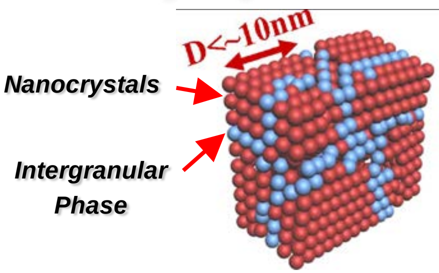
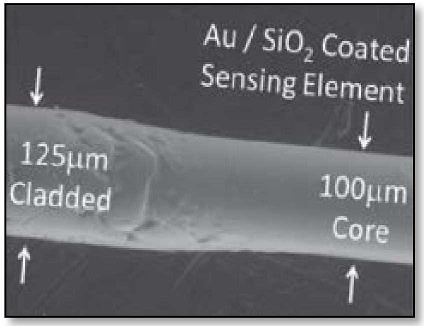
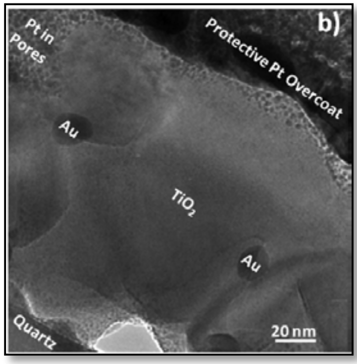
NATIONAL ENERGY TECHNOLOGY LABORATORY

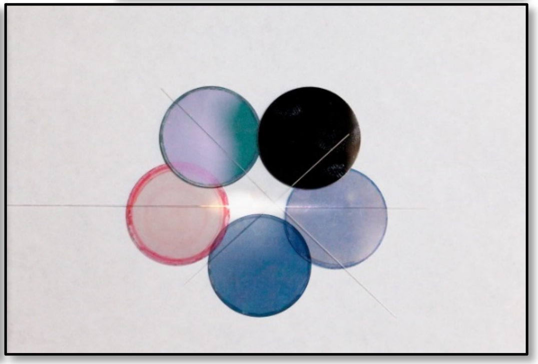


Sensing Material Enabled Harsh Environment Sensors



Magnetic Material Enabled Power Conversion Devices





Materials and Device Research for Electrical System Applications at the National Energy Technology Laboratory

Dr. Paul R. Ohodnicki, Jr.

Functional Materials Team

Materials Engineering & Manufacturing Directorate

NETL Research & Innovation Center (RIC)

U.S. DEPARTMENT OF ENERGY

Relevant Research Focus Areas in R&IC

- **Emerging Trends Driving R&D Opportunities in the Area of Grid Modernization**

- **Material and Device Development for System Level Impacts**
  - Active Focus Areas within R&IC
  - Recent NETL Funded Initiatives within the GMLC

- **Nanocomposite Soft Magnets and HF Transformers for Grid Integration**
  - Project Overview
  - Strategic Technical Thrusts
    - Magnetic Alloy and Manufacturing Development (NETL, CMU, and NASA)
    - Transformer Design and Manufacturing (NCSU and Eaton)
    - Power Electronics and Systems Level Design (NCSU and Eaton)

- **Optical Fiber Based Sensing for Asset Monitoring in Power Transformers**
  - Project Overview
  - Early Results and Proposed Targets

- **Summary and Conclusions**

Emerging Trends and Technical Needs in the T&D System

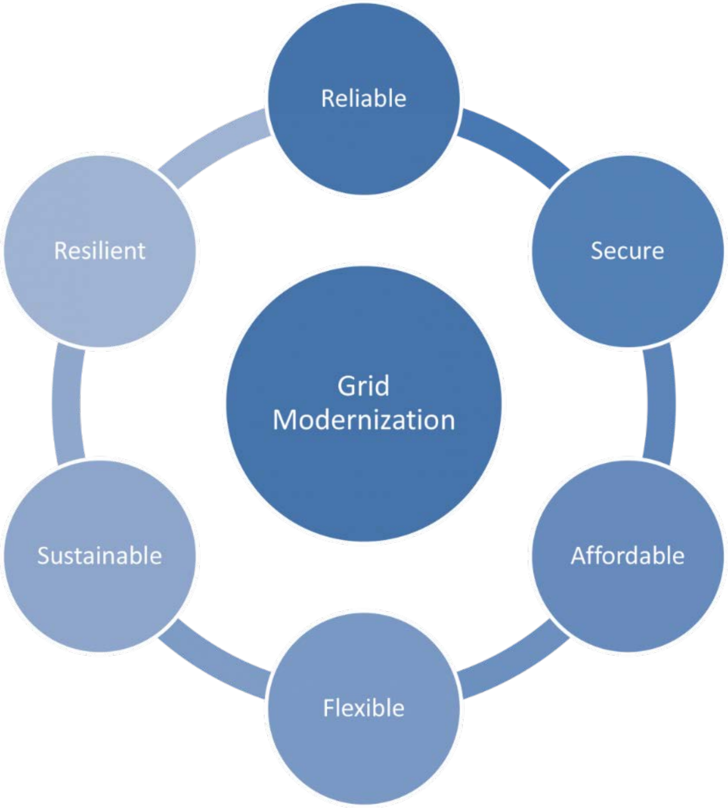
Changing Mix of Types and Characteristics of Electricity Generation

Growing Demands for a more Resilient and Reliable Grid for Weather and Cyber / Physical Attacks

Growing Supply and Demand Side Opportunities for Consumers to Actively Participate in Electricity Markets

Aging Electricity Infrastructure Presenting Opportunities and Challenges

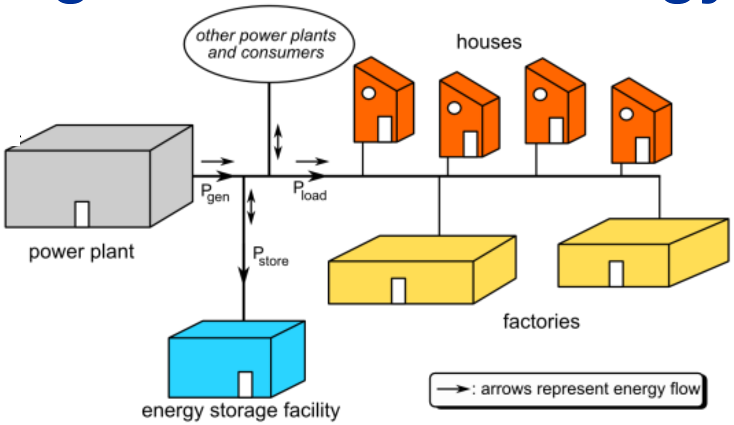
Grid Modernization INITIATIVE



Through the Recently Announced Grid Modernization Initiative and the Grid Modernization Laboratory Consortium, DOE Has Placed Grid Modernization at a High Priority.

http://gridmodernization.labworks.org/about

Urgent New Technology Development Needs Required



Grid-Scale Energy Storage Devices

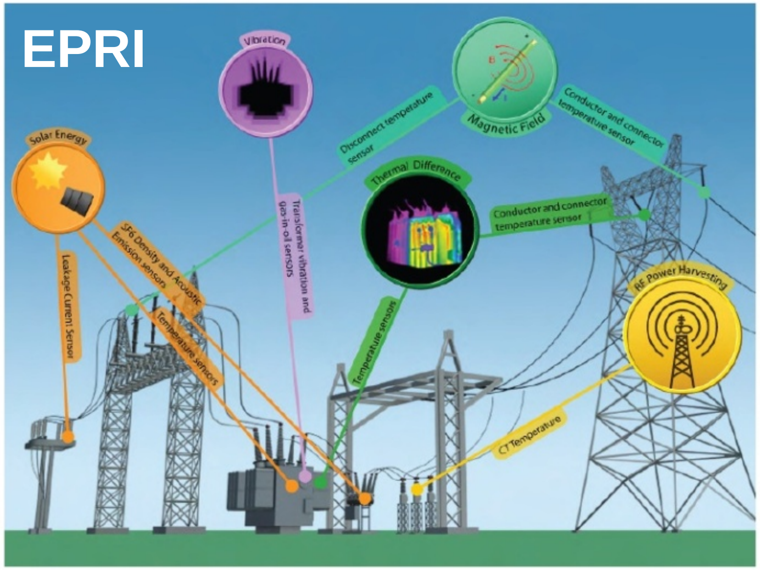
"The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited to the load."

ARPA-E

Power Electronics Converters

(Grid Integration, Power Flow Control, HVDC, and Power Conversion)

Sensors and Controls

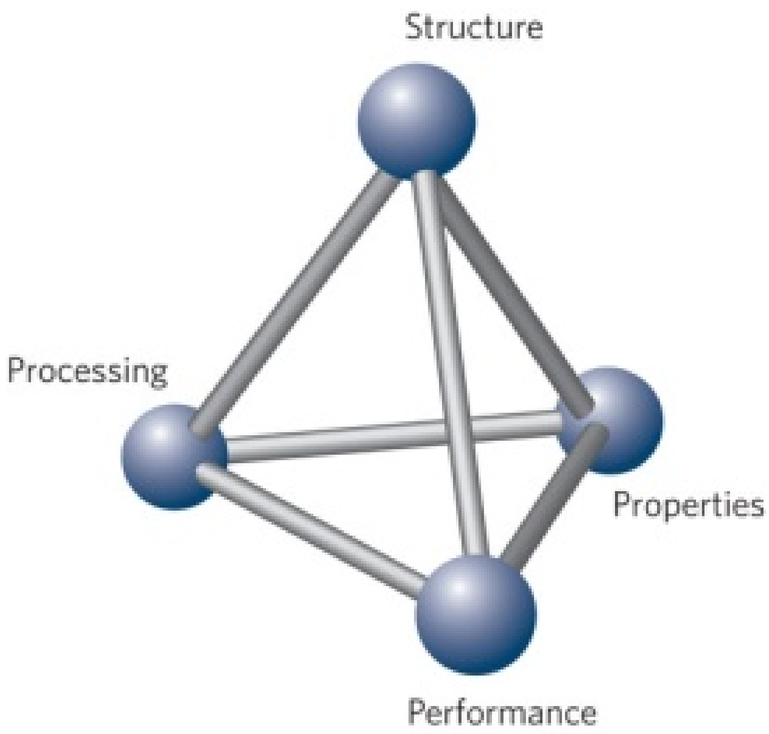


Technological Advances Are Required

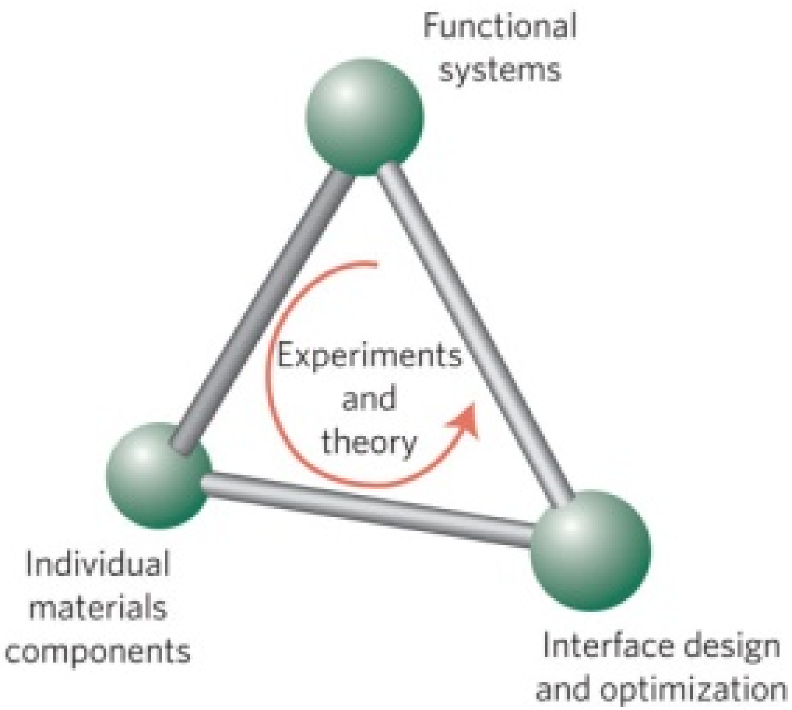
<u>Functional Materials Enable Revolutionary Advances in Devices</u>

Functional Material Development for Devices and Systems

Classic Materials Science Paradigm



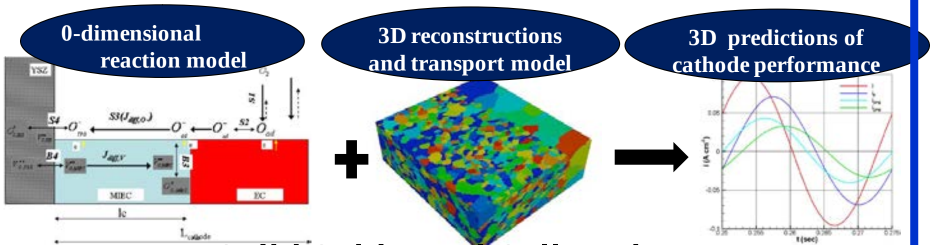
Emerging Paradigm
Materials Interface with Functional Systems and Devices



Materials Research Targeted at Device and System Level Benefits

Materials and Device Focus : Functional Material Team

Current Fiscal Year 2017

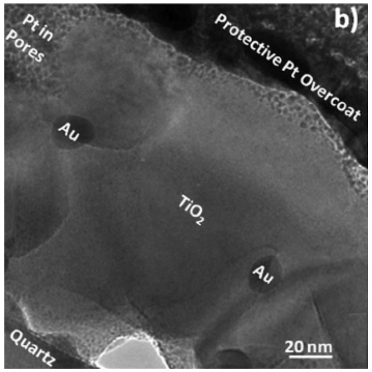


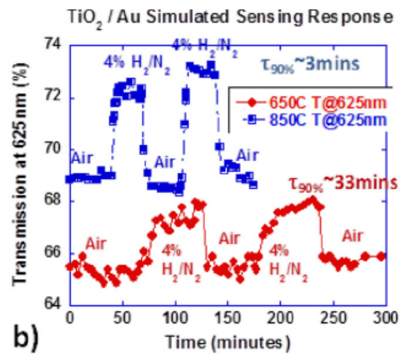
Solid Oxide Fuel Cell Devices

Modeling + Characterization → Optimal Device Performance

Solid Oxide Fuel Cell Materials / Devices
Function and Durability

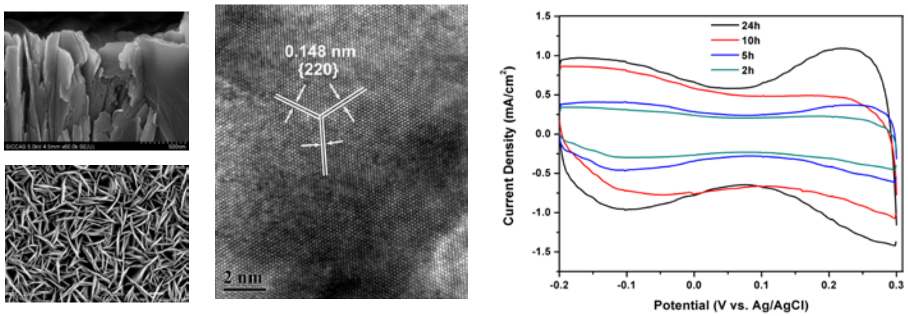
Current Fiscal Year 2017





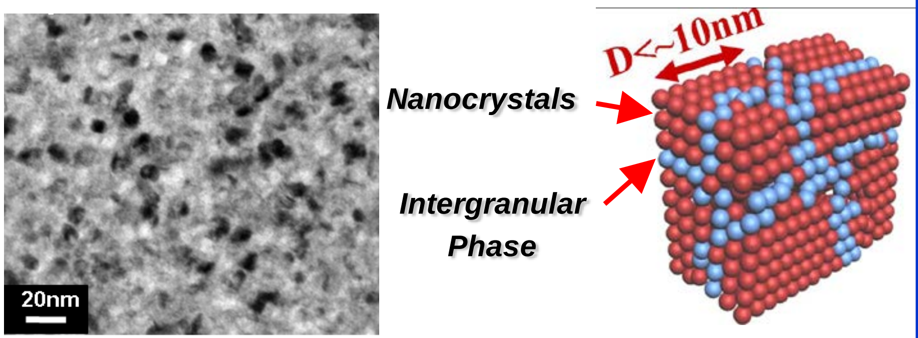
Sensor Materials / Devices
Chemical and Temperature Sensing

Not Currently Active



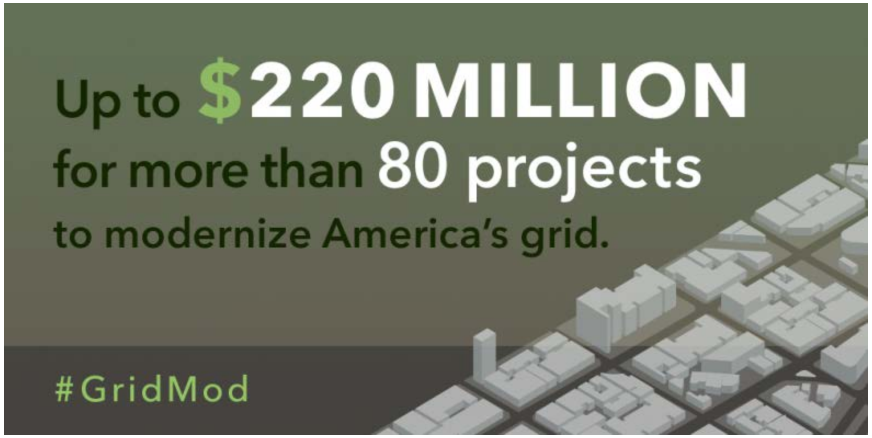
Energy Storage Materials / Devices
Enhanced Performance

Current Fiscal Year 2017



Soft Magnetic Materials / Devices
Inductors and Sensors

DOE Lab Call for Grid Modernization Research



Announced in January of 2016

Project #1: DOE EERE Solar Energy Technology Office (NETL Led)

Project 2: Combined PV/Battery Grid Integration with High Frequency Magnetics Enabled Power Electronics	Advanced DC-DC and DC-AC converter-based integrated modules and associated systems architectures and topologies will be developed for 13.8kV, 60Hz direct grid connection using SiC devices. In parallel, advanced magnetic cores and high frequency (HF) transformers built upon them will be developed to enable DC-DC and DC-AC converters with energy storage (ES) that serve as the building blocks for the proposed technologies. System architecture studies informed by market driven technical requirements will also be performed to provide guidance for the on-going R&D activities throughout.	NETL	NC State University, Eaton, Carnegie Mellon University, NASA	$4M proposed over three years

Project #2: DOE OE / BTO (NETL Partner)

Project 19: Advanced Sensor Development	Increase visibility throughout the energy system including transmission, distribution, and end-use by developing low-cost, accurate sensors. Additionally, next generation asset monitoring devices will help determine state of grid components prior to failure.	ORNL, PNNL, NETL, NREL, SNL, LBNL	EPRI, University of Tennessee, Southern Co, EPB, Entergy, Eaton, SmartSense, National Instruments, Dominion, TVA, CommEd, NASPI	$6M over three years

NETL was Successfully Awarded 2 Relevant Project Proposals Under the DOE GMLC Lab Call for Proposals in the Areas of Power Electronics and Sensor Development

http://energy.gov/doe-grid-modernization-laboratory-consortium-gmlc-awards

Nanocomposite Soft Magnets and High Frequency Transformers for Grid Integration

Project Effort #1: Overview

Combined PV / Battery Grid Integration with High Frequency Magnetics Enabled Power Electronics

Carnegie Mellon University

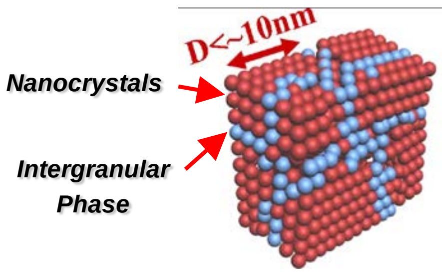
NC STATE UNIVERSITY

EATON Powering Business Worldwide

NASA

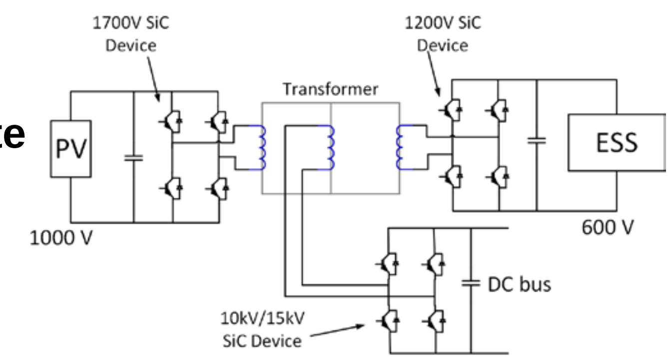
NETL

Nanocomposite Soft Magnets



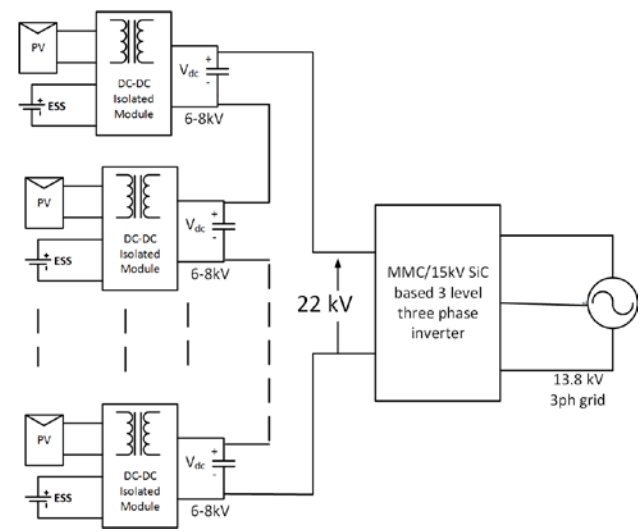
3-Winding Nanocomposite Core Transformer

Three Port Modular DC-DC Converter



High Frequency Magnetics + Wide Bandgap Semiconductors

Overall PV / ES Inverter System

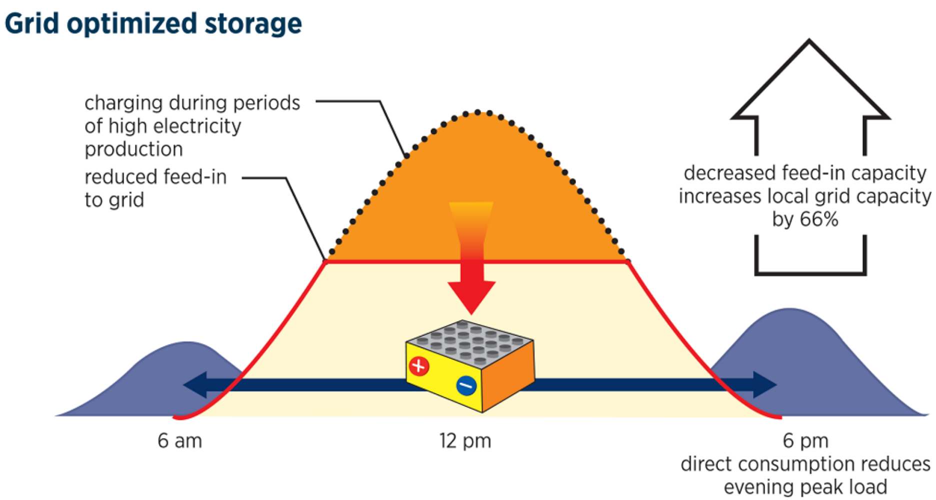


- **Team Structure Spans National Labs, Industry, and Universities**
- **Modular MW-Scale Inverter for Combined Photovoltaic and Energy Storage**

DOE SunShot Initiative SuNLaMP 01699

What are Advantages of Combined PV and Energy Storage?

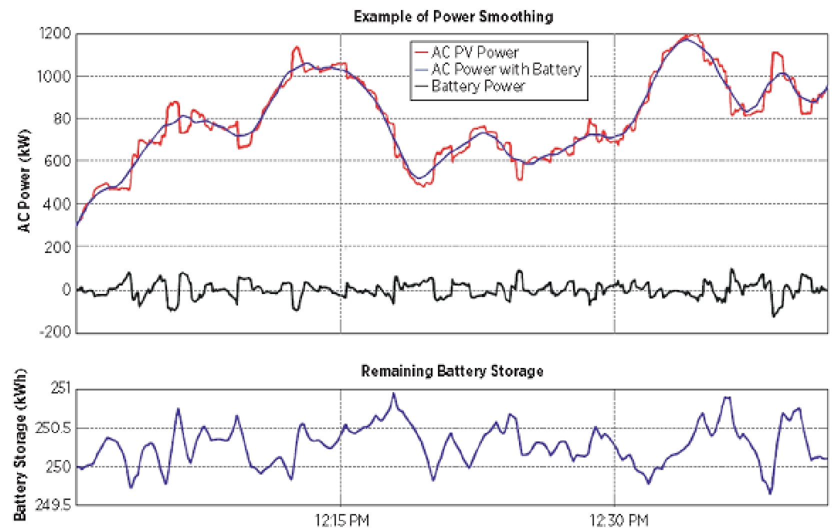
Time-Shifting of Electricity Production through PV



→ **Reduced Cost and/or Increased Value of Electricity Production**

→ **Reduced Requirements for Baseload Fossil Plant Cycling**

Smoothing of Power Fluctuations for Instantaneous Production



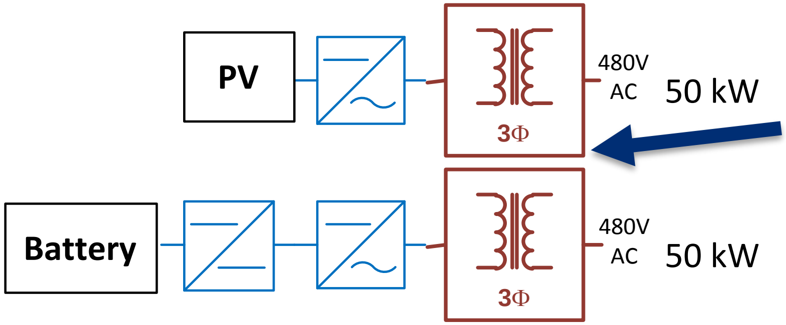
→ **Local Factors (i.e. Clouds) Result in Sharp Time Variations in PV Power**

→ **Increased Reliability of PV Generated Electrical Power**

Combining PV with Energy Storage Allows for Improved Management of Variability in PV Generation

Why Use a Multi-Winding High Frequency Transformer?

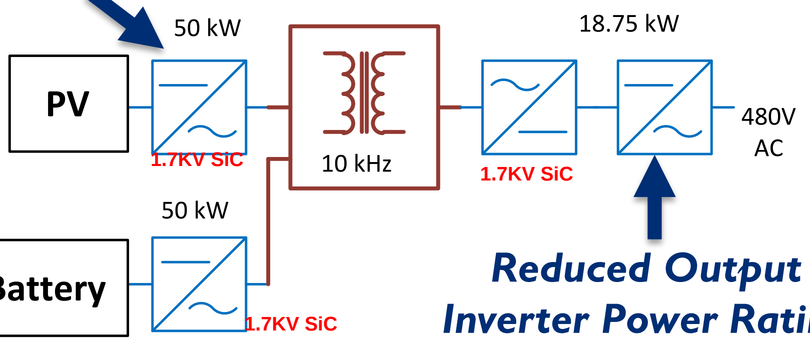
Conventional Solution



Elimination of Line Frequency Transformers

Multi-Winding HF Transformer Based Solution

Commercially Available SiC-Devices



Reduced Output Inverter Power Rating to Avg. Power

60Hz vs 20kHz

330kVA 60Hz Transformer 55" high and 2700Lb

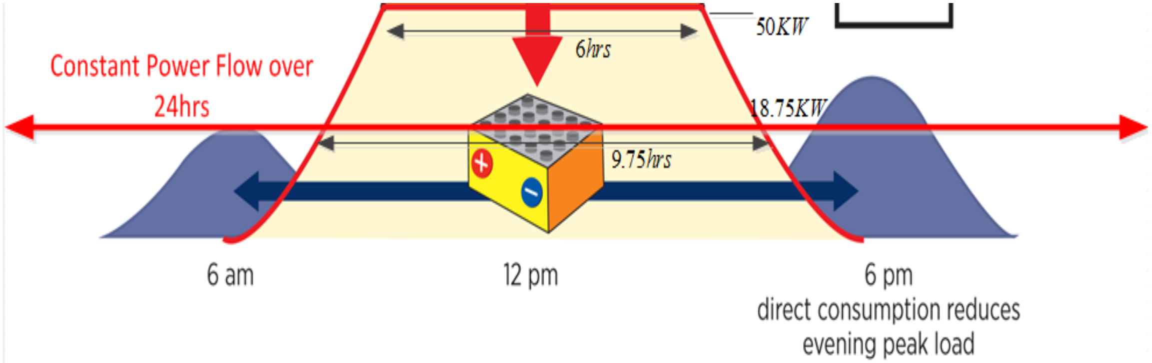
250kVA 20kHz Transformer 16" high and 75Lb

15kV Class > 1MVA Transformer Frequency	Fx to 60Hz Ratio	Transformer Core Mass Reduction Factor	Transformer Core Volume Reduction Factor
60Hz	1	1	1
400Hz	7	8	1.4
1kHz	17	10	1.7
20kHz	333	68	34
50kHz	833	82	34

Increased Power Density and Potential for Higher Efficiency Energy Storage Charging / Discharging

DOE SunShot Initiative SuNLaMP 01699

Architecture Studies to Understand Costs and Benefits



Commercial Scale Shows Significant Advantages

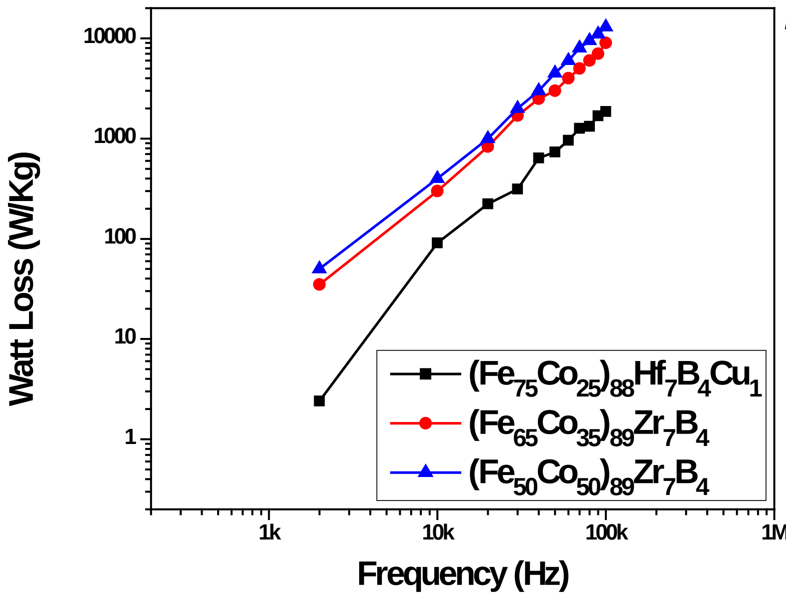
Architectures	Efficiency (PV to 480Vac)	Efficiency (PV to Battery)	Converter + Transformer Material Cost/W**	Power Density	Lifetime Saving	Reliability (MTBF)
Existing Solution (AC Coupled)	97-98%	**93-95%**	$0.30/W	8.4 KW/m^3	-	40.3 years
HF Transformer Solution (DC Coupled)	98%	**99%**	$0.295/W	114.1 KW/m^3	$5.6K	83.8 years

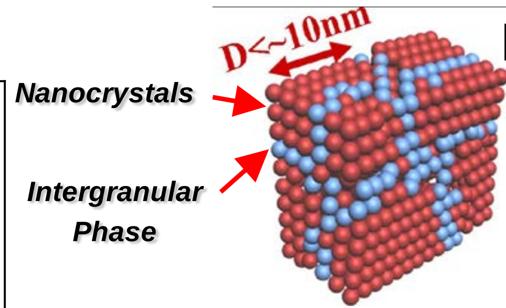
- **Higher Efficiency Energy Storage Charging / Discharging**
- **>10x Increase in Power Density**
- **>2x Increase in Reliability**
- **Cost Competitive with Significant Return on Investment**

DOE SunShot Initiative SuNLaMP 01699

Why Use Advanced Soft Magnetic Materials?

Nanocomposite Soft Magnets

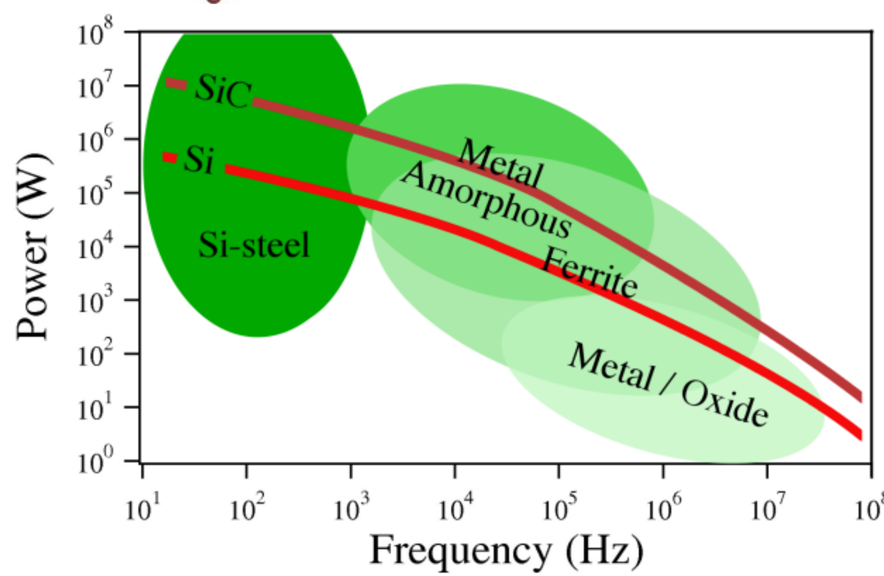




Engineered Magnetic, Electrical, and Mechanical Properties

$$P_t = k f^{\alpha} B^{\beta}$$

Increased Losses at Elevated Frequency (Eddy Currents)



Higher Frequencies and Novel Power Electronics / Transformer Designs Increase Needs for New Soft Magnets

High-Level Technical Project Objectives

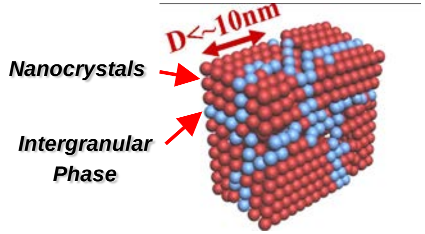
Task 1: Technical Requirement Definition and System Architecture

Task 2: DC-DC Converter Module Design and Build

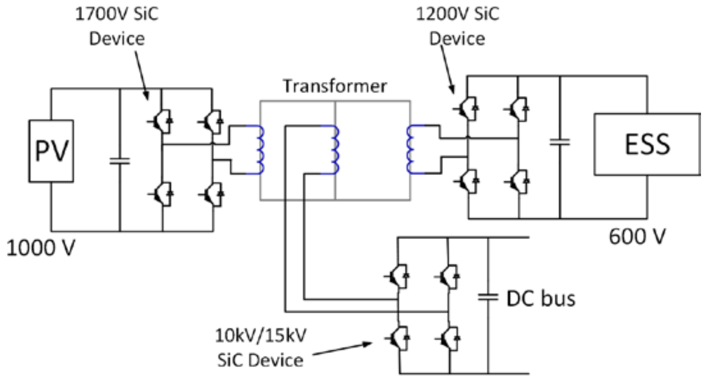
Task 3: Systems Integration Demonstrations

Task 4: Advanced Magnetics and High Frequency Transformer Technology

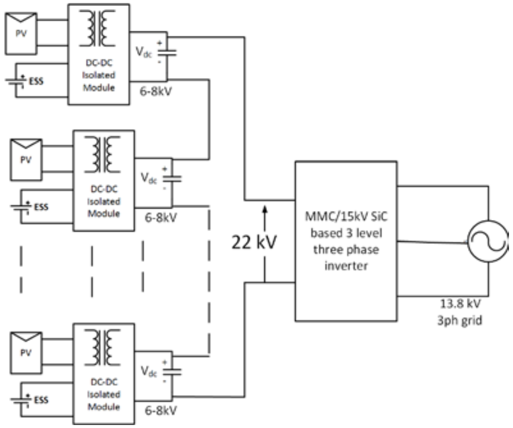
Enabling Magnetics



50-100kW DC-DC Converter Modules

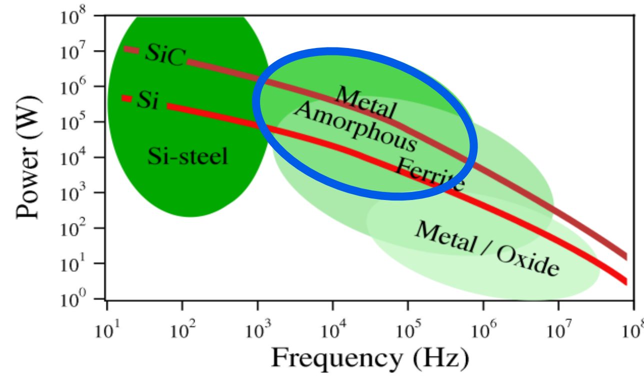


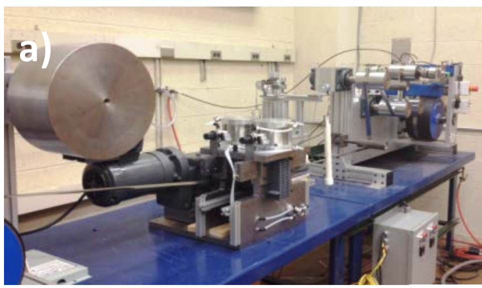
MW-Scale Inverter



Project Goal: Solar Inverter Technology that Addresses Performance Requirements and Cost Targets Relevant for the DOE SunShot Initiative

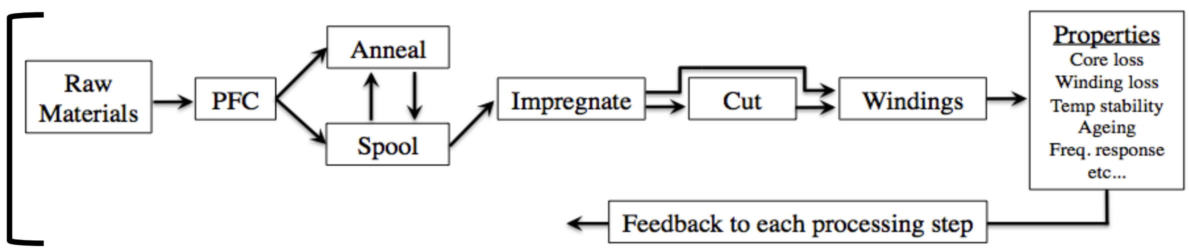
Research Focus Area #1 :
Alloy Design and Magnetic Core Manufacturing Efforts





Alloy	Remarks	Bm, T	µ	P0.2/20, W/kg	Tmax, °C
HTX 002	Nanocrystalline	1.55	1500	4-6	250
HTX 005C	Amorphous	1.02	670	5	
	Nanocrystalline	0.96	480	8	400
HTX 005F	Nanocrystalline	0.89	220	6-8	
HTX 007A	Amorphous	1.52	1k to 3k*	3-5	
HTX 003D	Nanocrystalline	1.20	9k to 18k*	1.5	
2605SA1	Amorphous	1.56	1k to 5k*	10	155
HTX012B	Nanocrystalline	1.25	15k to 20k*	2	125

Core Fabrication and Testing, Process Flow Diagram



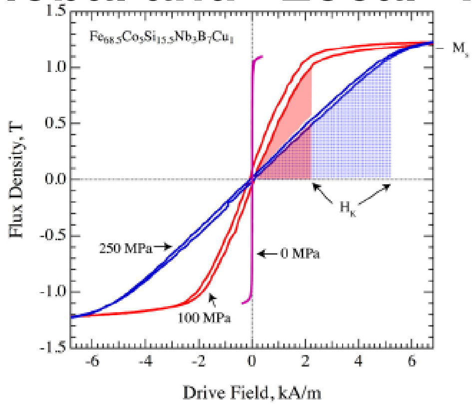
Previously Developed Alloys Under an ARPA-e Solar ADEPT Program are Being Modified for Advanced Processing and Ease of Core Fabrication

DOE SunShot Initiative SuNLaMP 01699

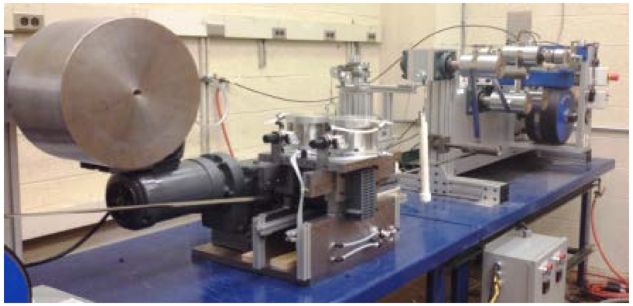
Research Focus Area #1 :
Alloy Design and Magnetic Core Manufacturing Efforts

Rapid Solidification

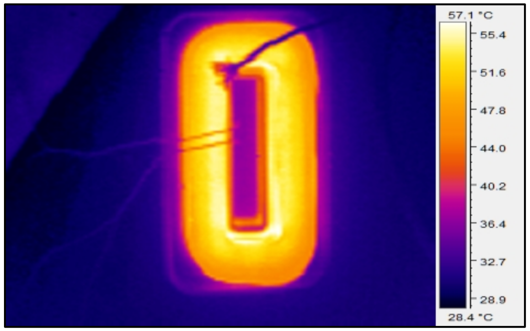
Global and "Local" Permeability Engineering

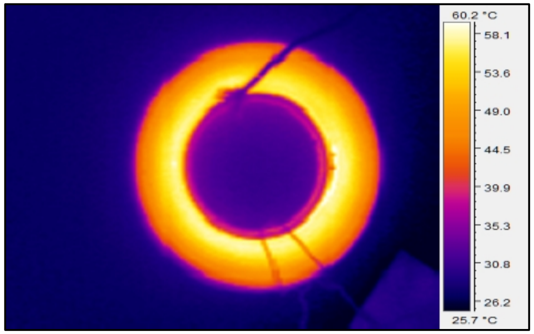


Strain Annealing



Loss and Heat Management of Components





Key Emphasis #1 :

Advanced Processing Methodologies Involving Strain and Field Annealing for Permeability Engineering

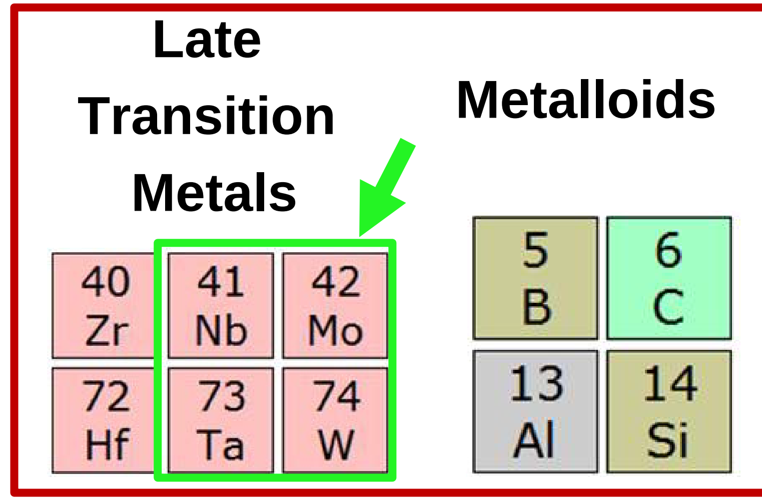
Research Focus Area #1 :
Alloy Design and Magnetic Core Manufacturing Efforts

Glass Former Element Substitution Demonstrated Successful

Fe76.5-xMxCu1Si15.5B7

Run	M	Bm, T	At σ=200MPa			At max stress			Resistance, μΩ*m	
			μ	Ku, kJ/m3	Ku/σ	σ, MPa	μ	Ku, kJ/m3	As cast	200MPa
19	Nb3 (HTX 012)	1.200	262	2.19	10.9	300	147	3.90	141	1.16
21	Nb4	1.012	234	1.74	8.7	300	142	2.87	1.41	1.20
22	Nb5	1.057	349	1.27	6.4	200	349	1.27	1.43	1.31
26	Nb6	0.959	255	1.44	7.2	300	133	2.75	1.46	1.29
37	Nb1.5 Mo1.5	1.214	221	2.65	13.3	300	148	3.96	1.37	1.09
32	Nb2 Mo2	1.045	171	2.54	12.7	500	50	8.69	1.39	1.12
33	Nb2.5 Mo2.5	1.043	193	2.24	11.2	500	60	7.21	1.41	1.16
24	Nb3 Mo3	0.947	215	1.66	9.3	400	88	4.05	1.44	1.20
59	Nb2 Mo2 Cr2	0.891	162	1.95	9.7	300	107	2.95	1.42	1.22
63	Nb2 Mo2 Ni1	1.184	250	2.23	11.2	200	250	2.23	1.40	1.16
66	Nb2 Mo2 Ni2	1.135	247	2.08	10.4	200	247	2.08	1.37	1.15
70	Nb2 Mo2 V1	0.922	202	1.67	8.4	200	202	1.67	1.47	1.23
77	Nb2 Mo2 V2	0.953	221	1.64	8.2	200	221	1.64	1.46	
74	Mb2 Mo2 W1	0.870	177	1.70	8.5	300	159	1.89	1.45	1.20

Early Transition Metals



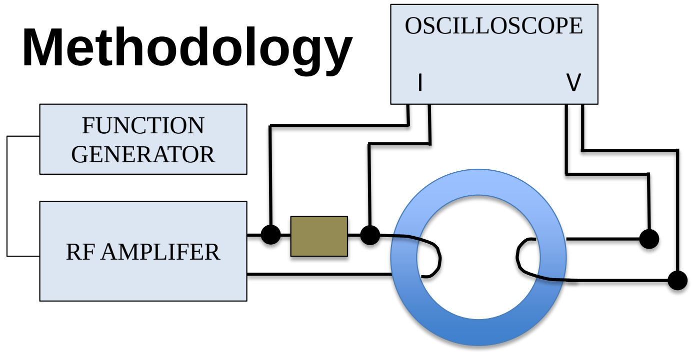
Glass Former Elements

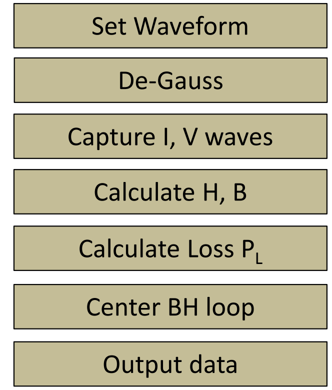
Key Emphasis #2 :

Improving Mechanical Properties of Low-Cost Fe-Based Alloys for Improved Core Manufacturability

Research Focus Area #1 :
Alloy Design and Magnetic Core Manufacturing Efforts

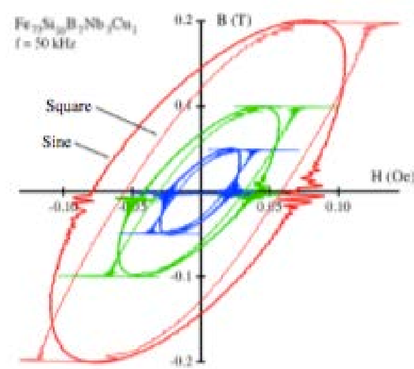
Loss Methodology



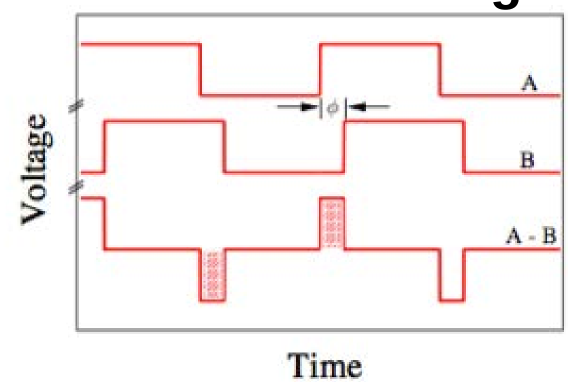


Fabricated Test Cores

B-H Loops



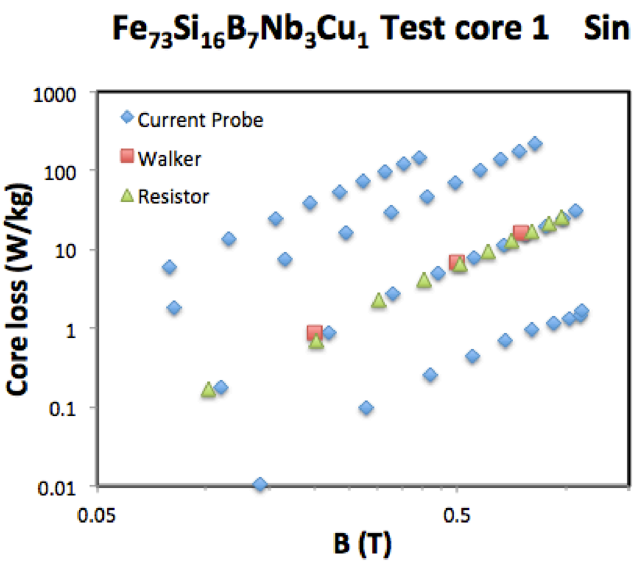
Dual Active Bridge

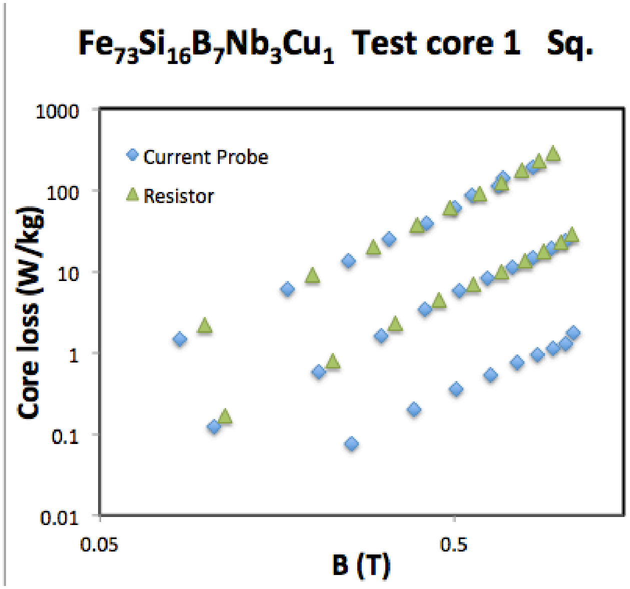


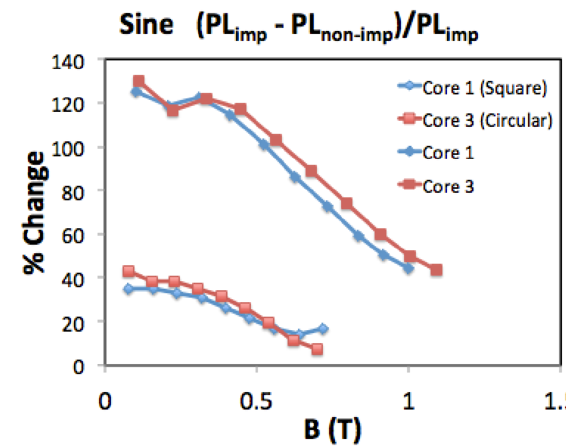
Key Emphasis #3 :

Application Relevant Loss Measurements to Enable Performance Testing of Fabricated Components

Research Focus Area #1 :
Alloy Design and Magnetic Core Manufacturing Efforts







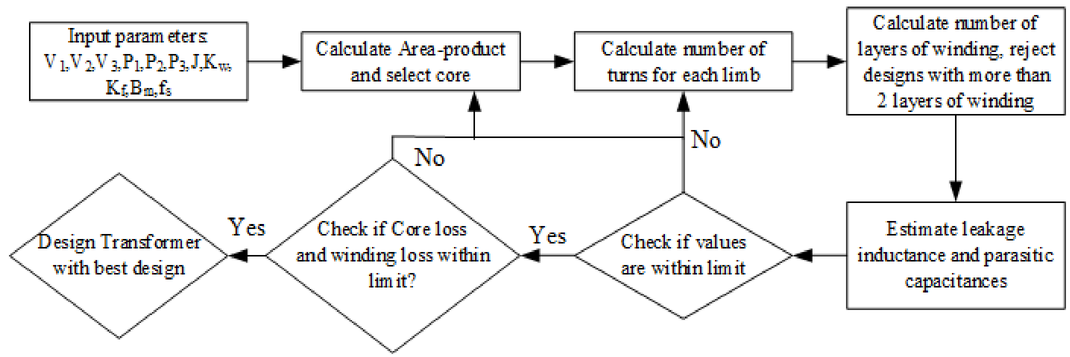
Increased Losses Upon Core Impregnation

Consistent Methodology for Loss Measurements Including Lower Square Wave Excitation Losses

Key Emphasis #3 :

Application Relevant Loss Measurements to Enable Performance Testing of Fabricated Components

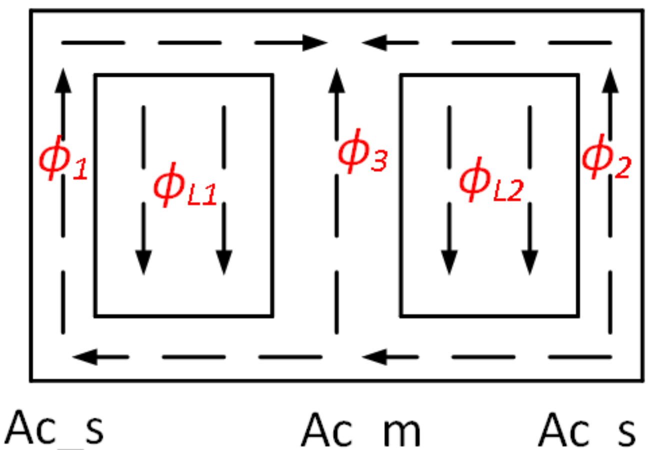
Research Focus Area #2 :
Transformer Design and Modeling

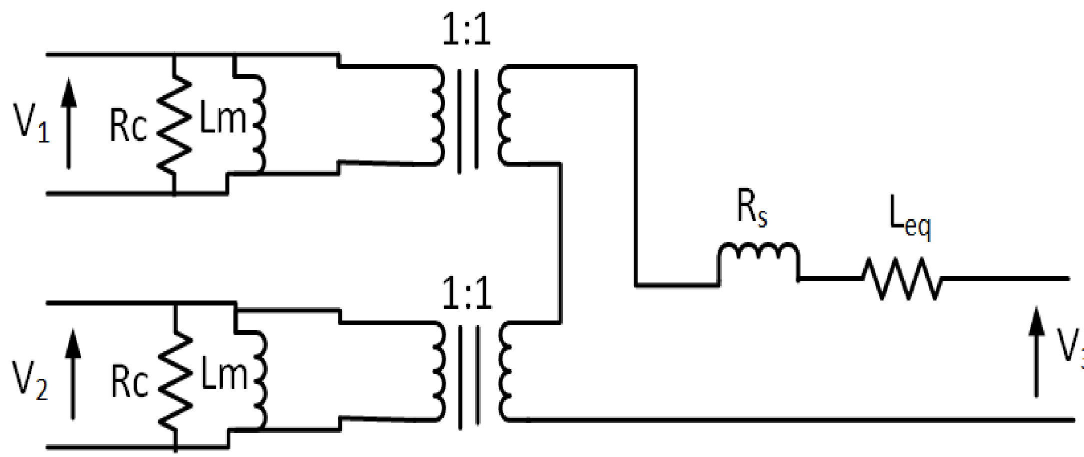


- Bm = 0.2T for ferrite core, 0.8T for nano crystalline
- Winding with Litz Wire
- Leakage Inductance and parasitic capacitance estimation using FEA simulation

Transformer Designs are Being Developed for 3-Limb and 3-Winding Transformer Configurations

Research Focus Area #2 :
Transformer Design and Modeling

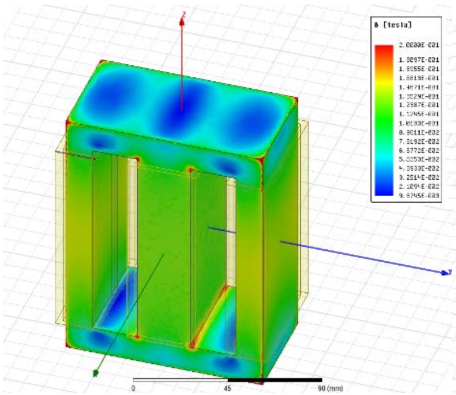




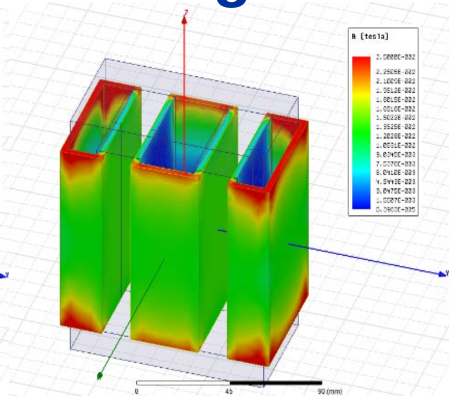
Key Emphasis #1:

Developing Equivalent Electrical and Magnetic Circuit Models for 3-Winding and 3-Limb Transformers

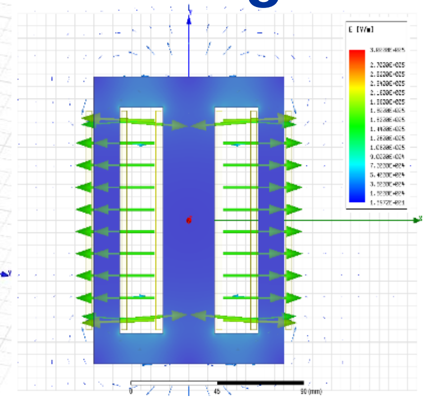
Research Focus Area #2 :
Transformer Design and Modeling



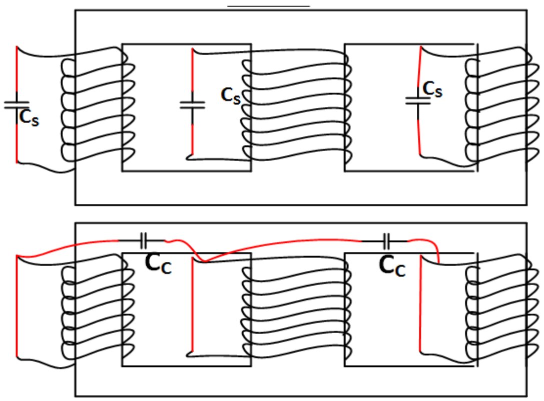
Core Field Distribution

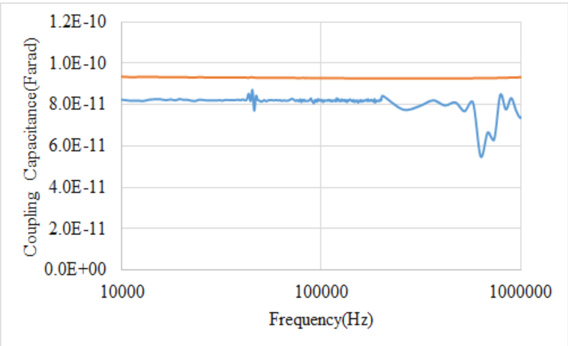


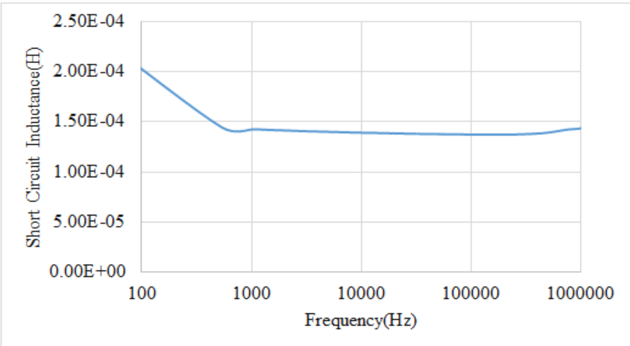
Winding Field Distribution



Electric Field Distribution







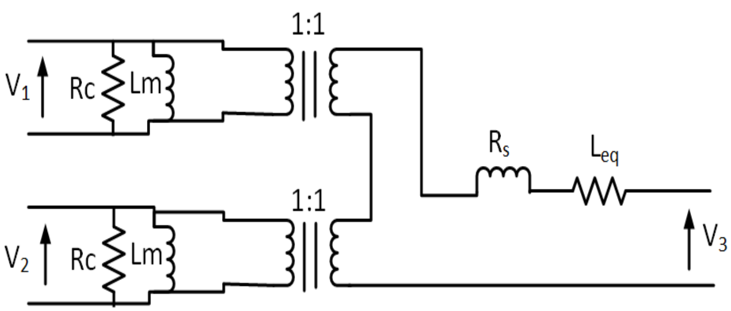
Key Emphasis #2:

Estimating Various Transformer Design Parameters Including Leakage Inductance, Parasitic Capacitances Through Simulation and Experiment

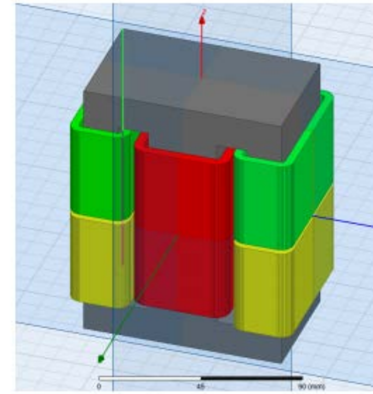
DOE SunShot Initiative SuNLaMP 01699

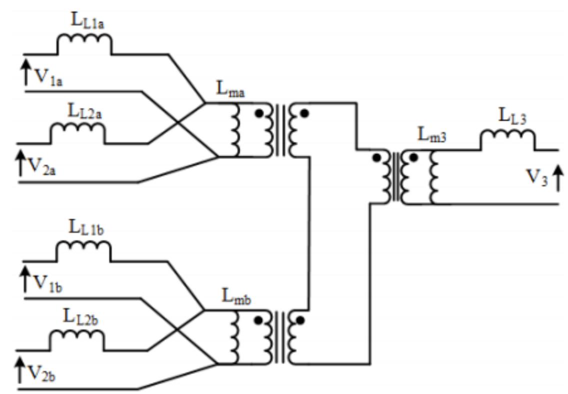
Research Focus Area #2 :
Transformer Design and Modeling

3-Limb, Single-Winding



3-Limb, Split-Winding

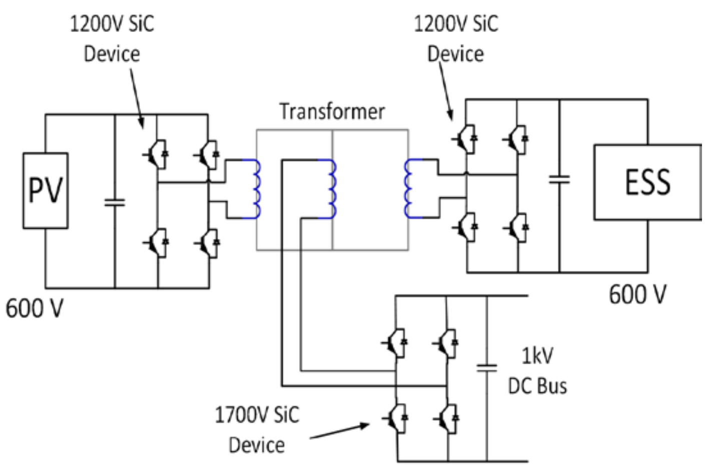




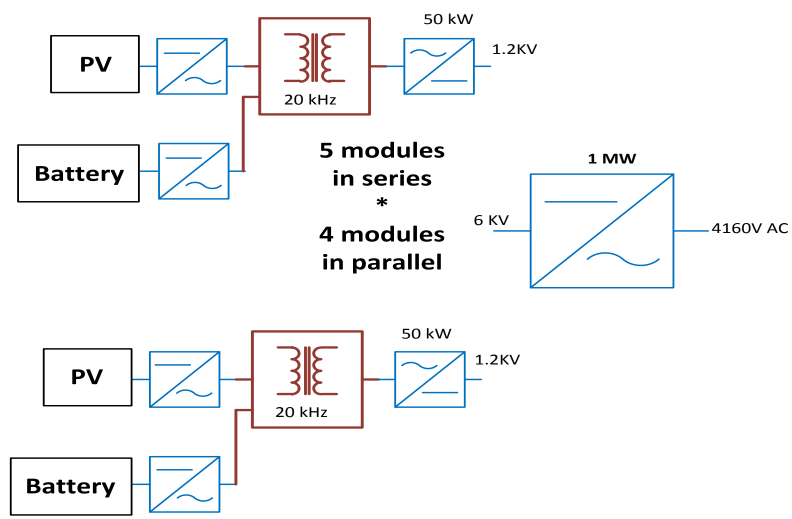
Key Emphasis #3:

Core Material Selection and Geometry / Winding Designs to Achieve Targeted Transformer Parameters and Losses While Having Correct Power Flow for End-Use Cases

Research Focus Area #3 :
Power Electronics and System Level Modeling / Experiment

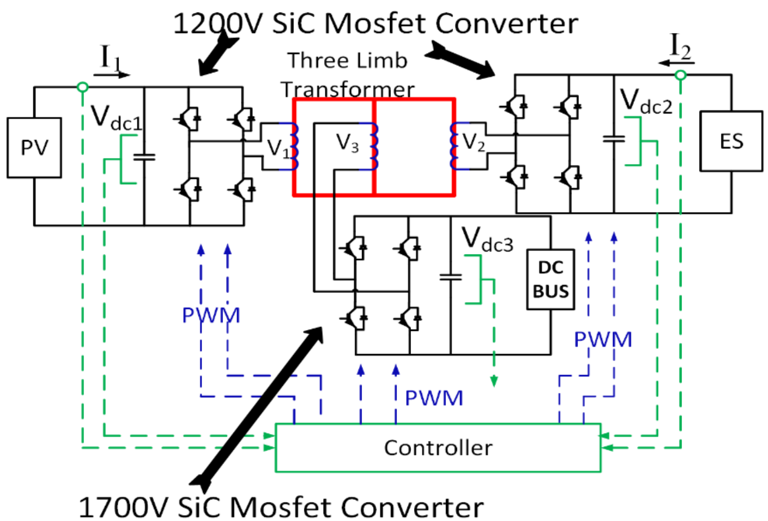


HF Transformer based solution – 4160 Vac

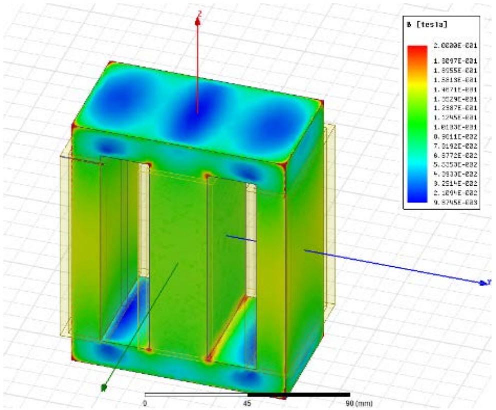


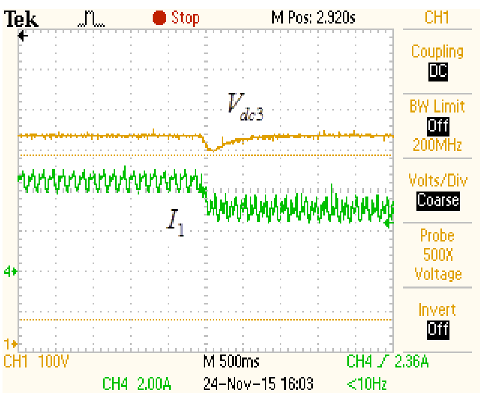
Power Electronics Designs and Systems Level Integration for Overall Converter Efficiency, Cost, and Performance

Research Focus Area #3 :
Power Electronics and System Level Modeling / Experiment

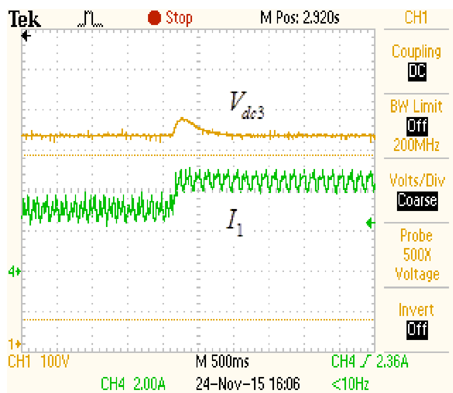


Core Field Distribution





PV1 Current I_1 Changes from 5A to 3A



PV1 Current I_1 Changes from 3A to 5A

Early Results:
Ferrite Core
50kHz, 3kW
DC Voltage Transients on PV Step Current Changes

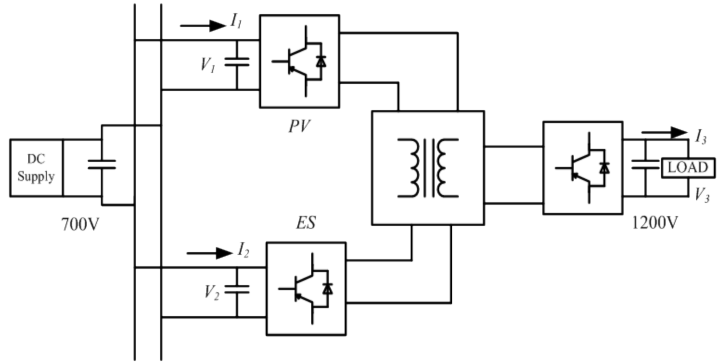
Preliminary Designs and Prototypes Have Been Demonstrated Capable of Maintaining Constant DC Bus at the Third Winding.

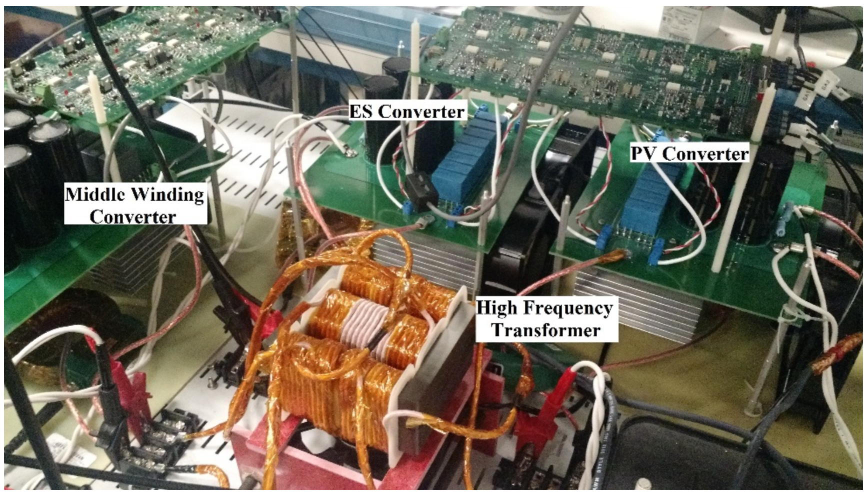
Research Focus Area #3 :
Power Electronics and System Level Modeling / Experiment

New Enabled Use Case

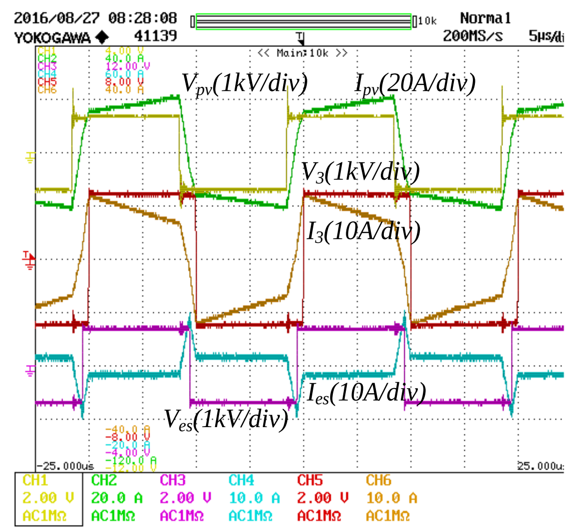
PV / ES Charging and Discharging Scenarios

#1	PV Delivering Maximum Power	ES Charging from PV
#2	PV Delivering Maximum Power	ES Charging from Grid
#3	PV Delivering Maximum Power	ES Discharging to Grid
#4	PV Delivering Reduced (or Zero) Power	ES Charging from Grid
#5	PV Delivering Reduced (or Zero) Power	ES Discharging to Grid
#6	PV Delivering Maximum or Reduced Power	ES Idle (Not Charging or Discharging)





Successful Power Flow



Early DC-DC Converter Prototypes at the 10kW Level Demonstrate Efficiencies of > 98% and Successful Power Flow in All Use Cases.

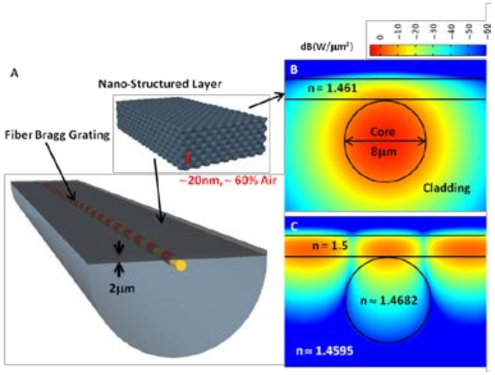
Optical Fiber Based Sensing for Asset Monitoring in Power Transformers

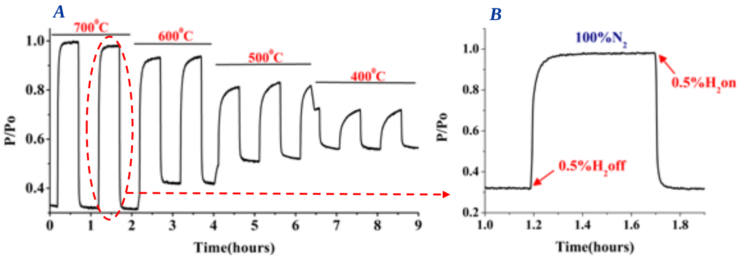
Project Effort #2: Overview

Low-Cost Optical Fiber Based Sensors for Multi-Parameter Asset Monitoring in Power Transformers

Dissolved Gas Analysis

Gas	Normal	Elevated	Abnormal	Interpretation
Acetylene	<15 ppm	>15 ppm and <70 ppm	<70 ppm	Arcing
Carbon Dioxide	< 10 000 ppm	>10000 ppm and <15000 ppm	> 15000 ppm	Severe Overloading
Carbon Monoxide	< 500 ppm	>500 ppm and < 1000 ppm	>1000 ppm	Severe Overloading
Ethane	<10 ppm	>10 ppm and < 35 ppm	> 35 ppm	Local Overheating
Ethylene	<20 ppm	>20 ppm and <100 ppm	>100 ppm	Severe Overheating
Hydrogen	<150 ppm	>150 ppm and < 1000 ppm	>1000 ppm	Arcing, Corona
Methane	<25 ppm	>25 ppm and <80 ppm	>80 ppm	Sparking
Nitrogen	1-10%			Normal ageing
Oxygen	0.2 – 3.5%			Normal Ageing
Total Combustible Gases	< 720 ppm	>720 ppm and <5000 ppm	>5000 ppm	Total Combustible Gas Limit





Low-Cost and Multi-Parameter Sensors are Being Developed for Insulation Oil Monitoring in Power Transformer Applications

Characteristic Gases Depend on Fault Type

- ❑ Thermal faults: H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2
- ❑ Electrical faults—partial discharges: H_2, CH_4, C_2H_2
- Desired H_2 concentrations for sensing application: <100 ppm to >2000 ppm
- Good selectivity against interferences (hydrocarbons, CO)

Table 1—Dissolved gas concentrations

	Status	Dissolved key gas concentration limits [μL/L (ppm)[a]]							
		Hydrogen (H_2)	Methane (CH_4)	Acetylene (C_2H_2)	Ethylene (C_2H_4)	Ethane (C_2H_6)	Carbon monoxide (CO)	Carbon dioxide (CO_2)	TDCG[b]
Normal	Condition 1	100	120	1	50	65	350	2 500	720
Abnormal	Condition 2	101–700	121–400	2–9	51–100	66–100	351–570	2 500–4 000	721–1920
High	Condition 3	701–1800	401–1000	10–35	101–200	101–150	571–1400	4 001–10 000	1921–4630
Excessive	Condition 4	>1800	>1000	>35	>200	>150	>1400	>10 000	>4630

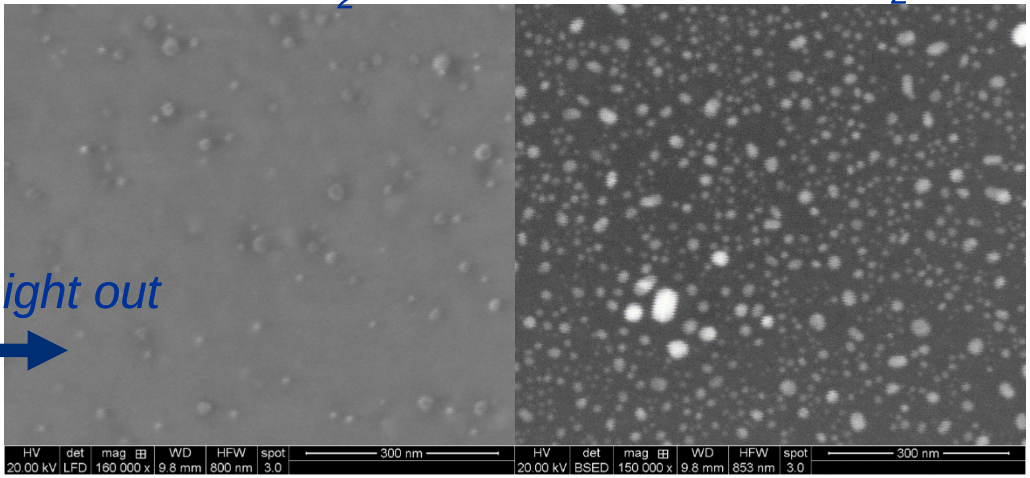
IEEE Std C57.104-2008

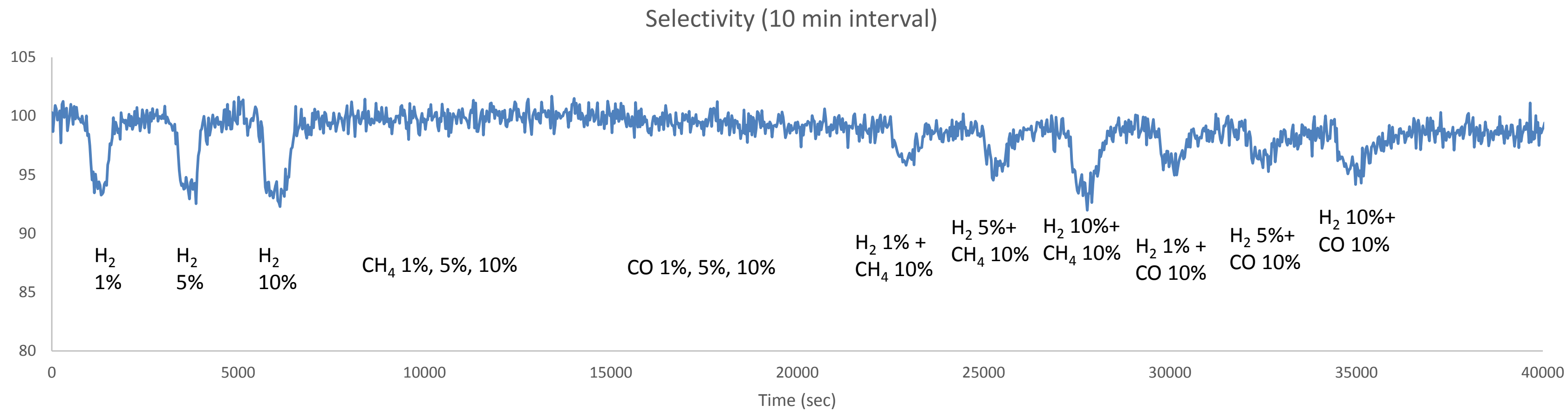
Low Cost Chemical Sensing Devices Could Allow for Condition Monitoring and Substitution for Costly, Time-Consuming DGA.

Functionalized Optical Fiber Sensors

Functionalized Optical Fiber Sensors for Chemical Response

Pd / SiO_2 *$AuPd / SiO_2$*





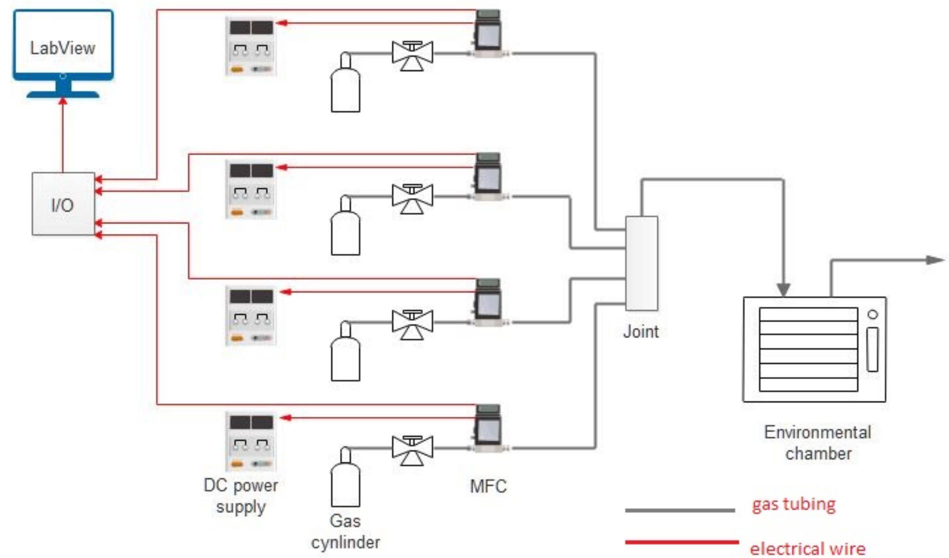
Initial Work Leveraging Prior Results Demonstrates a Selective Response to H_2 to Be Further Optimized for Low Level Detection.

Proposed Targets and Early Efforts

Early Proposed Sensor Development Targets

- Target: gases extracted from the oil or in gas space (H_2, CH_4, CO)
- Detection limit: 1–100 ppm
- Dynamic range: > 1000 ppm
- Temperature: ambient to 110 ℃
- Detection method: optical sensor
- Requirements: selectivity, stability

Laboratory Facilities Have Been Established for Sensor Testing



The Project is Nearing the 3rd Quarter and Increased Emphasis is Being Placed on Investigating and Optimizing a Range of Sensor Materials.

Summary and Conclusions

- **Emerging Trends Have Highlighted the Importance of Grid Modernization and DOE Has Placed the Area as a Significant Priority**

- **NETL Has a Strong Focus Area in Functional Materials Integrated with Devices**

- **Key Current Focus Areas for Materials / Device Research**
  - **Electrochemical Materials (Solid Oxide Fuel Cells)**
  - **Optical Materials (Sensor Devices)**
  - **Magnetic Materials (Inductive Devices)**

- **Significant Needs Exist for Materials to Enable Grid Components**
  - **Materials for Power Electronics, Transformers, and Energy Storage Components**
  - **Sensor Devices for Power Flow and Asset Monitoring**

- **NETL Has On-going Project Work Supported Through the Grid Modernization Initiative**
  - **(EERE Funded) Magnetic Materials and Components for Transformers**
  - **(OE / BTO Funded) Sensors for Asset Monitoring**