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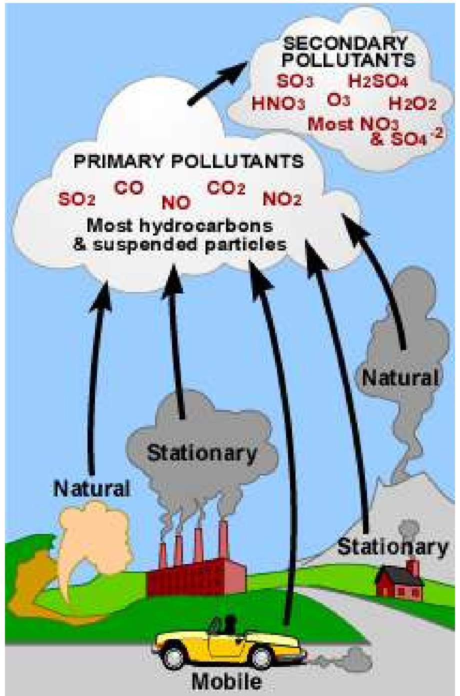
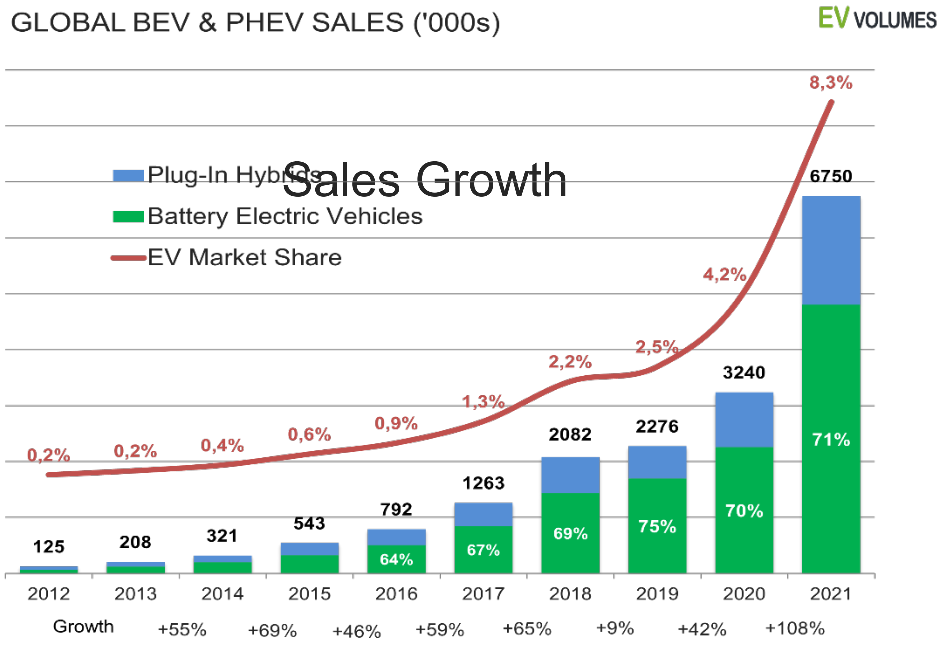
Electric Machines and Drives for Transportation Electrification

Iqbal Husain
Director, FREEDM Systems Center
ABB Distinguished Professor, ECE
NC State University
FREEDM Annual Symposium 2023

Trends: Electric Transportation

- **Market Drivers for Electric Transportation:** Energy diversification, environmental concerns and economic growth. Global sale of EVs that include both battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs) exceeded the 6 million mark in 2021
- **Innovation Opportunities**: Increased telematics, autonomous vehicles, WBG power electronics, lightweight electric machines, energy storage
- **Charging Stations:** Fast and Extreme Fast Charging Stations that will give the customer similar experience as that in a gas station





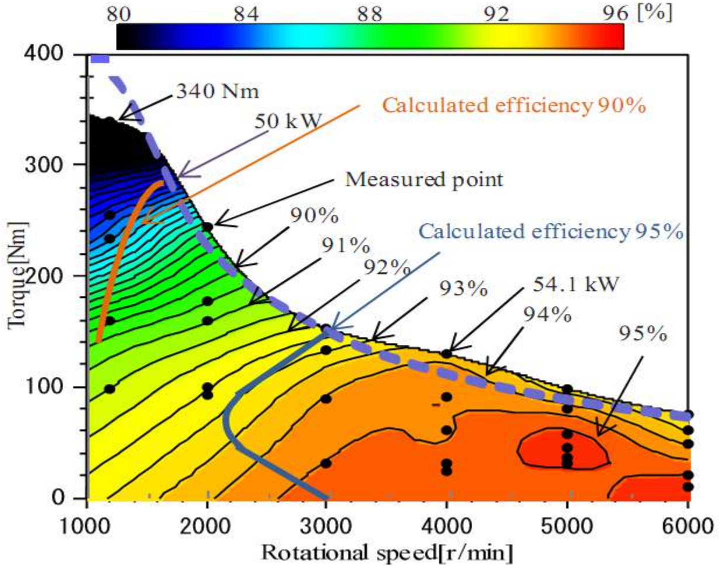
Source: ev-volumes.com

Trends in Traction Electric Machines

- Electric Machines and Inverters ➡ Key components of Electric Powertrain

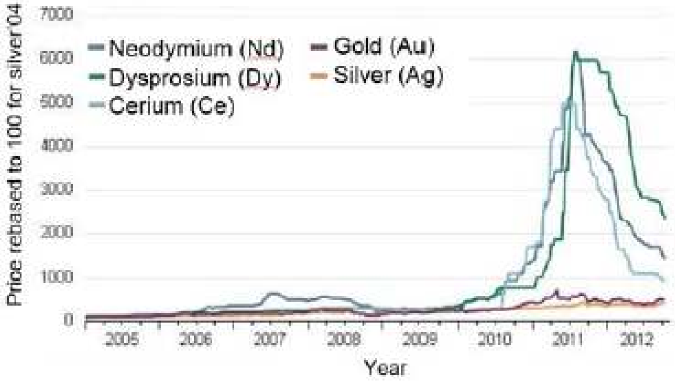
Objectives for Traction Machines:

- High density (P_{den}, T_{den})
- High efficiency (η)
- High speed operation (ω)
- Low acoustic noise
- Low torque ripple
- Thermally stable
- Structural integrity
- Low $/kW design



Trends:

- IPMSMs: Most popular with Rare Earth (RE) PMs.
- Instability in RE's price drives R&D for alternatives
- Novel magnet and lamination materials, designs, and winding configurations



RE price vs gold & silver (source: Thomson Reuters)

Electric Machine Design Trends: Increase DC-link Voltage and Machine Speed

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High Pole Design

- Increases torque density
- Reduces end turn length
- Reduces cost of PMs

High Speed Design

- Increases power density $(T \infty D^2 L)$
- Reduces system mass

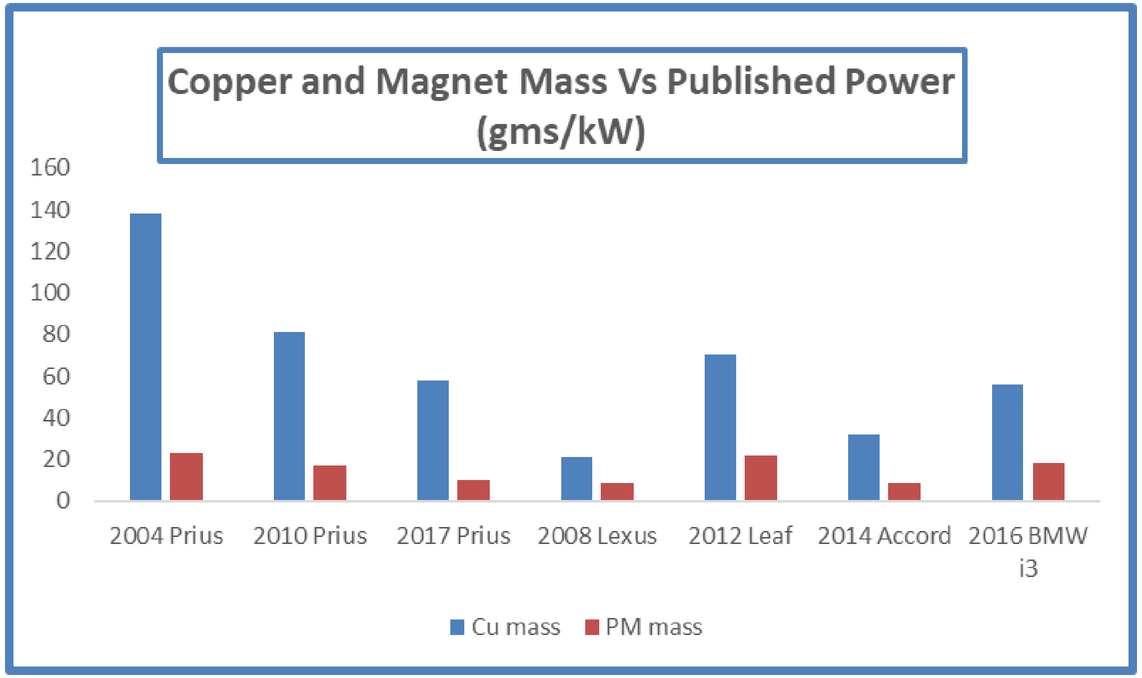
Adoption of Hairpin Winding

- Increases efficiency
- Improves torque-density
- Improves overload capability

$(P_{den} \uparrow)$
$(T_{den} \uparrow)$

Wide Band Gap (WBG) Drives

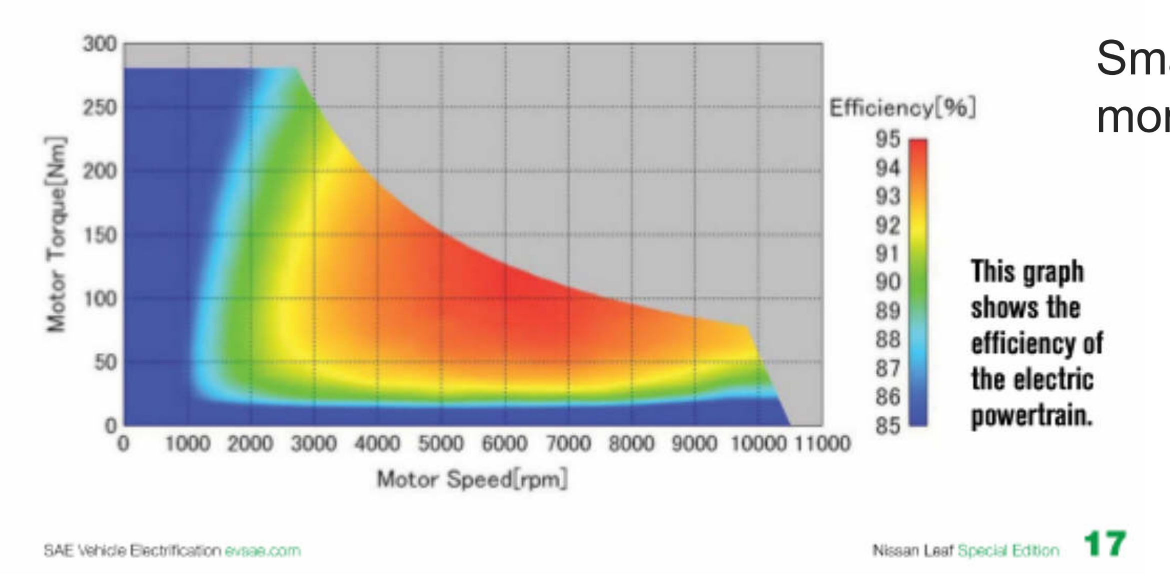
- System power density increase
- Better current regulation
- System efficiency increase

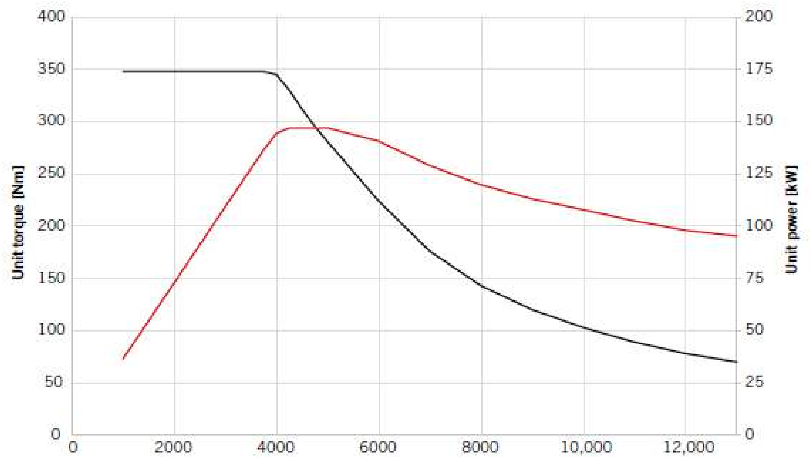


Trends in Design Requirements

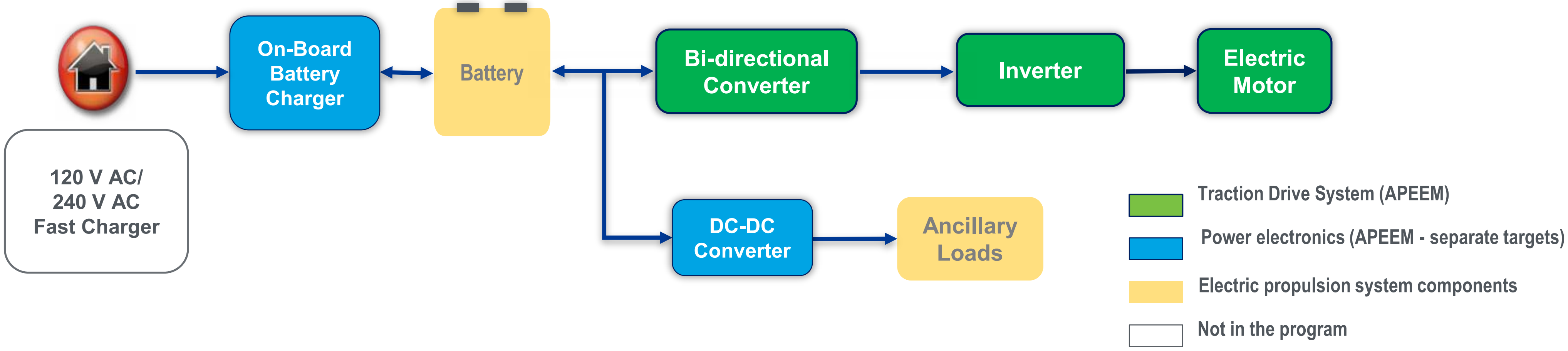
Magnet Weight Minimization

- Higher current/ Current density
  - Better Cooling
  - Bar Windings → AC loss minimization
- Higher speeds
  - AC loss minimization
    - Smaller/ more bars
  - Structural issues
    - Wrapped rotor, smaller rotor OD
- RE/HRE free designs
  - WFSM
  - Improved magnet technology





Electric Vehicle Powertrain Research



➢ US Department of Energy targeted research for reduced rare-earth based electric machines

Traction Drive Systems (TDS)			
Impact	Reduce Cost	Reduce Weight	Reduce Volume
Year	Cost ($/kW)	Specific Power (kW/kg)	Power Density (kW/l)
2010	19	1.06	2.6
2015	12	1.2	3.5
2020	8	1.4	4.0
2025	6		33

	Power Electronics (PE)		
	($/kW)	(kW/kg)	(kW/l)
2010	7.9	10.8	8.7
2015	5	12	12
2020	3.3	14.1	13.4
2025	2.7		100

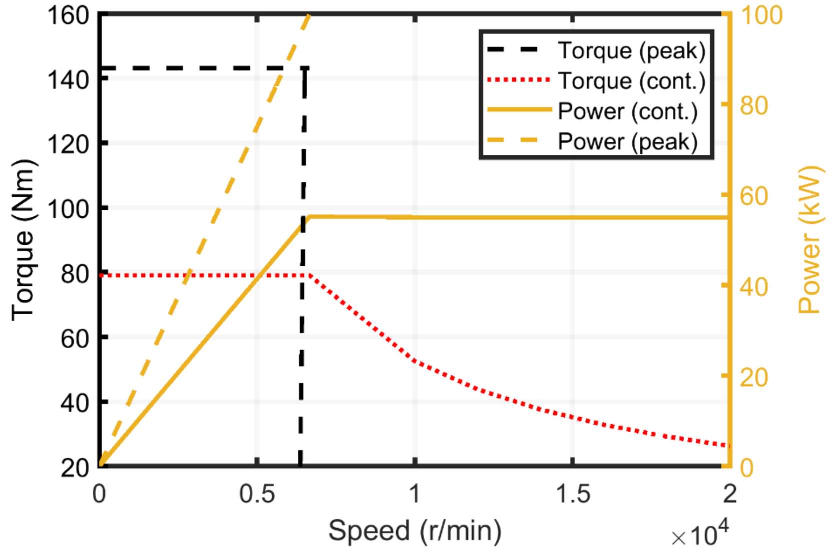
	Electric Motors (EM)		
	($/kW)	(kW/kg)	(kW/l)
2010	11.1	1.2	3.7
2015	7	1.3	5
2020	4.7	1.6	5.7
2025	3.3		50

Electric Vehicle Machine Design

Department of Energy's U.S. Drive roadmap 2025 targets a power density of 50 kW/liter for electric vehicle traction motors:

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

Target Design Specifications



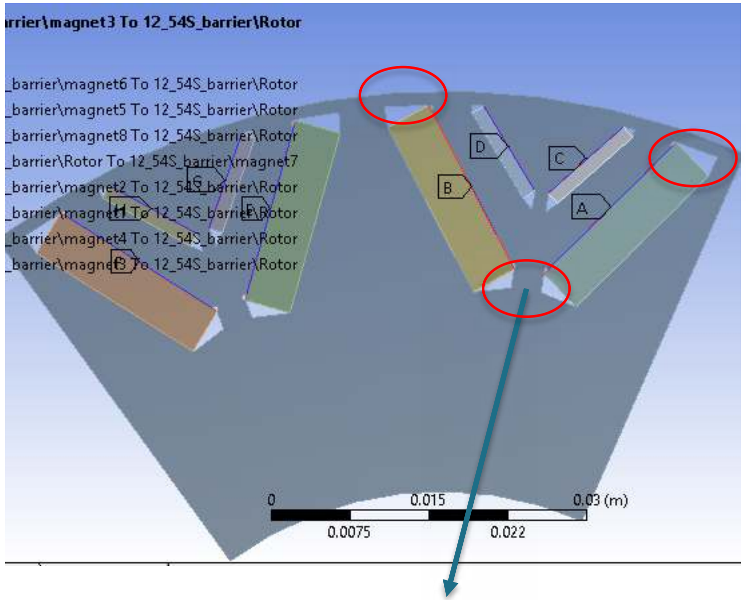
Target Torque Speed Profile

Design of two motors which meet the target specifications while addressing the issues:

- **Design I:** Space-shifted Asymmetrical Dual Three Phase IPM Synchronous Machine, SS-ADTP IPMSM
- **Design II:** Outer Rotor Slotless SPM with Halbach Array and Winding Embedded Liquid Cooling

Issues with Next Generation High Speed Electric Machines

- Excessive magnetic loss (Core and PM)
- High centrifugal forces on rotor pole ribs
- Skin and proximity effects become prominent
- Mechanical power losses increase
- Use of Amorphous Magnetic Material or super core may reduce the core loss of the machines.
- Thinner lamination reduces mechanical strength and maximum flux density



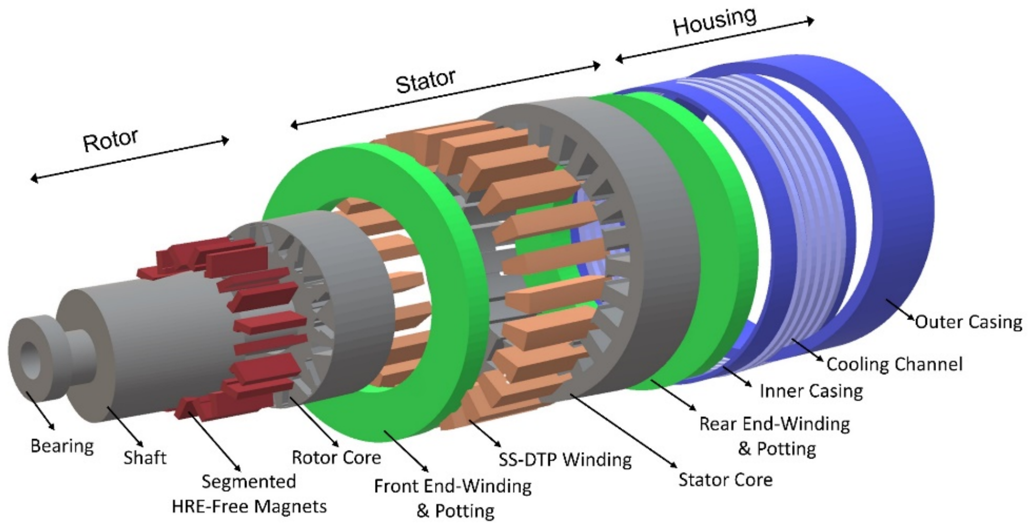
- Magnet demagnetization
- Thermal limits of heavy rare earth free magnet materials
- High dv/dt due to the short rise time and fall time increases the possibility of bearing damage, insulation degradation, and first turn short of the winding

Simultaneous Electromagnetic, Structural and Thermal optimizations are essential during design stage

Design 1: Space-Shifted Asymmetrical Dual Three Phase IPMSM

Design 1 Features:

- Dual space-shifted windings
- Segmented magnets and rotor shape optimization
- Hiperco 50 steel laminations
- End winding potting with SC-320



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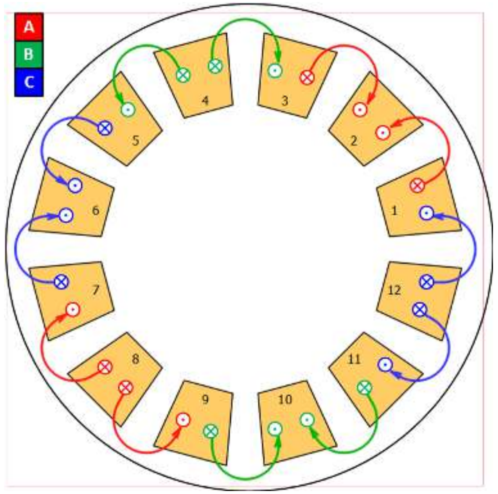
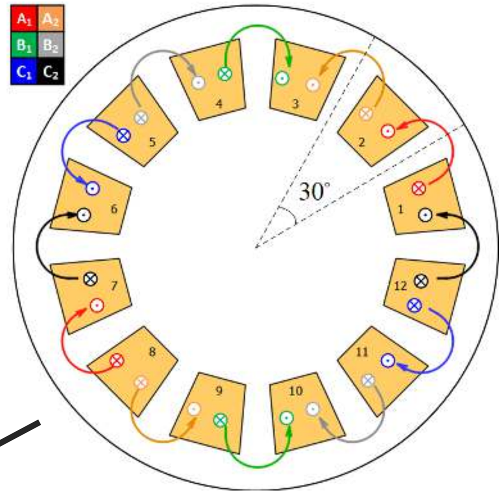
Design I: Proposed Winding Arrangement

12 slot, 10 pole , 3-Φ Winding → 12 slot, 10 pole , Dual 3-Φ Winding

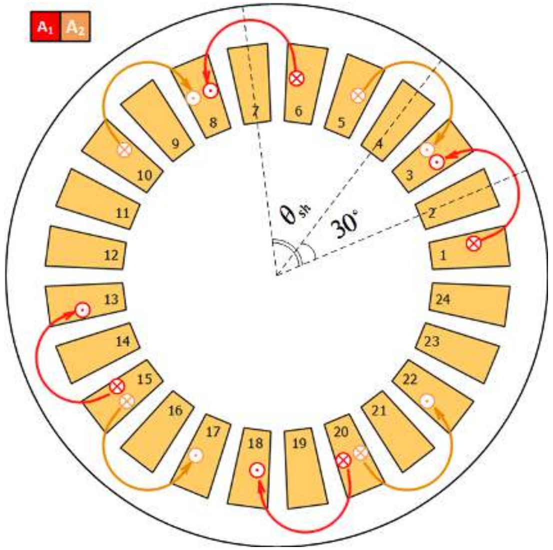


- ✓ High winding factor
- ✓ Low cogging torque
- ✓ Short end-turns
- × Rich harmonic content
- × High core and magnet loss
- × High rotor temperature



- ✓ Increase in winding factor
- ✓ Cancellation of subharmonic content
- ✓ Increased fault tolerance
- × Slight increase in super harmonics

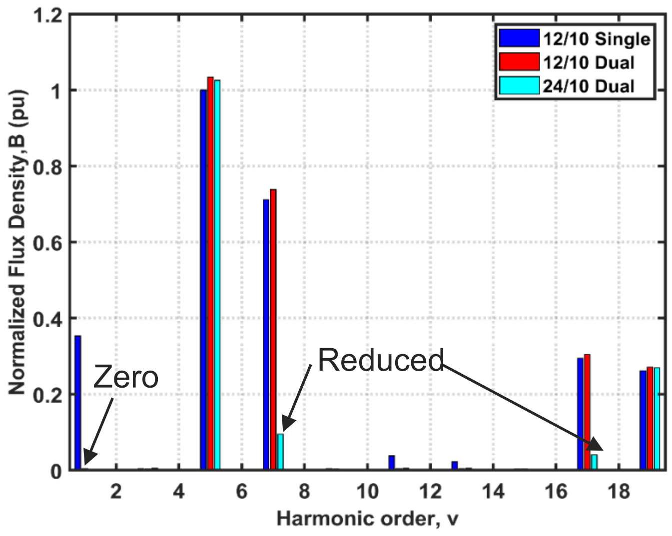
24 slot, 10 pole , Space-shifted Dual 3-Φ Winding



$$MMF = \sum_{v=1,-5,7}^{\infty} \frac{12NI}{v} \sin\left(\frac{v\pi}{12}\right) \sin\left(\frac{(v-1)\pi}{12}\right) \cos\left(\frac{v\theta_{sh}}{2}\right) \sin\left(v\theta - \omega t - \frac{(v-1)\pi}{12} - \frac{v\theta_{sh}}{2}\right)$$

7th Harmonic Cancellation : θ_{sh} = 77.15° (Choose θ_{sh} = 75°)

- ✓ Cancellation of 1st order harmonic
- ✓ Significant reduction of 7th and 11th order harmonic
- ✓ Reduced core loss and eddy current loss
- ✓ ~2.5% increase in winding factor
- × Slightly higher copper loss (coil pitch =2)



Normalized armature flux density in a 12 slot, 10 pole winding and a 24 slot, 10 pole space shifted dual three phase machine

Rotor Design and Optimization

- Standard V-type magnet arrangement
  - ✚ Widely established manufacturing process
- HRE-free Magnets
  - ✚ Low Cost
  - — Demagnetization risk at high temperature

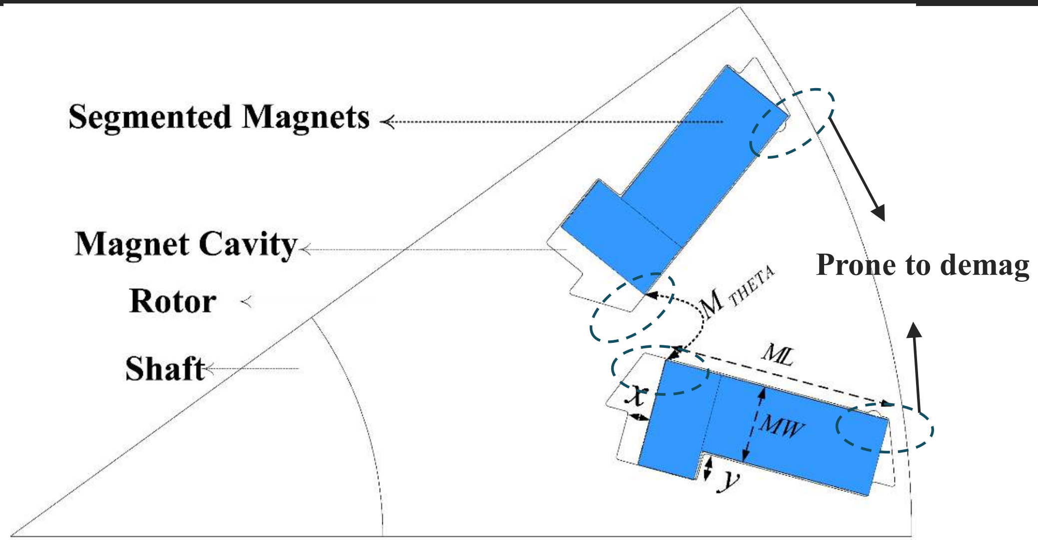


Fig: Single pole of the proposed magnet arrangement

Proposed Segmented Magnet Approach

- Segment magnet into several pieces to reduce eddy currents
- Strengthen magnet in sections closest to the d-axis
- Displace magnet in the cavity
- Include demagnetization consideration in the rotor optimization

Optimization I: maximize torque and minimize torque ripple

$$Max(T_{avg}), Min(T_{ripple}) = f(ML, MW, M_{THETA}, x, y, TW, \gamma)$$

$$\text{Subject to } I_{A/mm^2} \le 33.3$$

$$MV(kg) \le 0.75$$

Optimization II: Demagnetization at worst case scenarios

$$Max(B_{cornerMagnet}) = f(ML, MW, M_{THETA}, x, y)$$

$$\text{Subject to } I_{A/mm^2} = 33.3$$

$$\gamma = 90^{\circ}$$

Electromagnetic Performance

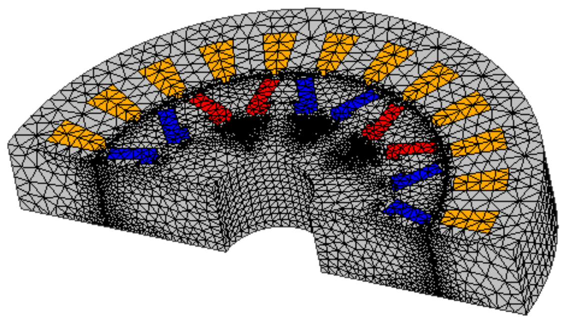
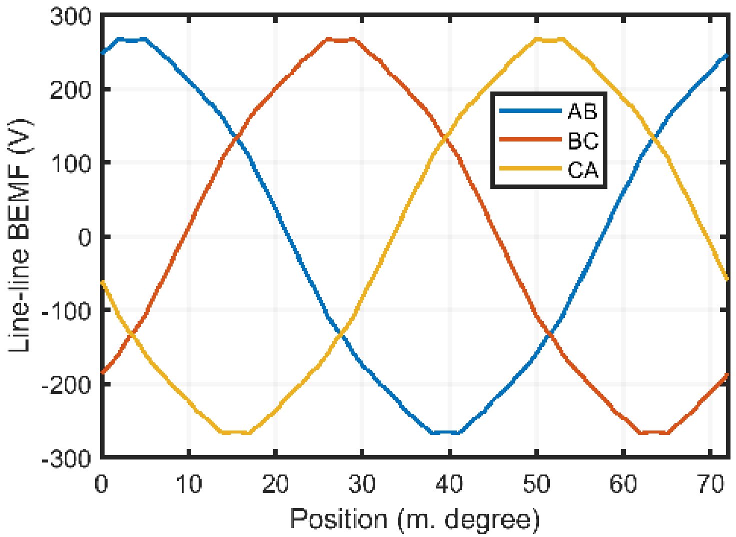
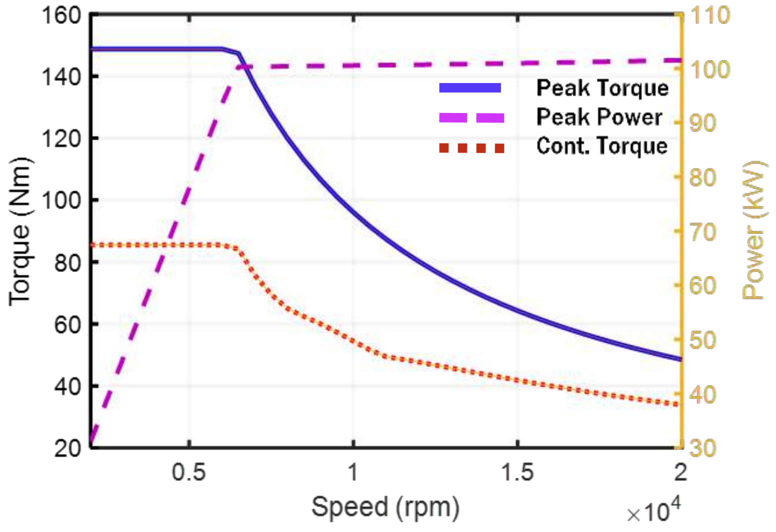


Fig: 3D FEA Model



Line-line BEMF voltage



Torque-Speed Characteristics

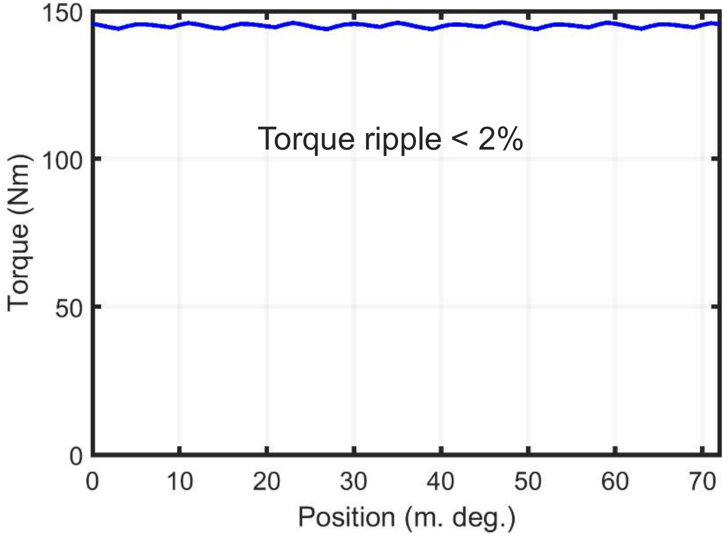
Materials

Steel Laminations

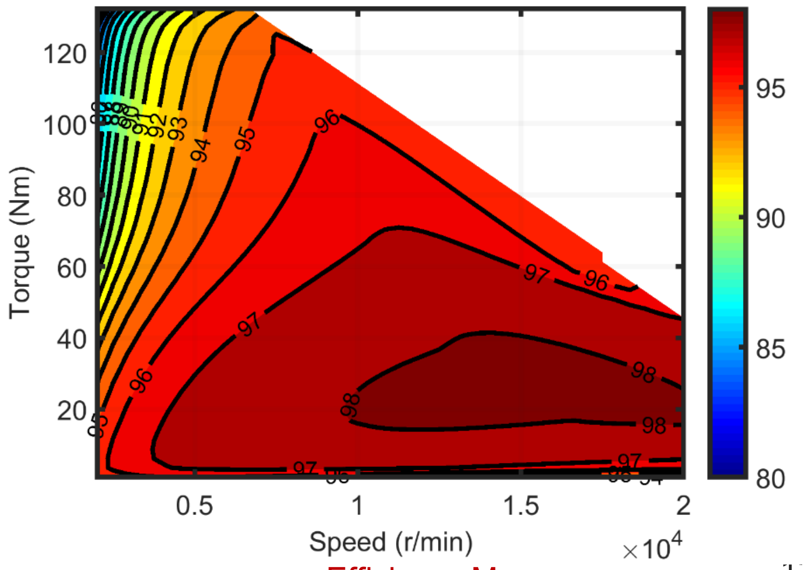
- Hiperco50 (0.15mm)

Magnets

- NEOREC45MHF (HRE-free)



Electromagnetic Torque

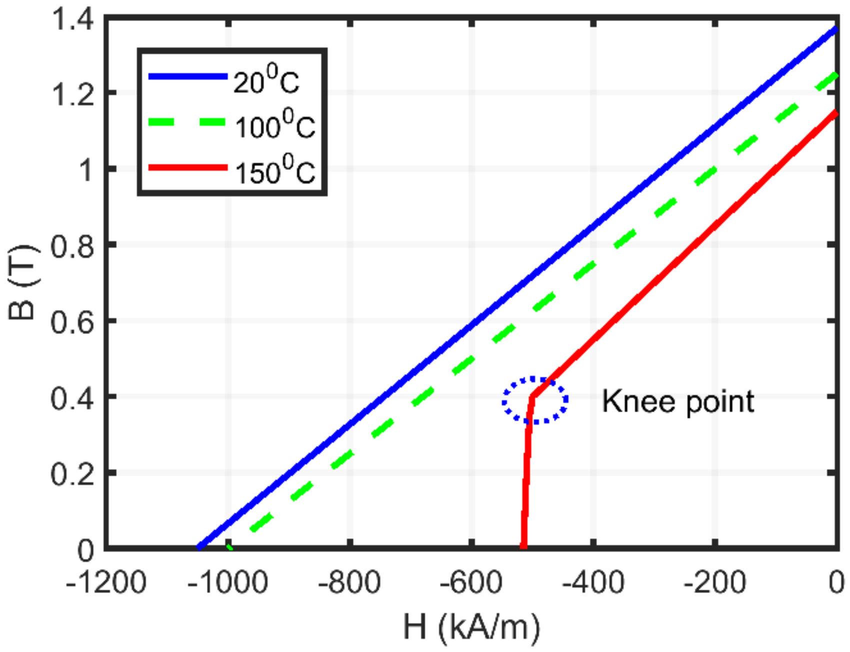


Efficiency Map

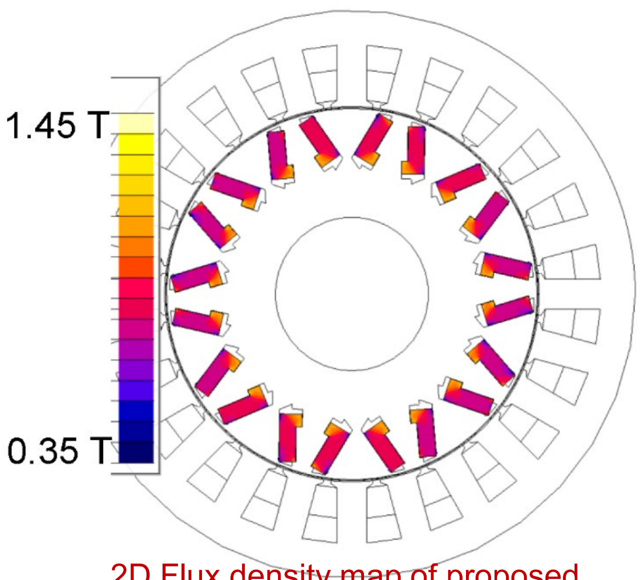
Demagnetization Analysis

Worst Case Scenario

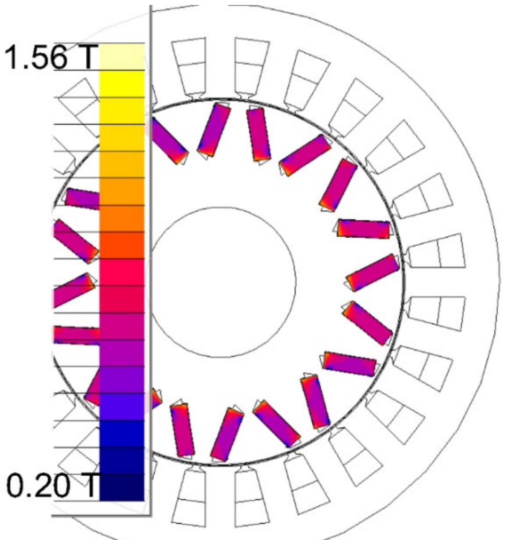
- Maximum Current in the negative d-axis at high temperature of 140°C and maximum speed



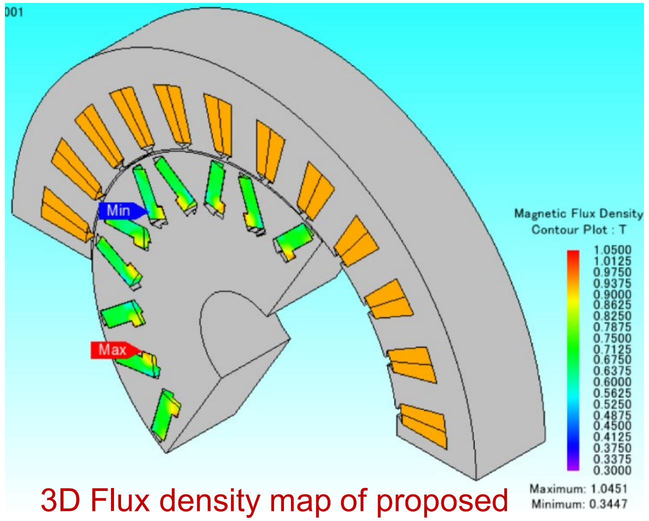
B-H characteristic of HRE-free Magnet



2D Flux density map of proposed segmented V-magnets



2D Flux density map of conventional V-magnets



3D Flux density map of proposed segmented V-magnets

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Cost-Performance Analysis of Core Materials

	Case I	Case II	Case III	Case IV
Material				
Stator	Hiperco 50	Hiperco 50	HF-10	HF-10
Rotor	Hiperco 50	HF-10	Hiperco 50	HF-10
Electromagnetic Performance				
Torque @ peak load (Nm)	145	146.9	118	125
Output power density (kW/L)	50	51.5	41.4	43.4
Iron Loss				
Stator core loss @ full load and rated speed (W)	488.5	439.9	1017	928.4
Rotor core loss @ full load and rated speed (W)	122.6	308.6	96.9	256.0
Electromagnetic Performance with Thermal Limit				
Torque @ peak load (Nm)	145	132	115	110
Output power density (kW/L)	50	46.3	40.34	38.6
Cost				
Cost of stator ($ per-unit)	1	1	0.24	0.24
Cost of Rotor ($ per-unit)	0.75	0.30	0.75	0.30

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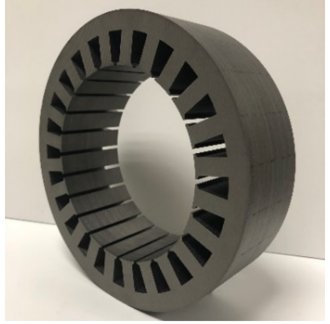
Concept Validation with Prototypes

Completed

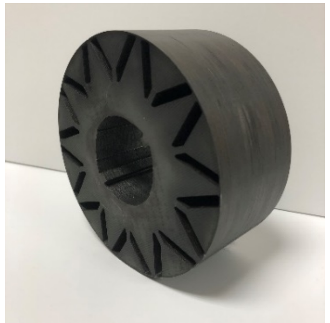
- Concept verified with a scaled prototype of ADTP winding structure using a model free predictive current controller*
- Stator and rotor built for fabricating the 100 kW prototype of Design I.
- HRE-Free magnets acquired

Next Steps

- Replace stator of a 2010 Nissan Leaf Motor with the proposed 24-slot asymmetrical dual three-phase winding and HF-10 core.
- Pot end winding with SC-324.
- Replace the rotor with the proposed 10-pole rotor with HRE-free magnets and HF-10 core.



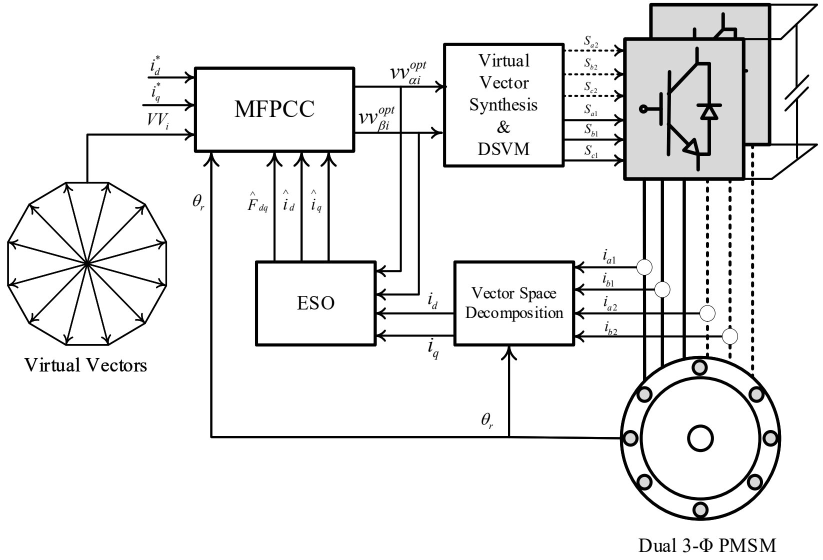
Stator lamination



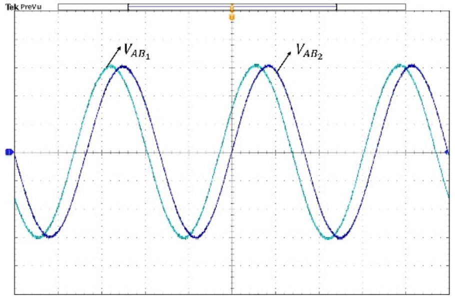
Rotor lamination

Spiral Water Jacket Housing

Scaled prototype of ADTP winding



Drive System block diagram



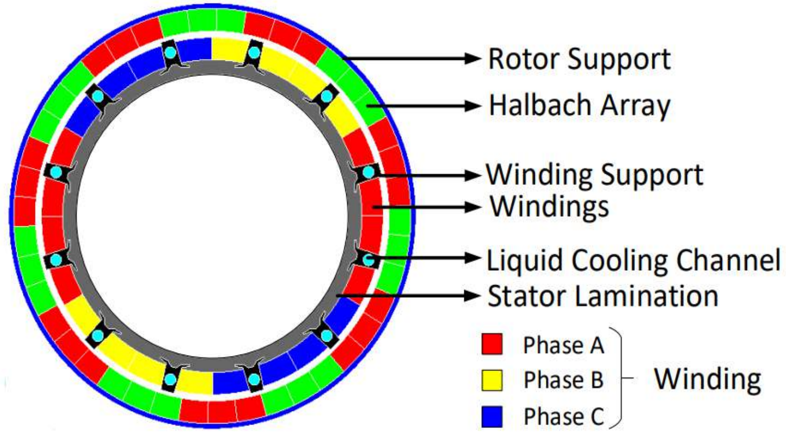
Back-EMF waveform of prototype ADTP winding

Rotor Shaft

Winding Process

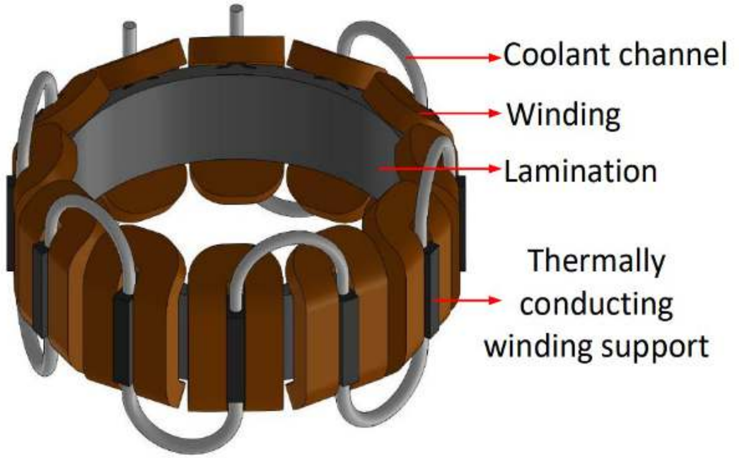
*S. Agoro and I. Husain, "Model-Free Predictive Current and Disturbance Rejection Control of Dual Three-Phase PMSM Drives using Optimal Virtual Vector Modulation," in IEEE Journal of Emerging and Selected Topics in Power Electronics; doi: 10.1109/JESTPE.2022.3171166.

Design II: Slotless HalBach Permanent Magnet Synchronous Machine with Winding Embedded Liquid Cooling



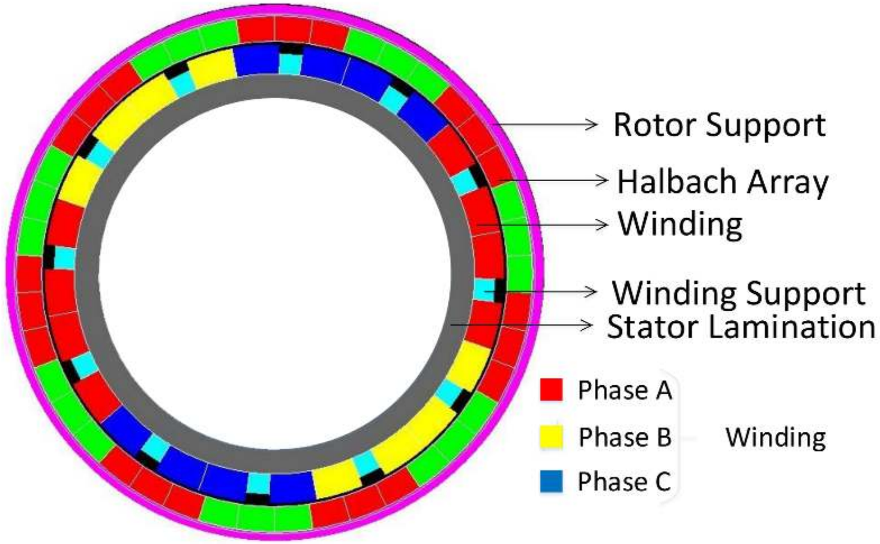
Design II Features:

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

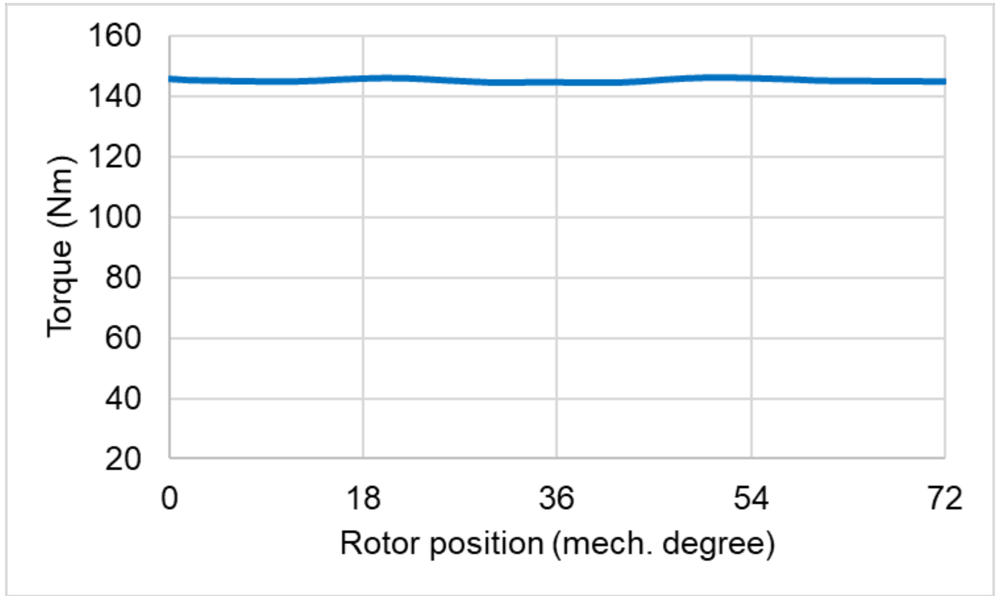


Design II: Slotless Halbach PM

- HRE free PM in Halbach Array Rotor.
- Absence of rotor lamination and reduced stator lamination leads to low thermal mass; needs good thermal management.
- Thermally conducting plastic winding supports with Winding Embedded Liquid Cooling (WELC).



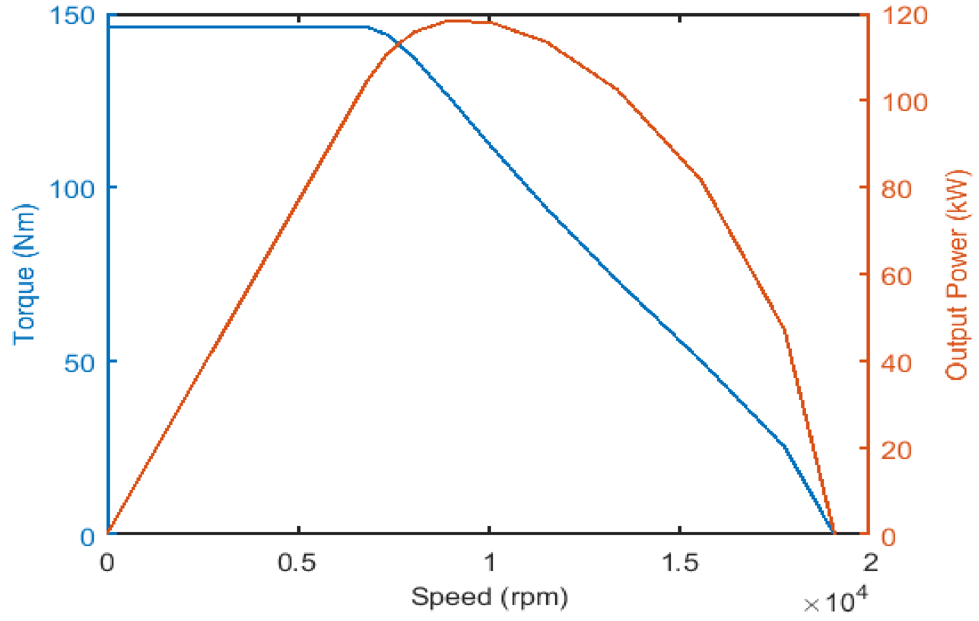
Schematic of Slotless Motor with Halbach Array



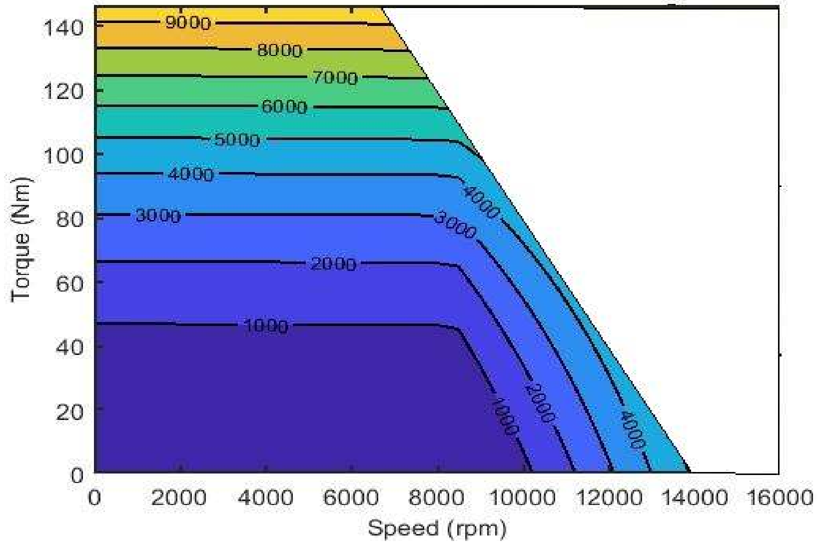
Torque Profile

Electromagnetic Performance

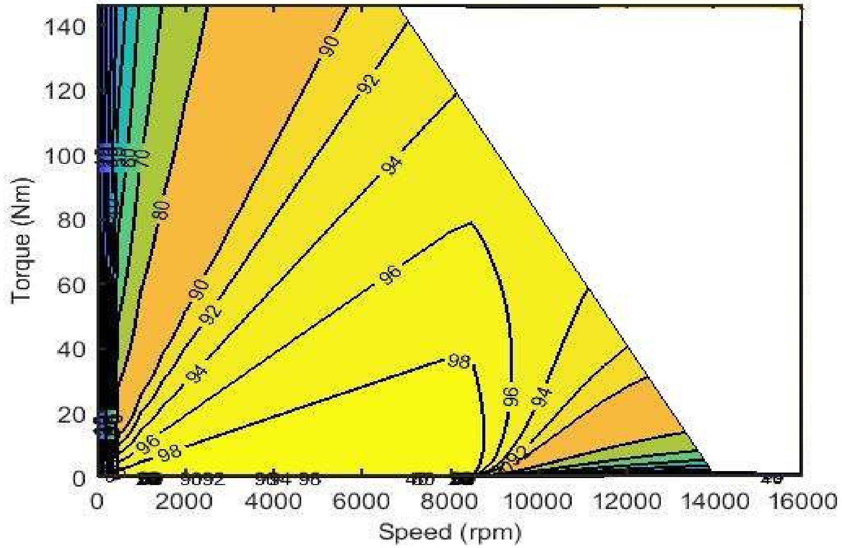
- The roadmap specifications of output power, power density and efficiency (>=97%) are met.



Torque and Output Power Characteristics

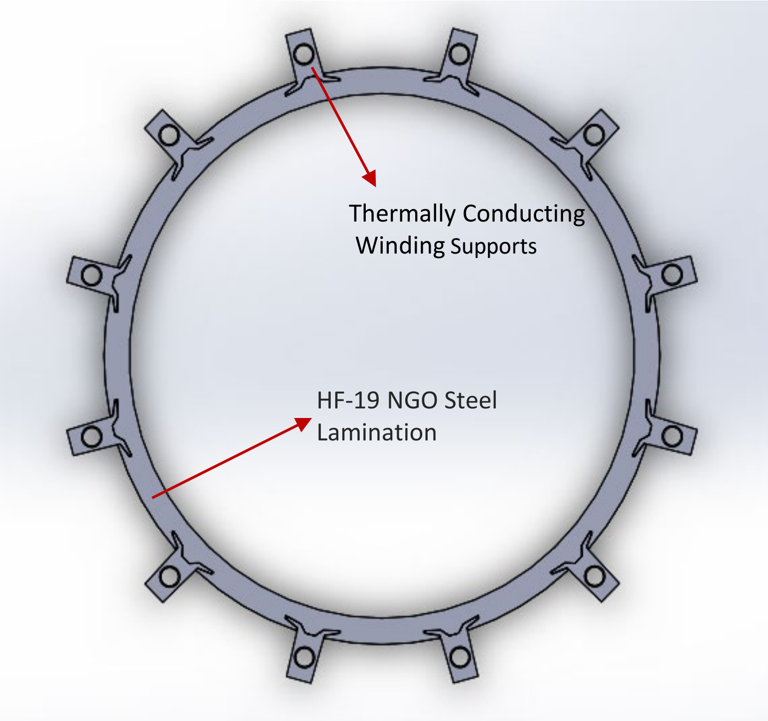


Total Loss Map



Efficiency Map

Prototype Design for a 10kW Slotless Machine with WELC



CAD schematic of stator of slotless motor with WELC

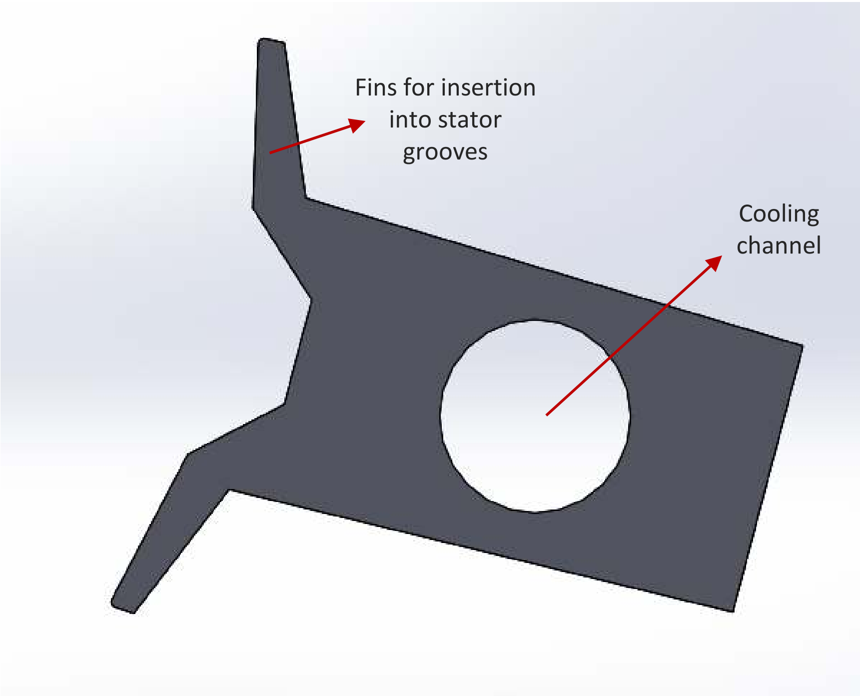


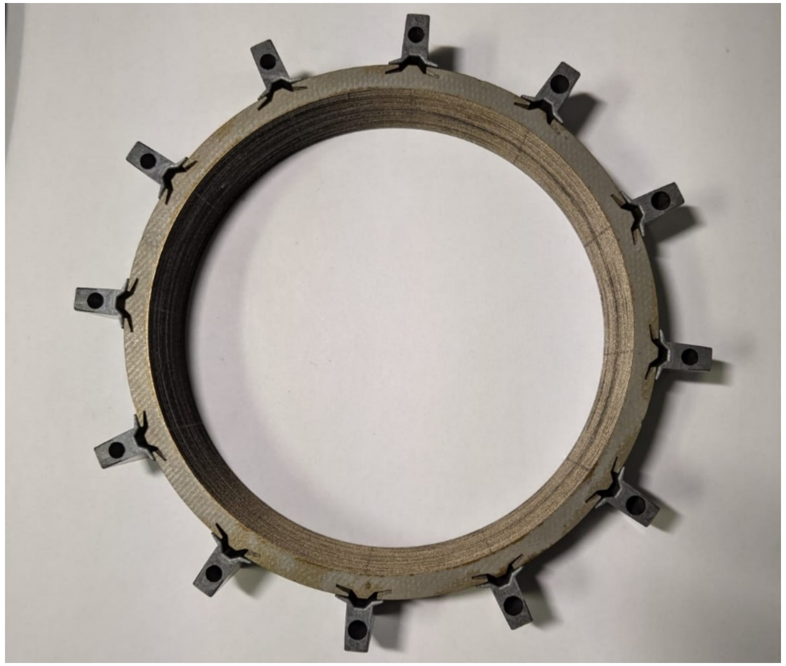
Fig. Zoomed in view of stator winding support showing cooling channel

Parameters	Value
Rotor Outer Diameter (mm)	145
Length (End-turn included) (mm)	40
Active Length (mm)	28
Stator Inner Diameter (mm)	94
Stator Outer Diameter (mm)	135
Output Power (kW)	10.8
Power Density (kW/L)	28.2

Table. Parameters of the scaled-down prototype

Slotless Machine with WELC

- Lamination and thermally conducting winding supports have been fabricated.
- Due to absence of laminated teeth, saturation within lamination is low.
- Using FEA, only a 6% difference in iron loss was found between HF-10 and Hiperco laminations at the base speed point.
- Therefore, HF-10 non-oriented cobalt-free steel laminations are used in the prototype.



(a)

(b)

(c)

Fig. Prototype as fabricated: (a) Full stator (b) Lamination and (c) Winding Support with cooling channel

Slotless Machine with WELC

- Winding supports constructed of D5506 thermally conducting polymer (9.6 W/mK) fabricated using injection molding.
- Windings encapsulated in Resbond 906 (5.8 W/mK) ceramic epoxy.
- WELC concept validated for continuous current densities up to 19 A/mm^2 and peak current densities up to 39 A/mm^2.

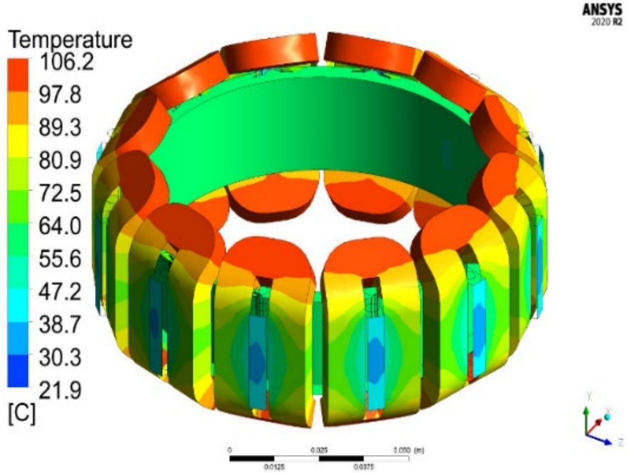
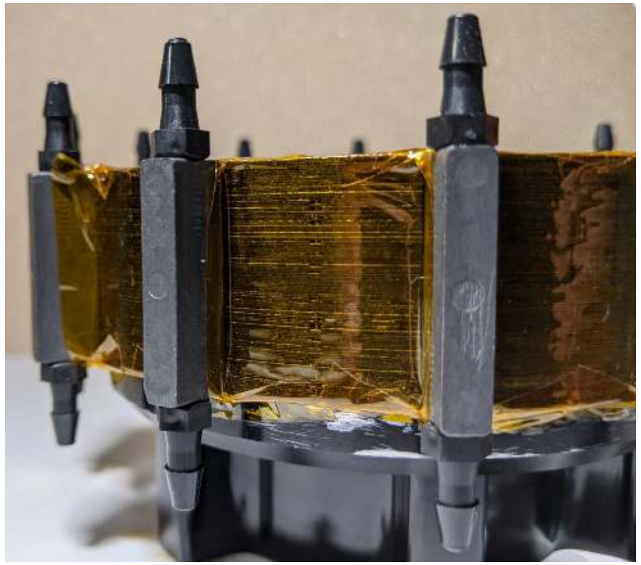
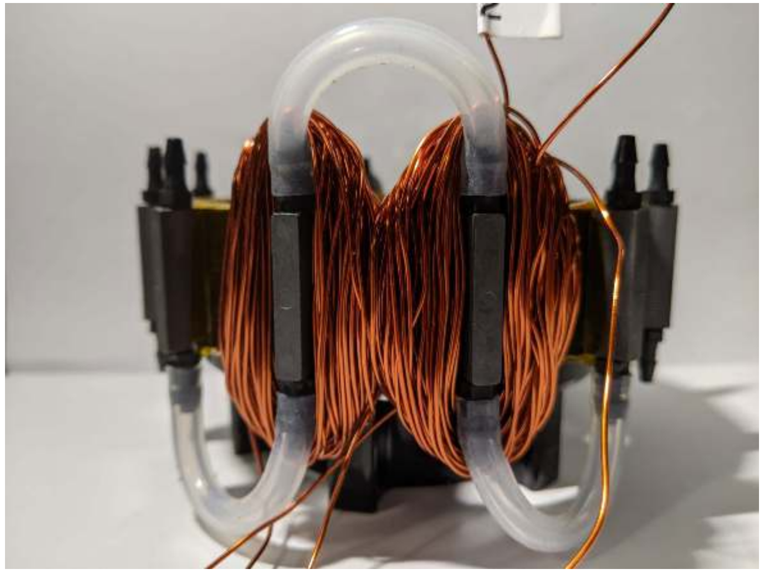


Fig. Simulation temperature distribution at continuous duty



(a)



(b)

Fig. Prototype as fabricated: (a) Close up of winding supports, tube fittings, and lamination (b) Coil assembly showing injection molded cooling channels and windings

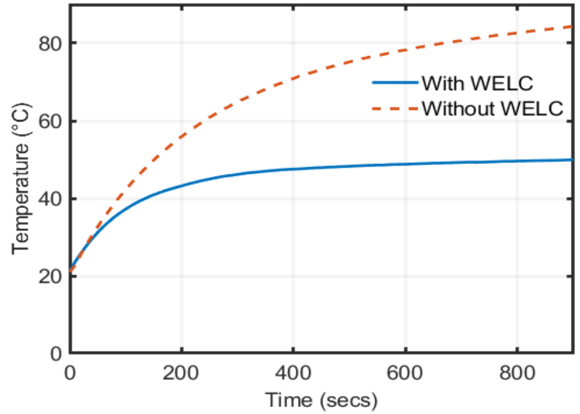
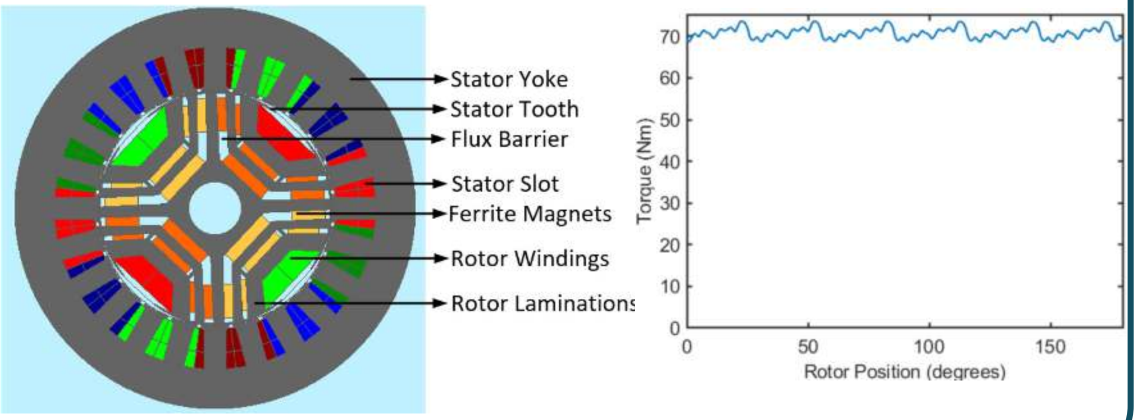


Fig. Experimental temp rise comparison at 12 A/mm2

Other Machine Technologies

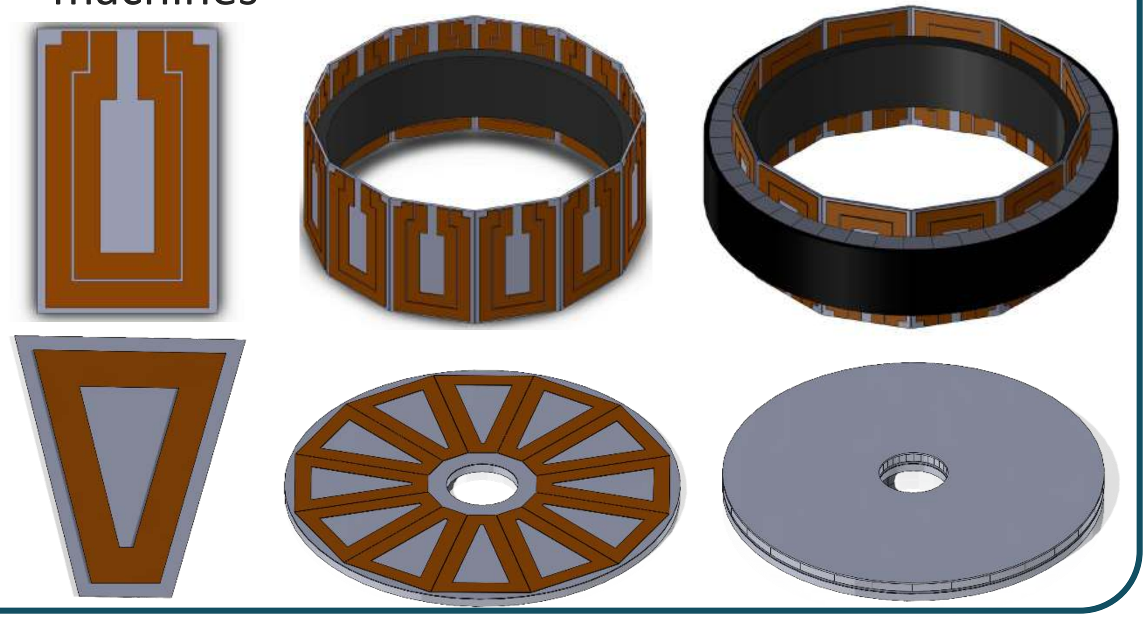
Bi-axial Excitation Machine

- Rotor construction similar to WFSM with magnets embedded along q-axis
- Torque density comparable to WFSM (28 Nm/L at 70 Nm)
- Uses non-rare earth ferrite magnets; low cost also comparable to WFSM
- Unity power factor operation leads to inverter size and cost reduction
- 7.5 kW prototype under fabrication



Ceramic Winding

- Copper on ceramic (DBC, AMB, electroplated) substrate windings allow higher current densities vs. conventional windings
- Highly conductive thermal path from copper to coolant
- Winding volume and weight reduction
- Ideal for slotless radial and axial flux machines



EV Electric Powertrain

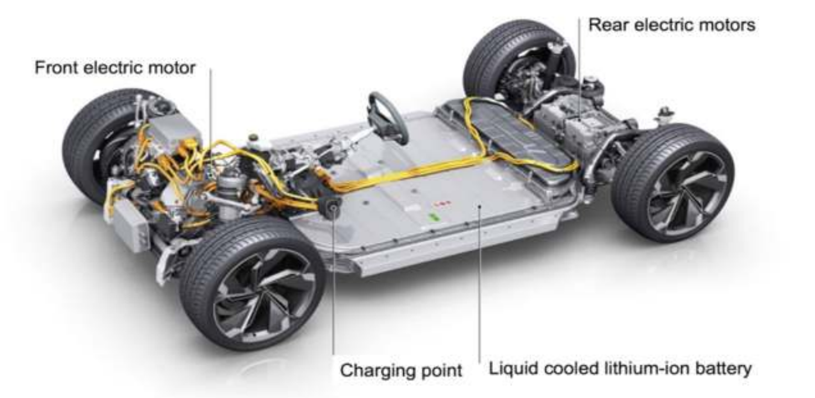
- ➢ Skateboard Chassis with Dual motors is a popular choice in automotive industry
- ➢ Si-IGBT inverters is still widely used, but SiC inverters are emerging

Traction Inverter:
- ✓ 90-350kW+ motor drive inverter
- ✓ Single, dual or in hub drives

Why SiC?
- ✓ Vehicle range extension
- ✓ Battery cost reduction
- ✓ System cost reduction
- ✓ Bi-directional energy flow for regenerative breaking

SiC Advantages :
- ✓ ~80% lower drive loss
- ✓ ~30% smaller system size
- ✓ Lower system cost

SiC Issues to be Solved :
- ✓ Module cost
- ✓ Protection and Reliability
- ✓ System EMI issues

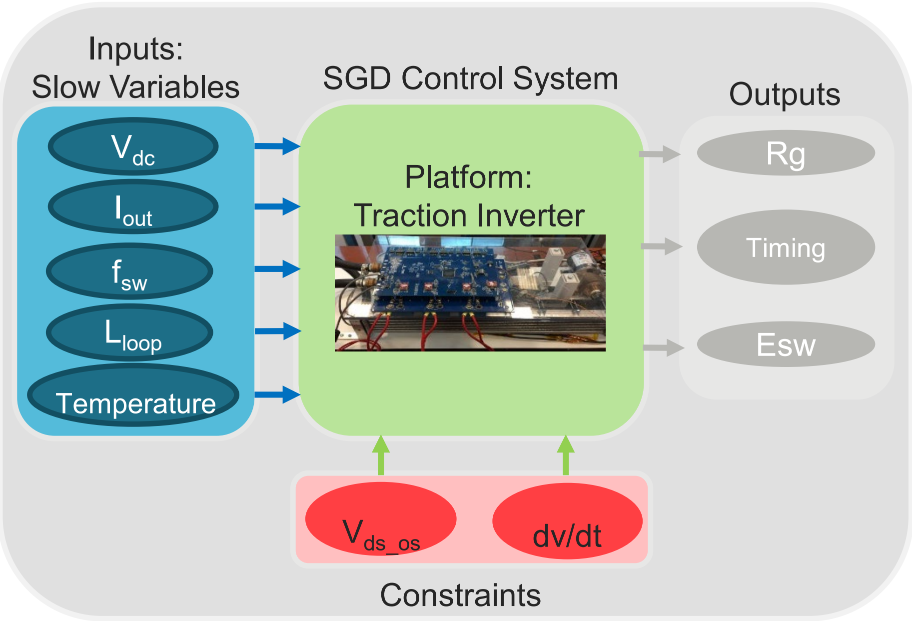


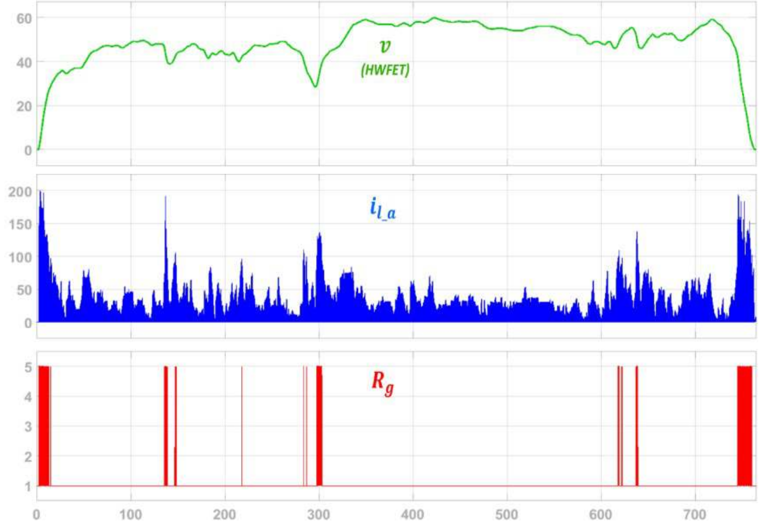
Audi E-tron Skateboard Chassis

Tesla Model S Skateboard Chassis

Selective Gate Driver (SGD) for SiC EV Inverter

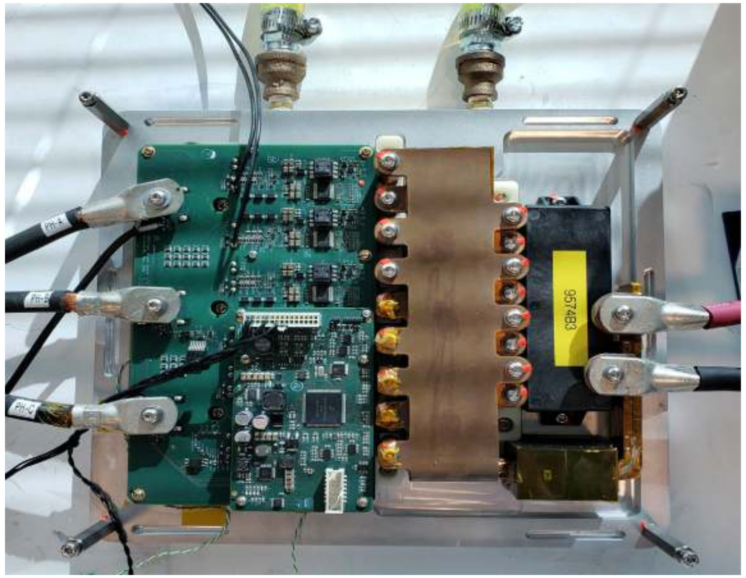
- SGD: a new strategy is proposed with adjustable Rg for the next switching cycle, according to different inverter operating conditions (V_{dc} and I_{out}), to minimize the switching loss (E_{sw}) and maintain the switching stress (V_{ds_os} and dv/dt) at the same time.
- Benefits of SGD:
  - Maintain the switching stress (V_{ds_os} and dv/dt) and reduce switching loss.
  - Feedback on real-time variables (V_{dc}, I_{out}, and can be extended to Temperature, etc.)
  - Slower requirement on dynamic control (us level).
  - Good application in EV traction inverter: most of the time, low Rg is needed.



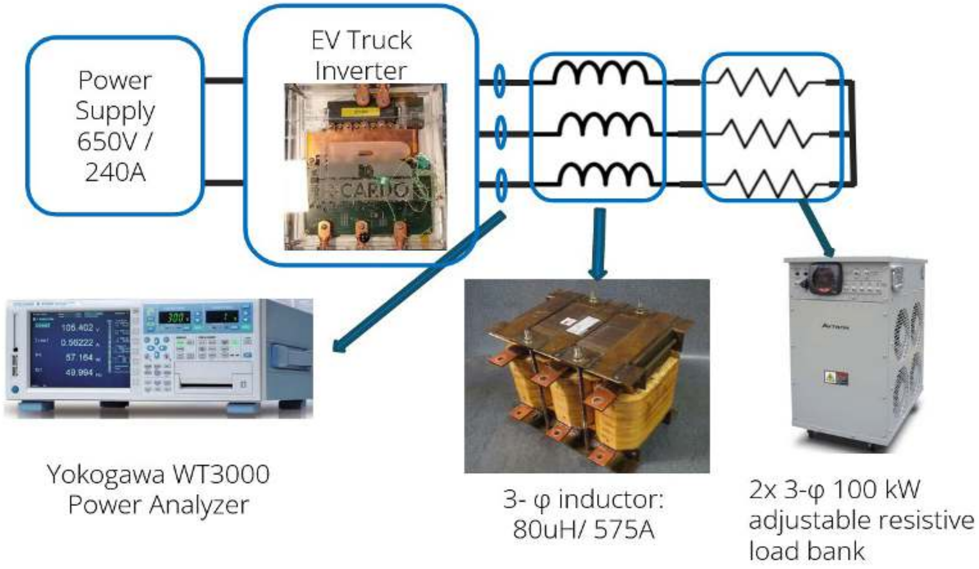


Green: Vehicle Speed (v); Blue: Traction Inverter Output Current (I_{out}); Red: Gate Resistance (R_g)

All Electric 250kW SiC Truck Inverter



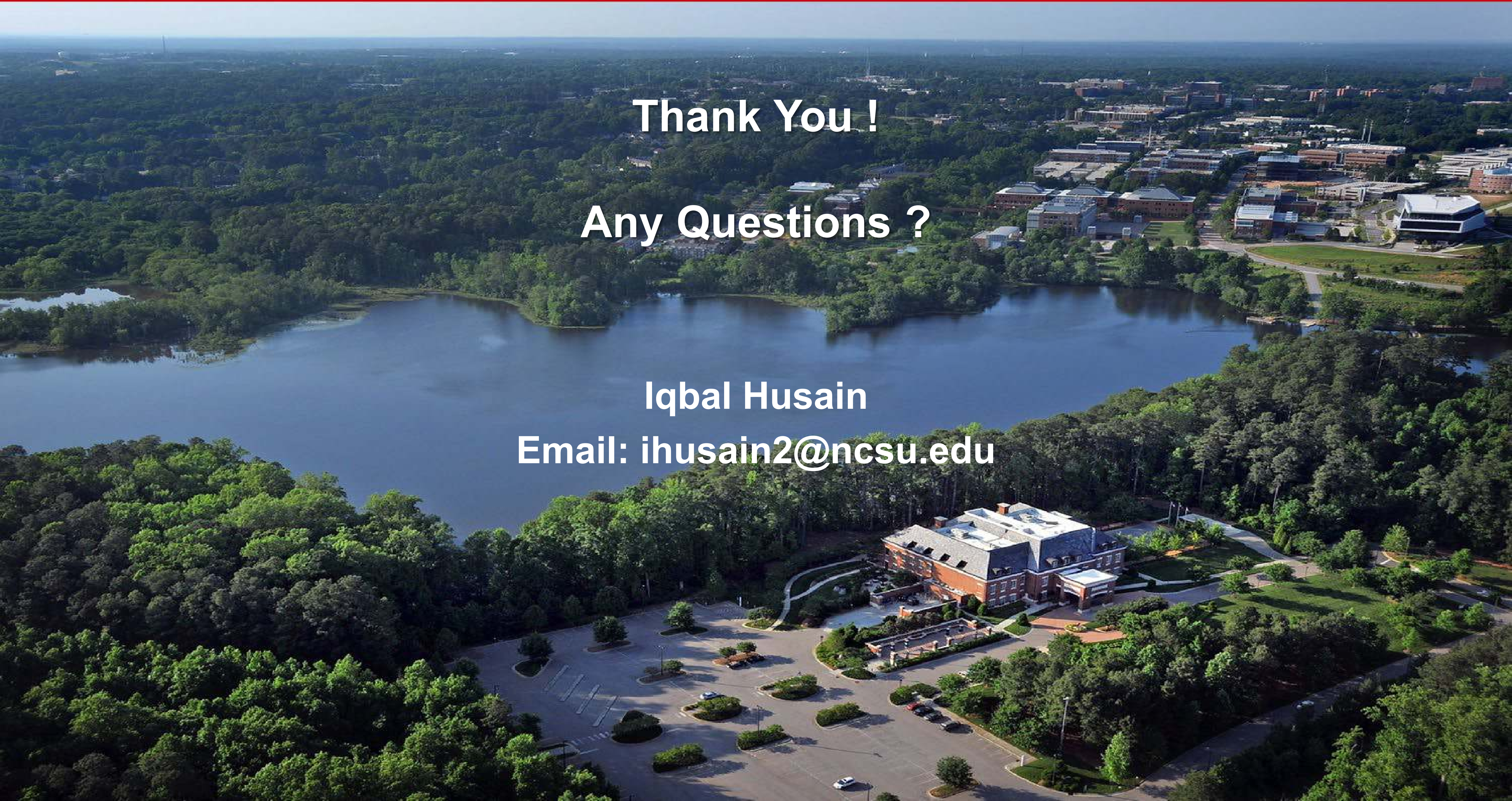
250kW, 800V SiC Inverter with > 98% efficiency



Inverter Test set-up at FREEDM

- An electric drivetrain is being developed for a Class 8 heavy duty truck funded by DOE-VTO
- The truck must meet DoE specifications for transport of materials to and from a shipping port, with range of approximately 250 miles
- FREEDM provided inverter design and hardware testing support

D. Rahman, M. Kercher, W. Yu and I. Husain, "Comparative Evaluation of Current Sensors for High-Power SiC Converter Applications," *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2021.



Thank You !

Any Questions ?

Iqbal Husain

Email: ihusain2@ncsu.edu