WBG devices enabled Power Conversion System and DC Grids

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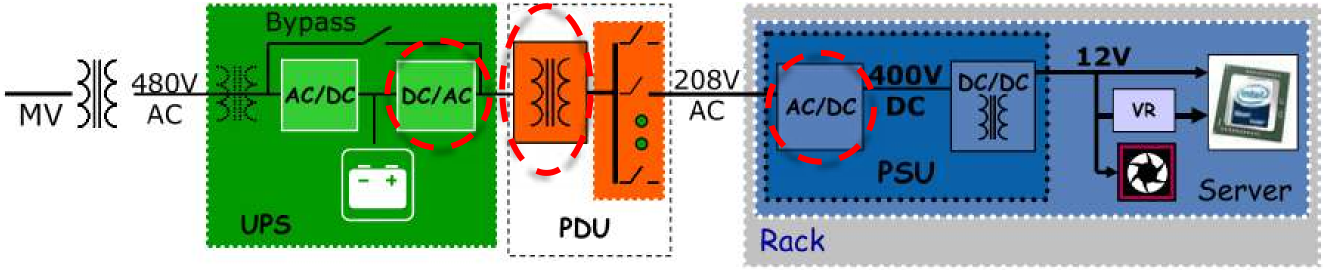
Current Data Center Power Distribution Architecture

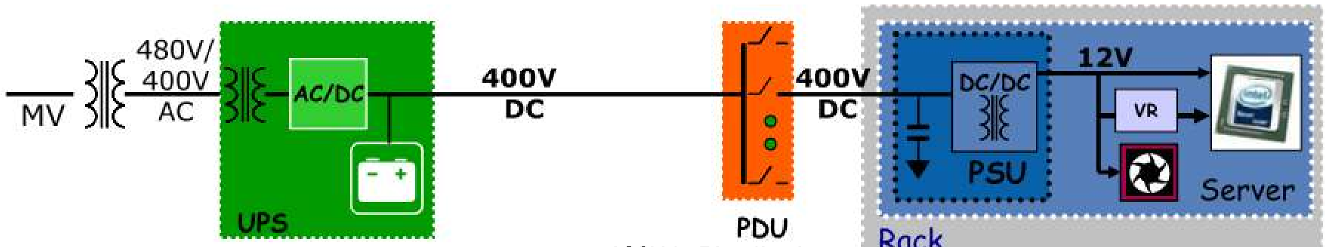
- 480 Vac Distribution
- Multiple stages of conversion
- 13.8 kV or 4160Vac -> 480Vac -> 415/240Vac ->208Vac
- Drawbacks
  - Power loss at each conversion stage
  - Low voltage transmission, large size copper cable

AC vs DC Distribution



480Vac Distribution

- 480V AC Distribution
  - 51.64% Efficient



400Vdc Distribution

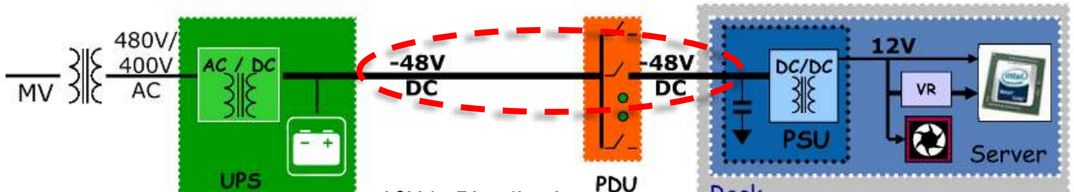
- 400V DC Distribution
  - 72.7% Efficient
  - Fewer conversion stages

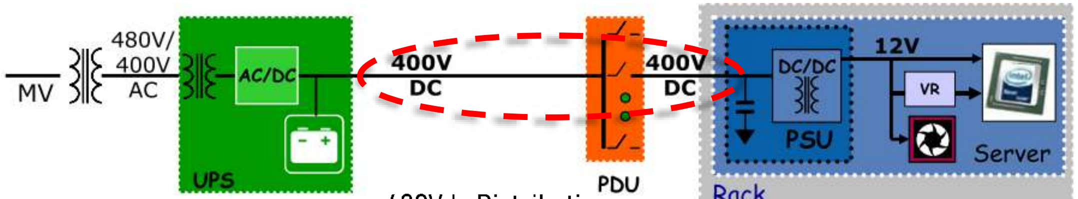
400V DC Distribution is 21% more efficient than existing 480V AC

Pratt, A., Kumar, P., & Aldridge, T. V. (2007). Evaluation of 400V DC distribution in telco and data centers to improve energy efficiency. *INTELEC 07 - 29th International Telecommunications Energy Conference*, 32–39. https://doi.org/10.1109/INTLEC.2007.4448733

DC Distribution and Cable Size

- Higher the distribution voltage
- Lower the current drawn
- 16 times copper surface area reduction for 400Vdc vs 48Vdc



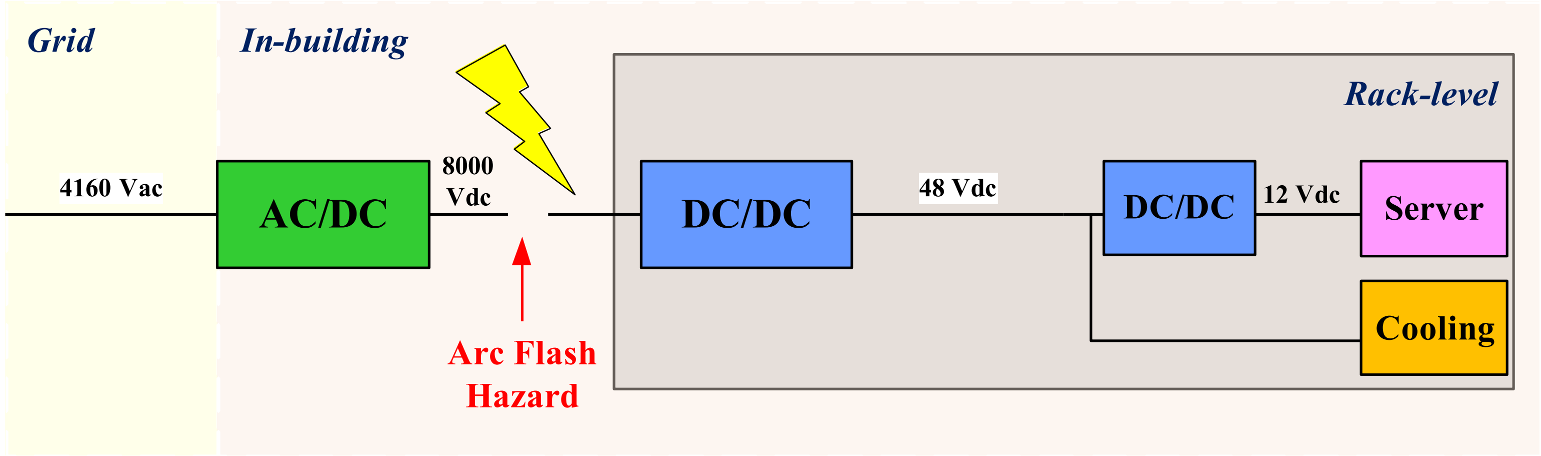


	48 Vdc	400 Vdc
No of Cables	20	2
Copper Area per Cable [mm2]	325	200
Total Copper Area [mm2]	**6500**	**400**

The higher the DC Distribution voltage, the less copper is required

Pratt, A., Kumar, P., & Aldridge, T. V. (2007). Evaluation of 400V DC distribution in telco and data centers to improve energy efficiency. *INTELEC 07 - 29th International Telecommunications Energy Conference*, 32–39. https://doi.org/10.1109/INTLEC.2007.4448733
Fukui, A., Takeda, T., Hirose, K., & Yamasaki, M. (2010). HVDC power distribution systems for telecom sites and data centers. The 2010 International Power Electronics Conference - ECCE ASIA -, 874–880. https://doi.org/10.1109/IPEC.2010.5543344

Challenge of Supplying MVDC to Data Center

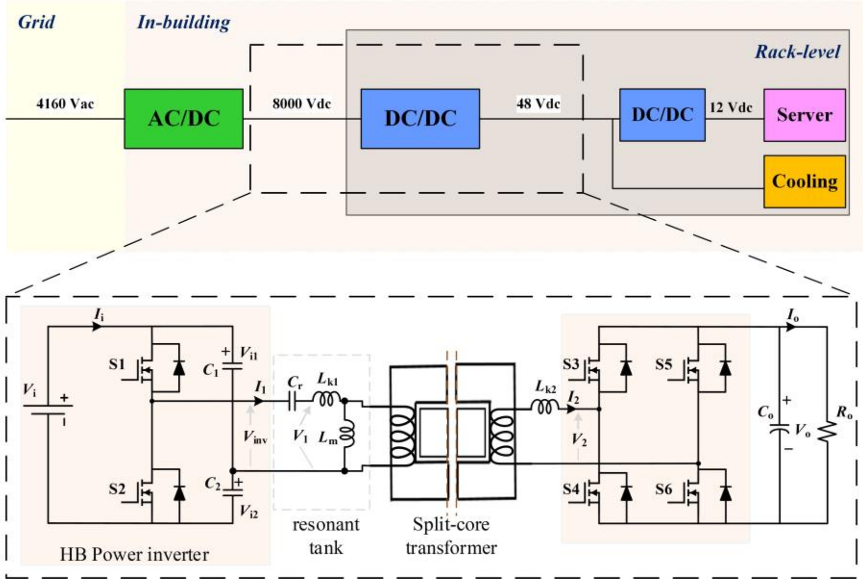


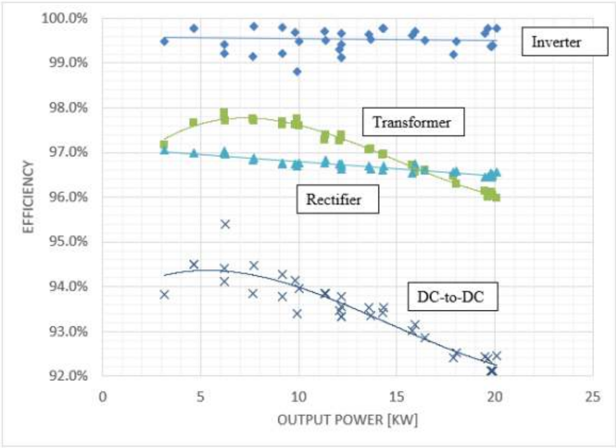
- Arc Flash Hazard
- 8000 Vdc needs to be disconnected when the server units need maintenance
- Arc flash is likely to occur due to high voltage difference
- Not economical to have MVDC switchgears at every server rack
- Require arc flash mitigation at the power supply level

Medium Voltage Contactless Power Transfer for Data Center Application

Arc-flashing Free Solution for MVDC Distribution

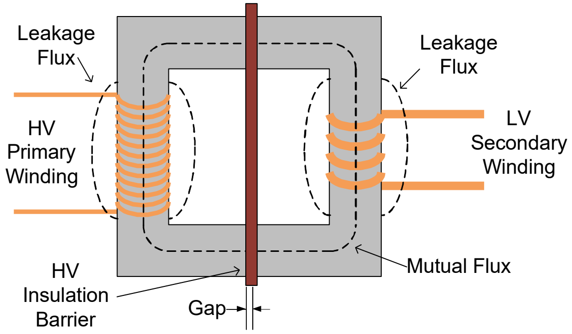
- Power transfer via inductive coupling
- Split-core transformer as a “magnetic plug”
- No conductors in ohmic contact
- No high dv/dt
- Arc-flash mitigated

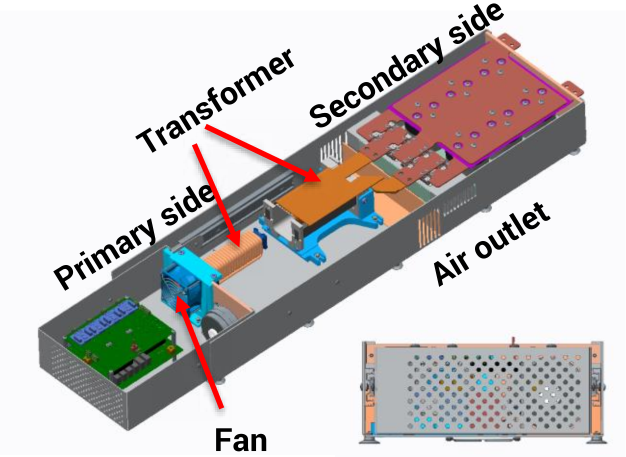


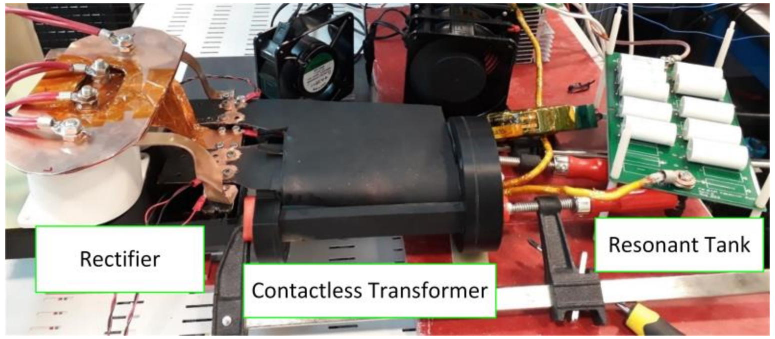


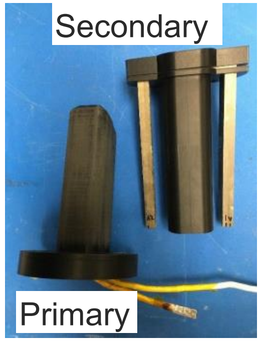
Converter Topology

- LLC is a direct match for “contactless” transformer
- Only one series capacitor needed
- Series inductor: Leakage inductance
- Parallel inductor: Magnetizing inductance



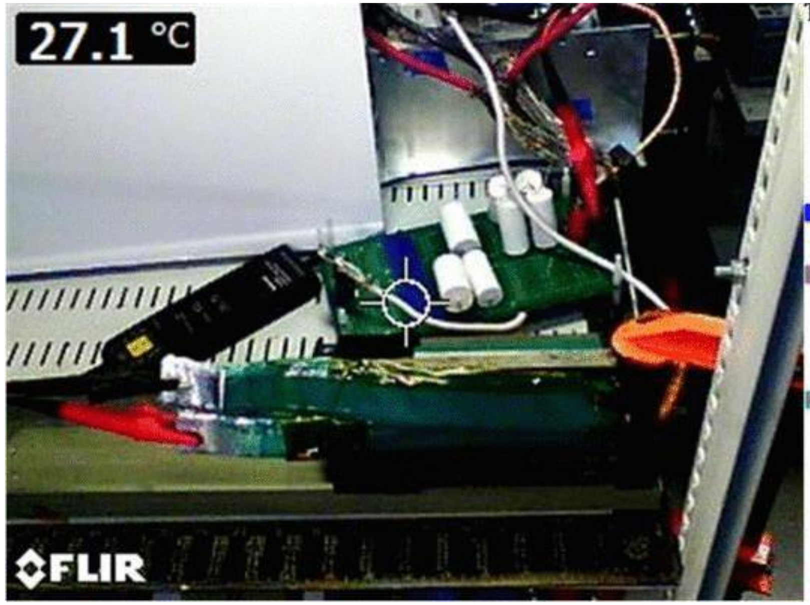


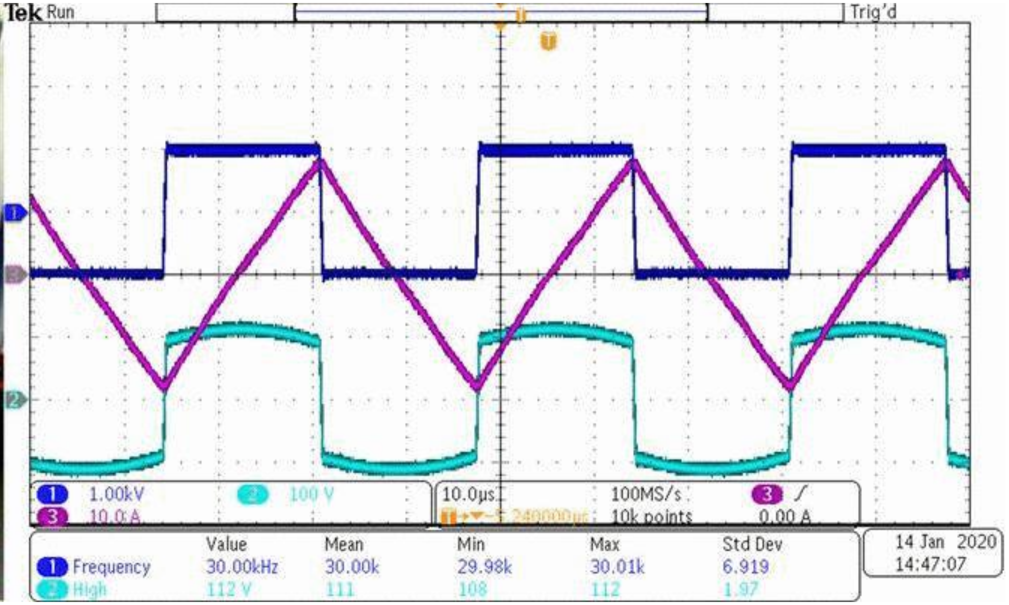




I. Wong, S. Samanta and S. Bhattacharya, "Medium Voltage Contactless Power Transfer for EV Fast Charging," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020, pp. 814-819, doi: 10.1109/ECCE44975.2020.9235679.

Transformer Unplug Action: Arc-Flash Free Operation





Transformer Primary Voltage (Blue), Transformer Secondary Voltage (Green), Transformer Primary Current while being unplugged

GaN HEMTs for Motor drives

- The transport sector is going through revamping to reduce greenhouse gas emissions.
- The current trend is towards using high-speed, low inductance motor drives to increase power density and efficiency.

Electric vehicle

eVTOL

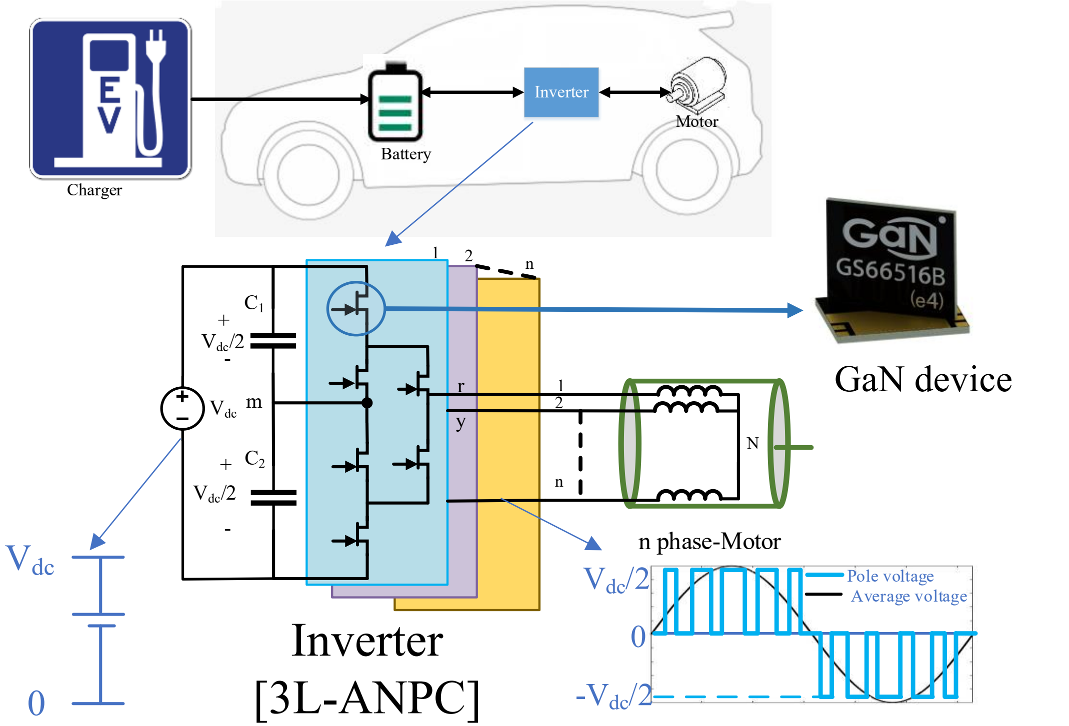
MEA

Requirements for high power motor drives

- ❑ 400-800V DC bus operation with low effective dv/dt.
- ❑ High efficiency at high switching frequency operation for controlling low inductance motors.
- ❑ The generation of high fundamental frequency with low current THD to control low inductance machines.

Opportunity with GaN devices

- ✓ 3L-topology for reaching 800 DC bus with 650V GaN devices
- ✓ 3L-topology enables low dv/dt at the motor terminal
- ✓ GaN devices enable high switching frequency operation → required for high fundamental frequency generation with low current THD [Total Harmonic Distortion].



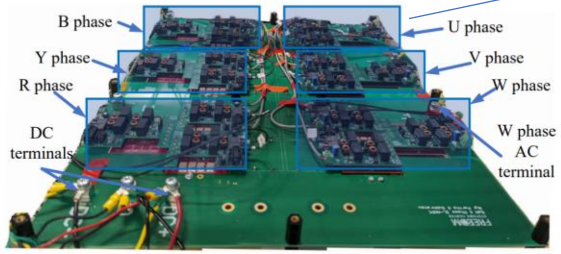
Constant DC voltage

Variable frequency, variable voltage AC

GaN HEMTs enabled high speed Motor drives demo (10kRPM PMSM)

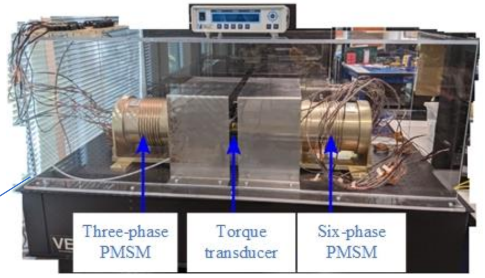
DSP-board

650V/60A bottom cool GaN device based 3L ANPC inverter



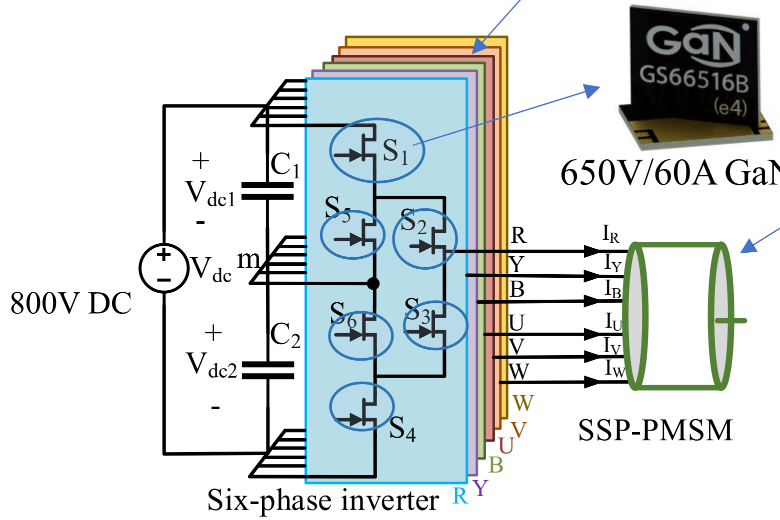
GaN device

High speed PM motor-generator setup



- GaN-based Six-Phase 3L-ANPC inverter
- 650V/60A GaN bottom cool GaN device

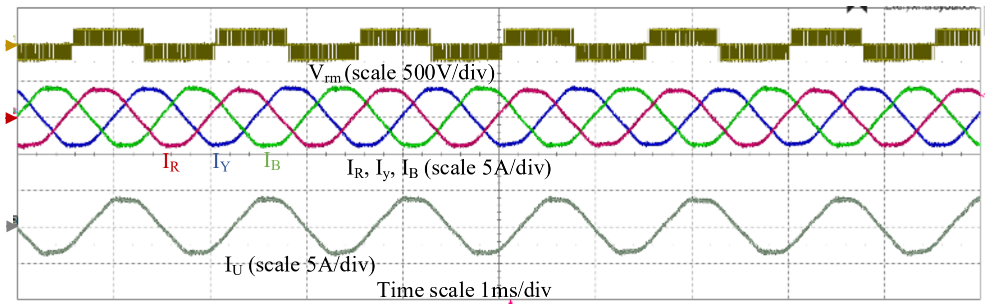
Demonstration of GaN based high-speed motor drives



650V/60A GaN device

3L-ANPC [Active Neutral Point Clamped Converter]

High speed operation of GaN based drives



Steady-state operation at 10,050 RPM (670Hz)

50kHz switching frequency

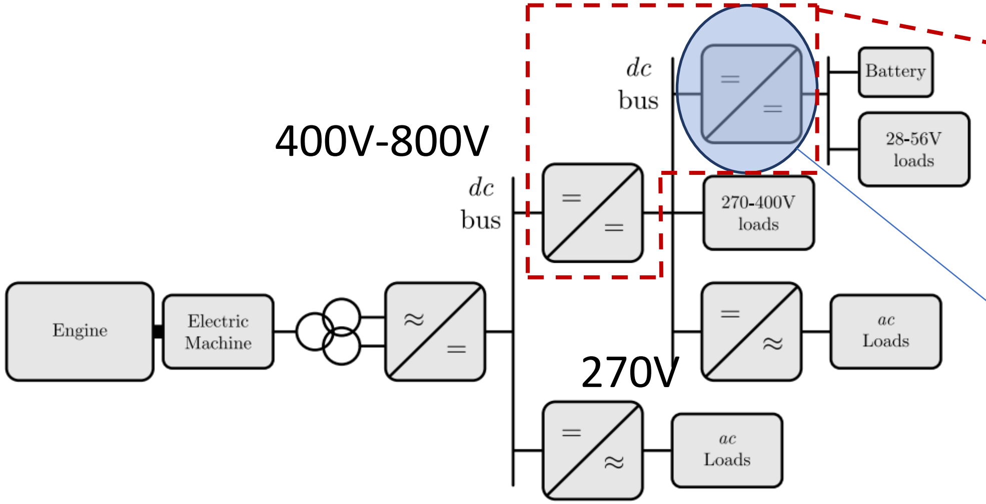
Applications: Non-propulsion loads in transportation applications

- Examples:
  - Power steering system, oil pumps, cooling fans, air-brake compressors.
  - Environmental control system, lighting, entertainment system.
  - Flight control actuators, landing gear, braking, cabin pressurization.
  - The GaN devices can enable high efficiency and power density by operating at high switching frequency
  - Challenging to design high-power converter with GaN devices.

Electric vehicle

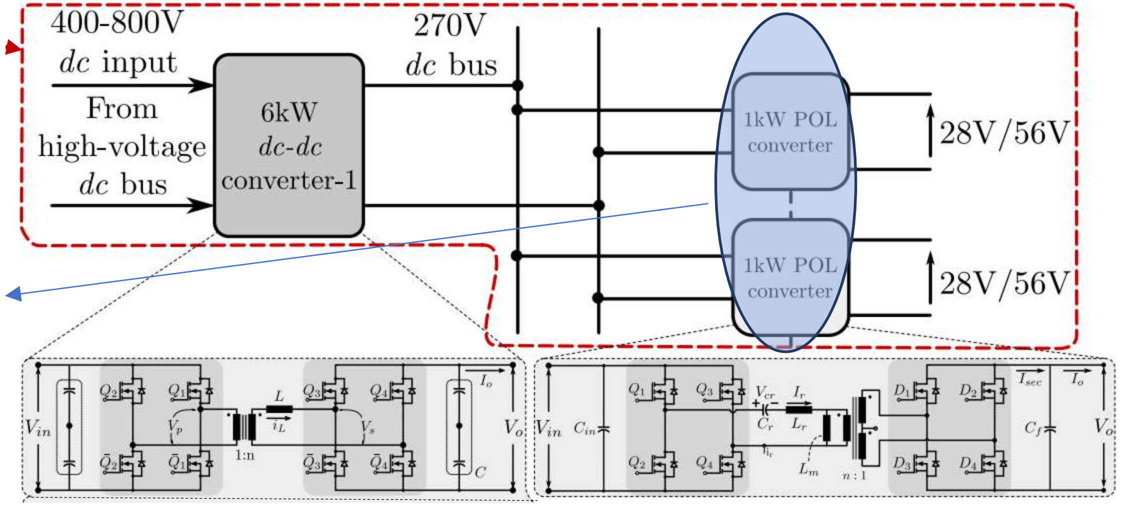
eVTOL

MEA

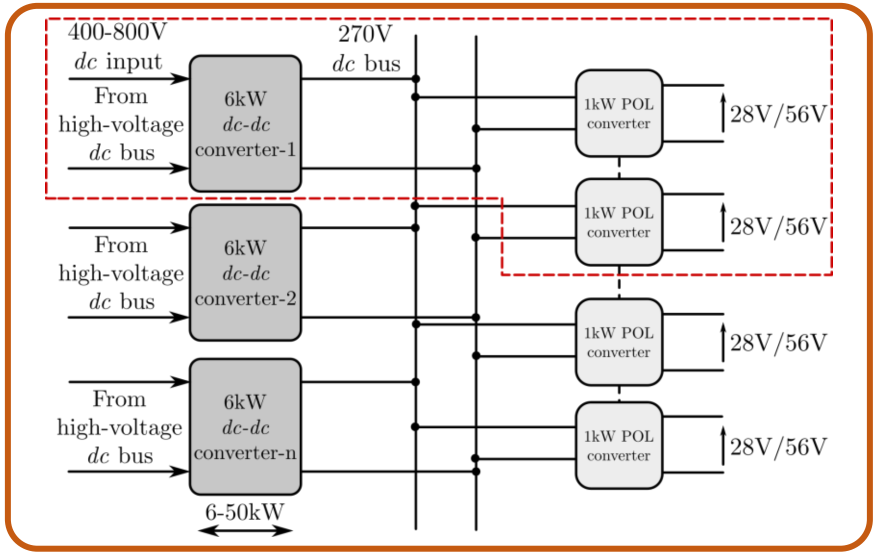


Typical power system inside a vehicle

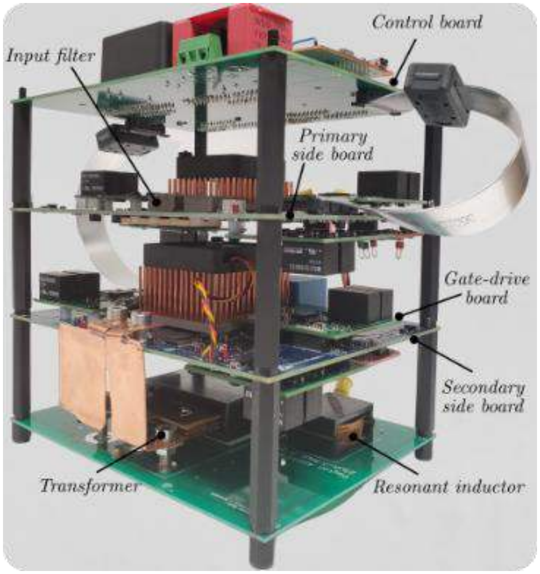
GaN-based converter



DC-DC Power Subsystem for Auxiliary Power in Heavy Vehicles



6kW, 400-800V/270V/56V DC-DC converter prototype subsystem



Full-bridge LLC resonant converter hardware prototype of the converter with control board and transformer-inductor board.

6 kW Power Supply System Prototype (Application of WBG semiconductors to automotive systems)

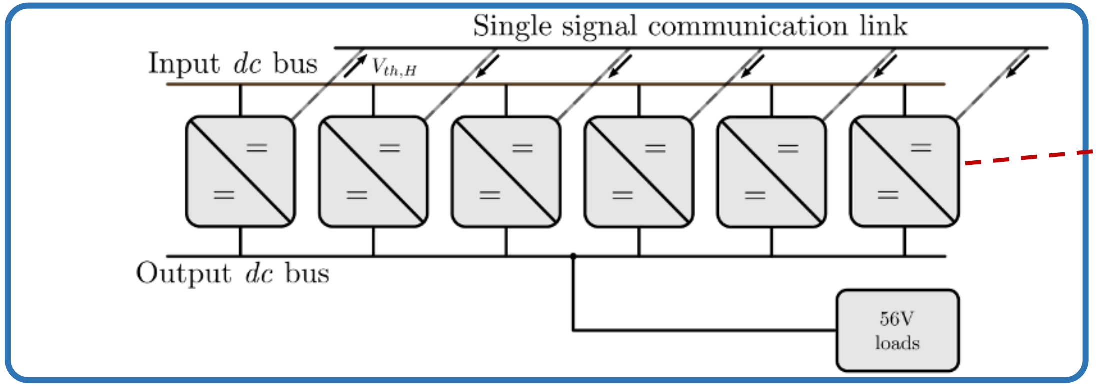
- Stage-1 conversion (400-800 V/270 V): 6 kW, 50 kHz 1-phase **dual active bridge converter**.
  - **1200 V SiC MOSFET** on primary and **650 V GaN Systems' GS66516T (2 in parallel)** on secondary side.
  - Sustained high temperature operation at **coolant temperature of 105 ^{o}C**.
- Stage-2 conversion (270 V/ 28 or 56 V): 1 kW, 200 kHz full-bridge **LLC resonant converter**.
  - **650 V GaN Systems' GS66516T** on primary and **100V GS61008T** on secondary side.
  - **Charge control method** for improved stability and current sharing in parallel-connected system.
- Advanced control methods for **high-power, high-frequency** DC-DC power supply system.

GaN semiconductor devices enable high frequency high-power conversion system at elevated temperature.

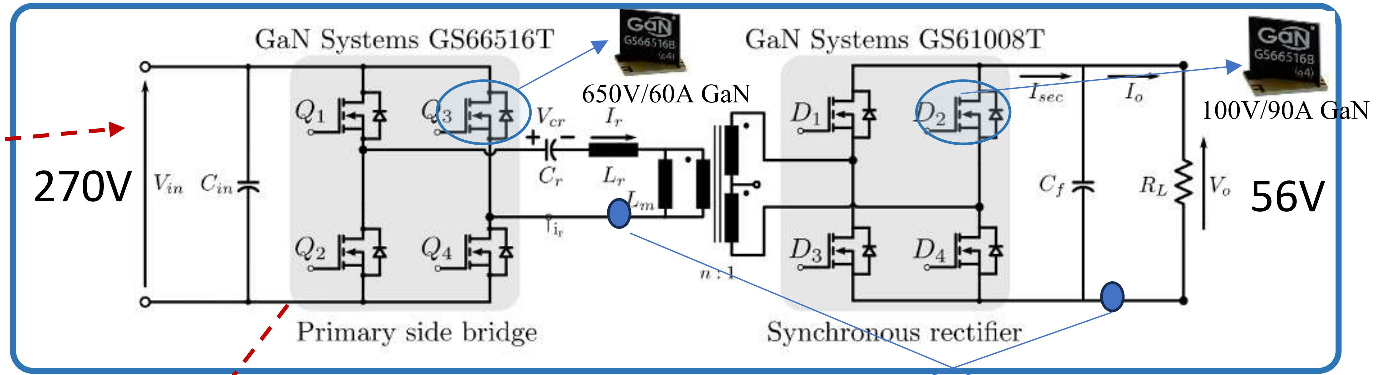
1. S. S. Shah, V. M. Iyer and S. Bhattacharya, "Exact Solution of ZVS Boundaries and AC-Port Currents in Dual Active Bridge Type DC–DC Converters," in IEEE Transactions on Power Electronics, vol. 34, no. 6, pp. 5043-5047, June 2019, doi: 10.1109/TPEL.2018.2884294.
2. S. S. Shah, S. K. Rastogi and S. Bhattacharya, "Paralleling of LLC Resonant Converters," in IEEE Transactions on Power Electronics, vol. 36, no. 6, pp. 6276-6287, June 2021, doi: 10.1109/TPEL.2020.3040621.

Paralleling of GaN based LLC converter to reach high power – 6kW

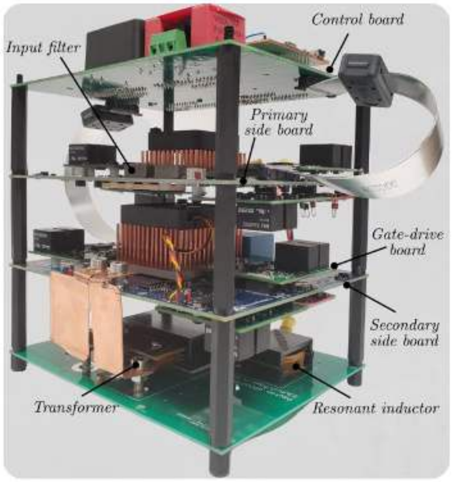
System structure



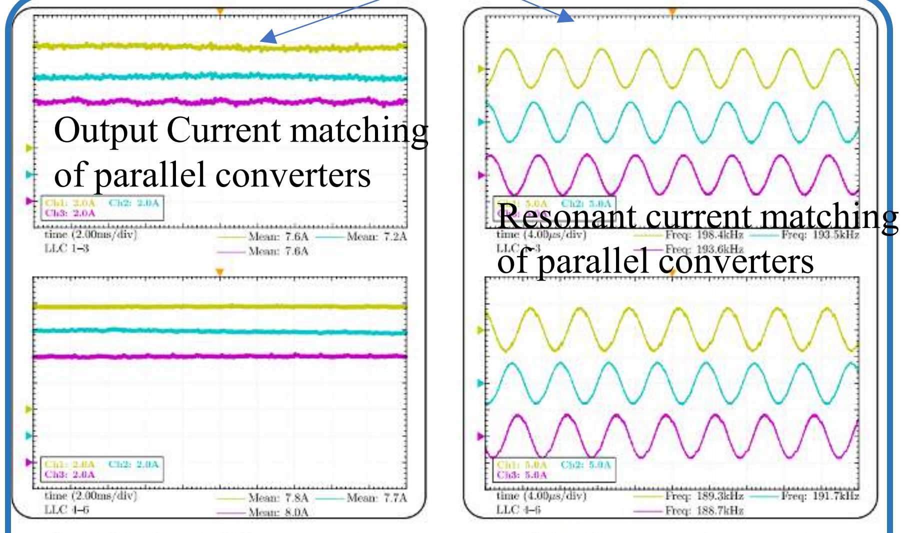
Circuit diagram of each block



- Paralleling of GaN-based converter can be used to reach a high-power.
- This work demonstrates the paralleling of six GaN-based 1KW LLC converter 6kW power.
- Input voltage: 270V
- Output voltage: 56V
- Current sharing is ensured by the droop technique (R_d = 0.2 Ω).
- Current distribution error: 4%.
- Voltage regulation error: 3.0%.
- System delivered to LMCO, JDES



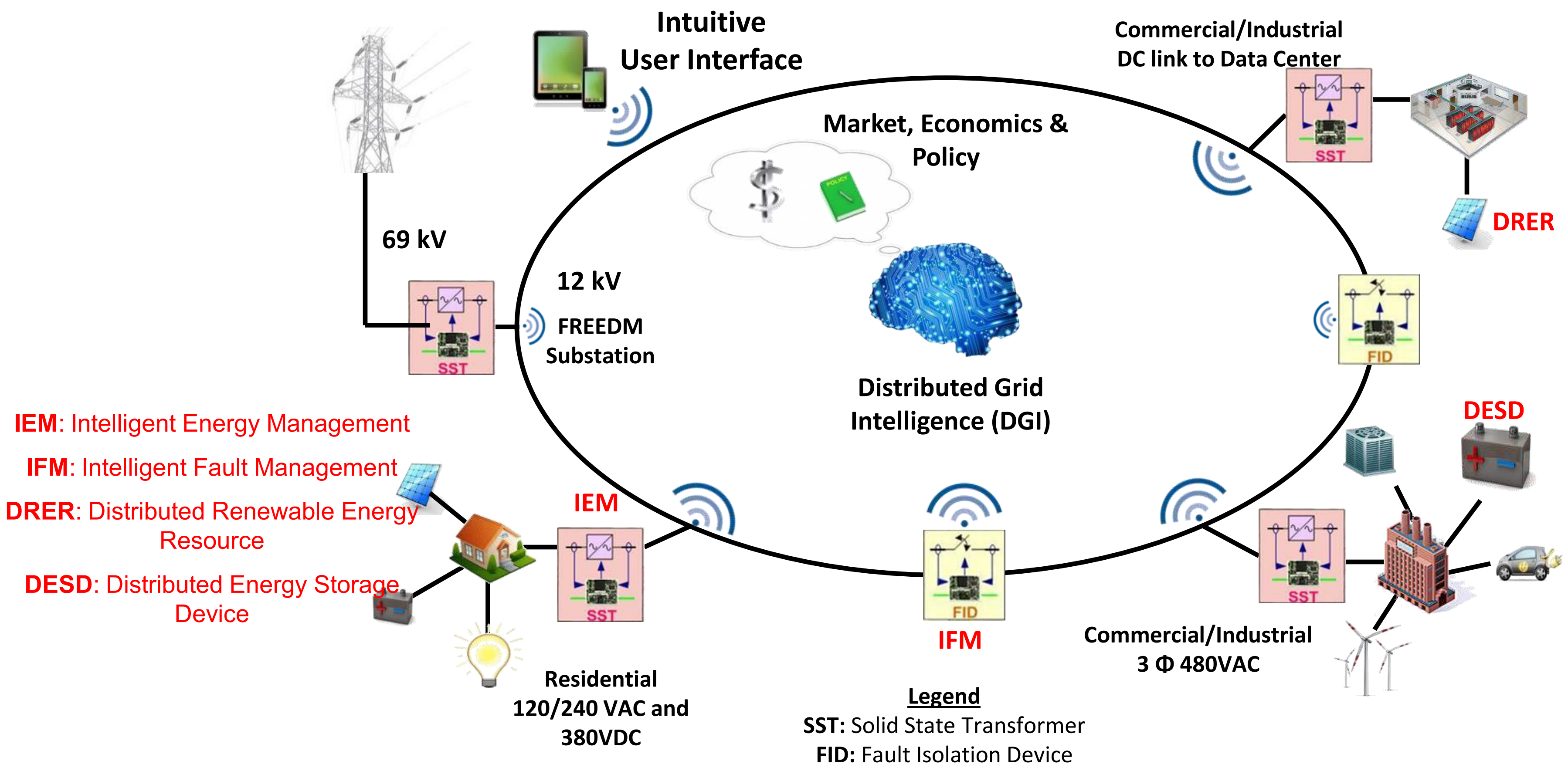
Designed LLC converter



(a) Output DC currents (b) Resonant currents

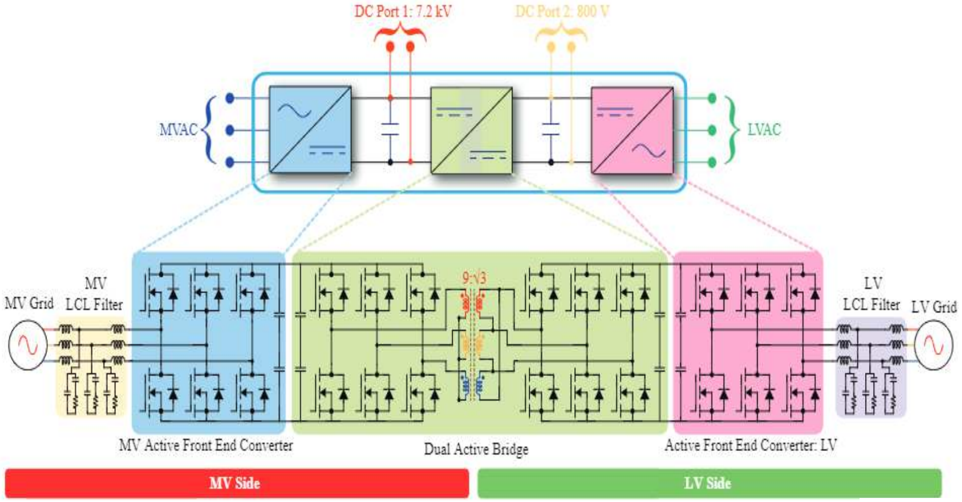
Experimental results
Current matching error: 4%

Solid State Transformer (SST): an enabler of distributed renewable energy integration →FREEDM System concept [2008]



Solid State Transformer installed at Naval Base [Port Heuneme, CA]

SiC 10kV MOSFET based Mobile Utility Support Equipment [MUSE] SST 100kVA, 4.16kV/480V

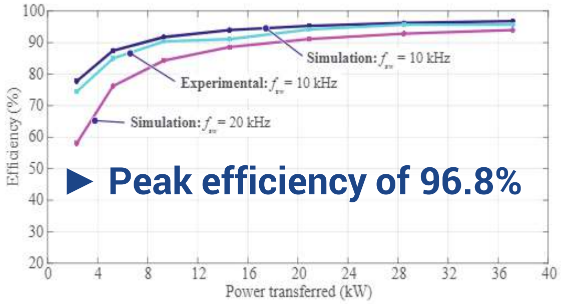


MV Side Device used:
10 kV SiC MOSFET module
XHV-6/XHV-9 half-bridge modules

LV Side Device used:
1200 V - 325 A SiC MOSFET
CAS325M12HM2 half-bridge module

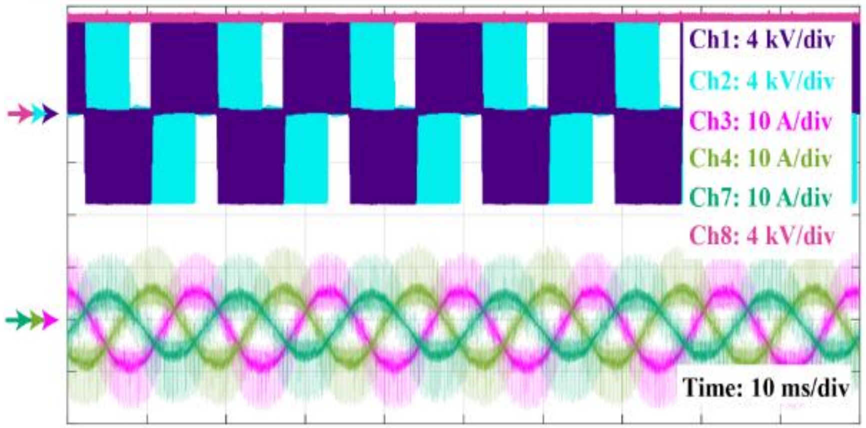
MUSE SST system container system

Internal dimensions: 4.4 m x 2.33 m x 2.33 m

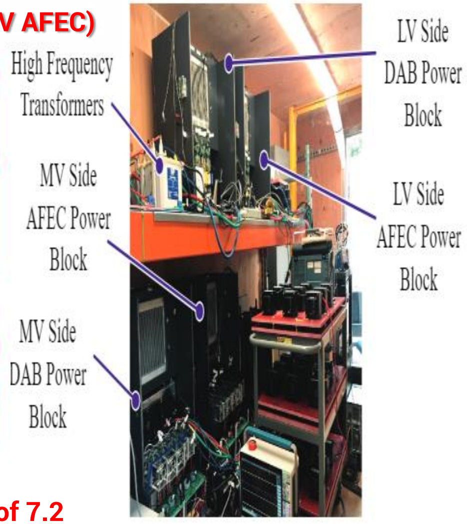


Efficiency of the MVac/MVdc system

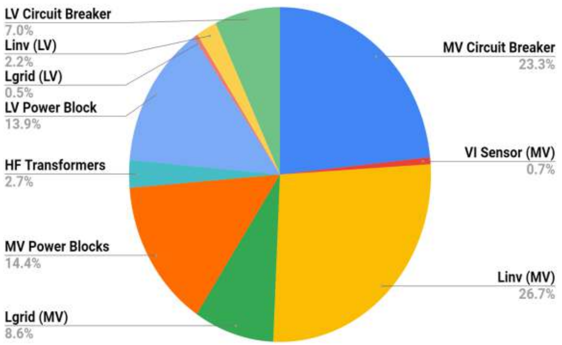
SST switching frequency: 10kHz (MV AFEC); 20kHz (DAB); 20kHz (LV AFEC)



Experimental results of MUSE SST HV converter at a DC-link voltage of 7.2 kV and 10kHz switching frequency (Ch1/Ch2: Line voltage (VYB/VRY); Ch3/Ch4/Ch7: R/Y/B inverter current; Ch8: DC bus voltage)



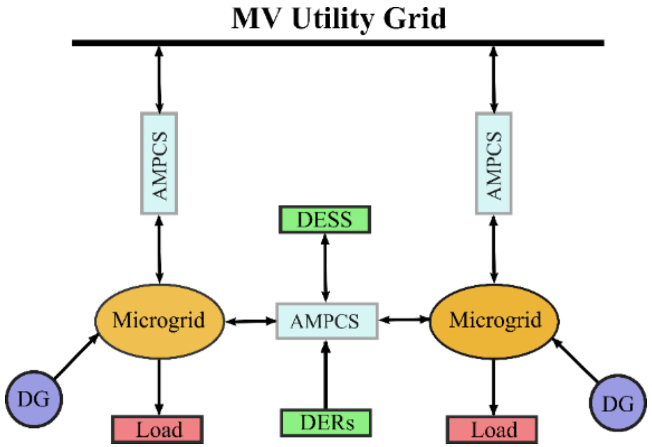
MUSE SST inside the container

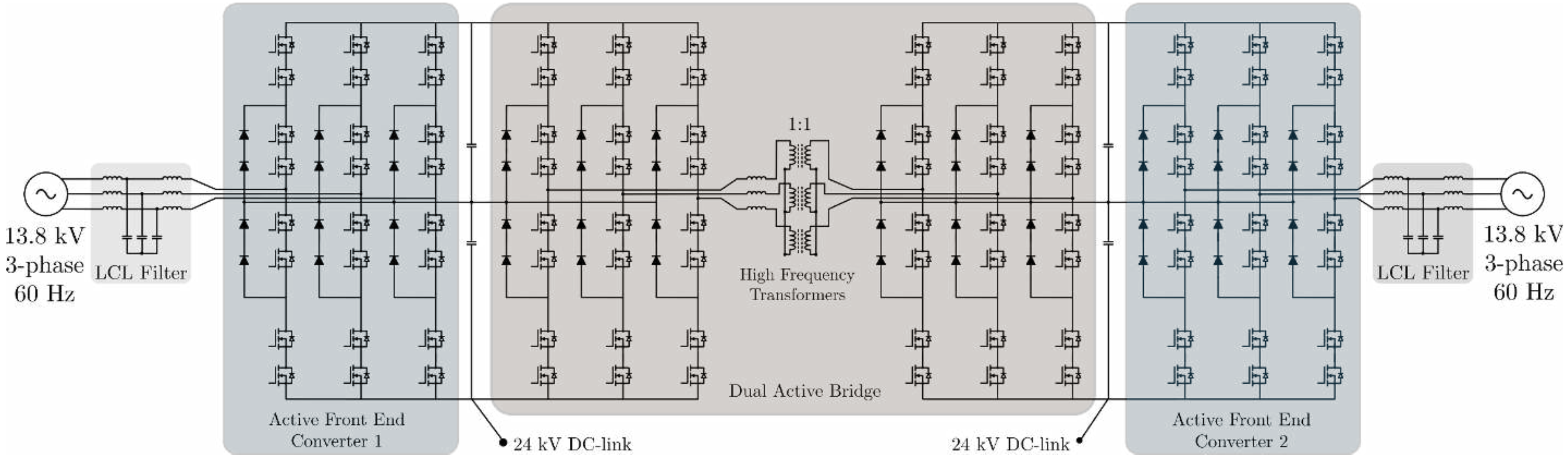


Power Density of MUSE SST

Medium Voltage SST enabled by 10 kV SiC MOSFETs

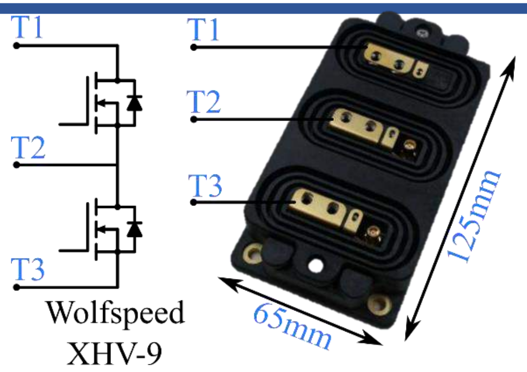
- AMPCS is an SST used for interconnecting a grid with a microgrid or two microgrids
- The high-frequency DC/DC isolation stage provides the galvanic isolation
- It enables asynchronous interconnections and has all the benefits of both ac and dc microgrids. It acts as a harmonic and fault isolator



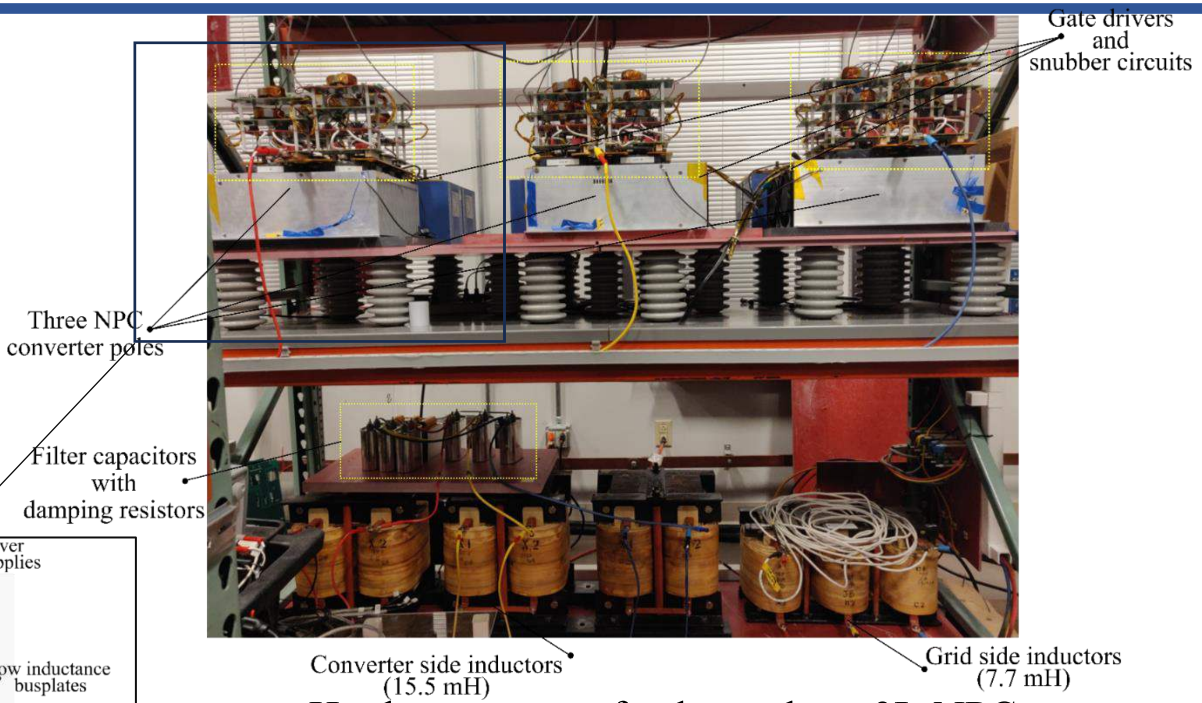


A. Kumar, S. Parashar, N. Kolli and S. Bhattacharya, "**Asynchronous Microgrid Power Conditioning System Enabled by Series Connection of Gen-3 SiC 10 kV MOSFETs**," *2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Atlanta, GA, 2018, pp. 60-67.

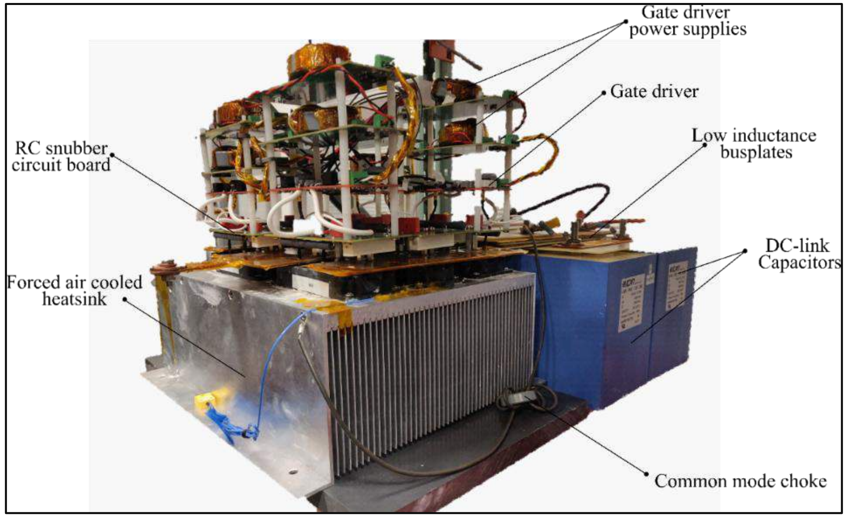
Medium Voltage SST enabled by series connection of 2 x 10 kV SiC MOSFETs



XHV-9 Half-bridge Module

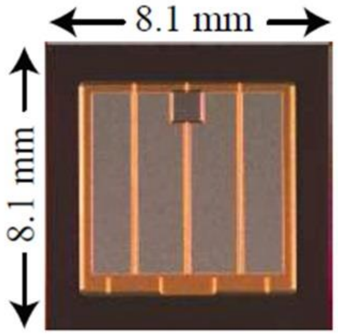


Hardware setup of a modular 3L-NPC pole



Hardware setup of a three-phase 3L-NPC

10kV, 15A SiC MOSFET Bare Die

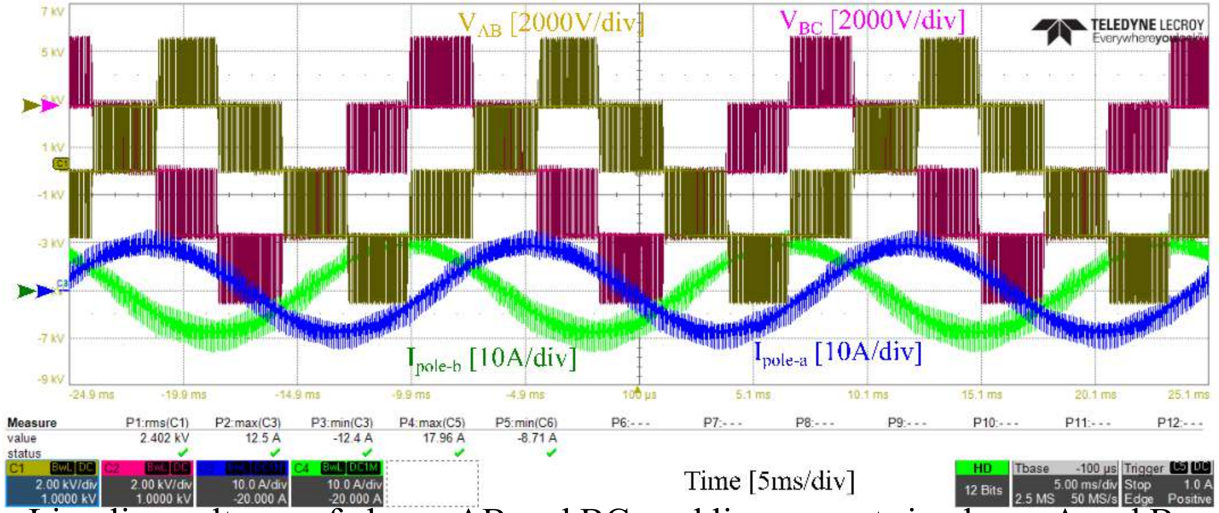


- **Need short circuit protection of the series-connected 10 kV SiC MOSFETs**

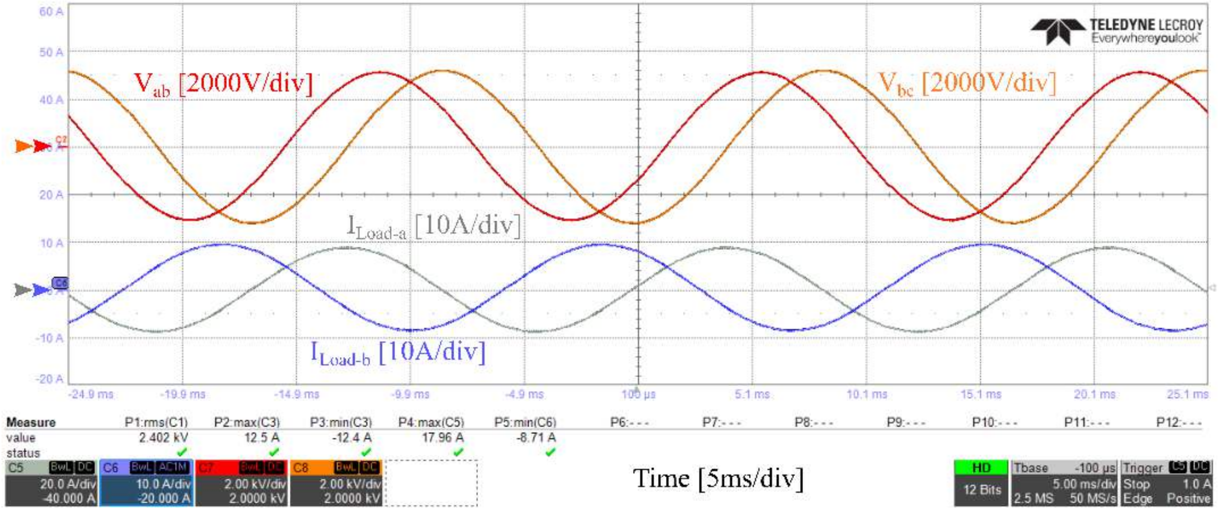
A. Kumar, S. Parashar, N. Kolli and S. Bhattacharya, "**Asynchronous Microgrid Power Conditioning System Enabled by Series Connection of Gen-3 SiC 10 kV MOSFETs**," *2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Atlanta, GA, 2018, pp. 60-67.

Medium Voltage SST enabled by series connection of 2 x 10 kV SiC MOSFETs

Experimental results summary	
Parameter	**Value**
Power	25 kW
DC-link	5.5 kV
Modulation index	0.7
Peak filter capacitor voltage	1800 V

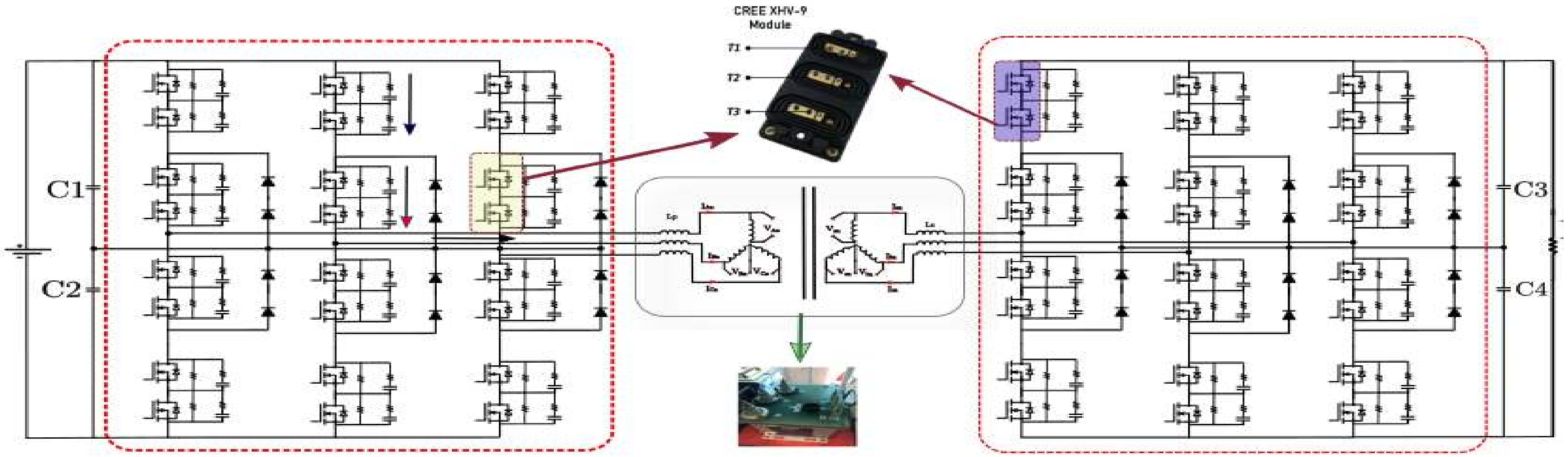


Line-line voltages of phases AB and BC, and line currents in phases A and B

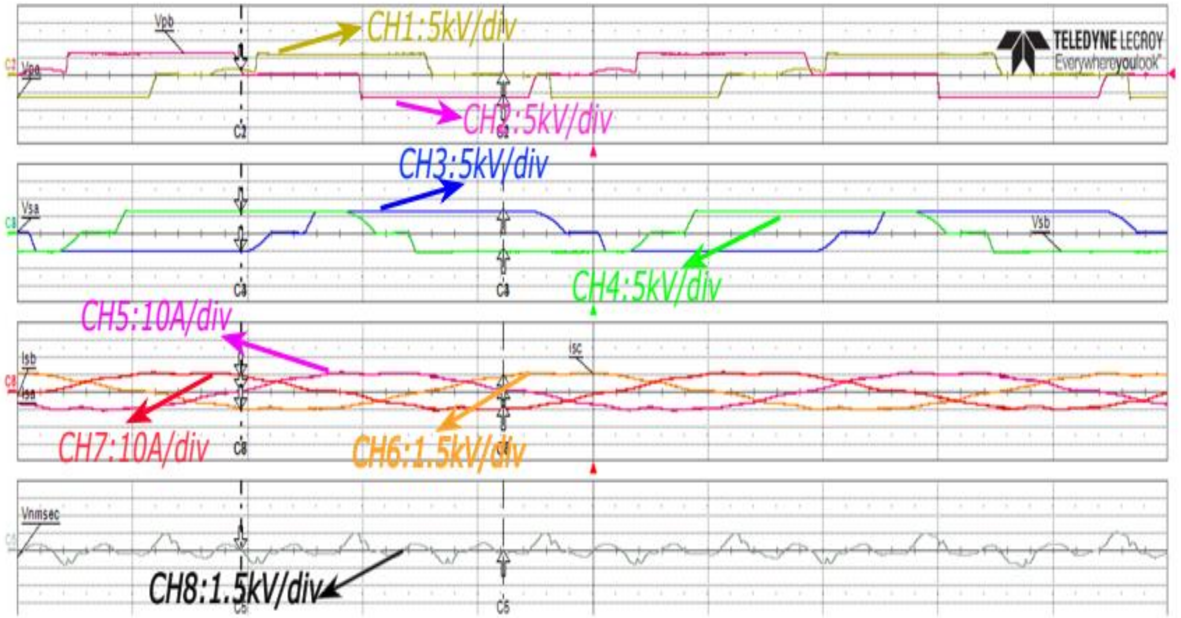


Line-line voltages measured at the load points ab and bc, and load currents in phases A and B

MV Asynchronous Microgrid Connector DAB



Schematic of three-phase three-level neutral point clamped (3L-NPC) Dual Active Bridge (DAB)



Experimental result:
Three-phase three-level DAB at **6.5 kV** DC bus and **28 kW** load

CH1, CH2: Phase A, Phase B primary voltages – 5 kV/div
CH3, CH4: Phase A, Phase B secondary voltage – 5 kV/div
CH5, CH6, CH7: Phase A, Phase B, Phase C transformer currents – 10 A/div
CH8: Neutral point voltage – 1.5 kV/div

Acknowledgements

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- This work made use of FREEDM ERC shared facilities supported by National Science Foundation under award no. EEC-0812121
- Prof. Anant Agarwal and his R&D team at Cree/Wolfspeed for collaborations on HV SiC devices [15kV IGBTs, 10kV MOSFET, 15kV MOSFETs]

https://research.ece.ncsu.edu/bhattacharya/

https://ece.ncsu.edu/people/sbhatta4/

Email: sbhatta4@ncsu.edu

Thank You!!!

Questions

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