SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Power Electronics Program Kickoff

A Reliable, Cost-Effective Transformerless MV Inverter for Gird Integration of Combined Solar and Energy Storage

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energy.gov/solar-office

Outline of Presentation

- ☐ Project Overview
  - —Impact to Solar Industry
  - —The way to **50%** LCOE Reduction
- ☐ Technical Approach
- ☐ Project Plan

Project Targets

Comparison of New Concepts to State-of-the-Art (SOA)

Category	Industry SOA	Target
LCOE	\$0.11/kWh	\$0.05/kWh
System Cost	\$0.1/W	<\$0.06/W
Peak Efficiency	98.7%	99%
Power Density	0.15 kW/L (Si)	6 kW/L (SiC)
Step-up Trans.	Yes	No
Agency Approvals	UL 1741	Extended UL1741 IEC 61850
Thermal Management	Liquid/Forced Air	Natural Convection
Maintenance Time	4-6 hours	30 min-1 hour
Redundancy/ Expendability	Limited and Stationary	Hot-Swap Economies of Scale

↓ 50%

↑ 40x

$$\text{LCOE} \approx \frac{\downarrow C_{Installed} + C_{O\&M} \downarrow}{E_{grid} + E_{enduse} \uparrow}$$

More energy & Less Heat

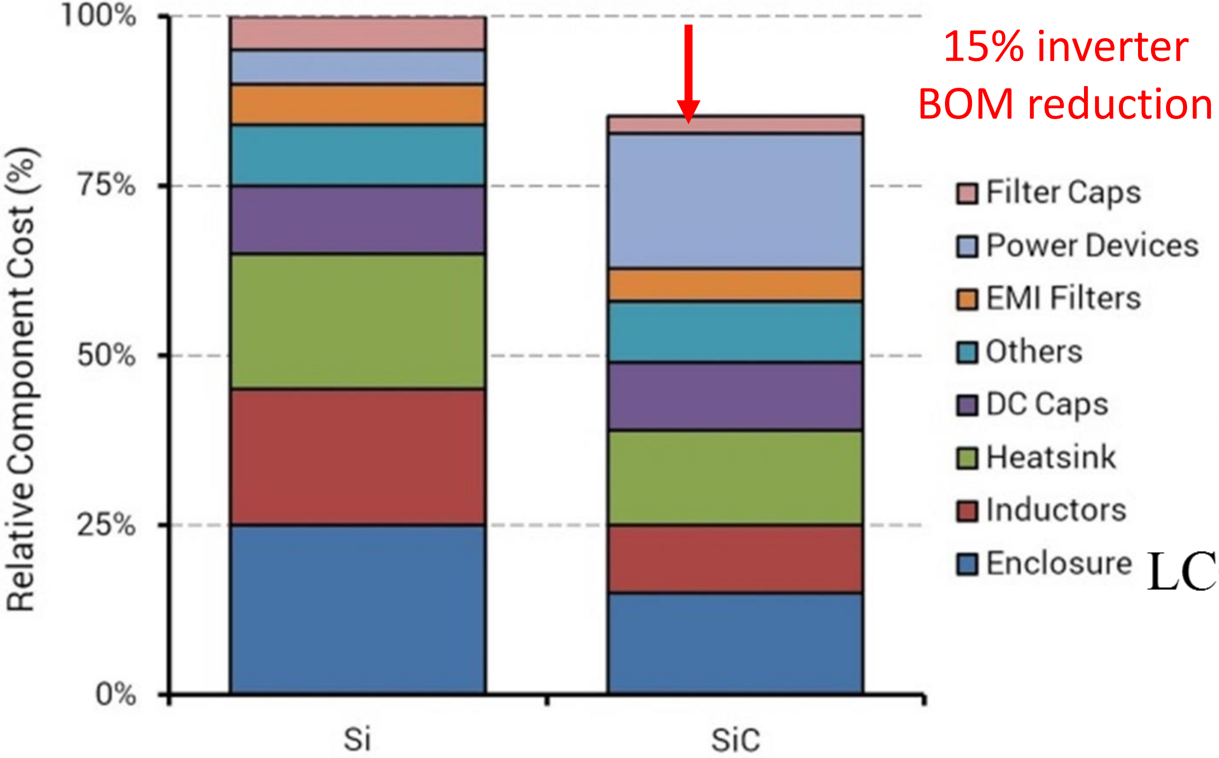
Easy Installation & Logistics

Fast Approval Cybersecurity

Higher Reliability & Less Downtime

Easy Maintenance & Less Upgrade

The Holistic Inverter Design Approach



15% inverter BOM reduction

Objective: > 50% LCOE Reduction

Compound Effect on LCOE

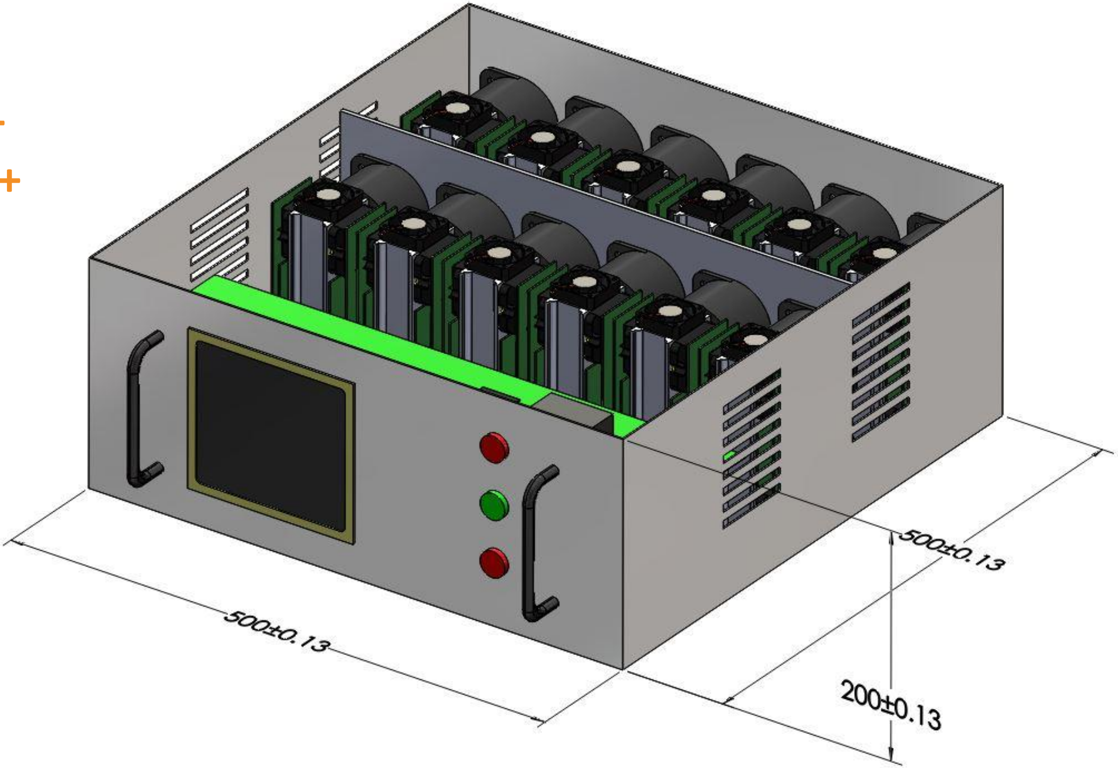
$$\mathrm{LCOE} \approx \frac{\downarrow C_{Installed} + C_{O\&M} \downarrow}{E_{grid} + E_{enduse} \uparrow}$$

*Marcelo Schupbach (Cree, Inc.), "SiC MOSFET and Diode Technologies Accelerate the Global Adoption of Solar Energy", Bodo's Power Systems, May 2015.

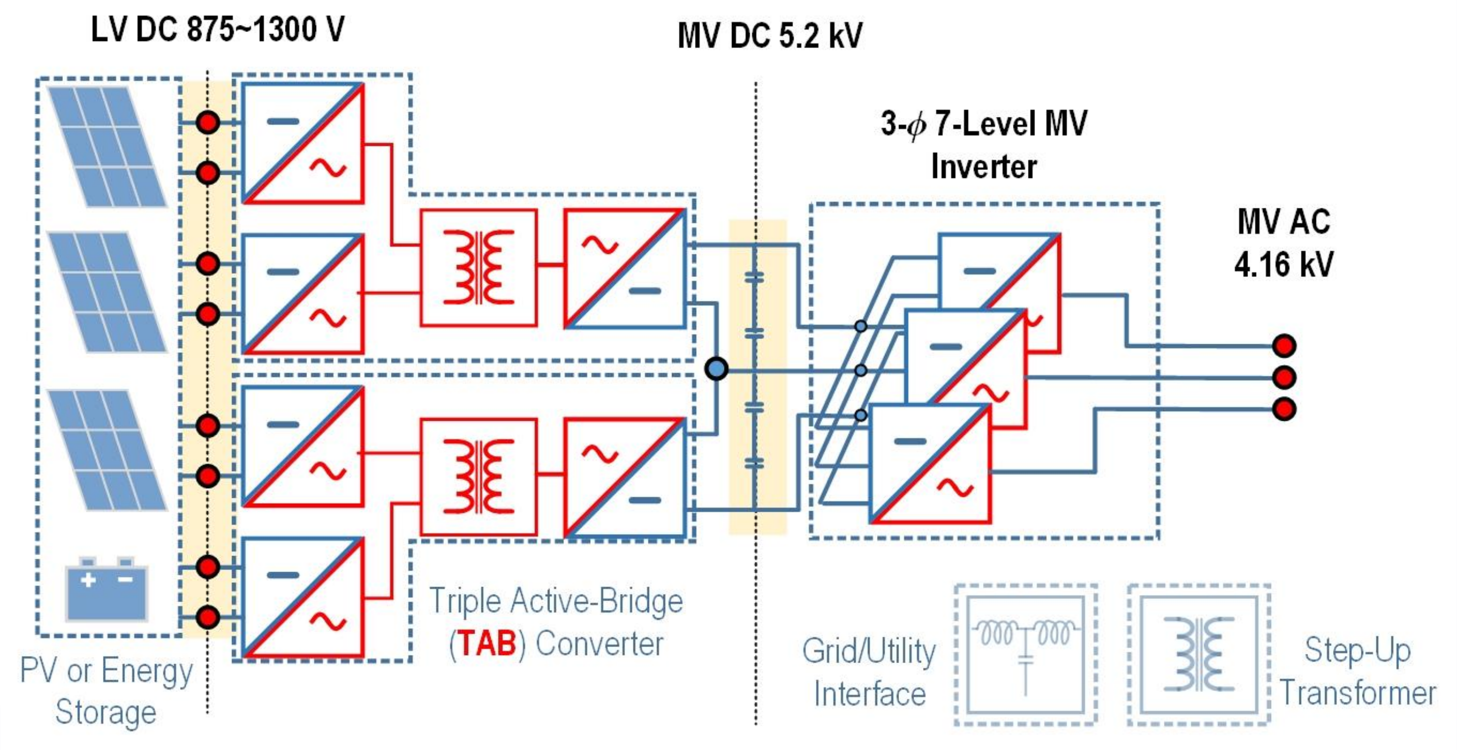
Technical Approach

Solar Inverter System =
(1) Power Electronics +
(2) High Frequency Transformers +
(3) Thermal Management System +
(4) Grid Interface / Filters +
(5) Control System

- Best-in-class SiC Modules
- Multi-Objective Optimization – A Holistic Inverter System Design Approach

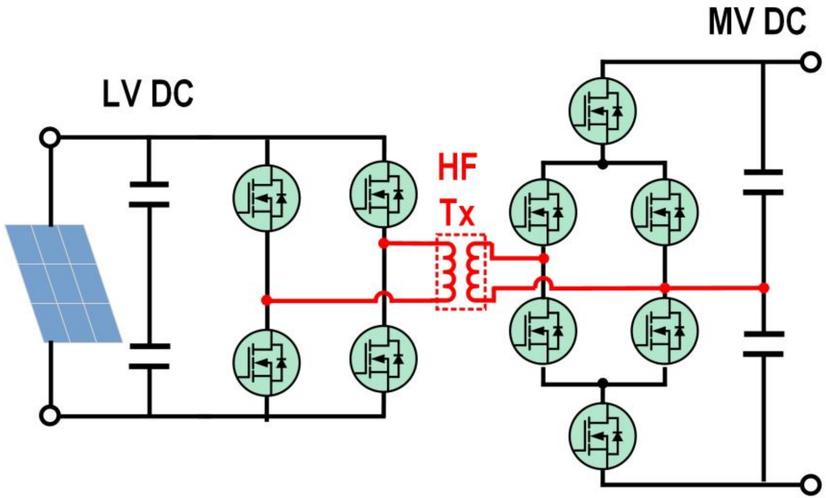


300 kW MV Solar Inverter

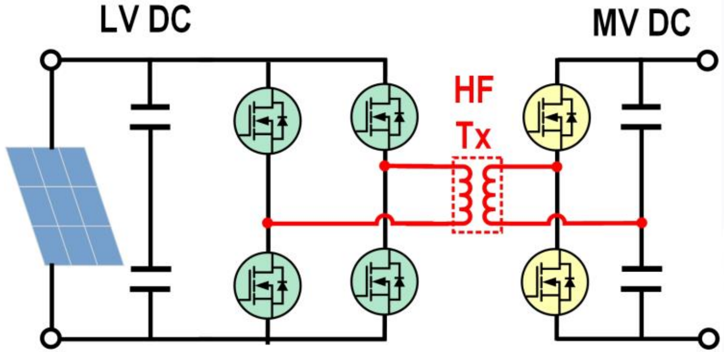


Power Electronics Circuits

SiC MOSFETs: 🟩 1.7 kV 🟨 3.3 kV 🟥 6.5 kV



All 1.7 kV SiC MOSFETs

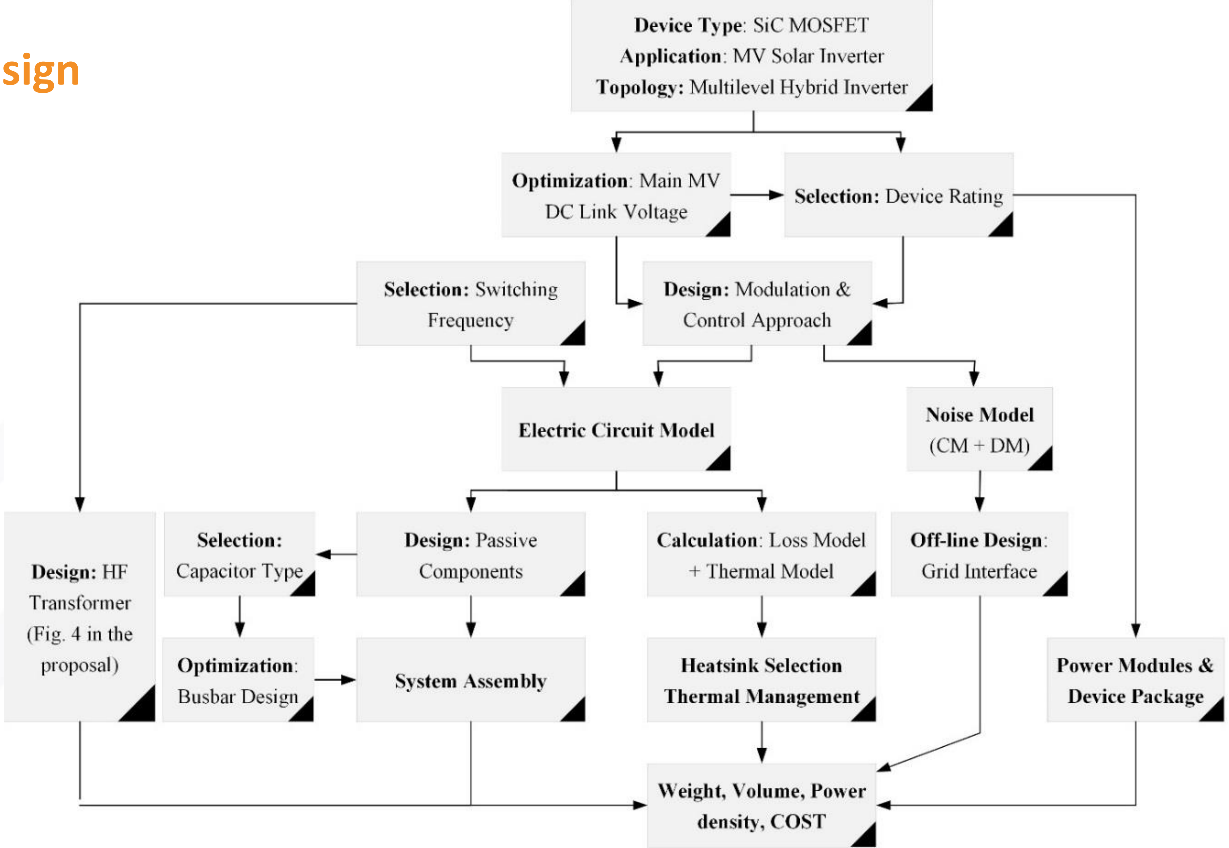


1.7 kV + 3.3 kV SiC MOSFETs

Multi-objective Optimization

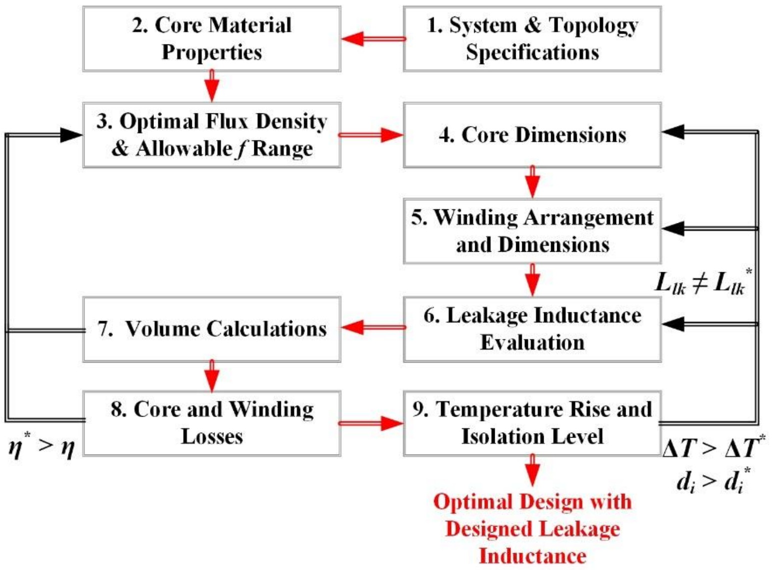
– A Holistic Solar Inverter Design

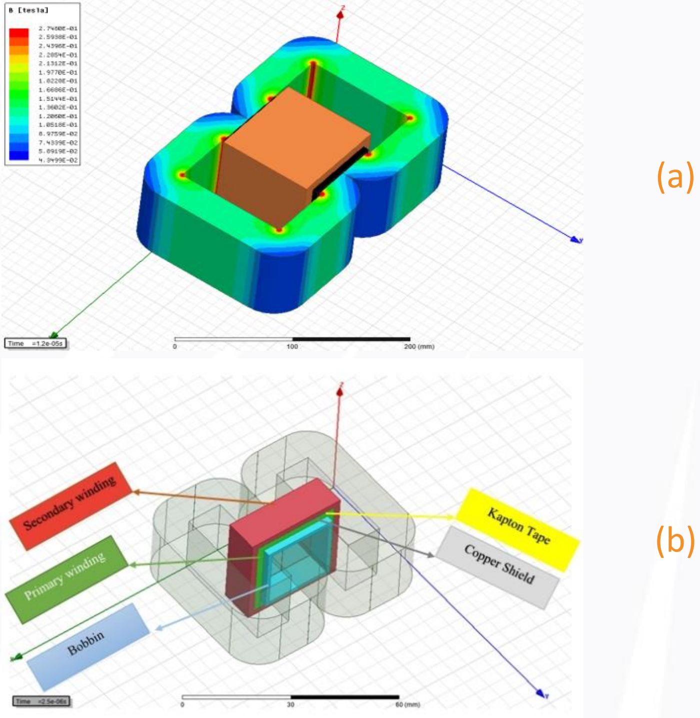
- Technology Readiness
- Economic Feasibility



High Frequency Transformer

Transformer Design Flow Chart

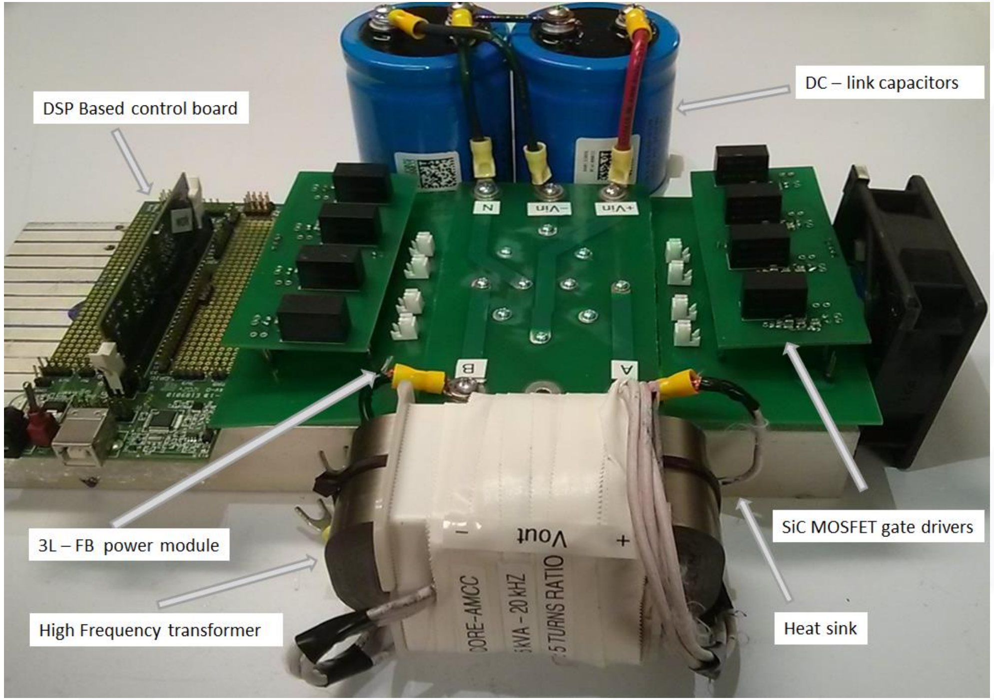


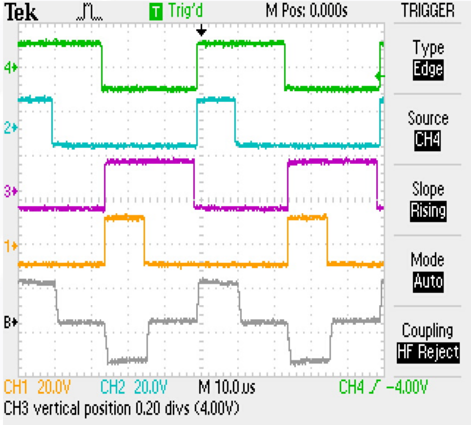


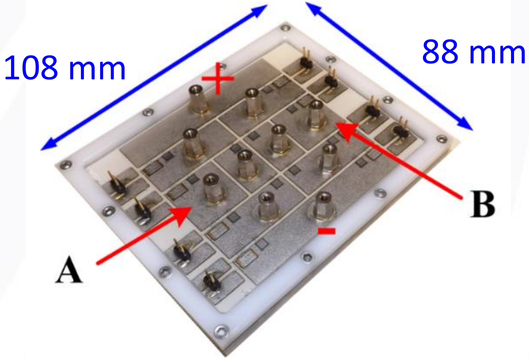
(a) The flux density fields and (b) shell-type structure of a nanocrystalline 72.8 kVA 20-kHz transformer.

High Frequency Transformer

“1.2 kV SiC MOSFET-Based 3L-FB” Experimental Results



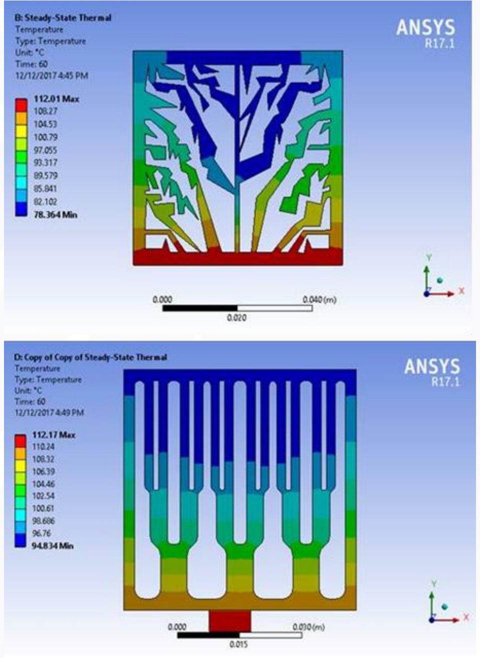




- Ratings: ~20 kVA, 1.2 kVdc, Tj=150 °C
- Power density: ~ 200 kVA/liter

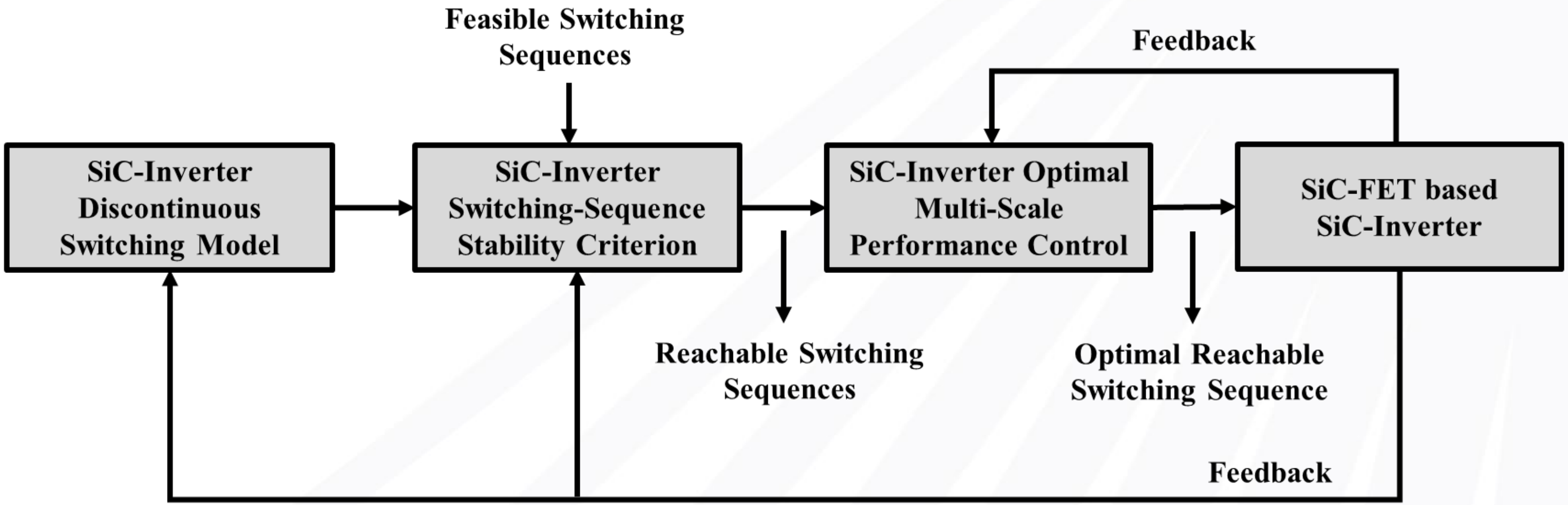
Integrated Thermal & Reliability Approach

- Co-design of Electrical and Thermal with mechanical layout optimization for reliability/failure risk.
- Thermally optimized design to reduce operating temperature swings compared to SOA and typical lifetimes (20% ΔT reduction ≈ >1.5x life/MTTF).
- Considerations important in determining contributions of operating T_{avg} and ΔT and *f* on thermomechanical reliability.
- Evaluation of impact of usage and the associated cooling scheme(s)
- Thermal management control scheme coordinated with building cooling utilities



3D printed channeled heat sinks for optimizing air flow and conduction, which can be incorporated with directed airflow through manifold structure

Control for Energy Efficiency & Reliability



Feasible Switching Sequences

Feedback

SiC-Inverter Discontinuous Switching Model

SiC-Inverter Switching-Sequence Stability Criterion

SiC-Inverter Optimal Multi-Scale Performance Control

SiC-FET based SiC-Inverter

Reachable Switching Sequences

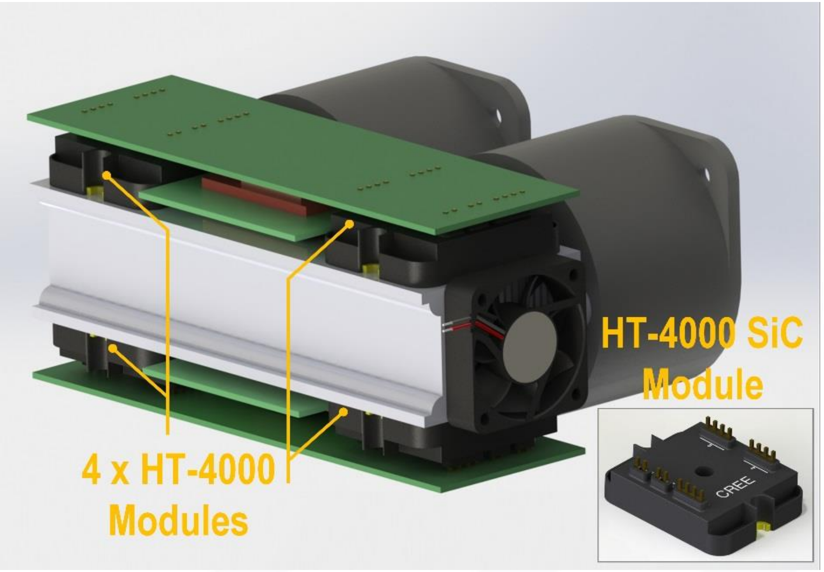
Optimal Reachable Switching Sequence

Feedback

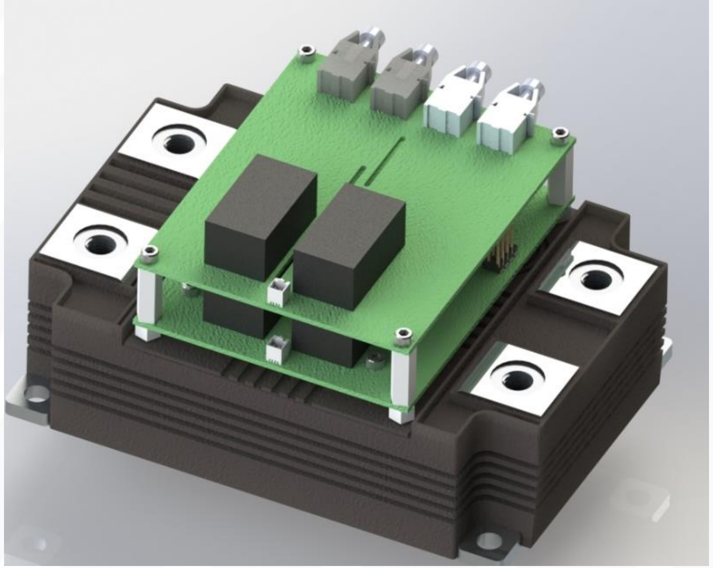
A novel switching sequence control (S^2C)

Fast Inverter Assembly and Prototyping

Power Electronics Building Blocks (PEBBs)



A PEBB using Wolfspeed 1.7 kV HT-4000 SiC Modules



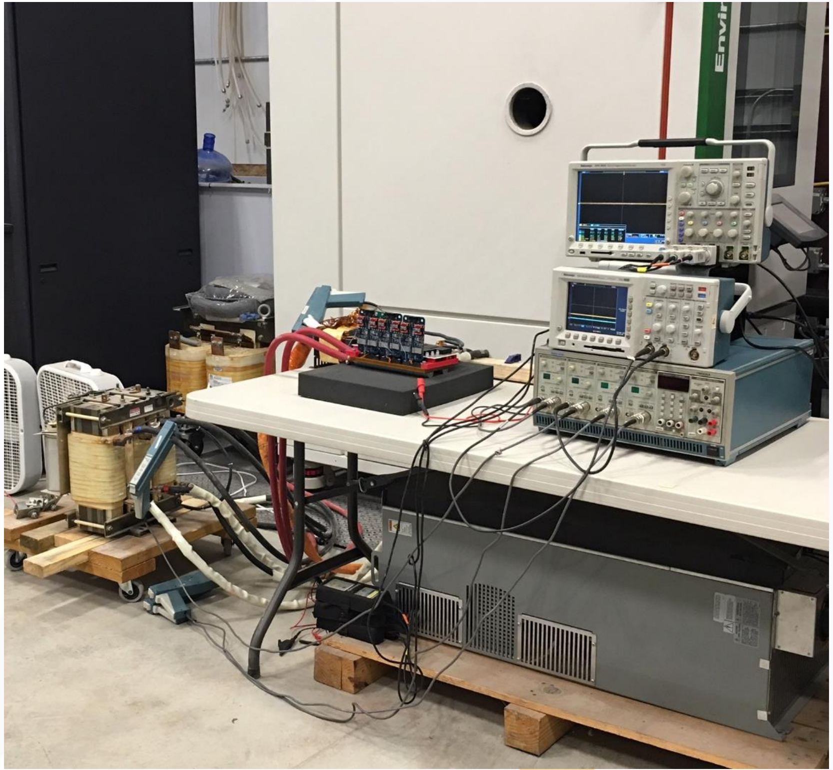
A Half-Bridge PEBB using Wolfspeed XHV-7 3.3 kV power module

Test and Evaluation

National Center for Reliable Electric Power Transmission (NCREPT) @ U of A

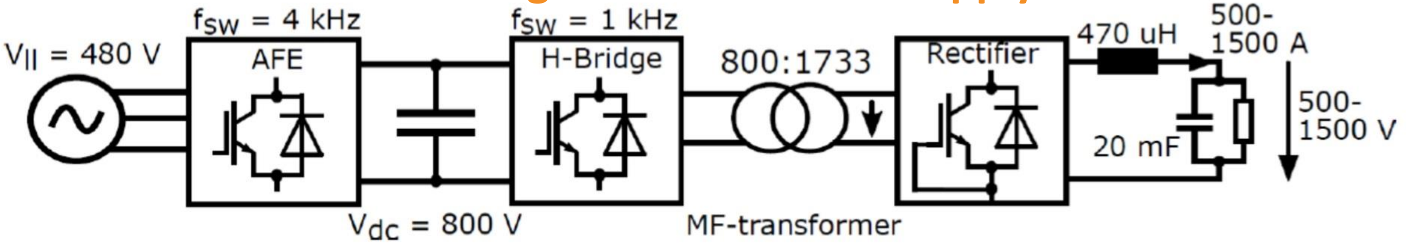
Table 2. Ratings of the NCREPT Test Facility

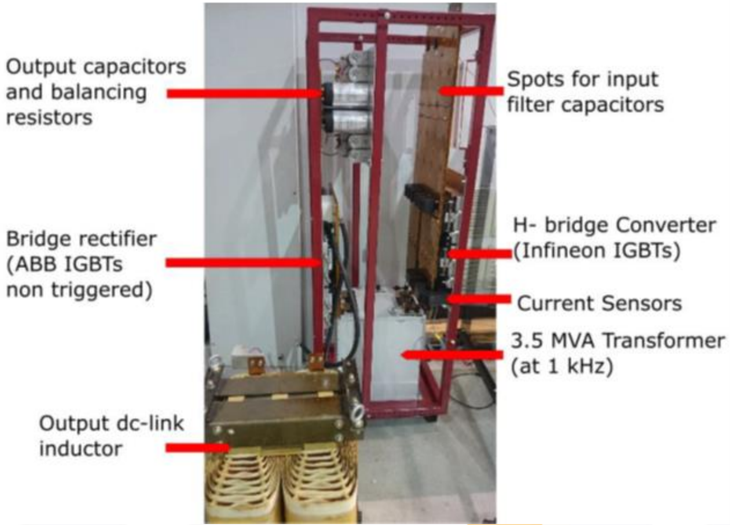
Parameter	Rating
Power	Up to 6 MVA
Medium Voltages	13.8 kV or 4.16 kV (line-line) Variable from 0 V to 15.18 kV
Low Voltages	480 V (line-line), Variable 0-528 V
Frequency	40 Hz to 70 Hz
Currents	300 A @ 13.8 kV; 1000 A @ 4.16 kV; 2500 A @ 480 V
Loads	Active loads fully programmable; Test energy is recirculated



Test and Evaluation

2 MW Programmable Power Supply





Target Metrics & Design Concepts

Requirements	Target Metric	Proposed Design Concepts
System Cost	< $ 0.06/W; > 50% LCOE reduction;	• 300 kW commercial scale central inverter; • MPP voltage 875 ~ 1300 V DC, max. 1500 V DC; • Output voltage 4.16 kV AC.
Service Life & Equipment Reliability	> 25 years lifetime; < O&M costs;	• Thermally optimized design to reduce operating temper swings compared to SOA and typical lifetimes (20% Δ reduction ≈ >1.5x life/MTTF) • Modular design to reduce O&M costs to swap compon and direct cooling needs • Design for maintenance: 30 min – 1 hour. • Optimized SiC control for partial load performance
Optimized Constituent Technologies Design	Optimization of efficiency, power density, mass density, component topology & switching, magnetics, passives, environmental impact, thermal systems, and manufacturing.	• Power Density > 6 kW/l; Specific Power > 3 kW/kg; • Cooling: air cooling or natural convection; • Topology: modular 5-level inverter; • Switching frequency 30~40 kHz; • EMI filter volume < 5% of total volume.
Grid-Support Controls	Compliance with ANSI, IEEE, and NERC standards.	• EPRI, SIWG • IEEE 1547.3 and IEC 61850.
Interoperable and Cyber Secure	Compliance with open interoperability standards and cybersecurity protocols.	

Technical Innovation & Impact

- Holistic solar/energy storage inverter design to enable significantly reduced lifetime costs
- Hierarchical 3-layer multi-objective optimization design
  - PEBBs; PE circuits; cabinet layout
- New PE topology + S^2C Control to take advantage of SiC technology for volumetric and EMI reductions
- Novel integrated thermal management and reliability approaches coupled with electrical design.
- Scalable to other MV applications in various market segments.

Project Plan – Approach

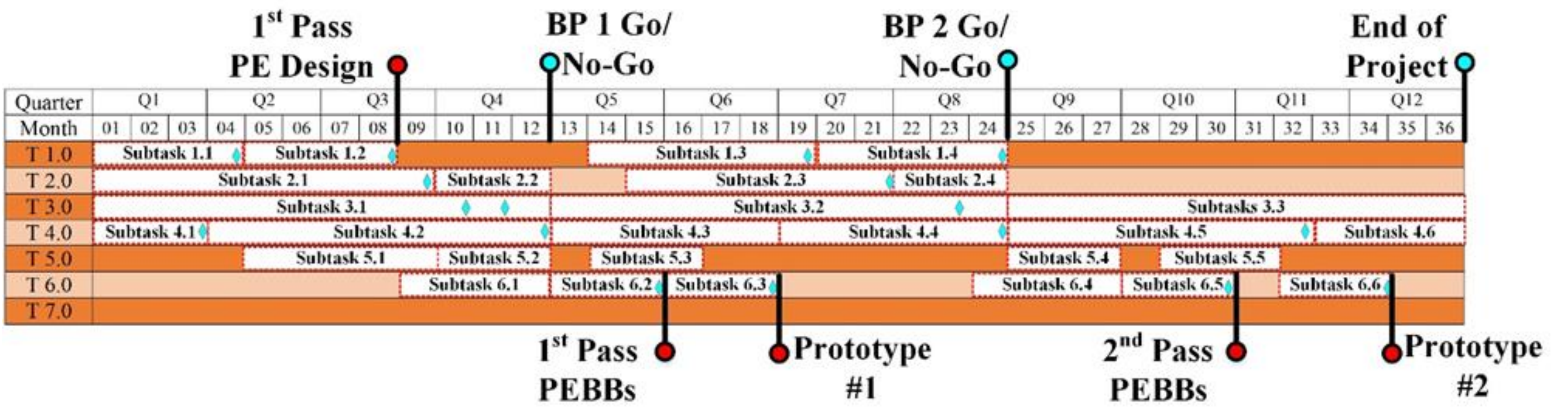
☐ Two-pass prototype approach

☐ Analyze critical issues in the 1st pass

☐ Drive out limiting factors in the 2nd pass

☐ Test and evaluate each pass to inform reliability

Schedule



Task 1.0: Power Electronic Circuit Design;

Task 2.0: High Frequency Transformer Design;

Task 3.0: Thermal Management & Reliability;

Task 4.0: System Control Development;

Task 5.0: Inverter Assembly & Prototyping;

Task 6.0: Test and Evaluation;

Task 7.0: Technology to Market (T2M).

Schedule

- **Go/No-Go decision point 1** (@ 12th Mo): 1) finish the 1st pass inverter cabinet level design; 2) use theoretical analysis, numerical simulation, and HIL simulation to validate the proposed design can meet the goal, i.e., 300 kW output power, 99% peak efficiency, 6 kW/L power density; 3) finish the initial economic analysis to show the cost of 1st pass design can achieve less than $ 0.08/W.
- **Go/No-Go decision point 2** (@ 24th Mo): 1) deliver the 1st prototype that meet the goal specified in Go/No-Go decision point 1; 2) deliver comprehensive testing report for 1st prototype; 3) finish the 2nd pass PEBB level design; and 4) present the plan and economic analysis to achieve less than $ 0.06/W.
- **End of the project goal** is to deliver: 1) 2nd prototype meeting the project targets; 2) prototypes of the PEBBs with various topologies, including half-bridge, DAB, ANPC; 3) a multi-objective optimization tool for electro-thermal co-design of WBG power electronic system; and 4) technical reports.

Thank you!

Comments & Questions?