Alternative High-Performance Motors with Non-Rare Earth Materials

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DOE Peer Review Presentation

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GE Global Research

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Project ID: EDT045

imagination at work

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Overview

Timeline

- Start: October 1, 2011 (official kickoff with DoE February 7, 2012)
- End: December 30, 2016
- 92% complete (Kickoff meeting Feb. 7, 2012)

Budget

- $ ~12M total budget
- $ ~6M DOE share
- $ ~6M GE cost share

•Funding received from the DoE to date: $ 5,500,000

Barriers

Very challenging set of specs

- High efficiency over a wide speed and load ranges
- High power density and high coolant inlet temperature
- Low cost targets based on 100,000 units/year
- High speed poses mechanical challenges
- No rare-earth permanent magnets

Partners

- GE Global Research (lead)
- GE Power Conversion/GE Licensing
- University of Wisconsin-Madison
- North Carolina State University
- University of Akron
- ORNL
- NREL
- McCleer Power
- Ames National Lab
- Arnold Magnetics

The Problem

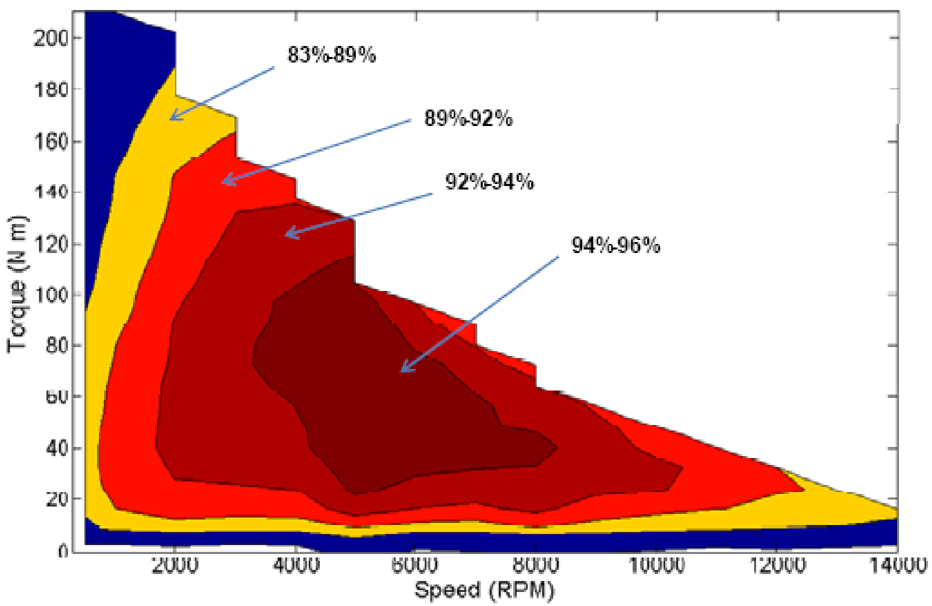
- The specifications for hybrid vehicle motors are challenging in terms of power density, efficiency and cost. This requires a comprehensive approach to advance the state of the art, including novel concepts to push past barriers.
- High speed is key to high power density
- High speed leads to higher electrical frequency
- Higher stator core and rotor losses
- On top of all these challenges, eliminating rare-earth permanent magnets makes the problem an order of magnitude more challenging

Project Objective (FY16/FY17)

Items	Specification
Max. Speed	14,000rpm
Peak Power	55kW @ 20% speed for 18sec
Maximum Current	400Arms
Cont. Power	30kW @ 20~100% speed @ Vdc=325
Efficiency	Refer to target efficiency map
Operating Voltage	200~450V (325V nominal)
Back EMF	<600Vpk line-to-line @ 100% speed
Torque Pulsation	<5% of Peak Torque @ any speed
Characteristic Current	< Maximum Current
Weight	≤35kg
Volume	≤9.7L
Cost @100k	≤$275
Ambient (outside housing) Operating Temperature	-40~140°C
Coolant inlet	105°C, <10LPM, 2psi drop, <20psi inlet
Minimum isolation impedance-phase terminal to GND	1Mohm

- Build and test final 55kWpk non-rare earth motor to meet DOE specifications

Figure 1. Motor Efficiency Targets



Relevance

Developing a low-cost, high-performance advanced traction motor is a key enabler to meeting the 2020 technical targets for the electric traction system. Elimination of rare-earth permanent magnets is very strategic in terms of eliminating the uncertainty regarding sustainability of rare-earth magnets

Table 1. Technical Targets for Electric Traction System

	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

[a] Based on a coolant with a maximum temperature of 90°C.

[b] Based on air or a coolant with a maximum temperature of 105°C.

[c] A cost target for an on-board charger will be developed and is expected to be available in 2010.

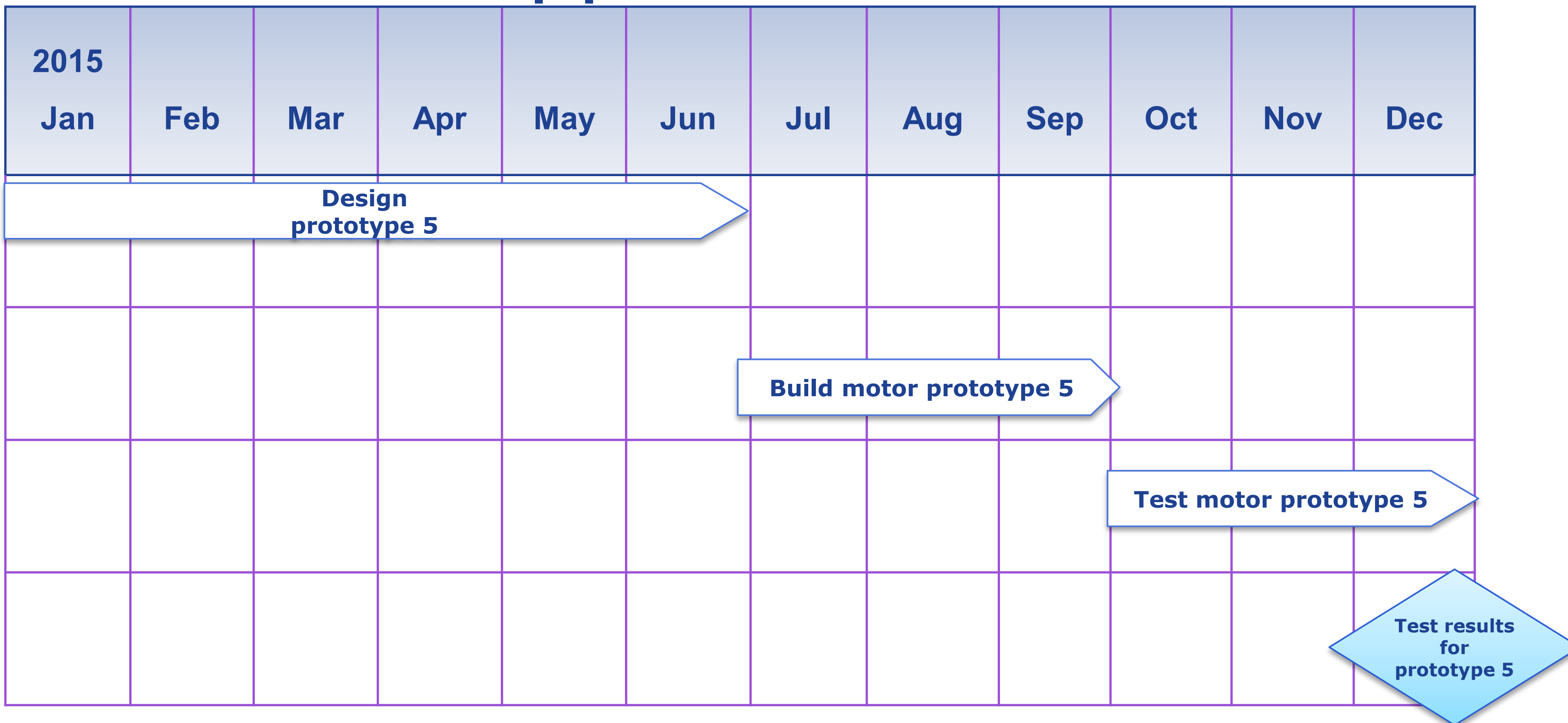
Project Uniqueness and Impacts

- The project proposes a very comprehensive approach in terms of identifying the technologies that will meet the required performance
- The project will explore various motor topologies; some include no magnets at all and some include non-rare earth magnets
- Some of the motor topologies use only conventional materials while others will be enabled by advanced materials that will be developed under the project
- Advanced materials including magnetic as well as electrical insulating materials will be developed to enable the motors to meet the required set of specifications
- Advanced motor controls and thermal management techniques will also be developed.
- By evaluating the wide range of motor topologies and advanced materials, down-selected topologies/materials are expected to meet the required set of specifications

Approach

- Perform tradeoff study of various motor topologies (≈10 topologies: some use conventional materials while others will be enabled by new materials)
- Identify promising scalable materials and produce coupons showing the expected properties (1 hard magnetic, 2 soft magnetic, 1 dielectric)
- Down-select promising topologies/materials
- Design/build/test 2-3 proof-of-principle motors
- Down-select final motor topology
- Build and test the final motor prototype
- Develop cost model for the final prototype

FY16/FY17 Approach and Milestones



Go No/Go Decision Point: This is the last year of the project so there are no Go No/Go decision points

Challenges/Barriers: The set of specifications is very challenging and eliminating rare-earth permanent magnets is a big hit in terms of torque density and efficiency

Accomplishments to Date

Motor accomplishments:

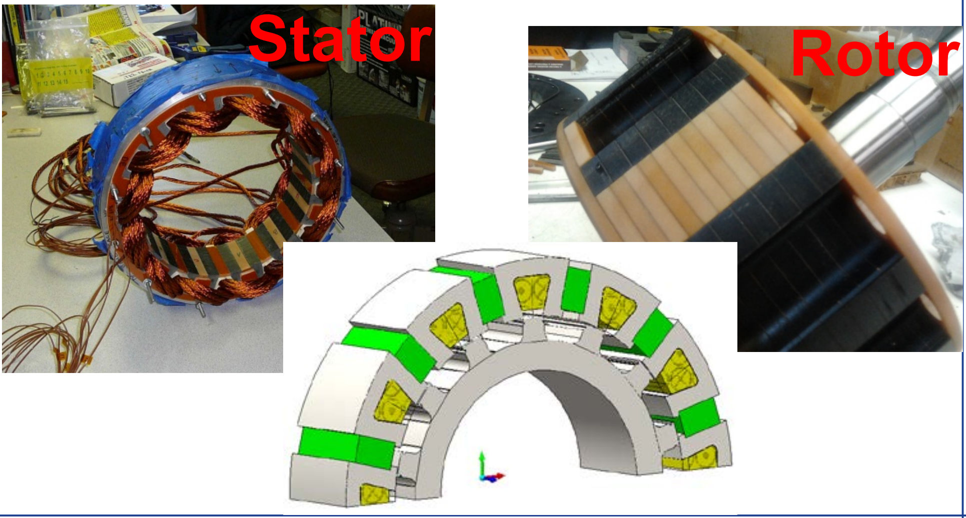
- Down-selected the first 4 topologies :
- First prototype has reduced rare-earth content (built and fully tested)
- Second prototype has non-rare earth magnets (built and fully tested)
- Third prototype has no magnets and includes one of the advanced materials (built and fully tested)
- Fourth prototype is a scaled-down version that includes the dual-phase magnetic material is built
- Fifth prototype is currently being designed

Materials accomplishments:

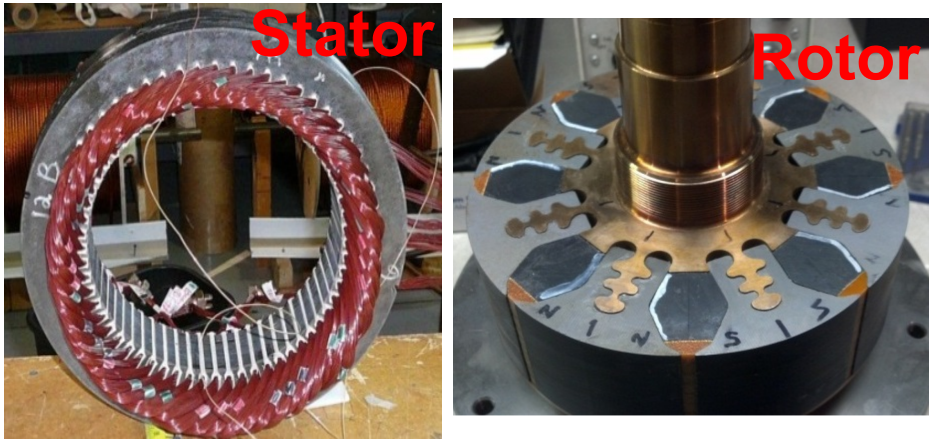
- Developed and scaled-up processing of high temperature (>250 °C) slot-liner insulation.
- Developed method for locally patterning non-magnetic regions on motor lams with < 100 μm interface widths that are stable > 5000 hours at 180 °C
- Produced test laminate with locally non-magnetic regions in preparation for scale-up.
- Demonstrated GE-synthesized non-rare-earth permanent magnets with Hci > 2.0 kOe. This technology was not selected for scale-up based on motor performance targets.
- Develop higher-strength silicon steel laminates. This technology was not selected for scale-up due to high core loss.

2014

Prototype 1: Flux Switching Machine with Dy-Free NdFeB permanent magnets



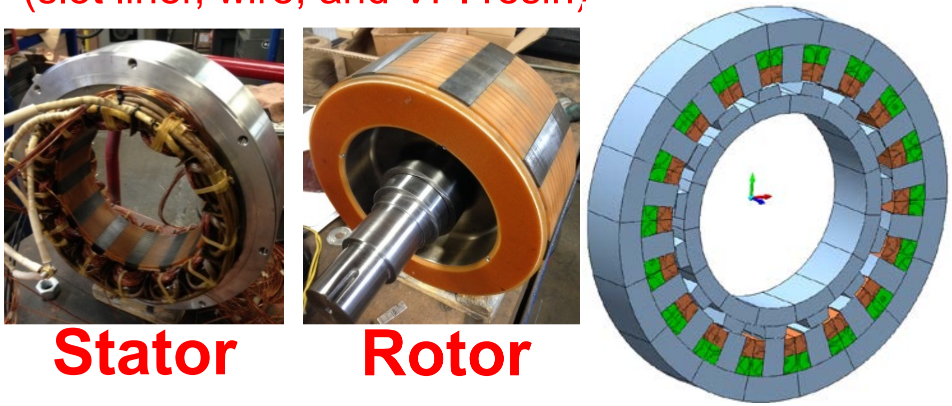
Prototype 2: Advanced spoke rotor with hexa-ferrite permanent magnets



2015

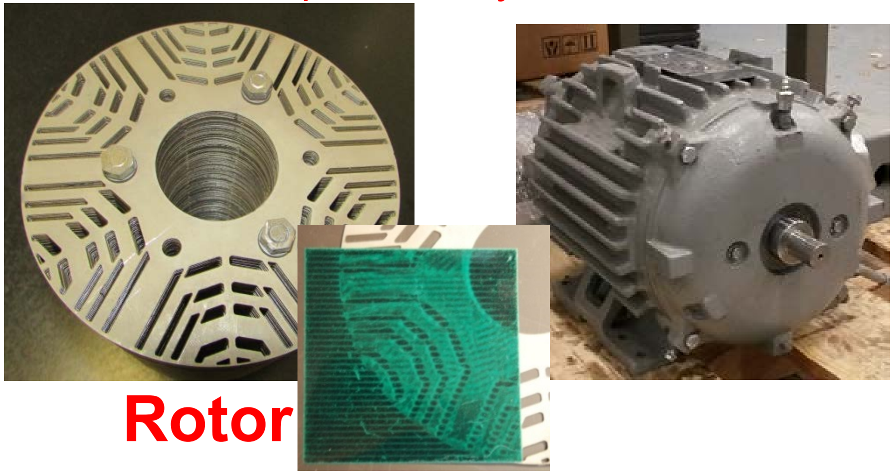
3: Doubly-excited switched reluctance machine

- Stator 1: Low temperature insulation
- Stator 2: Integrate high-temperature insulation (slot liner, wire, and VPI resin)



Prototype 4: Synchronous reluctance machine

- Rotor 1: Silicon steel laminates
- Rotor 2: Dual-phase alloy laminates



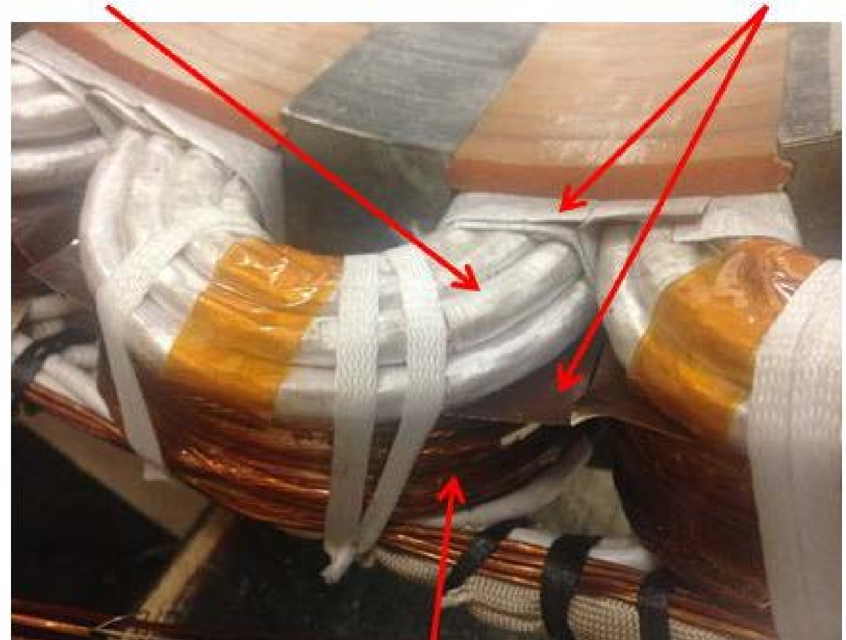
Testing of DC-excited reluctance machine with high temperature stator winding

Stator

Rotor

Type 2 Litz wire with high temperature insulation coating for armature winding

High temperature hybrid slot liner

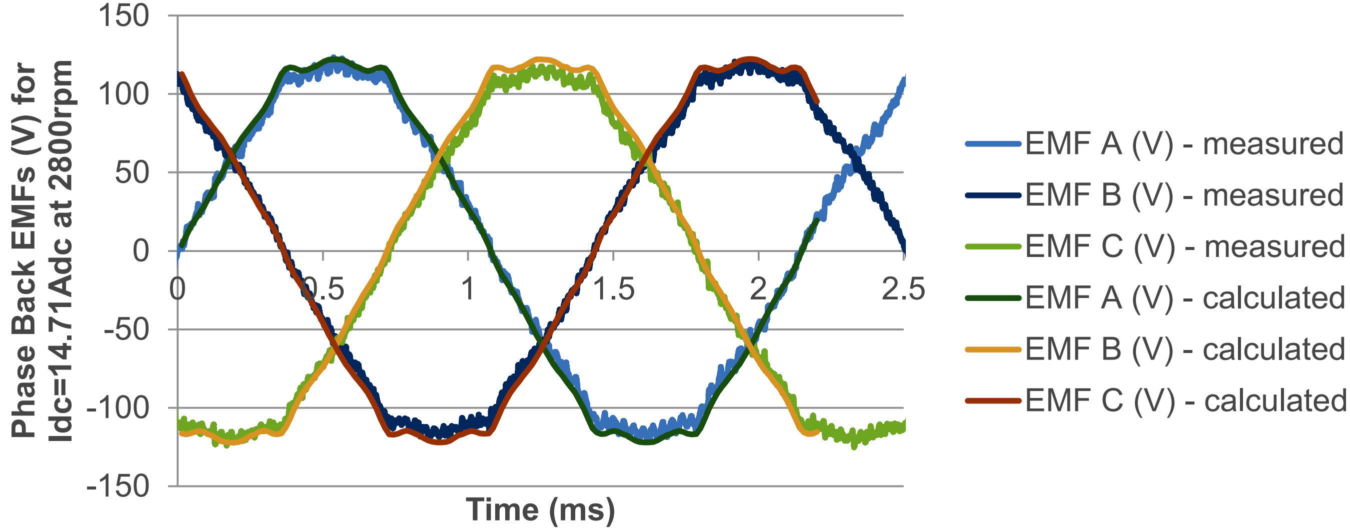


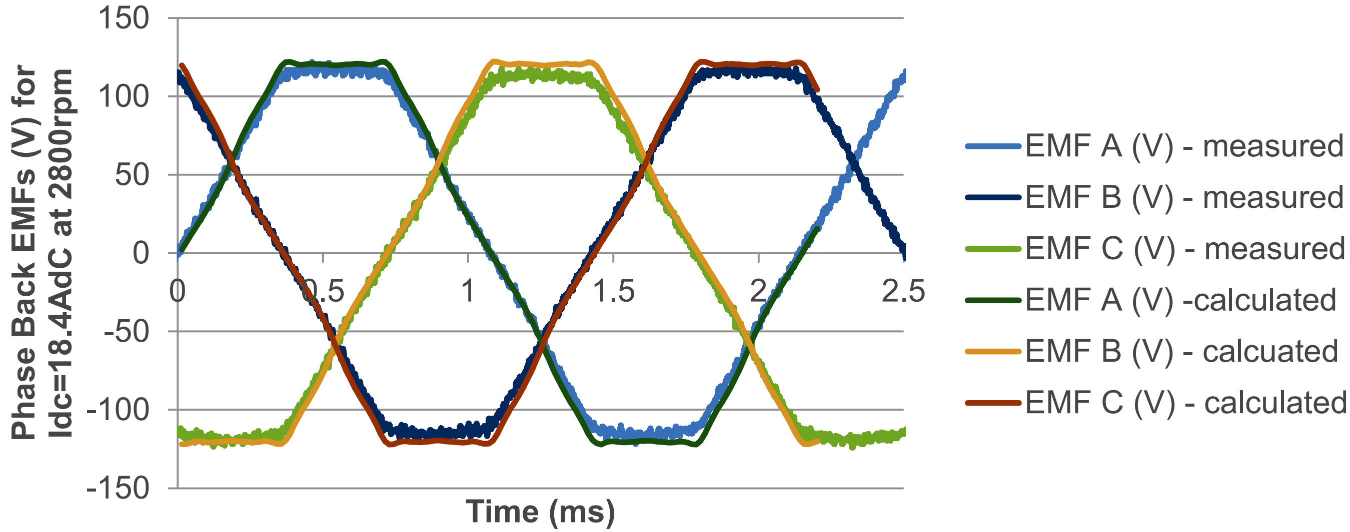
Type 1 Litz wire with high temperature insulation coating for field winding

VPI with high temperature varnish

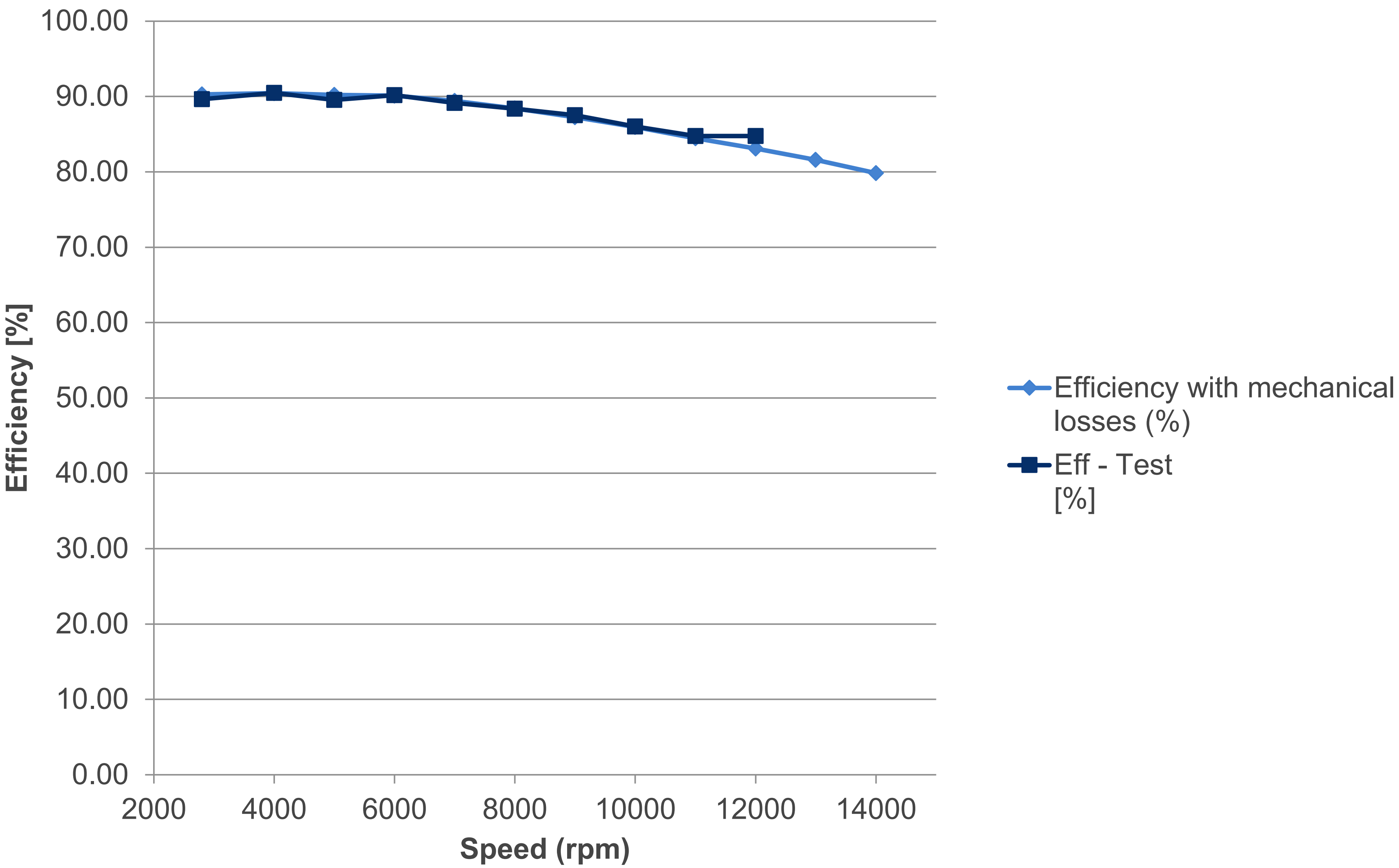
High temperature insulation

Phase back EMF waveforms at 2800rpm for two levels of DC excitation





Predicted efficiency for rated power (30kW) operation vs. test



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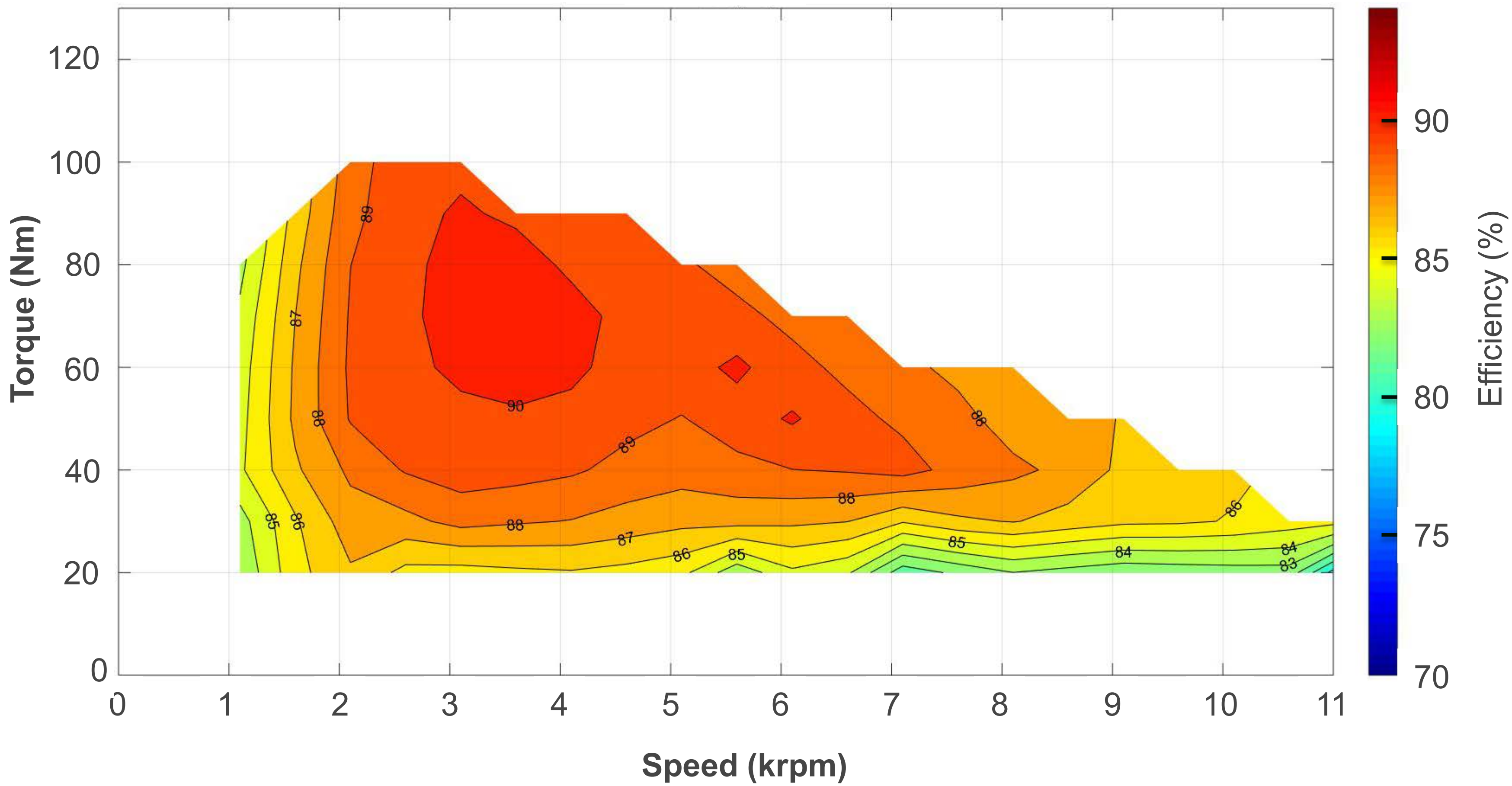
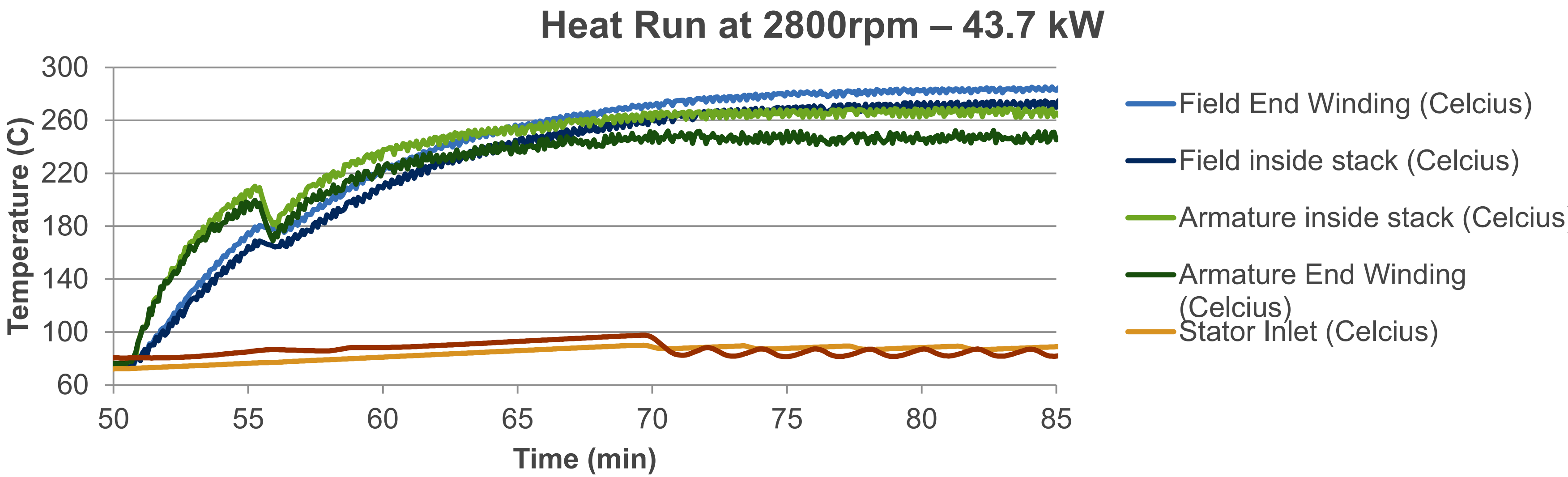
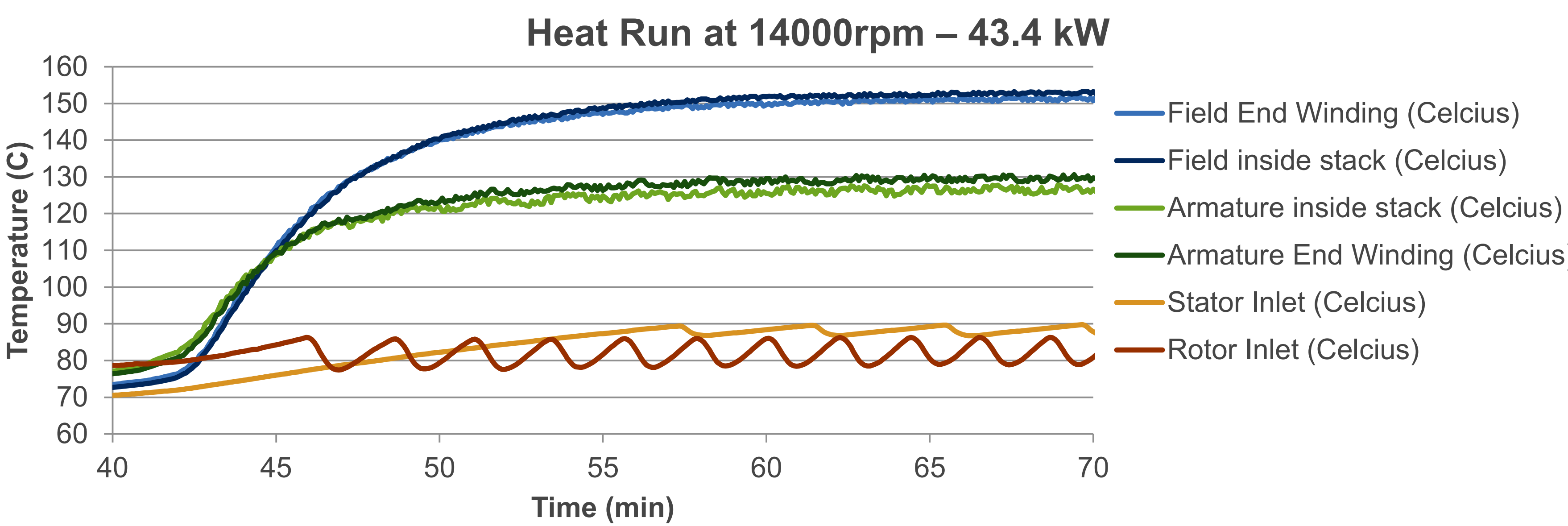
Efficiency Map (Test)



High temperature heat runs (Test)





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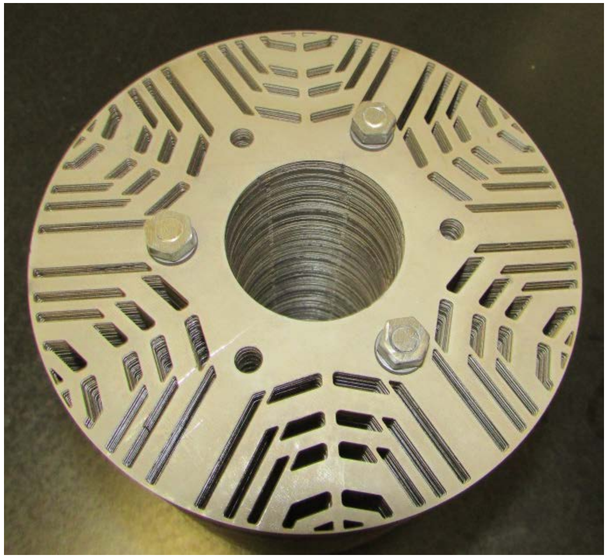
Dual phase magnetic laminate rotor assembly



- 375 laminates stacked and bonded to make 5.50” O.D. by 5.25” long rotor
- Significant force needed to compress stack due to sagging of lams during processing
- Nitrided bridges appear visible on perimeter of laminates

Dual phase magnetic laminate 5 hp (3.7 kW) subscale motor prototype



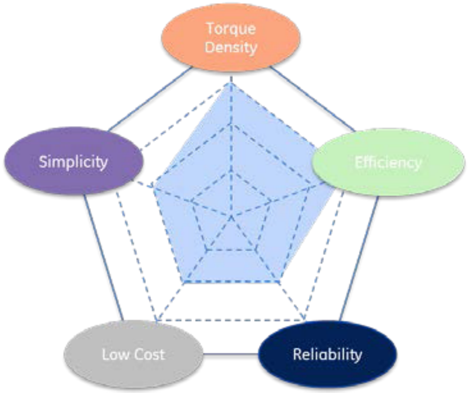
Rotor laminates shrunk fit to shaft and integrated into off-the-shelf stator and motor housing

Final Prototype Down-Selection

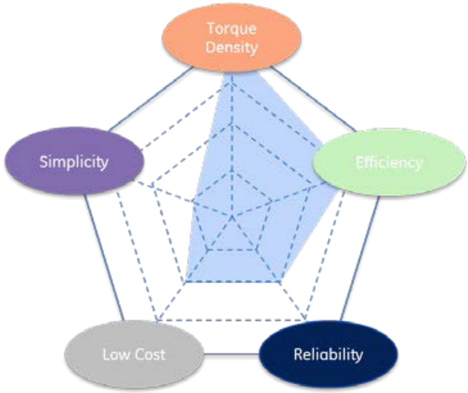
Topology	Induction Design 12c (S	WF Synchronous (Steve)	Dy-free FSM (Fidy)	Nd FSM (Fidy)	Ferrite FSM (Fidy)	Alnico FSM (Fidy)	WF FSM (Fidy)
Stator OD [mm]	243.00	273.97	323.85		280.08		356.86
Stator ID [mm]	171.66	176.46	241.46		211.46		241.46
Air gap thickness [mm]	0.83	0.73	0.86		0.73		0.73
Rotor OD [mm]	170.00	175.00	239.75		210.00		240.00
Rotor ID [mm]	90.00	60.00	165.00		156.10		161.50
Stack length [mm]	120.00	91.00	74.50		140.86		72.00
Stator Winding MLT [mm]	535.29	446.90	374.66		475.64		382.91 Arm. / 378.26 Field
Total length [mm] (end-to-end)	170.00	141.00	145.30		206.22		151.68
Airgap active volume [mm^3]	2750422.48	2207105.49	3363170.57		4878835.27		3257203.26
Total volume [mm^3]	7884085.946	8312071.517	11968598.50		12705250.04		15170990.75
Max tip speed at 14000 rpm [m/s]	124.62	128.28	175.74		153.94		175.93
Active Mass [kg]	35.44	38.08	28.40		32.61		37.50
Slot Cu fill factor [%]	50.00	45 Arm / 78 Fld	36.10		36.10		27.49 Arm. / 55 Field
Cu Mass [kg]	9.99	10.01	4.30		2.87		8.70
Fe Mass [kg]	25.44	28.07	20.10		21.68		28.80
PM Mass [kg]	0.00	0.00	4.00		8.06		0.00
Peak L-L back emf at 14,000 rpm [V]			804.56		716.18		N/A
Characteristic current [Arms]	-	-	220.00		133.00		N/A
Phase resistance [mOhm]	16.80	21.00	5.38		11.83		4.07
Rated Lq inductance [mH]	N/A		N/A		N/A		N/A
Rated Ld inductance [mH]	N/A		N/A		N/A		N/A
Peak Power @ 2800 rpm [kW]	55.00		67.09		55.04		62.66
Peak Torque [Nm]	197.67	0.00	228.80		187.71		213.72
Rated power @ 2800 rpm [kW]	30.00		40.33		30.21		34.32
Rated torque [Nm]	105.06	0.00	137.54		103.04		117.06
Rated power @ 14000 rpm [kW]	30.00		40.70		30.15		33.00
Peak specific power density [kW/kg]	1.55	0.00	2.36		1.69		1.67
Peak power desnity [kW/m^3]	6976.08	0.00	5605.22		4332.08		4130.57
Peak specific torque desnity [Nm/kg]	5.58	0.00	8.06		5.76		5.70
Peak airgap shear stress [psi]	5.21	0.00	4.93		2.79		4.76
Peak electric loading [ATrms/mm]	83.12	139.69	50.62		65.03		154.48
Magnetic loading [T]	0.43	0.00	1.98 Peak /1.89 Rated in Iron		1.98 Peak / 1.59 Rated in Iron		1.83 Peak / 1.63 Rated in Iron
Rated specific power density [kW/kg]	0.85	0.00	1.42		0.93		0.92
Rated power desnity [kW/m^3]	3805.13	0.00	3369.46		2377.94		2262.37
Rated specific torque desnity [Nm/kg]	2.96	0.00	4.84		3.16		3.12
Rated airgap shear stress [psi]	2.77	0.00	2.97		1.53		2.61
Rated electric loading [ATrms/mm]	63.83	87.31	26.95		28.78		93.46
Peak current density [Arms/mm2]	10.71	22.2	15.10		31.83		16.06 in Arm/13.54 in Field
Continuous current density [Arms/mm2]	8.22	11.1	8.04		14.07		9.44 in Arm. /8.27 in Field
Torque Ripple at Peak Power [%]	Unknown		3.82		31.90		6.28
Torque Ripple at Rated Power @ 2800 rpm [%]	2.43		2.72		16.50		2.64
Efficiency @ pak power @ 2800 rpm [%]	89.11		91.99		84.32		90.00
Efficiency @ rated power @ 2800 rpm [%]	90.52		94.43		92.38		91.00
Efficiency @ rated power @ 14000 rpm [%]	91.75		Not tested		89.55		86.50
Average efficiency based on drive cycle (4 cycles)							
Winding hotspot @ peak power @ 2800 rpm [°C]	No Thermal Analysis	No Thermal Analysis	16 rise		Not tested		Not tested
Winding hotspot @ rated power @ 2800 rpm [°C]	No Thermal Analysis	165.00	25.6 rise		Not tested		Not tested
Winding hotspot @ rated power @ 14000 rpm [°C]	No Thermal Analysis	No Thermal Analysis	Not tested		Not tested		Not tested
PM temp. @ peak power @ 2800 rpm [°C]	Cage 150	Fld 180	7 rise		Not tested		Not tested
PM temp. @ rated power @ 2800 rpm [°C]	Cage 150	Fld 180	17 rise		Not tested		Not tested
PM temp. @ rated power @ 14000 rpm [°C]	Cage 150	Fld 180	Not tested		Not tested		Not tested
Stator cooling scheme	Jacket+Spray	Jacket+Spray	Jacket/Spray		Jacket/Spray		Jacket/Spray
Rotor cooling scheme	Unknown	Shaft+Cooling Channels	Oil		Oil		Oil
Number of poles	8	8	28.00		20.00		20.00
Temp. limit for demagnetization (low or high)	-	-	Low Risk		Risk at Low Temperature		N/A
Acoustic noise	Low	Low	L		L		L
Cu wire cost [$] (Assume $10/kg for regular wire and $20/kg for Litz)	99.94	100.13	86.00		57.40		119.76
Fe (HF10) cost [$] (Assume $5/kg)	127.21	140.34	100.50		108.40		144.00

Knowledge and experience accumulated by evaluating a wide range of machine topologies and materials is a key strategic outcome of the project

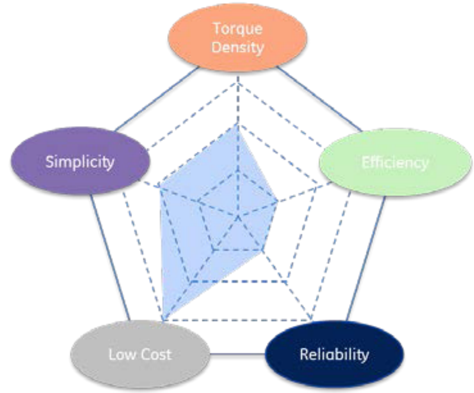
Motor Topologies Comparison



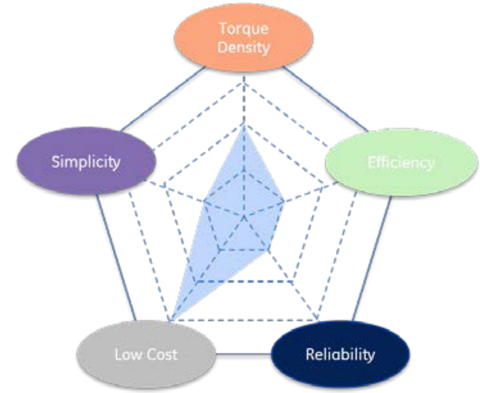
IPM Nd



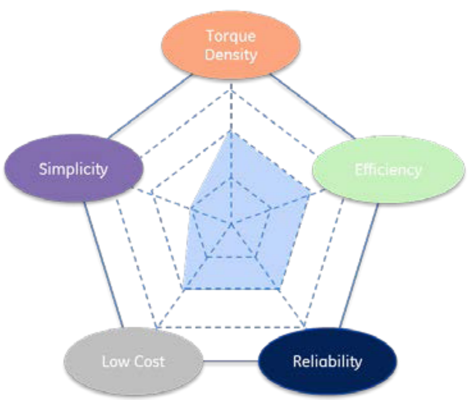
Spoke Dy-free



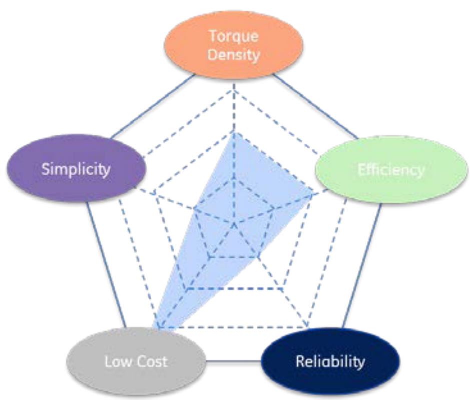
Induction



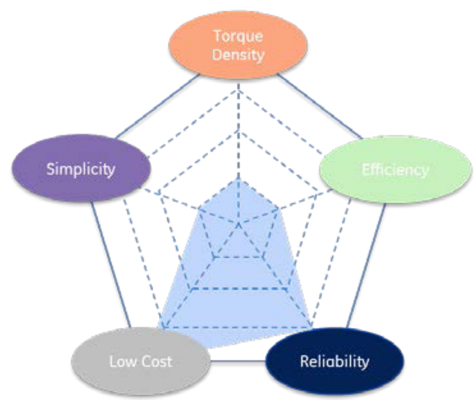
WF Synchronous



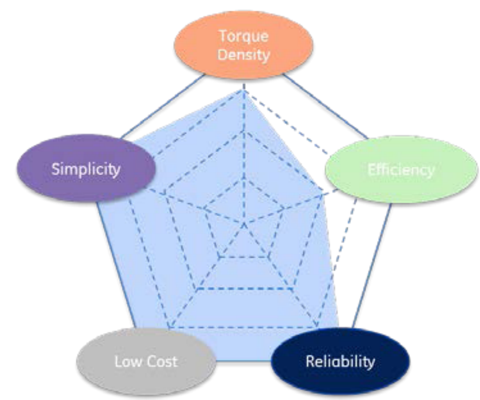
Dy-free FSM



Spoke Ferrite



DC-biased SRM



Dual-phase Syn Rel

Responses to Previous Year Reviewers' Comments (I)

- Question: Several topologies were evaluated, it would have been good to see the breakdown of how the different topologies performed and where they missed meeting the requirements.

- Response: There are several publications in the public domain that include the details of the various topologies as well as the test results. There will be a future publication presenting a comprehensive comparison of the various topologies

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Responses to Previous Year Reviewers' Comments (II)

- Question: The new method for creating locally non-magnetic regions in motor laminations sounds interesting, though it could be quite a challenge to manufacture such laminations in mass production

- Response: Building the rotor of the scaled-down 5 HP motor using the dual-phase material (375 laminations) is a big first step towards showing scalability. More extensive work beyond this project to follow.

Partners/Collaborators

Logo	Organization	Role
	North Carolina State	Evaluation of motor topologies
	University of Akron	Evaluation of motor topologies
	University of Wisconsin	Evaluation of motor topologies
NREL NATIONAL RENEWABLE ENERGY LABORATORY	National Renewable Energy Lab	Evaluation of thermal management schemes
OAK RIDGE National Laboratory	Oak Ridge National Lab	Evaluation of motor topologies and materials
	Ames National Lab	High resolution microscopy of magnetic materials
	Arnold Magnetics	Specialized magnetic material processing and characterization

Remaining Challenges and Barriers

- Finalizing the design, build, and test of the final prototype
- There are some technical risks regarding the rotor retention that need to be retired on multiple sample rotor stacks
- Conforming the predicted performance of the final prototype

Proposed Future Work
FY16/17

- Design, build and test the final motor prototype
- Develop cost model for the final motor prototype

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Summary

- **1st (FSM) and 2nd (ferrite spoke) motor prototypes fully-tested**
- **3rd (SRM) prototype tested with stator 1. as well as with stator 2 using high-temperature insulation**
- **4th (SynRel) prototype built and tested with Si-steel laminate rotor, dual-phase laminate rotor built**
- **Final prototype is being designed**
- **Higher coercivity Alnico**
  - Maximum Hci achieved is 2.2 KOe, stopped all work
- **Dual Phase rotor laminate material**
  - Spin test successful
  - Produced 400 lams for SynRel prototype
- **Hybrid dielectric slot liner insulation**
  - Scaled up and used for 3rd prototype stator 2

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