“Wound Field and Hybrid Synchronous Machines for EV Traction with Brushless Capacitive Rotor Field Excitation”

2021 DOE Annual Merit Review

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Illinois Institute of Technology

Project ID: elt092

Overview

Timeline

- Start Date: 10/1/17
- End Date: 7/31/21 (No-Cost Extension)
- Percent Complete: 85%

Budget

- Total project funding
  - DOE's Share: $999,752
  - Partner's Cost Share: $112,955
- FY 17 DOE Funding: $438,561
- FY 18 DOE Funding: $383,679
- FY 19+ DOE Funding: $177,512

Barriers

- Cost of EV traction motors resistant to decrease
- Rare earth permanent magnet (PM) market subject to significant price and supply volatility
- Power factors of IPMSM and IM increase power electronics cost

Project Partners

- Illinois Institute of Technology
  - Lead
- University of Wisconsin-Madison
- Lucid Motors (Atieva)

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Relevance/Objectives

Overall

- Develop cost effective wound field synchronous machines (WFSMs) and hybrid excitation synchronous machines (HESMs) which meet DOE cost and performance metrics
  - Final FY21 prototype targets: peak power ≥ 55 kW, continuous power ≥ 30 kW, specific power density ≥ 1.6 kW/kg, volumetric power density ≥ 5.7 kW/l, Cost ≥ 4.7 $/kW
  - Will also be compared with USDRIVE 2025 targets
- Develop cost effective and robust capacitive power coupler (CPC) for brushless rotor field excitation power transfer
- Create advanced torque/current regulation algorithms for WFSMs and HESMs
- Evaluate the performance and cost of final prototype WFSM using the capacitive power coupler

This Period

- Construction and testing of final prototype delayed by Covid-19 lab restrictions

Milestones

Remaining Milestones & G/No-Go Decision Points	Date	Status
Final WFSM/HESM prototype meets USDRIVE 2020 metrics with brushes and slip rings*	Planned 7/15/2021	On-going
Final WFSM/HESM prototype meets USDRIVE 2020 metrics with CPC*	Planned 7/31/2021	On-going
Final WFSM/HESM with integrated brushless power coupler BOM achieves ≤$4.7/kW target	Planned 7/31/2021	On-going

*Final prototype will also be compared with USDRIVE 2025 targets

Approach

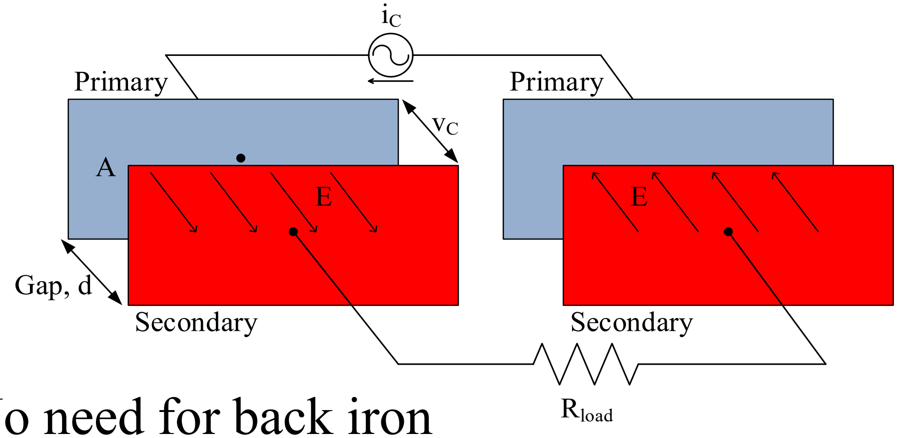
WFSM Power Density and Cost Reduction Approaches

- Die compressed windings (targeting ~70% to 80% slot fill)
  - Single thermal mass with no air voids
  - Potential to use aluminum wires with similar performance to 40 to 45% fill copper windings with significant cost and weight savings
  - In the stator flexible number of turns compared to bar/hairpin winding
  - Reduced AC losses at high frequency compared to hair-pin winding
  - Fractional slot concentrated winding maybe required for stator with multiple strands in hand orthocyclic winding
- Alternative high slot fill field windings
- Fully utilize machine's active materials
  - Refine in-house developed optimization tool and explore the use of topological optimization
- High performance controls development for WFSMs

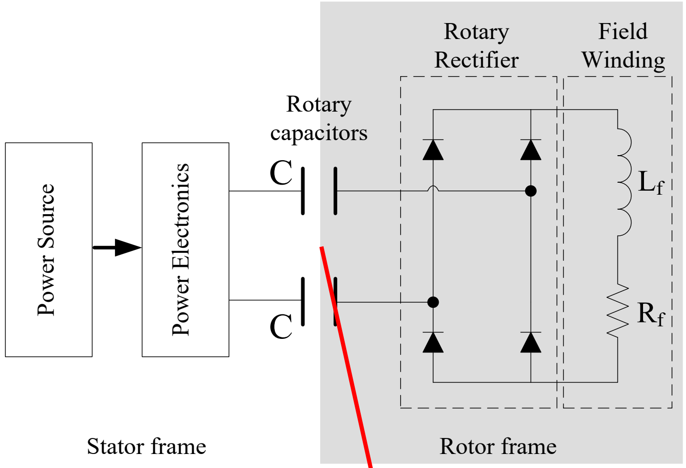
Approach

- Capacitive power transfer (CPT) to rotor field winding
  - Power transfer to WFSM field winding through electric field between rotary capacitors

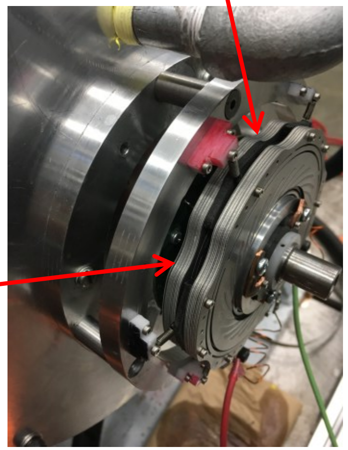
Basic Concept



CPT for WFSM Concept



  - No need for back iron
  - Electric flux lines terminate on charge, limited field outside of gap
  - Previous project used stacked anodized aluminum disks with spiral groove to form axial flux hydrodynamic coupling capacitors



Approach

Lower the cost of the capacitive power coupler

- Increase the frequency (MHz) to shrink required capacitance (A/Hz)
- Lower losses in the converter by operating in soft switching
  - Reduced thermal management and reduced switch rating
- Via OEM feedback use simple PCB for low cost and established production technology
  - Reduced capacitance

Develop Hybrid Excitation Synchronous Machines (HESMs) to lower field power requirements

- Bias the flux for most common operating point in drive cycle
- Reduce the amount of PM material compared to full PM machines
- Extend constant power speed range compared to full PM machines

WFSMs and HESMs Prototypes Developed

- Incremental development approach
  - Each prototype targeted a specific cost reduction approach/technology
  - Every prototype is designed to meet or exceed USDRIVE 2020 power conversion targets

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- Prototype 1: Increased power density classical WFSM with random field winding
- Prototype 2: Parallel radial flux dual rotor HESM
- Prototype 3: WFSM rotor with rectangular die compressed field winding
- Prototype 4: 3 phase wound rotor HESM (Winding needed)
- Prototype 5: Final WFSM with hairpin stator and three field winding variants (square conductor, twisted square conductor, and die compressed)

- Integrate and test Prototype 5 with CPC

Previous Technical Accomplishments and Progress

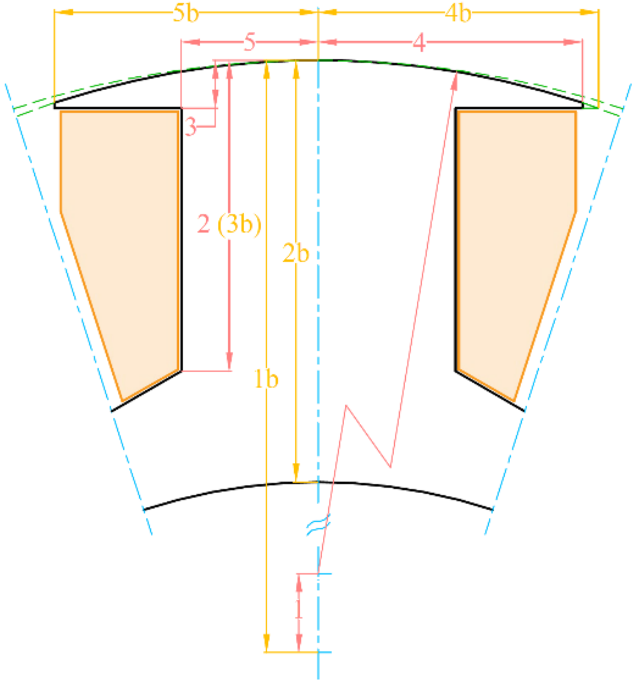
- Baseline WFSM with random wound rotor and distributed winding stator prototyped
- Rotor with rectangular die compressed field windings prototyped
- Hybrid excitation synchronous machine with parallel radial flux rotors prototyped
- High and low switching frequency deadbeat direct torque and flux control of WFSMs
- Multi-material magneto-structural topology optimization of WFSMs developed
- Several capacitive power coupler (CPC) technologies investigated
  - Journal bearing CPC
  - Integrated LC PCB
  - Large gap PCB CPC; Three phase version
- Minimization of parasitic capacitances and dielectric loss in CPC PCBs
- Large gap 3 phase CPC with MHz, soft switching, 3 phase GaN inverter prototyped and tested
- Low loss inductors for CPC
- Automatic frequency tracking for high efficiency CPC

Technical Accomplishments – Down Selection of Final WFSM Prototype Topology

- WFSMs at typical traction motor speeds/frequencies are dominated by ohmic loss.
  - High slot fills in stator and field winding are highly desirable in WFSMs
  - Particularly important in the field winding to balance the Ampere-turns of the stator with less area
- Two styles of WFSMs were evaluated for the final prototype
  - 12 slot 10 pole stator with concentrated die compressed windings for the stator and field
    - Die compressed stator winding difficult to prototype because of the orthocyclic multiple strands in hand winding
  - 72 slot 12 pole stator with hairpin distributed winding and three field winding variants
    1. Square conductor field winding
    2. Square rectangular conductor field winding
    3. Die compressed round conductor field winding
    - Chevy Volt Gen 1 stator used because of the difficulty in prototyping a hairpin winding in an academic setting
- The distributed winding (Chevy Volt Gen 1 stator) with three field variants was down selected

Technical Accomplishments – Electromagnetic Optimization

- Optimization to maximize the efficiency at multiple load points
- Metamodeling based design optimization



1: pole surface offset

2: pole depth

3: pole tip depth

4: pole tip width

5: pole width

b: base suffix

Parametric rotor & fixed stator geometry

Quantity	Type	Expression
Weighted Efficiency	Objective	Maximize
Torque at all Load Points (p.u.)	Constraint	≥ 0.985
Peak Voltage at all Load Points (p.u.)	Constraint	≤ 0.94
Stator Current Density at all Load Points (A_{rms}/mm^2)	Constraint	≤ 25
Field Current Density at all Load Points (A_{rms}/mm^2)	Constraint	≤ 20
Field Power (W), at LP1	Constraint	≤ 750
Field Power at all Load Points (W)	Constraint	≤ 3500
Torque Ripple at all Load Points (pk2pk, %)	Constraint	≤ 10

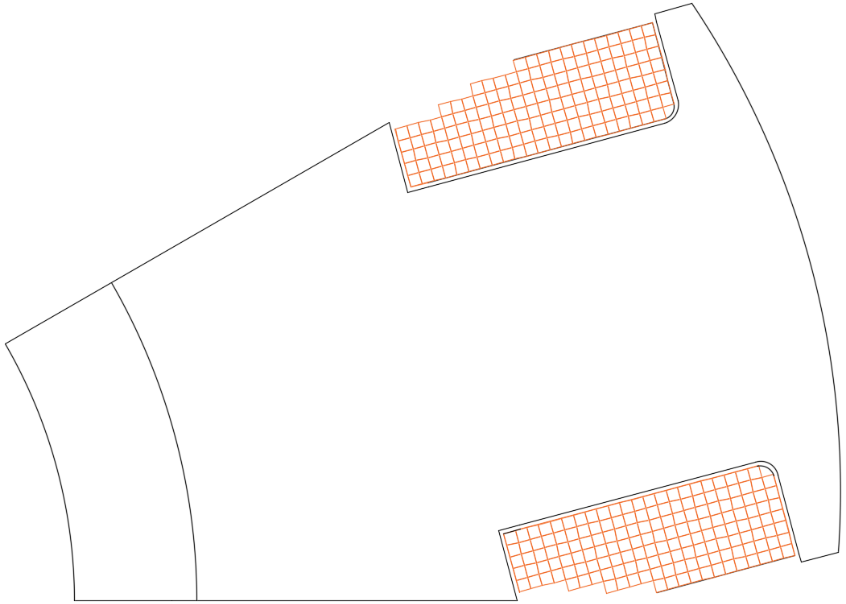
Technical Accomplishments – Electromagnetic Optimization

- Peak current stator peak current is ~608 A_{peak}, test dynamometer DUT drive limited to ~400 A
- Original stator base speed with IPMSM rotor ~2800 RPM, WFSM voltage limited corner speed is ~6000 RPM, dynamometer peak power point at 4,000 RPM – Base speed of 4,000 RPM selected to test to the maximum power capability of the dynamometer
- Target peak power output of 190 kW at 4,000 RPM, ~285 kW possible at 6,000 RPM (constant power speed range would need to be limited to 2:1 for structural reasons)

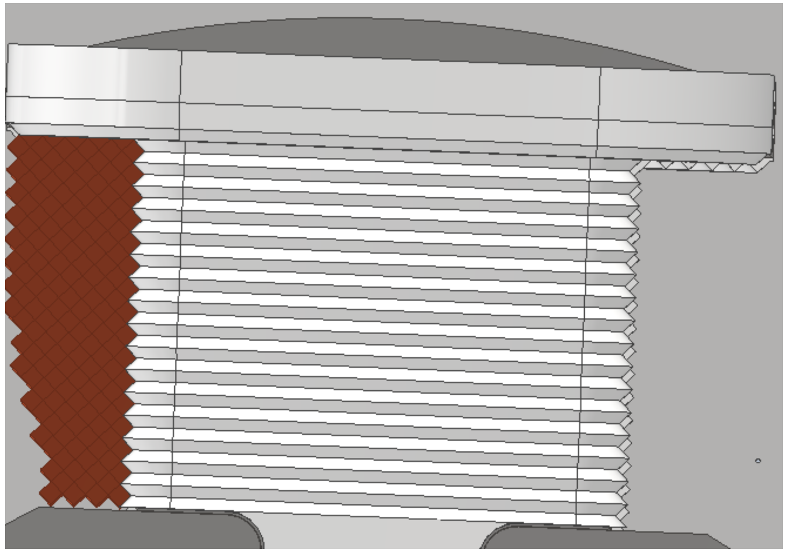
Operating Points	Speed (RPM)	Torque (Nm)	DC Link Voltage (Vdc)
1	4,000	131.3	600
2	8,000	65.65	600
3	2,000	119.4	600
4	4,000	453.59	600
5	12,000	151.2	600

Technical Accomplishments – Electromagnetic Optimization

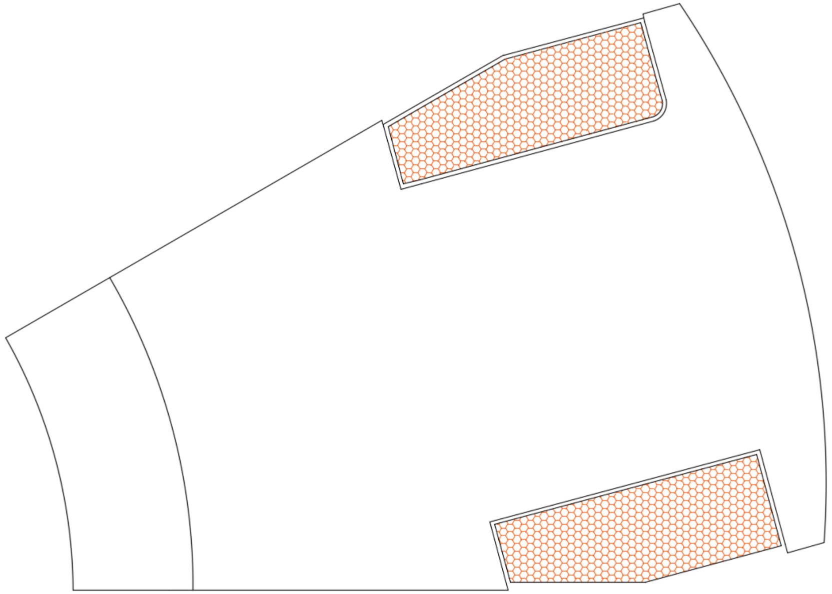
- Three field winding variants using the same lamination
- Achievable field slot fills and structural properties are different



Square Conductor



Twisted Square Conductor

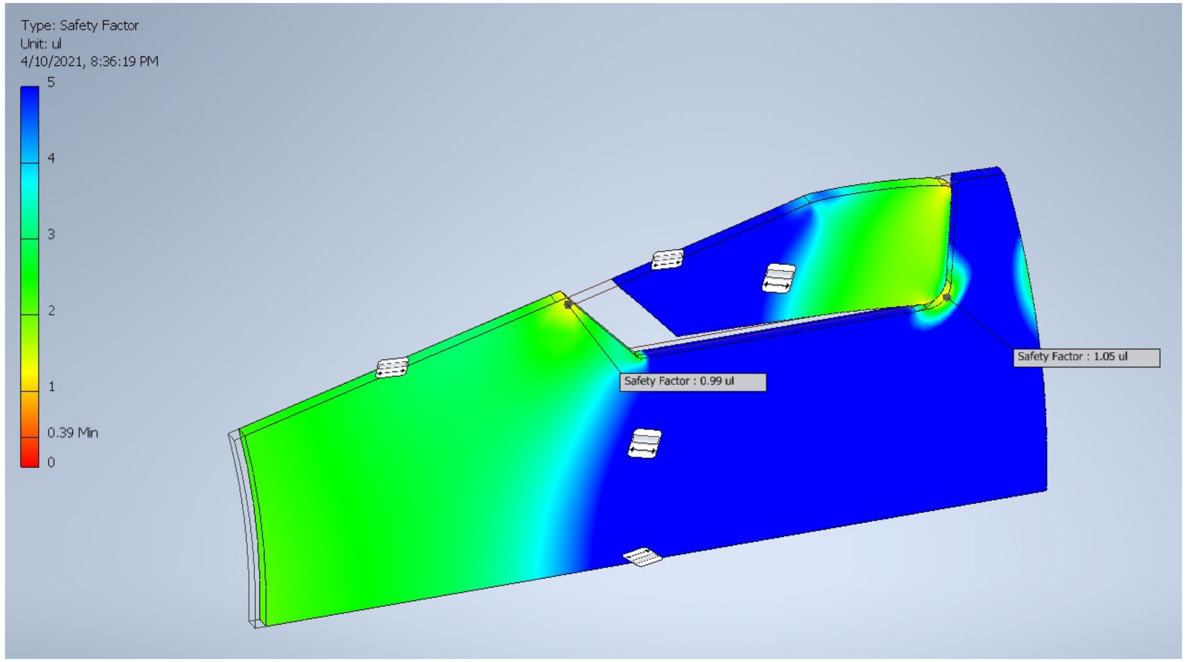


Die Compressed

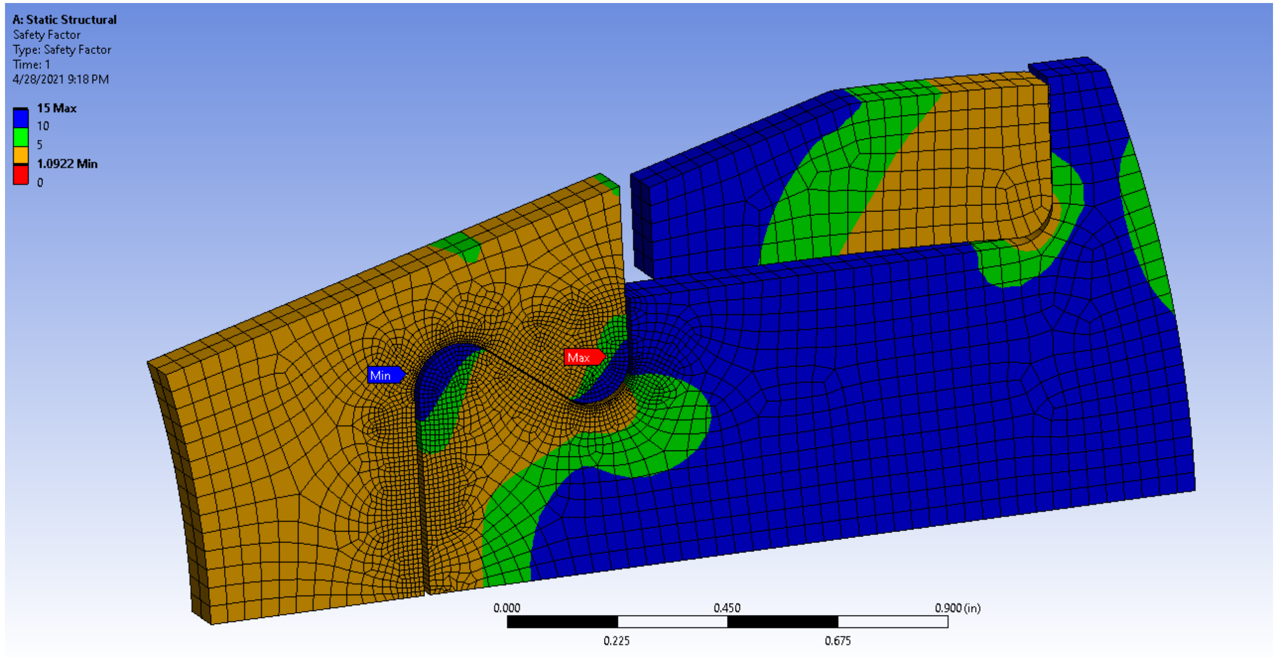
Technical Accomplishments – Structural Optimization

- Die compressed coils and twisted square conductor field windings require a joint in the lamination
- Structural optimization of the dovetail joint and pole tips for 20% overspeed condition (14,400 RPM)

Pole Tip Neck Fillet Optimization



Dovetail Joint Optimization



Technical Accomplishments – Final Prototype Performance Estimation

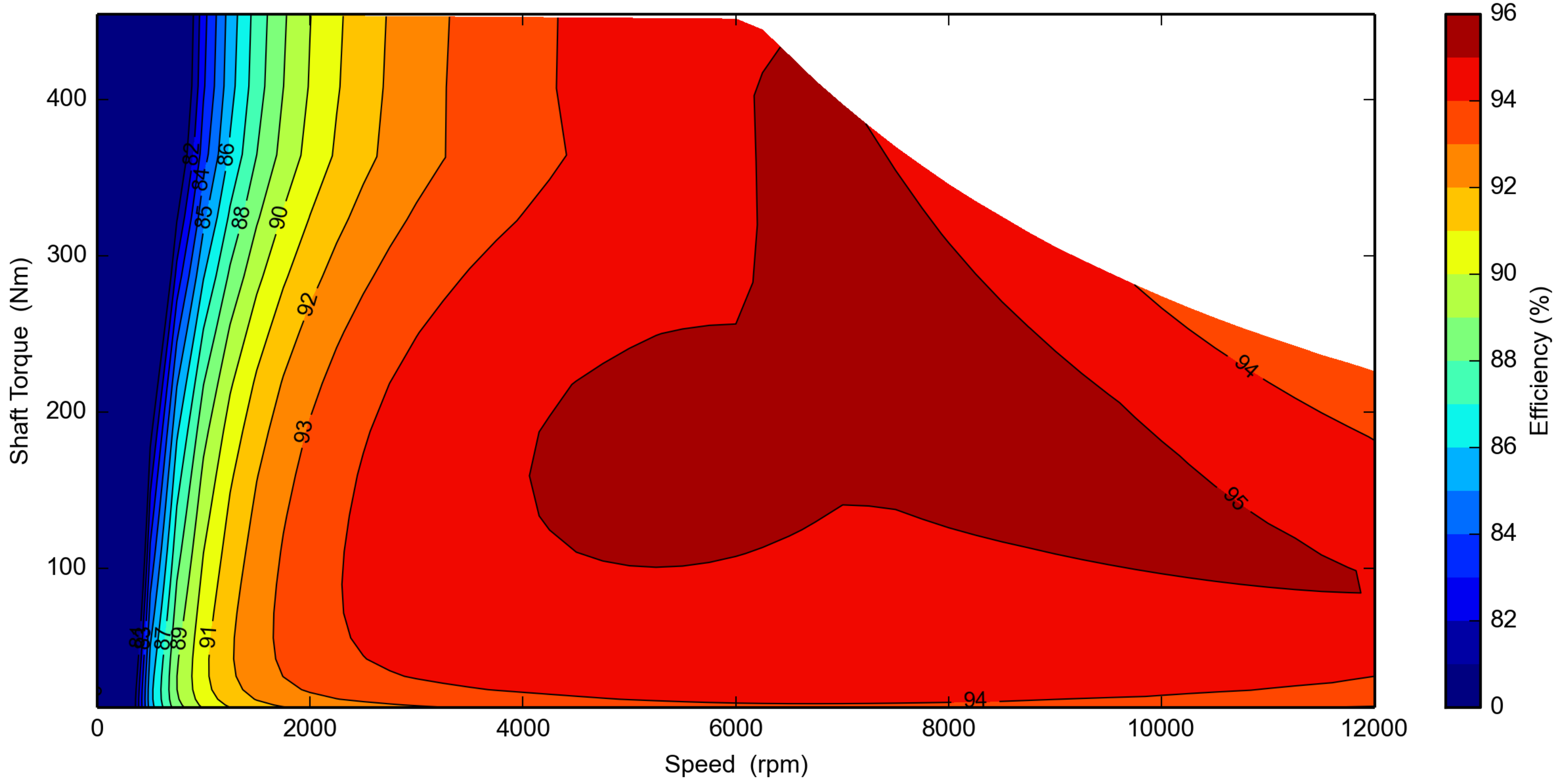
- Predicted performance at optimization load points (square conductor winding)

Load Point	Speed (RPM)	Torque (Nm)	Torque Ripple (pk2pk %)	I_s (A_{peak})	J_s (A_{rms}/mm^2)	I_f (A_{dc})	J_f (A_{rms}/mm^2)	Power Factor	Eff*,**,*** (%)	Total Loss*,**,*** (W)
1	4000	131.41	7.10	205.49	8.26	5.25	6.33	0.98	95.28	2727
2	8000	65.36	8.74	142.37	5.72	3.27	3.94	1.00	95.51	2576
3	2000	119.51	7.86	190.41	7.65	4.88	5.88	0.97	93.90	1627
4	4000	454.34	0.55	608.00	24.44	13.00	15.67	0.98	93.59	13,035
5	12000	151.27	6.83	412.82	16.60	5.97	7.20	0.99	94.66	10,722****

- *Winding temperatures of 120 C° assumed; ATF spray cooling of end turns
- **AC losses in stator conductors included
- *** 2 x iron loss build factor included
- **** Stator with 6 or 8 conductors would significantly improve efficiency at high speed

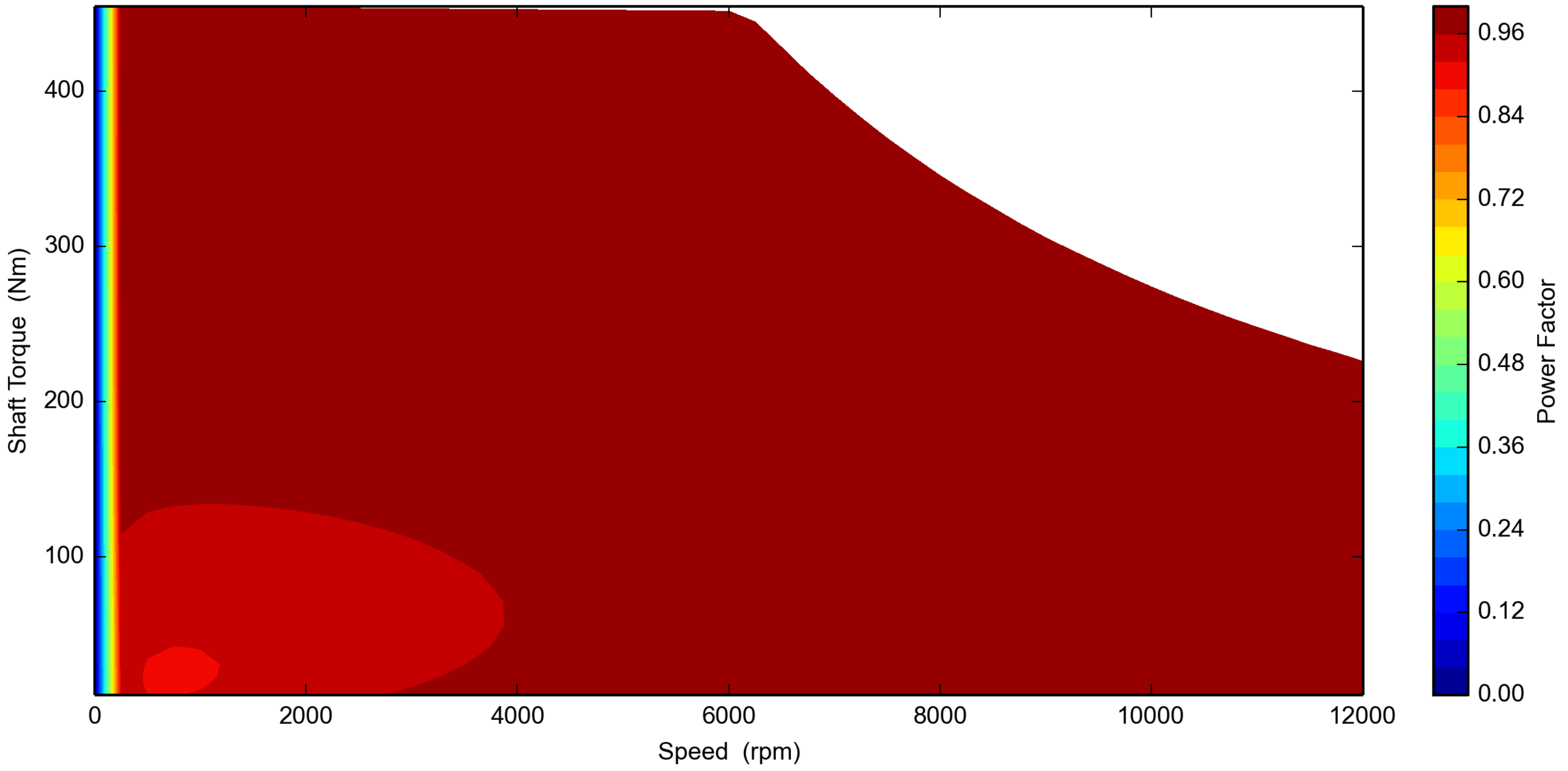
Technical Accomplishments – Final Prototype Performance Estimation

- Predicted efficiency map with square conductor field winding, $V_{dc} = 600$, $I_{s\text{-}max} = 608\ A_{peak}$

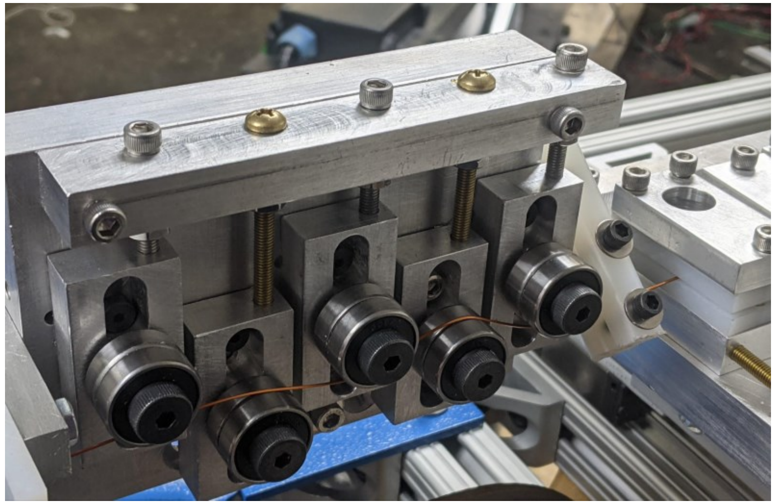


Technical Accomplishments – Final Prototype Performance Estimation

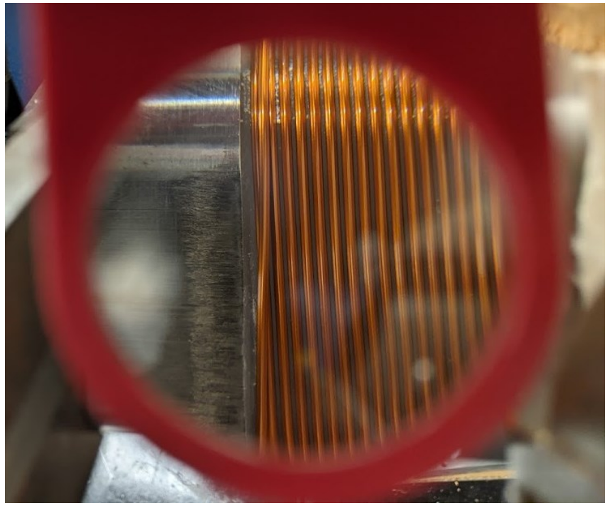
- Predicted power factor map with V_{dc} = 600, $I_{s\text{-}max}$ = 608 A_{peak}



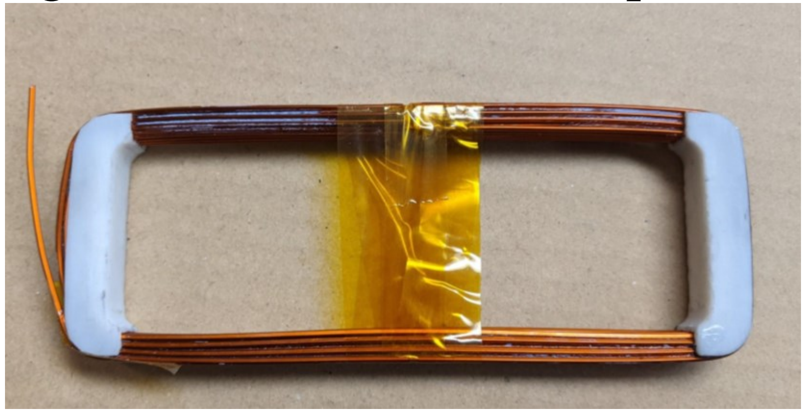
Technical Accomplishments – Twisted Square Conductor Field Winding Trials



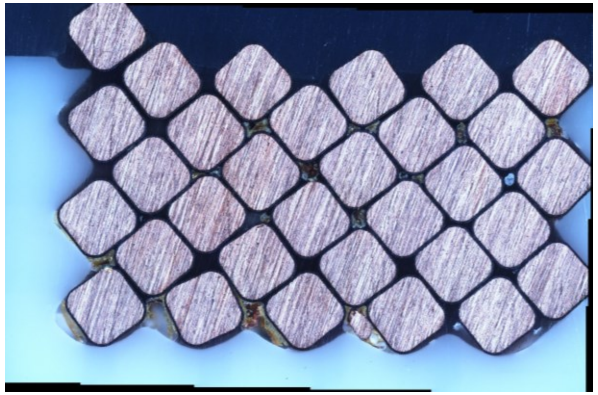
Winding machine for twisted square conductor



Trial endcaps



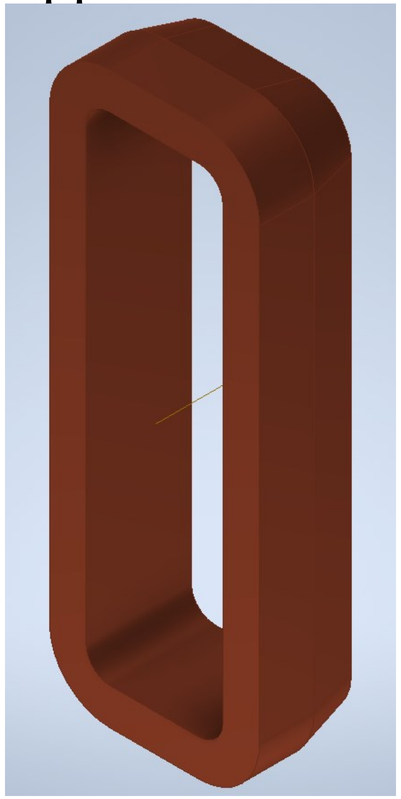
Trial coil



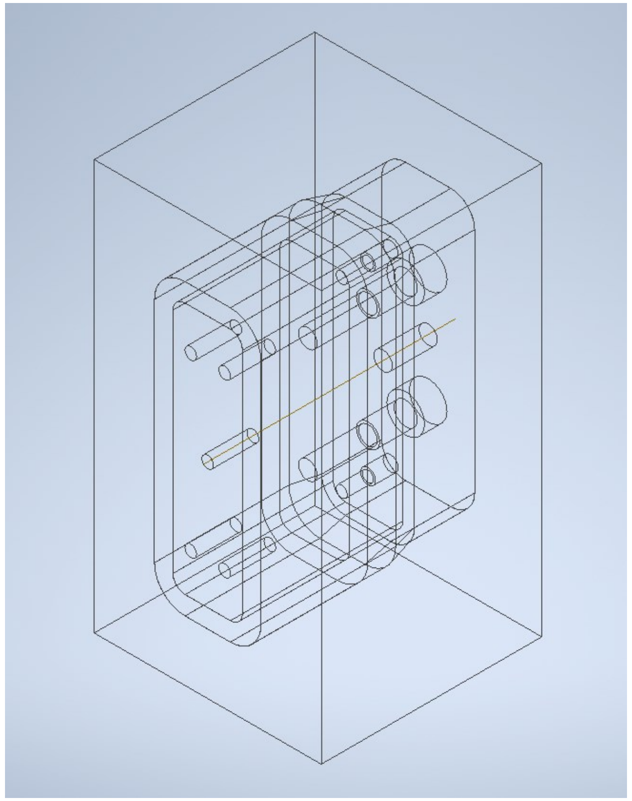
Trial coil cross-section

Technical Accomplishments – Die Design for Non-Rectangular Field Winding

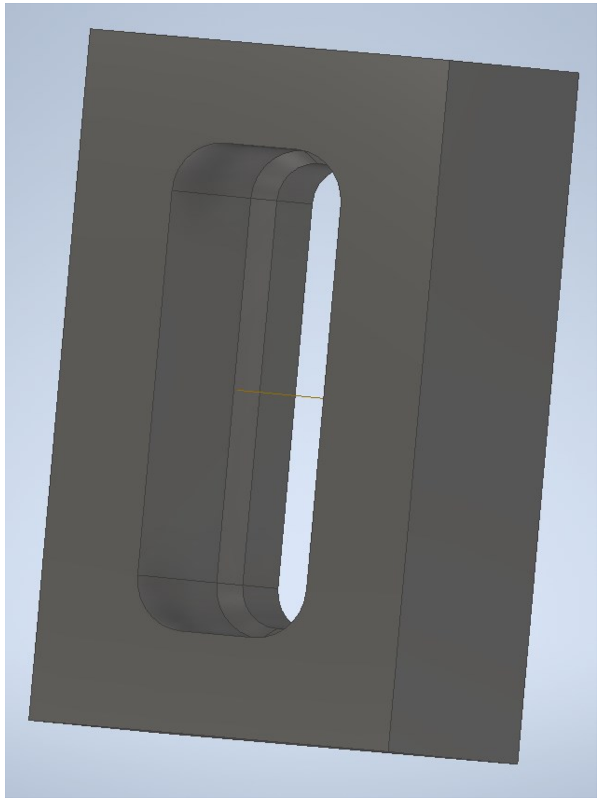
- Third field winding variant uses a die compressed non-rectangular field winding to maximize the field copper cross-section



Desired compressed coil

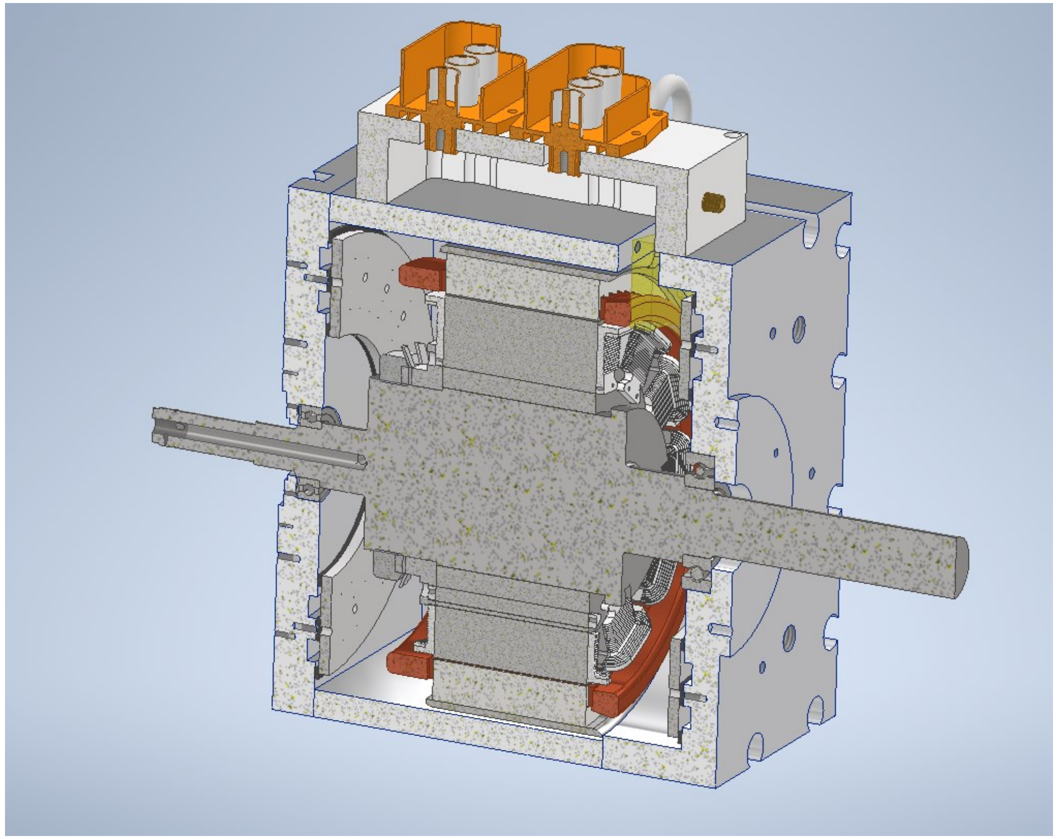


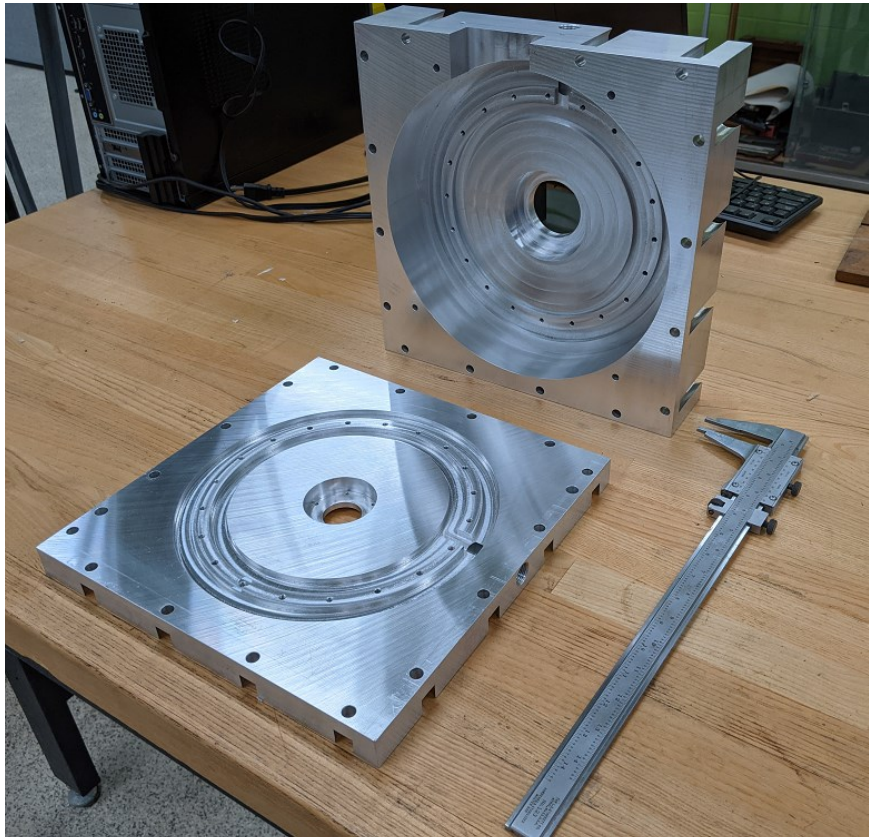
Die set cross-section

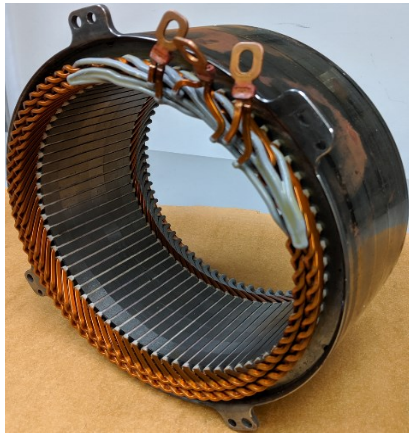


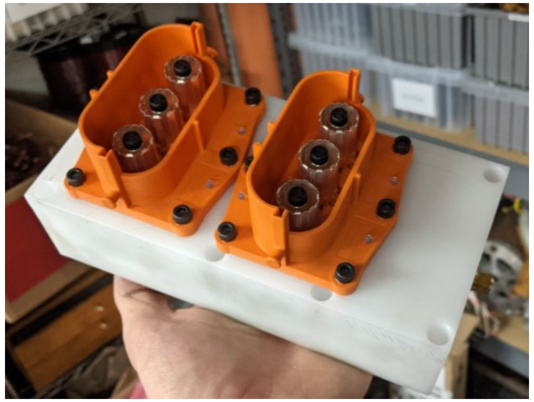
Outer Die

Technical Accomplishments – Construction of Final WFSM Prototype



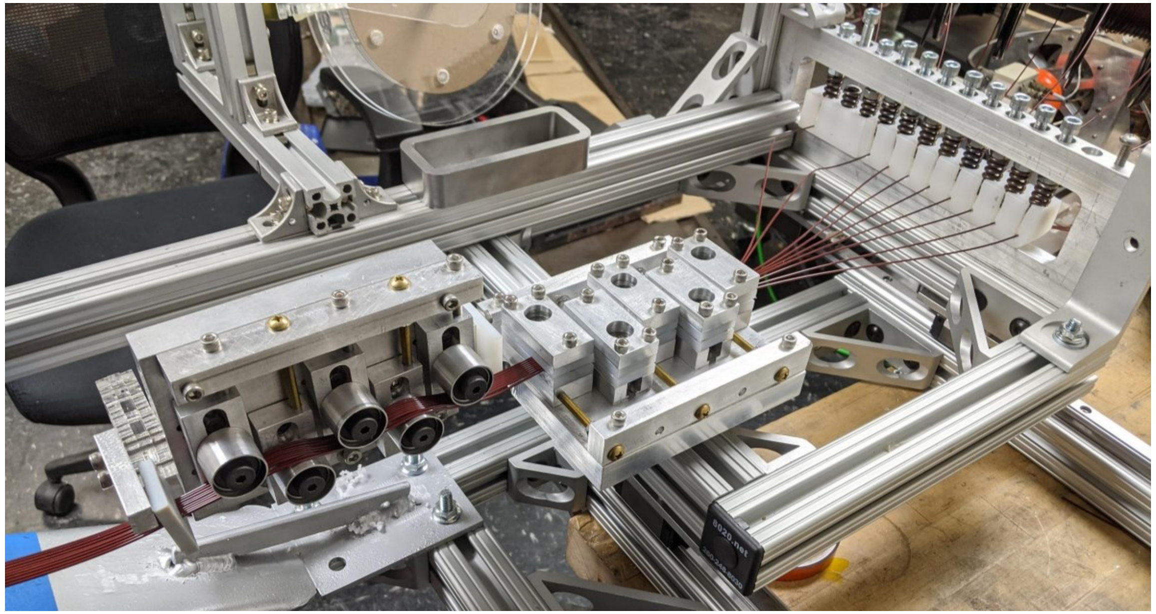






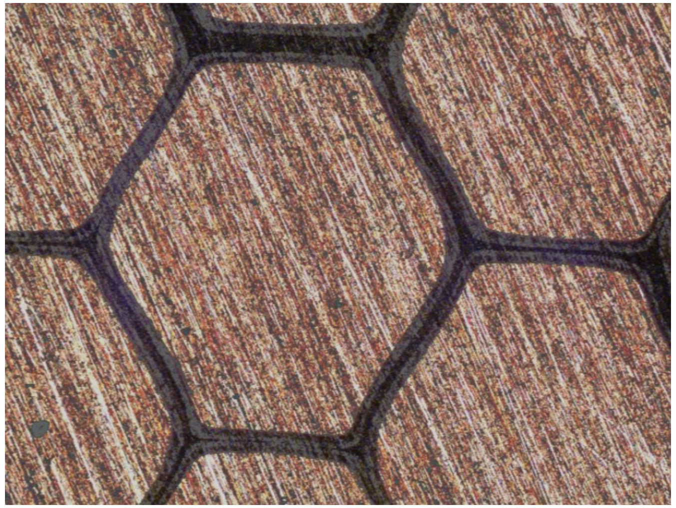
Technical Accomplishments – Custom Winding Machine for Multiple Strand Die Compressed Windings

- Custom winding machine for simultaneously winding multiple conductors orthocyclically for die compressed stator windings



Custom winding machine

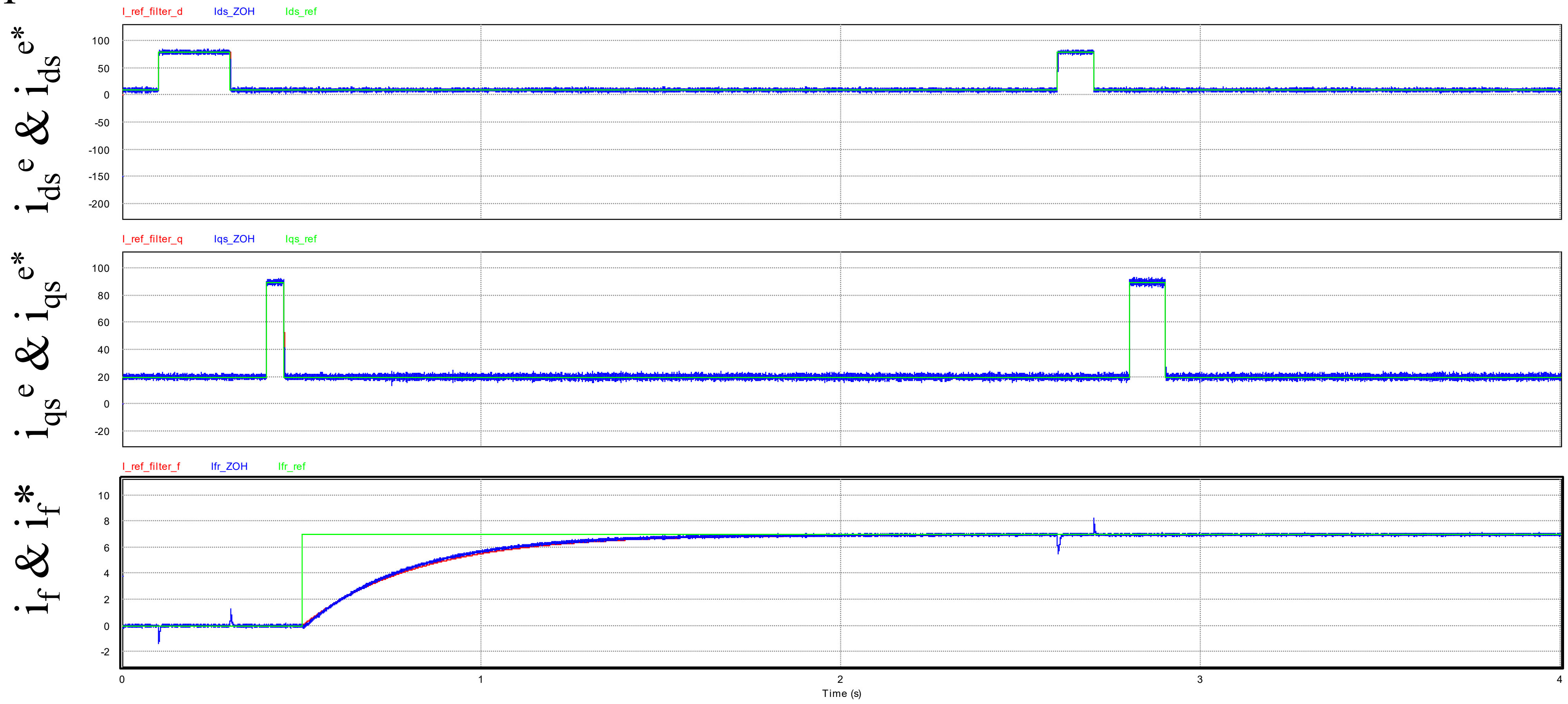
Example multiple strand orthocyclic winding



Compressed winding cross-section

Direct Discrete Time Current Regulator for WFSMs and HESMs

- Computationally feasible improved discrete time WFSM/HESM machine model and controller developed



Simulation result with 30% parameter estimate inaccuracy and voltage constraints

Response to Previous Year Reviewer's Comments

- This project was not reviewed last year

Collaboration and Coordination with Other Institutions

- Illinois Institute of Technology
  - Electromagnetic, thermal, and structural design of WFSM and HESM
  - Development of control strategies for WFSM and HESM
  - Responsible for prototyping and testing of WFSM and HESM
- University of Wisconsin-Madison
  - Design and construction of capacitive power coupler
  - High power dynamometer testing
- Lucid Motors
  - Previous design reviews of WFSM, HESM, and CPC
  - Assistance with cost estimation

Remaining Challenges and Barriers

- IIT and UW-Madison campuses were closed by state mandated “shelter at home” orders which substantially delayed construction and testing of final prototype WFSM
- High power dynamometer testing of the final WFSM is proceeding

Proposed Future Research

- This project is completing in July

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

Summary

- Relevance
  - WFSMs and HESMs offer a low system cost path for widespread adoption of EVs
    - Brushless and no or reduced permanent magnet usage
    - Potential for unity power factor operation to reduce inverter kVA rating
- Approach
  - Die compressed or square conductor windings for high slot fill
  - Capacitive power transfer using mechanically simple PCBs
- Technical Accomplishments
  - Multi-material magneto-structural topology optimization
  - WFSM with rotor die compressed and square conductor windings prototyped
  - Two HESMs prototyped with one provisional patent filed
  - Multiple high performance WFSM control techniques developed
  - Mechanically simple PCB CPC and 2 MHz GaN inverter

Technical Back-Up Slides

Previous Technical Accomplishments – Multi-Material Magneto-Structural Topology Optimization

- Optimization Results

Three Different Objective Functions and Constraints

	Example 1	Example 2	Example 3
Speed (RPM)	4,000	4,000	4,000
T_{avg} (Nm)	256	240	376
T_{ripple}	10%	9.9%	9.1%
L_{Cu} (W)	486.76	470.41	666.41
Active rotor copper volume (mm^3)	24000	22600	31900
Total Ampere-turns (A-turns)	2160	2031	2871
s_{max} (MPa)	36.8	20.5	76.7
Total Rotor Mass (kg)	7.12	7.54	7.68
u_{max} (mm)	0.014	0.0065	0.033
Compliance (J)	0.19	0.15	0.5

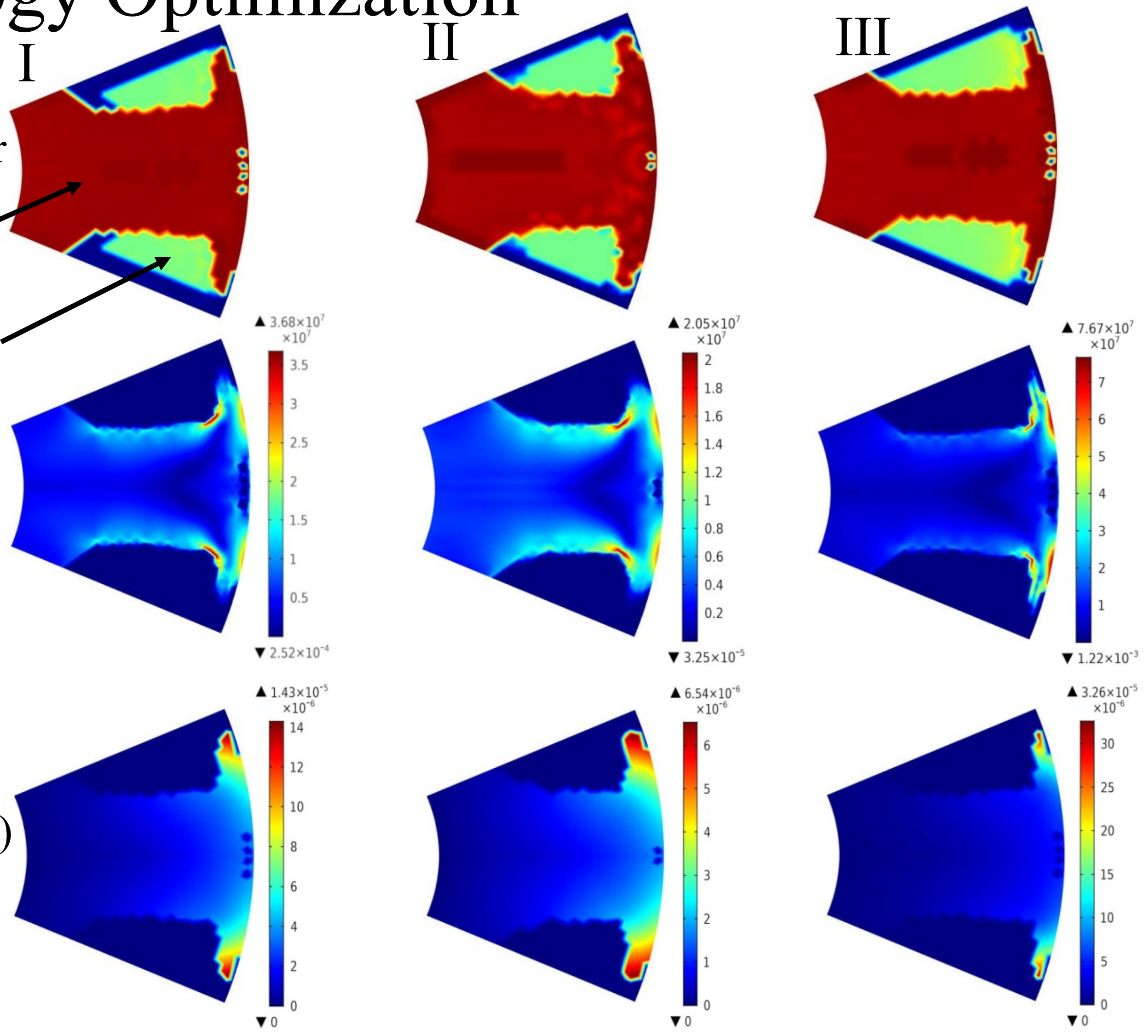
Steel and Copper Distributions

Electrical steel

Copper winding

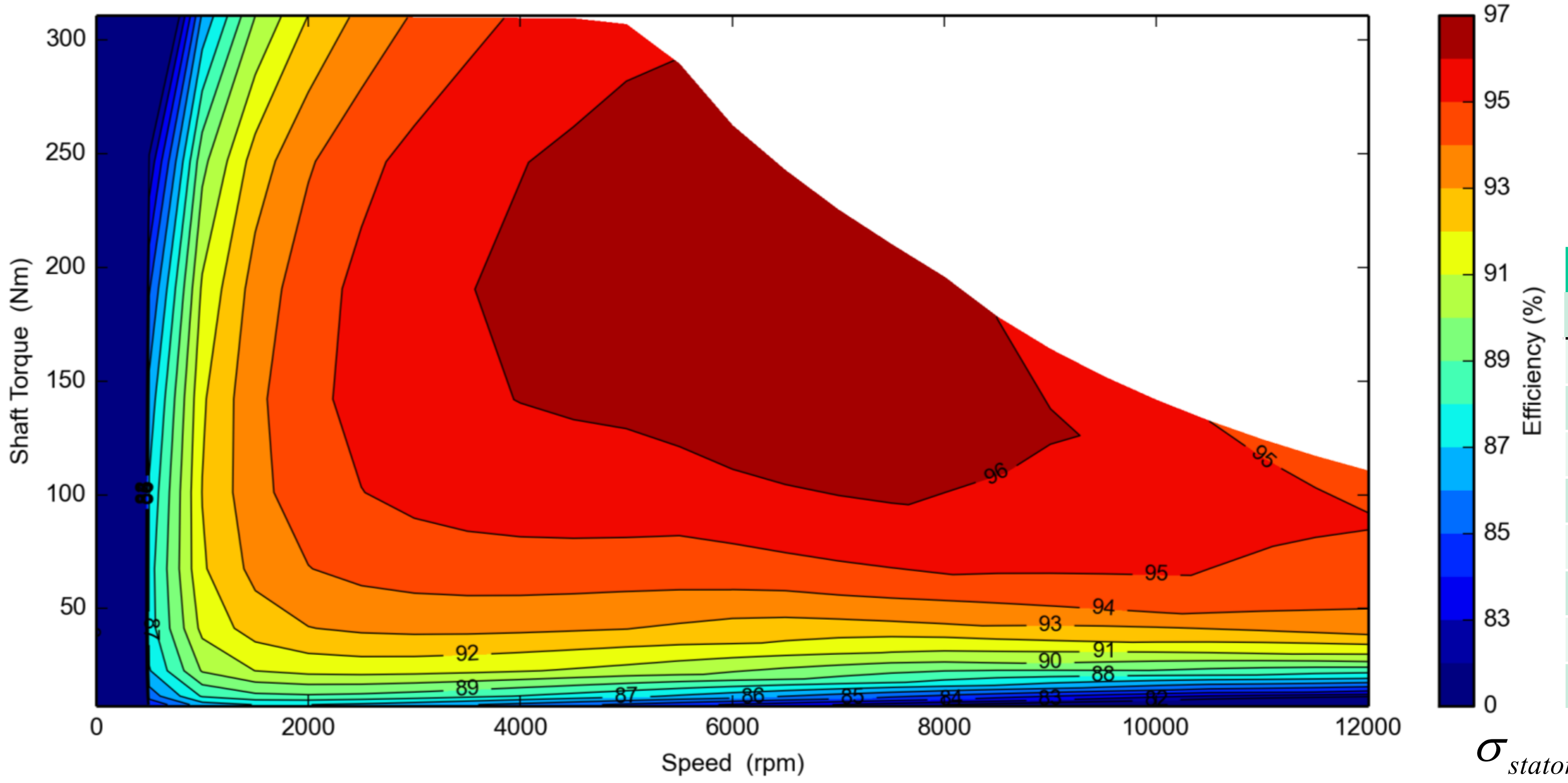
Von Mises Stress (Pa)

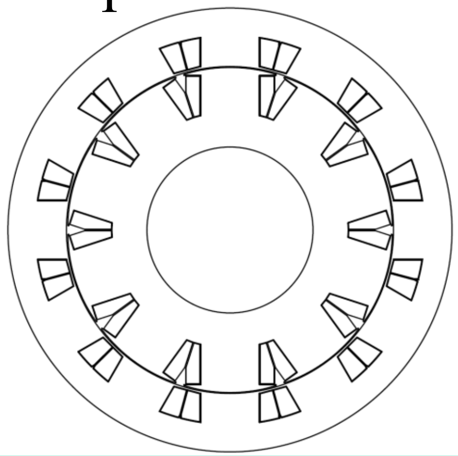
Displacement (m)



Previous Technical Accomplishments –Design with Die Compressed Stator and Field Windings Predicted Performance

- WFSM design with die compressed stator and rotor windings efficiency map
  - Winding temperatures of 40 Deg. C assumed
- Large region of high efficiency

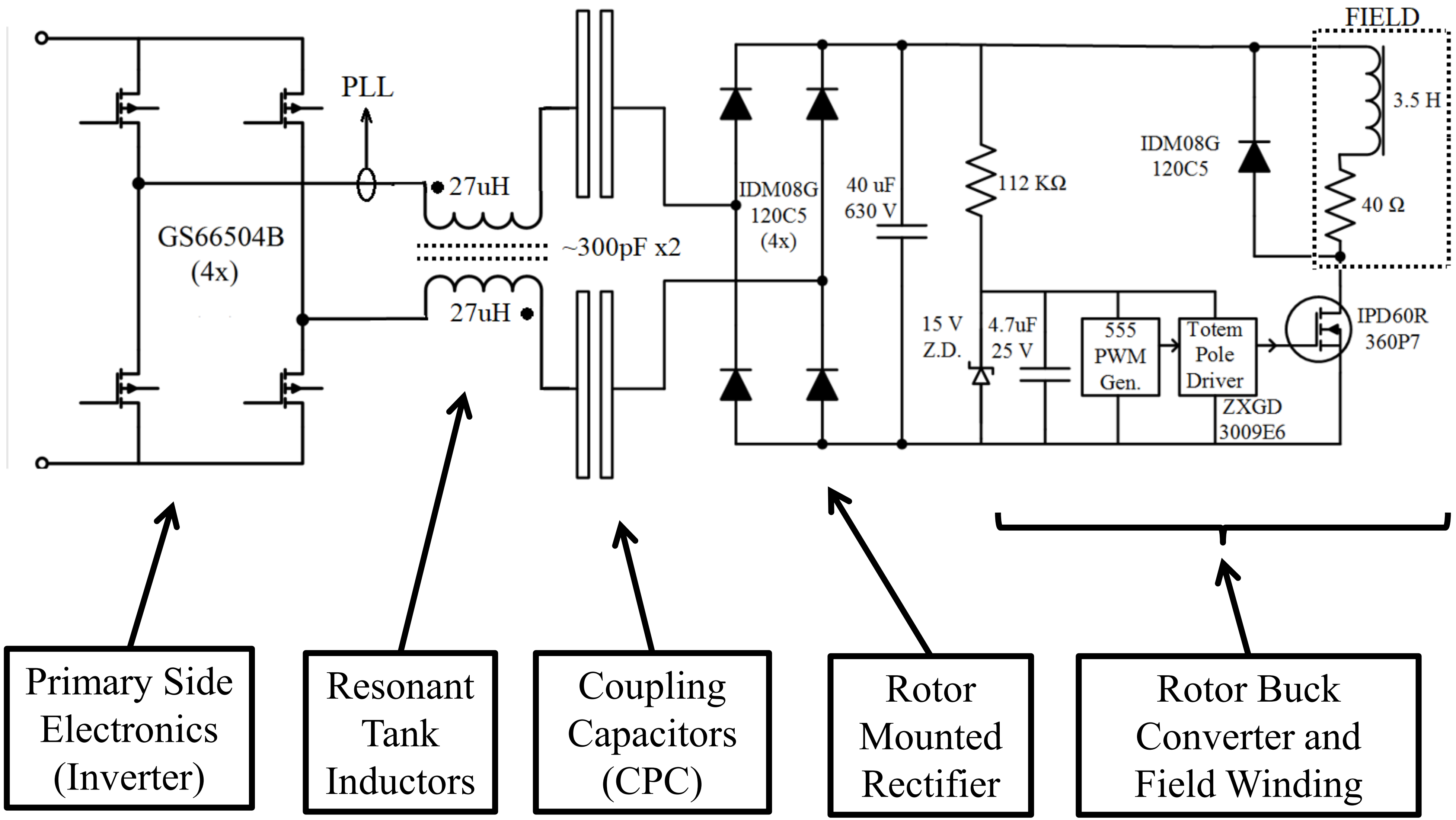




Estimated Final WFSM Performance	
Stack Length = 70 mm	Value
Shaft Torque [Nm] at -15 Deg. Phase Advance	357.54
Output Power @ 4000 RPM [kW]	151.4
Efficiency at 40 Deg. C [%]	94.41
Power Factor at -15 Deg. Phase Advance*	0.91
Active Volume [l] of Stator	3.55
Active Mass + End Turns [kg]	24.1
Volumetric Power Density [kW/l]	42.68
Specific Power Density [kW/kg]	6.28

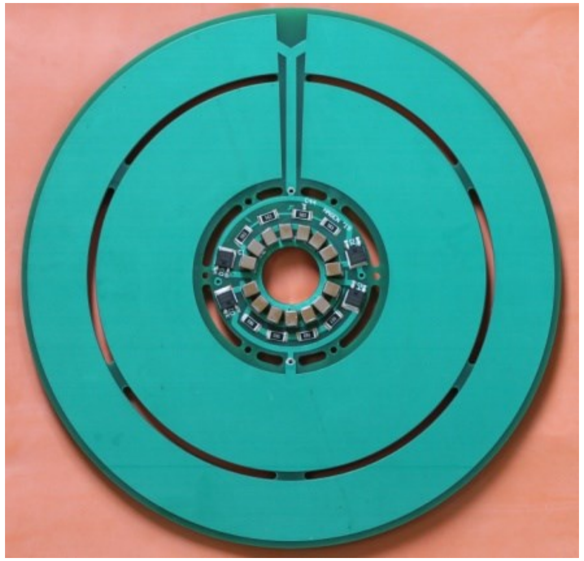
$\sigma_{stator} = 30\ A_{peak} / mm^2 \quad \sigma_{rotor} = 28\ A_{peak} / mm^2$

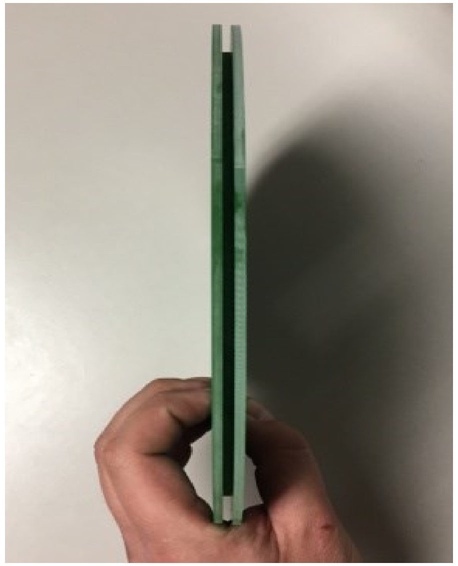
Previous Technical Accomplishments – Final CPT System Schematic

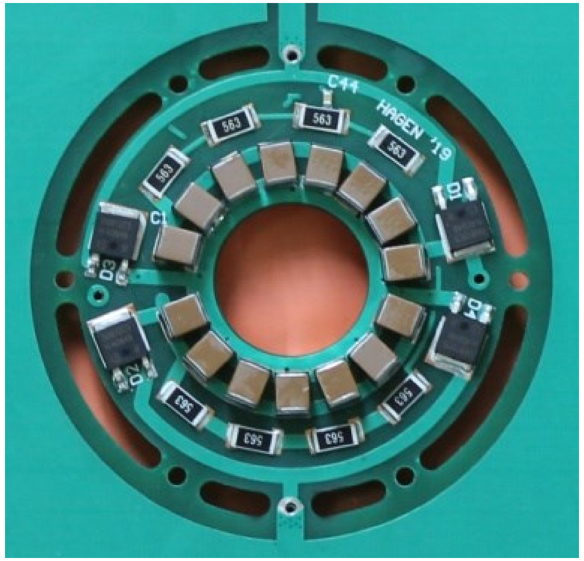


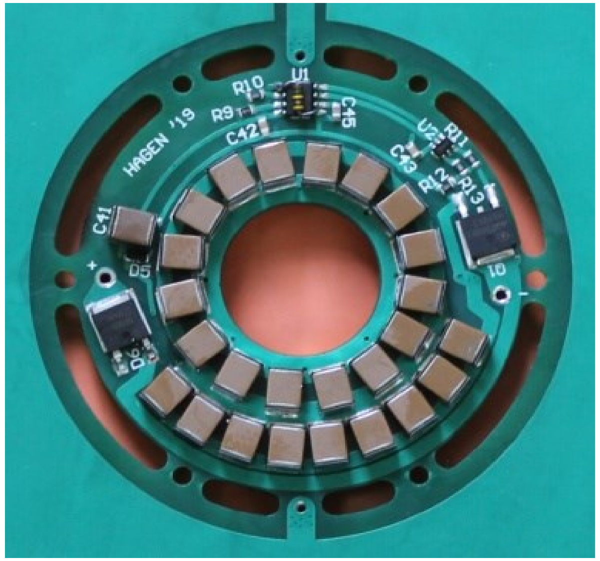
Previous Technical Accomplishments – Final Single Phase Capacitive Power Coupler Prototype with Rotor Mounted Buck Converter

- Impedance transformation using rotor mounted buck converter
  - More flexibility in field winding design while increasing effective impedance of load as seen by the CPC
- Rotor mounted buck converter specifications
  - $f_{switching}$ = 1770 Hz => low switching frequency => high efficiency
  - Duty ratio = 67 %
  - Buck gate drive powered by high voltage DC bus for fully self-contained operation on WFSM rotor

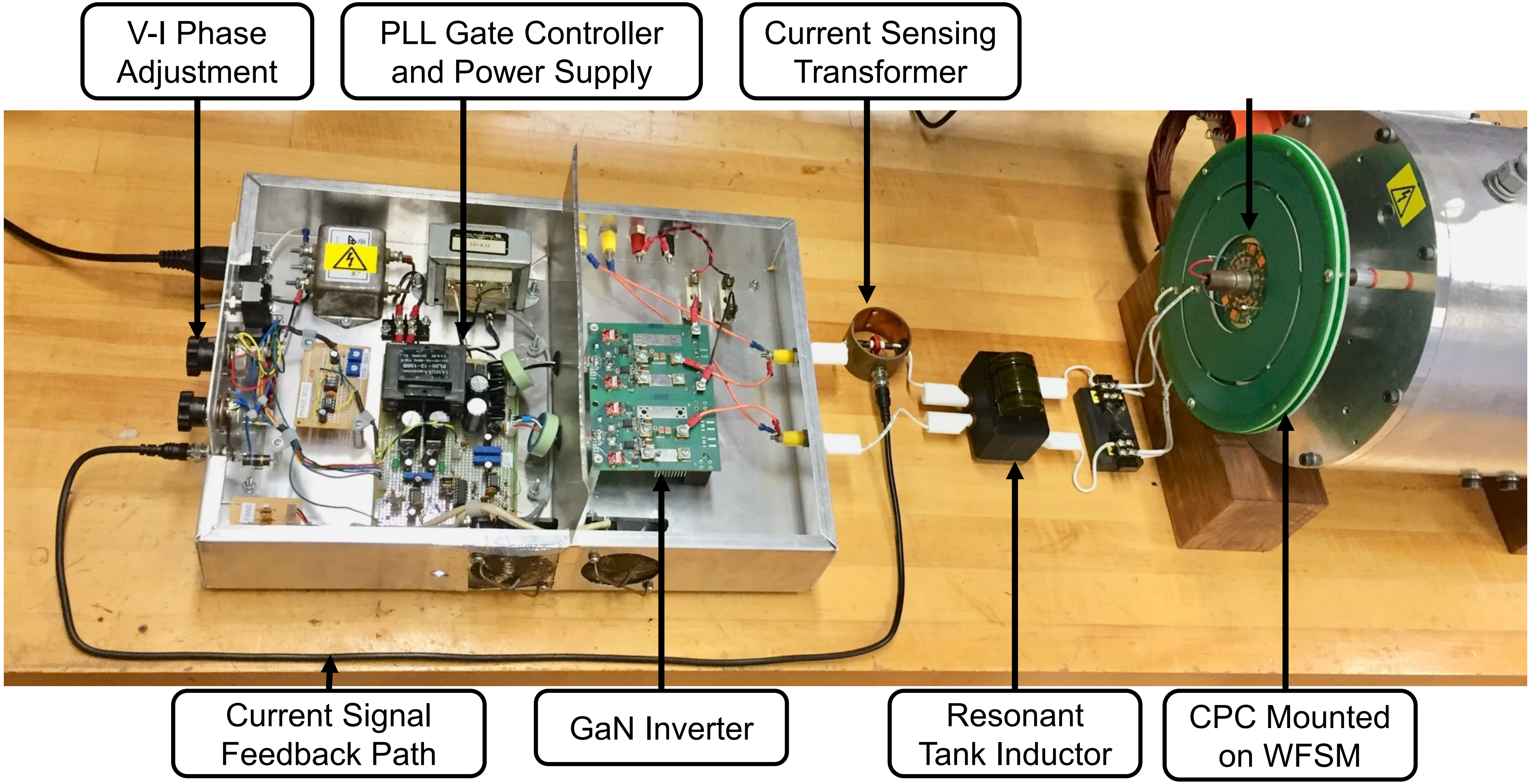








Previous Technical Accomplishments – Final Capacitive Power Transfer System Experimental Setup



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