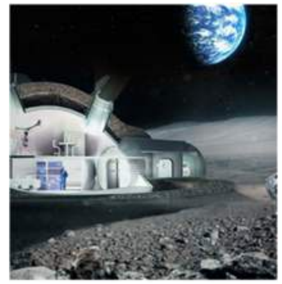
A Discussion on Power Electronics for Lunar Applications



Dr. Jin Wang

Professor, IEEE Fellow
Center for High Performance Power Electronics
The Ohio State University

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SPW | April 21-23, 2026
Torrance Marriott Redondo Beach Hotel | Torrance | CA

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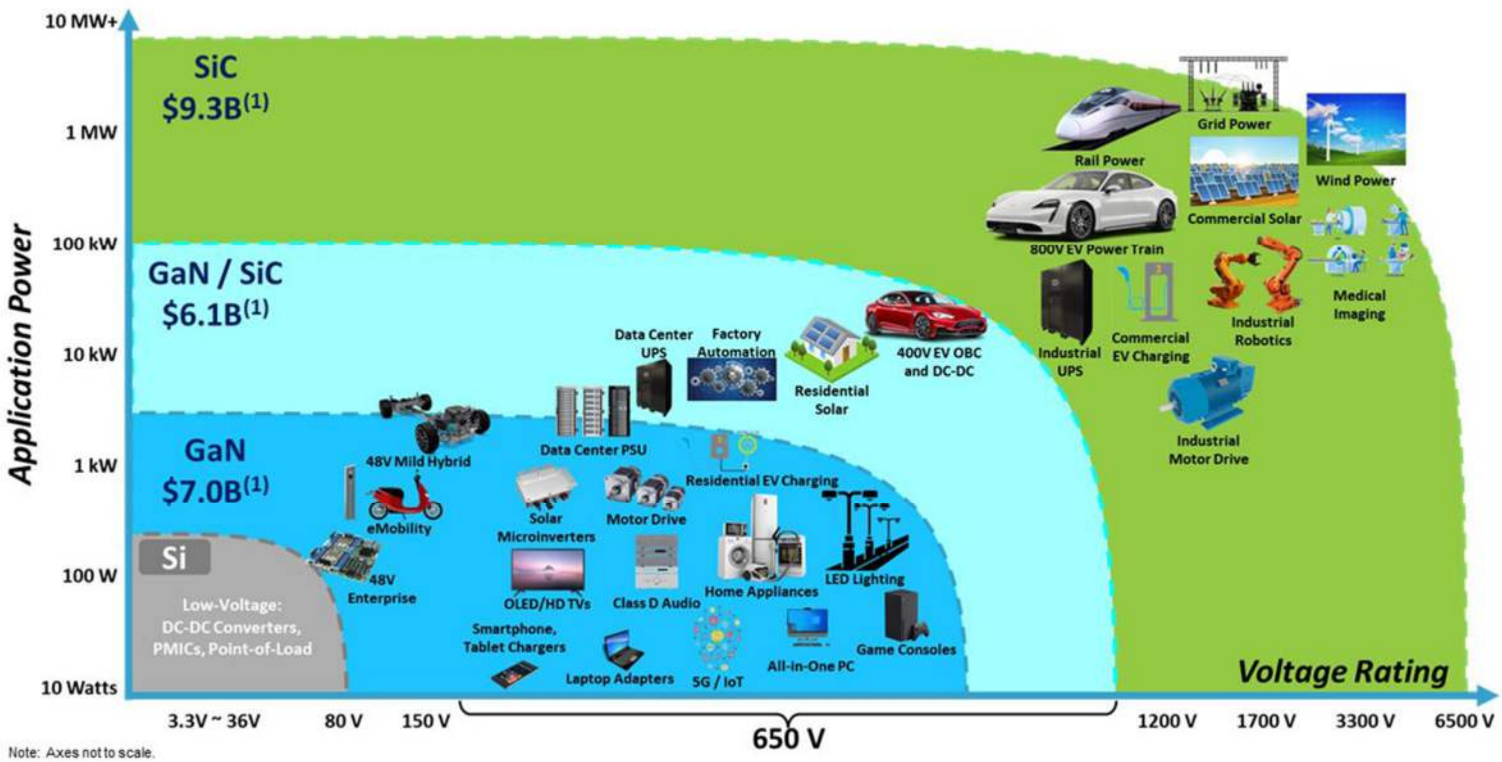
Applications of Power Electronics



Power electronics powers on every aspects of our lives.

Picture Source: Navitas Semiconductor

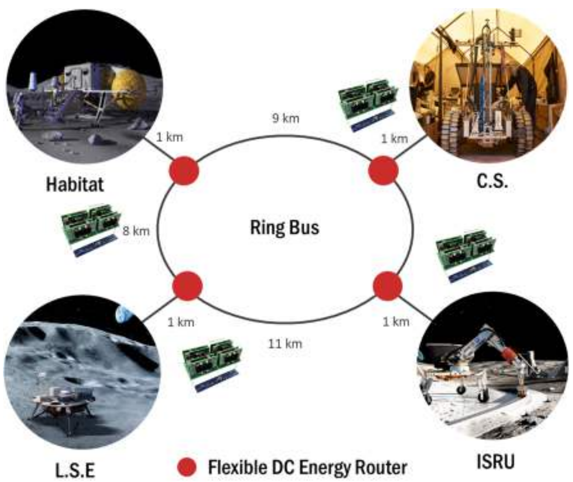
No major new circuit topology has appeared after the MMC was invented by Dr. Rainer Marquardt around 2003.

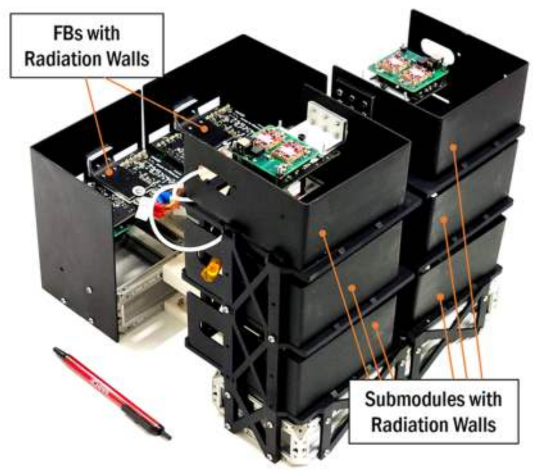
In the last three decades, Power Electronics innovations have been driven by new material, new devices, and new applications.

Space: Final Frontier for Power Electronics

OSU's Research Efforts:

- NASA LuSTR: Lunar DC Microgrid with Flexible DC Energy Router
- NASA Watts on the Moon: Electric Moon: GaN based multilevel converter for lunar power transmission





https://www.newyorker.com/news/the-lede/what-will-the-artemis-ii-moon-mission-teach-us

Outline

- GaN based multilevel converter for lunar power transmission
- A discussion on power architecture for lunar power transmission

Watts on the Moon - A NASA Challenge

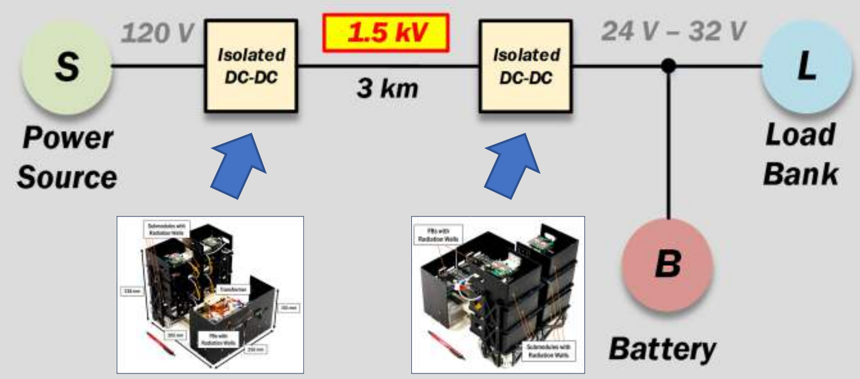
The Challenge

- Transfer 1.5 kW power over 3 km on the moon's surface.
- The total weight of the power conversion, energy storage and transmission system needs to be lower than 150 kg.
- Operate in the cryogenic and vacuum conditions.

Specifications

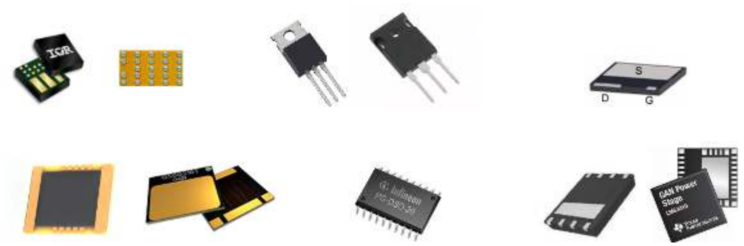
- Power source voltage: 120 V
- Load voltage: 24-36 V
- Ambient condition: -196 °C (77 K) and 10^{-3} Torr

Proposed Solution



High Voltage Transmission with Modular Multilevel Isolated DC/DC converters

GaN Devices Under Heavy-Ion Radiation



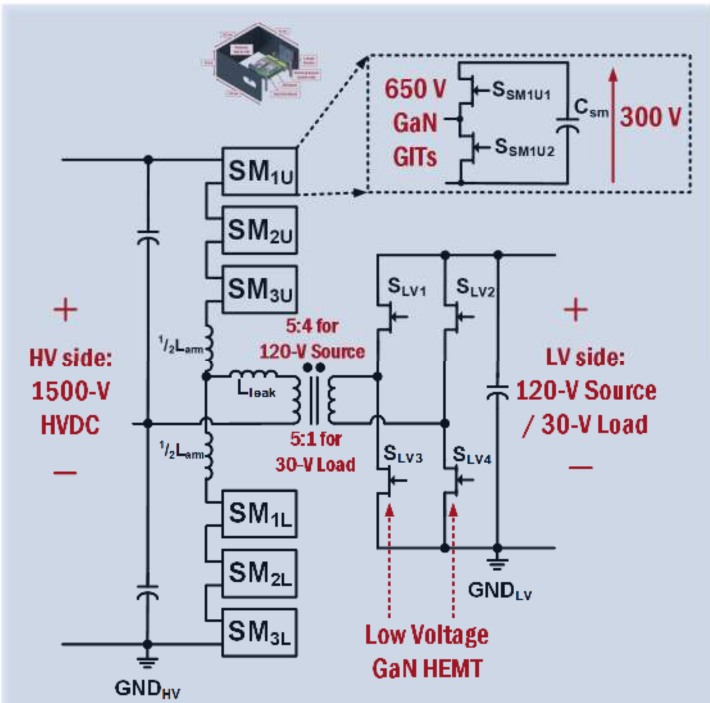
Part number	$V_{DS,max}$ (V)	Manufacturer	Ion	V_{Pass} (V)	V_{Fail} (V)
EPC2001C	100	EPC	Xe	100	–
EPC2012C	200	EPC	Xe	200	–
GS61008P	100	GaN System	Xe	90	–
PGA26E19I	600	Panasonic	Xe	300	350
PGA26E19I	600	Panasonic	Rh	350	375
IGOT40R07	400	Infineon	Xe	350	400
IGOT40R07	400	Infineon	Rh	375	375

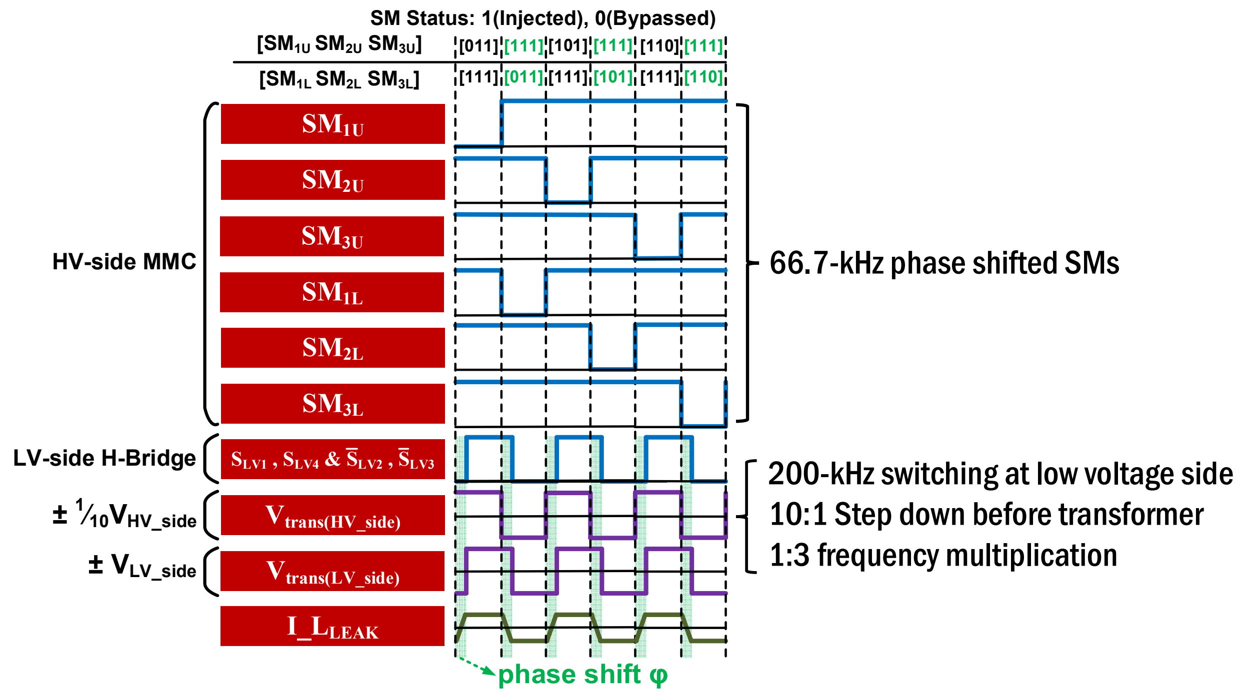
- Recently, Gallium Nitride (GaN) High-electron-Mobility Transistors (HEMTs) and Gate Injection Transistors (GITs) have been evaluated against heavy ion radiation [1, 2].

- Test results show that lower voltage rated (≤200 V) Gan HEMTs can pass radiation tests at their rated voltages. But for devices rated at 600 V, single event burnouts (SEBs) occurred at a voltage as low as 350 V.

[1] J. -B. Sauveplane et al., "Heavy-Ion Testing Method and Results of Normally OFF GaN-Based High-Electron-Mobility Transistor," in IEEE Transactions on Nuclear Science, vol. 68, no. 10, pp. 2488-2495, Oct. 2021
[2] E. Mizuta et al., "Single-event damage observed in GaN-on-Si HEMTs for power control applications," IEEE Trans. Nucl. Sci., vol. 65, no. 8, pp. 1956–1963, Aug. 2018.

Proposed Bidirectional Modular Multilevel Converters

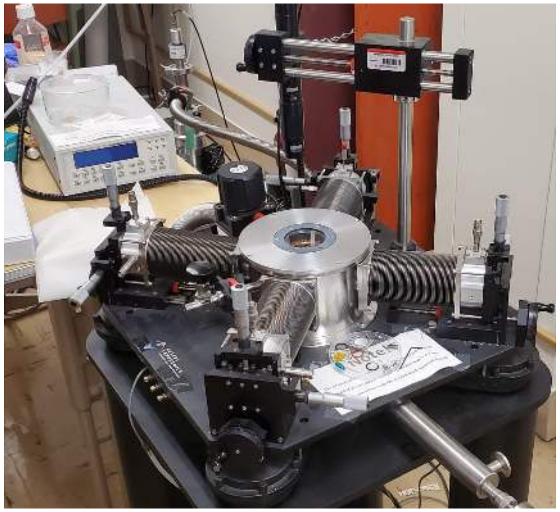




Key Features:

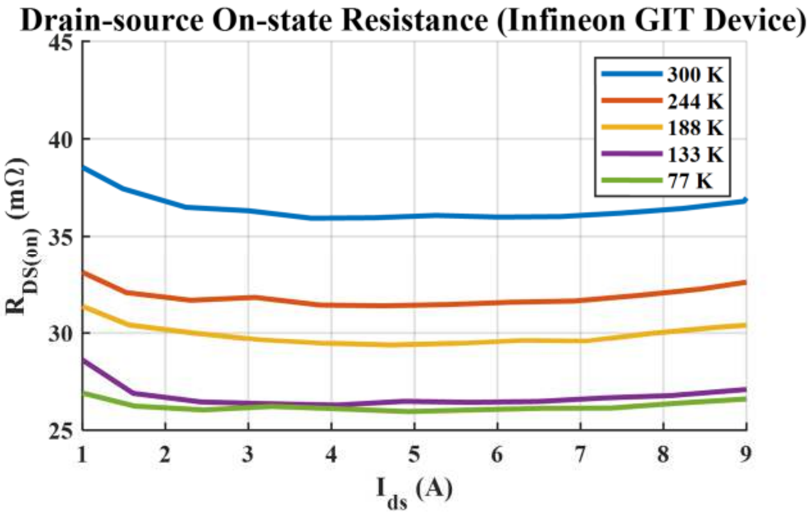
- ❑ High step-up/down voltage ratio (1500:150 V before transformer)
- ❑ Reduced voltage stress of switching devices (300-V on each device), enable using 350-V radiation-hardened GaN devices
- ❑ Frequency multiplication (200-kHz transformer operating frequency and 67-kHz switching frequency)

Cryogenic and Vacuum Evaluation for 650-V GaN GIT Device



The probe station is cooled by liquid nitrogen

Test conditions in the probe station	
Temperature	77 K
Pressure	$< 10^{-6}$ Torr



- GaN GIT device has the capability to operate under cryogenic with stable threshold voltage and breakdown voltage.
- On-state resistance reduced from 36 mΩ at 300 K to 26 mΩ at 77 K due to increased electron mobility at lower temperatures.

Transformer Core Material Selection

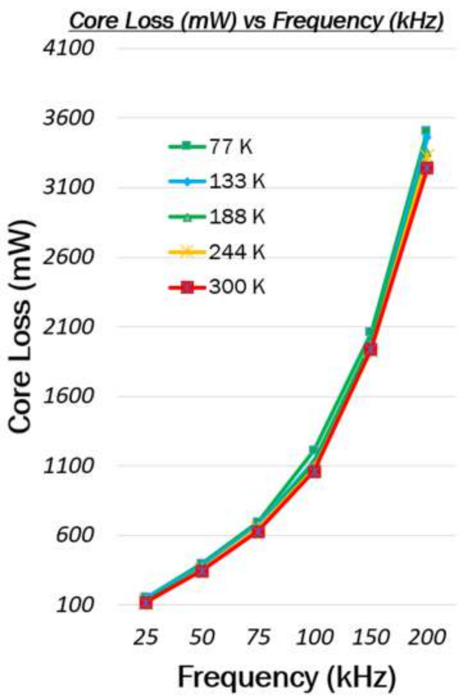
Core materials at cryogenic Temperature

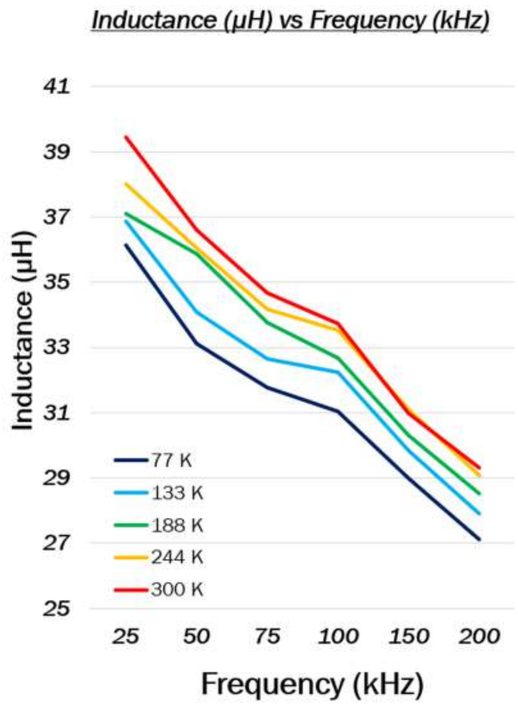
Material	Property	298 K	77 K	Change
Ferrite	μ	2200	350	↓ (−85%)
	P_{loss}	100 kW/m³	1000 kW/m³	↑ (+900%)
	B_{sat}	0.47 T	0.64 T	↑ (+36%)
Powder Iron	μ	125	75	↓ (−40%)
	P_{loss}	–	–	↑ (+40%)
	B_{sat}	–	–	–
Amorphous (AM)	μ	–	–	–
	P_{loss}	1250 kW/m³	1580 kW/m³	↑ (+26%)
	B_{sat}	1.53 T	1.58 T	↑ (+3.3%)
Nanocrystalline (NC)	μ	91700	82400	↓ (−10.1%)
	P_{loss}	45.1 kW/m³	48.8 kW/m³	↑ (+8.3%)
	B_{sat}	1.14 T	1.27 T	↑ (+11.4%)

- **Ferrite and powder iron** exhibit a sharp decline in permeability and a significant increase in core loss at low temperatures.
- **Amorphous metal (AM)** has high core loss and is therefore not suitable for high-frequency applications.
- **Nanocrystalline** offers low core loss and high flux density, which can help reduce core size.

Cryogenic and Vacuum Evaluation of Nanocrystalline

Nanocrystalline





Core loss of Nanocrystalline

Core loss increases as temperature decreases from 300 K to 77 K

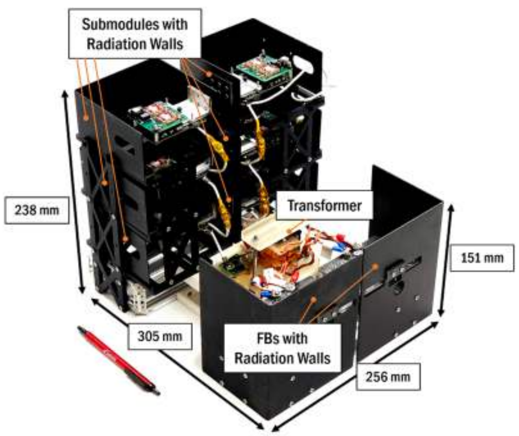
- ❑ Core loss increase of 8.3% @ 200 kHz

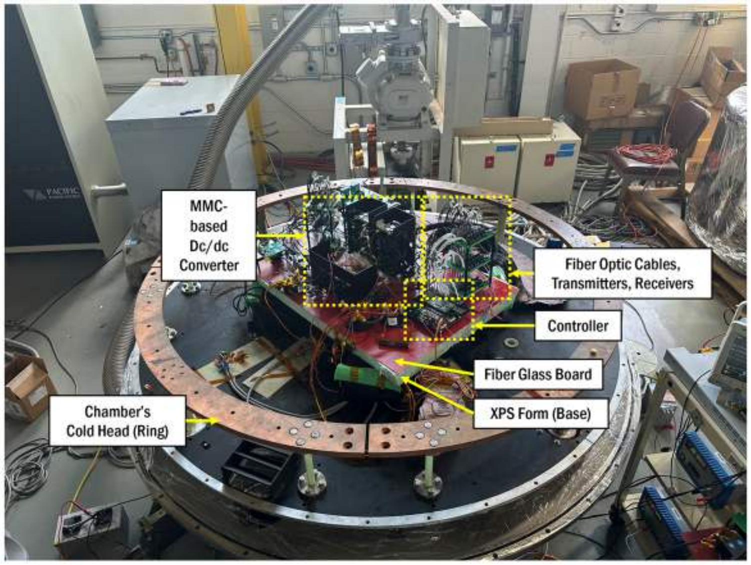
Inductance of Nanocrystalline

Inductance decreases (permeability decreases) as temperature decreases

- ❑ Inductance decrease is smaller than 11.4%

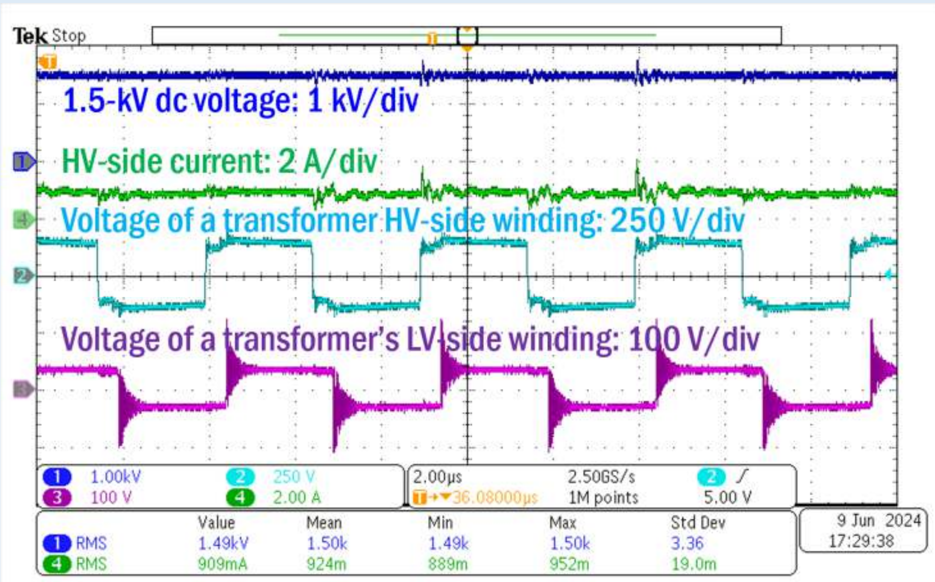
Converter Test in a Cryogenic Vacuum Chamber

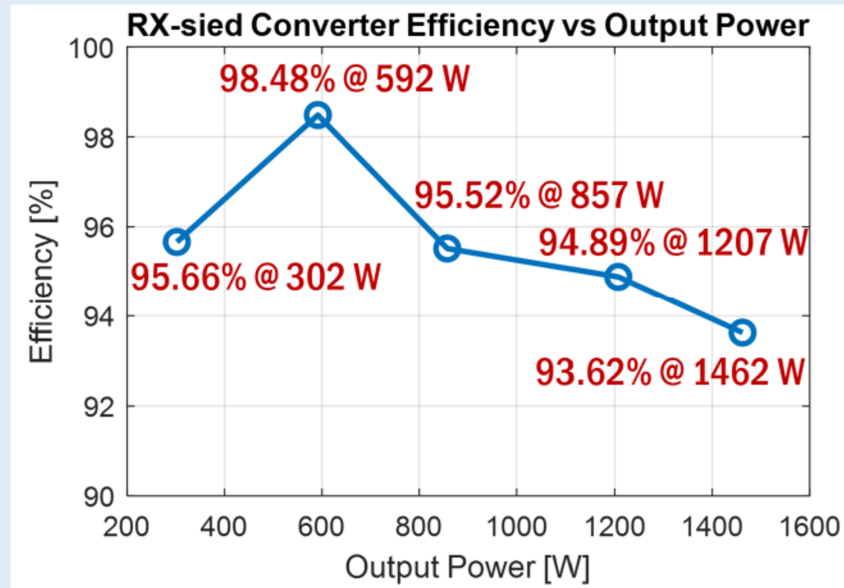




- The converter and all control electronics were placed inside the chamber.
- Test circuits were mounted on a fiberglass board with XPS foam to minimize heat conduction to the chamber surface.
- The chamber was evacuated to high vacuum (<1 mTorr).
- A compressor cooled the chamber to 114.6 K (−158.6 °C) over 2 days.

Converter Validation at 115 K (-158 °C) and Vacuum

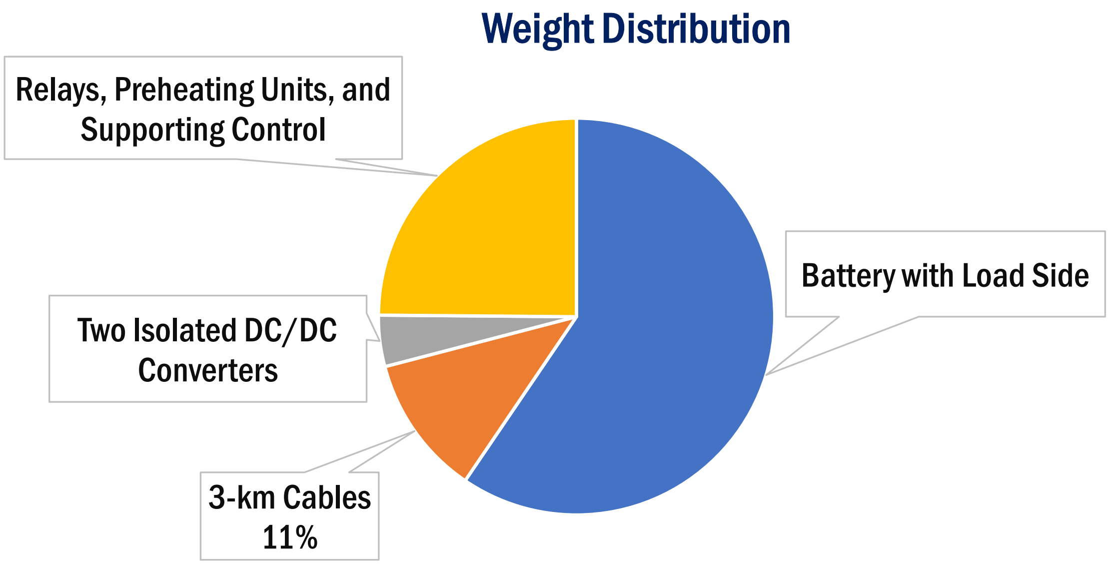




- A peak efficiency of a single converter of 98.48% was achieved at 600 W for a single converter.
- The end-to-end efficiency with 6-km 24-AWG transmission cable can reach 94.3%.

First kV-kW GaN based multilevel power converter validated under cryogenic and vacuum conditions

System Mass Breakdown



Components	Mass (kg)
Battery with Control Electronics	83.7
3-km Cables	16.1
Two Isolated DC/DC Converters	5.9
Relays, Preheating Units, and Supporting Control Electronics	35.0
Total System Weight:	140.7

- High voltage enables significant weight reduction for the cables
- The combined weight of two high voltage Isolated DC/DC Converters is only 4% of the total system weight.
- The 8.47-kWh battery is the heaviest component, contributing 59.5% of the total system mass

Outline

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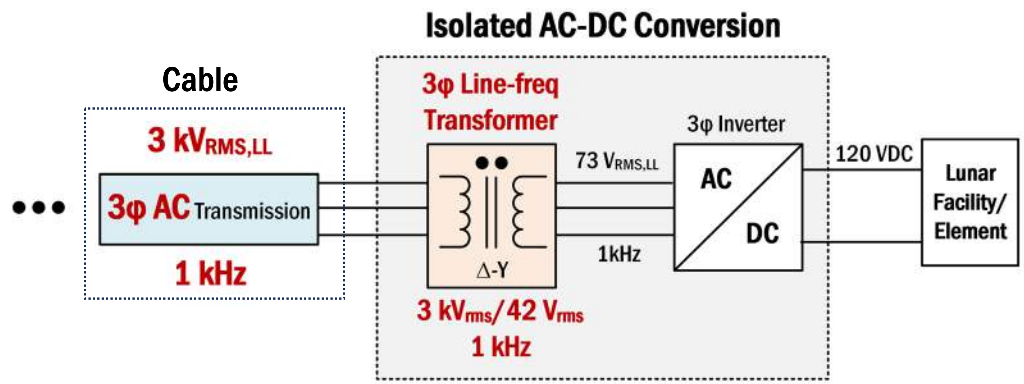
- A discussion on power architecture for lunar power transmission

AC vs. DC Transmission for the Lunar Surface

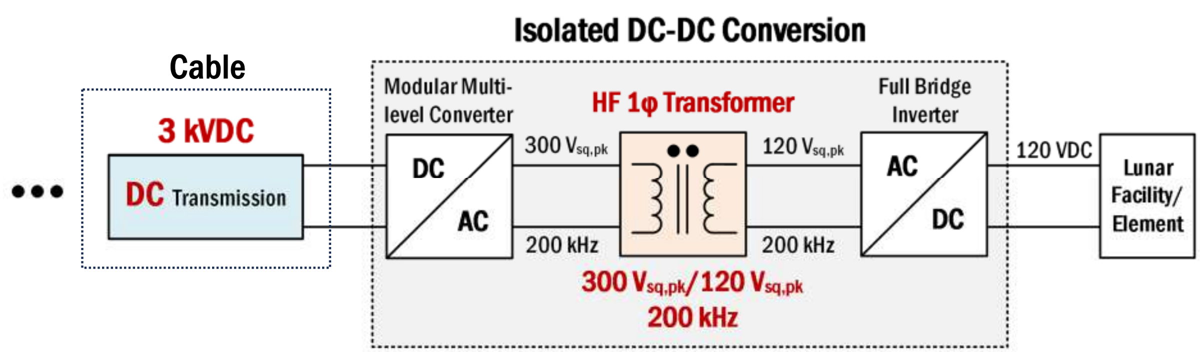
AC Transmission with Line Freq. Transformer

- ❑ Line-frequency transformers and transmission cables dominate the system mass.

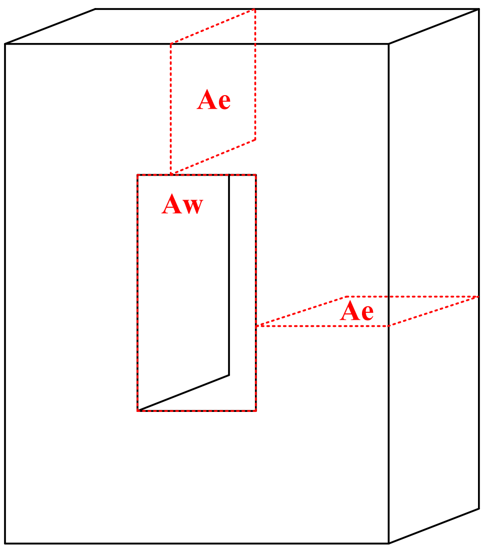


DC Transmission with High Freq. Transformer

- ❑ Mass of the transformer can be greatly reduced.
- ❑ Mass of the cable will increase.

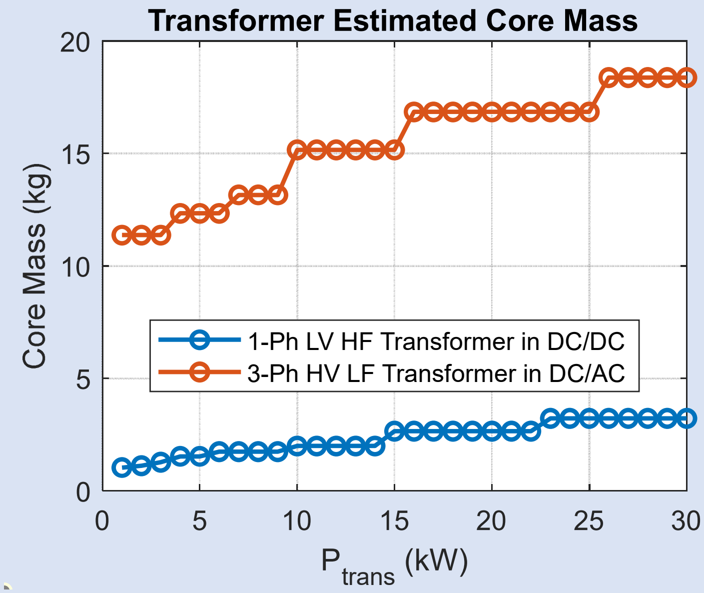


Transformer Mass



The Effective core area (Ae) and the window area (Aw) decide the weight of a transformer's magnetic core.

1-kHz 3-Ph Transformer vs. 200-kHz 1-Ph Transformer



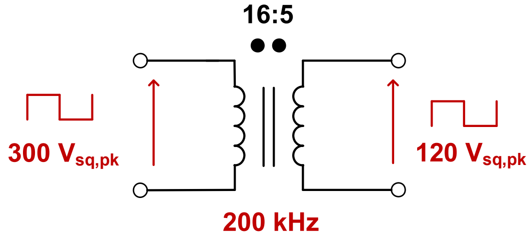
Transformer in the DC system can have

- A smaller ***Ae*** due to reduced volt-second integration (magnetic flux linkage).
- A smaller ***Aw*** due to fewer turns and thinner turn-to-turn insulation.
- Lower mass.

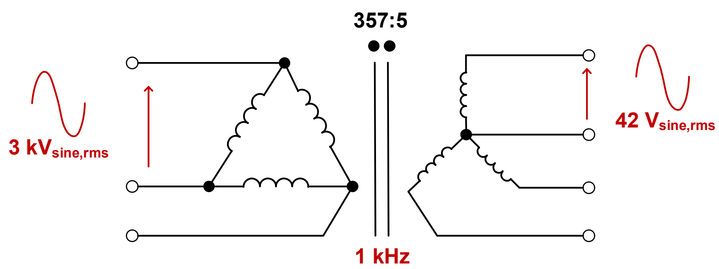
Transformers in a 3-kV 3-kW System

High Freq. Transformer in the multilevel isolated DC/DC converter for DC Transmission

The multilevel converter converts the 3 kV dc to 300 V ac for the transformer.



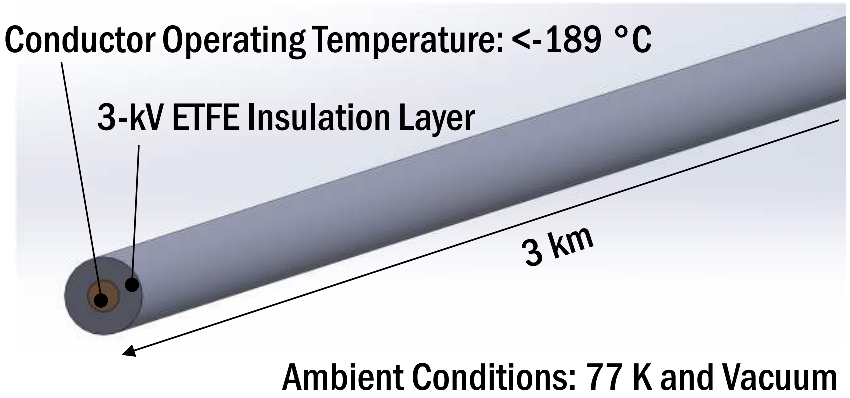
3-phase Line Transformer for AC Transmission



Transformers for 3-kV, 3-kW Transmission System

	DC Transmission	AC Transmission
Configuration	Single Phase	Three Phase
Winding Voltage (HV/LV)	300 $V_{sq,pk}$/ 120 $V_{sq,pk}$	3 $kV_{sine,rms}$/ 42 $V_{sine,rms}$
Operation Frequency	200 kHz	1 kHz
Turns Number (HV/LV)	16:5	357:5
Transformer Mass	2.5 kg	22.7 kg

Transmission Cables in 3-km 3-kV 3-kW Systems

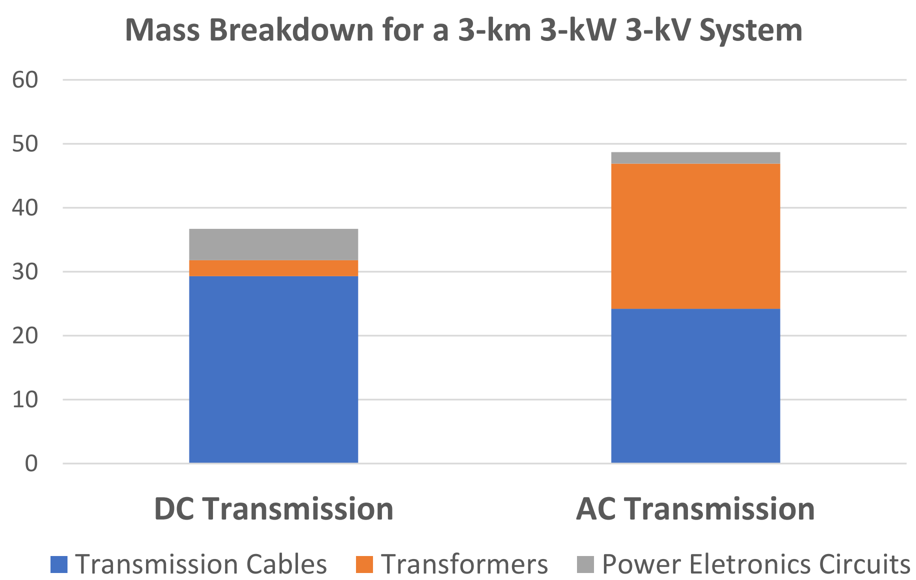


Transmission Cables for 3-kW, 3-km Transmission System

	DC Transmission	AC Transmission
Total Cable Length (km)	6	9
Cable Gauge (AWG)	24	26
RMS Current (A/ph)	1	0.58
Operating Temperature (°C)	-189	-193
Transmission Efficiency (%)	97.1%	97.8%
Total Cable Mass (kg)	29.3	24.15

- ❑ Cables are selected to ensure comparable efficiency and operation temperature.
- ❑ AC transmission systems can have lower total cable mass.

Mass Breakdown of 3-km 3-kV 3-kW Systems



For kilometer-level lunar power transmission :

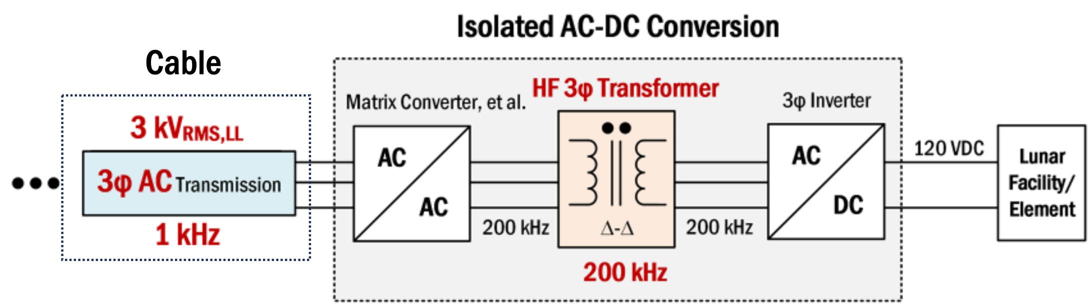
The DC transmission system has

- a **21%** increase in transmission cables mass,
- an **89%** reduction in transformer mass.
- an overall system mass reduction of **25%**.

A Possible Solutions that May Achieve Ultimate Weight Reduction

1-kHz AC Transmission with a High Frequency Transformer in an Isolated AC-DC converter

- ❑ AC transmission can achieve minimized transmission cable mass.
- ❑ Implementation of high frequency transformer can greatly reduce the transformer mass.
- ❑ The weight and complexity of power converters will increase.
- ❑ But the power converters are not the main contributor to the overall weight of the transmission system.



Thank you for your attention!

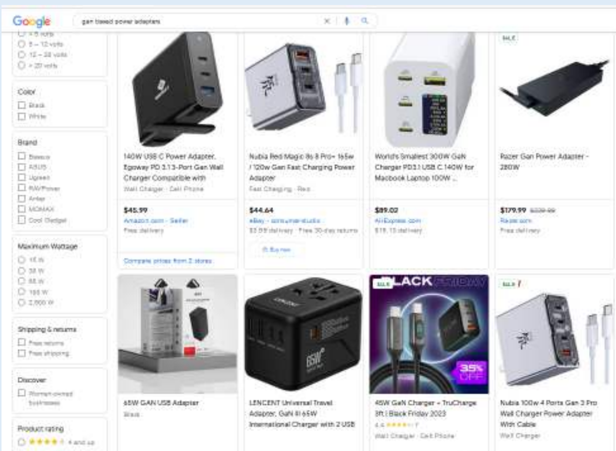
Questions?

Contact: Prof. Jin Wang

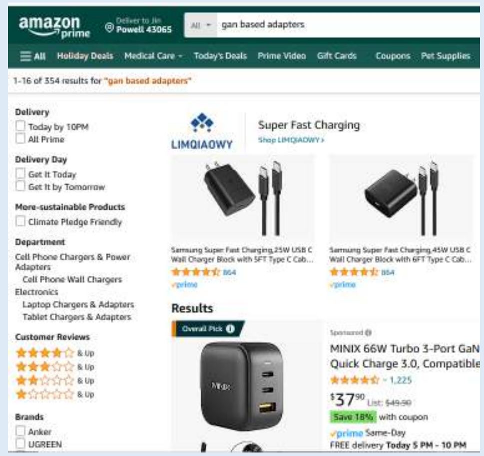
wang.1248@osu.edu

GaN based Power Adapters

OSU, “A GaN Transistor based 90W Isolated Quasi-Switched-Capacitor DC/DC Converter for AC Adaptors” WiPDA, 2013.



GaN Adapters on Google



>350 GaN Adapters on Amazon

https://youtu.be/lYfoRkzqAII?si=Db-30hEubBFYbKv

Apple’s 70-W GaN based power adaptor for 15-inch MacBook Air

Examples of SiC in Production Vehicles

Tesla Model 3

SiC based Dc/Ac traction drive inverter in Tesla Model 3

https://www.systemplus.fr/reverse-costing-reports/tesla-model-3-inverter-with-sic-power-module-from-stmicroelectronics/

BYD Han

1200 V, 1040 A rated SiC Power Module from BYD.

https://insideevs.com/news/557433/150000-byd-han-production/

Lucid Air

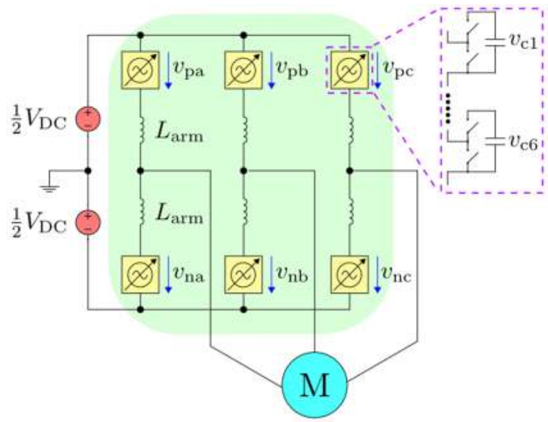
Automotive Qualified 1200V Silicon Carbide XM3 Half-Bridge Power Module from Wolfspeed.

https://www.wolfspeed.com/company/news-events/news/lucid-motors-integrates-wolfspeeds-silicon-carbide-semiconductors-into-the-award-winning-lucid-air/

7-kV 1-MVA Modular Multilevel Converter for Industrial 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/Jz3lkd734Pc



6 Submodules per arm

2016-2019
DoE NGEM

PowerAmerica
2019-2021

From University Research to Industry Product

OSU Research Prototypes

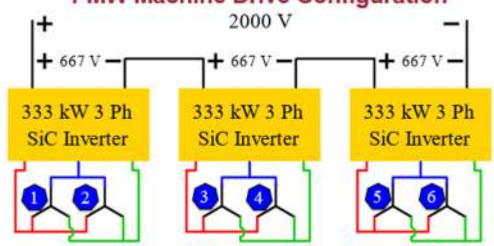
Toshiba North America Product

In production from 2023

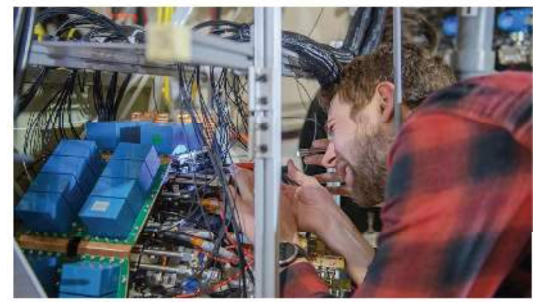
The first SiC based medium voltage mega-watt industry motor drive product that is manufactured in the United States

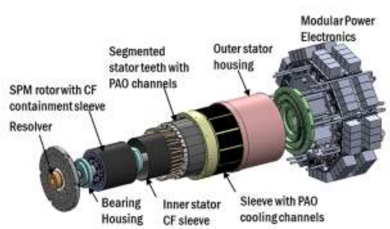
2-kV 1-MVA Integrated Modular Motor Drive for Turbo Electric Aircraft

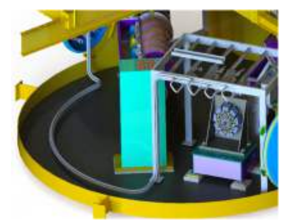
- Modular structure for high fault tolerance and voltage stress reduction
- PAO based in-slot cooling and insulation for the motor
- Partial discharge free at 2 kV
- Vol. Power Density : 13.5 kW/L
- Mass. Power Density: 9.0 kW/kg

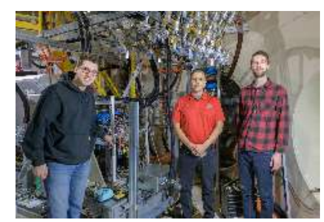


Megawatt-Class Electric Motor Shown Safe at High Voltage And Altitude



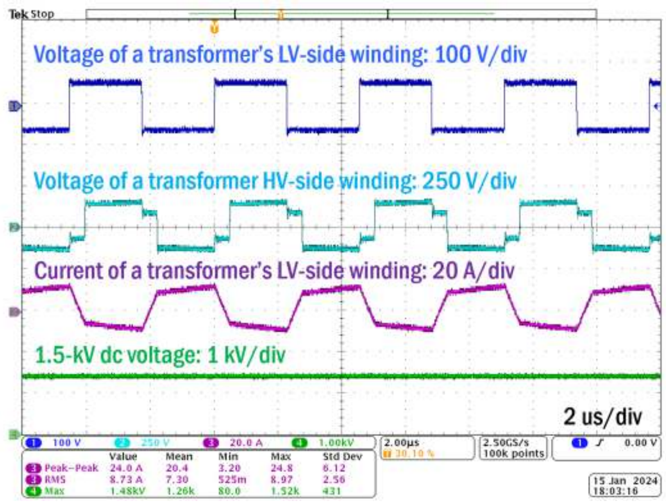




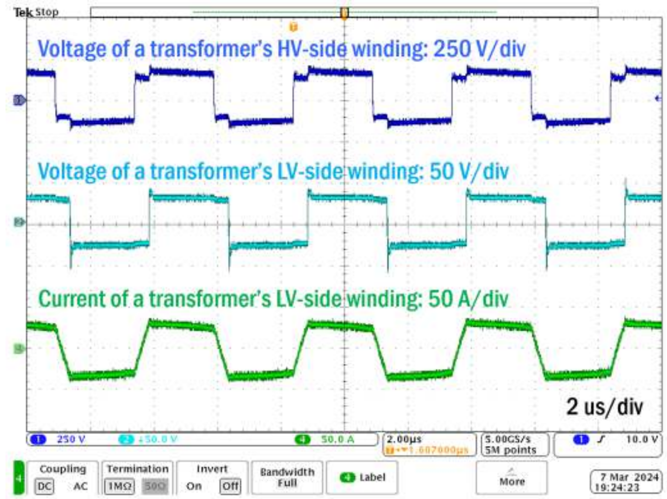


Converter’s Validation under Room Conditions

Step-up Converter

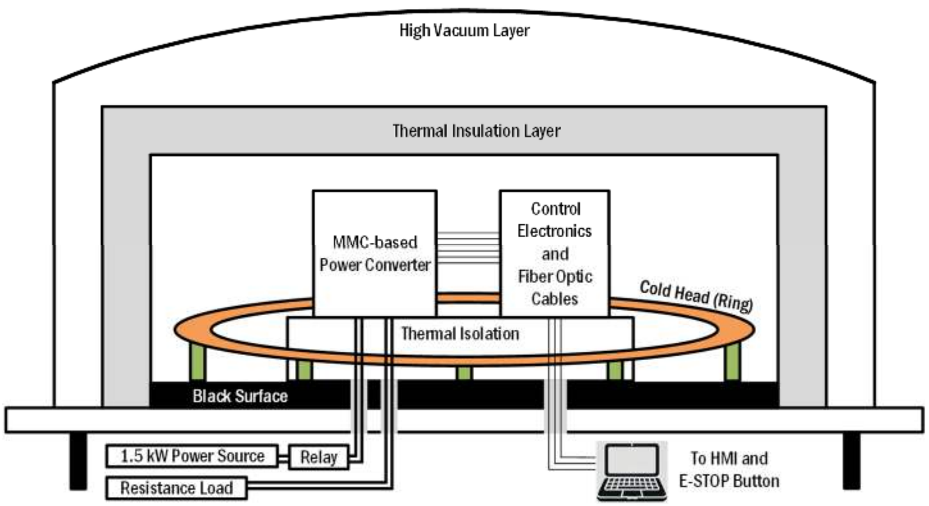


Step-down Converter



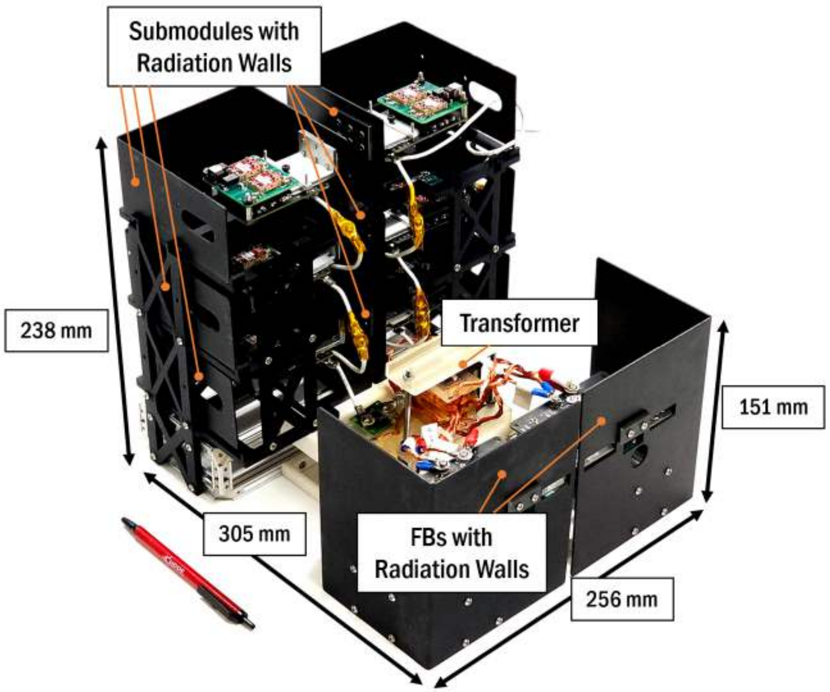
- Converters on both the source side and load side have been validated under room temperature and pressure.
- Full power operation at 1.5 kV and 1.5 kW has been achieved.

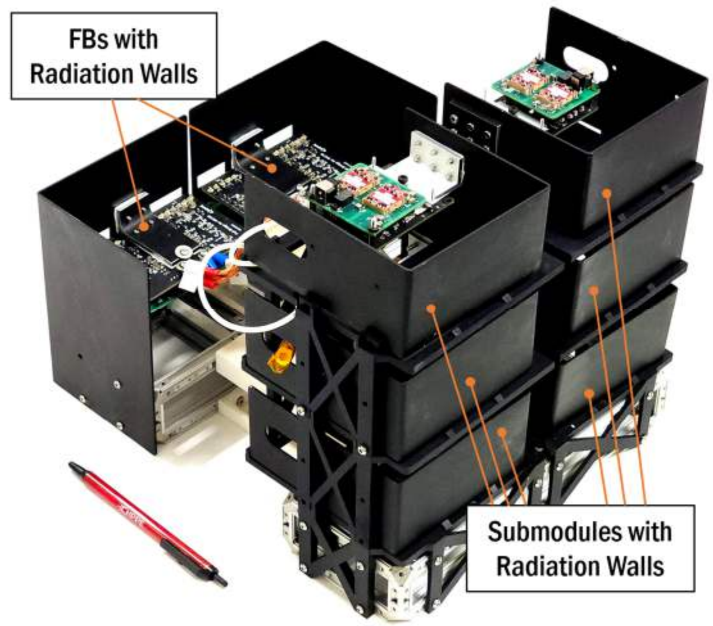
Experiment Setup in a Thermal Vacuum Chamber



- The system was tested in a large thermal vacuum chamber to emulate a lunar-like environment.
- The MMC-based DC/DC converter and all control electronics were placed inside the chamber.
- The power source, load, and monitoring/control interface (HMI and E-stop) were located outside due to environmental limitations

Converter Prototyping





The prototypes of the MMC-based isolated DC/DC converter, including the TX- side and RX-side converters, have been fabricated, assembled, and integrated to validate system performance