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

2019 DOE Annual Merit Review

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Illinois Institute of Technology

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Project ID: elt230

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Overview

Timeline

- Start Date: 10/1/17
- End Date: 9/30/19
- Percent Complete: 85%

Barriers

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

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

Project Partners

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

Relevance/Objectives

Overall

- Develop cost effective wound field synchronous machines (WFSMs) and hybrid excitation synchronous machines (HESMs) which meet DOE cost and performance metrics by 9/30/19
  - Final FY19 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 wound field or hybrid excitation synchronous machine using the capacitive power coupler

This Period (By 9/30/19)

- Final prototype WFSM achieves peak power ≥ 55 kW, specific power density ≥ 1.6 kW/kg, volumetric power density ≥ 5.7 kW/l with capacitive power coupler
- Final cost evaluation show WFSM with CPC is ≤ $4.7/kW

Milestones

Milestones & G/No-Go Decision Points	Date	Status
Initial journal bearing capacitive power coupler (CPC) prototype 1 meets initial power transfer metrics in s	3/31/17	Complete
Construction of best in class full power WFSM or HESM rotor prototype 1 complete	9/5/17	Complete
Best in class full power WFSM or HESM prototype 1 meets reduced peak power metrics using brushes during dynamometer testing	12/25/17	Complete
Journal bearing CPC prototype 1 transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W during bench testing	9/29/17	Complete
Rated field current through journal bearing CPC prototype	12/30/18	Complete
PCB CPC design meets initial power transfer metrics	3/30/18	Complete
Final prototype WFSM/HESM design meets power density metrics in simulation	10/17/18	Complete
Construction of final WFSM/HESM prototype complete	Planned 5/30/19	On-going
PCB CPC prototype transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W during bench testing	7/24/18	Complete
Final WFSM/HESM prototype meets USDRIVE 2020 metrics with brushes and slip rings	6/30/19	On-going
Final WFSM/HESM prototype meets USDRIVE 2020 metrics with CPC	8/31/2019	On-going
Final WFSM/PMWFSM with integrated brushless power coupler BOM achieves ≤$4.7/kW target	9/30/2019	On-going

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Approach

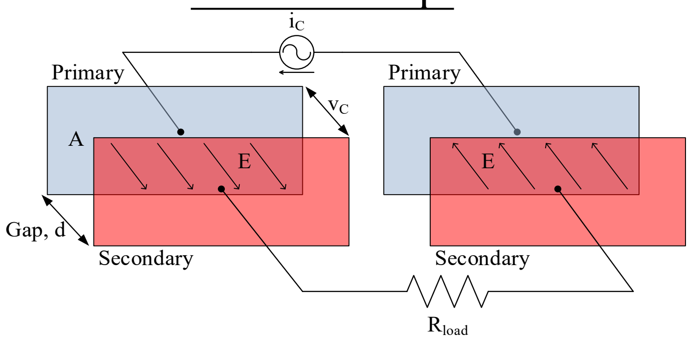
WFSM Cost Reduction Approaches

- Die compressed windings (targeting ~70% to 80% slot fill)
  - Flexible number of turns compared to bar/hairpin winding
  - Reduced AC losses at high frequency compared to hair-pin winding
  - 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
  - Fractional slot concentrated winding maybe required for stator
- Low scrap designs (typically 40% scrap for IPMSMs)
  - Leverage cut-core and roll-up techniques on stator and rotors
  - Potential to utilize lower grade electrical steel in rotor
- Fully utilize machine's active materials
  - Refine in-house developed optimization tool
  - Explore the use of topological optimization
- High performance controls development for WFSMs

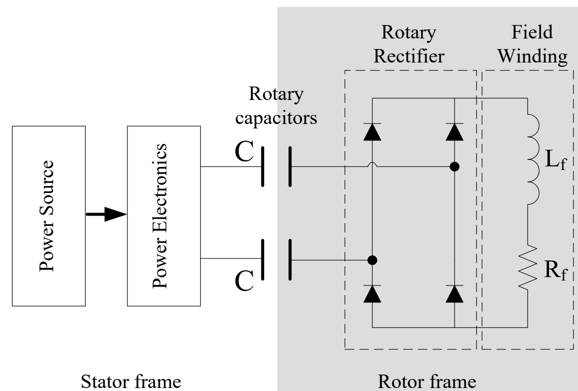
Approach

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

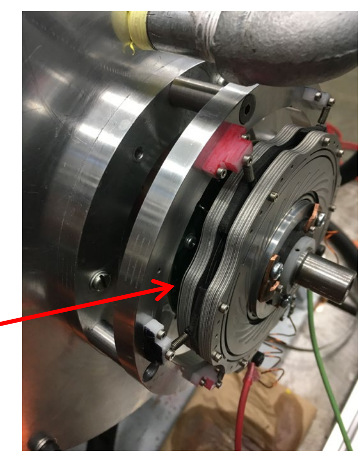
Basic Concept



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

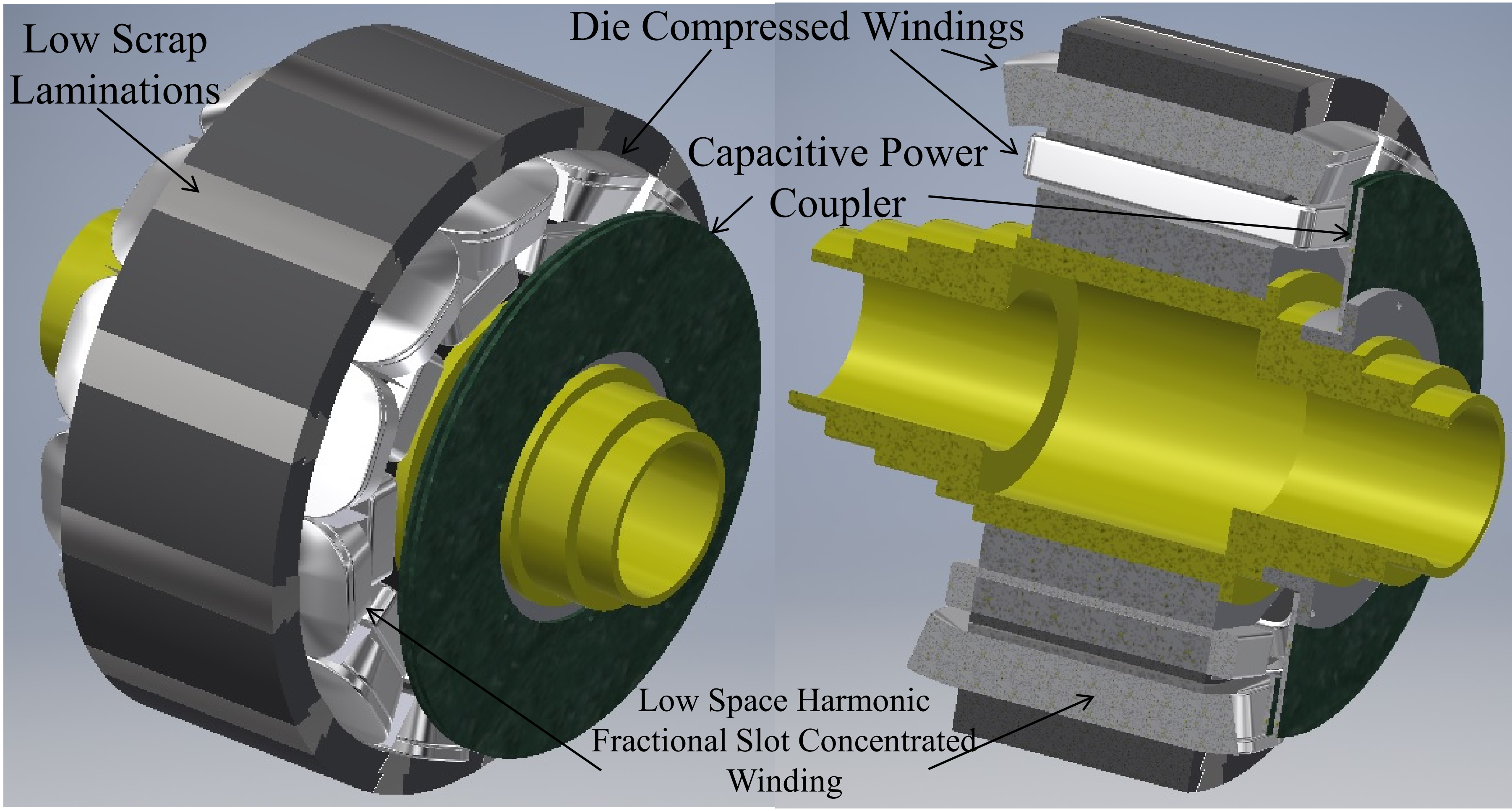
Lower the cost of the capacitive power coupler

- 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

Overall Machine and CPC Concept



WFSMs and HESMs Prototype Development Plan

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

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- Prototype 1: Increased power density classical WFSM (Finished)
- Prototype 2: Parallel flux dual rotor HESM (Finished)
- Prototype 3: WFSM rotor with die compressed field winding (Finished)
- Prototype 4: 3 phase wound rotor HESM (Under construction)
- Prototype 5: Final WFSM/HESM stator and rotor with die compressed windings (Under construction)

- Integrate prototype 3 & 5 with CPC

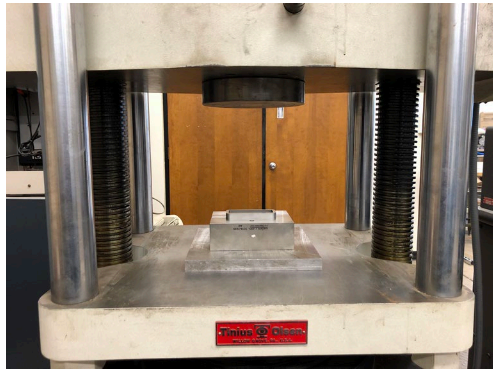
Previous Technical Accomplishments

- Baseline WFSM with random wound rotor and distributed winding stator prototyped
- Rotor with die compressed field winding electromagnetic and structural design completed
- Die for compressed rectangular field coil manufactured
- High and low switching frequency deadbeat direct torque and flux control of WFSMs
- HESM with parallel rotors prototyped
- Several power coupler technologies investigated
  - Journal bearing CPC
  - Integrated LC PCB
  - Large gap PCB CPC (Focus of continuing work)
- Large gap 3 phase CPC with 2 Mhz, soft switching, 3 phase GaN inverter prototyped and tested

Technical Accomplishments – WFSM Rotor with Die Compressed Field Winding Complete

- Manufacture of simplified die complete and field winding coils pressed

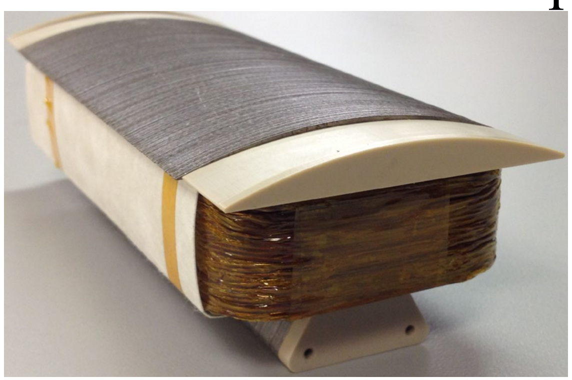
Simple Die



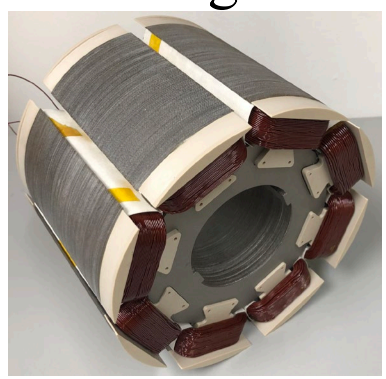
Die Set in Small Press

Compressed Field Winding Coil

- Rotor with die compressed windings assembled



Individual Pole Piece



Full Rotor

Full Rotor

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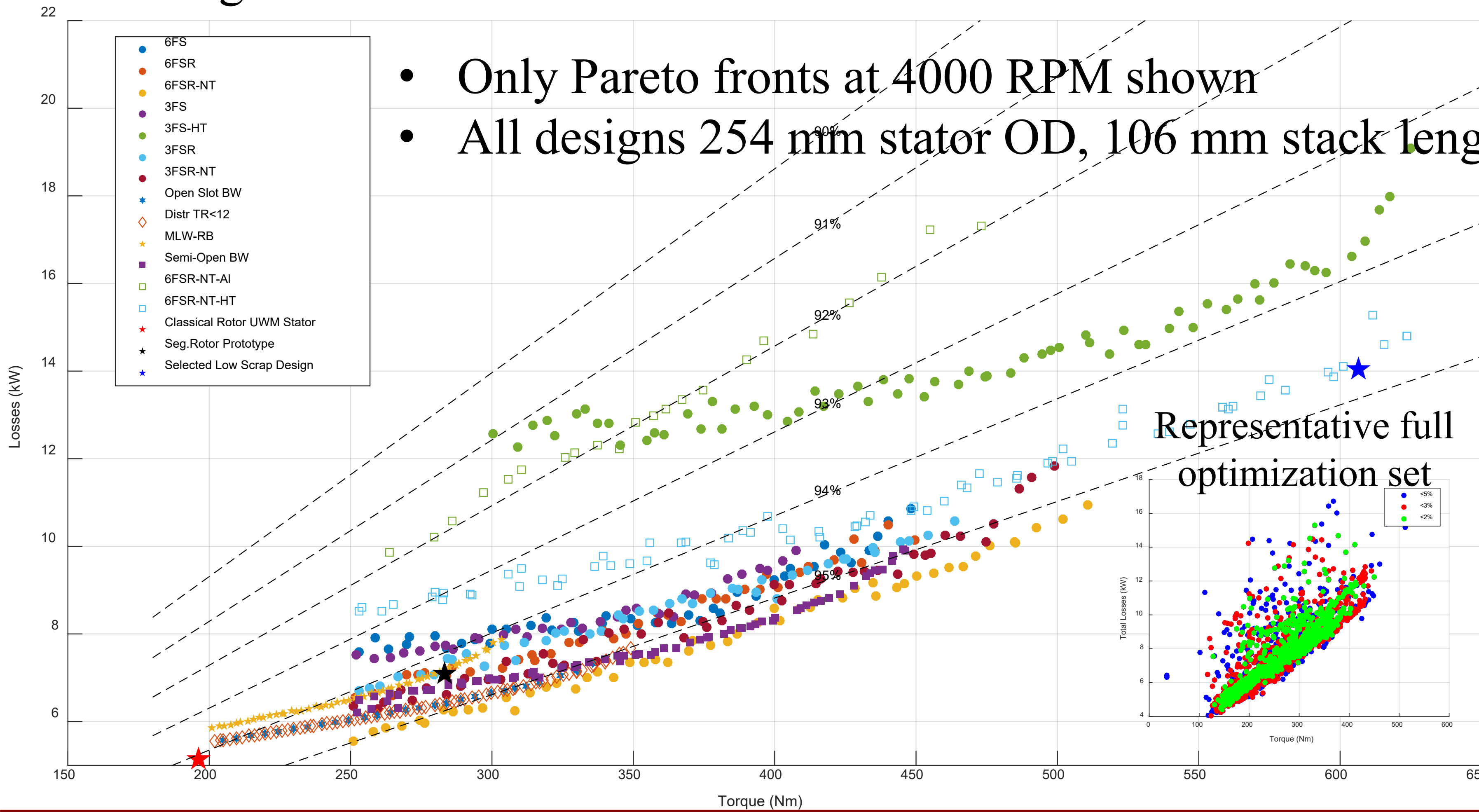
Technical Accomplishments – Final WFSM Prototype

- Extensive optimization studies of a large number of WFSM configurations

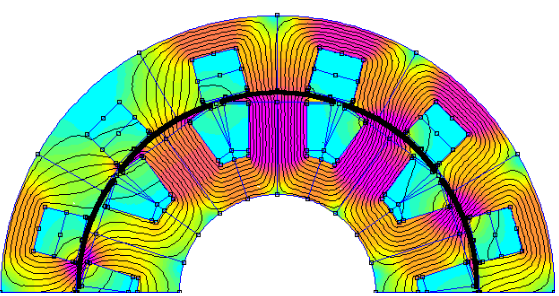
- Only Pareto fronts at 4000 RPM shown
- All designs 254 mm stator OD, 106 mm stack length



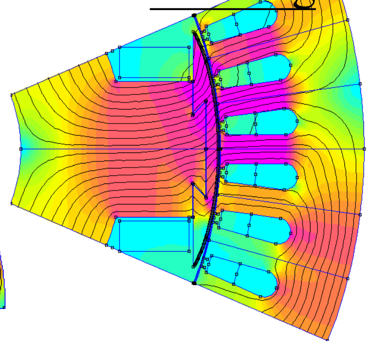
Technical Accomplishments – Final WFSM Prototype

- Alternative topologies investigated include but are not limited to the following:
  - 3 Phase 12 slot 10 pole FSCWs
    - Closed slot roll up and open slot non-roll up topologies
  - Multiple subset star delta 12 slot 10 pole FSCWs
    - Closed slot roll up and open slot non-roll up topologies
  - Hairpin/bar wound stator
    - Open slot and semi-closed slots
  - Classical random wound distributed windings
  - Die compressed aluminum winding (assuming conservative 0.7 slot fill)

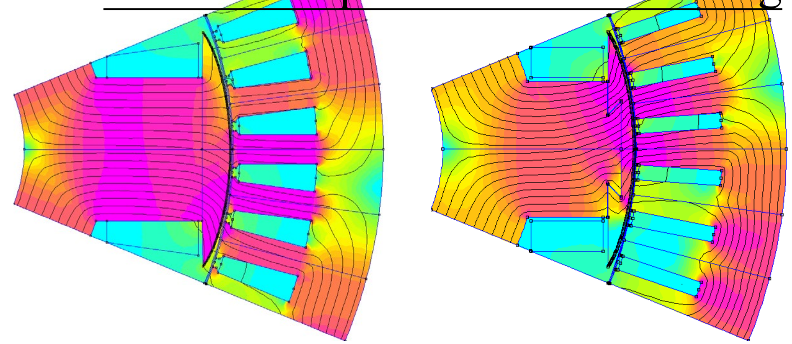
Representative 6 Phase Open Slot



Representative Distributed Winding



Representative Bar/Hairpin Stators & Die Compressed Rotor Winding



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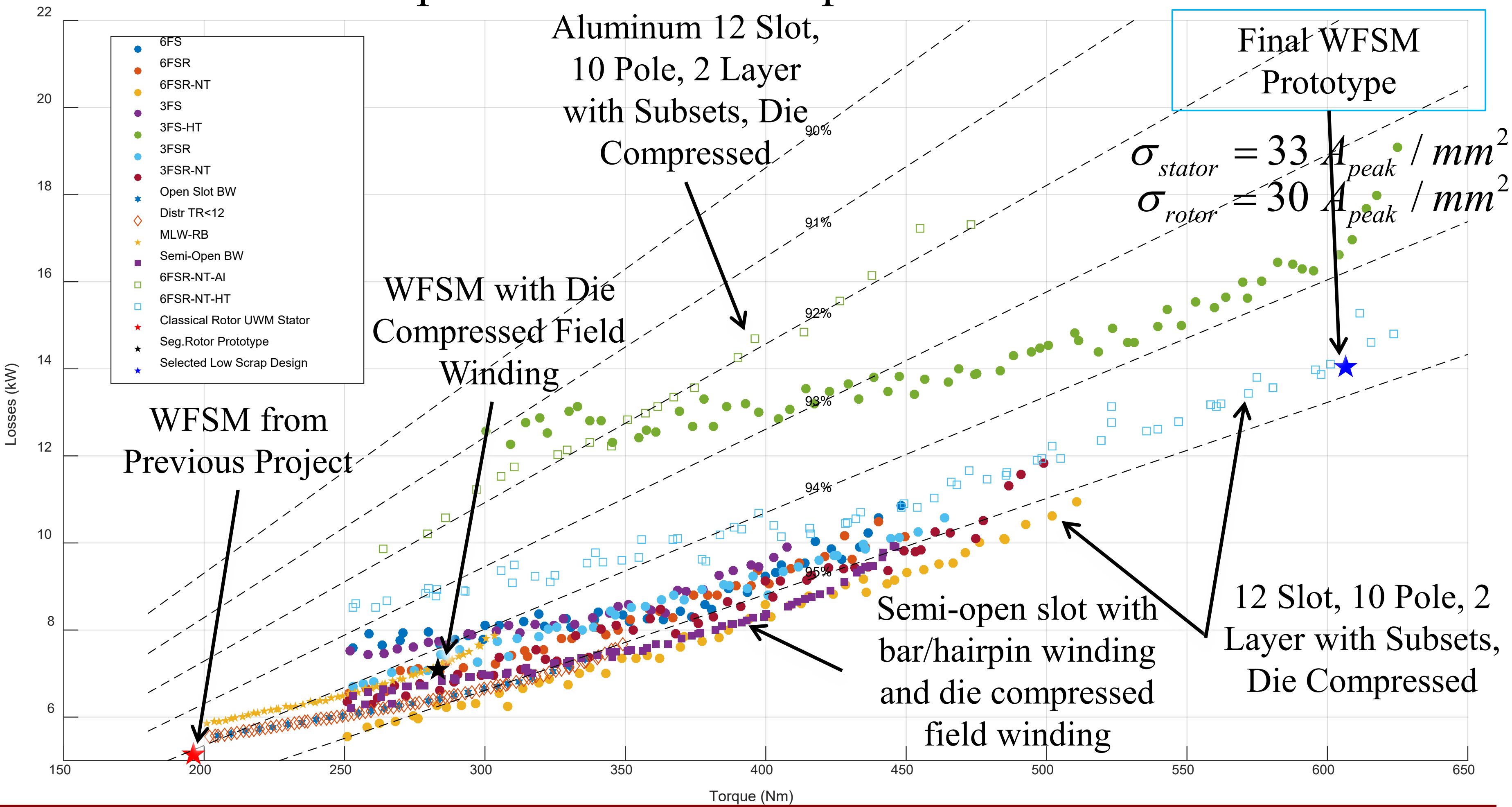
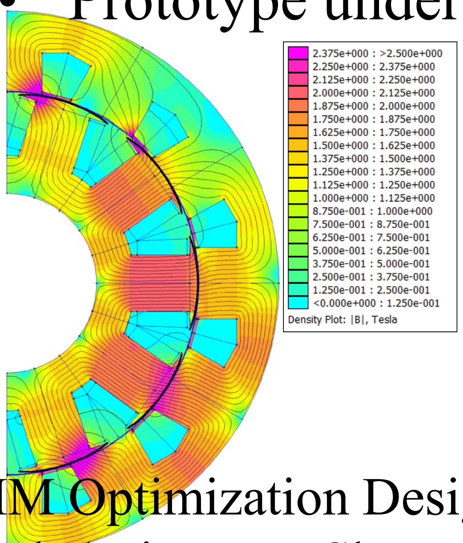
Technical Accomplishments – Final WFSM Prototype

- Conservative slot fills assumed; 0.4 for traditional windings and 0.7 for die compressed and bar/hairpin

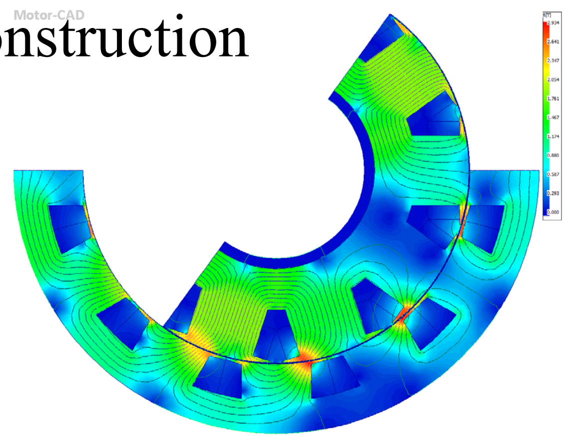


Technical Accomplishments - Final WFSM Prototype

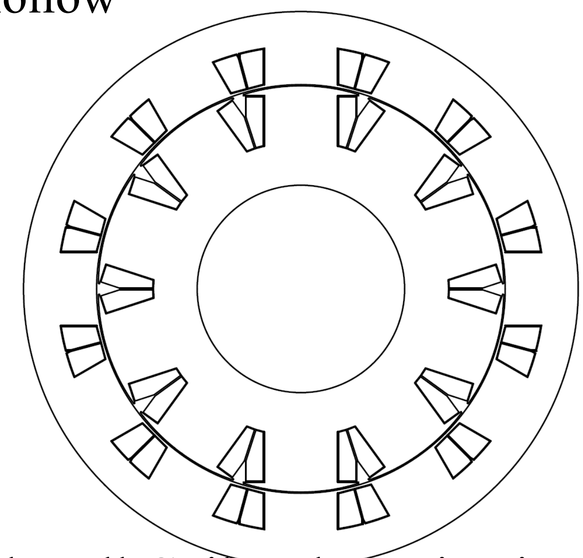
- Die compressed stator and field winding
  - Stator: 12 slot, 10 pole, 2 layer, 2 subsets spatially and time shifted
  - Field winding: Non-rectangular winding to fully utilize slot area
- Segmented stator and rotor to allow compressed coil insertion
  - Low scrap segmentation design; Currently exploring IP protection
  - Roll up segmentation not shown in designs that follow
- Prototype under construction



FEMM Optimization Design Result (Joints Not Shown)



MotorCAD EM and Thermal Performance Estimation



Full Coil and Lamination Design (Joints not shown)

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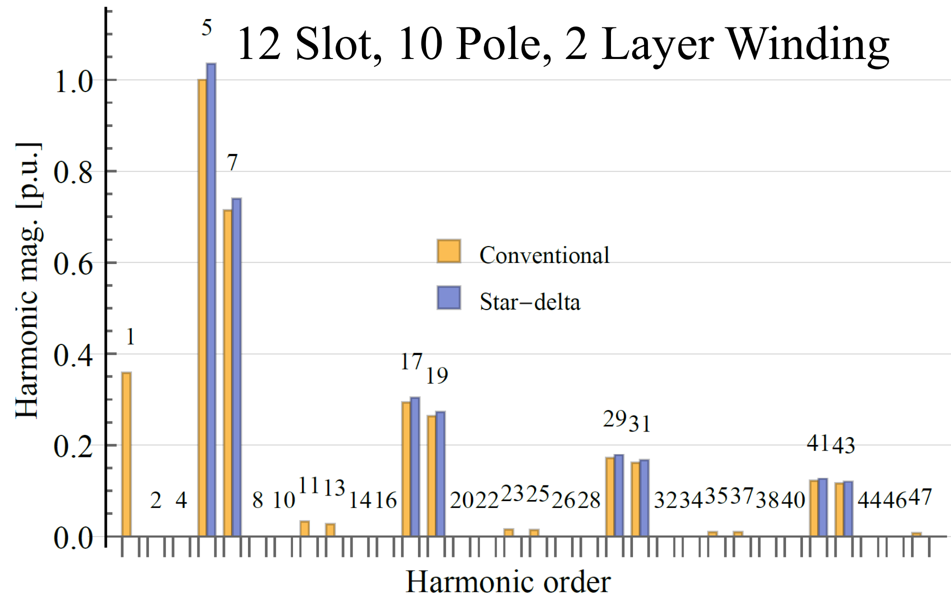
Technical Accomplishments – Final WFSM Prototype

- Die compressed windings require a concentrated winding
  - Fractional slot concentrated winding (FSCW) are likely required in the stator
  - FSCWs have high harmonic content which generally prevents their use in high speed machines
  - Target machine maximum speed is 12 kRPM
- To reduce the core losses at high speeds a 12 slot 10 pole double layer winding with two subsets is utilized
  - Two subsets are spatially displaced with one subset in star and one in delta
  - Emulates a six phase machine using a standard 3 phase inverter
  - Fundamental winding factor increased
  - Harmonics attenuated: 1, 11, 13, 23



Technical Accomplishments – Predicted Performance

- To scale the power output to the capabilities of the dynamometer and drive (~150 kW) the stack length was reduced to 70 mm from 106 mm
- Estimated results do not include the effect of segmentation and assume 0.7 slot fill
- Anticipated maximum current densities due to drive limitations

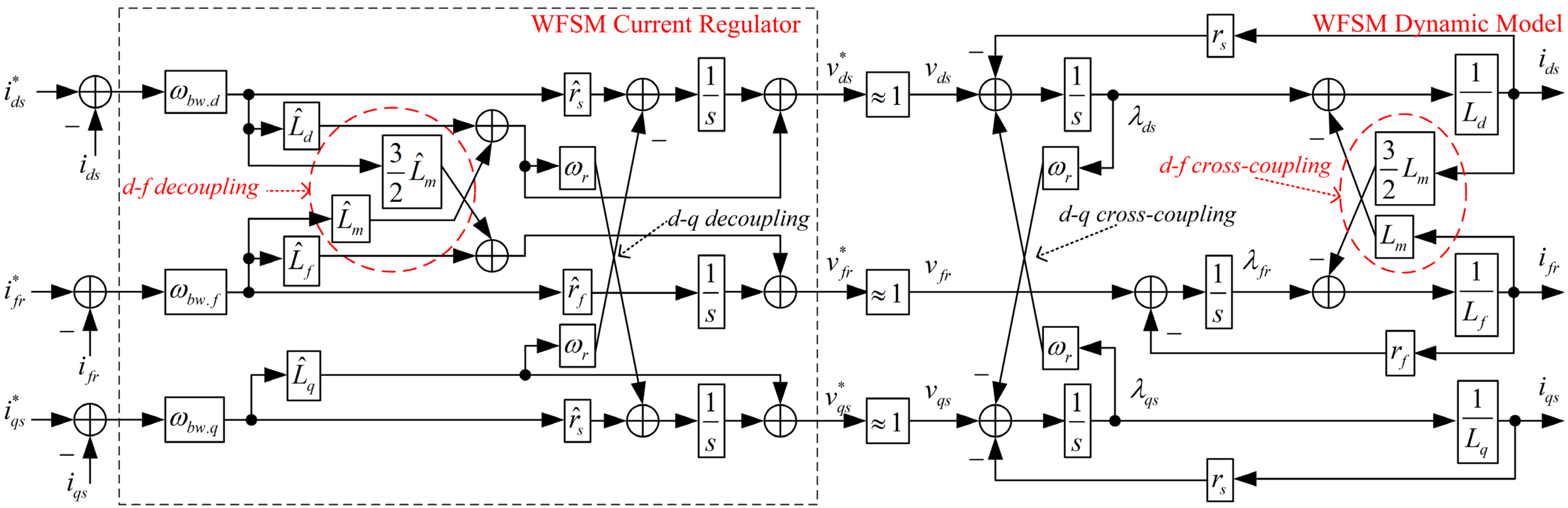
$$\sigma_{stator} = 30\ A_{peak} / mm^2 \qquad \sigma_{rotor} = 28\ A_{peak} / mm^2$$

Estimated Final WFSM Performance	**Stack Lengths**	
	106 mm	70 mm
Shaft Torque [Nm] at -15 Deg. Phase Advance	541.42	357.54
Output Power @ 4000 RPM [kW]	226.8	151.4
Efficiency at 40 Deg. C [%]	95.12	94.41
Power Factor at -15 Deg. Phase Advance*	0.91	0.91
Active Volume [l] of Stator	5.37	3.55
Active Mass + End Turns [kg]	35.0	24.1
Volumetric Power Density [kW/l]	42.23	42.68
Specific Power Density [kW/kg]	6.48	6.28

* Unity power factor available at reduced torque output

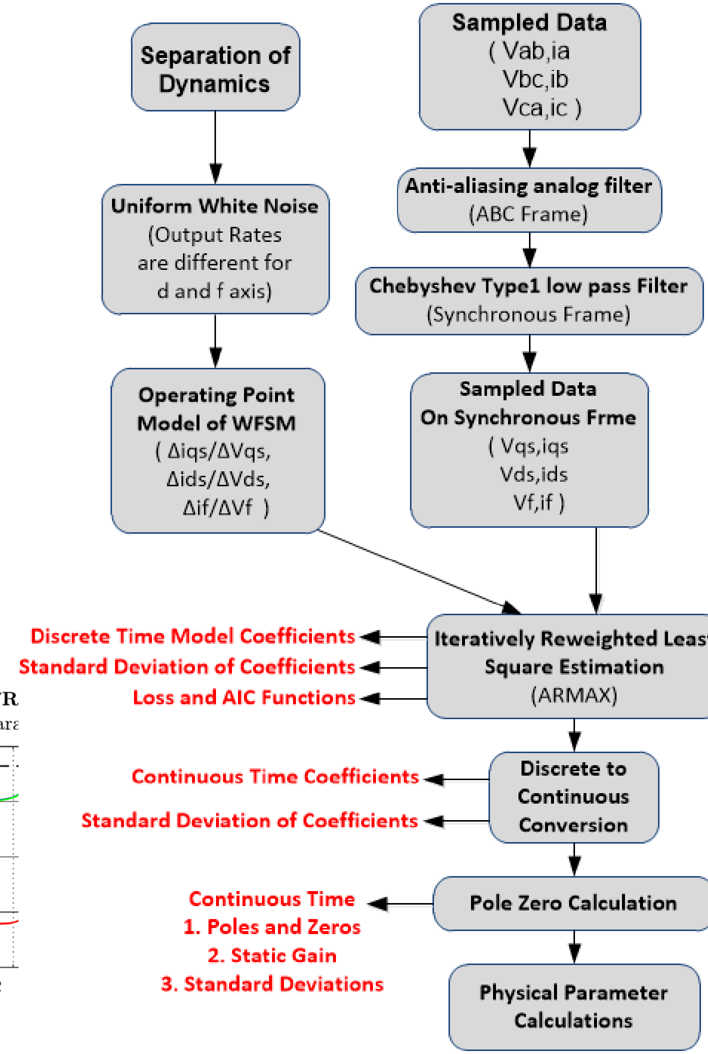
Technical Accomplishments – Improved WFSM Control

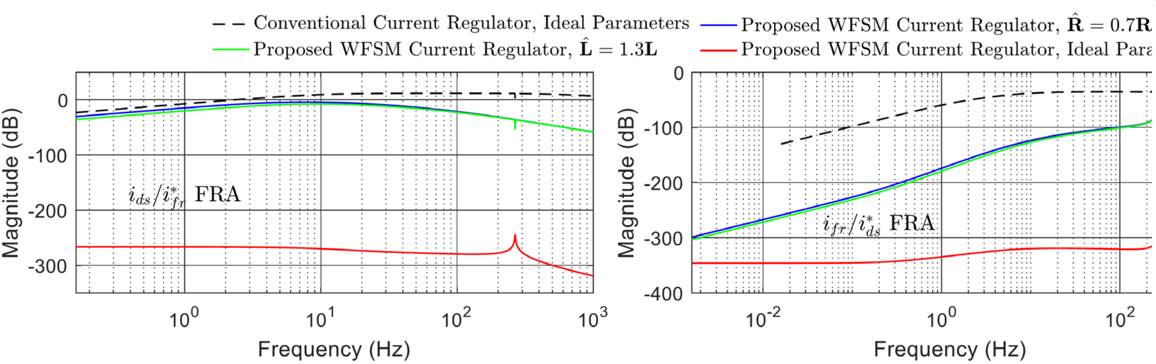
- Decoupling matrix current regulator further developed
- With perfect parameter estimates three axes are completely decoupled
  - Imperfect parameter estimates still provides good decoupling
- Command slew developed to avoid over-voltages on field axis



Technical Accomplishments – WFSM Parameter Estimation

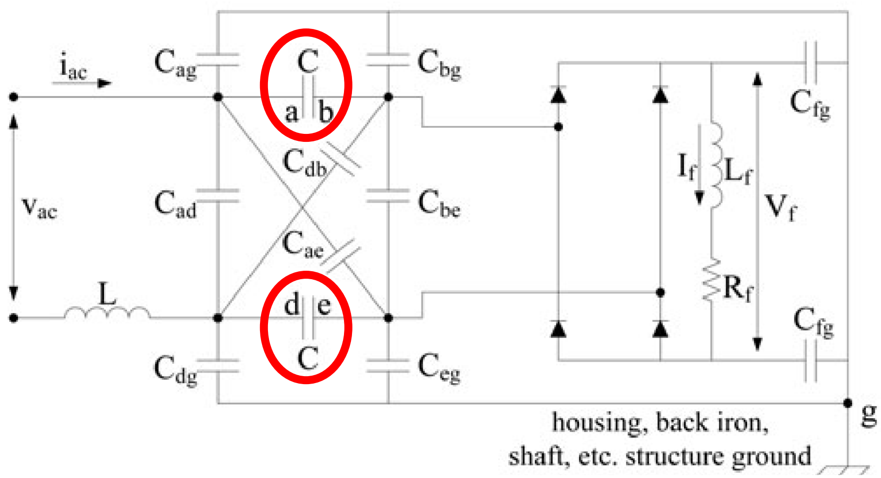
- Accurate estimates of the WFSM parameters aids the torque/current regulation and future efficiency optimization control
- Offline WFSM parameter auto-tuning being developed
  - Drive input signal and sample rate to separate axes subsystem dynamics



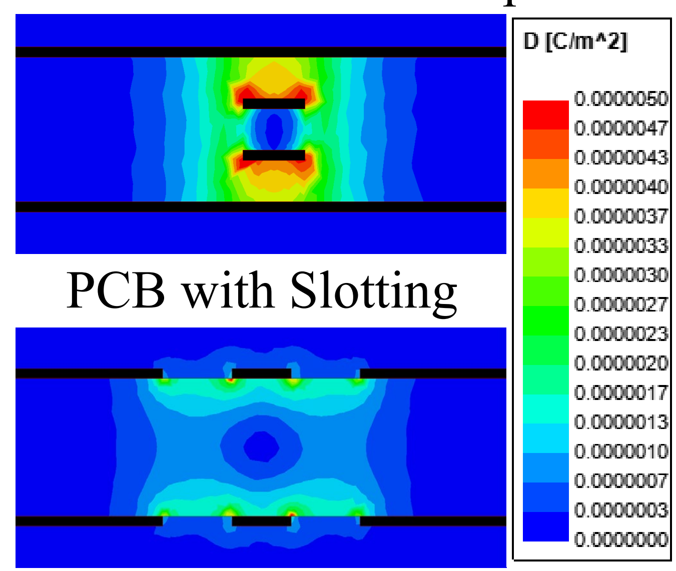


Technical Accomplishments – Minimization of parasitic capacitances and dielectric loss in CPC PCBs

- Desired coupling capacitances are circled in red; all other capacitances should be minimized
- Slotting to remove FR4 between phase conductors and eliminating trace overlap reduce D-field intensity by ~3x-4x in dielectric volume



PCB with Trace Overlap



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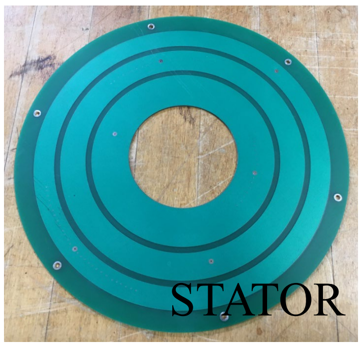
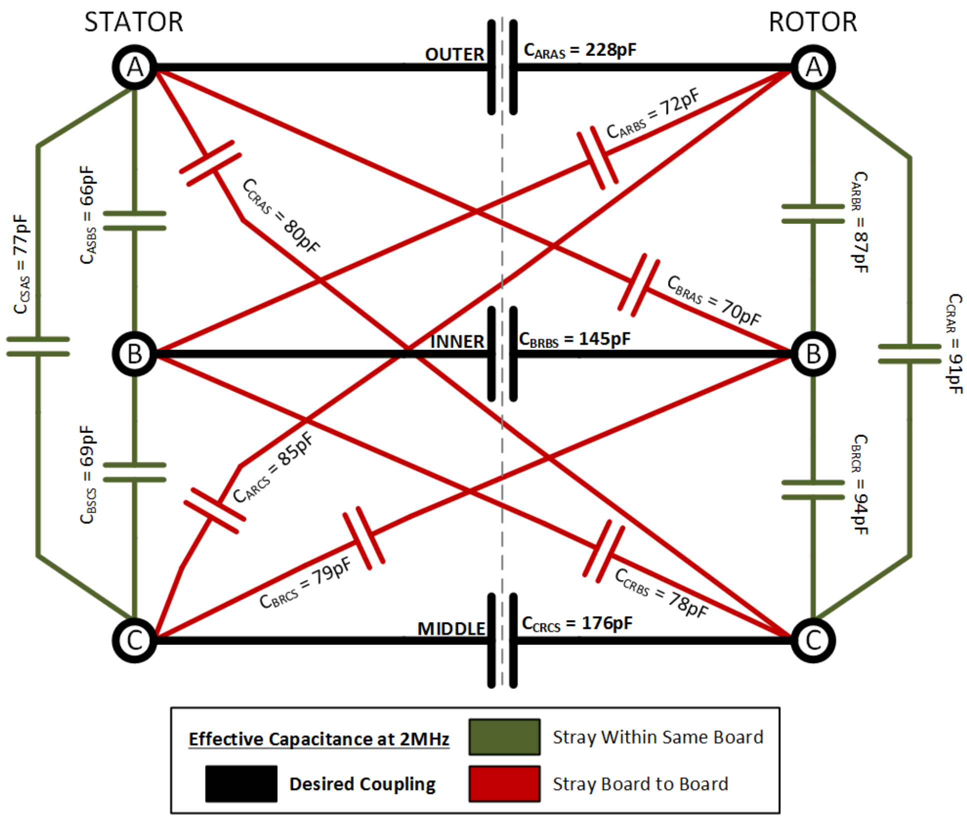
Technical Accomplishments – Capacitance and Dielectric Loss Measurements

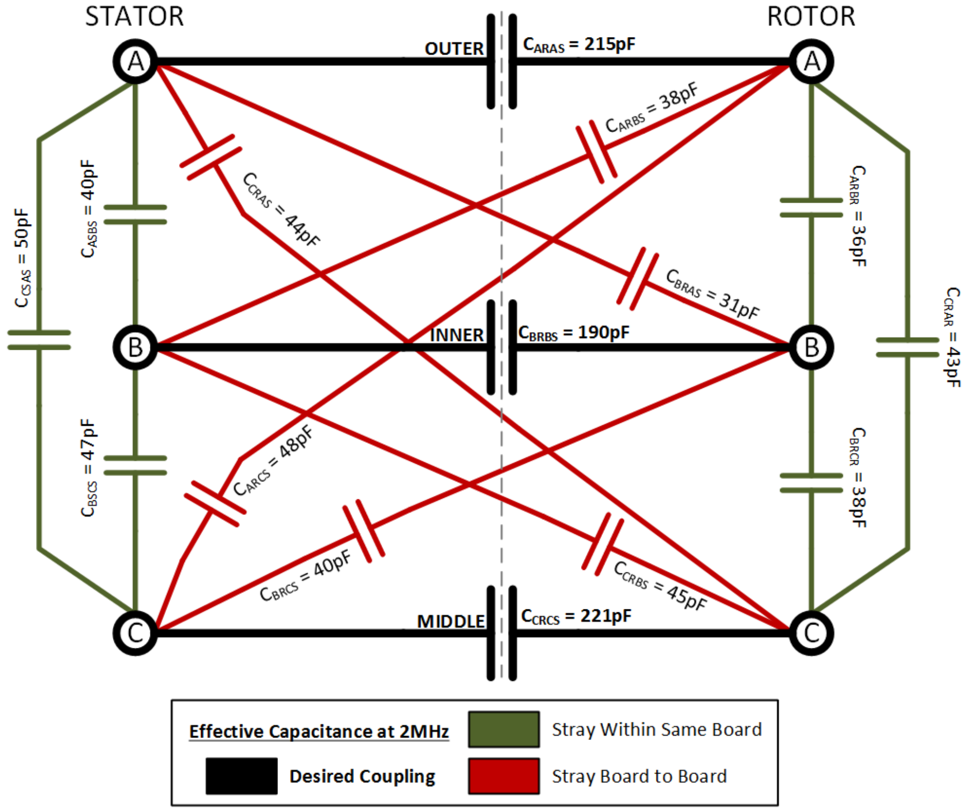
- CPC PCB Prototype 1
  - 3 phase structure; 4 layer rotor PCB, 2 layer stator PCB

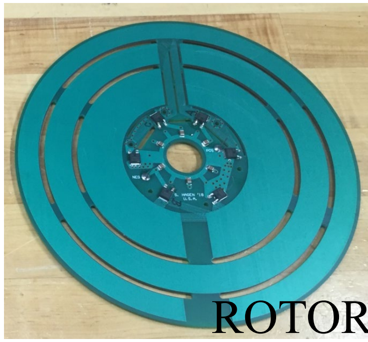




Technical Accomplishments – Capacitance and Dielectric Loss Measurements

- CPC PCB Prototype 2
  - 3 phase structure; elimination of overlapping phase conductors, reduction of lossy FR4 dielectric material between phases



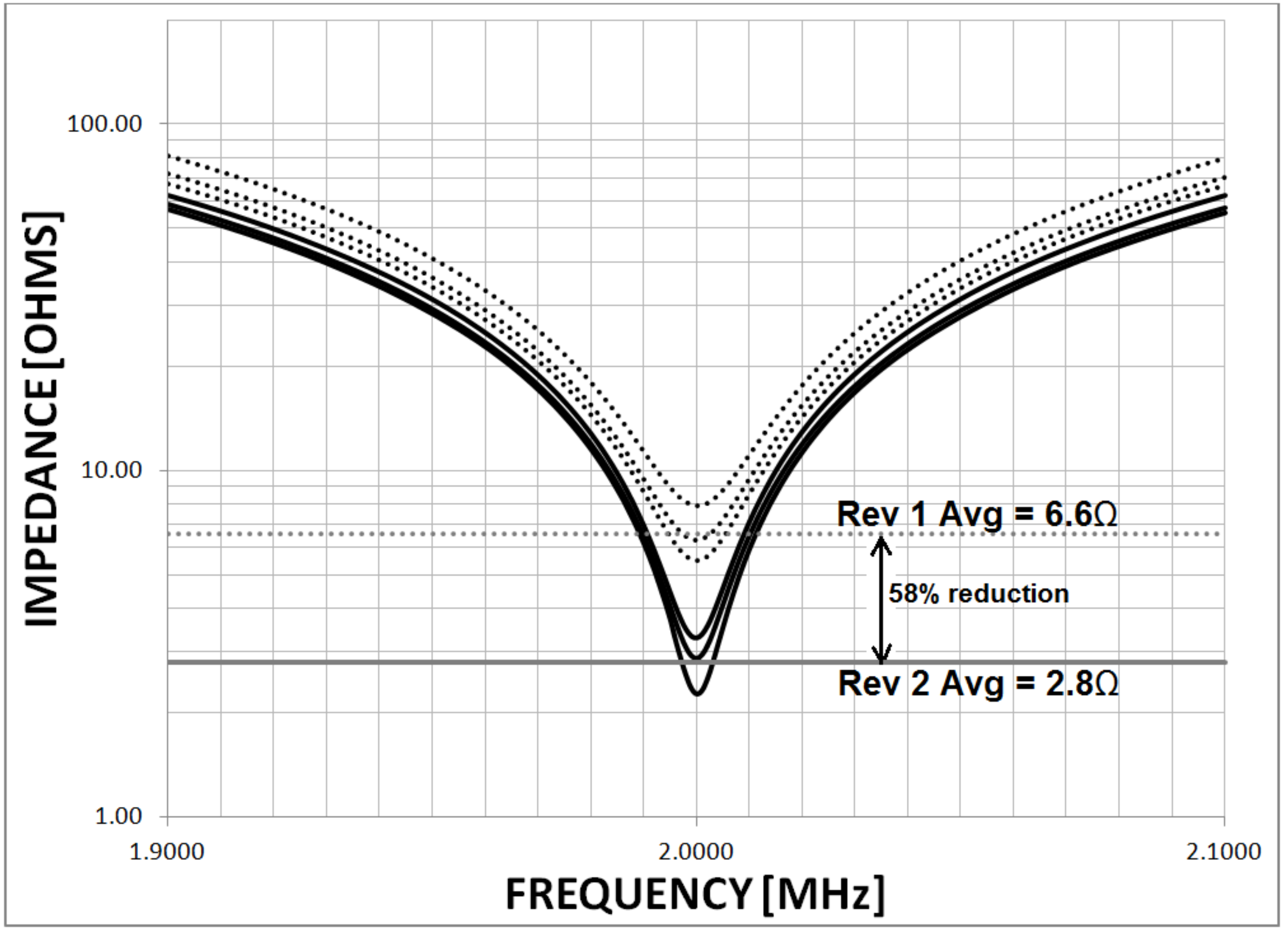


Technical Accomplishments – Summary of Capacitance Improvements

CLASS	CAPACITANCE	Prototype 1 [μμfd]	Prototype 2 [μμfd]	Δ%
DESIRED COUPLING	C_{ARAS}	228 **(+25% from mean)**	215 **(+3% from mean)**	-
	C_{BRBS}	145 **(-21% from mean)**	190 **(-9% from mean)**	-
	C_{CRCS}	176 **(-4% from mean)**	221**(+6% from mean)**	-
STATOR/ROTOR PARASITIC	C_{ARBS}	72	38	**-47%**
	C_{ARCS}	85	48	**-44%**
	C_{BRAS}	70	31	**-56%**
	C_{BRCS}	79	40	**-49%**
	C_{CRAS}	80	44	**-45%**
	C_{CRBS}	78	45	**-42%**
STATOR SELF PARASITIC	C_{ASBS}	66	40	**-39%**
	C_{BSCS}	69	47	**-32%**
	C_{CSAS}	77	50	**-35%**
ROTOR SELF PARASITIC	C_{ARBR}	87	36	**-59%**
	C_{BRCR}	94	38	**-60%**
	C_{CRAR}	91	43	**-53%**

- Significant reduction in parasitic capacitances and homogeneity of the coupling capacitances -> increased power throughput

Technical Accomplishments – Reduction in Dielectric Loss and Equivalent Series Resistance Measurements



- Significant reduction in ESR increases efficiency by 18%

Technical Accomplishments – Single Phase PCB CPC

- Prototype 3 – Single Phase PCBs and GaN Inverter
  - From a theoretical perspective three phase systems are able to delivery more power
  - Controlling leakage capacitance and dielectric loss is much more difficult in three phase systems
  - Controller for single phase system also easier to implement and tune

SINGLE PHASE ROTOR →

THREE PHASE ← ROTOR

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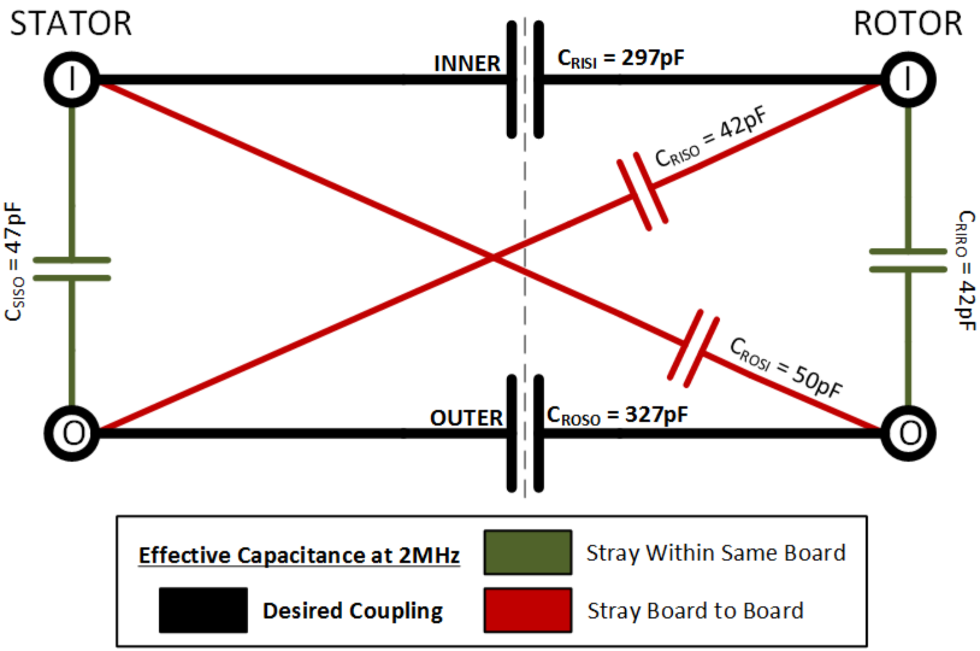
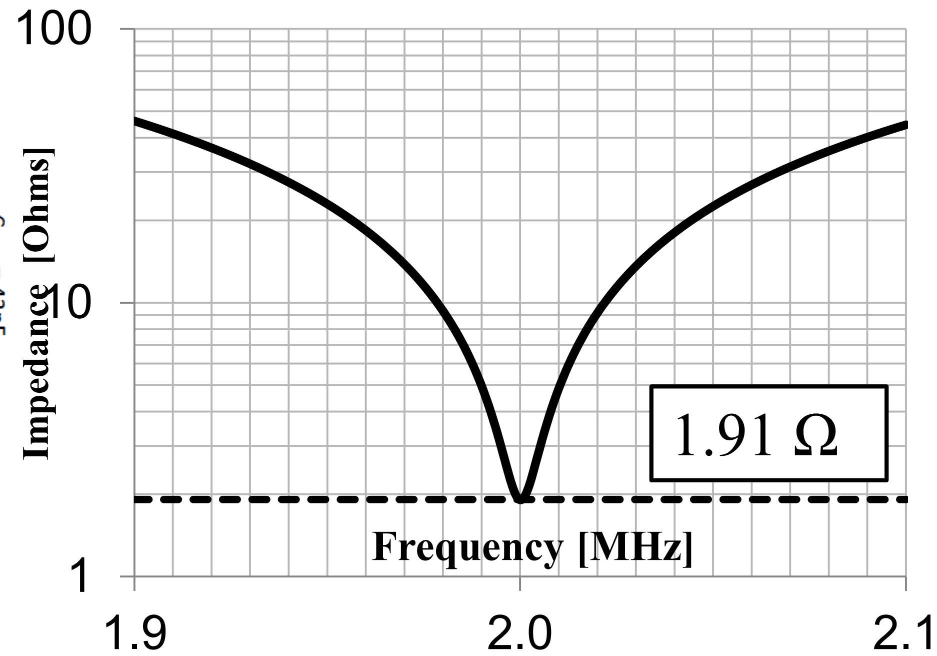
Technical Accomplishments – Single Phase PCB Capacitance and ESR Measurements

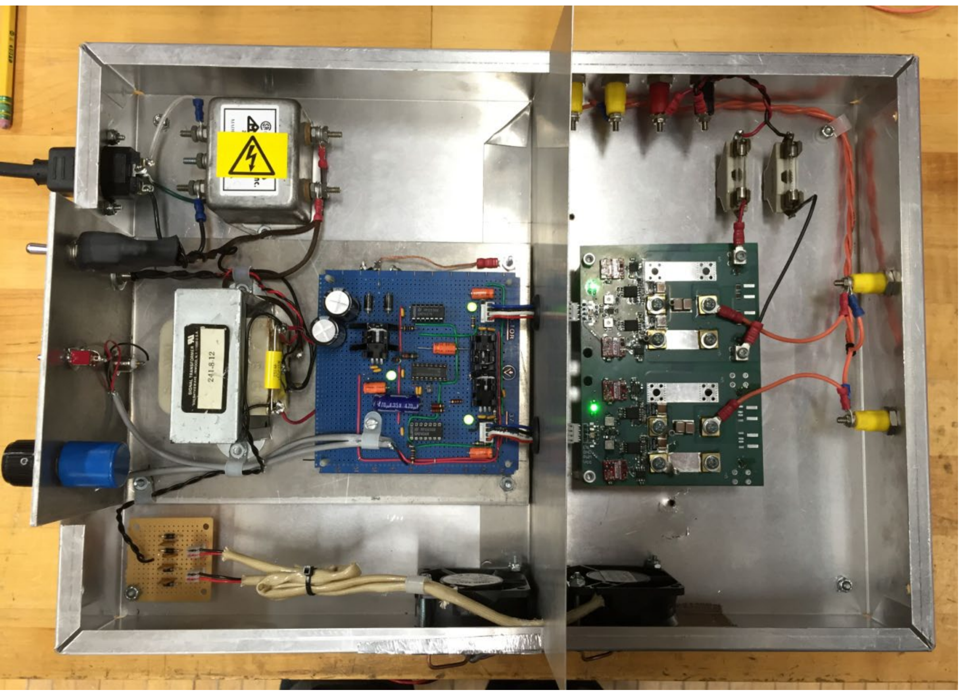


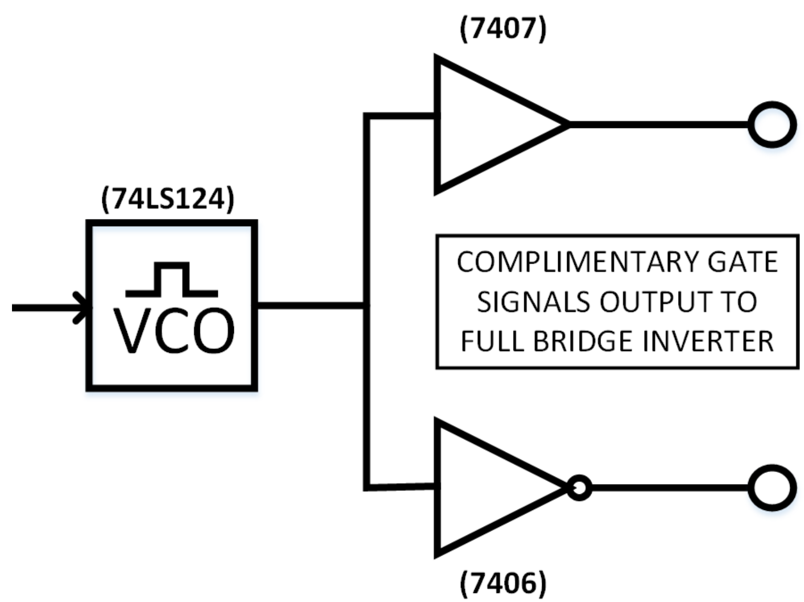


- Parasitic circulating current paths in the single phase PCB significantly reduced lowering ESR

Technical Accomplishments – Single Phase GaN Inverter with Simple Controller

- Single phase GaN multi-MHz H-bridge inverter
- Simple, low cost VCO generation of gate signals with tunable deadtime





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Technical Accomplishments – Prototype 3 Single Phase PCB CPC and GaN Inverter Testing

- Switching frequency 2 MHz, load resistance of 92 Ohms

I_{IN}	V_{IN}	I_{OUT}	V_{OUT}	P_{IN}	P_{OUT}	EFF %
1.30	85.54	1.05	96.19	111.20	101.00	90.83
1.83	121.77	1.47	136.51	222.84	200.67	90.05
2.25	151.72	1.82	169.54	341.37	308.56	90.39
2.66	185.19	2.25	206.36	492.61	464.31	94.26
3.06	216.43	2.58	238.94	662.28	616.47	93.08

- BP2 Go/No criteria met: Power goal 600 W with high efficiency, 93%.

Response to Previous Year Reviewer's Comments

- Reviewer Comment: The reviewer found the step-by-step incremental prototype machine building and testing plan to be good. Electrified powertrain community has a question mark regarding the long-term reliability of the GaN device. Hence, if GaN devices are avoided, the reviewer asked about the limitations and/or trade-offs for an alternative. For example, the reviewer wanted to know how low a frequency can one go if the alternative does not allow going with 2 MHz for capacitive power transfer and a certain assumption of capacitor size.
- Response: SiC devices could be a drop in replacement for the current 2 MHz inverters that may have less long term reliability concerns. SiC devices would also allow for higher voltage operation allowing the frequency to be reduced. If silicon devices are to be use it would be difficult to achieve the 2 MHz frequency without a complicated power converter topology. The capacitance can also be increased through stacked multiple PCBs to reduce the required frequency.

Response to Previous Year Reviewer's Comments

- Reviewer Comment: The reviewer suggested that hybrid excitation is worth investigating as an alternative candidate of interior permanent magnet synchronous motor (IPMSM) with heavy RE. The approach covers from material utilization (low scrap designs) to control scheme, which is very good. Also, the reviewer stated that the possibility of unity power-factor operation is attractive for drive-inverter. The reviewer said that it would be nice to have a description regarding why the capacitive power transfer has been chosen here, in particular, compared to the magnetic power transfer. It is fair to aim to meet 2020 target (55 kW, etc.), but because the updated target for 2025 has now been released with higher power ratings, the reviewer suggested that it would be a good idea to include a scalability study on this particular approach.
- Response: Capacitive power transfer was chosen because it does not require a heavy yoke structure to guide flux. The CPC PCB should be very low cost with mass manufacturing capability already existing from multiple sources. The electric fields are essentially contained between the capacitive surfaces. The final prototype machine will also be evaluated against the USDRIVE 2025 targets and the machine is designed to exceed the power level targets.

Collaboration and Coordination

- Illinois Institute of Technology (1 PI, 2 PhD Students)
  - 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 (1 PI, 1 PhD Student)
  - Design and construction of capacitive power coupler
  - High power dynamometer testing
- Lucid Motors
  - Design reviews of WFSM, HESM, and CPC
  - Assistance with cost estimation

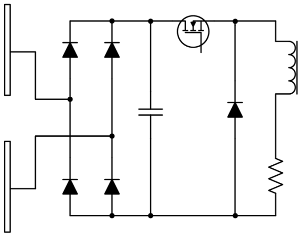
Remaining Challenges and Barriers

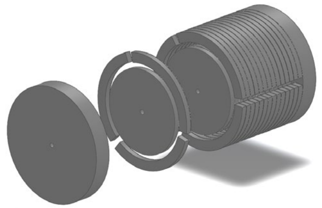
- Mechanical production of final WFSM prototype with segmented construction
  - Mechanical tolerances with prototype production processes
- High power dynamometer testing of HESM and WFSM prototypes at UW-Madison requires significant time this summer
- To give flexibility to the WFSM field winding incorporate an additional transistor and diode on the rotating CPC PCB to act at DC-DC matching transformer with free running fixed duty ratio
  - Reliability and robustness of rotating components
- Compact low loss cored inductor design for CPC power electronics which minimizes core and conduction losses while being rated to kV

Proposed Future Research

Budget Period 3 (Through 9/30/19)

- Finish construction of final WFSM prototype with die compressed stator and rotor windings
- Creation of rotor PCB with simple, free running, low switching frequency, fixed duty ratio buck converter to act as a DC-DC "matching transformer"
- Develop compact, high Q, MHz, kVAR, cored inductor
- Rotor based injection of signal via CPC to allow for tracking of rotor position potentially eliminating the resolver
- High power dynamometer test remaining prototypes:
  - Final WFSM with die compressed stator and rotor windings
  - WFSM with die compressed field winding
  - HESM with parallel flux dual rotors
  - HESM with three phase winding with brushes and slip rings
- High power dynamometer test final WFSM prototype with PCB CPC
- Detailed cost evaluation of final design and PCB CPC





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
    - Unity power factor operation to reduce inverter kVA rating
- Approach
  - Die compressed windings for high slot fill and potential use of aluminum
  - Low punching scrap segmented design with reduced space harmonic content FSCW
  - Capacitive power transfer using mechanically simple PCBs
- Technical Accomplishments
  - WFSM with die compressed winding prototyped
  - Two HESMs prototyped with one provisional patent filed
  - Mechanically simple PCB CPC and 2 MHz GaN inverter
- Future Work
  - Finish construction of final WFSM prototype with die compressed stator and field windings and three phase winding HESM
  - Full power dynamometer testing with CPC and brushes and slip rings

USDRIVE 2020 WFSM/HESM Targets Have Been Met

Metric	Target	Est. Final 70 mm stack WFSM
Peak Power (kW)	55	151
Cont. Power (kW)	30	151 (Not limited by cooling)
Specific Power Density (kW/kg)	1.6	6.28
Vol. Power Density (kW/l)	5.7	42.68