# Rugged WBG Devices and Advanced Electric Machines for High Power Density Automotive Electric Drives

**PI**: Victor Veliadis, NCSU
**Key Collaborators & Roles:** Iqbal Husain (Co-PI), Electric Machines;
Subhashish Bhattacharya (Co-PI) WBG Devices;
**Total Project Cost:** $ 1.5 M
**Project to Date Cost:** $600K
**BP2 Electric Machines Budget: $150K**
**Project Duration:** 2nd Year of Five Years

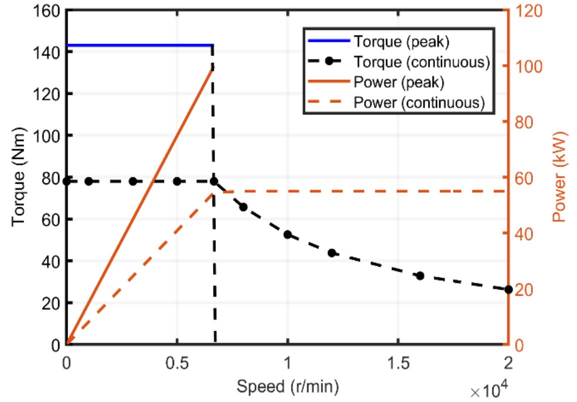
NC STATE UNIVERSITY FREEDM SYSTEMS CENTER **With Collaborators:** OAK RIDGE National Laboratory

- **Critical Path / Key Milestones:** Fabricate a 100 kW Electric Machine that achieves ≥ 50kW/L Power Density.
- **HRE-Free High Power density Electric Machines**

**Proposed Research:** Design and evaluate two variations through comprehensive electromagnetic, thermal and structural analyses

**Technology Summary:** Design and analyze PM machines with HRE-Free Magnets to meet target specifications set forth by the consortium

| Design Parameter | Value |
|---|---|
| Peak Power (kW) | 100 |
| Vol. Power Density (kW/L) | 50 |
| CPSR | 3 |
| Efficiency (%) | >97 |




**Challenges & Opportunities:** Thermal management, Demagnetization of HRE-free magnets, manufacturing with innovative concepts (Challenges); Utilizing innovative concepts in stator and rotor designs and emerging materials (Opportunity); Interaction with consortium members (Opportunity).

# Project Deliverables and Approach

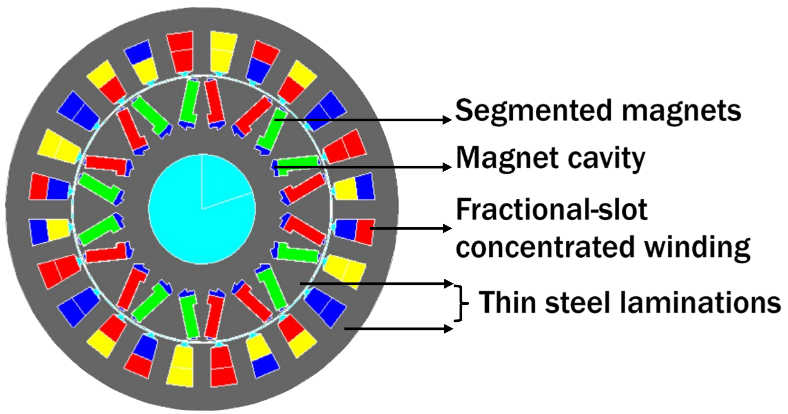
## Project Deliverables

- Design a 100 kW electric machine which meets the target power density of 50kW/L
- Evaluate proposed design through comprehensive 2D and 3D finite-element performance analysis, thermal analysis , demagnetization analysis and structural analysis incorporating innovations in rotor, stator and windings and using emerging materials
- Fabricate the final design and validate the performance results obtained in simulation

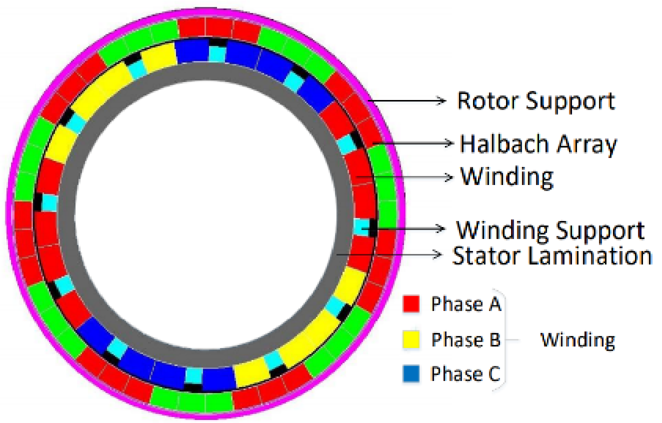
## Approach

- **Design I**: Space-Shifted Asymmetrical Dual Three Phase Interior-type Permanent Magnet Synchronous Machine.
- **Design II:** Slotless Outer-Rotor Halbach Permanent Magnet Synchronous Machine with Winding Embedded Liquid Cooling (WELC)

**Design I**




**Design II**




## Enabling Technologies

### Design I

- Dual space-shifted windings
- Segmented magnets and rotor shape optimization
- Hiperco steel laminations
- End winding potting with SC-320

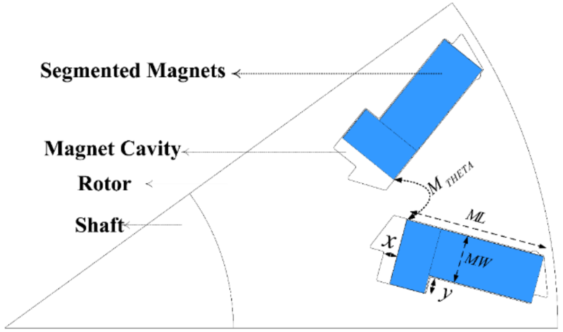
### Design II

- Multi-segment halbach array
- Slotless stator made from Coolpoly D5506 thermally conductive plastic.
- Winding embedded liquid cooling

# Design I: Space Shifted Dual Three-Phase IPMSM

## Technical Approach

- Segmented magnets used to reduce eddy currents
- Strengthen magnet in sections closest to the d-axis
- Displace magnet in the cavity
- Demagnetization included for rotor optimization
- End winding potting with SC-324

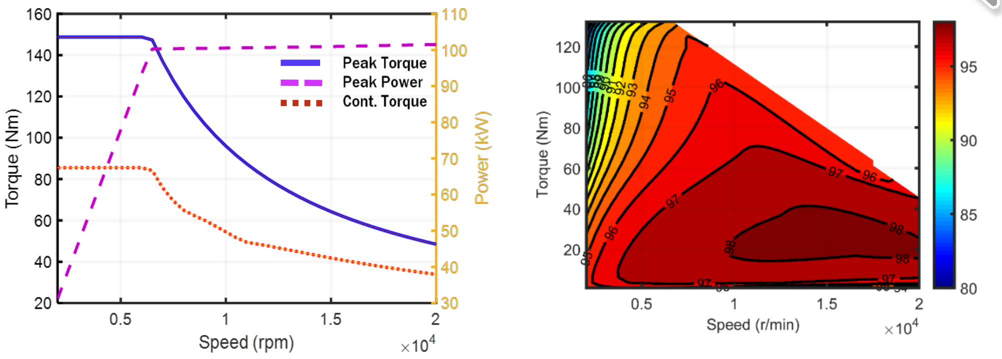



## Materials

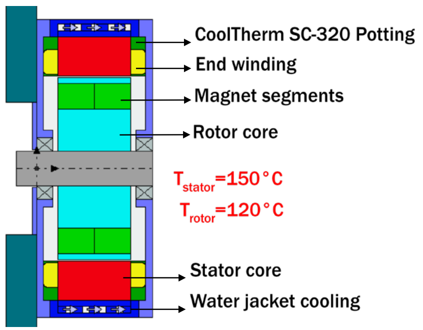
**Steel Laminations:** Hiperco50 (0.15mm)
**Magnets:** NEOREC45MHF (HRE-free)

## Technical Accomplishments

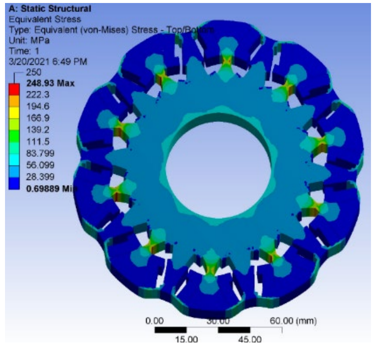
- Meets power density (50kW/L), peak torque (145 Nm) and torque speed specifications
- End-winding potting significantly improves thermal performance.
- HRE-free magnets are demag-free at the worst operating condition.
- Structural integrity of the rotor at a maximum operating speed is also confirmed.



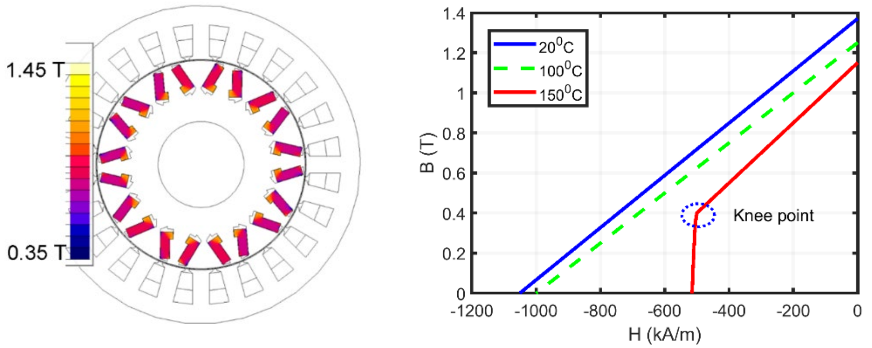
Torque and Output Power Characteristics with Efficiency Maps



Thermal Management



Stress Analysis at 20,000 rpm
(Yield strength of Hiperco is 400MPa)



Worst-case Demagnetization with maximum current in d-axis at 140°C and maximum speed

# Design II: Slotless Outer-Rotor Halbach PMSM

## Technical Approach

- HRE free PM in Halbach array rotor.
- Absence of rotor lamination and reduced stator lamination leads to low (thermal) mass
- Winding Embedded Liquid Cooling (WELC) concept used with thermally conducting plastic supports.
- Winding supports are constructed of high conductivity (9.4 W/mK) plastic (Coolpoly D5506)
- Aluminum water jacket beneath stator provides a parallel path for heat flow out of windings.

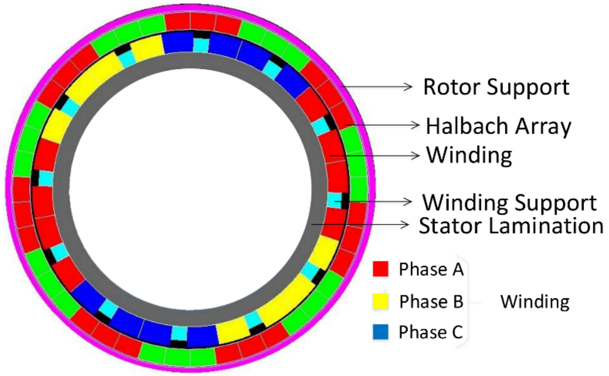
## Technical Accomplishments and Next Steps

- Continuous current density is 23.3 $\mathrm{A/mm^2}$ for 85 kW output power for a flow rate of 8 liter/ minute
- For peak power duration of 18 seconds, 120 kW output is possible using the proposed concept.
- Meets the target power density (50kW/L) and peak torque (145Nm) requirements; peak efficiency is 97%

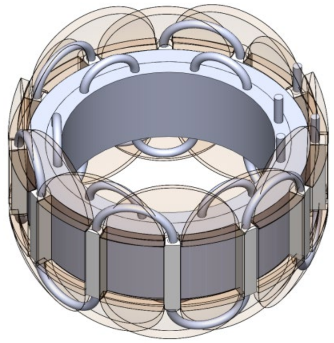
## Next Steps

- Validate the performance of the WELC concept through experiments on a single slot excitation.
- Fabricate a scaled version of the proposed designs to validate the adopted technologies.

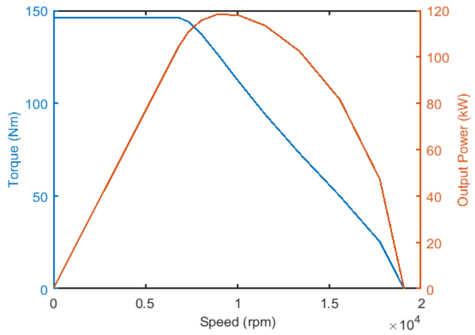
Any proposed future work is subject to change based on funding levels

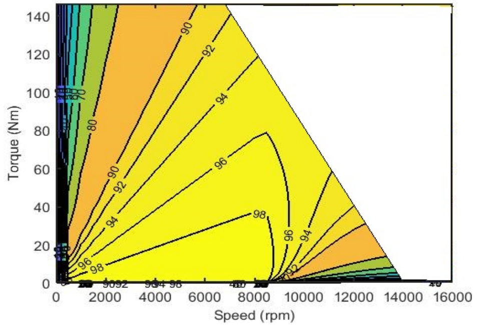



Slotless Motor with Halbach array

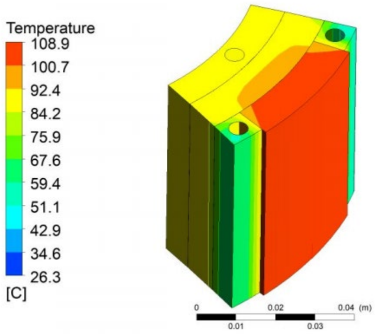


WELC concept

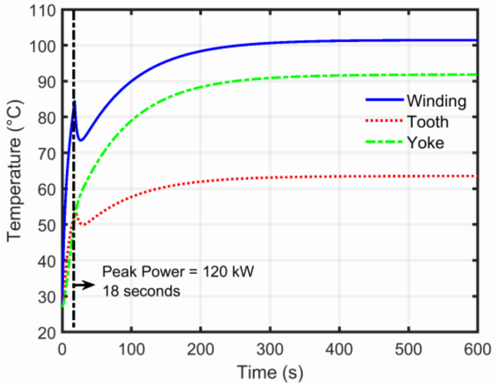



Torque and Output Power Characteristics with Efficiency Maps




Slot Temperatures for current density of 23 $\mathrm{A/mm^2}$

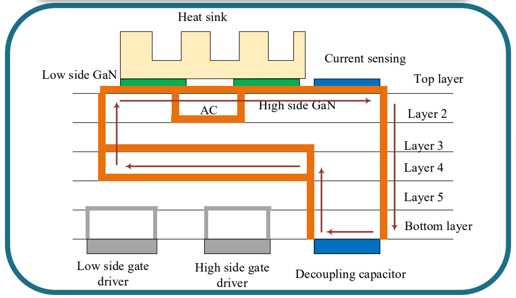



Transient thermal performance

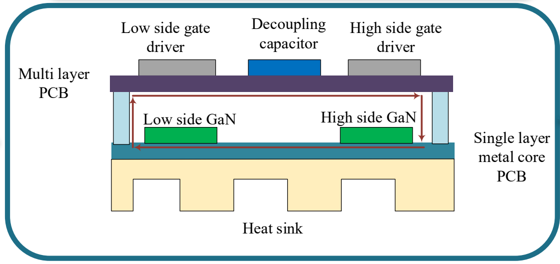
# Develop Gate Drivers for GaN Module Evaluation

- Double Pulse Testing (DPT) evaluation of designed gate driver at 400V, 160A (4 paralleled 650V, 60A GaN devices)
- Tested conditions:
  1. Turn on: dv/dt = 11.7kV/μs, di/dt = 5.3kA/μs
  2. Turn off: dv/dt = 42.5kV/μs, di/dt = 3.9kA/μs
- Total Switching Loss at 400V/160A = 1645 μJ
- Short Circuit (SC) Protection: Detection + Turn-off time = 200ns

## Gate Driver Evaluation for Parallel GaN Devices

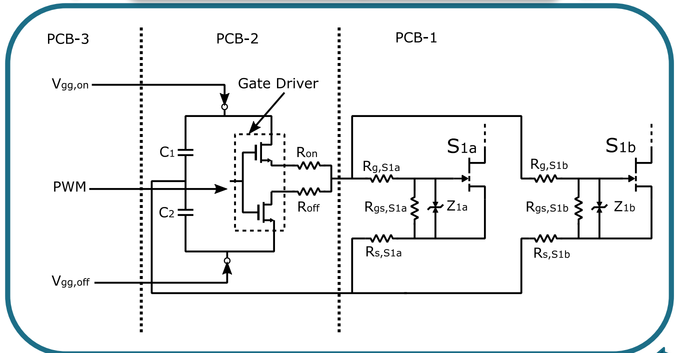



## Prototype Design for 3L-ANPC Phase Leg

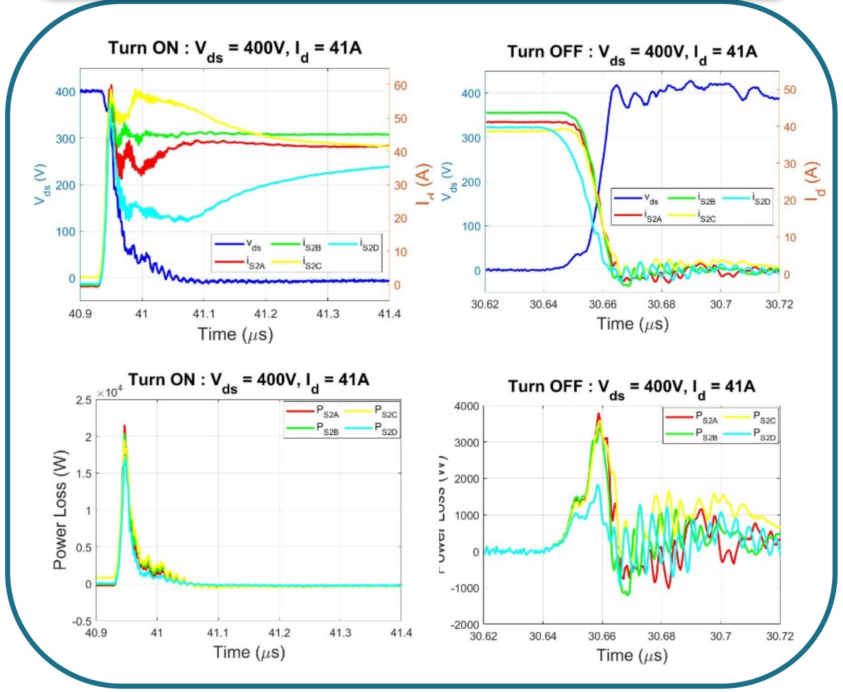



- 3-phase 3-level Active Neutral-Point-Clamped (ANPC) design with targeted operation of >35kW.
- Bottom-cooled two parallel GaN devices with IMS PCB for better thermal performance.
- Optimized short and long loop inductance for safe switching of devices.

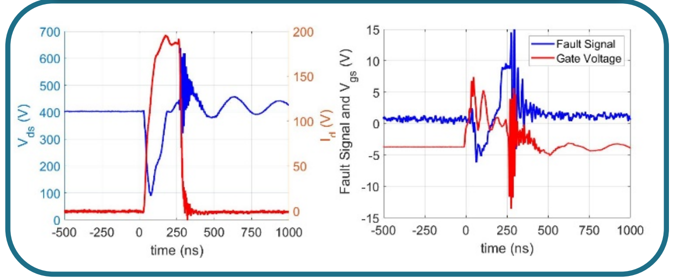
## Evaluated Gate Drive design

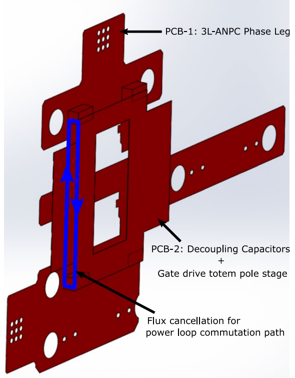



## Experimental Results for DPT of 4 Parallel GaN Devices

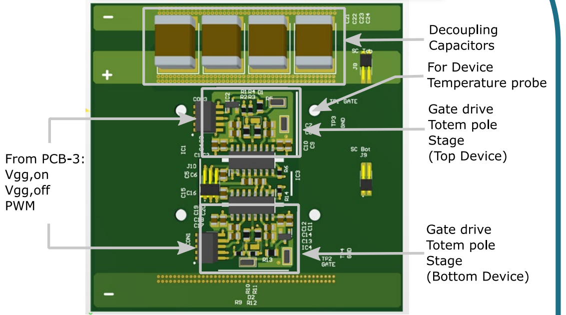



## Experimental Evaluation of SC Protection at Vdc = 400V

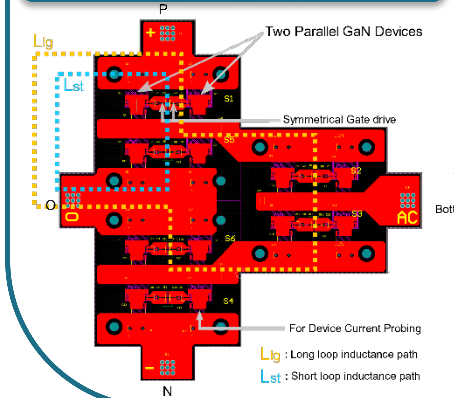


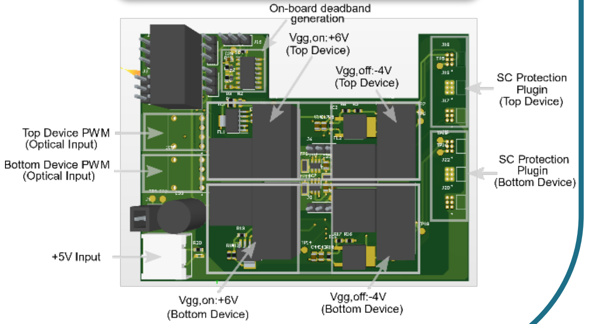

## PCB-2: Gate Drive Totem Pole Stage




## Insulated Metal Substrate PCB-1: 2x GaN




## PCB-3: Gate Drive Power Supply Stage

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