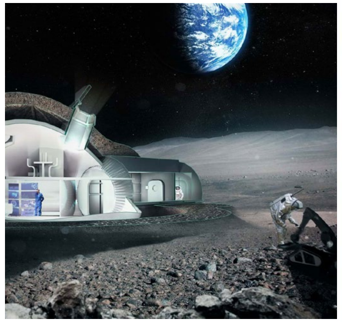
CHPPE Progress Report

May 2022 to November 2023



Dr. Jin Wang

Professor, IEEE Fellow

Center for High Performance Power Electronics

The Ohio State University

Nov, 22 2023

CHPPE

The Ohio State University

College of Engineering

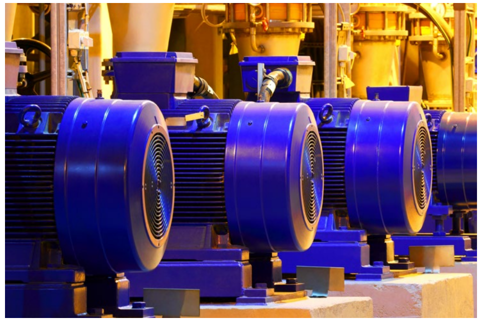
Center for High Performance Power Electronics

Faculty:	5 Core Profs. and 5 Affiliated Profs.
Research scientists/engineers:	6
PhD Students:	35
MS Students	15
Research Expenditures:	>$5 Million/year

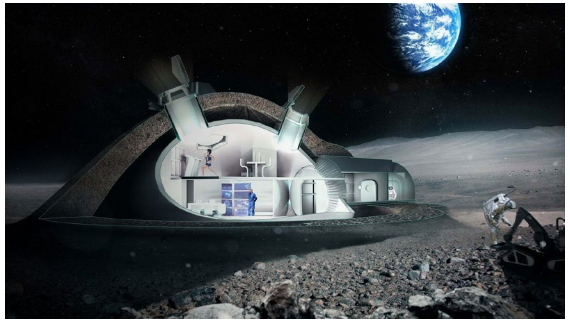
- ❑ Power Semiconductors
- ❑ Power Electronics
- ❑ Electric Machines and Drives
- ❑ High Voltage
- ❑ Power Systems and Smart Grid

Key Application Areas of Research:

- Electrification of transportation: more electric aircrafts, electric vehicles, charging stations…
- Renewable energy integration: solar and wind
- Energy conservation: data centers, industry motor drives, power supplies and drives for home appliance and consumer electronics
- Stationary and mobile microgrids for aerospace, land and sea applications





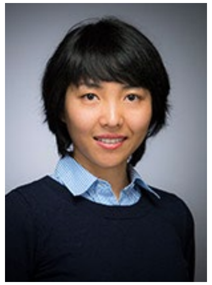


CHPPE Faculty Members

Dr. Jin Wang, Co-founder, Director

Core members:

Dr. Anant Agarwal



Dr. Julia Zhang

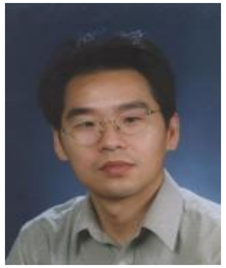
Dr. Mahesh Illindala

Dr. Longya Xu (Founder, Past Director, NAE Member)

Affiliated members:

DR. Matilde D'Arpino

Dr. Siddharth Rajan



Dr. Wu Lu

Dr. Hongping Zhao

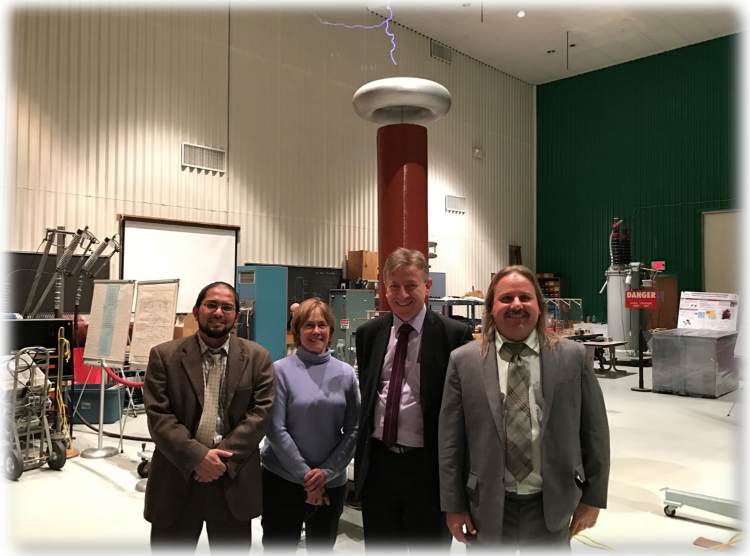
Dr. Ayman Fayed

Good News on Technology Transfer

7-kV 1-MVA Modular Multilevel Converter for Motor Drives

- Based on 1.7-kV SiC devices
- Capacitor size reduction with common mode current injection
- Peak efficiency: 99.3%
- 3 times of loss reduction
- 4 times power density improvement

https://youtu.be/Jz3Ikd734Pc



DoE Visit During the Kick-off Meeting on Mar. 3, 2017

2016-2019
DoE NGEM

POWERAMERICA
2019-2021

From University Research to Industry Product

OSU Research Prototypes

Toshiba North America Product

The first SiC based medium voltage mega-watt industry motor drive product that is manufactured in the United States

Outline

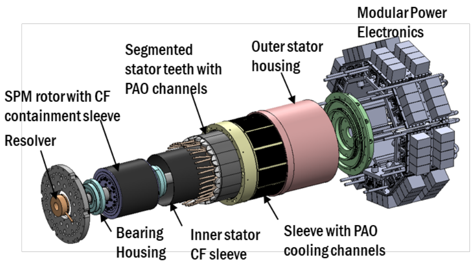
- Examples of Finished Projects and Projects That Are Ending Soon
- 2022-2023 Statistics

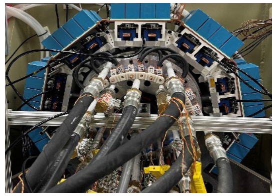
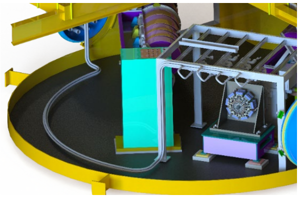
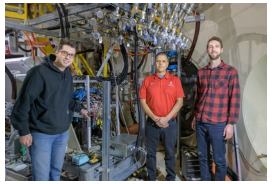
Examples of Finished Projects and Projects That Are Ending Soon

- 2-kV 1-MV ULI Integrated Motor Drive
- Modular Multilevel Converter for Grid-tied Applications with 10-kV SiC Power Modules
- 20-kV 1-MW T-Breaker
- Energy Router for Lunar Microgrid
- Watts on the Moon Challenge

2-kV 1-MVA Integrated Modular Motor Drive for Turbo Electric Aircraft

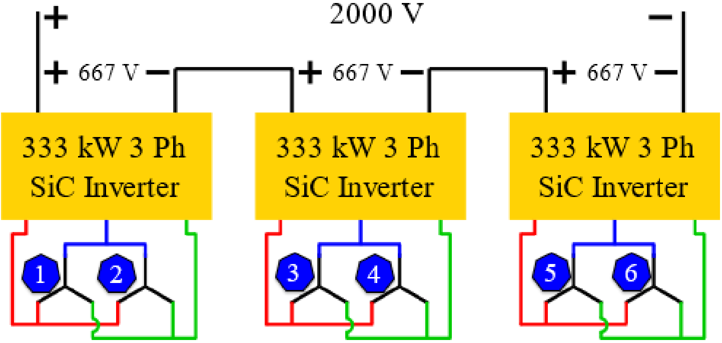
- Modular structure for high fault tolerance and voltage stress reduction
- Partial discharge free at 2 kV
- PAO based in-slot cooling and insulation for the motor



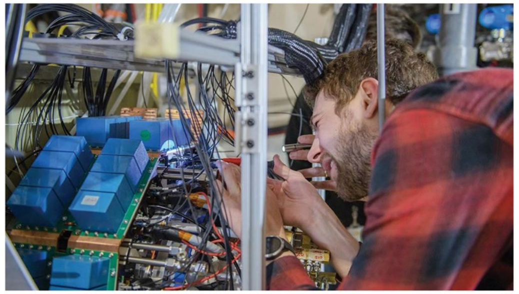
Tests were concluded at NASA's NEAT facility on June 30th, 2023

1 MW Machine Drive Configuration



Megawatt-Class Electric Motor Shown Safe at High Voltage And Altitude

Graham Warwick September 12, 2023



In the Integrated Modular Motor Drive, the power electronics submodules in the blue boxes are mounted directly onto the three-stage motor.

Credit: NASA

Designed mass power density: **9 kW/kg**

Designed volume power density: **13.5 kW/L**

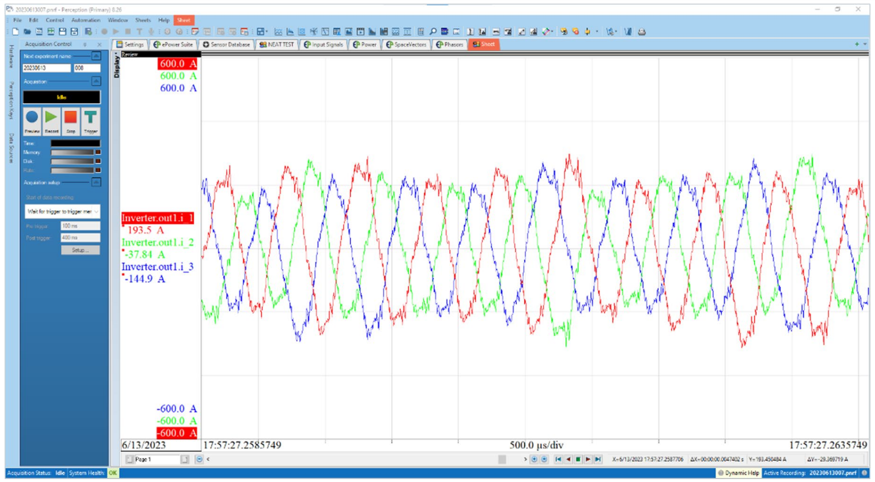
PE designed efficiency: **99%**

IMMD achieved efficiency: **95.8%**

Maximum achieved speed: **20,000 RPM**

Maximum achieved power: **258 kW, 333 kVA**

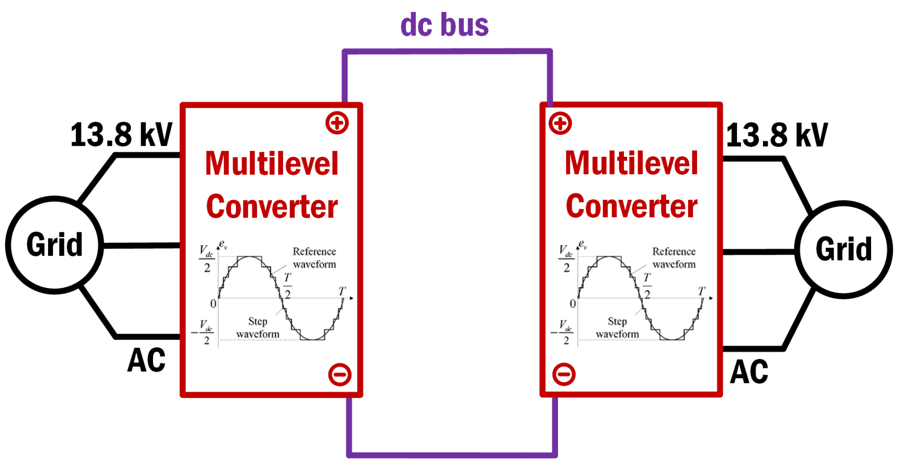
Partial discharge free: **2-kV at 87 torr**



Current waveforms at 19,000 RPM, 124 N m, 258 kW

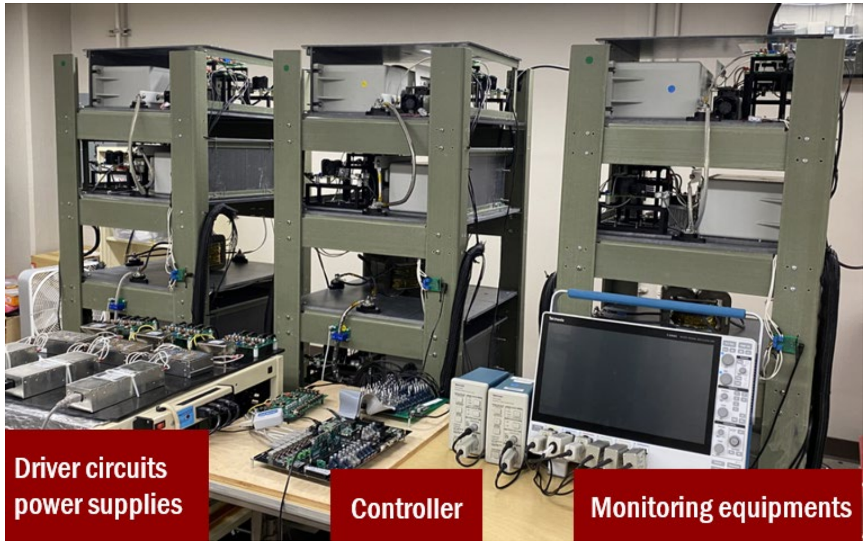
Back-to-back MMC with 10-kV SiC for Synchronization of AC Grids

This project aims to develop a back-to-back multilevel converter as the interface between two asynchronous 13.8 kV AC grids utilizing 10 kV SiC power modules.



Medium Voltage Back-to-back System

10 kV SiC Power Module



OSU Three-phase MMC with 10-kV SiC Power Modules.

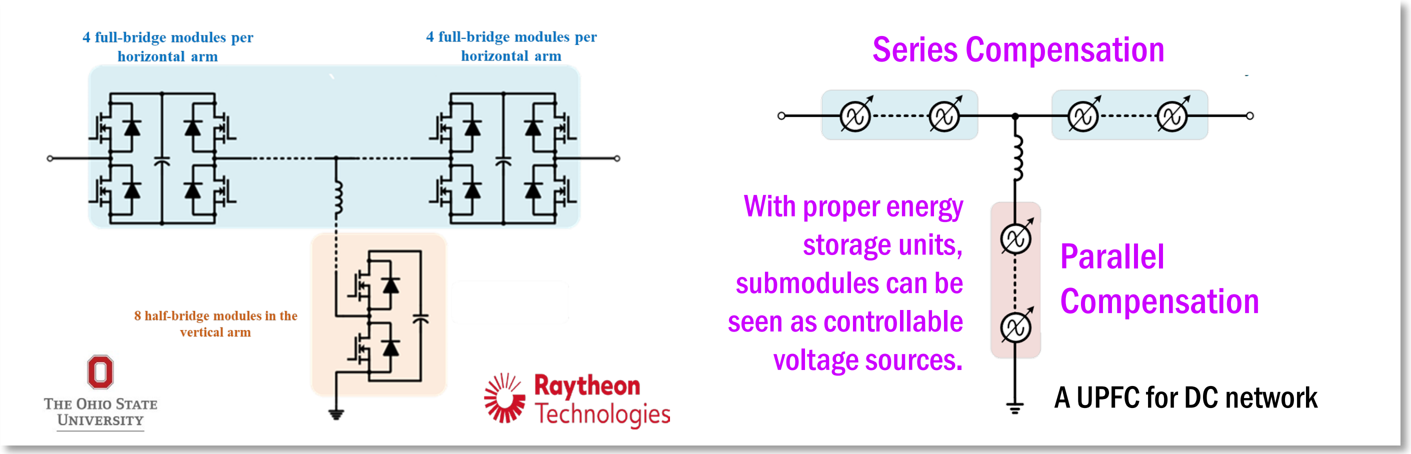
The OSU Three-phase Reconfigurable MMC with 10-kV SiC devices were delivered to NREL, reassembled, and fully tested in September 2023. Back-to-back tests with FSU MMC is planned in December 2023.

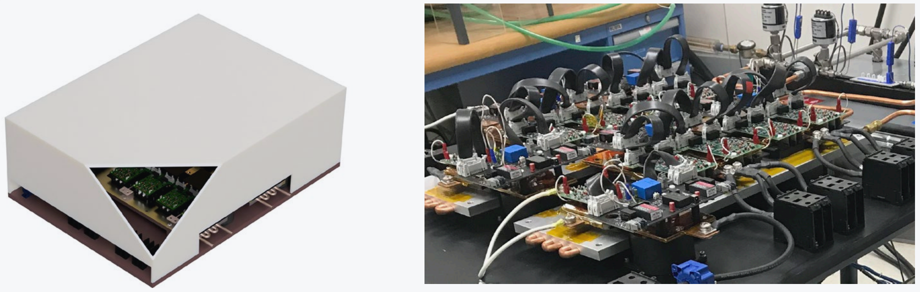
U.S. DEPARTMENT OF ENERGY | NREL Transforming ENERGY | The Ohio State University | Florida State University 1851

20-kV T-Type Modular DC Circuit Breaker (T-Breaker) for Future DC Networks

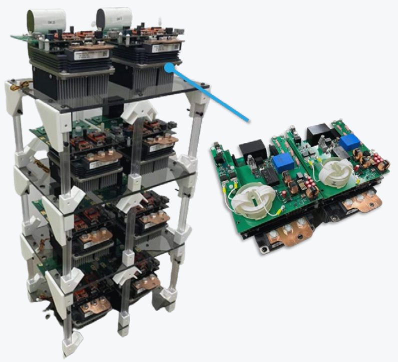
- A 20-kV solid state circuit breaker with 500-A breaking capability based on 3.3-kV SiC power modules
- 60.2 MW/m^3 active power density;
- 99.977 % measured efficiency
- Unmatched ancillary functions
- High immunity towards control signal misalignments

arpa·e
CHANGING WHAT'S POSSIBLE

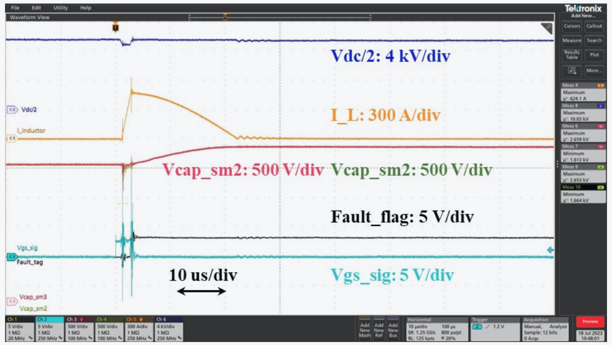




1-kV 500-A Prototype, built at OSU, tested at RTRC

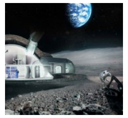


One tower of the 20-kV prototype



Breaking a 500-A fault current at 20 kV

The validation of the T-Breaker concept has led to a new energy router project for microgrids on the lunar surface.

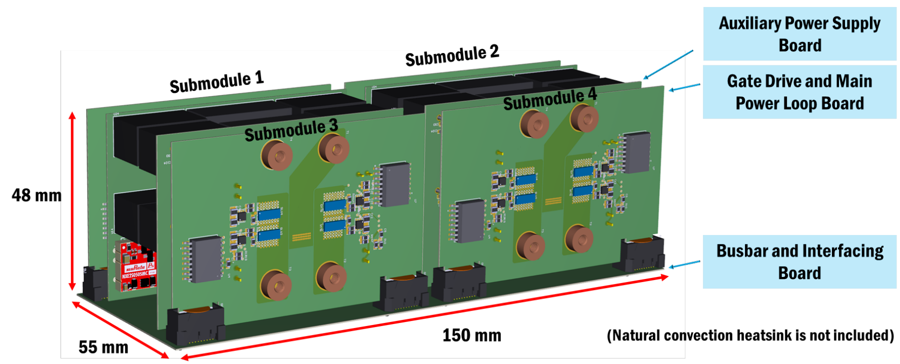


NASA

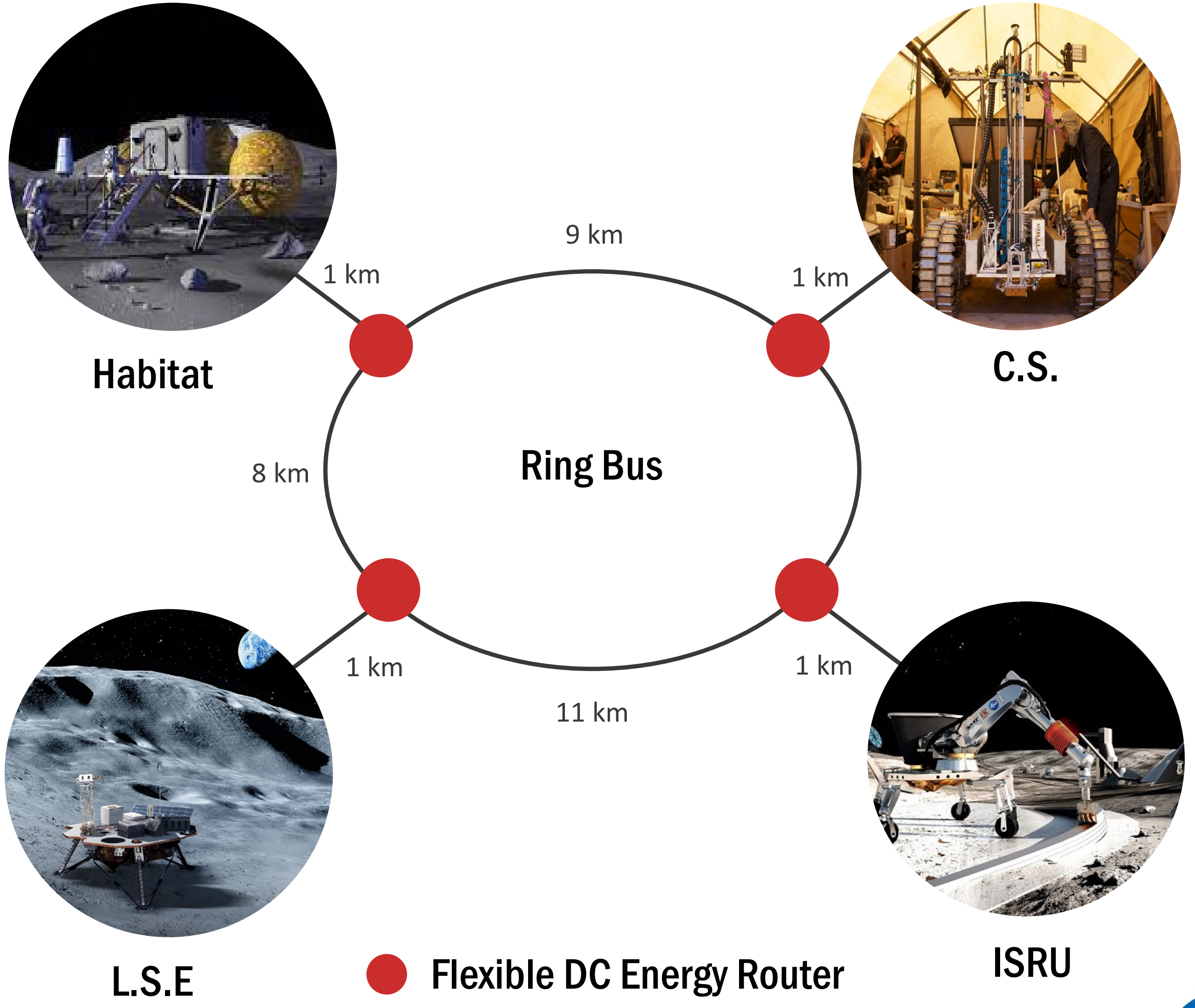
NASA LuSTR: Lunar DC Microgrid with Flexible DC Energy Router

Lunar microgrids interconnected in a ring architecture with Flexible DC Energy Routers

Microgrid	Rating
MG1: Habitat	20 kW
MG2: Charging Stations (C.S.)	2 kW
MG3: In-Situ Resource Utilization (ISRU)	60 kW
MG4: Lunar Science Experiments (L.S.E.)	5 kW



Flexible DC Energy Router



Demonstration of the project is scheduled on Nov. 30th, 2023 .

Watts on the Moon - A NASA Challenge for the Near Future

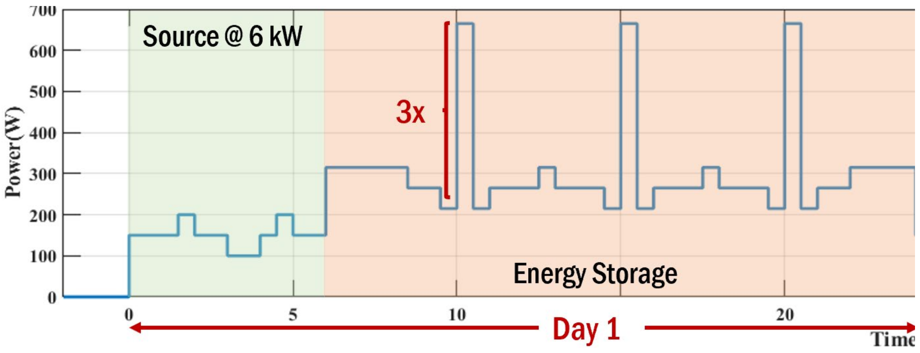
The Challenge

- Transfer 1.5 kW power over 3 km on the moon surface
- The total weight of the power conversion, energy storage and transmission system needs to be lower than 150 kg

Specifications

- Power source voltage: 120 V
- Load voltage: 24-32 V
- Ambient condition: 77 K and 10-3 Torr

Operation Profile



(2 days, 48 hrs, Day2 identical to Day1)

Grand Prize: $1 M

Electric Moon: An OSU Student/Faculty Team

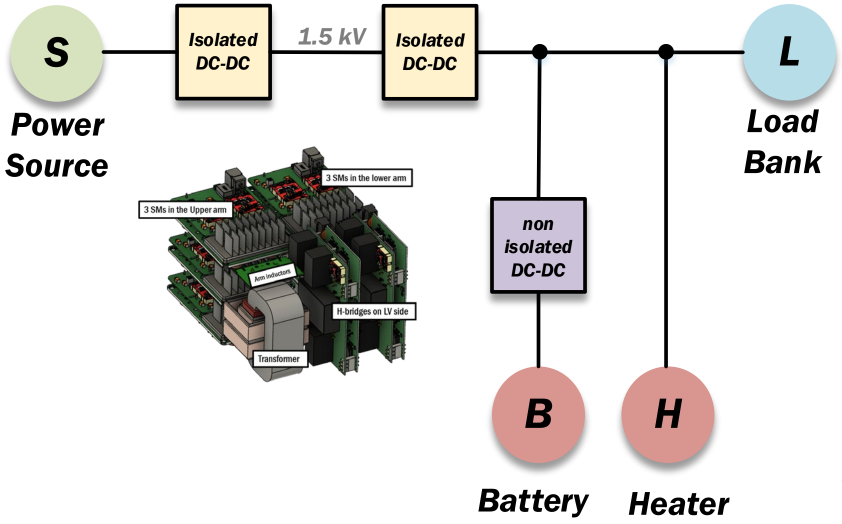
Solution and Approaches by the Electric Moon Team

- 1.5 kV high voltage dc transmission with modular multilevel converter based dc/dc converters
- GaN GIT and Nanocrystalline based converter and transformer designs
- LiFePO4 batteries with multi-layered thermal insulation

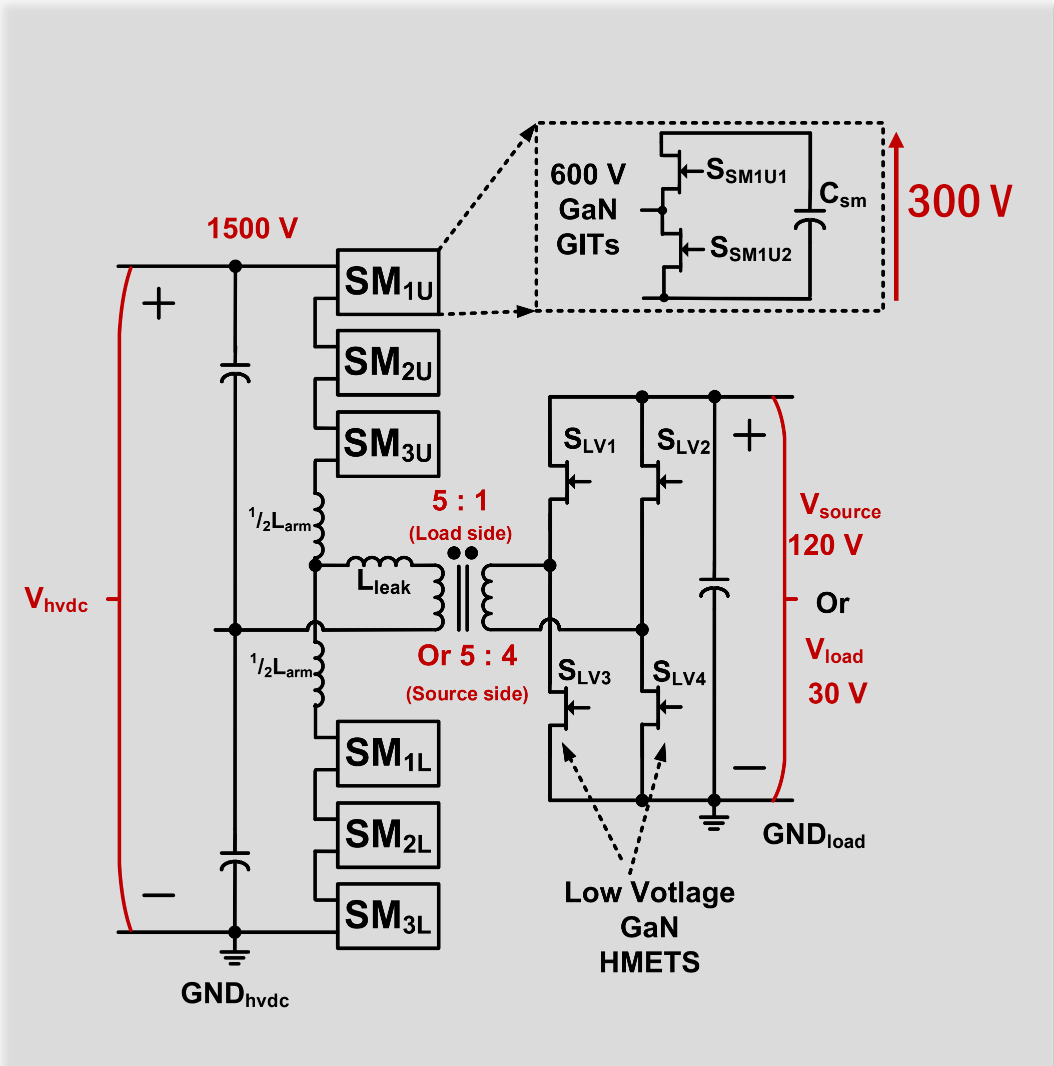
Expected Total Weight and Converter Efficiency

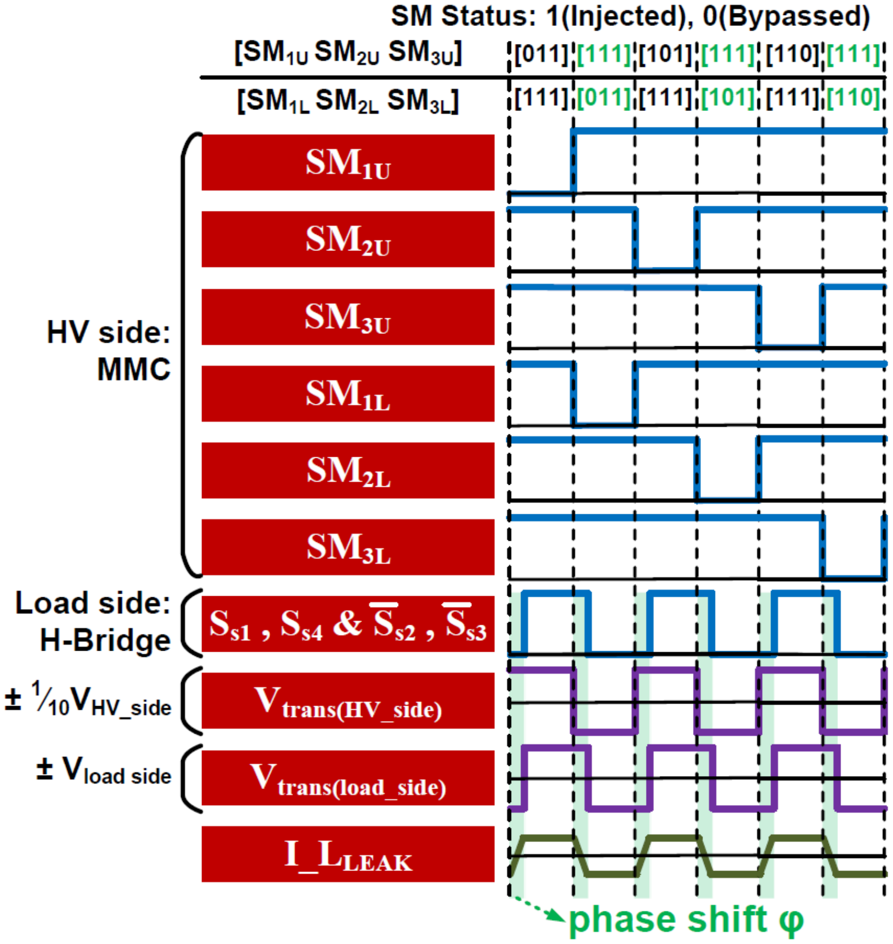
- Total weight: 77.61 kg
- Converter efficiency: 97.7%

System Architecture



Topology of the Isolated Dc/dc Converters and Its Operation Principle





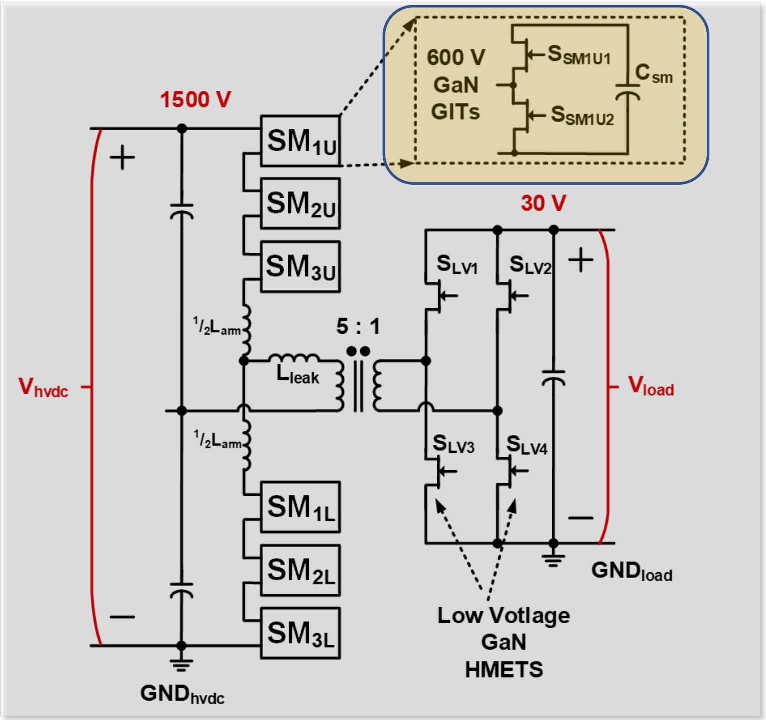
- 66.7-kHz phase shifted SMs
- 200-kHz switching at low voltage side
- 10:1 Step down before transformer
- 1:3 frequency multiplication

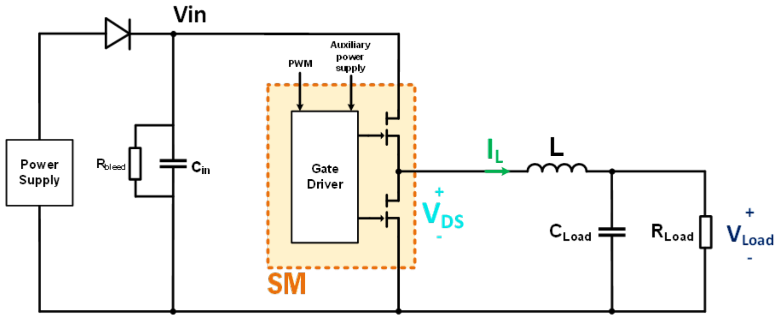
D. Xing, X. Li, Y. Zhang, Q. Cheng, Z. Zhang, B. Hu, A. Agarwal, J. Wang, "MMC-Based High Gain Solid-State Transformers for Energy Storage Applications," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1996-2002, doi: 10.1109/APEC42165.2021.9487233.

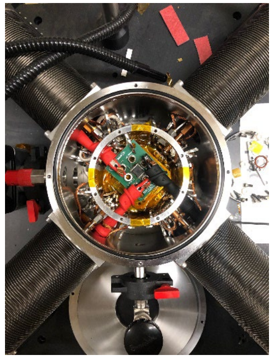
Submodule Demonstration on March 30th 2023

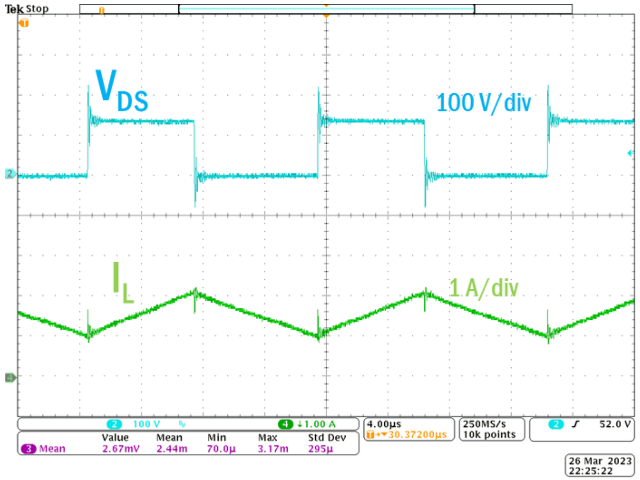
- A submodule (SM) of the isolated dc/dc converter was tested in a vacuum chamber at the cryogenic temperature.
- The SM was controlled to operate as a buck converter in this demonstration.

	Required conditions in Level 3	Test conditions in the chamber
Temperature	77 K	77 K
Pressure	$< 10^{-3}$ Torr	$< 10^{-6}$ Torr



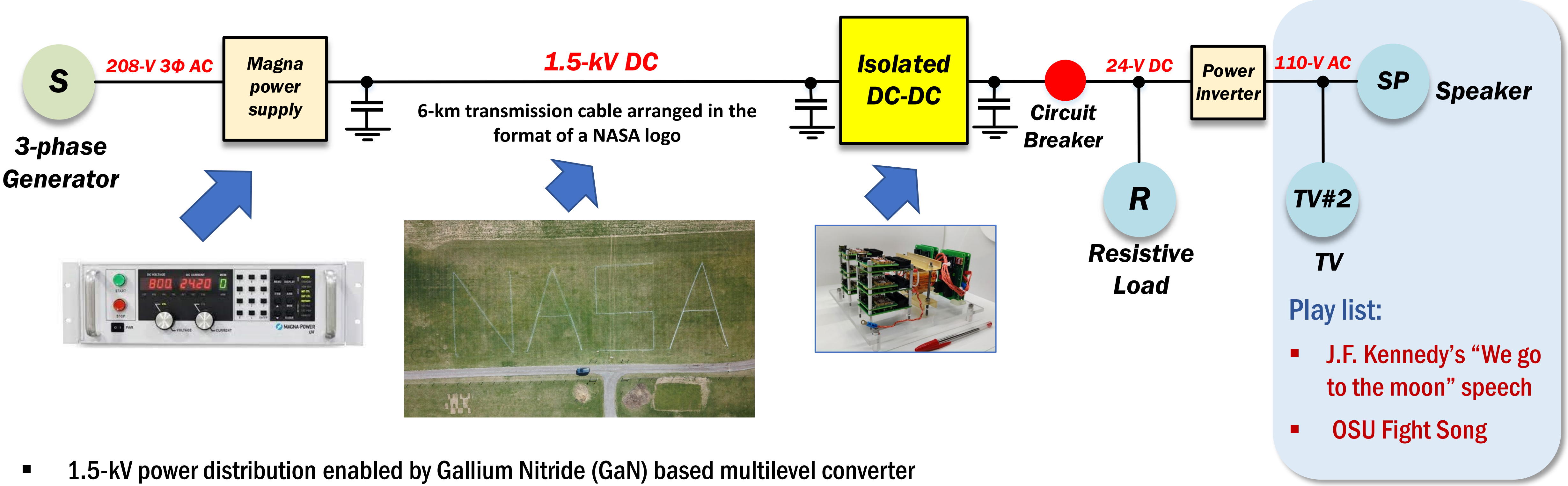






The Ohio State University

Electric Moon Team System Demonstration on March 30th 2023



- 1.5-kV power distribution enabled by Gallium Nitride (GaN) based multilevel converter
- 3-km transmission with 6-km long cables (AWG 22 3.3 kV rated)
- A combination of loads including resistor loads, a TV, a speaker, etc.
- Efficiency of the isolated dc/dc converter: >97%

THE OHIO STATE UNIVERSITY

[Video of the public demonstration]

"We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard." - J. F. Kennedy

2022-2023 Progresses In General

- **Research Focuses and New Initiatives**
- **Newly Contracted Projects**
- **Publications and Awards**
- **Graduated Students**

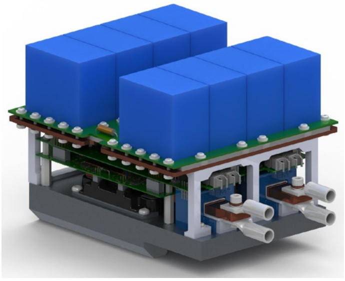
Research Focuses and New Initiatives

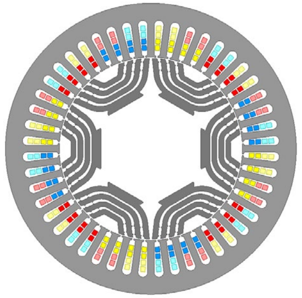
Devices

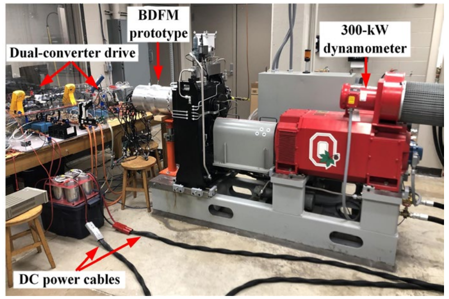
- High voltage WBG and U-WBG power devices
- Screening methods for SiC devices

Circuits and Systems

- Radiation hardened cryogenic circuits in vacuum
- Liquid metal-based cooling
- High speed electric machine design and control
- Partial discharge with high dv/dt PWM
- Circuits with bi-direction switches

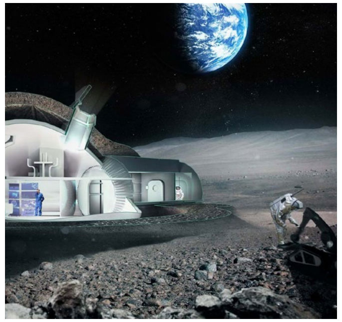






Applications

- Medium and high voltage power converters for utility applications
- UAVs and megawatt electric propulsion systems for aircraft
- Power distribution on lunar surface



New Federal Projects Started after May 2022

Solid State Material and Devices

Sponsor	OSU Lead	Topic
NSF	Ayman Fayed	Semiconductor Work Force Training
DoD	Ayman Fayed	System on Chip
AFSOR	Hongping Zhao	Ultrawide-band-gap LiGaO2 for Extreme Environment
NSF	Hongping Zhao	High Voltage Ultra-widebandgap Transistors for Utility Applications
ONR	Hongping Zhao/WU Lu	Vertical High Voltage GaN
ARPA-E Ultrafast /UCSB	Jin Wang (OSU Lead)	20-kV Light-controlled Ga_2O_3

New Federal Projects Started after May 2022

Circuit, Electric Machine, System

Sponsor	OSU Lead	Topic
ARPA-E	Julia Zhang	Vehicle Traction Electric Machines
DoE/SBIR	Mahesh Illindala	Real-time Simulation Tool for Grid-tied Power Electronics
US Airfoce/STTR	Mahesh Illindala	Integrated Liquid Hydrogen Energy Systems for Long Range UAV
US Army	Mahesh Illindala	UAV Liquid Hydrogen Autonomous Refueling System
DoD	Matilde D’Arpino	Battery Optimization for Air Force Ground Electric Vehicles
DoT	Matilde D’Arpino	Battery Report for Electrified Transit Activities and Services
NASA/SBIR	Jin Wang	Cable for Lunar Applications
AFRL/UES	Jin Wang	Partial Discharge Studies for UAV
NASA	Jin Wang/Wu Lu	Watts on The Moon Challenge (Phase II, III)
DoE/Sandia	Jin Wang	Semiconductor based Galvanic Isolation with Bi-direction Devices

New Industry Projects Started After May 2022

Sponsor	OSU Lead	Topic
Ford	Anant K. Agarwal	SiC Reliability
Lucid Motor	Anant K. Agarwal	SiC Devices
II-VI Foundation	Anant K. Agarwal	SiC Devices
Boeing	Julia Zhang	Integrated Starter and Generator
Grainger	Julia Zhang	Surrogate model of PM Machines with AI
Mahesh Illindala	Caterpillar	Resilient Inverter Control

Publications and Publication Awards

Publications from May 2022 to November 2023:

62 conference papers 27 journal papers

Publication Awards

Manmeet Singh and Ayman Fayed , IEEE Tran. on Power Electronics Second Place Prize Paper Award for the paper titled "*A 1-A 6-MHz Digitally Assisted Buck–Boost Converter With Seamless Mode Transitions and Fast Dynamic Performance for Mobile Devices, " in IEEE Transactions on Power Electronics, vol. 36, no. 4, pp. 4338-4351, April 2021*

Junchong Fan , Zhining Zhang, Siddhant Shah, Jin Wang, and Anant Agarwal, Best Paper on Components, at the AIAA/IEEE Electric Aircraft Technologies Symposium 2023 for the Paper Titled "*Development of Ultra High Power Density Liquid Metal Cooled Inverter*"

Junchong Fan , Best Student Paper, at the AIAA/IEEE Electric Aircraft Technologies Symposium 2023 for the Paper Titled "*Development of Ultra High Power Density Liquid Metal Cooled Inverter*"

Faculty Awards

Ayman Fayed, Best Associate Editor (2022-2023), IEEE Transactions on Circuits and Systems I

Ayman Fayed, IEEE Circuits & Systems Society Outstanding Technical Committee Award, Analog Signal Processing Technical Committee, 2022

Matilde D'Arpino, The Ohio State University Lumley Research Award, 2022

Jin Wang, IEEE Power Electronics Emerging Technology Award, 2022

Faculty Recognition

Prof. Longya Xu was elected to become a member of the National Academy of Engineering in 2022

"for contributions to high-performance electric machines and variable-speed drives for aerospace and wind turbines."

Graduated Masters Students

Master Students	Current Affiliations
Zach Adamson	Air Force Research Laboratory
Naeem Bharmal	BorgWarner
Qianyi Cheng	Delta Electronics
Kyungjoong Kim	Hyundai Motor Company
Jesse Zhang	Microchip Technology Inc.
Alex Schnabel	National Renewable Energy Laboratory
Chaoyi Chien	Onsemi
Can Cao	OSU Ph.D. Candidate
Michael Nye	OSU Ph.D. Candidate
Rob Borjas	OSU Ph.D. Candidate
Peiwen Jiang	OSU Research Technician
MD Hadiul Islam	SLB
Gurpreet Singh	Stellantis
Siddhant Shah	TDK-Lambda Americas

14 Masters Students Graduated between May 2022 and November 2023.

Graduated Ph.D. Students

Doctoral Students	Current Affiliations
Xiao Li	Apple
Karthikeyan Subramaniam	Eaton
Yuxuan Zhang	Finwave Semiconductor, Inc
Tianshi Liu	Ford
Shengnan Zhu	Ford
Balaji Guddanti	GE Energy Consulting
Ye Cheng	GM
Khalid Alkhalid	King Saud University
Faisal Alsaif	King Saud University
Vishank Talesara	Navitas Semiconductor
Sree Subiksha Madhavan Reshikeshan	Shell
Tanner Tengberg	Texas Instruments
Utsav Gupta	Texas Instruments
Junao Cheng	Texas Instruments
A F M Anhar Uddin Bhuiyan	University of Massachusetts Lowell

15 Ph.D. Students Graduated between May 2022 and November 2023.

CHPPE Sponsors

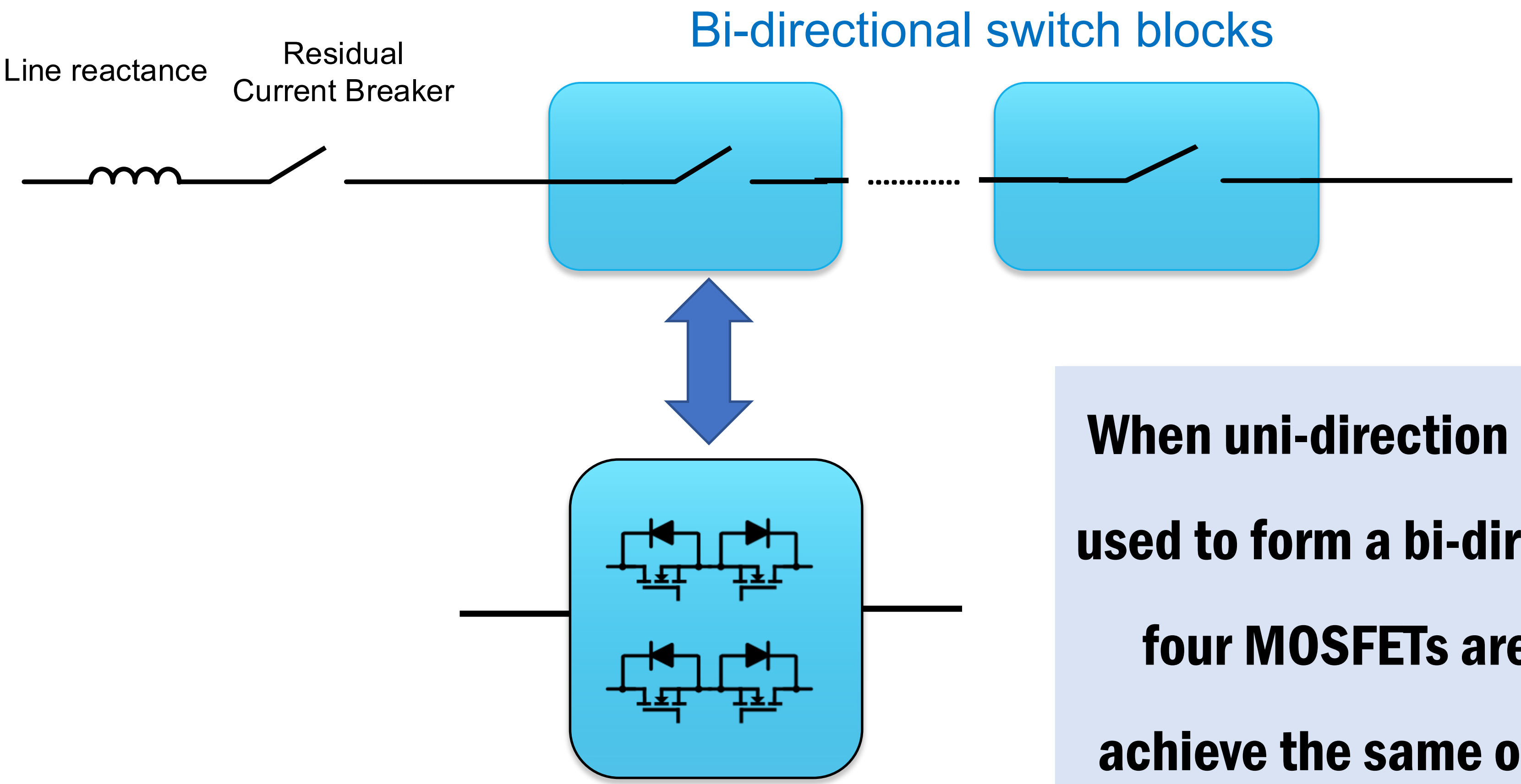
Thank you for your attention!

Questions?

Contact: Prof. Jin Wang

wang.1248@osu.edu

Bi-direction Switches in Solid State Circuit Breakers



When uni-direction MOSFETS are used to form a bi-direction switch, four MOSFETs are needed to achieve the same on resistance.

The 4:1 ratio needs to be solved with new monolithic bi-direction switching devices .

Efficiency Requirements for Inverters for Electric Vehicles

		2020	2025	2035
Inverter Indicators	Cost ($/kW)	3.5	2	1.7
	Volumetric Power Density (kW/l)	17	25	35
	Gravimetric Power Density (kW/kg)	13	20	25
	WLTP Average Efficiency	93%	95%	97%

UK Automotive Council (Power Electronics Roadmap 2020)[1]

		2020	2025
Inverter	Cost ($/kW)	8	6
	Power Density (kW/L)	4.0	33
	Peak efficiency	97%	98%

US DOE (Electrical and Electronics Tech Team Roadmap)[2]

[1] https://www.apcuk.co.uk/wpcontent/uploads/2021/09/https www.apcuk .co .uk app uploads 2021 02 Exec-summary-Technology-Roadmap-Power-Electronics-final.pdf
[2] https://www.energy.gov/eere/vehicles/articles/us-drive-electrical-and-electronics-technical-team-roadmap

Efficiency of PV Inverters and Desired Efficiency for Circuit Breakers

PV Inverter Type	Highest CEC Efficiency [1]	Example[1]
Transformer-less PV Inverters	99%	SMA America, Sunny Highpower PEAK3, 150 kW, 1500 VDC, 600 VAC, 3-phase
Transformer-isolated PV Inverters	98.5%	NEXTRACKER, 3340 kW, 800 Vac Grid Support Power Conversion System with a 3340 kVA liquid-immersed distribution transformer

[1] https://solarequipment.energy.ca.gov/Home/InverterSolarList

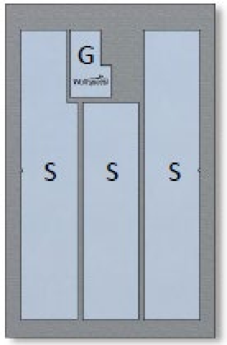
Desired Efficiency of Circuit Breakers

ARPA-E: ≥99.97 (1 kV to 100 kV, ≥1MW)

NASA Advanced Air Transport Technology (AATT) Program : 99.3% (800 V), 99.5% (1 kV), 99.97 (>2 kV)

Asmall efficiency difference between 99% to 99.97% means a 33 times of power loss reduction. At 1 MW, this means from 10 kW to 0.3 kW.

A 200-KW Inverter Reference Design



1200 V, 16 mΩ, GEN III
SiC Bare Die

https://www.wolfspeed.com/1200v-bare-die-silicon-carbide-mosfets-gen3/

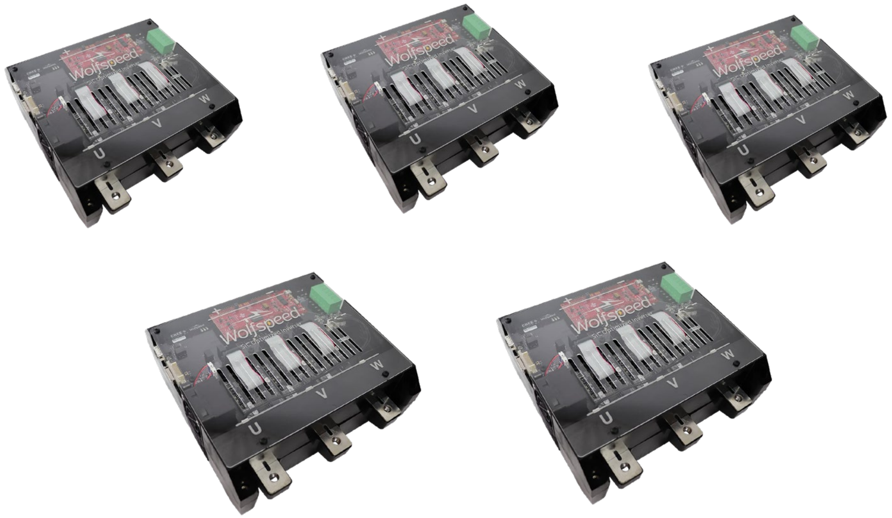
1200 V, 4 mΩ, XM3, Half-Bridge
SiC Power Module

Potentially <u>4</u> SiC bare dies
per switch position

200 kW Liquid Cooled Inverter with
XM3 power modules

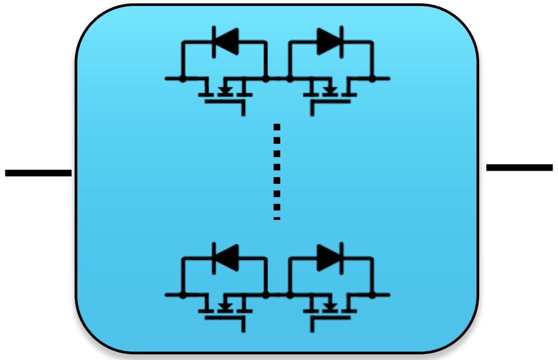
Potentially <u>24</u> SiC bare dies
for the inverter

Comparison with SSCBS



Five 200 kW Liquid Cooled Inverters to form a 1-MW system.

At least 120 SiC bare dies are needed for one 1-MW 3-phase inverter with an efficiency of 99%



- 1200 V rated SiC ac switches in parallel for 800-V 1-MW SSBC
- 28.8 mΩ per die at 175 ° C

1-MW 800-V Circuit Breaker			
Efficiency	99%	99.5%	99.97%
Power Loss (W)	10000	5000	300
Number of SiC Dies	18	38	**602**

- The total die area of a SSBC would be 5 times larger than a same power rated dc/ac inverter.
- Monolithic bi-directional switches and ancillary functions would make SSCBs more feasible.