Unique Lanthanide-Free Motor Construction

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APE044

Overview

Timeline

Project start date: 10/01/2011

Project end date: 10/31/2015

Percent complete: 60%

Budget

Total project funding

- $2,667K DOE Share
- $889K UQM Share

Funding received in FY13: $765K

Funding for FY14: $806K

Barriers Addressed

A: Electric motor cost

B: Elimination of rare-earth elements

E: Efficiency

Partners

Ames Laboratory: improved magnet properties

NREL: motor thermal management

ORNL: motor testing

Coordination provided by UQM Program Manager

Relevance – Objectives

Focus Area: Motors with Reduced or Eliminated use of Rare Earth Permanent Magnets for Advanced EDV Electric Traction Drives

Overall Objectives

- This project pursues unique motor construction that:
  - Eliminates rare earth elements
  - Meets DOE size, weight and efficiency targets
  - Performs comparably to rare-earth motors

- Compliance with the DOE motor specifications
  - Use of low cost magnet (AlNiCo) to meet cost targets
  - High air-gap flux to meet size, weight and efficiency targets
  - 55 kW baseline design
  - Scalable to 120 kW or higher

Relevance – Addressing Barriers

- Electric motor cost
  - Rare-earth magnet prices have been fluctuating (roughly \$80/kg to \$750/kg to \$120/kg)
  - AlNiCo has been far more stable at ~ \$40/kg
  - UQM approach requires roughly 3X the magnet material for a given power rating, leading to cost competitiveness and stability
- Elimination of rare-earth elements
- Efficiency
  - Permanent magnet motors offer efficiency advantages
  - Proposed technology offers PM motor flux levels to maintain efficiency advantages

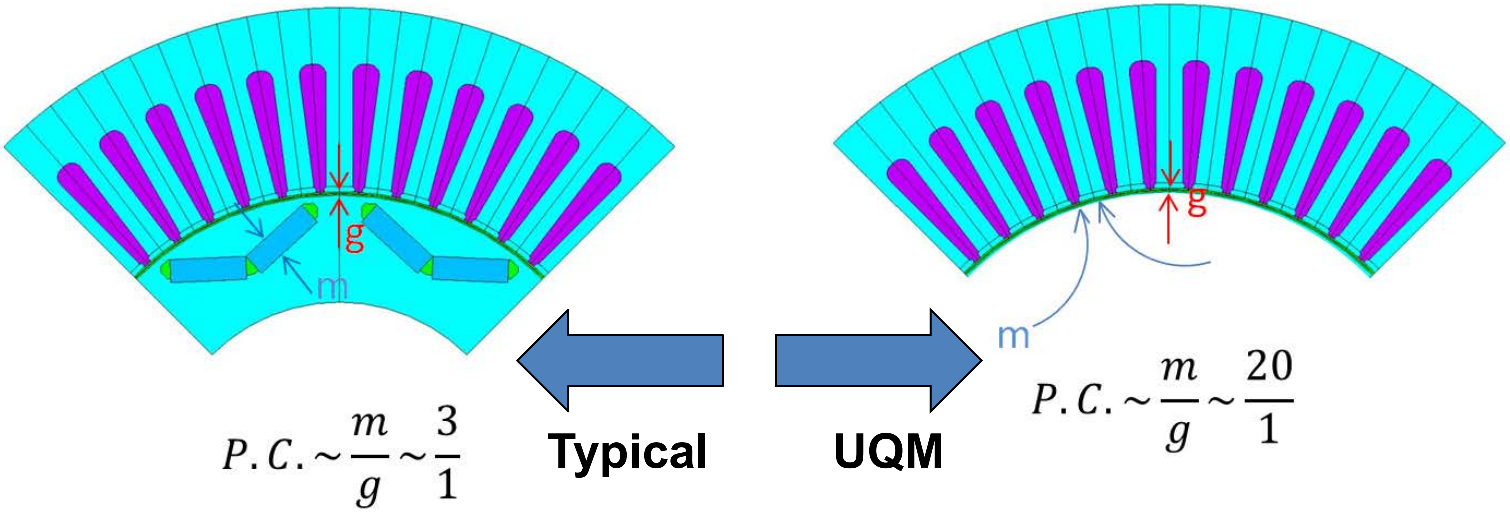
Approach - Milestones

Month/Year	Milestone or Go/No-Go Decision
02/2013 ✓	Milestone: complete motor assembly concept
04/2013 ✓	Milestone : Complete Period 1 and Enter Period 2
11/2013 ✓	Milestone: motor drawing package complete
04/2014 ✓	Milestone: motor build complete and ready for dynamometer testing
07/2014	Go/No-Go: UQM dynamometer testing demonstrates technology feasibility
09/2014	Milestone: delivery of proof of concept motor to ORNL for independent testing

Approach - Project Strategy

- Non-rare-earth magnet chemistries such as AlNiCo are capable of supporting the high flux densities needed to meet cost, power density, specific power, and efficiency targets
- These magnets are not used because they will demagnetize if used in existing magnetic circuit designs

UQM’s project strategy is to use and refine a magnetic circuit that avoids demagnetization ⇨ high permeance coefficient and low armature reaction fields experienced at the magnets



$$P.C. \sim \frac{m}{g} \sim \frac{3}{1}$$

$$P.C. \sim \frac{m}{g} \sim \frac{20}{1}$$

Responses to Previous Year Reviewers' Comments

Comment #1: The design criteria for demagnetization was left to the discretion of the investigator

Answer #1: The demagnetization analysis was performed using the required current needed to meet maximum torque requirements at the expected operating temperature. Higher current events (transient spikes) have not been defined, and with definition, can be analyzed. Ultimately, UQM expects improved magnet coercivity to be a requirement prior to product release.

Comment #2 : The design has a high risk of not meeting the performance objectives due to demagnetization and the requirement for a variable DC bus voltage to meet the speed targets.

Answer #2: The demagnetization risk exists and coercivity improvement research at Ames Laboratory is an important element of this program. Variable DC bus voltage has been implemented in production inverters and UQM recognizes that inverter cost increases need to be considered in the overall system cost comparison.

Responses to Previous Year Reviewers' Comments

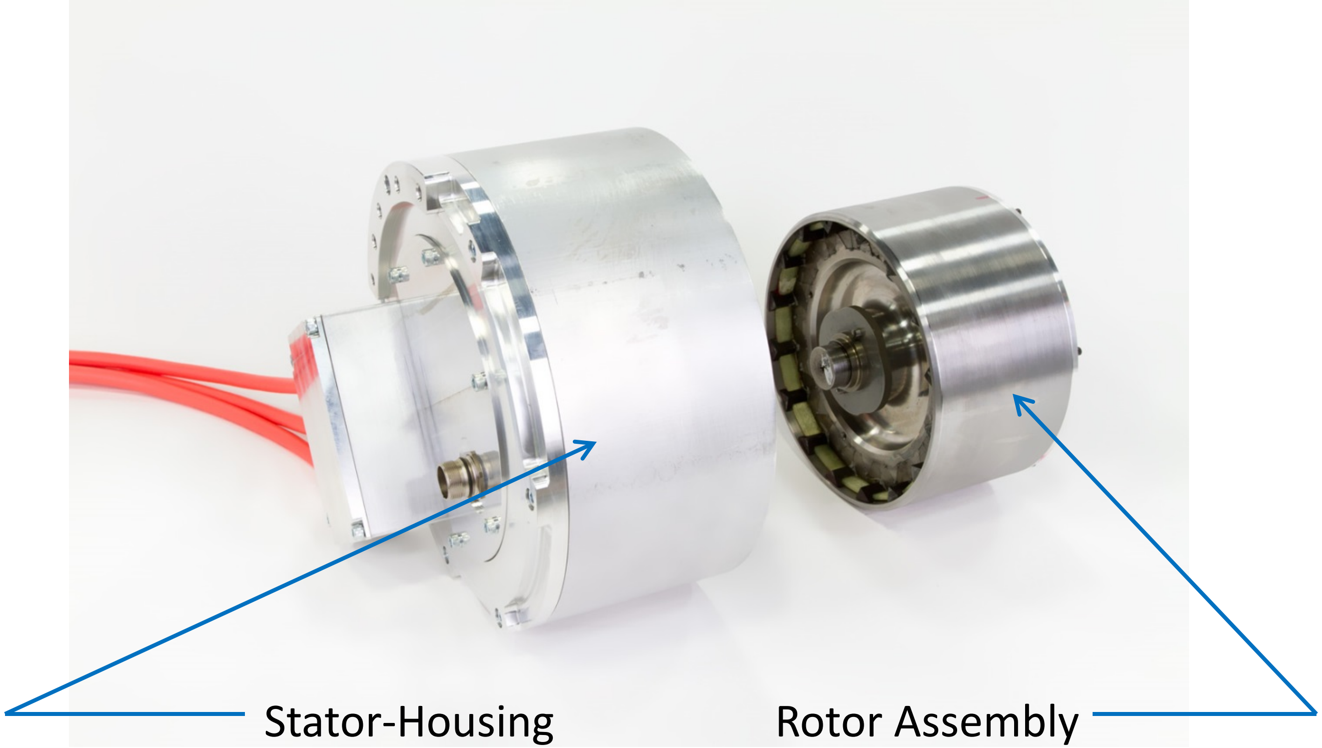
Comment #3: An issue identified by the researchers is the significantly higher magnet mass in this type of machine (three times the mass of NdFeB magnets) for the same machine performance. These drawbacks will increase the system cost significantly and may negate the cost savings with the AlNiCo magnets.

Answer #3: The AlNiCo magnet content is a function of coercivity properties (improved coercivity results in lower content) and cost comparisons will depend upon content and fluctuating element prices. This program provides an alternative to rare earths, whether economics or politics create future rare earth issues.

Collaboration and Coordination with Other Institutions

- Subcontractor: Ames Laboratory, FFRDC within the VT Program, for incremental improvements in high flux, low coercivity magnet materials
  - Enable high loads (current density) and minimize magnet content
- Subcontractor: National Renewable Energy Laboratory, FFRDC within the VT Program, for thermal management
  - Assembly heat rejection for power density and cost
- Subcontractor: Oak Ridge National Laboratory, FFRDC within the VT Program, for testing
  - Confirmatory testing; results to be used for design refinement between Year 2 and 3

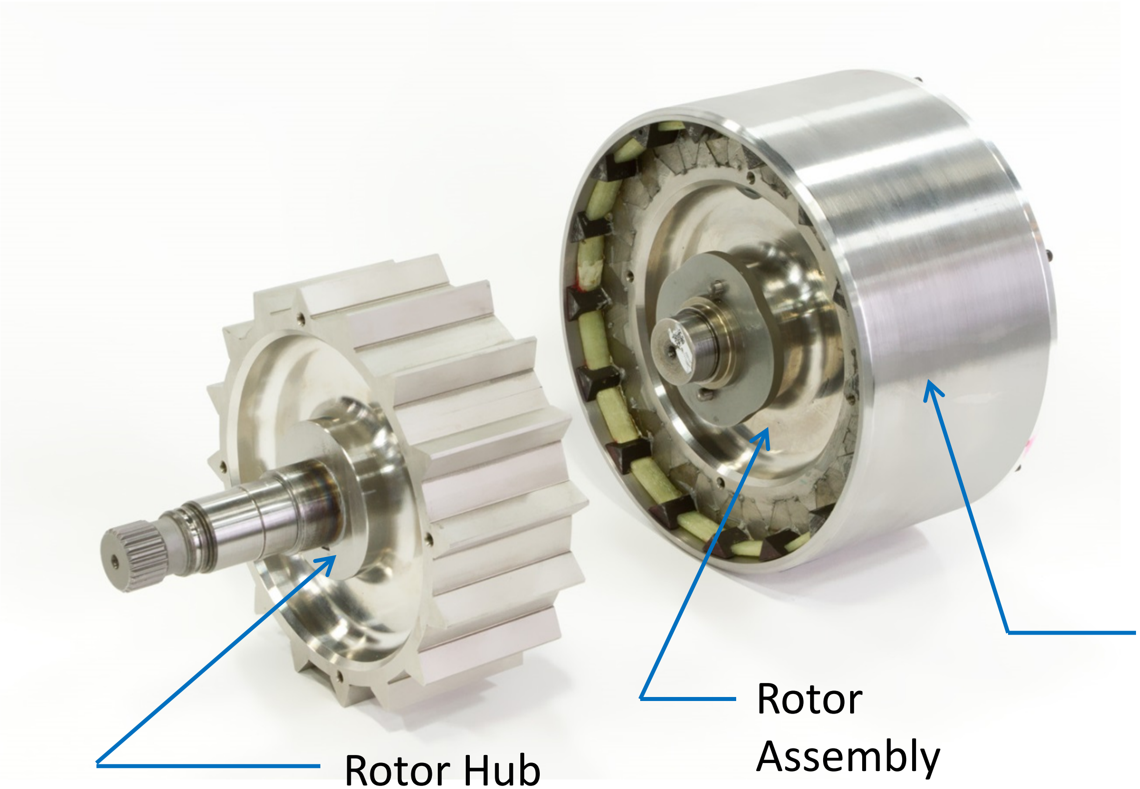
Prototype 1 Motor Build



Stator-Housing Assembly

Rotor Assembly (With Keeper)

Rotor Construction

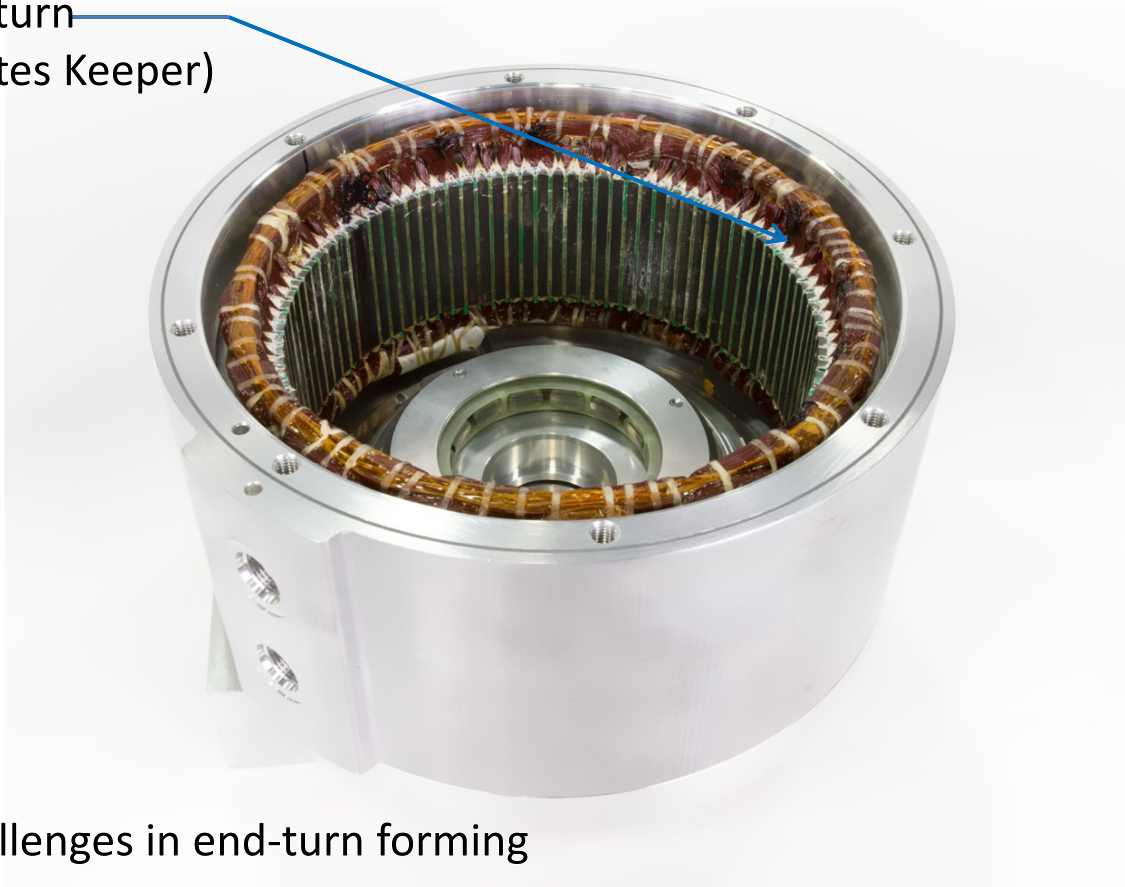


Keeper

Rotor
Assembly

Rotor Hub
and Shaft

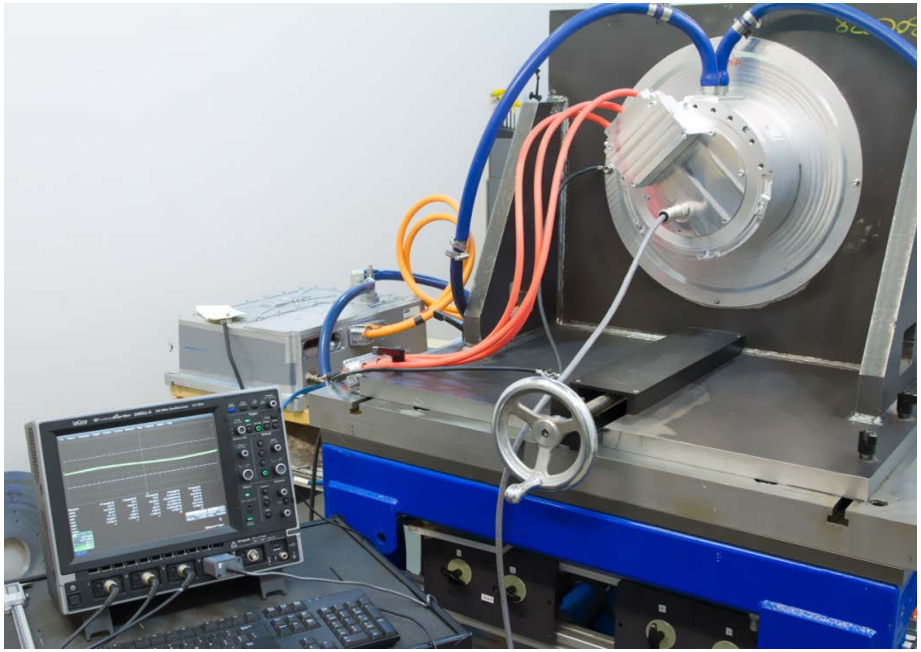
Stator Construction

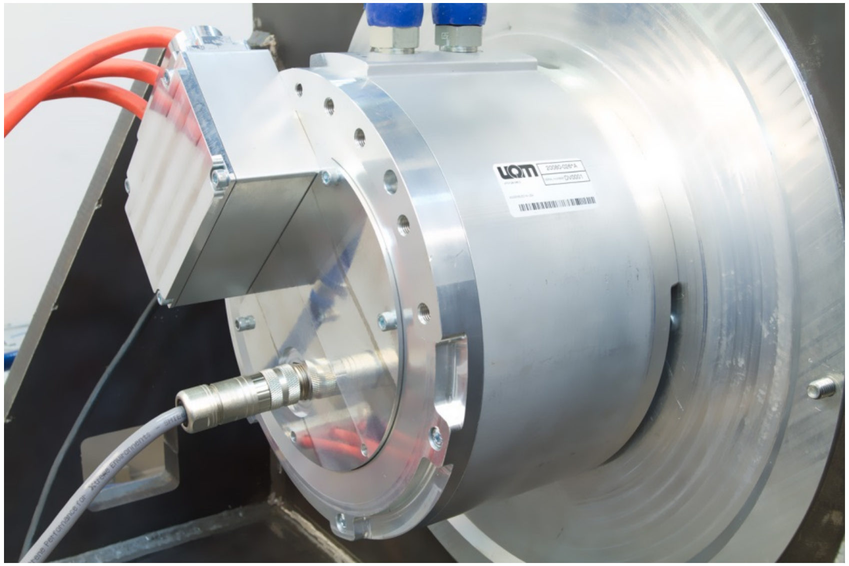


Tapered End-turn
(Accommodates Keeper)

- Challenges in end-turn forming

POC #1 on UQM Dynamometer





Key Specifications

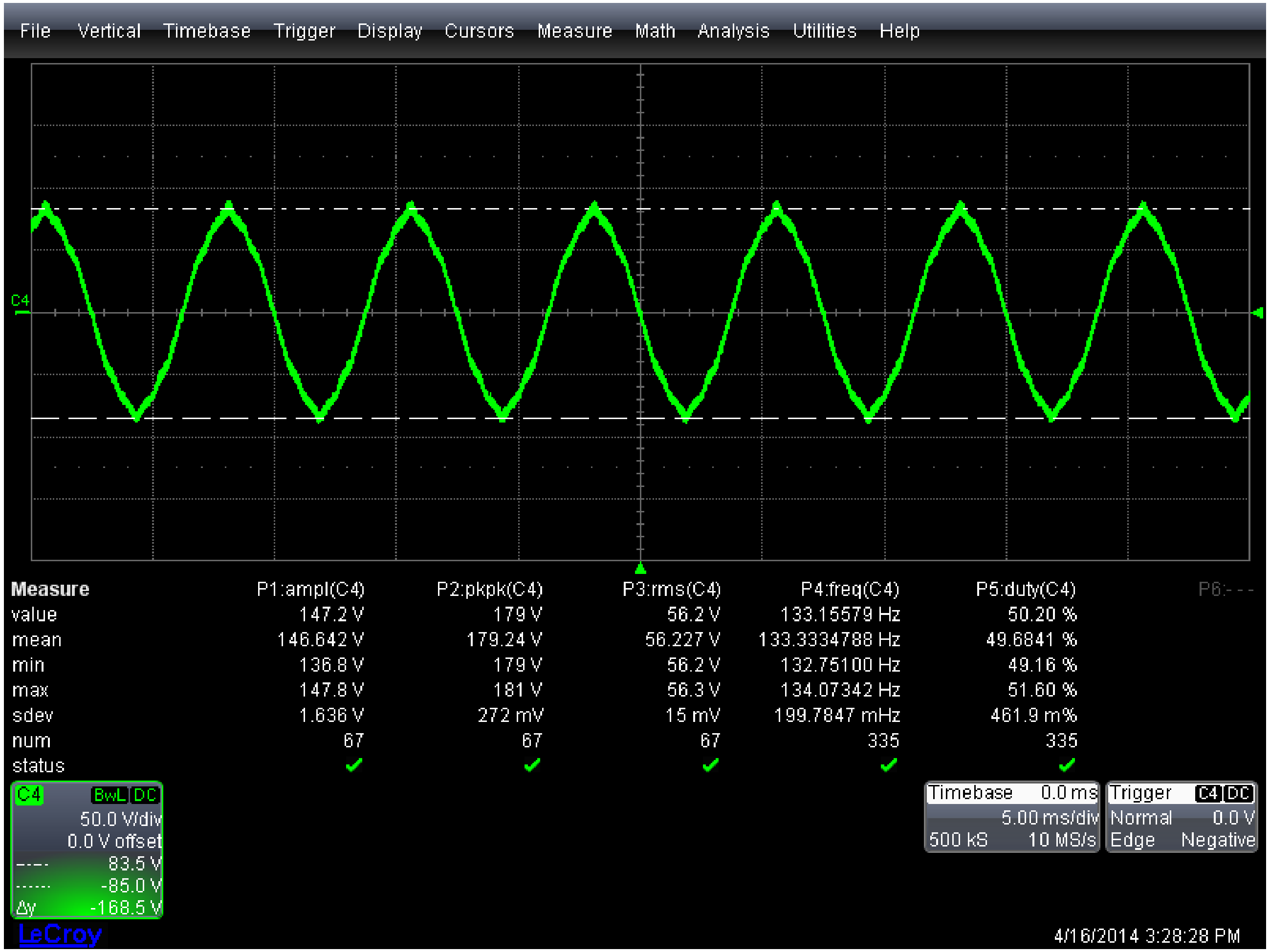
Requirement		Value	Model Prediction	POC #1
DOE Requirements	Efficiency	>90%	Analyzed, Comply	TBD
	Peak Power	55 kW	55 kW	TBD
	Maximum Speed	10,000 rpm	10,000 rpm	TBD
	Operating Voltage Range	200-450 VDC 325 VDC Nominal	Analyzed, Comply [1]	Comply [1]
	Maximum phase current	400 A	Analyzed, minimal demagnetization	TBD
	Torque	262 N-m	Analyzed, minimal demagnetization	TBD
	Total Volume	≤ 9.7 L	9.59 L	9.59 L
UQM Internal Requirements	Max Stator Diameter	10 inches	9.875 in.	9.875 in.
	Pole Coverage	50%-90%	55 %	55 %
	Magnet Weight Limit (For Cost)	4.5 kg	4.5 kg	4.5 kg
	EMF Voltage	83.6-92.4 V/krpm L-L	88 V/krpm L-L	84.25 V/krpm L-L
	EMF THD	< 10%	2.86%	TBD
	EMF Harmonics	< 5% of Fundamental	2.27%	TBD
	Cogging Torque	< 4 N-m	3.85 N-m	TBD
	Specific Power	1.57 kW/kg	1.57 kW/kg	TBD
	Power Density	5.74 kW/Liter	5.74 kW/Liter	TBD

Notes:

1. Complies using voltage boost topology inverter

Tested Back-EMF

- 84.25 V/krpm
- Expected Range 83.6 – 92.4 V/krpm



Measure	P1:ampl(C4)	P2:pkpk(C4)	P3:rms(C4)	P4:freq(C4)	P5:duty(C4)	P6:- - -
value	147.2 V	179 V	56.2 V	133.15579 Hz	50.20 %	
mean	146.642 V	179.24 V	56.227 V	133.3334788 Hz	49.6841 %	
min	136.8 V	179 V	56.2 V	132.75100 Hz	49.16 %	
max	147.8 V	181 V	56.3 V	134.07342 Hz	51.60 %	
sdev	1.636 V	272 mV	15 mV	199.7847 mHz	461.9 m%	
num	67	67	67	335	335	
status	✓	✓	✓	✓	✓	

C4 BwL DC
50.0 V/div
0.0 V offset
-·-·- 83.5 V
······ -85.0 V
Δy -168.5 V

Timebase 0.0 ms
5.00 ms/div
500 kS 10 MS/s

Trigger C4 DC
Normal 0.0 V
Edge Negative

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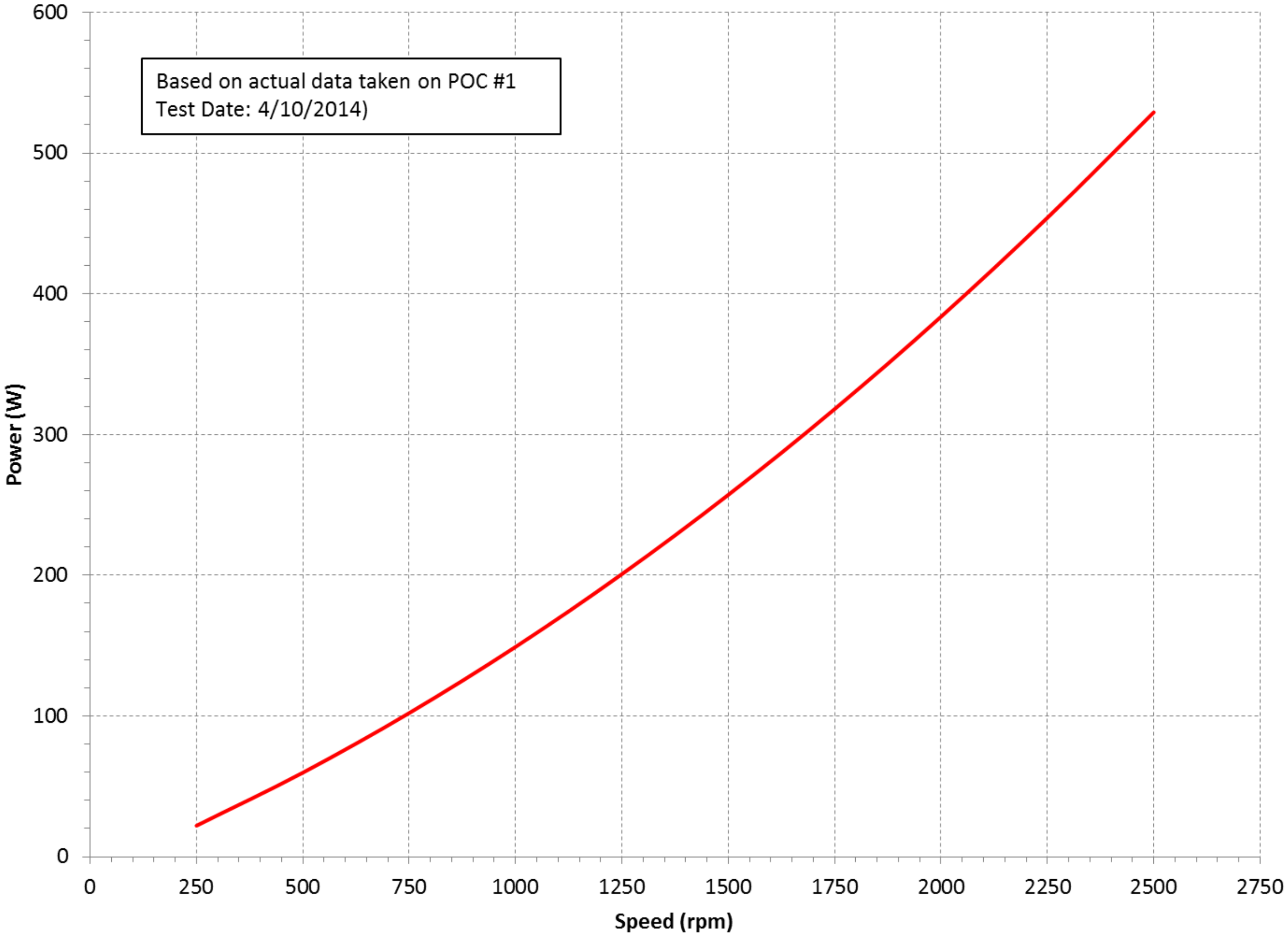
Tested No-Load Losses



Stator Thermal Management Enhancements

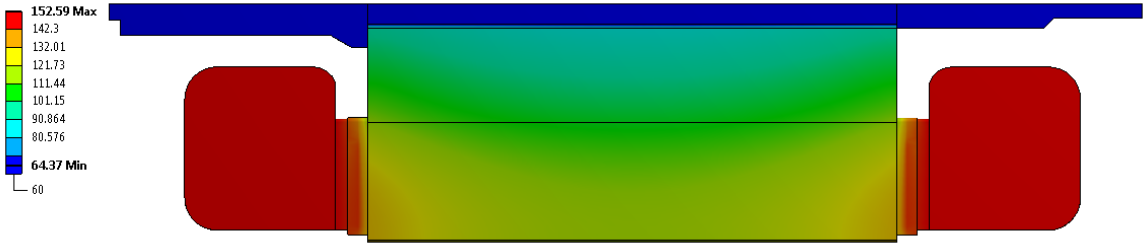
- Improving the cooling jacket design does not appear to significantly improve the overall thermal performance because of other thermal constraints such as the stator laminations and the stator to case interference fit.
- Investigating potential thermal management enhancements to bypass thermal constraints to cool end windings

Impact of End Winding Potting

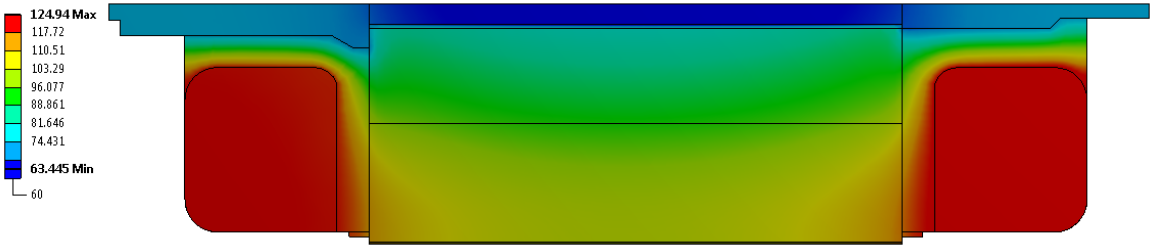
- Applied potting compound around end windings
- Analyzed model at two continuous operating points with same water jacket

Results:

- Preliminary modeling indicates potting end windings may be of significant benefit
- The benefit is very dependent on end winding geometry



Base FEA model

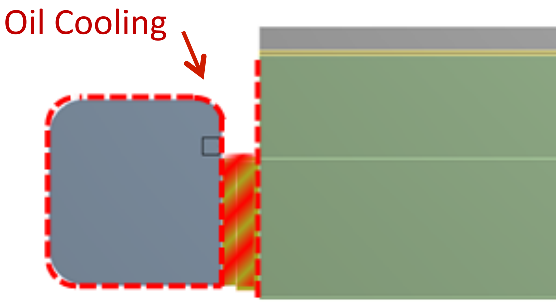


Potting compound added (1 W/m-K)

	No potting (Baseline)	With Potting [1 W/m-K]	% Improvement in Winding to Coolant Temperature Difference
	Max Winding T [°C]	Max Winding T [°C]	[%]*
30 kW; 2,000 RPM	152.6	124.9	30%
30 kW; 10,000 RPM	170.4	152.4	16%

*Based on 60°C coolant inlet temperature

Preliminary Oil Cooling Results

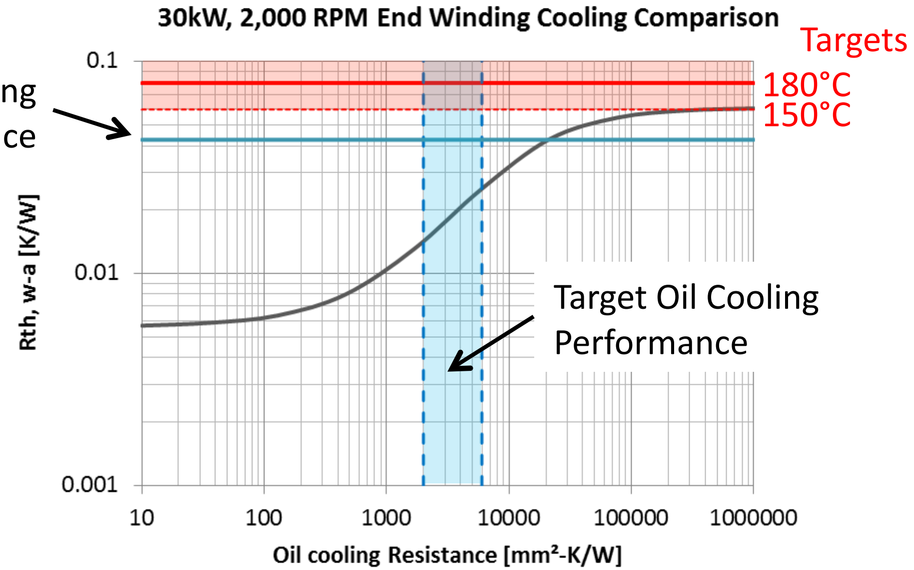


Oil Cooling of End Windings

- Applied convection coefficient in FEA to represent oil circulation at same temperature as case cooling (60°C)
- Swept oil cooling resistance over a range of performances values to determine potential benefit

Results:

- Oil cooling of the end winding appears to have significant potential for improving thermal performance
- The target oil cooling performance band is based on DOE funded oil cooling experiments performed at NREL



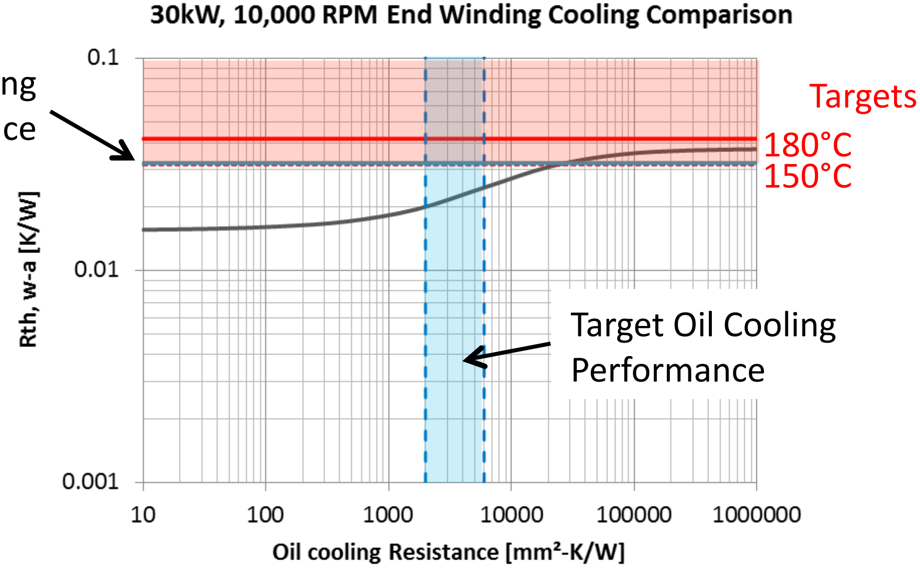
Potting Performance

Targets

180°C

150°C

Target Oil Cooling Performance



Potting Performance

Targets

180°C

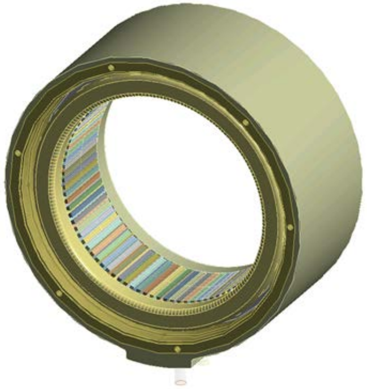
150°C

Target Oil Cooling Performance

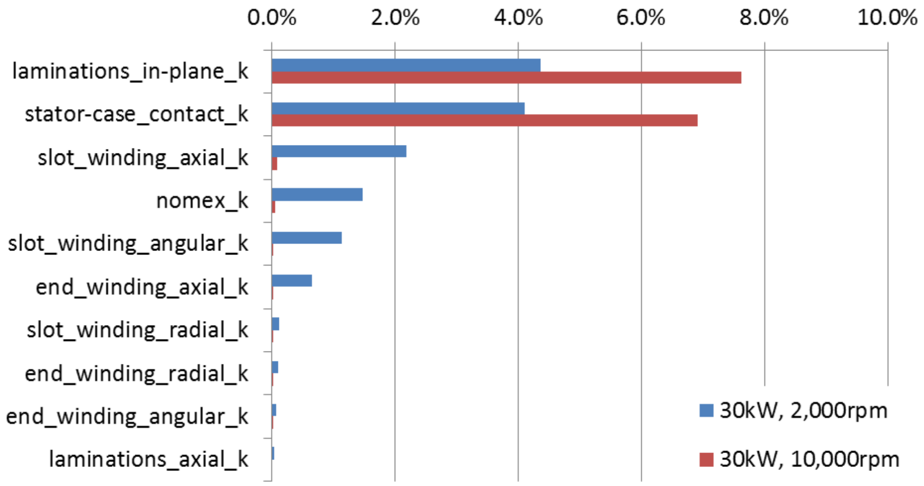
Passive and Active Cooling

- Completed computational fluid dynamics (CFD) analysis of stator cooling jacket (active cooling) focusing on channel flow distribution and case temperature variation
- Performed sensitivity study of passive thermal stack elements to identify key passive stack thermal resistances
- Measuring in-plane lamination thermal conductivity and stator-case contact resistance under high pressure

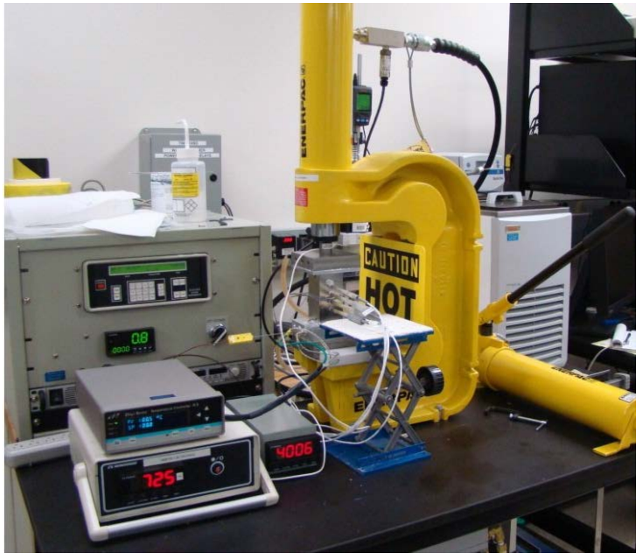
Stator and Cooling Jacket CFD Model



Change in Maximum Temperature with 20% Decrease in Thermal Conductivity



High Pressure Thermal Resistance Measurements



Future Work

- Complete Build of POC #2 – May 2014
- Motor Characterization – May thru mid-July 2014
  - Verify fundamental parameters (Bemf, cogging torque no load losses ..)
  - Initial operation at limited voltage and current to validate control algorithms
  - Verify performance (peak and continuous torque/power and efficiency)
- Demonstrate Proof-of-Design testing at UQM – July thru August 2014
- ORNL (3rd party) Testing – September thru October 2014
- Vision for Period 3 work (second motor build)
  - Oil cooled variant if analysis shows significant thermal improvement
  - Improved magnet properties from Ames' process work

Summary

- Magnetic finite element analysis demonstrates a feasible architecture to enable the use of non-RE magnets
- Motor ⇔ Inverter analysis indicates that the design is not field weakening compatible and will require a voltage boost inverter
- NREL models to optimize water cooling channel are being finalized for first motor; analysis to establish direction for second motor
- Ames' work is demonstrating methods to increase magnet coercivity, which will ultimately reduce magnet content required for the motor
- Proof-of-concept motor, through analysis, shows compliance with DOE and UQM-internal specifications
- Motor build will demonstrate the feasibility of the approach