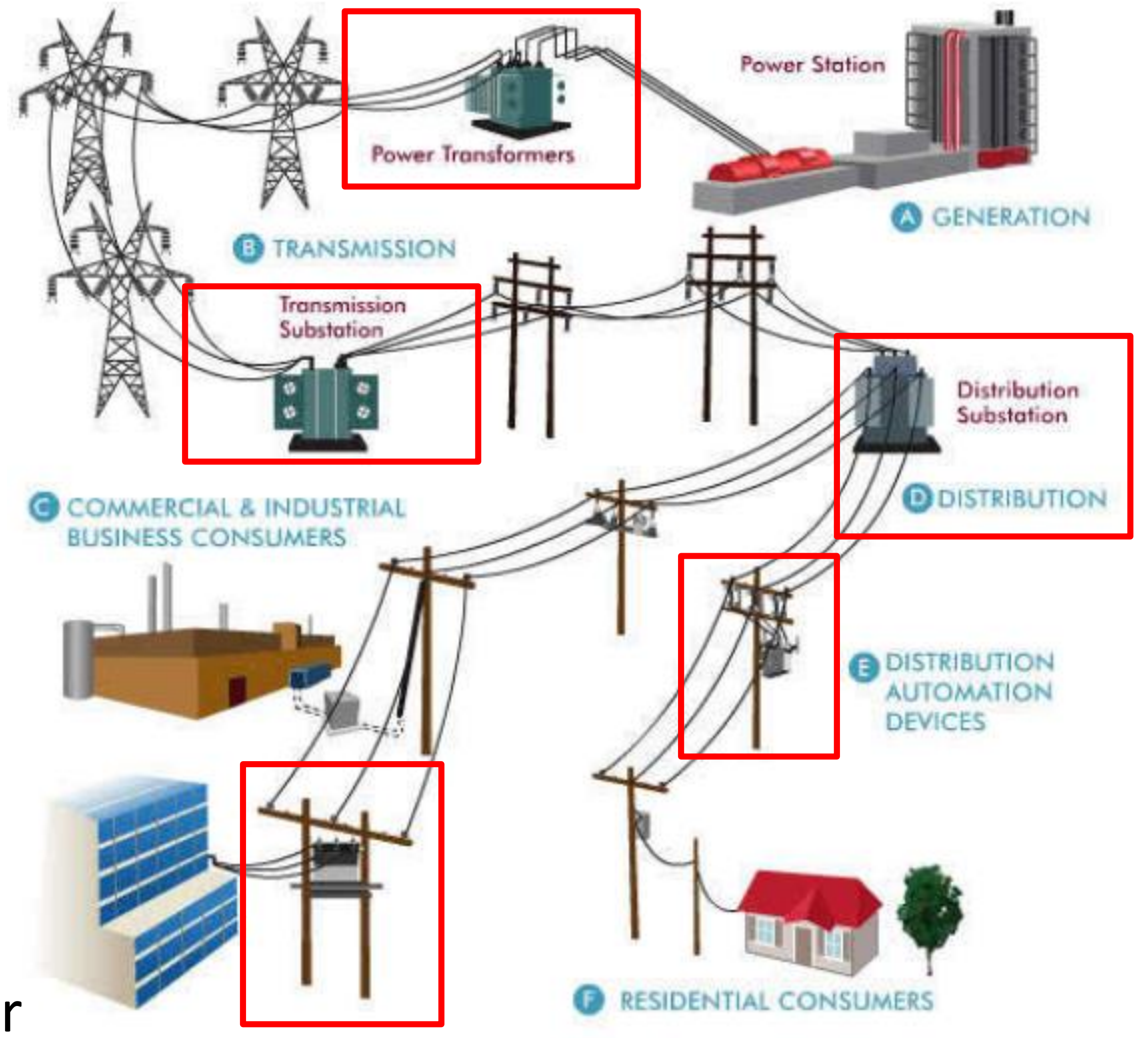
- In support of OE TRAC, NETL is performing power electronics relevant measurements and publishing advanced data sheets for the power electronics community as a resource.



The need for characterization at scale and at MV

- Magnetic cores and components used in Large Power Transformers (LPTs) and Solid-State Transformers (SSTs), including future, Solid-State Power Substations (SSPSs), must be tested and characterized at relevant scales and voltages



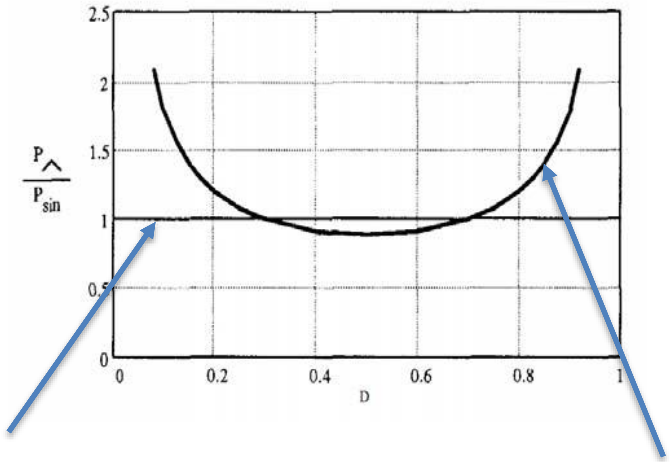


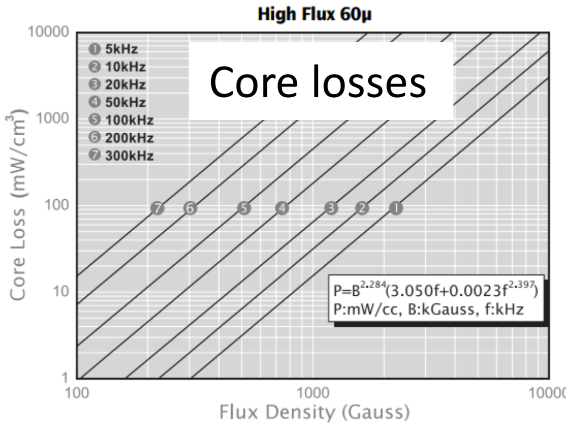
- Scaled down cores and voltages enable magnetic core material characterization, but do not consider component level impacts (resonances, dielectric breakdown and losses, scaled manufacturing, etc.)

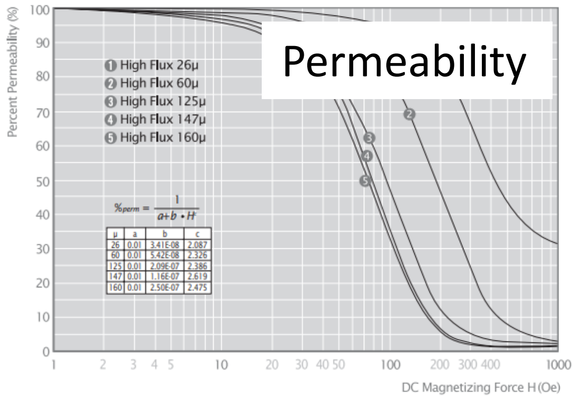
State of the Art Approaches: Limited information on typical data sheets

- Information from manufacturers' data sheets are not only difficult to extract, but also the core characteristics are typically based on sinusoidal excitation measurements.

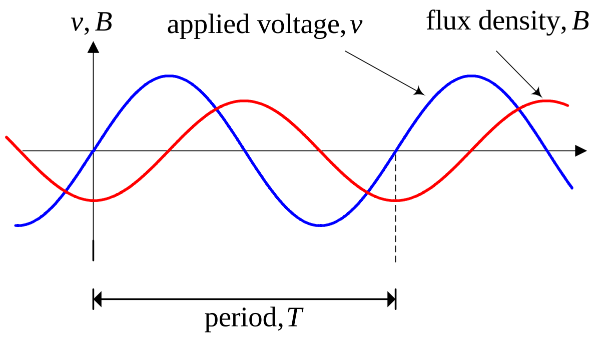
Normalized core losses of different duty cycle [1]



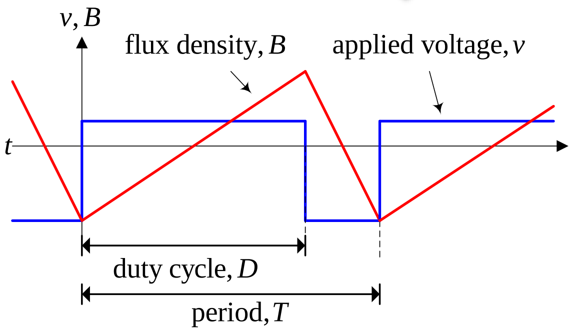




Manufacturer's Data sheet [2]



Sinusoidal excitation



Square excitation

[1] Albach, M. Durbaum, T., Brockmeyer, A. , "Calculating core losses in transformers for arbitrary magnetizing currents a comparison of different approaches," Power Electronics Specialists Conference, 1996.
[2] Changsung. *Magnetic Powerded Cores Catalog ver.13*. Available: http://www.mhw-intl.com/assets/CSC/CSC_Catalog.pdf

State of the Art Approaches: Estimating core characteristics

- Various techniques are utilized in the literature to estimate core characteristics based on sinusoidal measurements from the manufacturers' data sheets.

- These include, but are not limited to,
  - Modified Steinmetz Equation(MSE) [1],
  - Generalized Steinmetz Equation (GSE) [2], and
  - Improved GSE (iGSE) [3].

$$\overline{P}_v = k_1 \omega^\alpha \hat{B}^\beta \int_0^T \frac{1}{T} |cos\omega t|^\alpha |sin\omega t|^{\beta-\alpha} dt$$

$$k_1 = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |cos\theta|^\alpha |sin\theta|^{\beta-\alpha} d\theta}.$$

- Useful when empirical measurements are not available
- Hard to verify its accuracy under all conditions
- Utilization may require significant computation as compared to loss maps or empirical losses

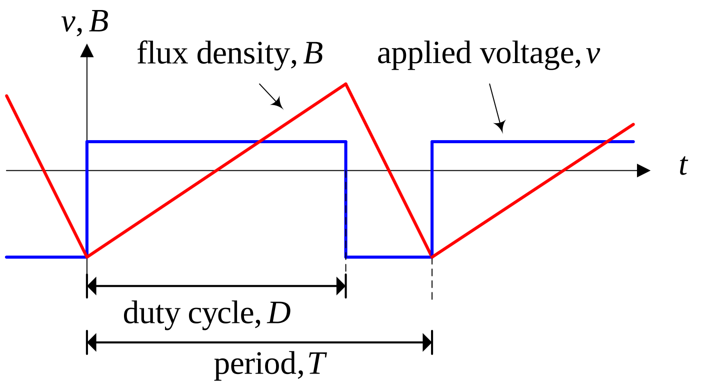
[1] M. Albach, T. Durbaum, and A. Brockmeyer, "Calculating core losses in transformers for arbitrary magnetizing currents a comparison of different approaches," in *PESC Record. 27th Annual IEEE Power Electronics Specialists Conference*, 1996, pp. 1463-1468 vol.2.

[2] L. Jieli, T. Abdallah, and C. R. Sullivan, "Improved calculation of core loss with nonsinusoidal waveforms," in *Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No.01CH37248)*, 2001, pp. 2203-2210 vol.4.

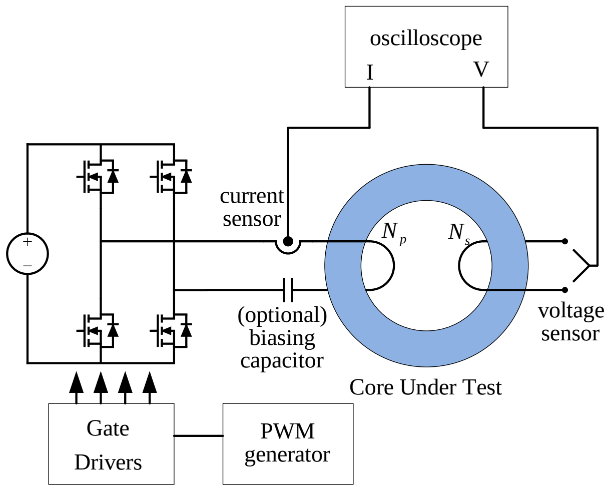
[3] K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," in *2002 IEEE Workshop on Computers in Power Electronics, 2002. Proceedings.*, 2002, pp. 36-41.

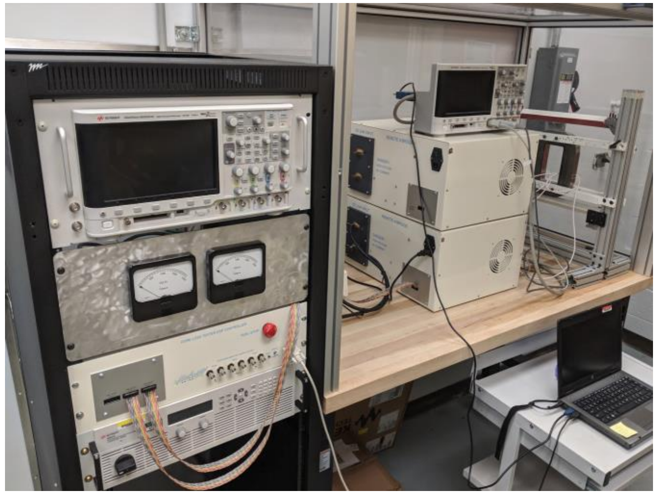
CLTS - Power electronics relevant characteristics measurements

- Core Loss Test Systems (CLTS) are developed to perform core characterization.
- To supplement manufacturers' data sheets, NETL is utilizing power electronics relevant square waveform CLTS to characterize soft magnetic materials on fabricated cores at scale.

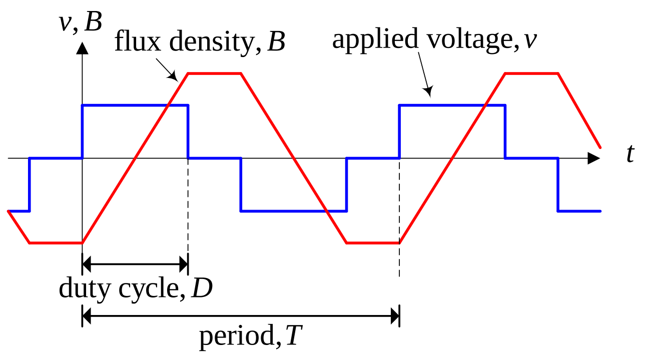


Asymmetrical square voltage excitation with triangular magnetizing current



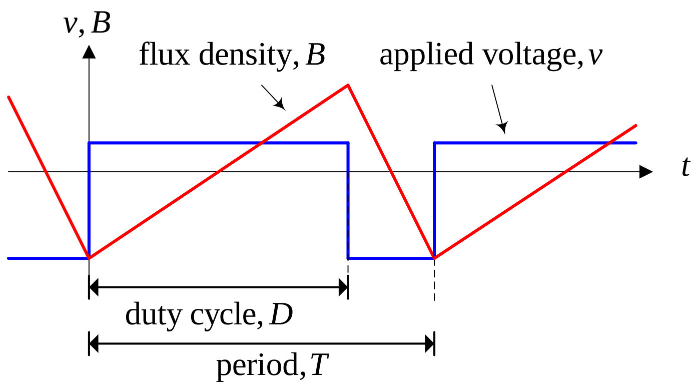


Square waveform core loss test system (CLTS)



Symmetrical square voltage excitation with trapezoidal magnetizing current

CLTS – Example applications of relevant waveforms



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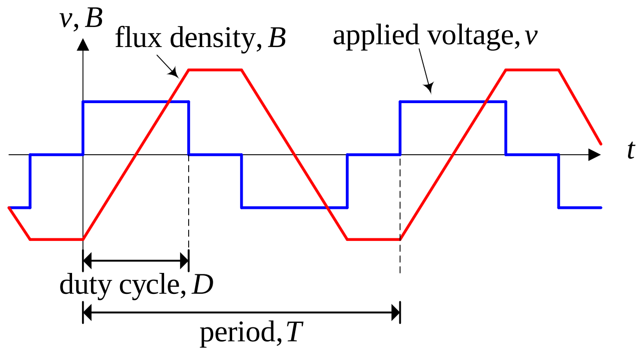
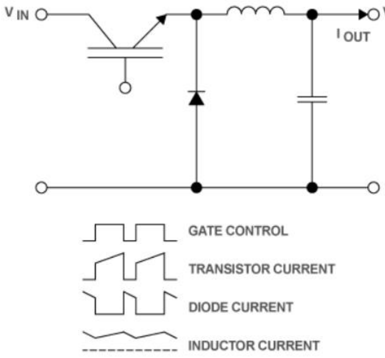
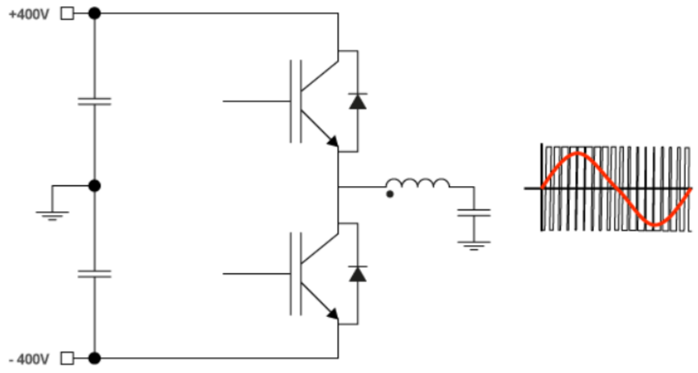
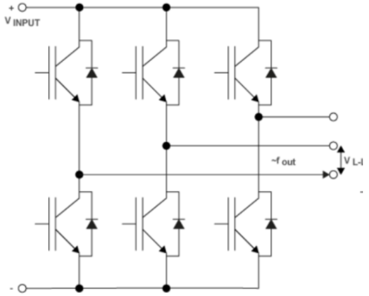


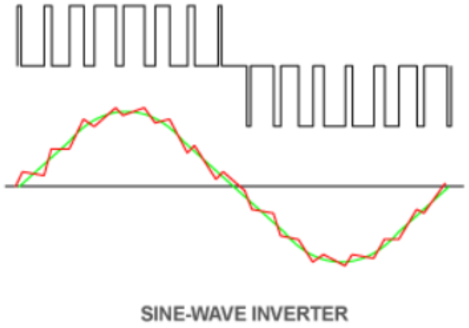
Symmetrical square voltage excitation with trapezoidal magnetizing current

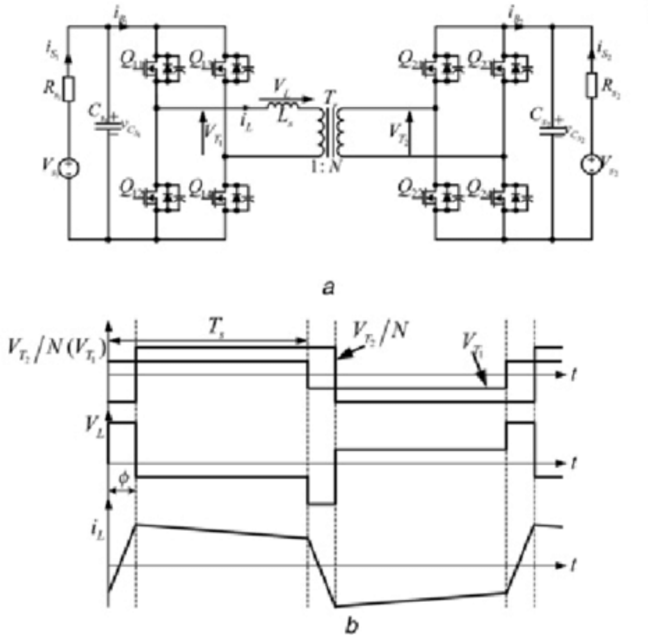




Can be observed on buck, boost, half-bridge, etc.







Can be observed on single- and three-phase inverters, dual active bridge, etc.

CLTS - Capability

- Core Loss Test Systems (CLTS) are developed to perform core characterization:
  - Core loss measurements
  - Permeability characterization (absolute and incremental permeability)
  - Thermal characterization

- Controllable variables are:
  - Asymmetrical and symmetrical square waveforms and its duty cycles
  - Switching frequency (>100 kHz)
  - Flux density (through equivalent volt-seconds excitation)
  - Pre-magnetized core characteristics (in progress)
  - Core temperature (future plan)

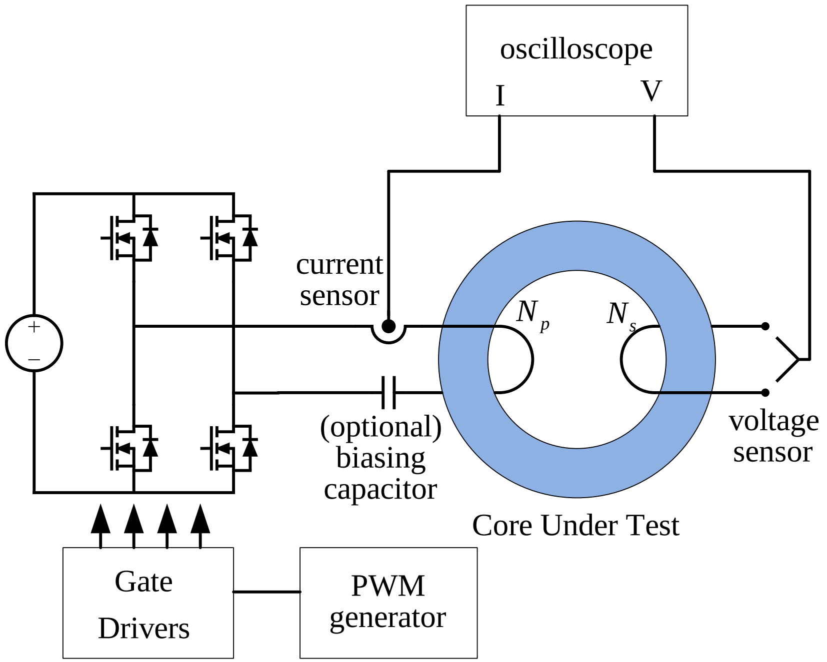
- Measurements are performed with power electronics relevant square waveform on full scale soft magnetic cores.

Technical Explanation of the Proposed Approach : LV CLTS

Popular two-winding method is utilized

- Advantage: Excludes the winding loss from the measured core losses
- Disadvantage: Sensitive to phase discrepancy. It becomes problematic at very high frequency measurements,

  i.e. > 1 MHz



The current from excitation winding is measured.
The voltage from sensing winding is measured.

Core losses

$$P_{loss} = \frac{1}{T}\int_T v(t)\cdot i(t)dt$$

Core BH

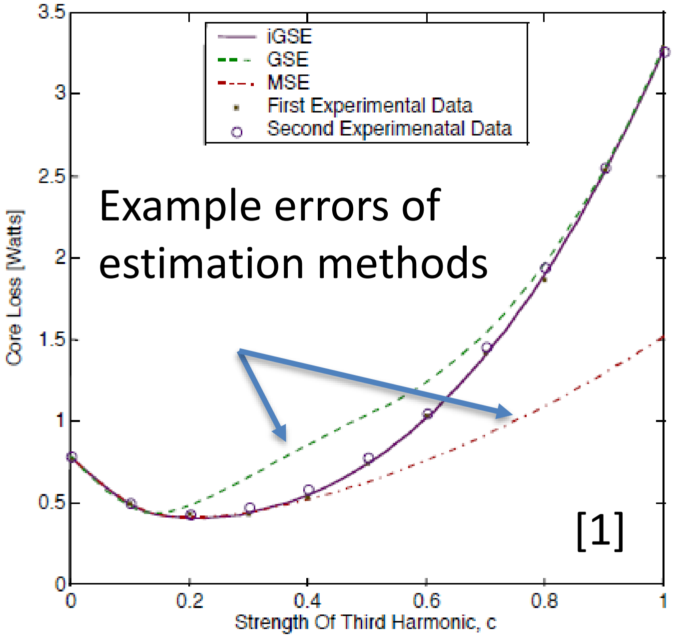
$$B(t) = \frac{1}{N_2 \cdot A_e}\int_0^t v(\tau)d\tau \qquad H(t) = \frac{N_1 \cdot i(t)}{l_e}$$

Technical Explanation of the Proposed Approach : LV CLTS

Estimation vs. Empirical

- Estimation methods, such as MSE, GSE, iGSE, etc.
  - Estimates the losses using the Steinmetz coefficients based on sinusoidal measurements
  - Difficult to verify accuracy under all relevant conditions
  - Utilization may require significant computation

- Core loss map based on empirical measurements
  - Easy to implement, but requires flexible CLTS capability
  - Improved accuracy if correct excitation waveform applied
  - Can be compared with estimation methods above



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

Magnetic Core Characterization Efforts

Published in data sheet format

METGLAS® 2605-SA1 core
datasheet

Grid Asset Performance > Next Generation Transformers

data sheet

The amorphous tape wound core is manufactured with iron-based 2605-SA1 amorphous foil. The 2605-SA1 amorphous foil is provided by METGLAS, Inc. and the core is manufactured by MK Magnetics. The 2605-SA1 amorphous foil is made up of mainly iron, with small percentages of Silicon and Boron. Applications include transformers, pulse power cores, motors, and high frequency inductors.

Date: June 2018
Revision 0.1

Fig. 1: METGLAS 2605-SA1 core

Dimensions

Table 1: Core dimensions

Description	Symbol	Finished dimension (mm)
Width of core	A	180
Height of core	B	240
Depth of core (or cast width)	D	30
Thickness or build	E	50
Width of core window	F	80
Height of core window	G	140

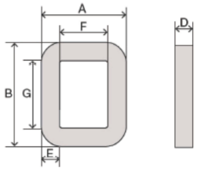


Fig. 2: Illustration of core dimensions

Acknowledgement

This technical effort was performed in support of the National Energy Technology Laboratory's ongoing research in DOE's The Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program under the RES contract DE-FE0004000.

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Characteristics

Table 2: Core physical characteristics

Description	Symbol	Typical value	Unit
Core stacking factor	k_f	0.82	Dimensionless
Effective area	A_e	1,230	mm²
Mean magnetic path length[1]	L_m	583	mm
Mass (before impregnation)		5.22	kg
Mass (after impregnation)		5.95	kg
Lamination thickness		0.001 (0.0254)	inch (mm)
Chemistry		$Fe_{80}Si_9B_{11}$	at%
Grade		Amorphous	
Anneal		Standard – No Field	
Impregnation		100% Solids Epoxy	
Supplier		MK Magnetics	
Part number		4216L1R-B	

Measurement Setup

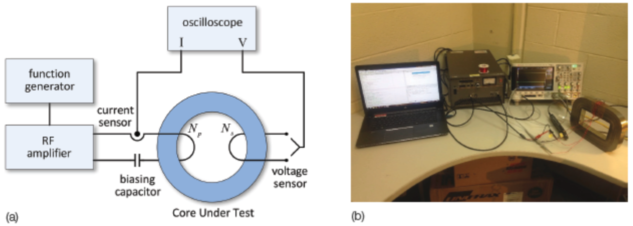


Fig. 3: Arbitrary waveform core loss test system (CLTS) (a) conceptual setup (b) actual setup

The BH curves, core losses, and permeability of the core under test (CUT) are measured with an arbitrary waveform core loss test system (CLTS), which is shown in Fig. 3. Arbitrary small signal waveforms are generated from a function generator, and the small signals are amplified via an amplifier.

[1] Mean magnetic path length is computed using the following equation. OD and ID are outer and inner diameters, respectively. $L_m = \dfrac{\pi(\mathrm{OD}-\mathrm{ID})}{\ln\left(\dfrac{\mathrm{OD}}{\mathrm{ID}}\right)}$

2

Two windings are placed around the CUT. The amplifier excites the primary winding, and the current of the primary winding is measured, in which the current information is converted to the magnetic field strengths H as

$$H(t) = \frac{N_p \cdot i(t)}{l_m}, \quad (1)$$

where N_p is the number of turns in the primary winding. A dc-biasing capacitor is inserted in series with the primary winding to provide zero average voltage applied to the primary winding.

The secondary winding is open, and the voltage across the secondary winding is measured, in which the voltage information is integrated to derive the flux density B as

$$B(t) = \frac{1}{N_s \cdot A_e}\int_0^T v(\tau)\,d\tau, \quad (2)$$

where N_s is the number of turns in the secondary winding, and T is the period of the excitation waveform.

Fig. 4 illustrates three different excitation voltage waveforms and corresponding flux density waveforms. When the excitation voltage is sinusoidal as shown in Fig. 4(a), the flux is also a sinusoidal shape. When the excitation voltage is a two-level square waveform as shown in Fig. 4(b), the flux is a sawtooth shape. The average excitation voltage is adjusted to be zero via the dc-biasing capacitor, and thus, the average flux is also zero. When the excitation voltage is a three-level square voltage as shown in Fig. 4(c), the flux is a trapezoidal shape. The duty cycle is defined as the ratio between the applied high voltage time and the period. In the sawtooth flux, the duty cycle can range from 0% to 100%. In the trapezoidal flux, the duty cycle range from 0% to 50%. At 50% duty cycles, both the sawtooth and trapezoidal waveforms become identical.

It should be noted that only limited ranges of the core loss measurements are executed due to the limitations of the amplifier, such ±75V & ±6A peak ratings and 400V/μs slew rate. The amplifier model number is HSA4014 from NF Corporation. For example, it is difficult to excite the core to high saturation level at high frequency due to limited voltage and current rating of the amplifier. Therefore, the ranges of the experimental results are limited.

Additionally, the core temperature is not closely monitored; however, the core temperature can be assumed to be near room temperature.

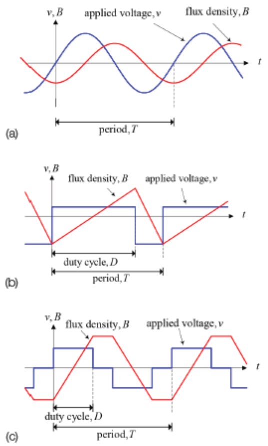


Figure 4. Excitation voltage waveforms and corresponding flux density waveforms (a) Sinusoidal flux, (b) Sawtooth flux, and (c) trapezoidal flux

3

Magnetic core characteristics of Custom and Commercially Available Cores are published in data sheet format. Includes BH loops and core loss measurements as a function of excitation waveform.

Magnetic Core Characterization Efforts

Low frequency measurement for Anhysteretic BH data

BH curves measured at low frequency, major loop is fitted with anhysteretic curves B(H), H(B)

- Function of field intensity H & flux density B

$$B = \mu_H\left(H\right)H$$

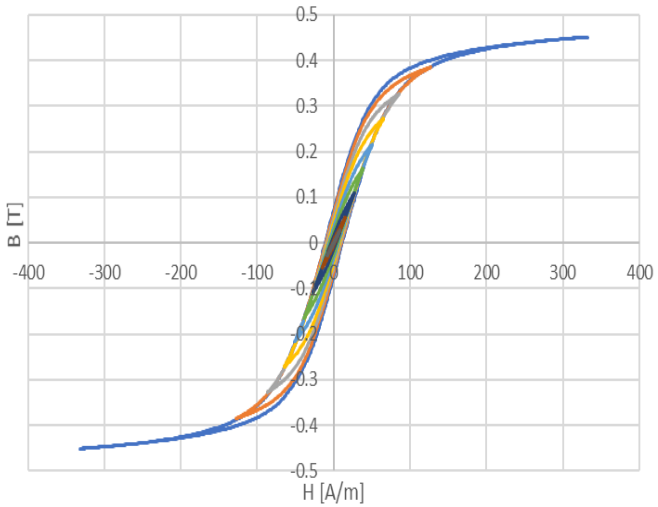
$$\mu_H\left(H\right) = \mu_0 + \sum_{k=1}^{K} \frac{m_k}{h_k} \frac{1}{1+\left|H/h_k\right|^{n_k}}$$

$$B = \mu_B(B)H$$

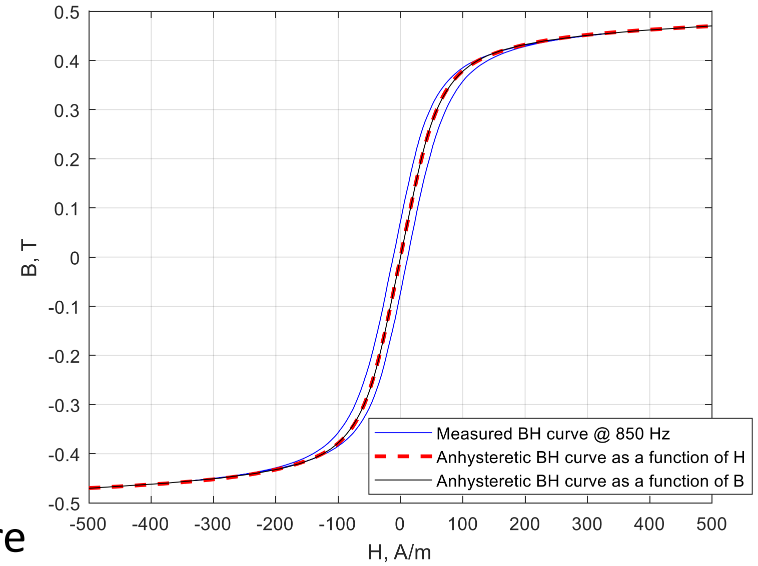
$$\mu_B\left(B\right) = \mu_0 \frac{r\left(B\right)}{r\left(B\right)-1}$$

$$r\left(B\right) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^{K} \alpha_k\left|B\right| + \delta_k \ln\left(\varepsilon_k + \zeta_k e^{-\beta_k\left|B\right|}\right)$$

$$\delta_k = \frac{\alpha_k}{\beta_k}, \varepsilon_k = \frac{e^{-\beta_k\gamma_k}}{1+e^{-\beta_k\gamma_k}}, \zeta_k = \frac{1}{1+e^{-\beta_k\gamma_k}}$$



Low frequency BH loops of ferrite core (excitation at 850 Hz, N_p = 26, N_s = 26)



Fitted anhysteretic BH curves

Table 3: Anhysteretic curve coefficients for B as a function of H

k	1	2	3	4
m_k	1.45432290901190	-0.787469528017856	0.305816513846983	-0.100099666071160
h_k	1.66901849037468	4.53941231474504	16.3984489615004	2.21434113438350
n_k	1	1.39181845814425	1.91929608345426	2.47225983230501

Table 4: Anhysteretic curve coefficients for H as a function of B

k	1	2	3	4
μ_r	122403.680741993			
α_k	0.601590372006389	0.0373154057929699	0.0371340984781102	0.00547195463929012
β_k	49.0941919818141	6.05165057248446	342.771453167956	26.7566654427740
γ_k	1.43228670933891	2.10625323925708	1.41322170444317	1.30002822552914
δ_k	0.0122537992320810	0.00616615340658217	0.000108334863171685	0.000204508093543767
ε_k	2.89556194654586e-31	2.91304528523862e-06	4.19291980155985e-211	7.82200715654711e-16
ζ_k	1	0.999997086954715	1	0.999999999999999

Coefficients are given in the data sheets

[1] G. M. Shane and S. D. Sudhoff, "Refinements in Anhysteretic Characterization and Permeability Modeling," *IEEE Transactions on Magnetics*, vol. 46, pp. 3834-3843, 2010.

Example usage of Anhysteretic BH data for designs

Input data to FEA designs programs

$$B = \mu_B(B)H$$

$$\mu_B(B) = \mu_0 \frac{r(B)}{r(B)-1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^{K} \alpha_k |B| + \delta_k \ln\left(\varepsilon_k + \zeta_k e^{-\beta_k |B|}\right)$$

$$\delta_k = \frac{\alpha_k}{\beta_k}, \varepsilon_k = \frac{e^{-\beta_k \gamma_k}}{1+e^{-\beta_k \gamma_k}}, \zeta_k = \frac{1}{1+e^{-\beta_k \gamma_k}}$$

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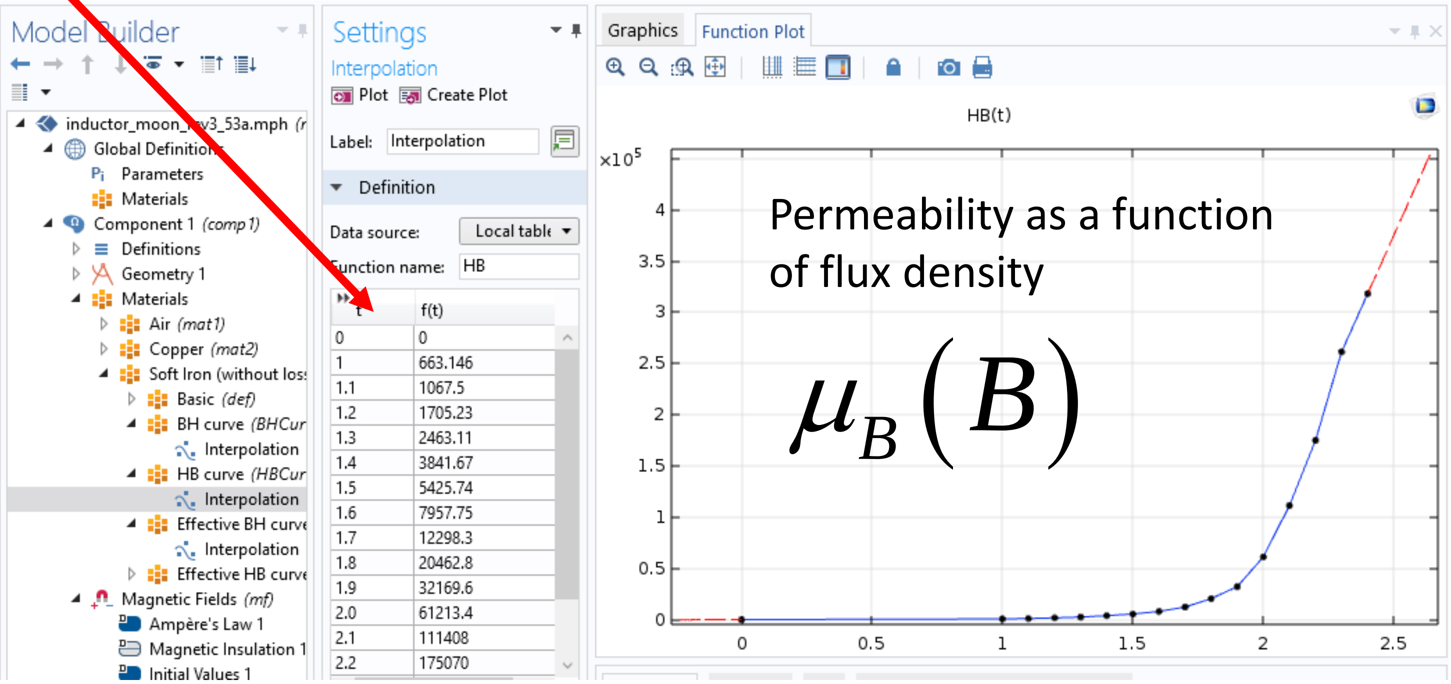
δ_k	0.0122537992320810	0.00616615340658217	0.000108334863171685	0.000204508093543767
ε_k	2.89556194654586e-31	2.91304528523862e-06	4.19291980155985e-211	7.82200715654711e-16
ζ_k	1	0.999997086954715	1	0.999999999999999

Numerical evaluation to create a table



COMSOL Finite Element Analysis Program

Example usage of Anhysteretic BH data for designs

Input data to Automatic Magnetic Component Design using Genetic Algorithms

$$B = \mu_B(B)H$$

$$\mu_B(B) = \mu_0 \frac{r(B)}{r(B)-1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^{K} \alpha_k |B| + \delta_k \ln\left(\varepsilon_k + \zeta_k e^{-\beta_k |B|}\right)$$

$$\delta_k = \frac{\alpha_k}{\beta_k}, \varepsilon_k = \frac{e^{-\beta_k \gamma_k}}{1+e^{-\beta_k \gamma_k}}, \zeta_k = \frac{1}{1+e^{-\beta_k \gamma_k}}$$

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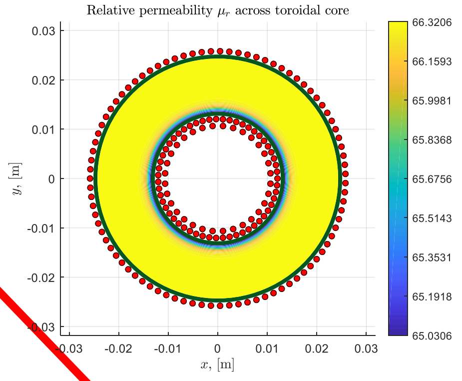
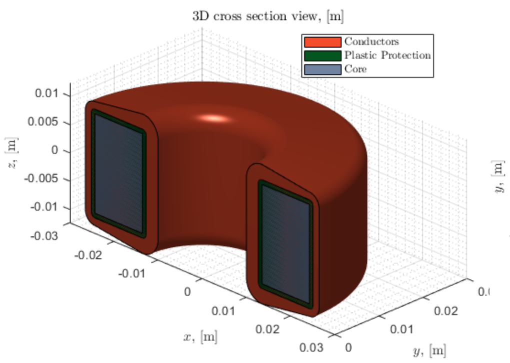
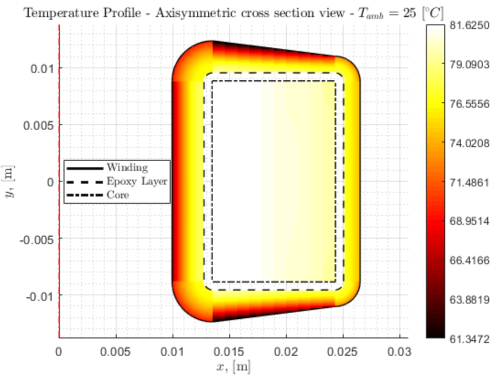
m_k	1.45432290901190	-0.787469528017856	0.305816513846983	-0.100099666071160
h_k	1.66901849037468	4.53941231474504	16.3984489615004	2.21434113438350
n_k	1	1.39181845814425	1.91929608345426	2.47225983230501

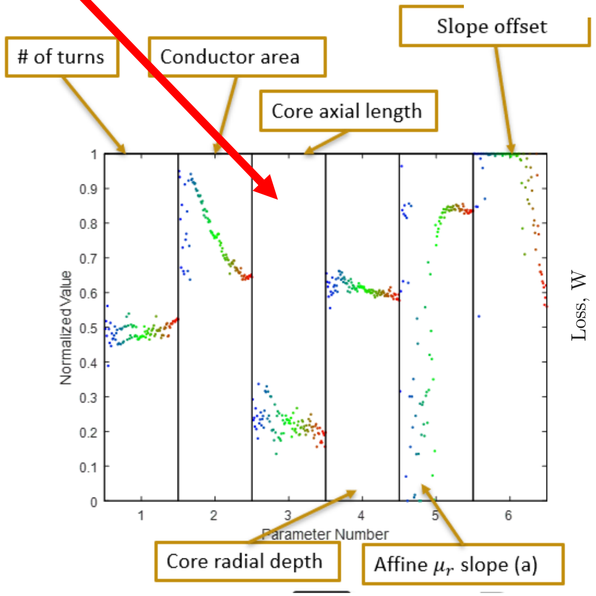
Table 4: Anhysteretic curve coefficients for H as a function of B

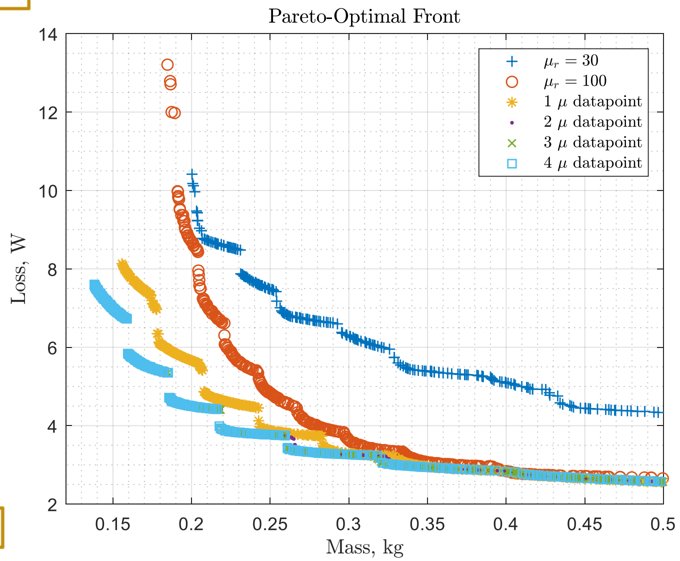
k	1	2	3	4
μ_r	122403.680741993			
α_k	0.601590372006389	0.0373154057929699	0.0371340984781102	0.00547195463929012
β_k	49.0941919818141	6.05165057248446	342.771453167956	26.7566654427740
γ_k	1.43228670933891	2.10625323925708	1.41322170444317	1.30002822552914
δ_k	0.0122537992320810	0.00616615340658217	0.000108334863171685	0.000204508093543767
ε_k	2.89556194654586e-31	2.91304528523862e-06	4.19291980155985e-211	7.82200715654711e-16
ζ_k	1	0.999997086954715	1	0.999999999999999











Automatic inductor design program by NETL and Purdue University

Publicly available data sheets

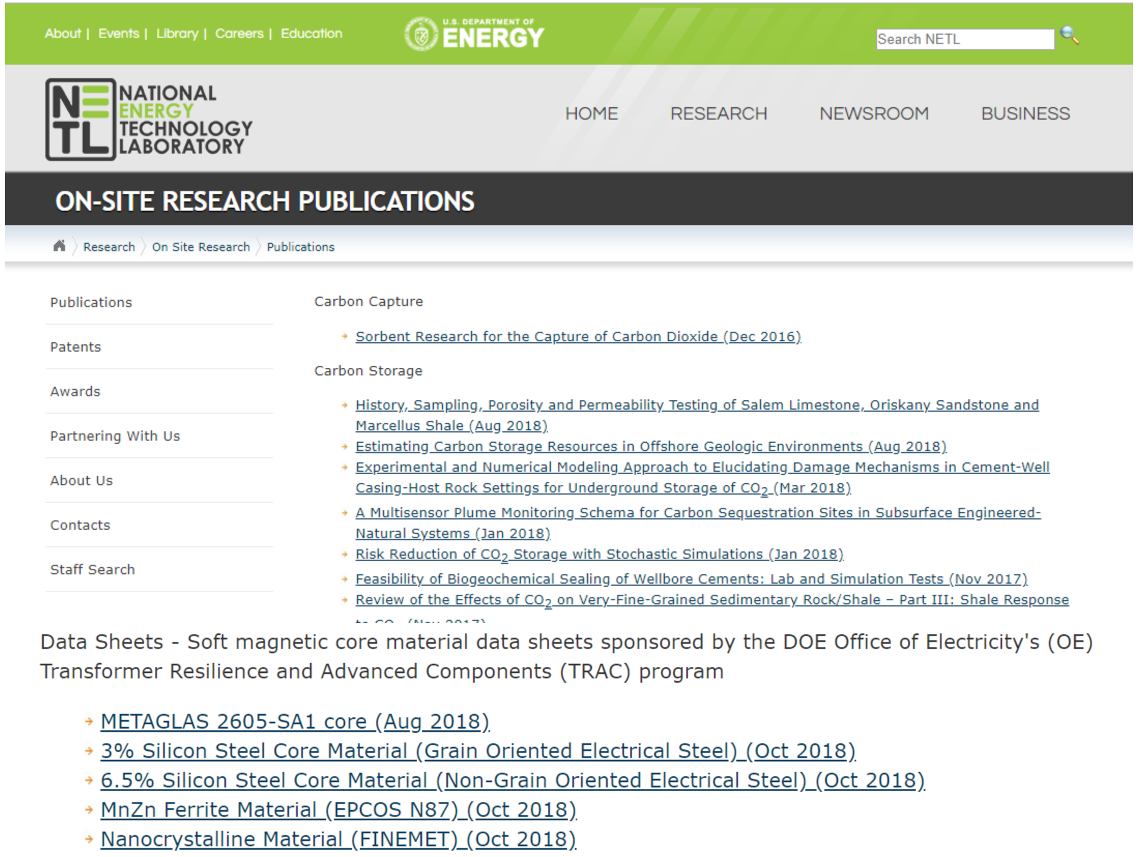
Five datasheets of five representative core materials are completed.

- Standard Electrical Steel (3% Si)
- Hi Si content electrical Steel core (6.5% Si)
- Nanocompsite cores (MK Magnetics)
- Amorphous Fe-based core (MK Magnetics)
- Ferrite core (EPCOS/TDK, N87 material)

Published to public under "Data Sheets - Soft magnetic core material data sheets sponsored by the DOE Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program" at

- Data sheets: https://netl.doe.gov/TRS
- Blogs: https://netl.doe.gov/node/8081
- Citable Publication: 2019 IEEE ECCE Conference "Soft Magnetic Materials Characterization for Power Electronics Applications and Advanced Data Sheets"

More data sheets on different materials are being generated and added as they become available.



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- Estimating Carbon Storage Resources in Offshore Geologic Environments (Aug 2018)
- Experimental and Numerical Modeling Approach to Elucidating Damage Mechanisms in Cement-Well Casing-Host Rock Settings for Underground Storage of CO_2 (Mar 2018)
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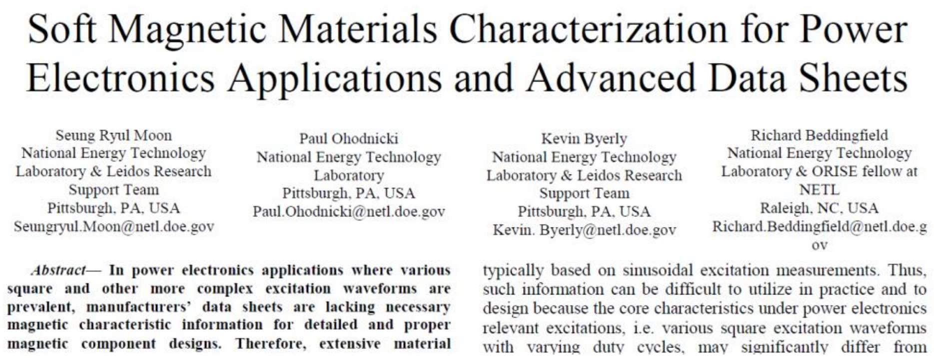
- Risk Reduction of CO_2 Storage with Stochastic Simulations (Jan 2018)
- Feasibility of Biogeochemical Sealing of Wellbore Cements: Lab and Simulation Tests (Nov 2017)
- Review of the Effects of CO_2 on Very-Fine-Grained Sedimentary Rock/Shale – Part III: Shale Response

Data Sheets - Soft magnetic core material data sheets sponsored by the DOE Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program

- METAGLAS 2605-SA1 core (Aug 2018)
- 3% Silicon Steel Core Material (Grain Oriented Electrical Steel) (Oct 2018)
- 6.5% Silicon Steel Core Material (Non-Grain Oriented Electrical Steel) (Oct 2018)
- MnZn Ferrite Material (EPCOS N87) (Oct 2018)
- Nanocrystalline Material (FINEMET) (Oct 2018)



Soft Magnetic Materials Characterization for Power Electronics Applications and Advanced Data Sheets

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Abstract— In power electronics applications where various square and other more complex excitation waveforms are prevalent, manufacturers' data sheets are lacking necessary magnetic characteristic information for detailed and proper magnetic component designs. Therefore, extensive material typically based on sinusoidal excitation measurements. Thus, such information can be difficult to utilize in practice and to design because the core characteristics under power electronics relevant excitations, i.e. various square excitation waveforms with varying duty cycles, may significantly differ from

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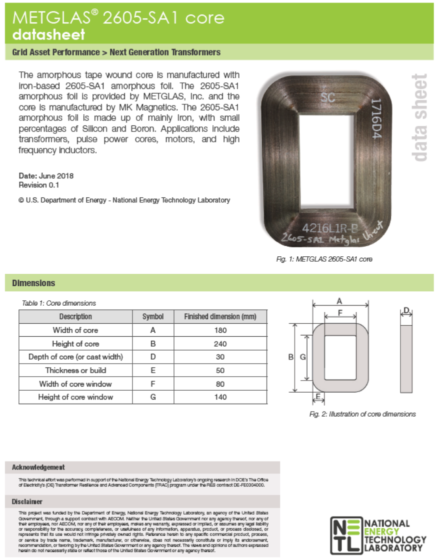
Specific Research Questions to Be Addressed : LV CLTS

- Establishment of advanced data sheets
  - Providing core loss data and permeability characteristics for magnetic component designs on FEA and custom programs
- Core loss and permeability comparison between different materials
- Fast characteristic verifications of developed cores using the on-site CLTS



METGLAS® 2605-SA1 core datasheet

Grid Asset Performance > Next Generation Transformers

The amorphous tape wound core is manufactured with iron-based 2605-SA1 amorphous foil. The 2605-SA1 amorphous foil is provided by METGLAS, Inc. and the core is manufactured by MK Magnetics. The 2605-SA1 amorphous foil is made up of mainly Iron, with small percentages of Silicon and Boron. Applications include transformers, pulse power cores, motors, and high frequency inductors.

data sheet

Date: June 2018
Revision 0.1

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SC
1716D4
4216L1R-B
2605-SA1 Metglas Uncut

Fig. 1: METGLAS 2605-SA1 core

Dimensions

Table 1: Core dimensions

Description	Symbol	Finished dimension (mm)
Width of core	A	180
Height of core	B	240
Depth of core (or cast width)	D	30
Thickness or build	E	50
Width of core window	F	80
Height of core window	G	140

A F D B G E

Fig. 2: Illustration of core dimensions

Acknowledgement

This technical effort was performed in support of the National Energy Technology Laboratory's ongoing research in DOE's The Office of Electricity's (OE) Transformer Resilience and Advanced Components (TRAC) program under the RES contract DE-FE0004000.

Disclaimer

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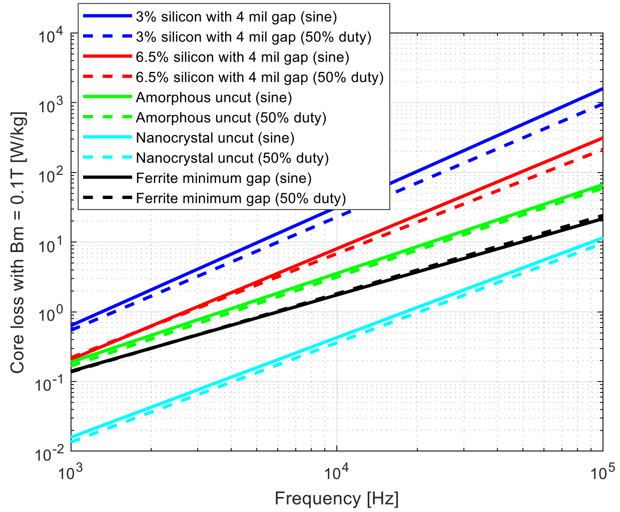
Advanced data sheets



Core loss comparisons

New low-loss, custom permeability tuned core

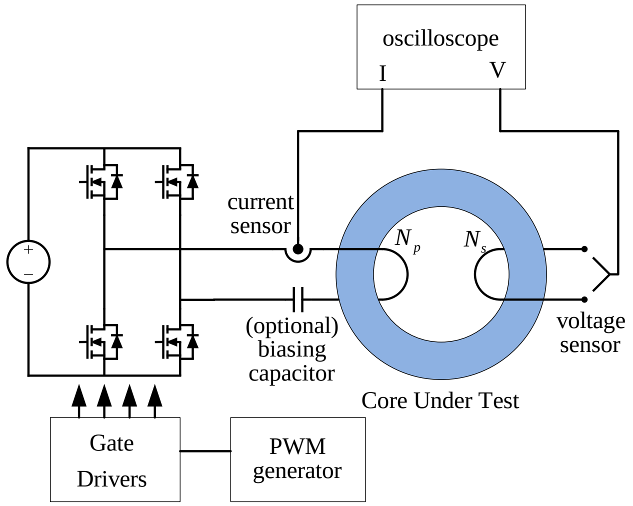
Technical Explanation of the Proposed Approach : MV CLTS and ICS

Extending CLTS capability to Medium Voltage (MV)

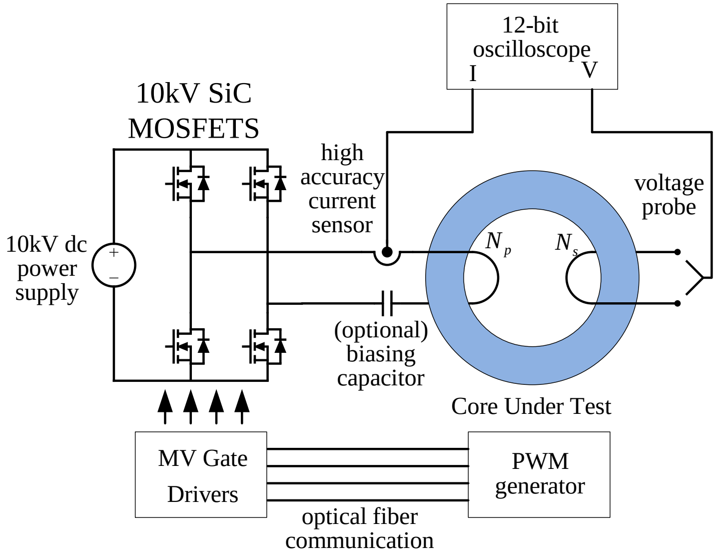
- Currently, the CLTS is constructed with commercially available 1.2 kV SiC MOSFETs.
  (LV CLTS → Generation 1 Established)

- New CLTS is being constructed with 10kV SiC MOSFETs.
  - Sourced via project partners from the Power America Center at North Carolina State University

- MV CLTS will be a valuable tool for designing, testing and verifying components for SSTs and eventually LPTs and SSPSs in the OE TRAC program.



Low Voltage CLTS



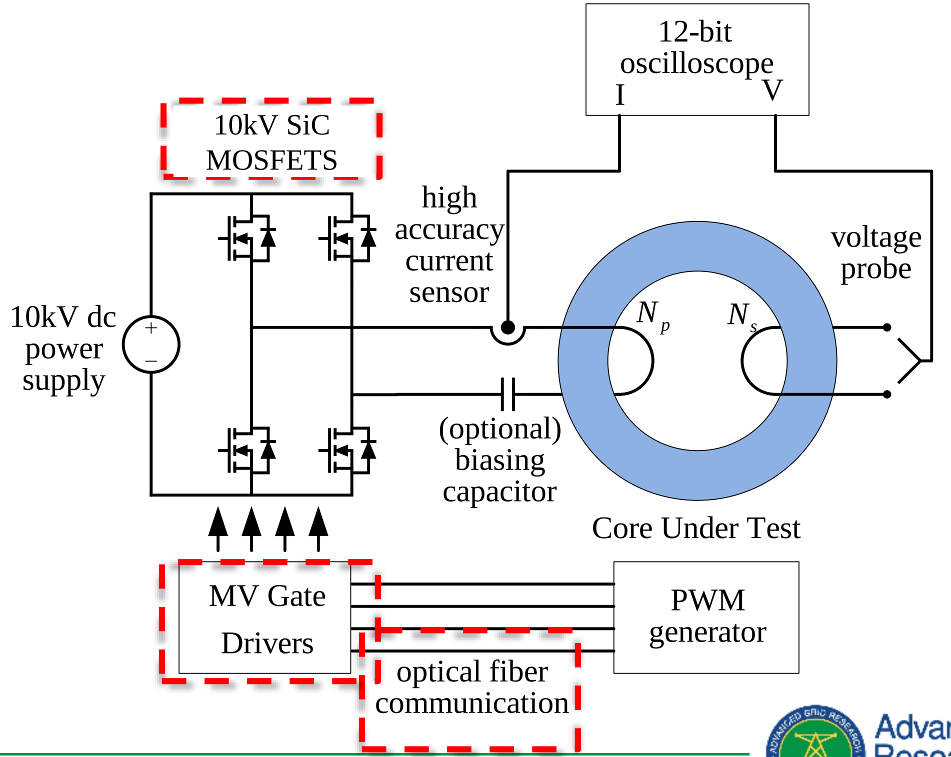
Medium Voltage CLTS

Technical Explanation of the Proposed Approach : MV CLTS and ICS

Specifications of Medium Voltage (MV) CLTS

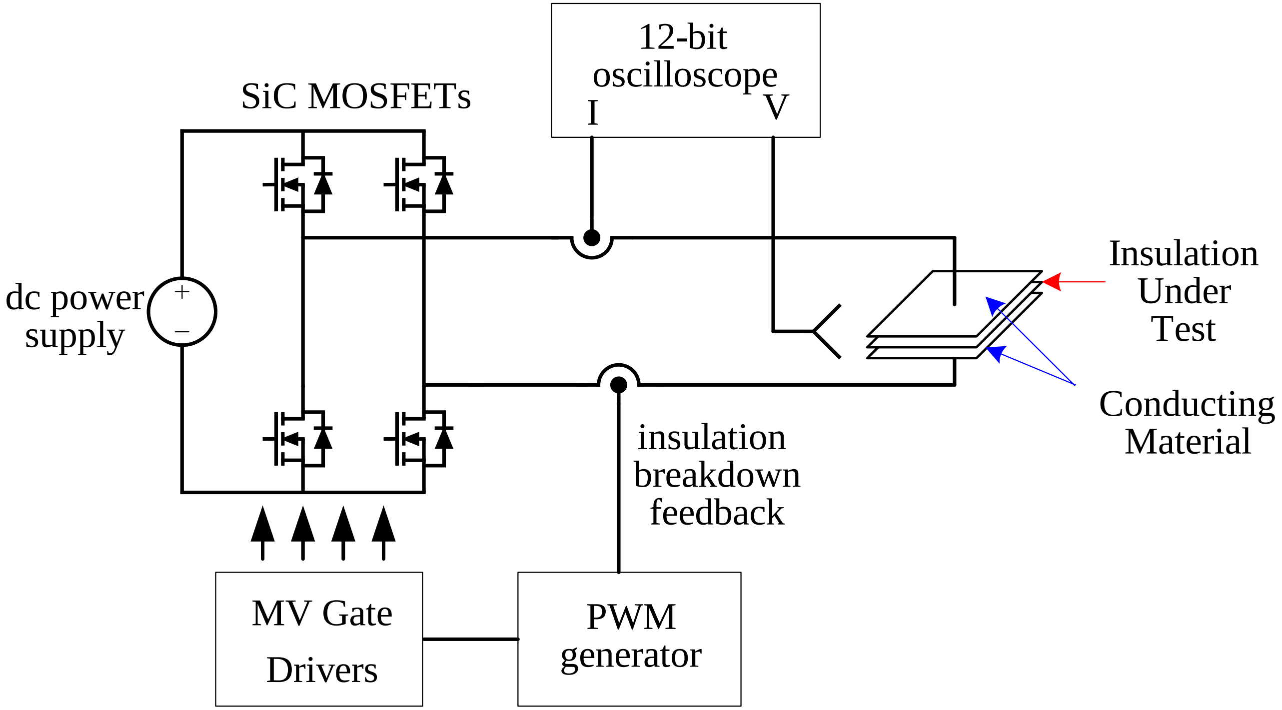
- 10kV SiC MOSFETs for voltage capability improvements
- Custom gate drivers with optical isolation for safety
- Custom DSP controller for more automated characteristic procedures
- 12-bit oscilloscope, high accuracy current sensor, & high voltage probe for high accuracy core characterization

	Anticipated Rating	Notes:
Voltage rating	10 kV	Limited by both power supply and SiC rating
Functionality	Core loss & permeability measurements. Fault tolerant design. Optical communication for gate and fault signals	
DSP controller	Current DSP board will be revised to be compatible with optical driver	



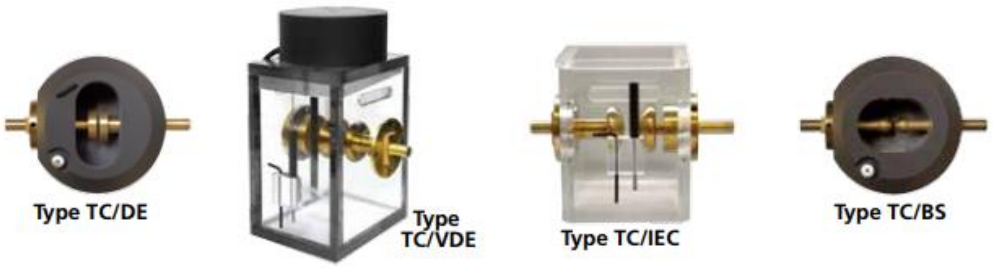
Insulation Characterization System (ICS)

- Leveraging the existing CLTS configuration, NETL is expanding on test capabilities by initiating the development of an insulation characterization system (ICS)

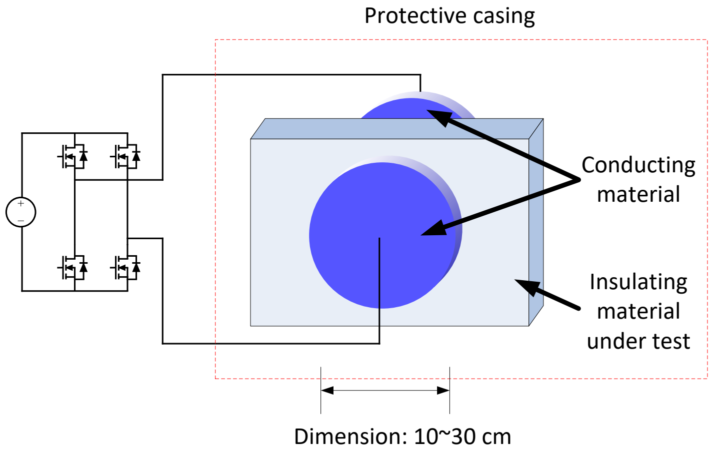


Insulation Characterization System (ICS)

	Commercial Hi-Pot Tester	NETL's ICS
AC Hi-Pot	- 60Hz Sinusoidal testing (typical) - EP loop plots	- Test with power electronics relevant square waveforms - Test at various frequency is possible - EP loop plots (electric field E vs. Polarization density P, similar to BH loops)
DC Hi-Pot	- Pass/Fail Test Possible - Leakage current measurements	- Pass/Fail Test Possible - Leakage current measurements
Test fixture	- Typically small for spot testing	- Large area testing for better characterization signals / application relevant characterization of insulation materials (including manufacturing scalability)
Test functions	- Limited to manufacturer's predefined functions	- Can be customized - Automatized testing possible using custom DSP control and python scripts



Existing small test fixtures



Proposed larger test fixture

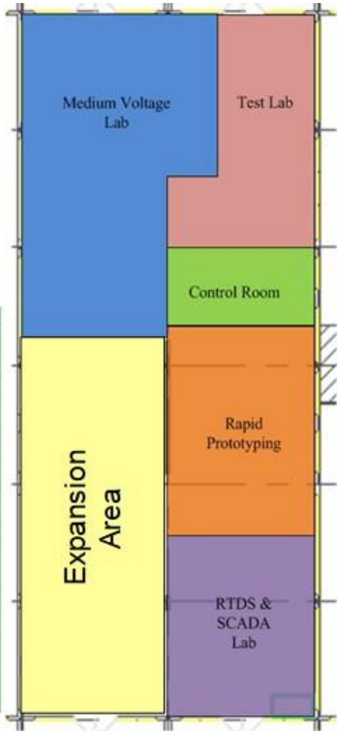
Technical Explanation of the Proposed Approach : MV CLTS and ICS

The need for MV characterization and its challenges

- Developed magnetic components may behave differently at MV levels due to
  - High dV/dt conditions and its effects on parasitic capacitances
  - Scalability of manufacturing processes used for fabrication of components
  - Ensuring successful insulation and isolation of designs
- Proper performance characteristic verification required on full fabricated cores at scale

- Challenges
  - HV SiC devices are not commercially available, and securing it can be difficult
  - Developing gate drivers with HV isolation can be difficult
  - For ICS, measuring very small leakage current accurately can be difficult.

Energy Innovation Center : NETL / University of Pittsburgh



Medium / Low Voltage AC Lab (15kV / 4.16kV / 480VAC)

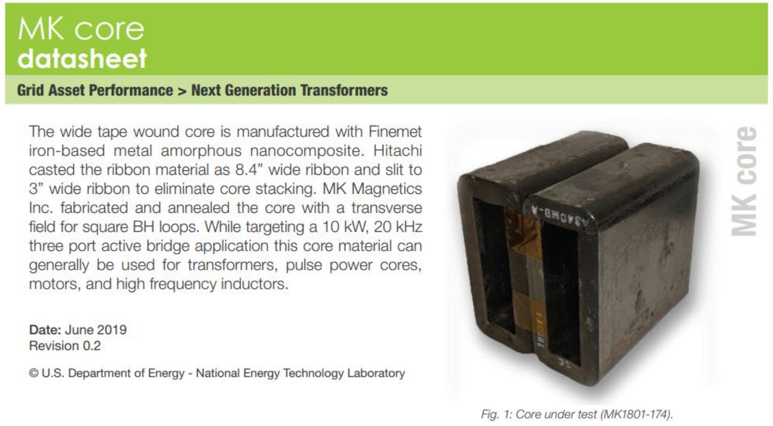
Medium / Low Voltage DC Lab (1kV / 380VDC)

- Current Plans : NETL / U. Pitt Facility to Be Leveraged at the Energy Innovation Center (EIC)
- Newly Commissioned Lab Facilities for Grid-Scale Testing From LV (480V) Up to MV (15kV)
- Dedicated Space for MV Core Loss and Insulation Testing Facility Being Commissioned
- Lab Capabilities For Utility Grid-Tied Testing in Addition to Component Level Testing

Specific Research Questions to Be Addressed : MV CLTS AND ICS

- NETL will continue to characterize various commercially available and custom developed soft magnetic materials and insulation materials, and publish advanced data sheets as they will become available.
  - Extend the core characterizations to MV levels
  - Extend the characterizations to insulation materials

- Verify the performances of inductor and transformer from internal and external sources, such as TRAC partners.
  - E.g. Collaboration with Dr. Dominic Lee and Dr. Zhi Li of ORNL on transformer characterization request



MK core
datasheet

Grid Asset Performance > Next Generation Transformers

The wide tape wound core is manufactured with Finemet iron-based metal amorphous nanocomposite. Hitachi casted the ribbon material as 8.4" wide ribbon and slit to 3" wide ribbon to eliminate core stacking. MK Magnetics Inc. fabricated and annealed the core with a transverse field for square BH loops. While targeting a 10 kW, 20 kHz three port active bridge application this core material can generally be used for transformers, pulse power cores, motors, and high frequency inductors.

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Revision 0.2

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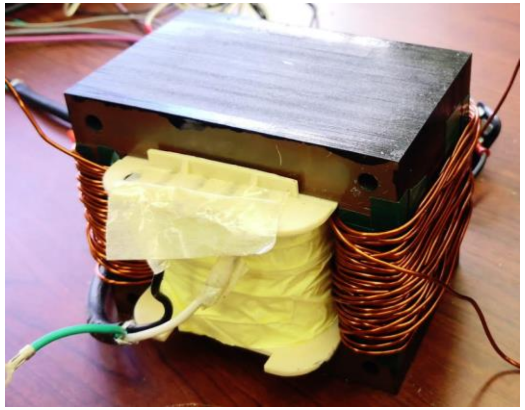
MK core

Fig. 1: Core under test (MK1801-174).

Unpublished data sheets



ORNL sourced transformer

Uniqueness of the CLTS and ICS

- Characteristic measurements are based on power electronics relevant excitation waveforms, i.e. square waveforms, and performed on full fabricated cores at scale rather than constituent core materials under idealized testing conditions.

- Raw measurement data is available. (Plan for inclusion in future data sheets)

- Can measure BH loops in magnetic materials and EP loops in insulating materials.

- Once all the functionalities are implemented on CLTS and ICS, full core characterizations of existing and future magnetic components are possible.

- Characterization can be automatized and standardized, but also flexible.

Significance of the results, if successful

- Advanced data sheets on various commercially available and custom developed soft magnetic materials and insulation materials will become available to TRAC program partners and the public.

- The information on advanced data sheets can be utilized to perform and obtain more detailed and highly accurate component designs.

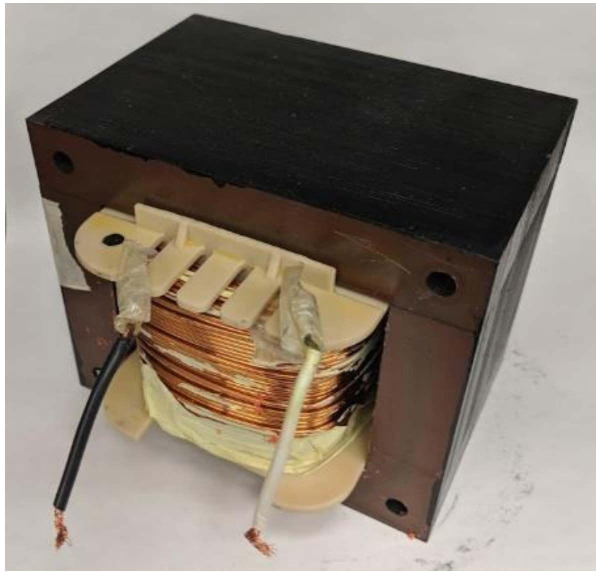
- TRAC program partners can request NETL to validate the performance of their custom developed magnetic components.

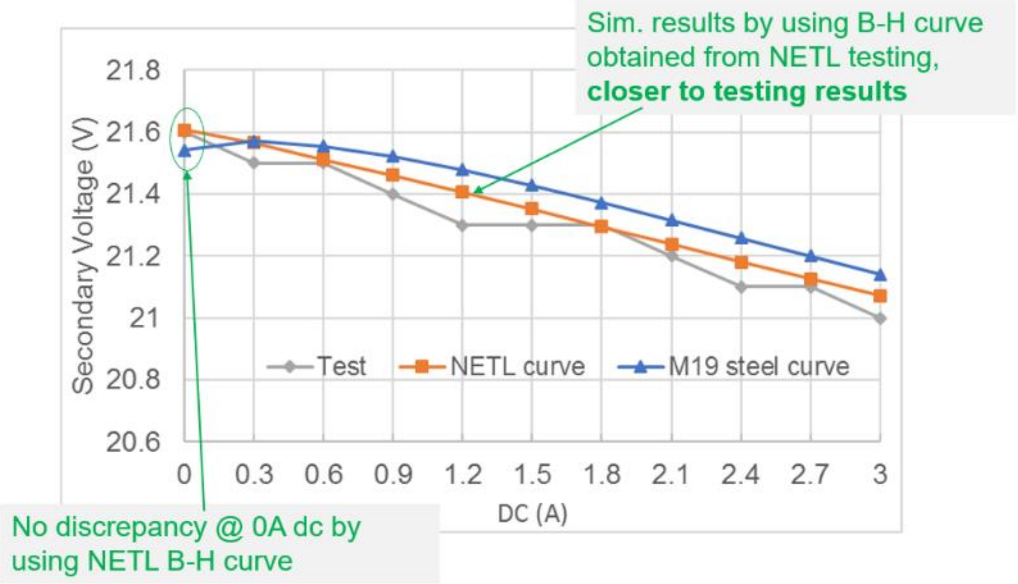
- A foundation is established for future, more optimized and effective magnetic component design and characterization at MV level moving forward.

Significance of the results, if successful

- <u>Example:</u> The information on advanced data sheets can be utilized to perform and obtain more detailed and highly accurate component designs.

- In the collaboration with Dr. Zhi Li from ORNL, measured core data from NETL is used to improve the ORNL's finite element analysis (FEA) and analytical modeling simulation fidelity





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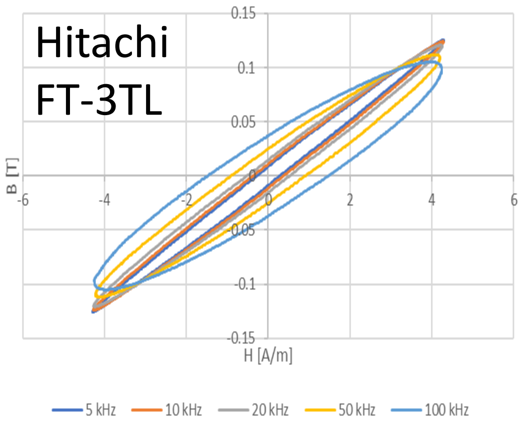
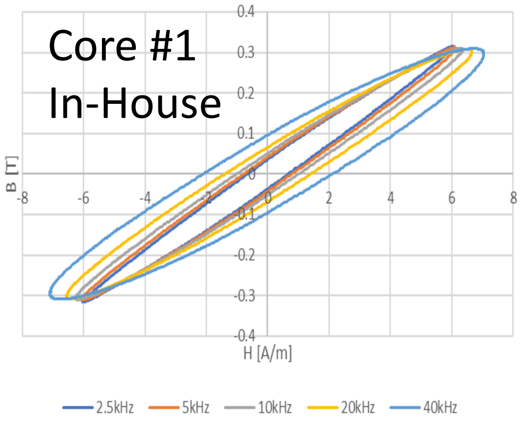
Significance of the results, if successful

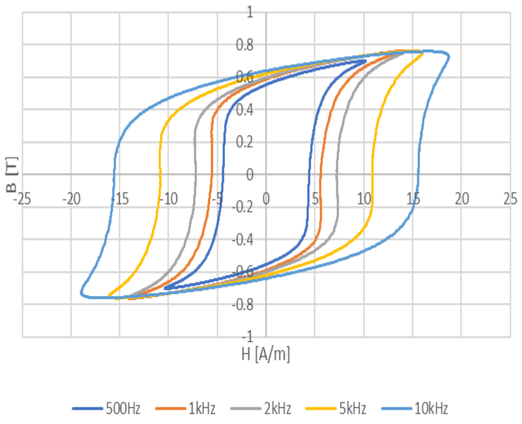
- Example: TRAC program partners can request NETL to validate the performance of their custom developed magnetic components.

- Two custom cores were fabricated under another DOE program, utilized to study the core losses in optimized 10kW transformers.

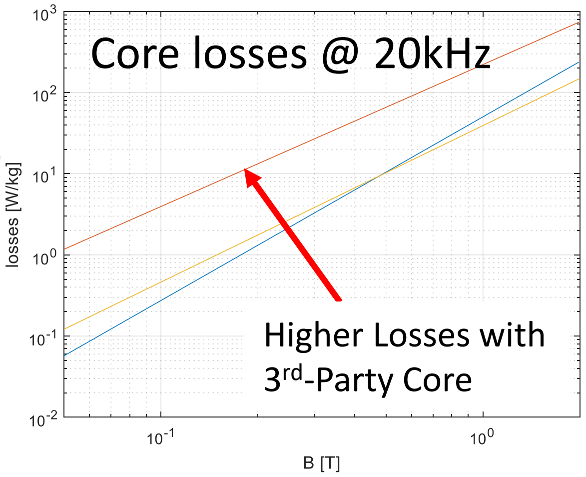
- The cores under test are expected to have similar characteristics as Hitachi FT-3TL core.
    - 3rd-Party Source core is significantly more lossy at 5 kHz and higher frequency
    - This confirms the importance of core characterization capability.







Core #2
3rd-Party Sourced



Project schedule, deliverables, and current status

Milestones On Track

Milestones:

BP1: Seed Funding for Initial Project and Capability Establishment

- *√ Establishment of Initial LV CLTS System (Complete)*
- *√ Characterization of five commercially available cores (Ferrite, 3% & 6.5% Si-Steel, Amorphous, and Nanocomposite cores) (Complete)*

BP2: Further Application and Improvements of LV CLTS Capability (Complete)

- *√ Review the latest loss models for data fitting and refine data sheet formats (Complete)*
- *√ Identify an improved excitation circuit and generate three additional core data sheets (Complete)*

BP3: Extend the CLTS capability to MV and perform initial designs of ICS

- *√ Design the MV CLTS system and specify necessary components and a MV source, 6/30/2019 (Complete)*
- *√ Complete first design specifications for insulation material testing for review, 6/30/2019 (Complete)*
- *- Secure necessary critical components and MV power source for the MV CLTS, 9/30/2019*
- *- Initiate necessary facility modifications for MV CLTS system, 9/30/2019*
- *- Develop the gate drivers for the high voltage SiC devices, 12/31/2019*
- *- Assemble the MV CLTS and perform MV tests on at least 1 inductor or transformer developed for MV application, 3/31/2020*
- *- Develop a detailed report of insulation material test facility status and future plans, 3/31/2020*
- *- Develop a draft insulation material data sheet for review and feedback by DOE , 3/31/2020*

Total Budget = ~$550k
BP3 Budget Remaining = ~$175k
Spending On Track

Deliverables:

Deliverables On Track

- *- Designs and specifications for a new MV CLTS and insulation material test system, 9/30/2019*
- *- MV testing and a data sheet for a MV inductor or transformer, End of Q4*
- *- Full design specifications for MV insulating material test facility and progress report, 3/31/2020*
- *- Initial data sheet for a representative insulation material (Nomex 410), 3/31/2020*

Anticipated challenges and risk mitigation strategies

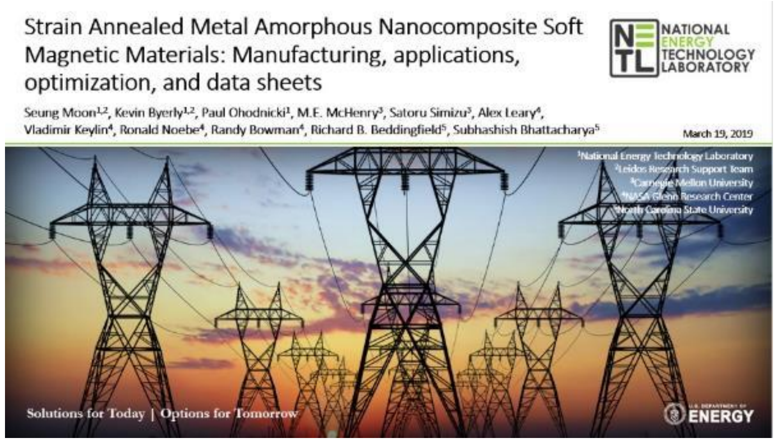
Challenges/Risks	Severity	Probability	Mitigation Strategy
Cannot secure HV SiC MOSFET components	High	Low	Leverage on-going programs and collaborations with NCSU / Power America
Very low current level with ICS	Medium	High	Instead of using non-contact current sensor, use resistive shunt for current measurements
Facility modification delays for MV lab establishment	Low	Medium	MV CLTS and ICS lab established at U. of Pitt. EIC facility being commissioned to minimize facility modifications
Project outputs are not leveraged by industry, university, or TRAC partners	Medium	Medium	Presentations are delivered at major conferences and industry workshops, and results are posted publicly on NETL website and referenced in citable literature
Data sheets are not used in optimization and designs	Medium	Medium	Provide parameterization of both conventional Steinmetz (sinusoidal) and empirically derived equivalent Steinmetz coefficients for various waveforms. Parameterize B-H loops and permeability using standard models in existing optimization and design tools.

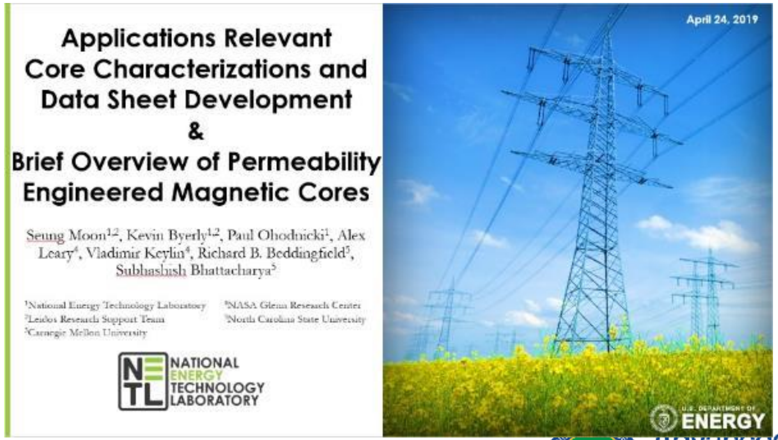
Next steps

- Secure necessary components, such as HV SiC MOSFETs, and design gate drivers
- Build new CLTS and ICS setups using the secured components
- Design high accuracy and precision measurement setups for CLTS and ICS
- Develop automated measurement procedures for magnetic / insulation materials
- Publish new data sheets on various magnetic cores and insulating materials
- Perform magnetic component verifications / characterization for TRAC partners
- Implement pre-magnetization and temperature controlled core characterization

Broader Impact

- Past presentations
  - Power Sources Manufacturers Association (PSMA) Magnetic Workshop on March 16, 2019 at Anaheim, CA
  - Applied Power Electronics Conference (APEC) Industry Session: High Frequency Magnetics: New Magnetic Materials on March 19, 2019 at Anaheim, CA
  - The Transformer Association (TTA) Spring Meeting, Technical/Engineering Forum on April 24, 2019 at Nashville, TN
- Future planned presentations
  - 2019 Coil Winding Expo (CWIEME) America, Chicago, IL, Sept 17-18
  - 2019 IEEE Energy Conversion Congress & Expo (ECCE), Baltimore, MD, Sept 20-Oct 3 (Including Publication)
- Feedback from the power electronics community at the APEC conference and TTA meeting were overwhelmingly positive, indicating this was a key need for the community.
- A simulation company, SIMPLIS (https://www.simplistechnologies.com/), has shown interests to incorporate the measured core characteristics to their simulation packages.
- Collaboration with private companies on magnetics optimization efforts leveraging developed data sheets





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