SANDIA NATIONAL LABORATORIES

Sandia National Laboratories

Exceptional service in the national interest

RESILIENT ENERGY SYSTEMS DEVELOPMENT AT SANDIA NATIONAL LABORATORIES

Lee Rashkin

Power Electronics and Energy Conversion Workshop 2025

Albuquerque, NM July 15-16, 2025

U.S. DEPARTMENT of ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2025-08477C

OUTLINE

- Resilient Energy Systems Mission Campaign (RES)
- EMP Resilience
- Solid State Transformers (SST)
  - AC-to-AC SST
  - E3 Controls and Protection
  - E1 and E2 Vulnerabilities
- Materials
- Summary

SANDIA SEES MULTIPLE ASPECTS OF GRID RESILIENCY TO BE OF VITAL IMPORTANCE

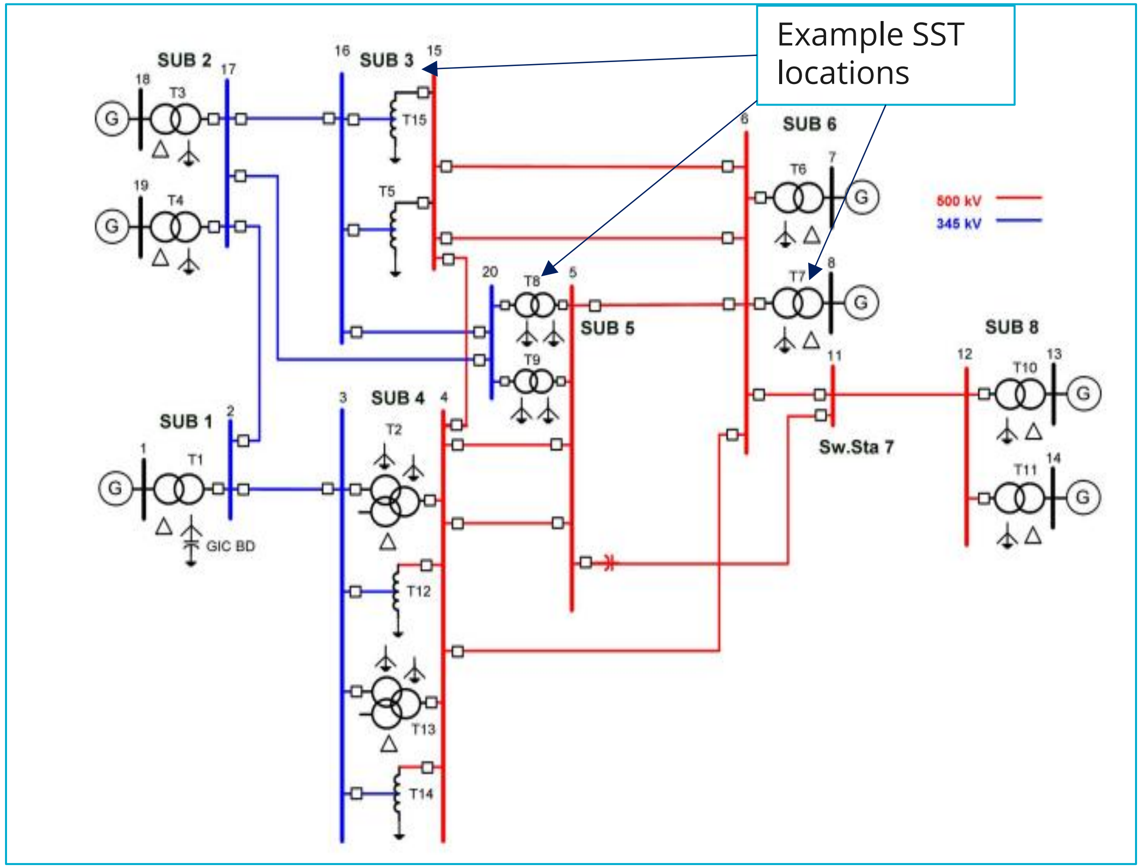
"The Resilient Energy Systems (RES) Mission Campaign (MC) seeks to create new capabilities that enhance the resilience of the nation's energy infrastructure to intentional threats … **test and validate novel system architectures, to increase energy and critical-infrastructure resiliency.**" – Sandia LDRD Call

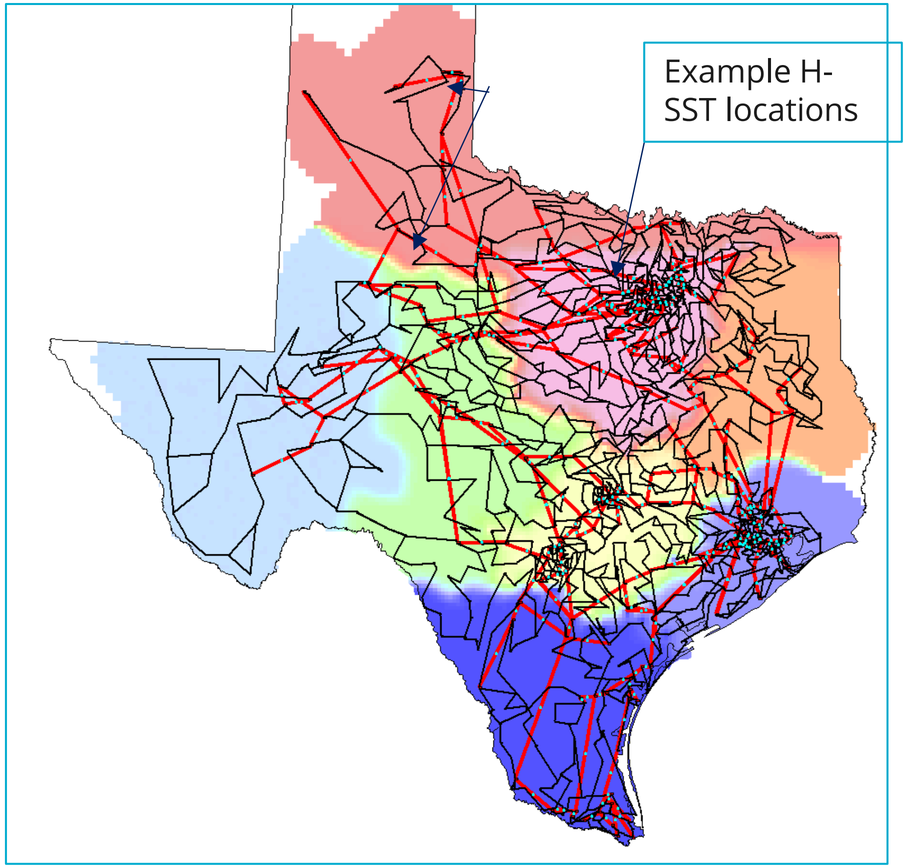
"As the electric power system evolves to accommodate new generation sources, new loads, and a changing threat environment, there are new and pressing challenges that face the electricity delivery network, especially for substations. **Given the ubiquitous nature and importance of these critical nodes, advanced substations present a tremendous opportunity to improve performance of the grid.**" –DOE "Solid State Power Substation Technology Roadmap"

"Solid State Power Substation Technology Roadmap," U.S. DOE Office of Electricity, Transformer Resilience and Advanced Components (TRAC) Program, June 2020.

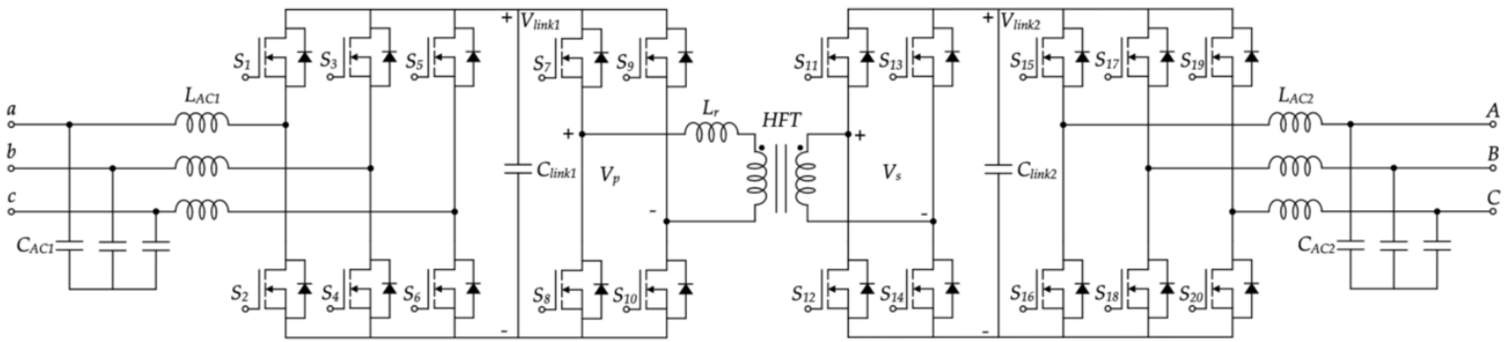
CONTROLS TECHNIQUES ARE BEING DEVELOPED TO FIND OPTIMAL POWER ELECTRONICS PLACEMENTS

- Solid state transformers (SST) can replace convention transformers in grid systems
  - Optimal placements will achieve specified control objectives (e.g. energy storage usage, voltage sag/swell, power factor, …)





SOLID STATE TRANSFORMERS ALLOW FOR CONTROLLED POWER FLOW



Conventional SST Design

✓ Smaller size/weight compared to Xformers

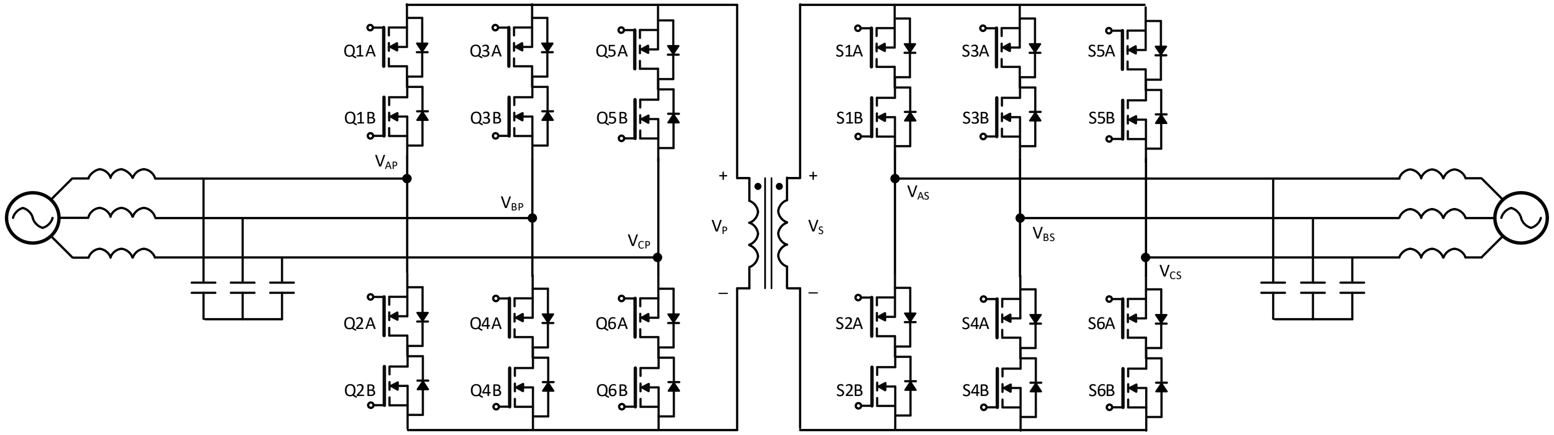
✓ Switching control allow for adaptive protection and power quality enhancement

X High voltage DC link capacitor (Reliability, size, cost concerns)

X High switch count (20 MOSFETs shown here)

X Complex switching schemes required for converters/cascaded systems for capacitor voltage balance

AC-TO-AC CONVERTER DESIGN ALLOWS FOR GREATER POWER DENSITY AND LOWER COMPLEXITY



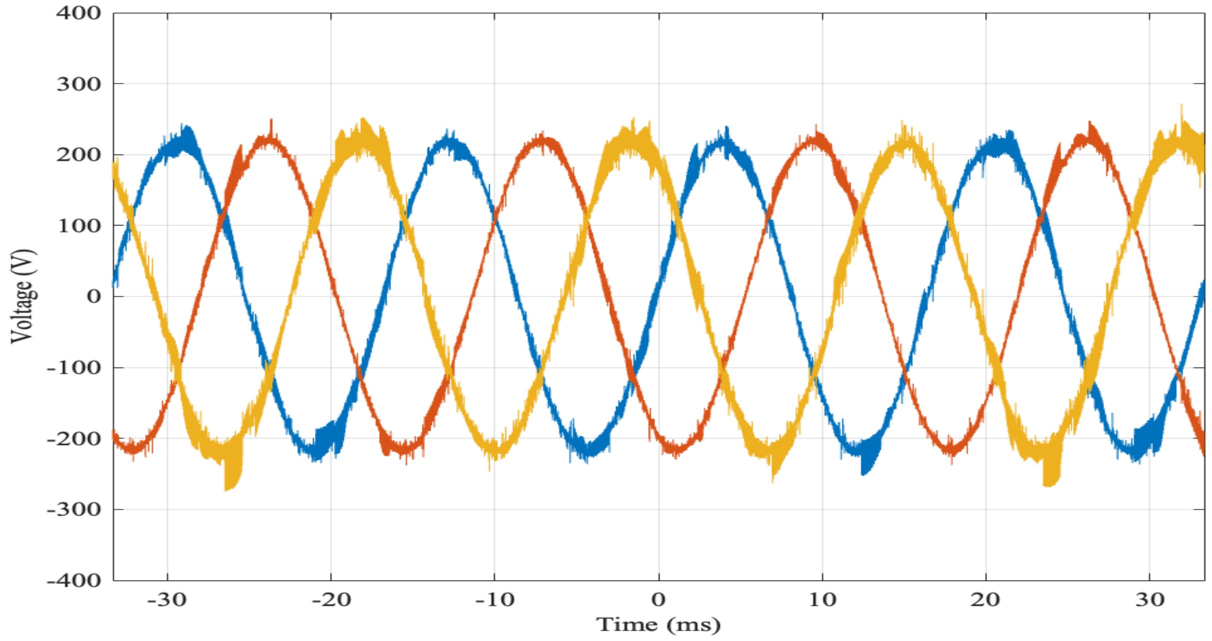
AC-AC Dual Active Bridge converter (AADAB)

- ✓ Smaller size/weight compared to Xformers
- ✓ Switching control allow for adaptive protection and power quality enhancement
- ✓ No DC link capacitor
  - → Reliability increase
  - → simpler cascading of modules at higher voltages
- ✓ Bidirectional switches reduce component count (20 to 12)
- ✓ Reduction in topology size and complexity
- ✓ Single stage increases efficiency, long-term lifetime

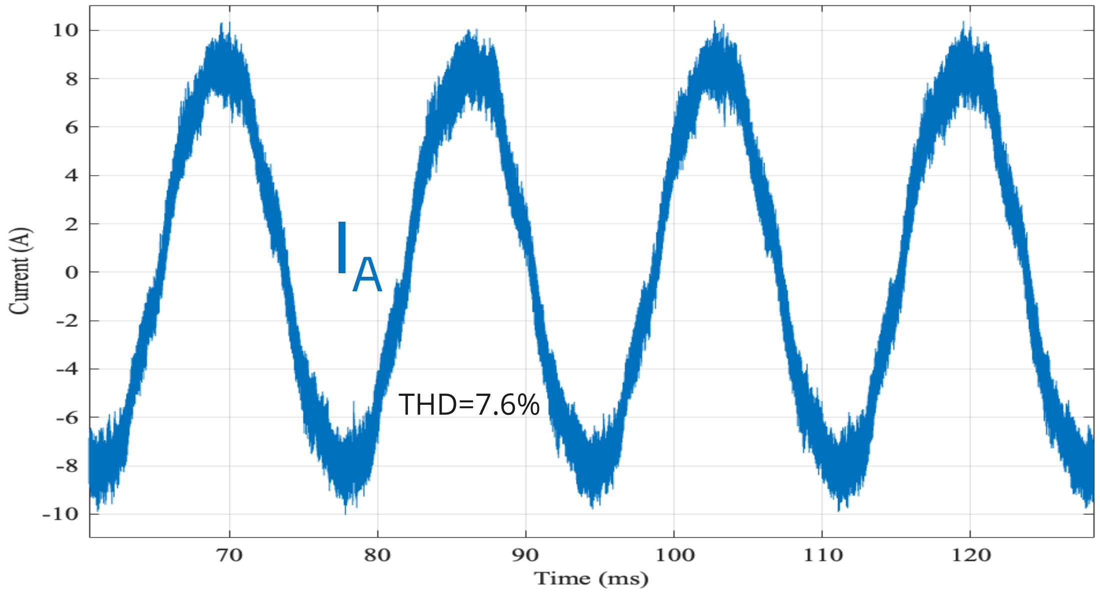
Minimal component count, minimum cost, maximum reliability, maximum efficiency AC/AC converter

POWER CONTROL

AC Voltage (Primary and Secondary)



AC Current (Secondary)



Power Transfer: 3 kVA (100%)

Average Efficiency: 95%
Peak Efficiency: >99%
Open Loop: ✔

Closed loop P: ✔
Closed loop Q: ✔
Bidirectionality: ✔

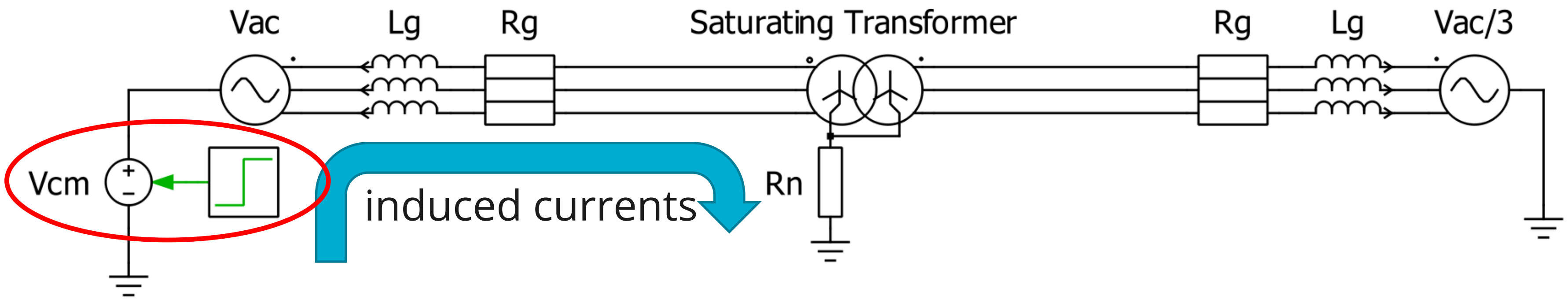
$f_{in} \neq f_{out}$: ✓

$Q_{in} \neq Q_{out}$ 🕐

$V_{in} \neq V_{out}$: ✓

$\phi_{in} \neq \phi_{out}$:✓

CONVENTIONAL TRANSFORMER RESPONSE TO CM INSULT



- E3 component of high altitude electromagnetic pulse (HEMP) or geomagnetic disturbance (GMD) will cause Common Mode (CM) voltages
- CM voltage causes induced currents, leading to half-cycle saturation of magnetic core
- Saturation causes:
    - distorted waveforms
    - increased losses
    - potential for thermal damage, etc.

Half-cycle saturation

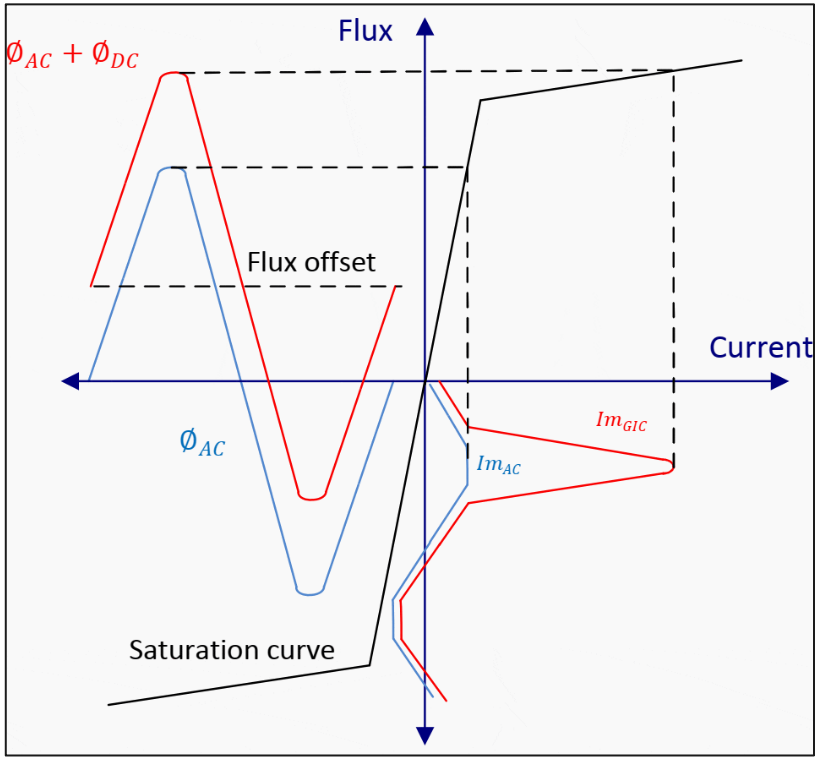
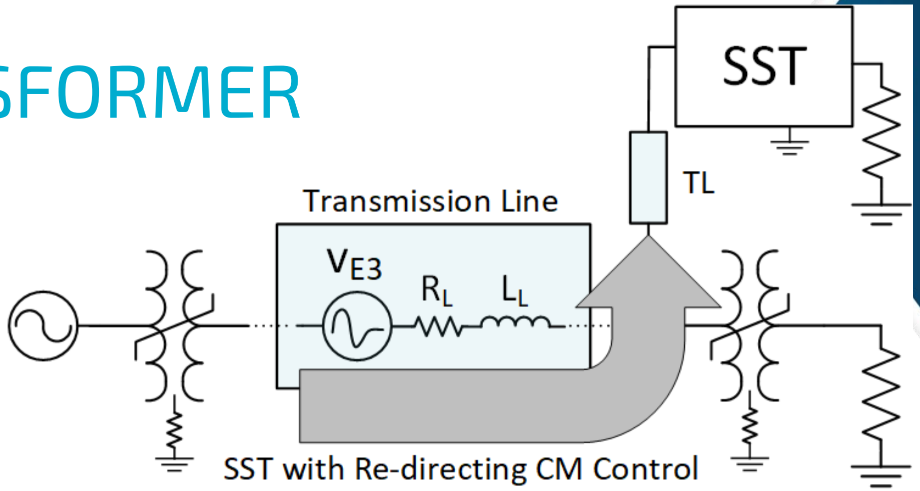


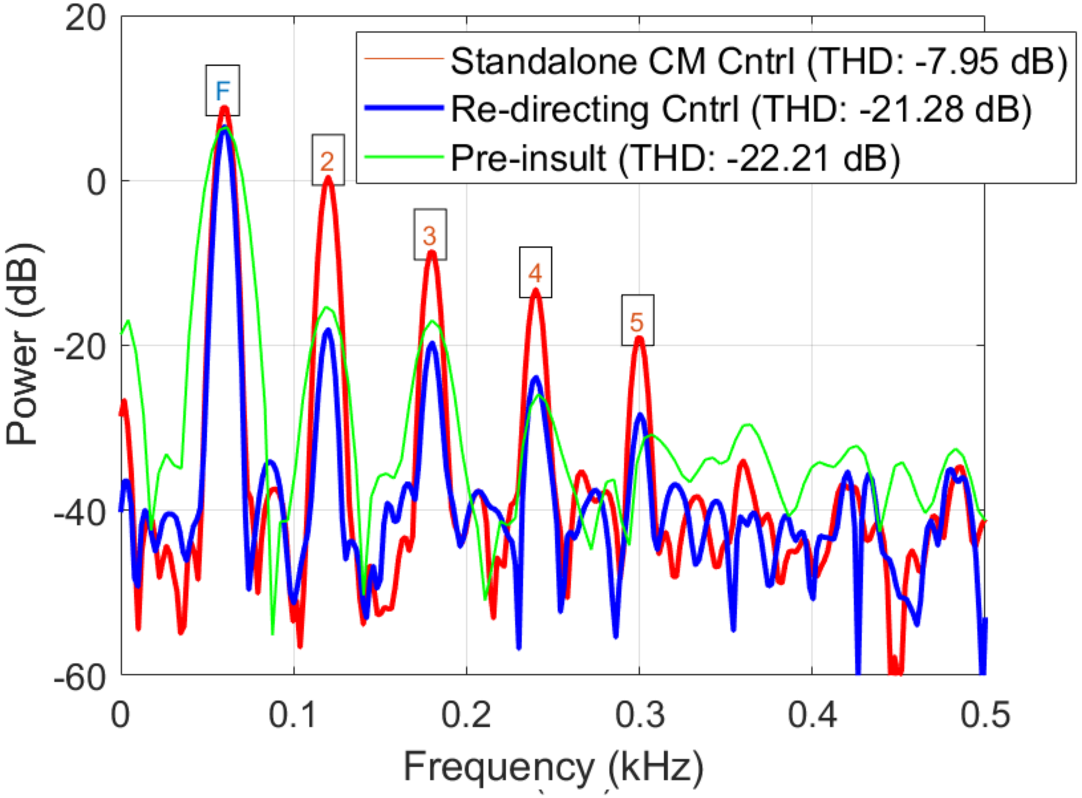
image credit: electrical-engineering-portal.com, *Geomagnetic-induced-current*

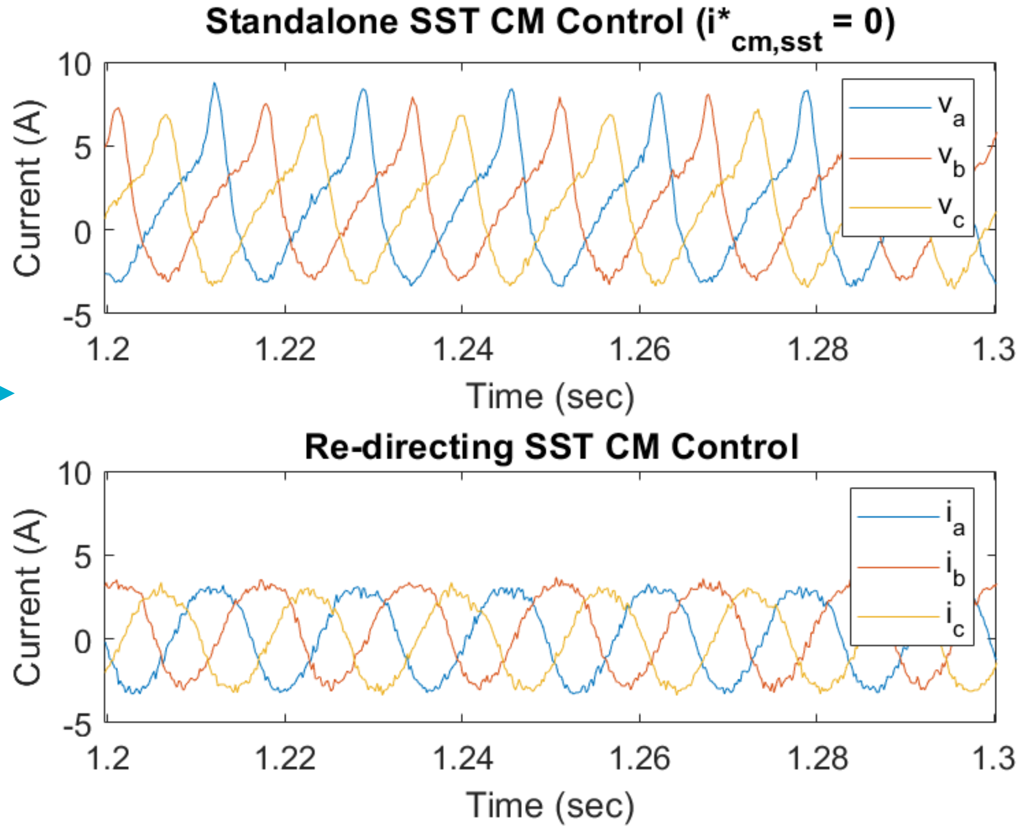
SST IN PARALLEL WITH CONVENTIONAL TRANSFORMER



- Local control blocks CM current going <u>into SST</u>
- Global control blocks CM current from going <u>into Conv. Txfrmr</u>

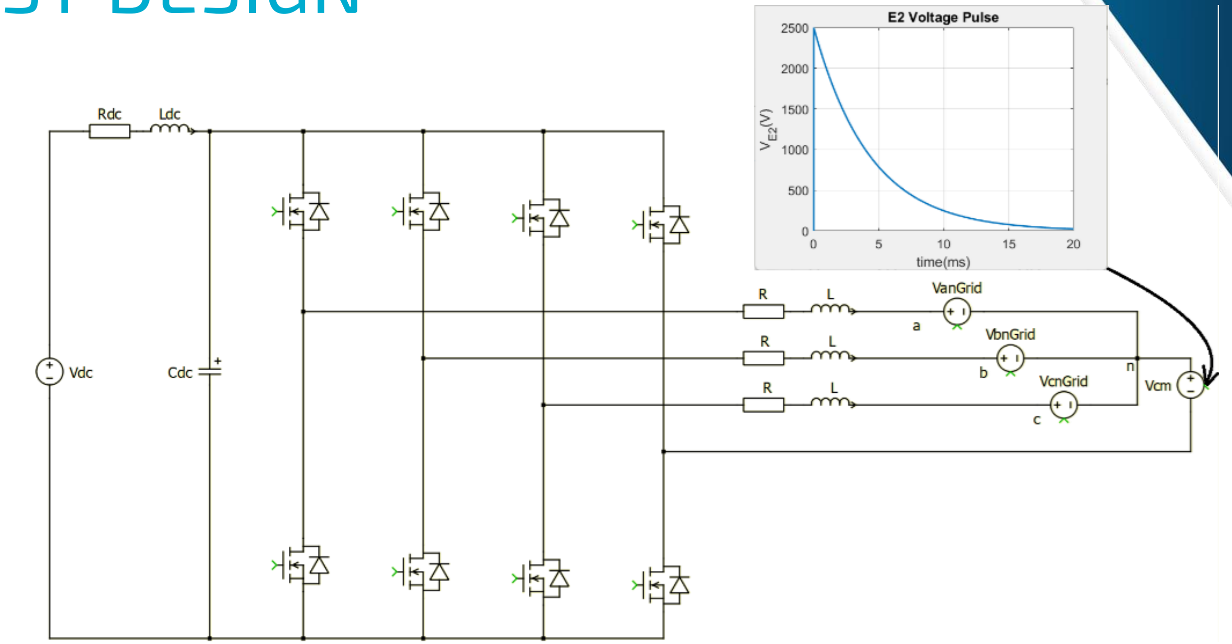
Conventional Transformer Current



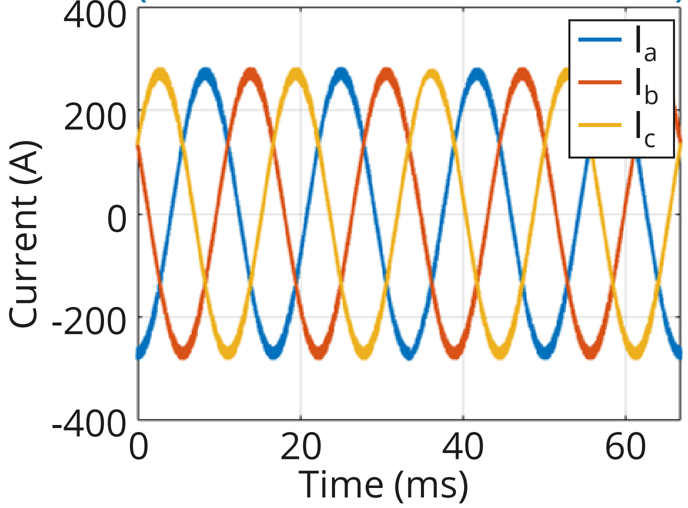


MODELED E2 HEMP RESPONSE OF SST DESIGN

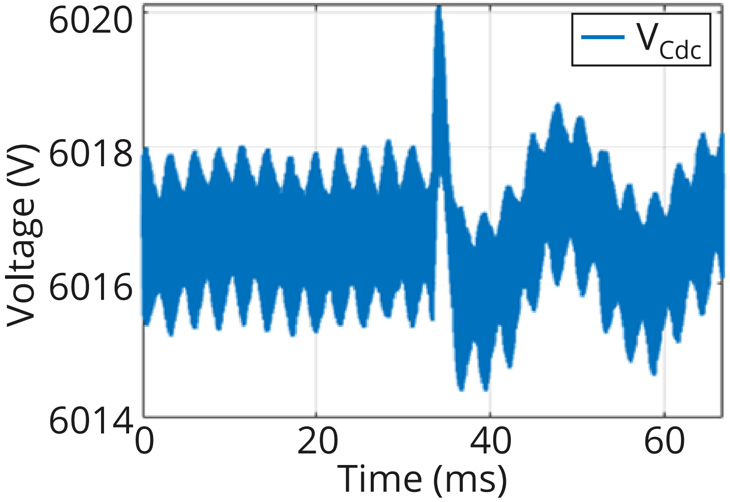
- Modeling shows E2 response is effective within the control voltage (half the DC bus voltage).
- Larger microsecond impulses are recoverable but don't account for potential equipment damage.
- Looking into mitigation options.



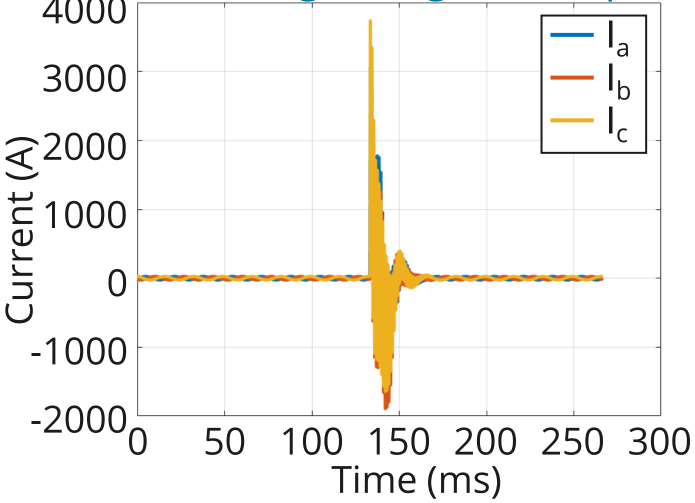
Phase Current Response (MIL-STD-188-125 E2 HEMP)



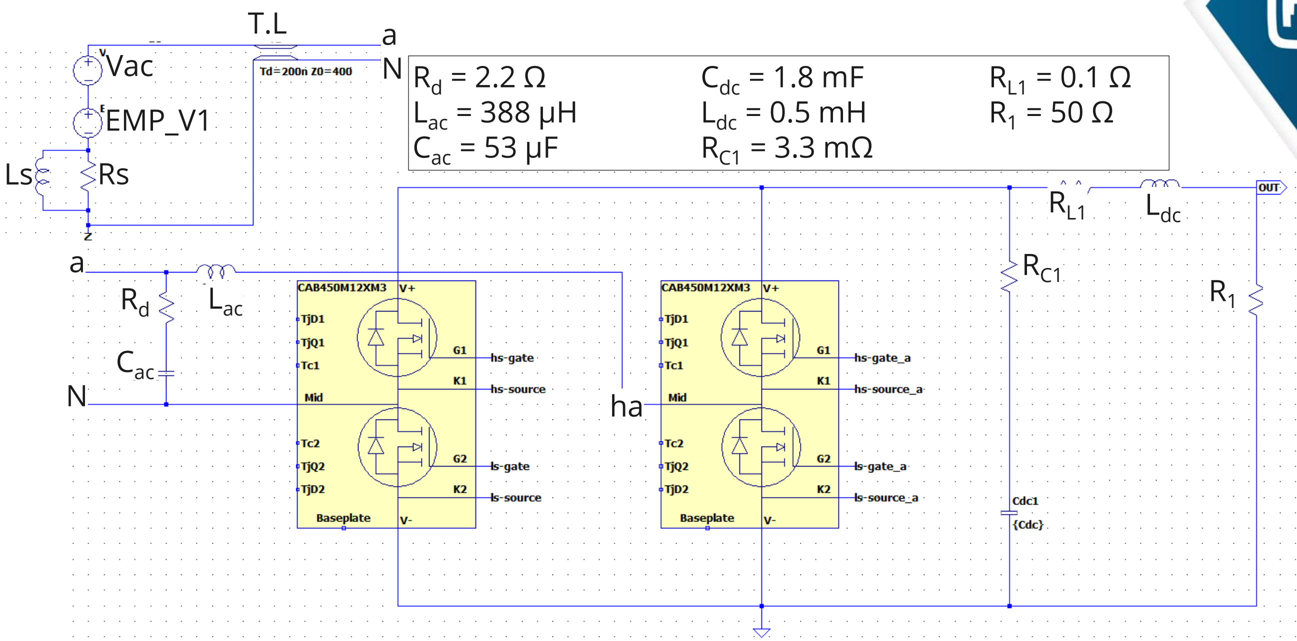
DC Voltage Response (MIL-STD-188-125 E2 HEMP)



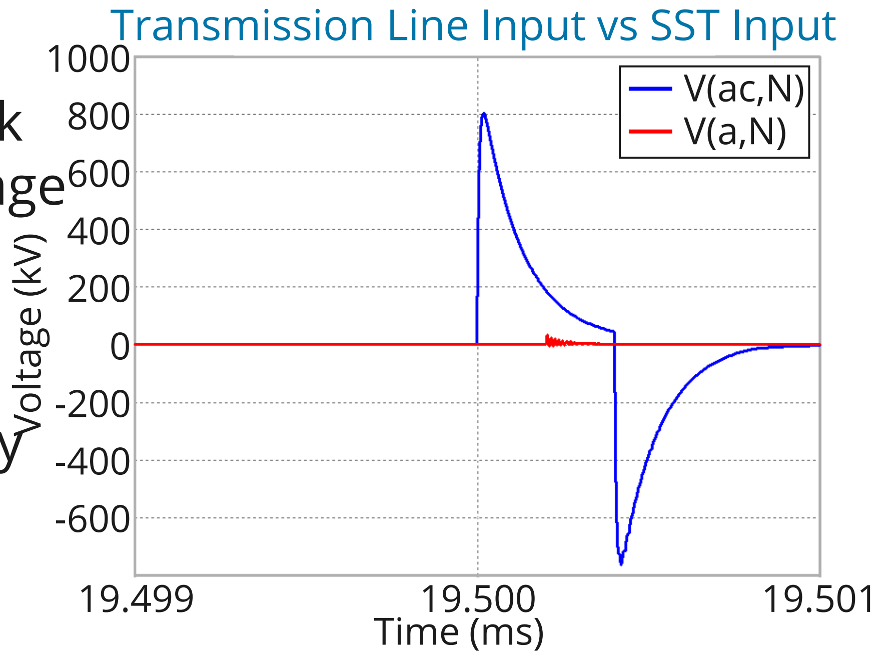
Phase Current Response (80 kV Lightning, 1.2/50 μs)

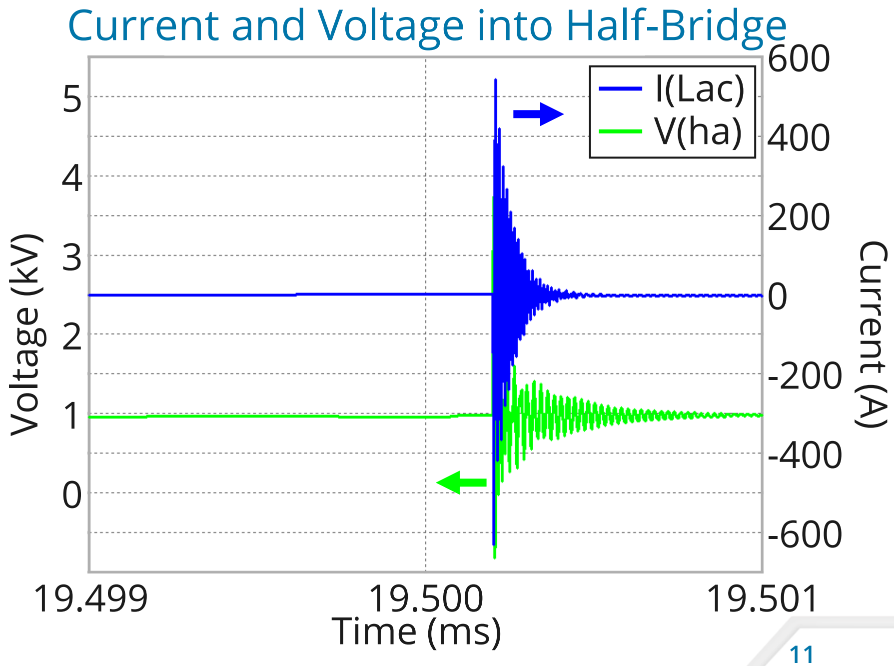


MODELED E1 RESULTS OF SST PHASE

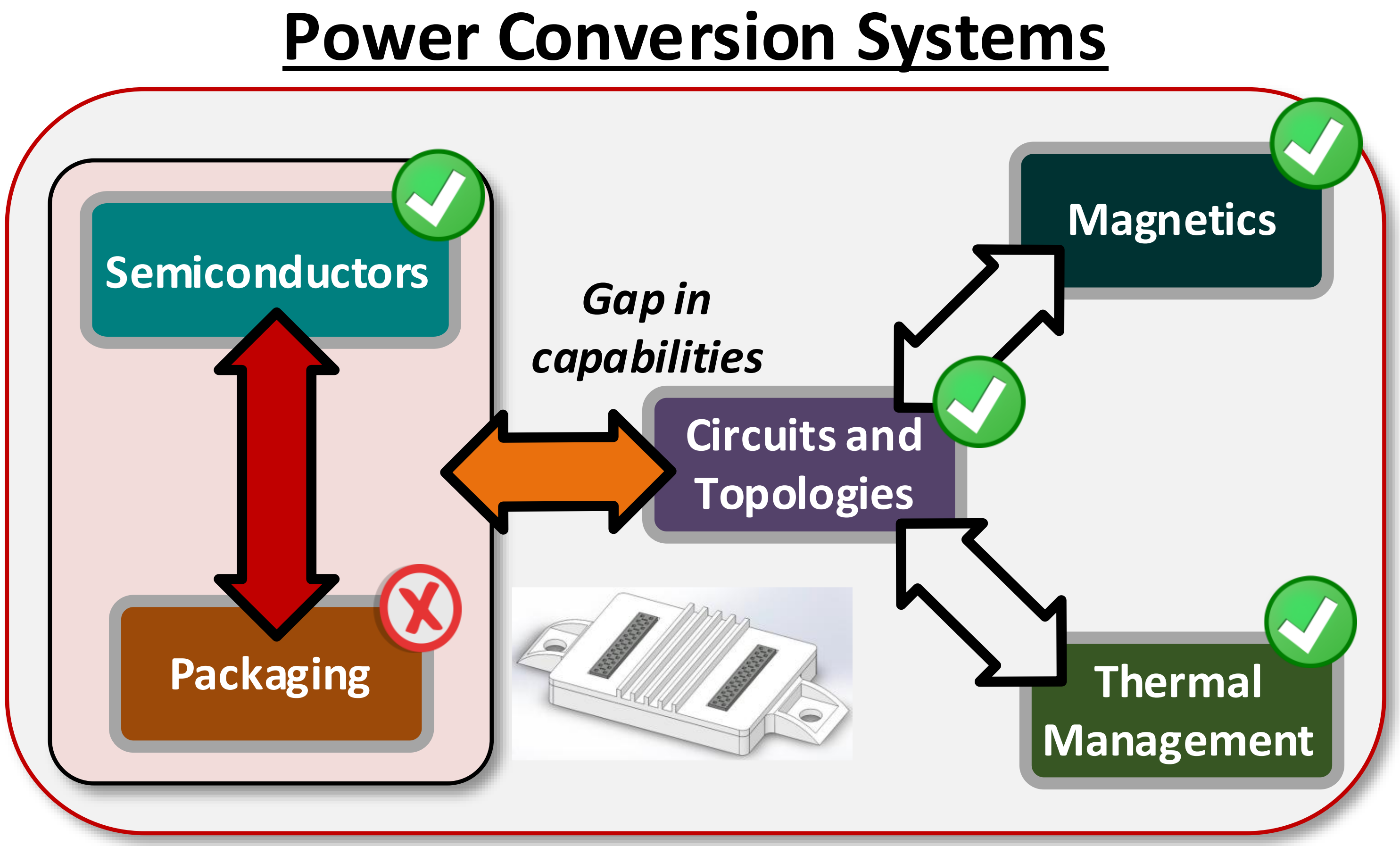


- E1 insult expected to be too fast for control mitigation.
- Low high-frequency shunt impedance at inverter input significantly reduces transient voltage.
- Upcoming testing to check voltage and current damage thresholds.
- Results show high-severity E1 from IEC 61000-2-10 (800 A into 400 Ω).





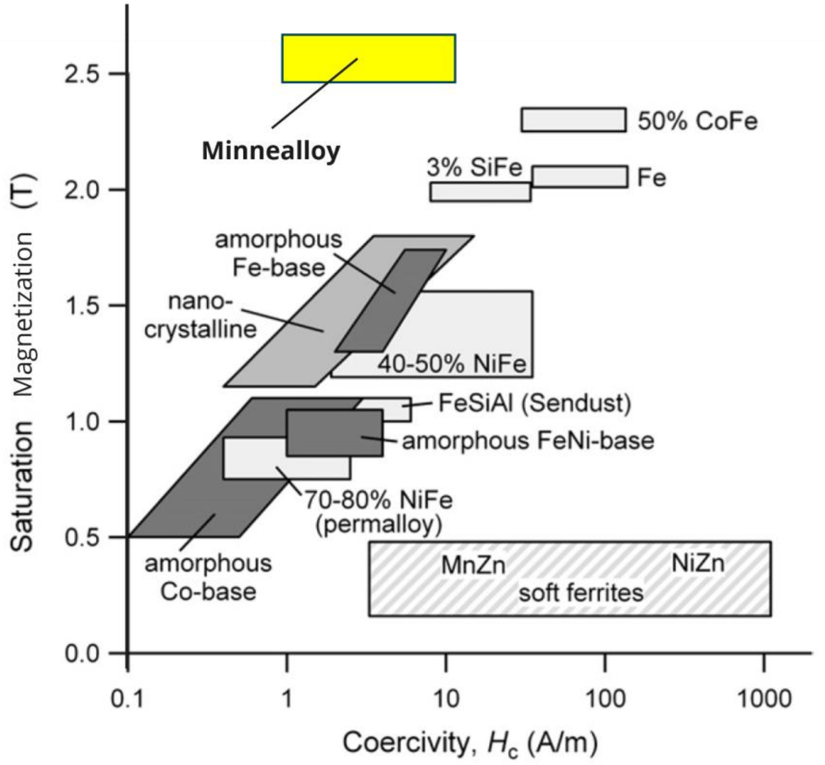
Power Electronics Advanced pacKaging lab (PEAK)



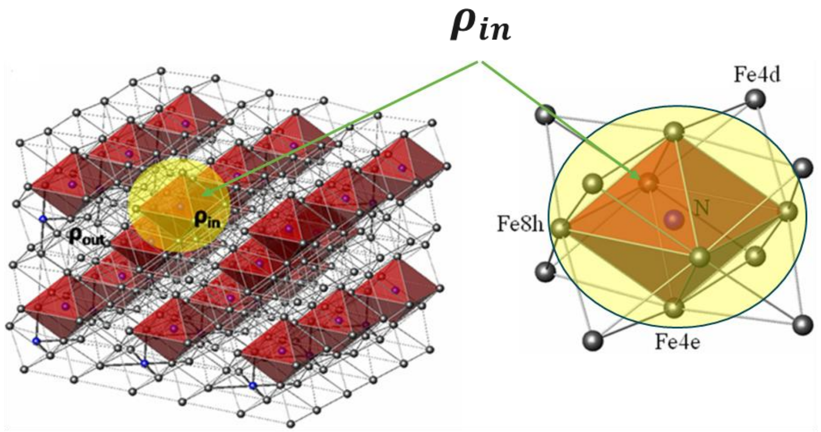
Why?

- Accelerate solution deployment
- Discovery of unique/novel phenomena
- Increase vertical integration

MINNEALLOY ($Fe_{16}NC$): HIGH-POWER HIGH-FREQUENCY TRANSFORMER CORES



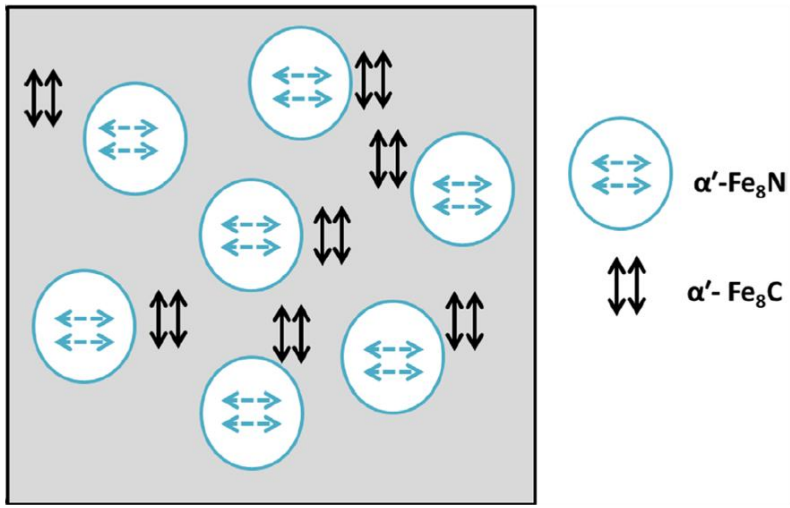
Large Power Transfer



3d electron partial localization

- Coulomb repulsion difference between Fe-N octahedral cluster and metallic environment
- 3d electron transfer from Fe 4d site to octahedral cluster
- Stoner like term arising from strong Fe-N coupling stabilizes charge transfer

Low Hysteresis Losses



Opposing monocrystalline anisotropies lead to low coercivity in the bulk

- α'-Fe_8N easy axis [001]
- α'-Fe_8C easy axis [100]

N Ji *et al* 2010 New J. Phys. **12** 063032

Md Mehedi *et al* 2017 *J. Phys. D: Appl. Phys.* **50** 37LT01

Herzer, Giselher. "Modern soft magnets: Amorphous and nanocrystalline materials." *Acta Materialia* 61.3 (2013): 718-734

SUMMARY

- Power electronics development at Sandia is heavily interested in system resiliency
- Components such as solid state transformers are being developed to:
  - Implement controlled power transfer in grid systems
  - Respond to potential threats such as HEMP and GMD
  - Have increased survivability to Electromagnetic insults
- In support of the development of these sorts of power electronic components requires development of new packaging and materials

BACKUP SLIDES

POWER CONTROL

Power Transfer: 3 kVA (100%)

Average Efficiency: 95%

Peak Efficiency: >99%

Open Loop:

Closed loop P:

Closed loop Q:

Bidirectionality:

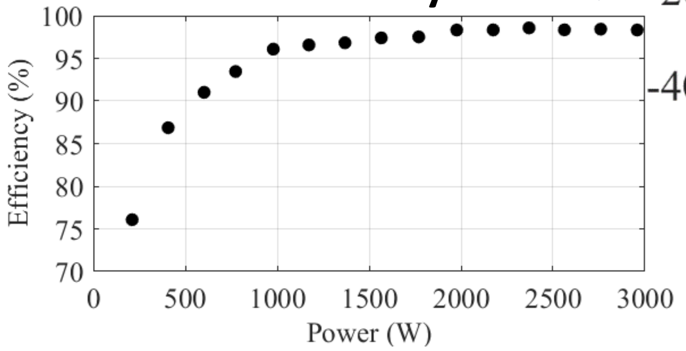
$f_{in} \neq f_{out}$:

$Q_{in} \neq Q_{out}$

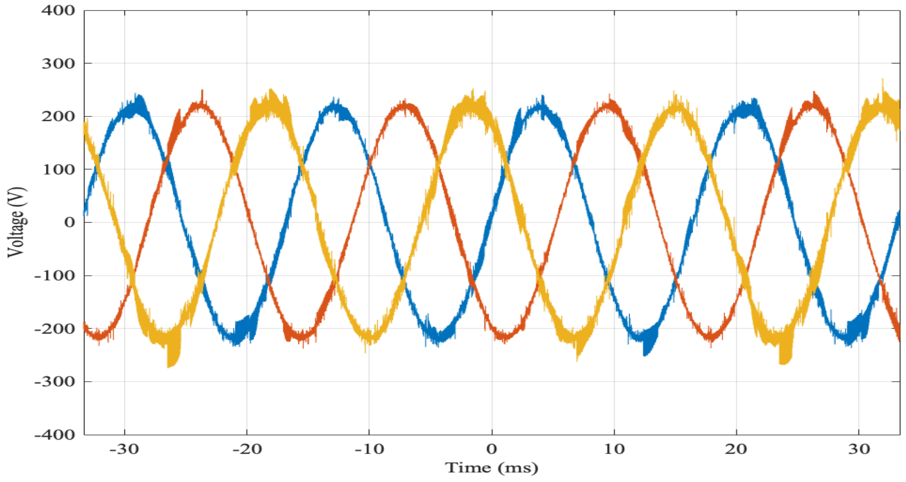
$V_{in} \neq V_{out}$:

$\phi_{in} \neq \phi_{out}$:

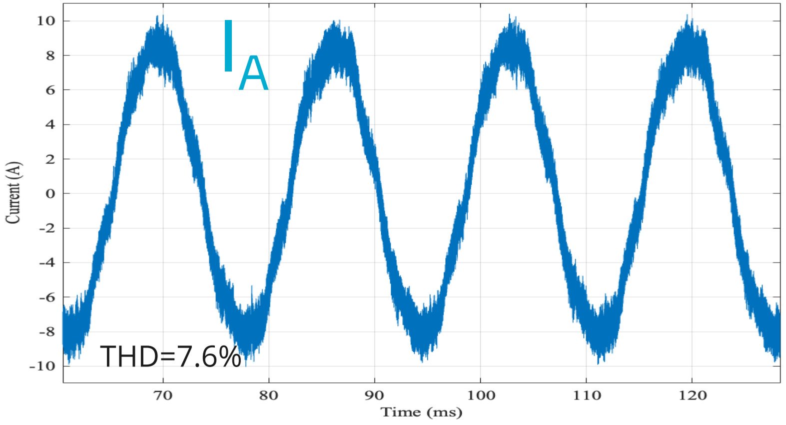
Efficiency



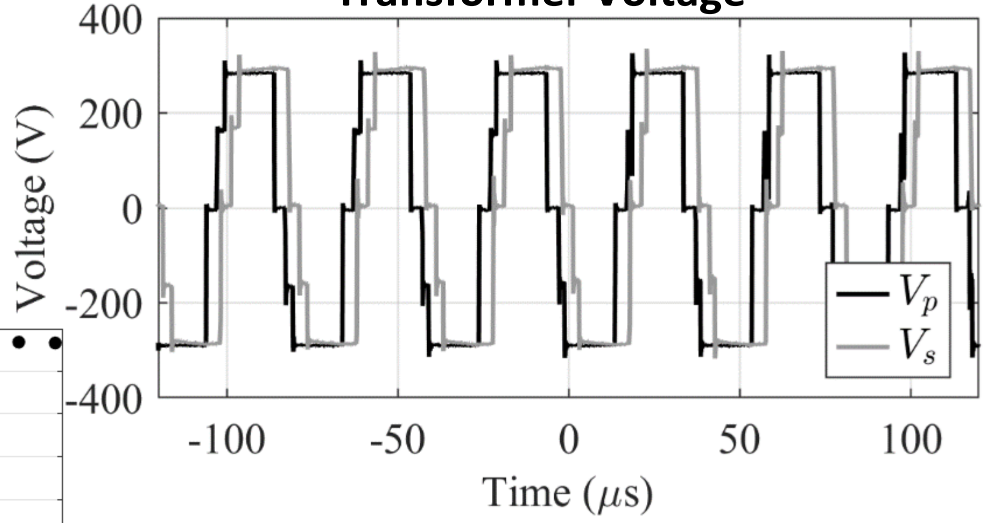
AC Voltage (Primary and Secondary)



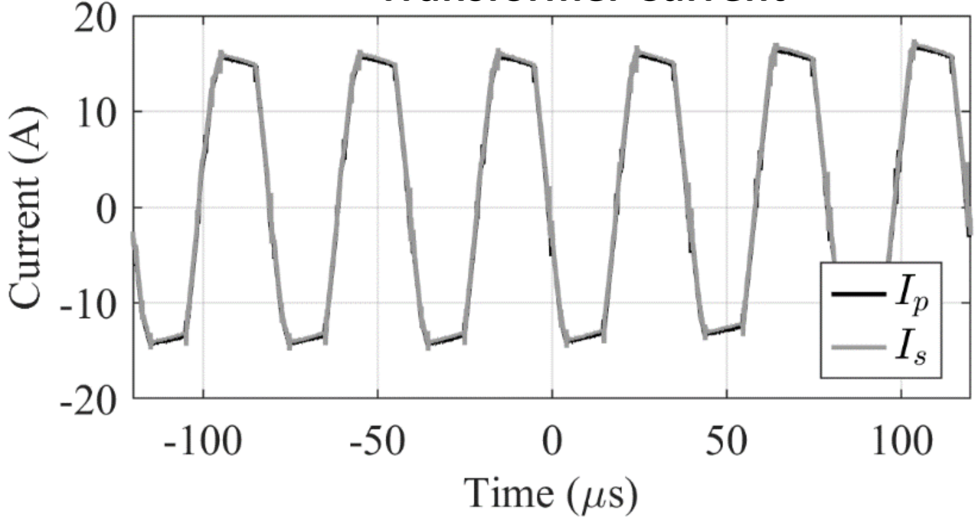
AC Current (Secondary)



Transformer Voltage

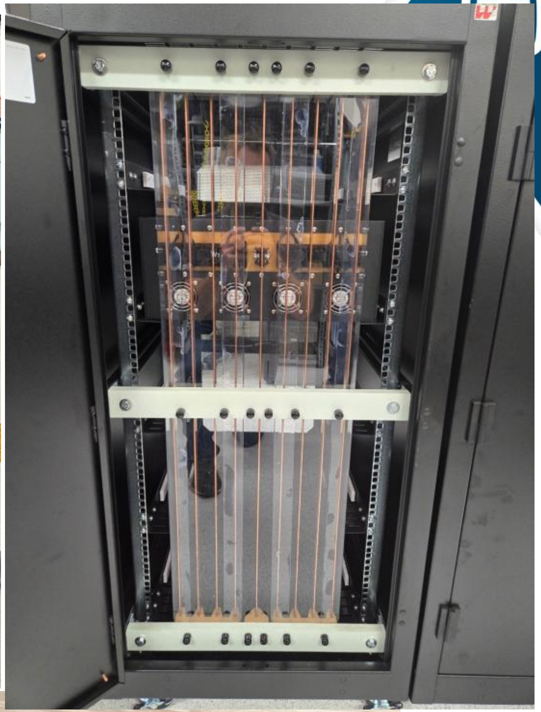


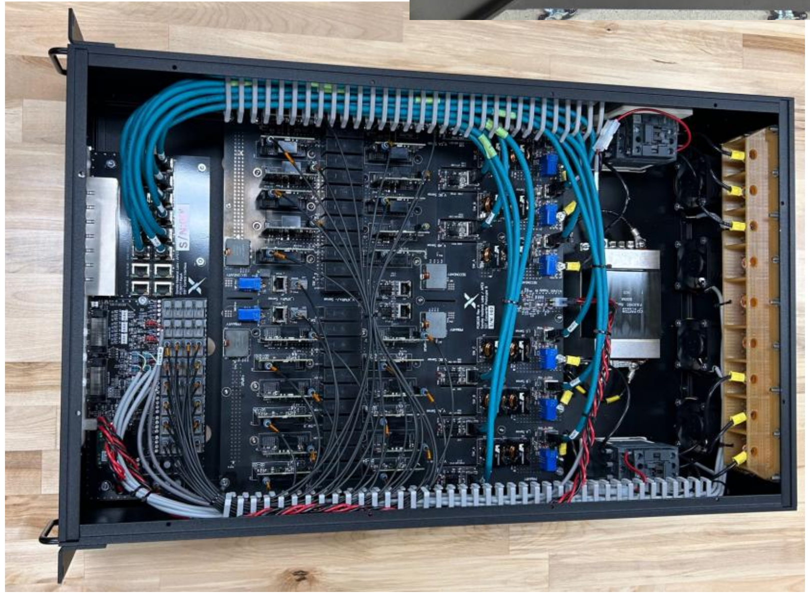
Transformer Current



YEAR 2 RESULTS

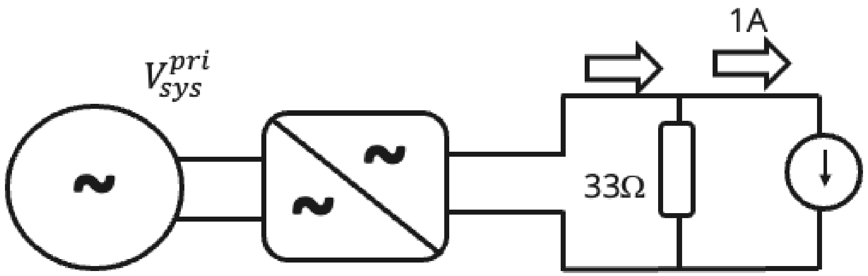
- 50% reduction in board size from Rev A
- Single 3U Module footprint
- ½ Rack Parallel system architecture
    - Back busbar system
    - Hot-swappable

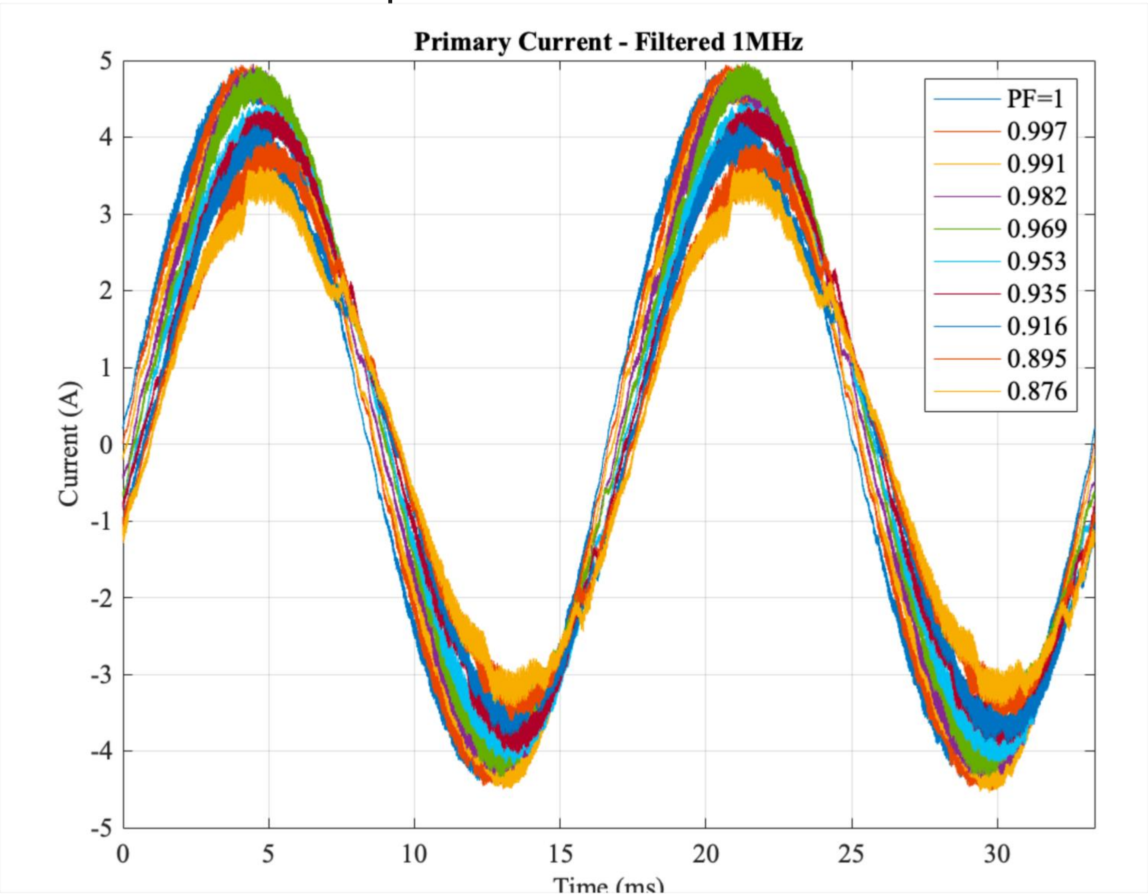


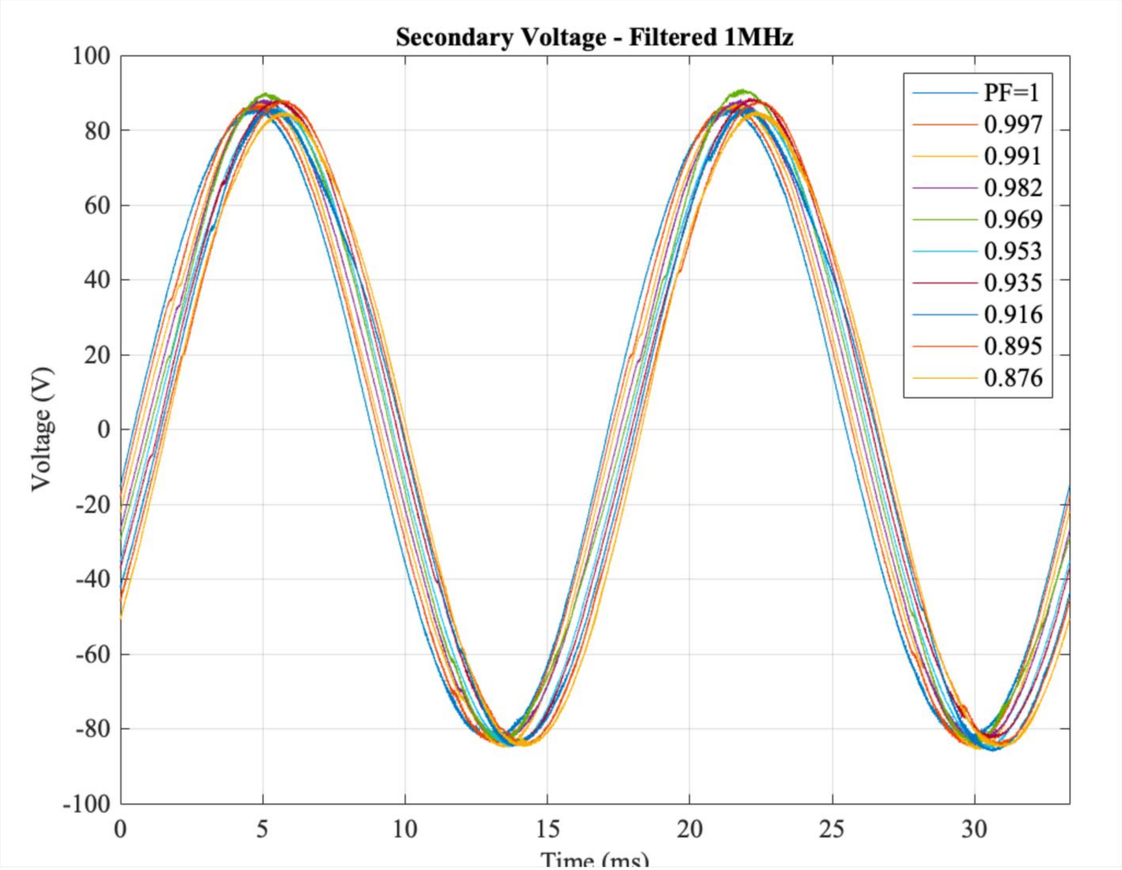


YEAR 3 RESULTS

- Demonstrated operation at non-unity power factor
- Phase angles from -90 to 90^o
- Effective total PF from 1 to +/-0.876 inductive and capacitive

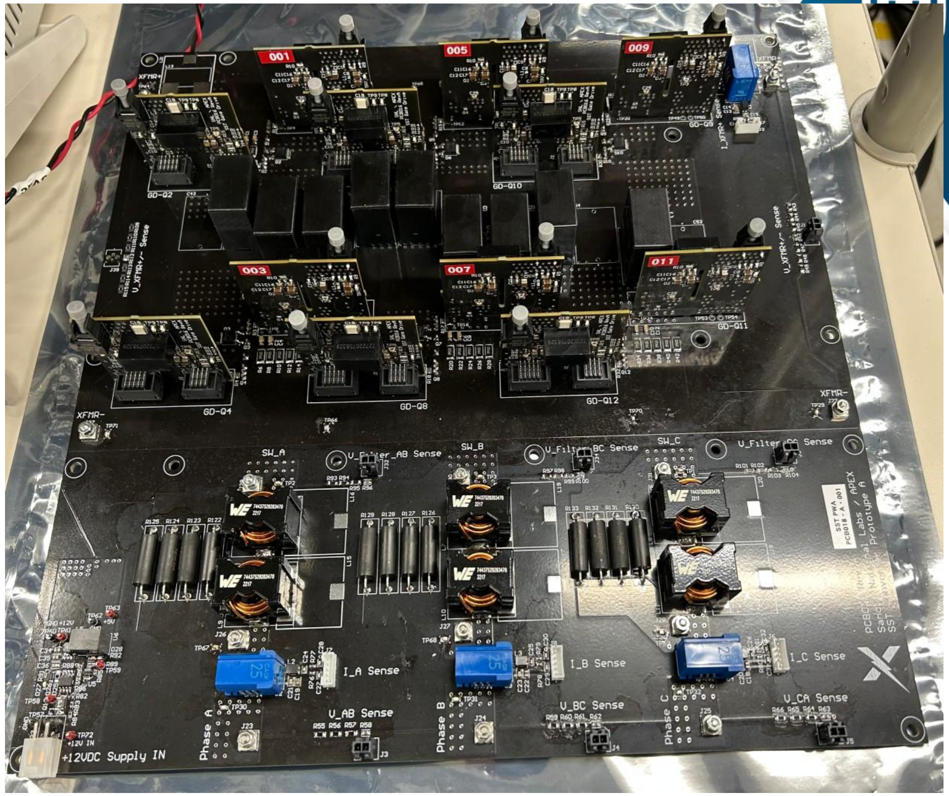






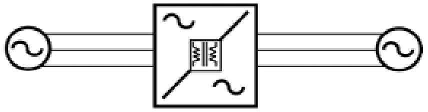
SOLID STATE TRANSFORMER PROJECT

- 3-year project funded by the Sandia Mission Campaign (LDRD)
- Select topology and run simulations
- Build control software
- Utilize and Improve SiC BiDFETs in custom packaging
- Improve magnetics and capacitors
- Build to 30kW 3ϕ



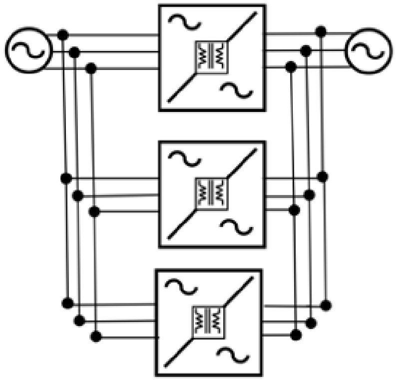
Year 1

Prototype A
208:480V, 3ϕ, 3kW
Single SST Module



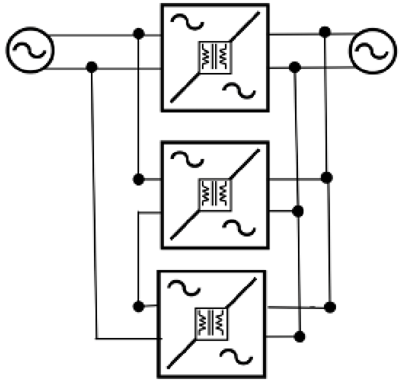
Year 2

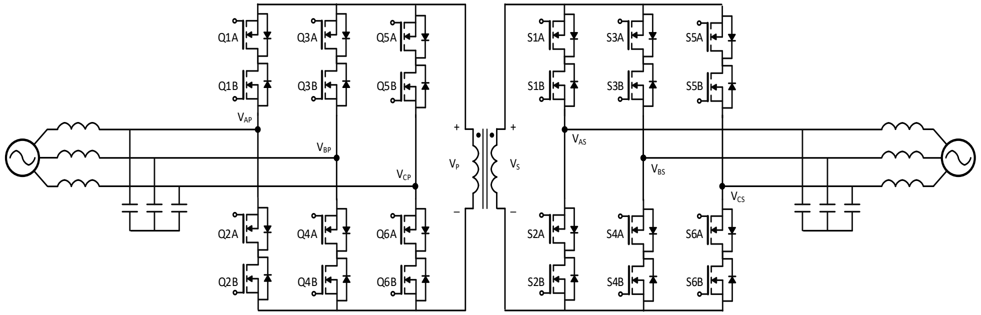
Prototype B
208:480V, 3ϕ, 15kW
Paralleled Prototype A



Year 3

Prototype C
3ϕ, 30 kW
Cascaded Prototype B



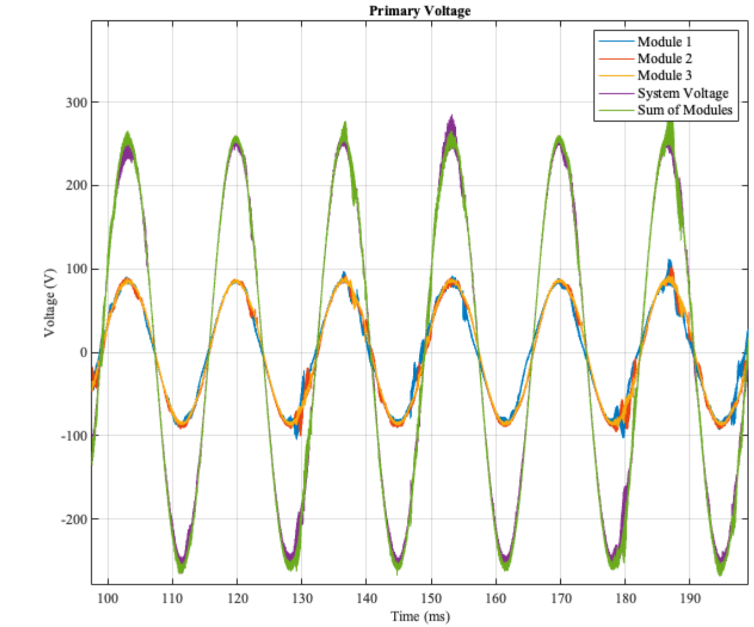


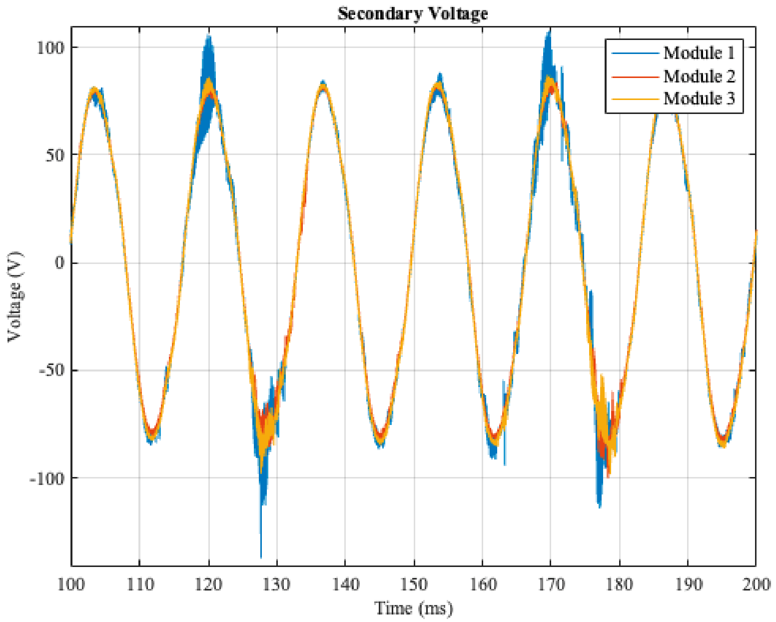
YEAR 3 RESULTS

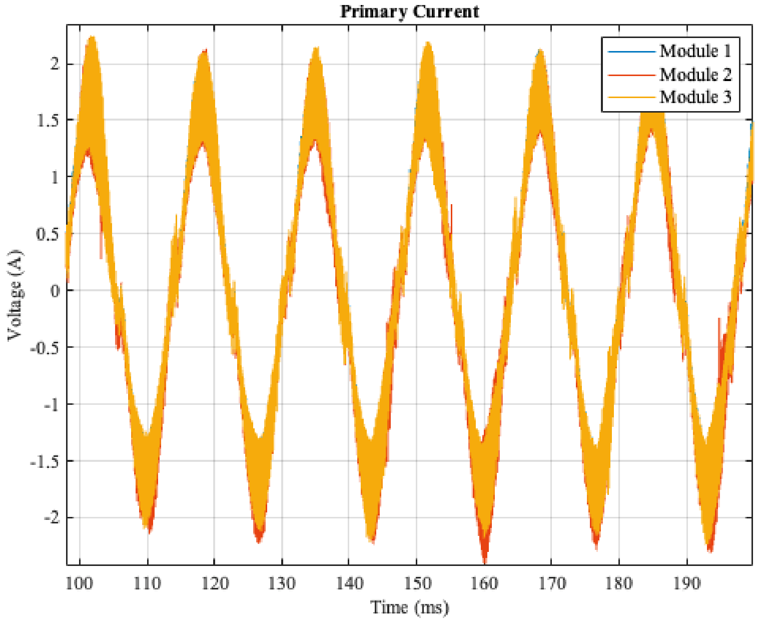
Single-phase, cascaded operation

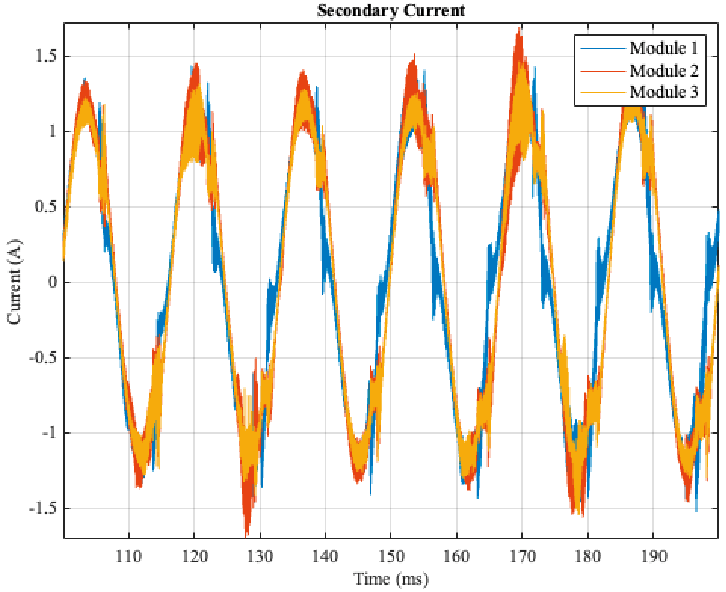
Voltage sharing on primary

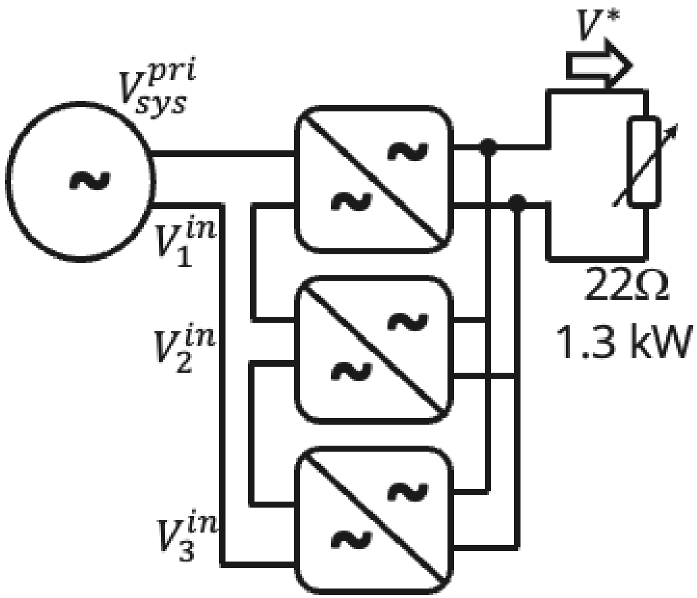
Current sharing on Secondary



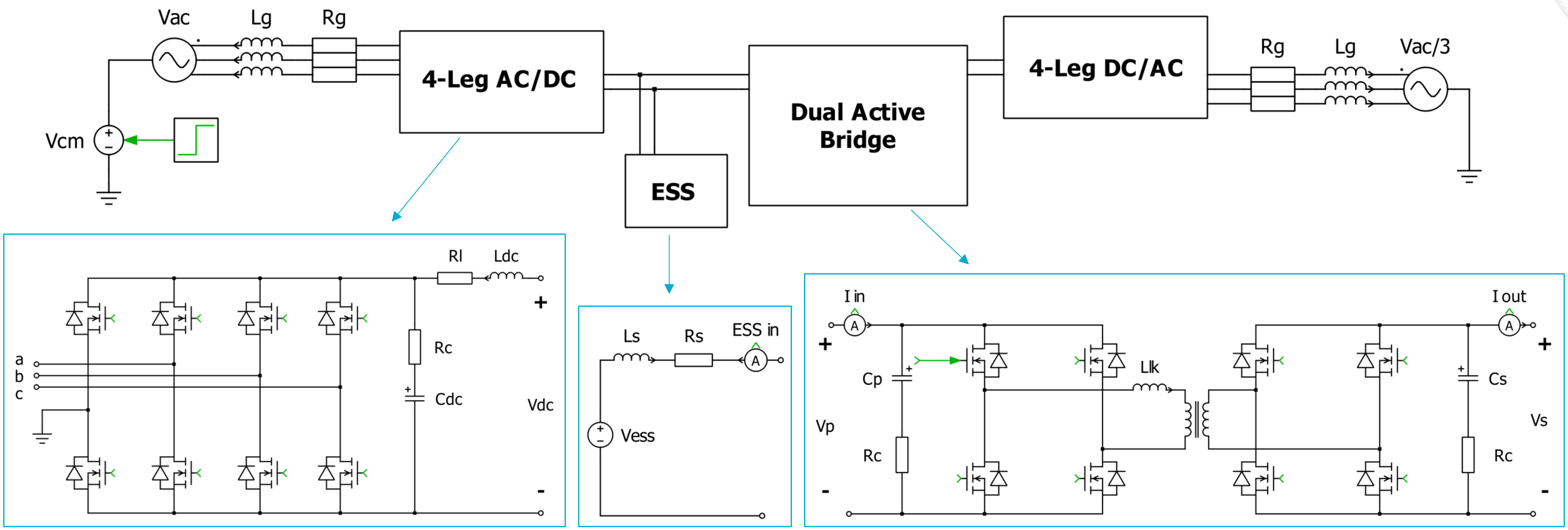






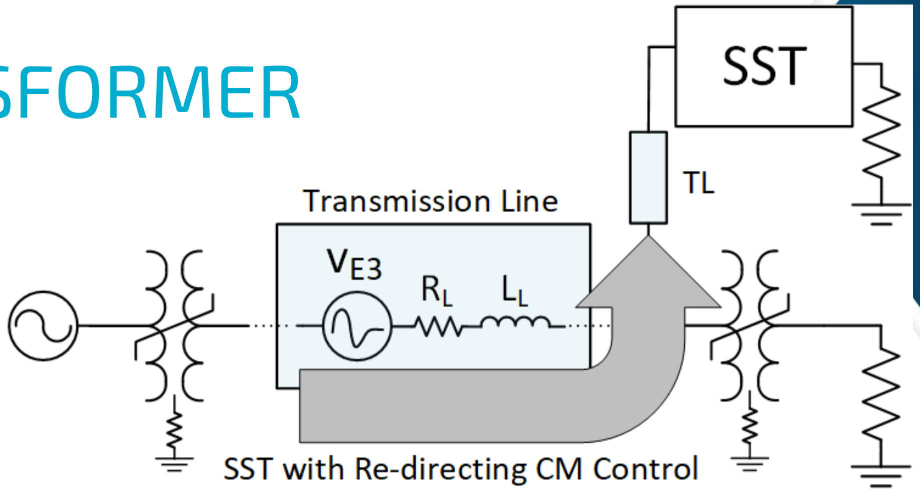


BUILDING AN SST WITH 4-LEGGED CONVERTERS TO RESPOND TO COMMON MODE INSULTS

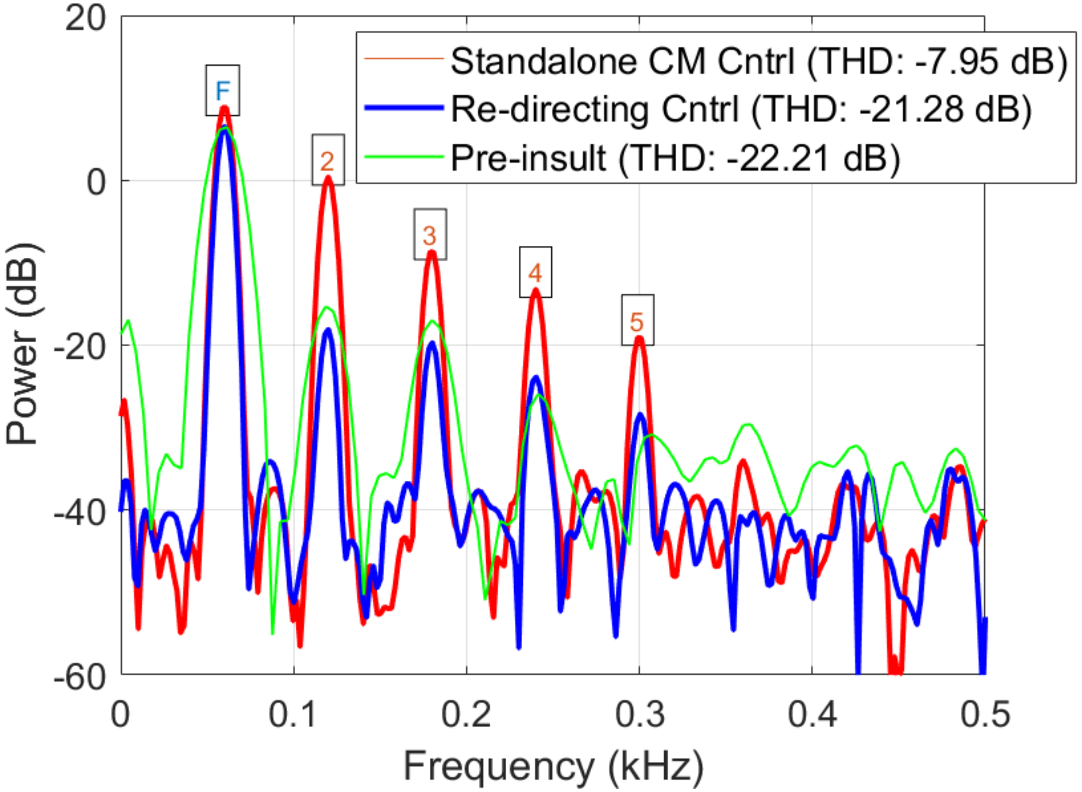


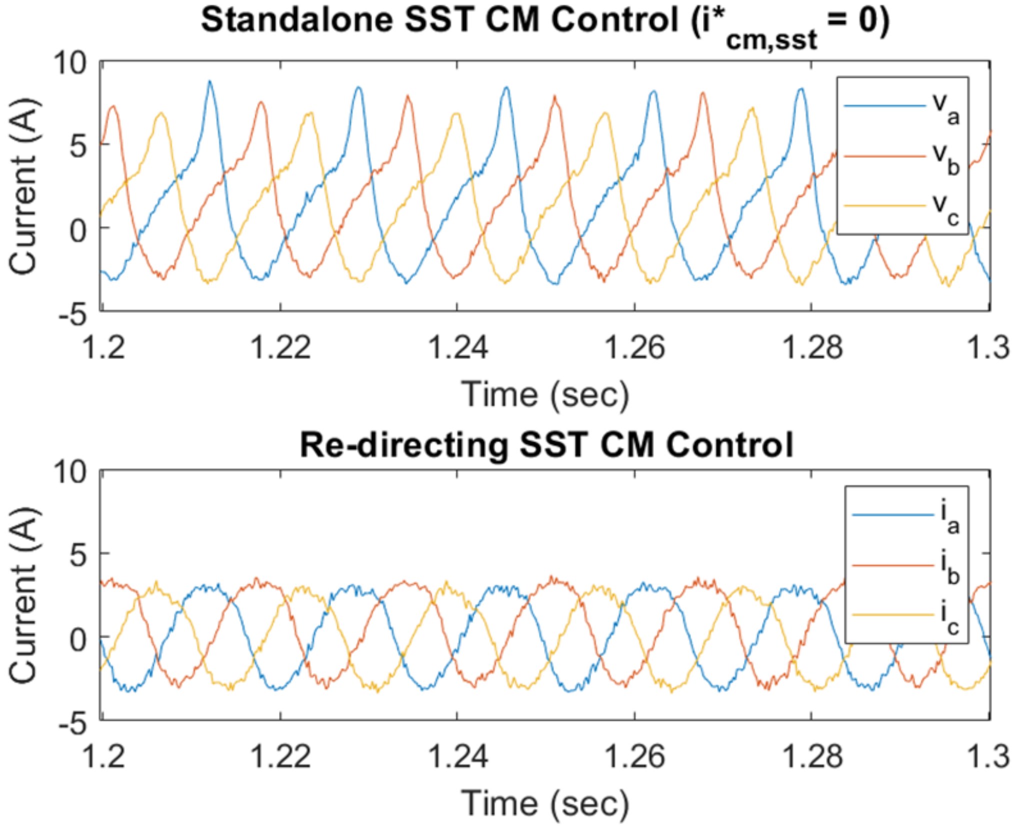
SST IN PARALLEL WITH CONVENTIONAL TRANSFORMER

- Local control blocks CM current going <u>into SST</u>
- Global control blocks CM current from going <u>into Conv. Txfrmr</u>



Conventional Transformer Current

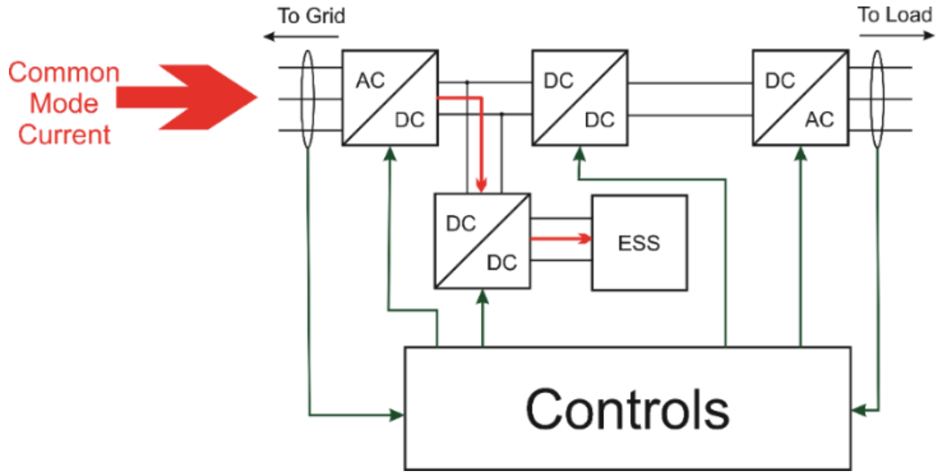




SOLID-STATE TRANSFORMERS ADD CONTROLLABILITY TO THE GRID

Solid-State Transformers (SST) will improve grid resilience and controllability

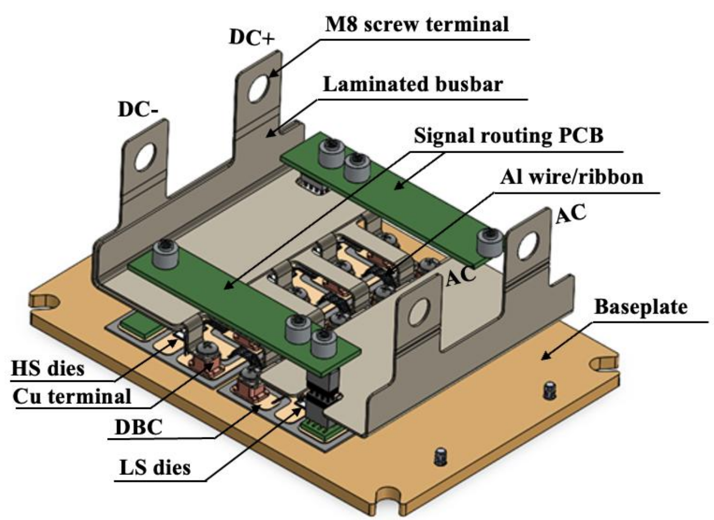
- Active components
  - Respond to threats
- Architecture and control options
  - Absorb/dissipate CM currents
  - Enable distributed architectures and controls for the grid

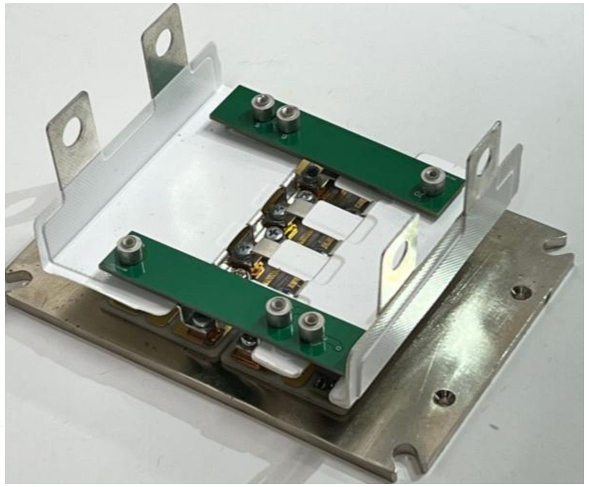


- **Preliminary design for a 3.3 kV SiC module**
  - Industrial standard XHP 3 packaged
  - Wire-bonded-less (Ribbon Bonded) interconnects
  - 3.3 kV/400A half-bridge configuration
  - 4 SiC MOSFETs paralleled at each switching position

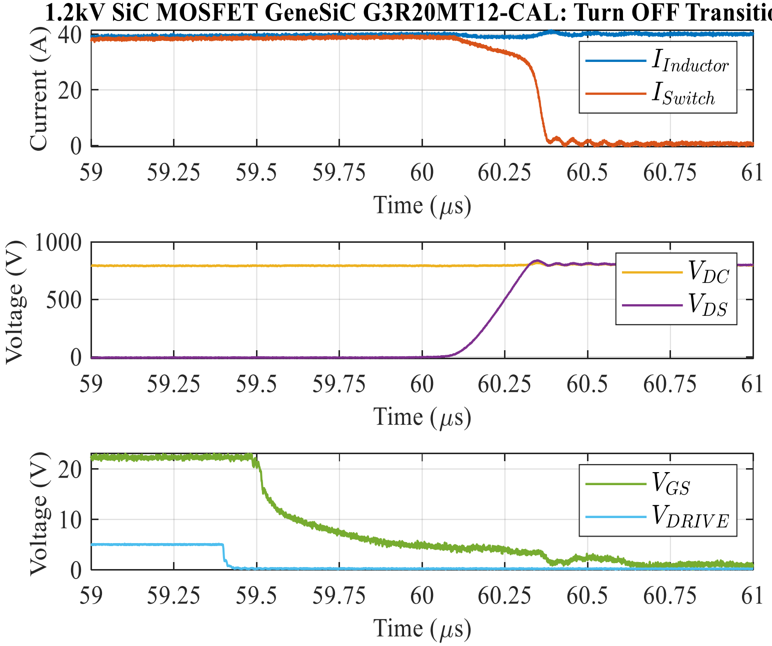
Module Specification

V_{DSmax}	3300 V
I_D	200 A
Targeted f_{sw}	80-100 kHz
Packaging size	140 x100 x40 (mm)
Gate loop wire	5 mil Al
Power loop wire	12 mil Al





- Power loop inductance calculated by ANSYS Q3D
  - DC bus bars
  - DBC copper
  - SiC devices
  - Al bonds included in calculation
- **Low power loop inductance:** 9.0 nH
- 149.1 W per die (100 kHz @ 4 kW/m²·°C convection)



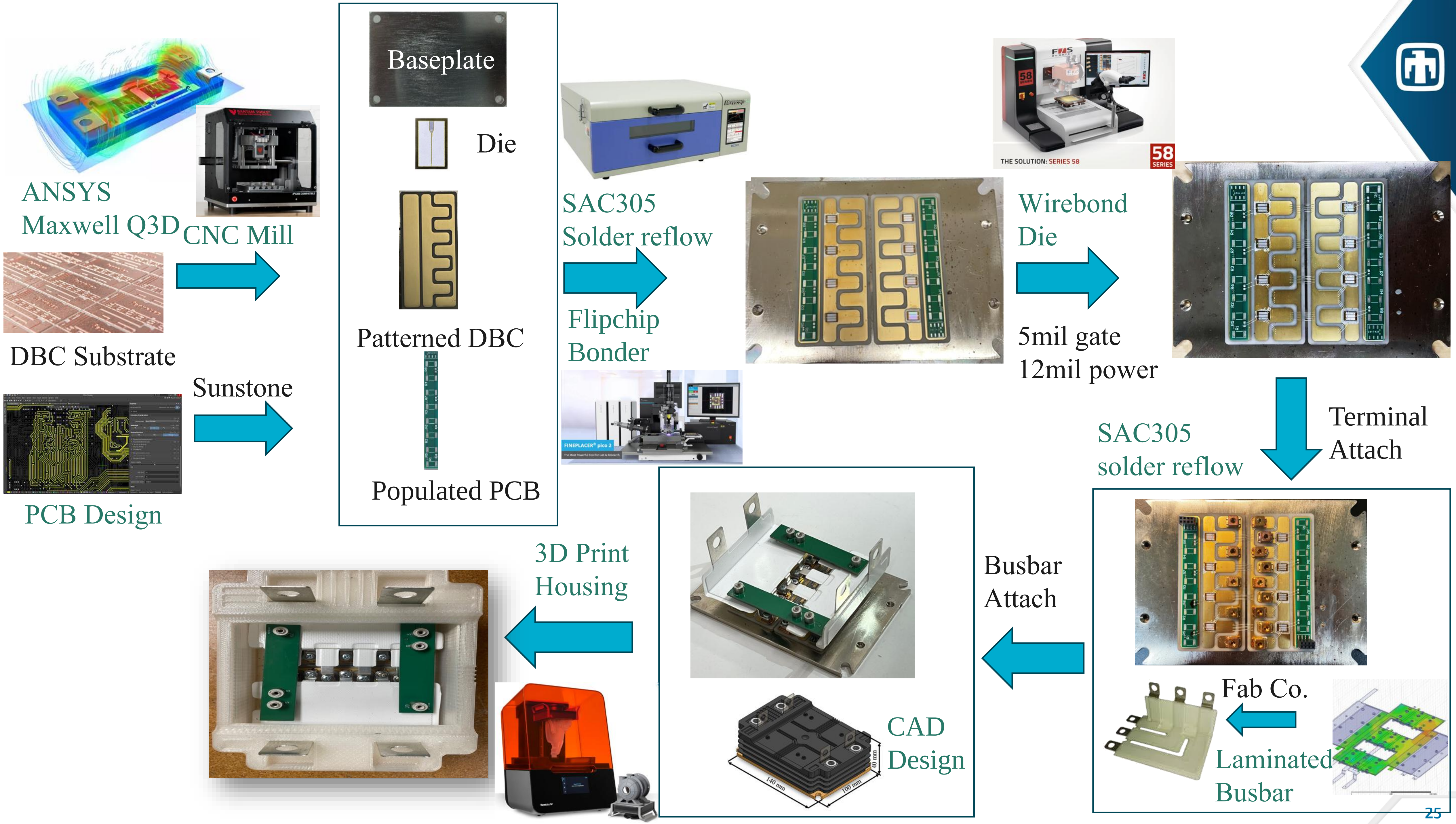
Double Pulse Switching of 1.2 kV version shows promising dynamics

3.3 kV version under evaluation

	SiC 1.2kV MOSFET	Improvement to Si
$t_{d(OFF)}$	5.2316 μs	88%
t_f	0.9405 μs	98%
t_{OFF}	6.1721 μs	87%

Sandia National Laboratories

Stony Brook University


ANSYS
Maxwell Q3D
CNC Mill
DBC Substrate
Sunstone
PCB Design
Baseplate
Die
Patterned DBC
Populated PCB
SAC305
Solder reflow
Flipchip
Bonder
FINEPLACER® pico 2
Wirebond
Die
5mil gate
12mil power
THE SOLUTION: SERIES 58
58 SERIES
Terminal
Attach
SAC305
solder reflow
Fab Co.
Laminated
Busbar
Busbar
Attach
CAD
Design
140 mm
100 mm
40 mm
3D Print
Housing

PEAK Lab Fundamental Capabilities

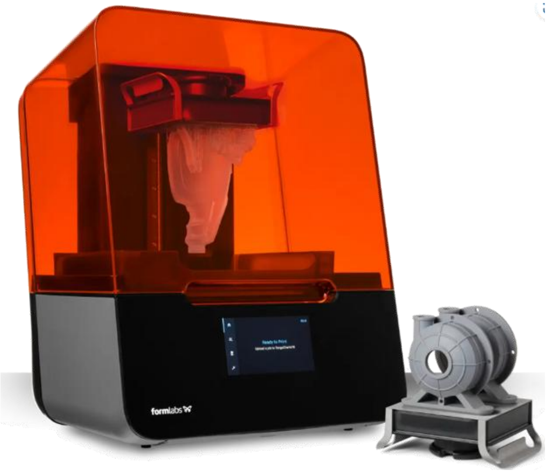
Commissioning 12/2024

Finetech pico 2 R&D-Grade Flip-chip and die bonder

F&S Bondtech Series 58 automatic wire bonder

MC301 Batch Re-flow Oven

PCB components and die attach



FormLabs Form3 Litho-based 3D Printer

3D printing of custom housings and busbar laminates

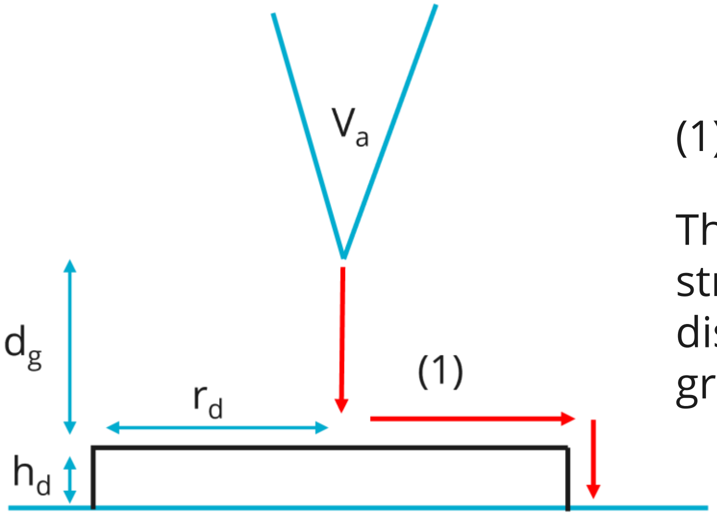
Bantam Tools Desktop CNC Miller

Custom milling of busbars and DBCs

HIGH VOLTAGE BREAKDOWN OF GAS-GAPPED DIELECTRICS

- Prior breakdown calculations approached the problem to determine a voltage at which the gas discharge would be self-sustaining
- Instead, let us assume that the field is large enough to start streamer breakdown at the tip (E_{tip} > ~32 kV/cm in P_{atm} air).
- Streamers have a sustaining field upstream of the streamer head necessary to continue propagation (E_{sf} ~ 4.7 kV/cm* in free space). Also, the streamer channel has a small field (E_s).

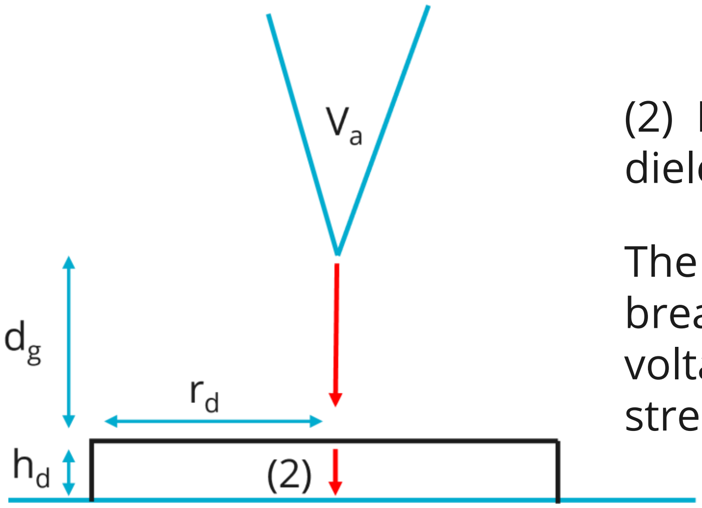
There are 2 paths breakdown could take:



(1) Surface flashover:

The field upstream of the streamer head at distance *s* must remain greater than E_{sf}:

$$E_{sf} < \frac{V_{a,1} - E_s s}{s} \rightarrow V_{a,1} > \left(E_{sf} + E_s \right)(d_g + r_d + h_d)$$



(2) Breakdown through the dielectric:

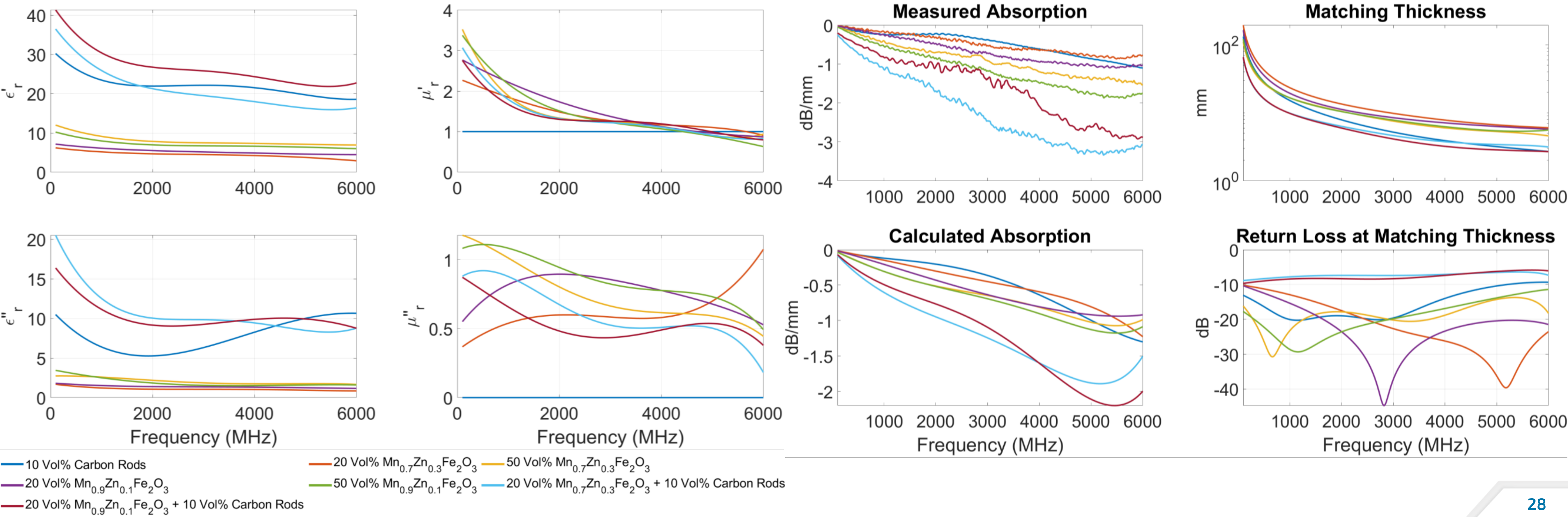
The gas gap must breakdown and has a voltage drop across the streamer and sheath:

$$\frac{V_{a,2} - E_s d_g - \Delta V_{sheath}}{h_d} > E_d \rightarrow V_{a,2} > E_d h_d + E_s d_g + \Delta V_{sheath}$$

*L. Warne, R. Jorgenson and E. Kunhardt, "Criterion for Spark-Breakdown in Non-Uniform Fields," Journal of Applied Physics, vol. 115, 2014.

HYBRID ABSORBERS: PROTECTING SENSITIVE ELECTRONICS FROM EMI

- Two or more load components embedded in a polymer matrix that can be conformally coated
- Decrease cavity quality factor to dampen resonances
- Line apertures to prevent EMI penetration and reduce surface currents
- Utilize overlapping dielectric and magnetic loss mechanisms to achieve broadband absorption



COMMON MODE SOLID STATE TRANSFORMER

AC-TO-AC SOLID STATE TRANSFORMER

SOLID STATE TRANSFORMERS (SST)

MATERIALS DEVELOPMENT

POWER ELECTRONICS ADVANCED PACKAGING LAB (PEAK)