HIGH-SPEED HYBRID RELUCTANCE MOTOR WITH ANISOTROPIC MATERIALS

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General Motors
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Project ID#: ELT093

GENERAL MOTORS

OVERVIEW

Timeline

Start Date: October, 2016
End Date: June 2020
Duration: 3 years

Completion: 95%

Barriers

- Implement lower cost HRE-free magnets with higher coercivity and designs protecting against demagnetization
- Design improved Cu-Al interfaces for better rotor efficiency and reduced cost
- Validate motor performance and endurance for vehicle reliability

Budget

Total funding for 3 years

$4.64M – DOE Share

$2.44M – GM Share

$7.08M – Total

FY2019 DOE Funds Rec'd:

$1,136,109

FY2020 DOE Fund Forecast:

$503,000

Project Lead

General Motors

Partner

- Oakridge National Lab

OBJECTIVE

Design and validate three motor variants with no heavy rare earth (HRE) content:

Heavy rare earth elements have limited sources and price volatility

- Variant 1: HRE-free permanent magnet (PM) motor
- Variant 2: Synchronous reluctance motor (SyRM) with HRE-free PM assist
- Variant 3: Hybrid induction motor with cast aluminum (Al) and insert copper (Cu) bars

Variants should be capable of meeting the following DoE year 2020 targets:

- Cost ($/kW) less than $4.7
- Specific Power (kW/kg) greater than 1.6
- Power density (kW/L) greater than 5.7

	Application	Primary Traction motor	Rear axle traction (AWD)
Variant 1	HRE-free PM motor	X	
Variant 2	SyRM with HRE-free PM assist		X
Variant 3	Hybrid Cu-Al Induction Motor	X	X

APPROACH TO BARRIERS

- HRE-free magnets provide less energy-product for motors, and experience permanent demagnetization at lower temperatures
  - Identify capable materials and validate and test on a magnet level
  - Perform demagnetization tests on a rotor level to confirm simulation results

- Cu-cast Al interfaces tend to be poor and fail rapidly under motor conditions
  - Demonstrate improved Cu-Al interfaces on cast coupons
  - Optimize rotor casting parameters for best Cu-Al interfaces

- Many efforts to improve demagnetization resistance or power come at the expense of high speed mechanical strength
  - Validate novel designs compensating for mechanical strength while maintaining torque

MILESTONES

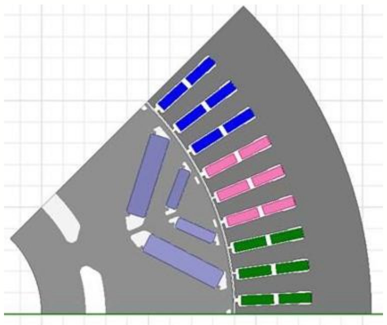
Milestone	Description	Planned Completion Date
Budget Period 2 (Jan 2018 – May 2019)		
Rotor and Stator Fabricated and Assembled	Rotor and Stator build complete and evaluate weight based on the active machine materials	Complete
Rotor High Speed Evaluation Complete	High Speed evaluation accomplished with report of burst test results	Complete
Production Process Developed	Production processes identified to achieve a cost production goal of $4.7/kW.	Complete (AMR 2019)
Motor cost in alignment with project targets	Motor cost assessment complete and used to construct test plan that aims to achieve a specific power of 1.6 kW/kg and power density of 5.7 kW/Liter	Complete (AMR 2019)
Budget Period 3 (May 2019 – June 2020)		
Initial Preparation for Motor Testing complete	Electric traction motors have been built and prepared for testing	Complete
Motor Calibration Complete	Electric machine calibration completed for all motors	Complete
Fatigue Tests Complete	Durability testing on two of the three motor types will be completed	Complete
Performance Evaluation Complete	Performance Evaluation and Correlation – the results of performance testing will be compared to simulation results (Actual vs. Predicted).	6/30/2020

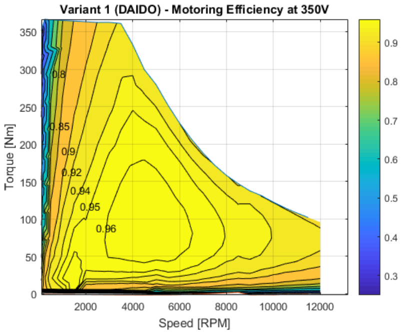
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

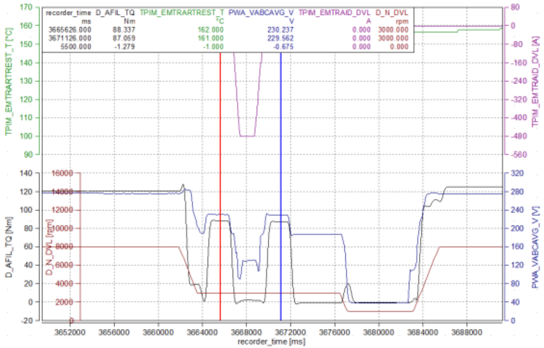
- 3 Variant designs were designed to meet vehicle electromagnetic performance, mechanical, and thermal requirements

	HRE-free PM Motor	Synchronous Reluctance Motor with HRE-free PM Assist	Hybrid Induction Motor with Insert Cu Bars and Cast Al End-rings
Stator Outer Diameter (mm)	208	190	190
Rotor Outer Diameter (mm)	139.5	139.1	139.1
Stator Core Length (mm)	200	100	100
Power, analytical (kW)	148	86	84
Torque, analytical (N-m)	372	249	310
Max RPM	12000	16650	12950
Nominal Voltage (V)	350	350	350
Maximum Current (Arms)	400	450	450

VARIANT 1 – HRE-FREE PM MOTOR







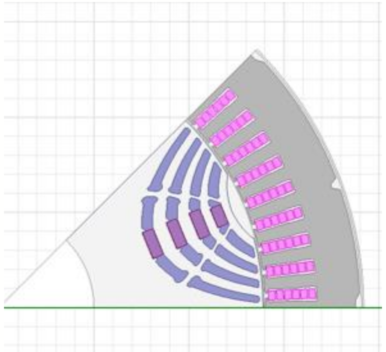
Demagentization testing

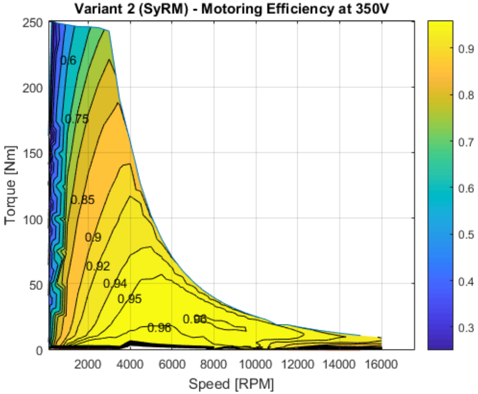
Burst testing

Testing demonstrates demagnetization resistance consistent meets operating conditions and efficiency as predicted by the initial design.

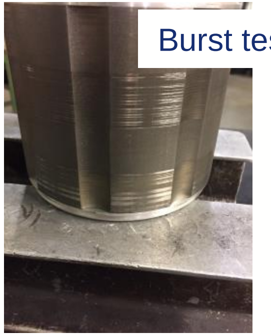
Performance						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target				≥1.6 kW/kilogram	≥5.7 kW/Liter	$4.7/kW
Variant 1	35.2 kg	6.6 L	146 kW	4.1 kW/kg	22.1 kW/L	Meets

VARIANT 2 – SYRM WITH HRE-FREE PM ASSIST





Rotor endurance

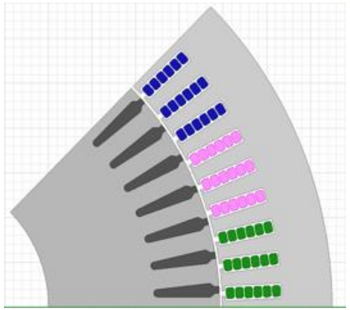


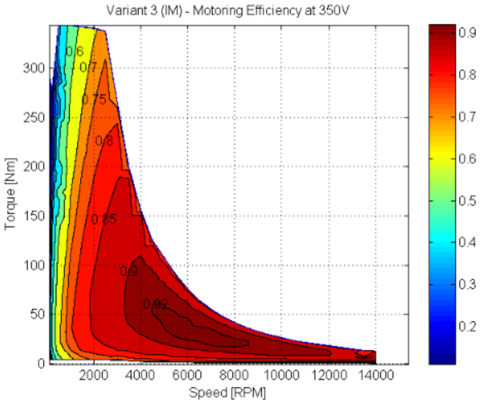
Burst testing

Testing demonstrates high speed endurance consistent with expectations and efficiency as predicted by the initial design. Peak power is lower than predicted

Performance						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target				≥1.6 kW/kilogram	≥5.7 kW/Liter	$4.7/kW
Variant 2	24.1 kg	5.4 L	76 kW	3.15 kW/kg	14.1 kW/L	Does not meet

VARIANT 3 – HYBRID CU-AL INDUCTION MOTOR





Rotor endurance

Burst testing

Testing demonstrates high speed endurance consistent with expectations and efficiency as predicted by the initial design. Power is slightly higher than predicted

Performance						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target				≥1.6 kW/kilogram	≥5.7 kW/Liter	$4.7/kW
Variant 3	27.3 kg	5.4 L	88 kW	3.2 kW/kg	16.3 kW/L	Does not meet

RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

- The three motor variants designed have different mass, different volume, and a different power. This makes it extremely difficult to compare the three designs.

The three designs are designed for different applications and therefore are not intended to be compared directly to one another. However, Variant 2 and Variant 3 have an overlapping functions as eAWD applications. These two have the same package space. The volume and power targets for these two designs are the same. Torque and speeds are different due to the topologies of the machines but could be accommodated by designing with appropriate gear ratios.

	Application	Primary Traction motor	Rear axle traction (AWD)
Variant 1	HRE-free PM motor	X	
Variant 2	SyRM with HRE-free PM assist		X
Variant 3	Hybrid Cu-Al Induction Motor	X	X

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

Oakridge National Lab collaboration (Partner)

Prepared with assistance from Tim Burress, Ercan Cakmak, Yanli Wang

Motor steel sample analysis

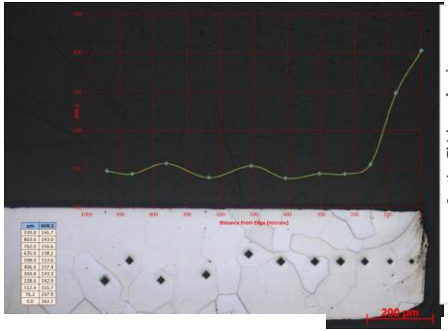
- Edge analysis – optical analysis of sheared edge from stamping operation
- Microhardness – harness in various locations in cross-section
- Compositional analysis – to determine composition of material
- Coating thickness – important for stacking factor and resistance between laminations
- Coating composition – same as above
- Density
- Electromagnetic properties – permeability, loss, and exciting power vs flux density and frequency
- Tensile and fatigue

Induction motor bar analysis

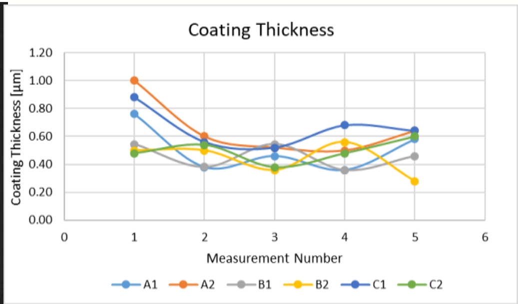
- Porosity of casting
- Tensile and fatigue testing of copper/cast aluminum interface

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

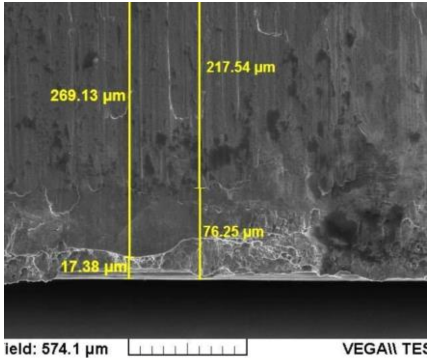
Cu-Al interface testing



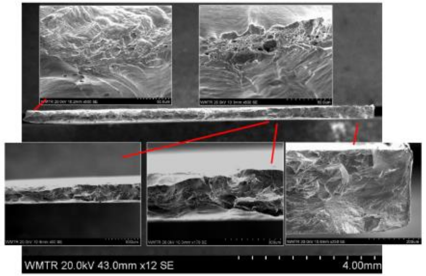
Steel microhardness



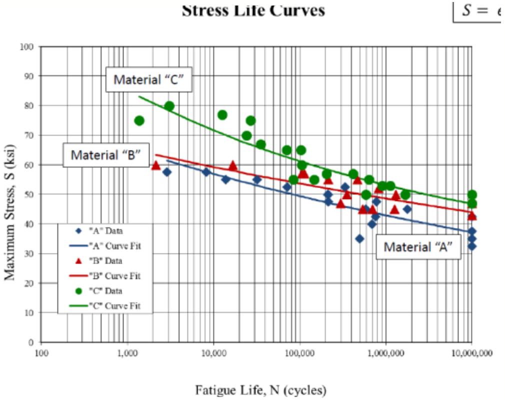
Coating evaluation



Stamped edge evaluation



Fatigue fractography



Fatigue testing

REMAINING CHALLENGES AND BARRIERS

- Complete analytical and test result comparisons

- Complete demagnetization studies

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

SUMMARY

- All three designs meet DoE performance targets and address initial design barriers on a materials level.
- Testing confirms performance and durability of the three machine variants
- Performance to be compared to analytical results for confirmation

Performance (test results)						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target 2020				≥1.6 kW/kilogram	≥5.7 kW/L	≥$4.7/kW
Variant 1	35.2 kg	6.6 L	146 kW	4.1 kW/kg	22.1 kW/L	Meets 2020
Variant 2	24.1 kg	5.4 L	76 kW	3.6 kW/kg	15.9 kW/L	Does not meet 2020
Variant 3	27.3 kg	5.4 L	88 kW	3.2 kW/kg	16.3 kW/L	Does not meet 2020

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

TECHNICAL TEAM

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TECHNICAL BACK-UP