U.S. DEPARTMENT OF ENERGY
Office of Electricity

NEXT-GENERATION MODULAR FLEXIBLE LOW-COST SILICON CARBIDE (SIC)-BASED HIGH-FREQUENCY-LINK TRANSFORMER

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

August 13, 2019

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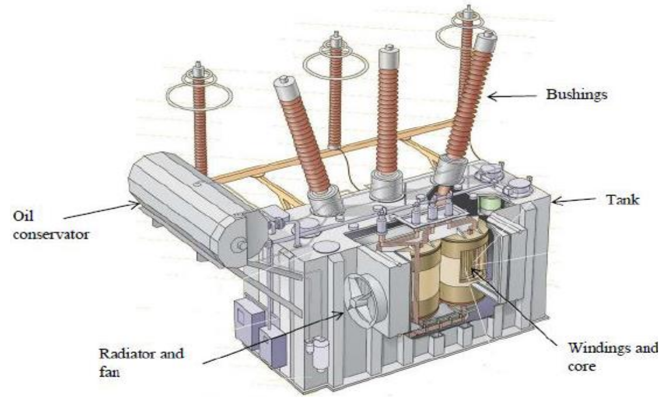
Project Overview

- **Project summary:** Overall research efforts will focus on developing a lab-scale prototype that demonstrates proof-of-concept of a modular high-frequency-link (HFL) large-power-transformer (LPT) and allows for performance evaluation. Year 1 will lead to design, fabrication, and testing of a 100-kVA module for a HFL-LPT (i.e., 20 kHz) while Year 2 will demonstrate a cascaded multi-HFL-LPT module for three phase high-power operation.
- **Total value of award (federal + cost share):** $1,874,906 (anticipated)
- **Period of performance:** August 4, 2019 – August 3, 2021 (anticipated)
- **Project lead and partners:** NextWatt LLC (Lead), University of Arkansas (subawardee), Industry Advisors (ABB and Eaton)

Context concerning the problem being addressed

- Conventional monolithic LPTs that form the backbone of US power grid
  - Are reaching their end of service lives in several cases creating energy-security issues
  - Are often not interchangeable with each other
  - Have high costs and limited spare inventories more so considering that on an average only 1.3 LPTs are manufactured for individual design.
  - Are posing potential issue for critical infrastructure resilience in the US
- Due to the significant capital expenditure, long lead time, and unique specifications associated with the procurement and manufacturing of a replacement LPT, there is an opportunity to research and develop more flexible and adaptable LPT designs.
- Although the costs and pricing vary by manufacturer and by size, a LPT can cost millions of dollars and weigh between approximately 100 and 400 tons (or between 200,000 and 800,000 pounds).
- Two raw materials—copper and electrical steel—account for over 50 percent of the total cost of an LPT. The average prices of both copper and steel have increased significantly over the years, which have clear implications for conventional LPTs.
- Therefore, the goal of our project is to provide an innovative design for LPTs using a HFL approach that is more compact, light-weight, modular, flexible, economical, and adaptable than current LPT designs and help create greater LPT design standardization to increase grid resilience in the event of the loss of one or more LPTs.



Voltage Rating (Primary-Secondary)	Capability MVA Rating	Approximate Price ($)	Approximate Weight & Dimensions
Transmission Transformer			
Three Phase			
230–115kV	300	$2,000,000	170 tons (340,000 lb) 21ft W–27ft L–25ft H
345–138kV	500	$4,000,000	335 tons (670,000 lb) 45ft W–25ft L–30ft H
765–138kV	750	$7,500,000	410 tons (820,000 lb) 56ft W–40ft L–45ft H
Single Phase			
765–345kV	500	$4,500,000	235 tons (470,000 lb) 40ft W–30ft L–40ft H
Generator Step-Up Transformer			
Three Phase			
115–13.8kV	75	$1,000,000	110 tons (220,000 lb) 16ft W–25ft L–20ft H
345—13.8kV	300	$2,500,000	185 tons (370,000 lb) 21ft W–40ft L–27ft H
Single Phase			
345–22kV	300	$3,000,000	225 tons (450,000 lb) 35ft W–20ft L–30ft H
765–26kV	500	$5,000,000	325 tons (650,000 lb) 33ft W–25ft L–40ft H

Advanced Grid Research
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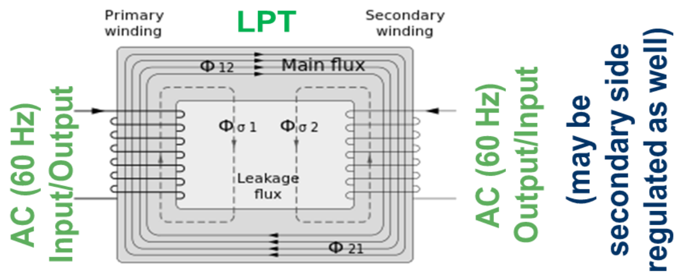
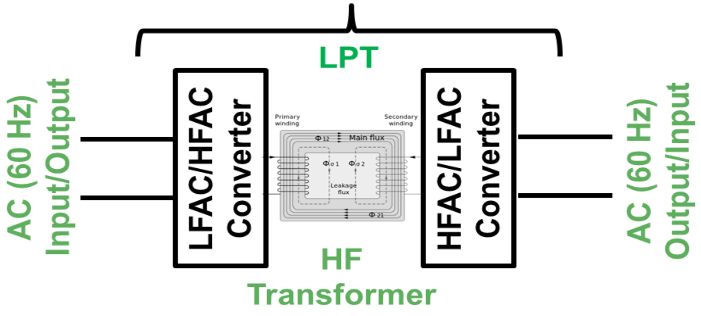
State of the art approaches for addressing the problem

- **Have others attempted to address this problem?**
  - HFL-LPT: Solid-state transformers, indirect matrix cycloconverter
  - LPT: 60 Hz, PE-based secondary tap-changing solution
- **If so, what are the merits of the alternative approaches that have been developed.**
  - SST, matrix cycloconverter: compact, flexible, modular
  - LPT: Relatively lower cost, higher efficiency, more rugged
- **If so, what are the drawbacks of the alternative approaches that have been developed.**
  - SST, matrix cycloconverter: higher cost, higher design and system complexity
  - LPT: Enhanced weight and size, reduced flexibility

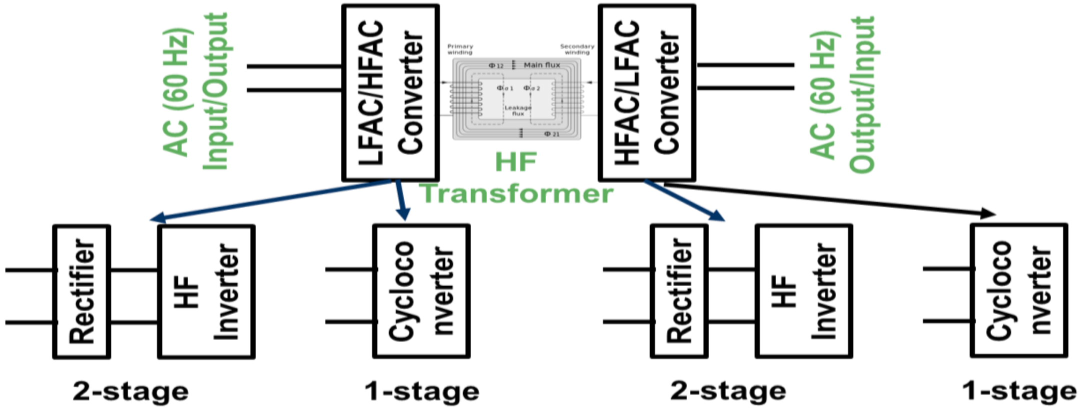


Conventional LPT Approach: Bulky transformer because flux cycle is 60-Hz



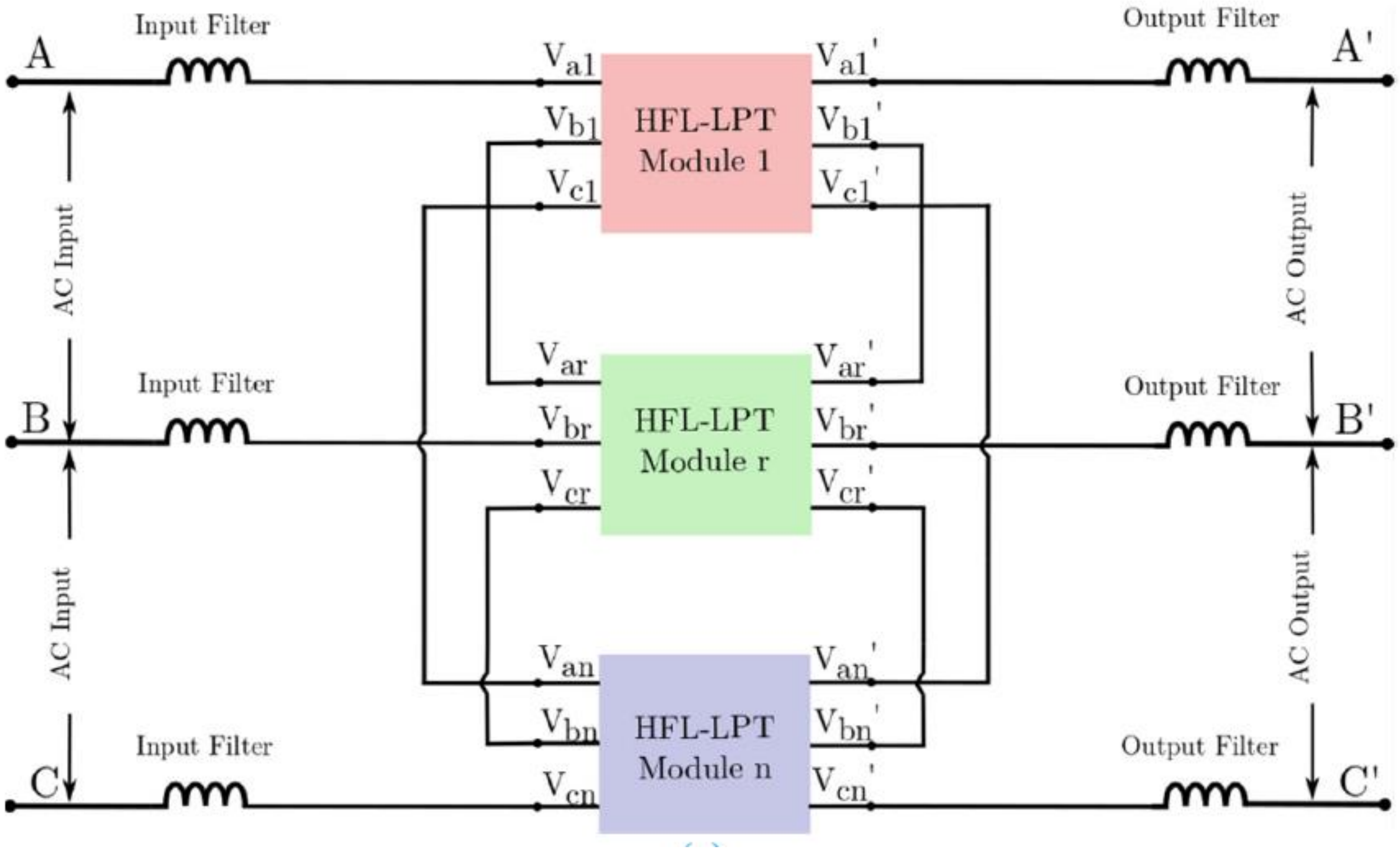
HFL-LPT Approach: Lightweight transformer because flux cycle is at HF

HFL-LPT Approaches



Uniqueness of the proposed solution

- **What separates this solution from others that have been proposed or tested? What are the unique advantages?**
  - (True) single-stage power conversion
  - Reduced device count
  - Up/down capability
  - Modularly scalable
  - Input-output continuous
  - EMI filtering reduced
  - Multi-functional

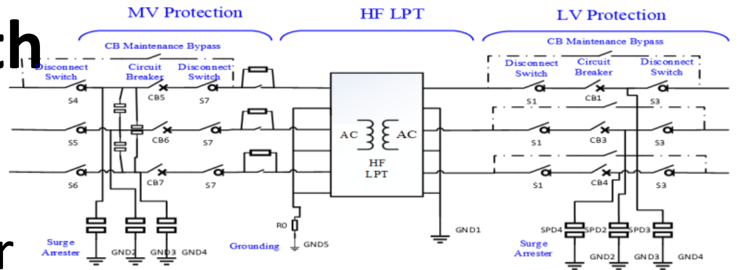


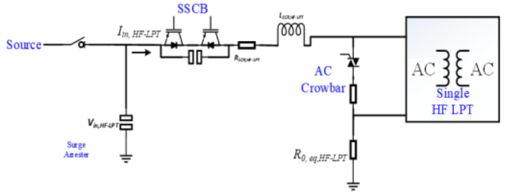
Significance of the results, if successful

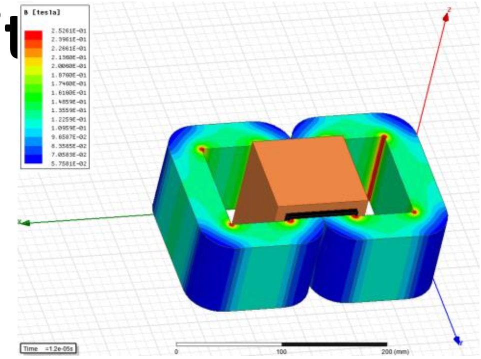
- **If this project is successful, how will the project outcomes be utilized?**
  - IP planned
  - Licensing possibility
- **What will change, with regard to the problem and its larger context, once these research results are available?**
  - The novel HFL-LPT solution has the potential to provide a flexible LPT that is compact, economically viable, simple to design and fabricate, and reliable
  - Next-generation smart grid using the new HFL-LPT can yield flexibility, and resilience and easy and economically-scalable manufacturability in USA

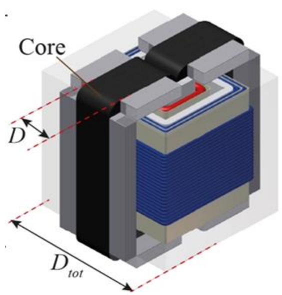
Specific research questions being addressed

- ❑ **Resolve design and fabrication challenges associated with the 3-phase HFL-LPT based on next-generation SiC devices**
  - Achieve high efficiency and high power density/high specific power simultaneously
  - Economic implementation of wide-bandgap technological solution
  - Protection issues
- ❑ **Resolve design and fabrication challenges associated with nanocrystalline-core based HF transformer (HFT)**
  - Reduced core and winding losses
  - Low leakage inductance
- ❑ **Experimental validations for performance metrics evaluation**
  - Packaging design
- ❑ **Resolve design, fabrication, and characterization challenges of cascaded HFL-LPT modules for higher power**
  - Module synchronization
  - Communication latency
  - EMI issues related to multilevel floating nodes





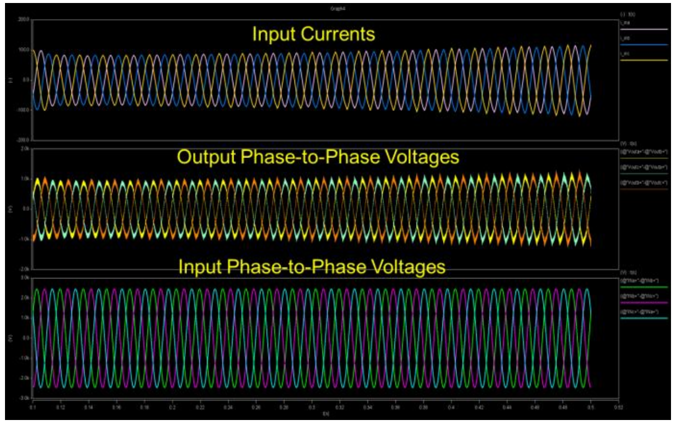




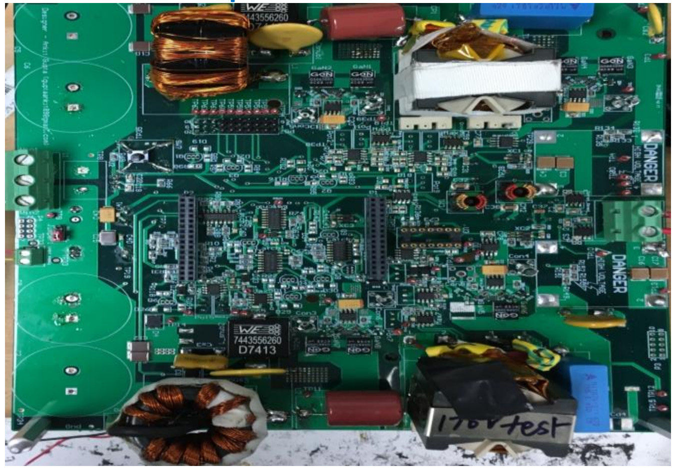
Technical explanation of the proposed approach

- **Describe the process by which the research results will be obtained.**
  - Simulation and parametric analysis
  - Experimentation and characterization on the fabricated HFL-LPT standalone and cascaded modules
- **Describe the rationale for the approach proposed.**
  - HFL-LPT is a modular approach to high-power realization
  - First, a 3-phase rated-power module will be developed and subsequently, 2 such modules will be connected in cascaded to investigate the feasibility for high-power and high-voltage scaling
- **Demonstrate that the approach being proposed is based on sound scientific reasoning and is likely to produce that which is intended.**
  - Some preliminary simulation and low-power experimentation have been conducted
  - In years 1 and 2 aside from rated-power three-phase standalone and cascaded validations, we plan to also conduct a lower power validation that will precede the rated-power work to investigate potential issues

Preliminary simulation results



Preliminary low-power experimental unit



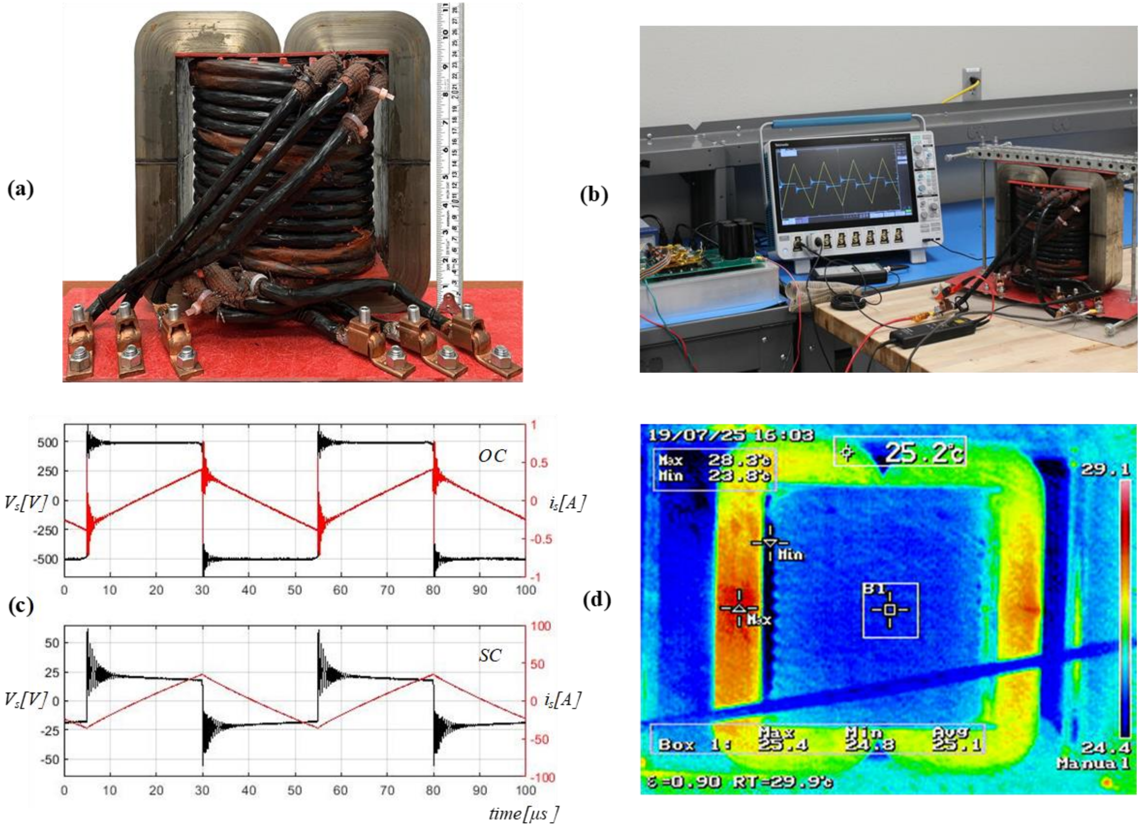
Project schedule, deliverables, and current status

- **Current status:** project has not started yet and we are awaiting a contract
- **Anticipated budget:** $1,874,906 (federal + cost share)
- **Projected deliverables:**
  - Design, optimization and analysis results for the HF transformer (HFT) and the filter inductor
  - Functional design and evaluation of the nanocrystalline core HFT and the filter inductor supporting the HFL-LPT submodule voltage and efficiency targets
  - Power and control stage design parameters, power and control stage performance analysis and performance projections
  - Functional design and evaluation of the HFL-LPT submodule regarding the performance targets for Year 1 includes PCB layouts; BOM for parts; and control software
  - Testing results and any redesign details for all HFT and filter inductor modules needed for realizing one HFL-LPT module and two cascaded HFL-LPT modules
  - Functional design and evaluation of the HFL-LPT three phase module to the performance targets for Year 2 includes information on PCB layouts and BOMs
  - Functional design and evaluation of the HFL-LPT cascaded three phase modules regarding performance targets for Year 2
  - Develop a preliminary business plan/commercialization strategy for potential implementation after the completion of the project based on the project technical results and with consideration of the technical advice obtained from the project technical advisor(s)

Anticipated challenges and risk mitigation strategies

- **Low-leakage nanocrystalline HFT**
  - A base level experience with UARK

150-kW HFT construction and experimental results (UARK)



(a) Constructed *TPT*. (b) Experimental setup . (c) OC and SC Test Waveforms. (d) Thermal image for OC.

Open- (OC) and short-circuit (SC) tests results:

$$L_m \approx 17\text{ mH}$$
$$R_m \approx 14.7\text{ k}\Omega$$
$$L_{lk} \approx 3.5\ \mu H$$
$$R_s \approx 14.7\text{ k}\Omega$$

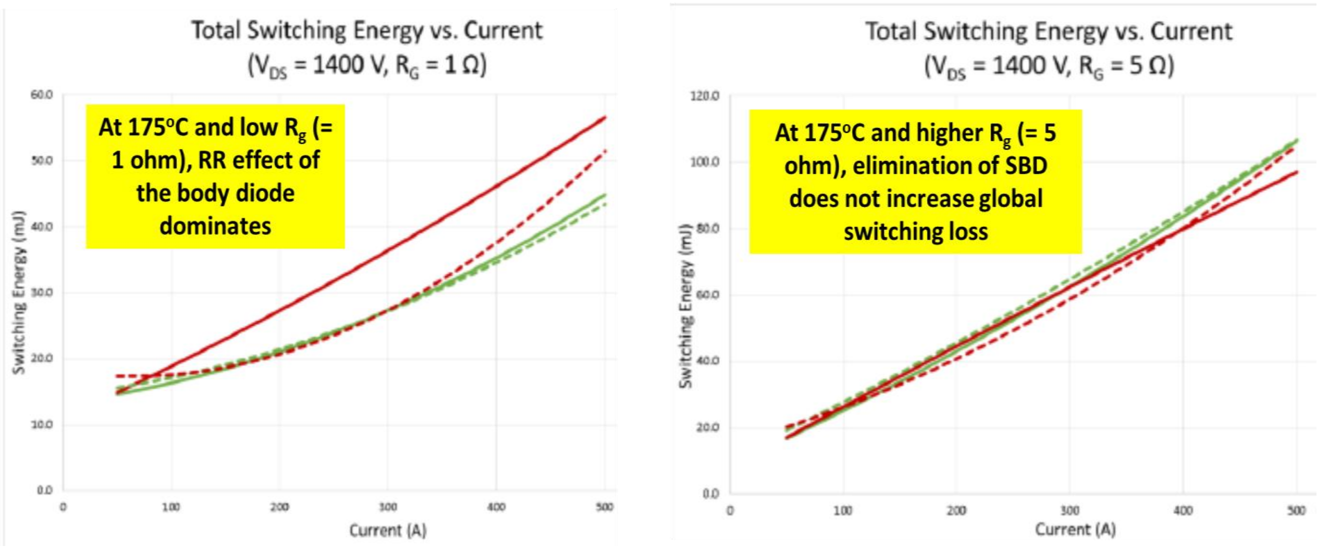
Expected efficiency at rated power using R_m and R_s

$$\eta = 99.86\%$$
$$\Delta T < 60°C$$

Anticipated challenges and risk mitigation strategies (continued)

- **HV SiC MOSFET module currently without antiparallel Schottky diode**
  - HFL-LPT operates at 20 kHz
  - At this speed a slightly slower incoming MOSFET of a HF module appears to show limited performance difference between a SBD-based module and one without it (based on Cree/Wolfspeed's published work – left picture below)
  - SiC JFET cascode is an alternate option (right picture below)

Loss comparison of 1.7 kV SiC MOSFET with/without antiparallel Schottky diode (Cree, APEC'17)



SiC cascoded JFET (United Silicon Carbide)

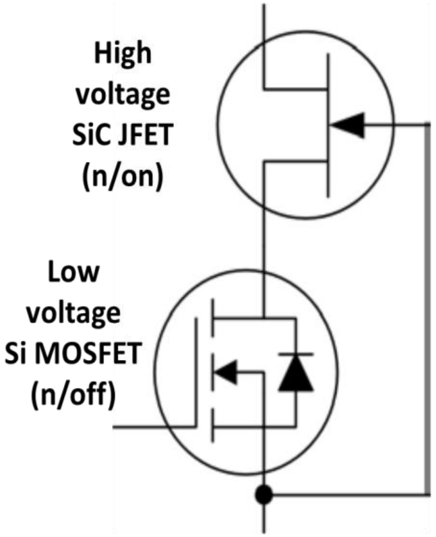
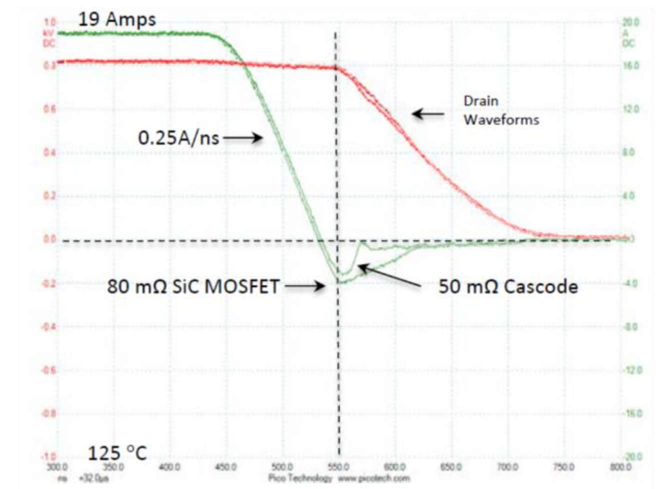


Illustration: QRR Comparison (SiC MOSFET,381Nc vs. Cascode 155 nC)

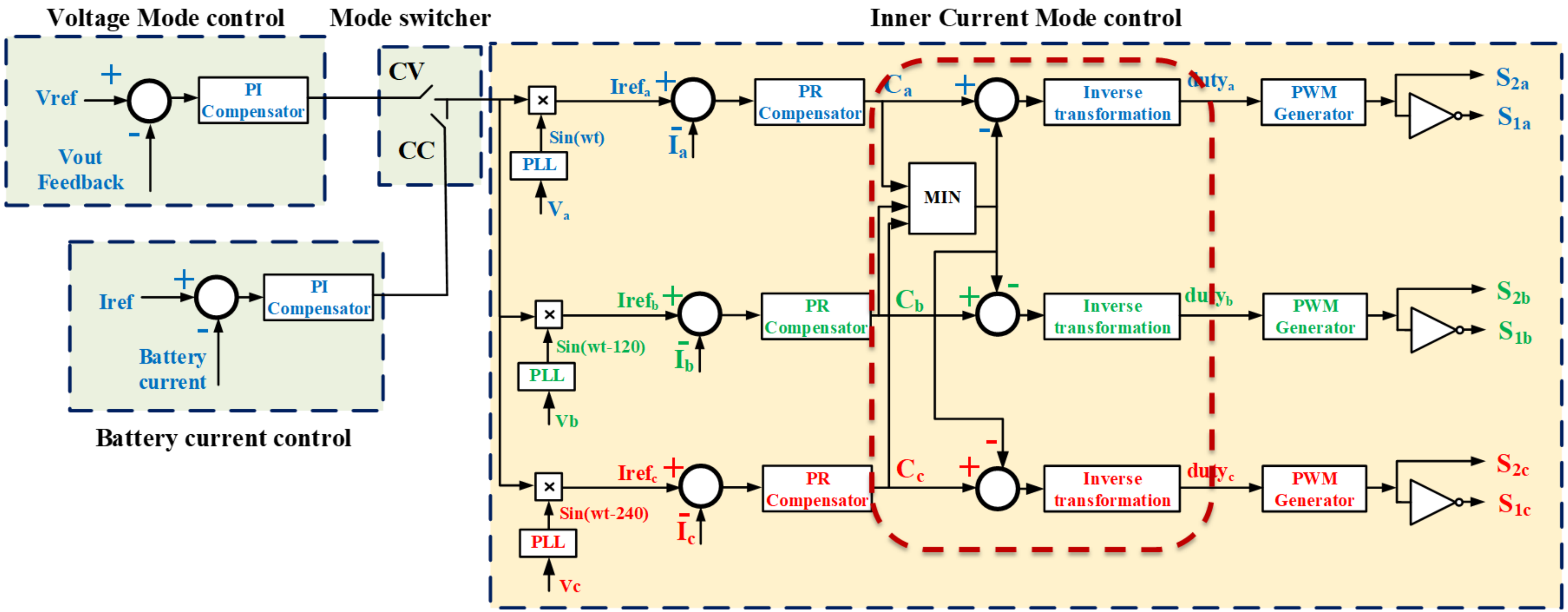


The reverse recovery of the SiC MOSFET is 2.5x that of the cascode, and that is a 50 mOhm cascode solution vs. 80 mOhm MOSFET. Putting QRR in context, a SiC MOSFET's QRR will essentially triple over a 100 °C rise, where a cascode's QRR will increases by only 10%.

Anticipated challenges and risk mitigation strategies (continued)

- **Control to compensate for nonlinearity**
  - A new transformation has been developed that simplifies PR control

A control architecture illustration using an ac/dc that demonstrates how transformation simplifies PRC



Anticipated challenges and risk mitigation strategies (continued)

- **Coordination of HFL-LPT modules**
  - At a switching speed of 20 kHz (i.e., for a period of 50k ns), a fiber-optic-based coordination if needed is expected to be sufficient. Impact of delay on stability will be analyzed.

Next steps

- **Based on the current status of the project, comment on anticipated future actions or activities.**
  - Project has not started yet
  - Once the contract is executed, the broad goals for Year 1 are as follows:
    - Design of the 3-phase HFL-LPT module power stage
    - Design of the 3-phase HFL-LPT module control stage
    - Nanocrystalline HFT design and fabrication
    - Fabrication of the 3-phase HFL-LPT module
    - Experimental characterization of the 3-phase HFL-LPT module

Broader Impact

- **Comment on activities in the project that provides additional value beyond its research findings.**
  - Patent on the novel HFL-LPT innovation expected
  - Journals and conference papers and tutorials (consistent with PIs' past performance)
  - Tech-to-market is a possibility given that an industry advisory team comprising ABB and Eaton is place, a patent is expected, and considering the potential impact of the novel and power-, voltage-, and function-scalable technology
  - Collaboration exists between NextWatt LLC, University of Arkansas and University of Illinois. Additional collaborations with ABB and Eaton expected.

Contact Information

- If attendees have further questions concerning the project, to whom should they direct communications?

  - **Dr. Sudip K Mazumder**
  - President
  - NextWatt LLC
  - sudipkumarmazumder@gmail.com

- What means is best for reaching the project point of contact?
  - E-mail: sudipkumarmazumder@gmail.com

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