*M*otor with *A*dvanced *C*oncepts for *H*igh power density and *IN*tegrated cooling for *E*fficiency (MACHINE)

DE-EE0008867

DOE/VTO Annual Merit Review Presentation

Jagadeesh Tangudu (Principal Investigator)
Raytheon Technologies Research Center

June 1-4, 2020

Project ID: ELT253

Raytheon Technologies

Project Overview

Timeline

Project Start Date:	Oct 2019 (Jan 2020)
Project End Date:	Dec 2022
Percent Complete:	10%

Budget

Total Project Budget	
DOE Share:	$750k
Cost Share:	$187.5k
Funding for 2020:	$599.6k
Funding for 2021:	$337.9k

Program Barriers

Project goals include the following

- High power density (>8X)
- Lower motor cost (< $6/kW)
- Improve life (>2X)

These project goals are extremely challenging…

- Increased power density require reduction in volume
- One option to achieve is by increasing the speed (>20 kRPM)
- High speed operation would present mechanical challenges along with limited pole count
- High frequency also brings in higher loss density and challenging thermal management

Partners

- Raytheon Technologies Research Center (formerly known as United Technologies Research Center)
- John Deere

Multi-Disciplinary Team

Sponsor: U.S. DEPARTMENT OF ENERGY

Project Management: Raytheon Technologies

Project PI: Dr. Jagadeesh Tangudu

Co-PI's: Dr. Aritra Sur

Motor Design — Raytheon Technologies

Dr. Zhentao (Stephen) Du

Dr. Jagadeesh Tangudu

Thermal Management — Raytheon Technologies

Dr. Kimberly Saviers

Dr. Ram Ranjan

Dr. Aritra Sur

Application Specifications — John Deere

Co-PI: Dr. Brij Singh

- Seedling project
- Evaluate proposed technology during BP-1 and down-select technologies suitable for meeting target metrics
- Path for risk reduction using sub-component demonstrations during BP-2
- Multi-disciplinary team to explore the optimal solutions

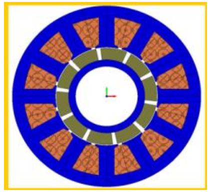
Challenges

- Increase in 8X volumetric power density is a challenging target to meet
- Achieving this would require increase in speed, but this posed two critical challenges
  - Trade between concentrated (limited slot-pole combination) vs. distributed winding (larger end winding)
  - Use of non-heavy rare earth magnets reduces the energy product and operating temperatures
  - Increase in fundamental frequency, i.e., increase in core losses as well as increase in AC winding losses in copper
  - Mechanical challenges such as rotor dynamics, centrifugal loads, larger air gap's (lower power density), bearing life, mechanical losses etc.
  - Thermal management of the motor is also critical for improved life and efficiency
- Use of reduced loss steel (for mitigating high frequencies) and Litz's wire (for AC winding losses) would increase material and manufacturing cost
- Impact of technologies required to meet the power density metrics while minimizing the cost and life is critical

Project Objectives (Year 2020 / 21)

- Explore machine trade space
- Identify optimal operating speed (>20 kRPM)
- Use of non-heavy rare earth magnets
- Identify suitable lamination steel for reduced losses
- Evaluate achievable slot fill factor with segmented stator sections
- Optimal use of Electromagnetic and thermal management solutions to meet these stringent targets

Motor



Motor Target Metrics		
Specifications	Units	Values
Pow er Density (greater than)	kW/L	50
Cost (less than)	$/kW	6
Life (greater than)	X	2
Derived Metrics from FOA		
Peak Pow er	kW	125
Min Speed (greater than)	RPM	20000
DC Bus Voltage	V	1050
Volume (Less than)	l	2.5
Unit Material Cost (Less than)	$	750
Based Speed	RPM	20000
Peak Torque @ Base Speed	Nm	59.68

Drive

John Deere Drive [1]		
Specifications	Units	Values
Pow er	kW	200
Pow er Density	kW/L	40
Drive DC Bus Voltage	V	1050
RMS fundamental line-line voltage	V l-l RMS	690
Drive Maximum Fundamental Frequency	kHz	2 (?)
Drive Sw itching Frequency	kHz	20 (?)
Number of Phases (>)	[-]	3

Source: 1. https://www.deere.com/en/electronic-solutions/news-room/news-articles/2nd-generation-sic-inverter/

Project Relevance

ETDS Targets			
Year	2020	2025	Change
Cost ($/kW)	8	6	25% cost reduction
Power Density (kW/L)	4.0	33	88% volume reduction

- Historically, VTO emphasized HEV applications, with target power levels at 55 kW [1]
- Vehicle mass has been increasing since then (>100kW) to meet consumer vehicle performance [1]
- Entire Electric Traction Drive Systems (ETDS) target metrics for 2025 <$6/kW & > 33kW/L [1]

Electric Motor Targets			
Year	2020	2025	Change
Cost ($/kW)	4.7	3.3	30% cost reduction
Power Density (kW/L)[1]	5.7	50	89% volume reduction

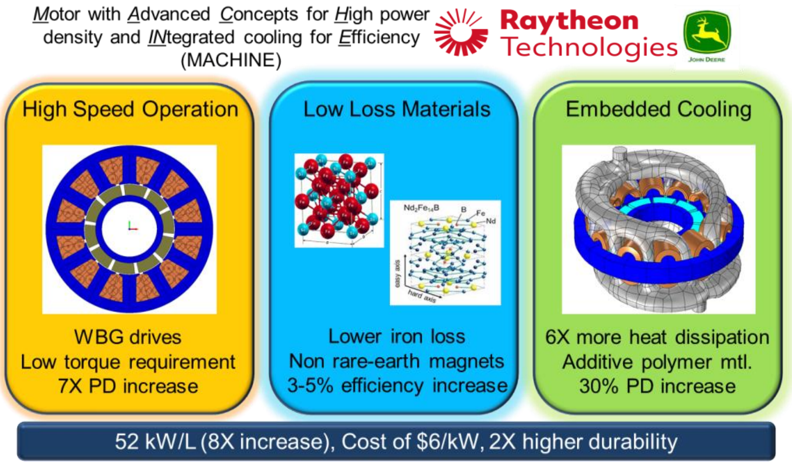
- Breaking down the target metrics to motor and drive would results in motor power density metrics > 50 kW/L with 89% reduction in volume [1]
- 100+ kW electric machine with its rotor, rotor shaft, stator with ending externs, housing and cooling but not reduction gearing [1]

1. Source: "USDRIVE Electrical and Electronics Technical Team Roadmap" October 2017

Uniqueness and Impact

In-order to meet the target metrics proposed MACHINE concept uses a Motor Drive architecture

a) Wide Band Gap (WBG) drive
b) Segmented stator fractional slot concentrated windings (FSCW)
c) Surface mounted permanent magnets
d) Operating at speed (>20,000 rpm)
e) Materials
    a) non-heavy rare earth
    b) low loss electric steel for reduced core losses
f) In-slot ultra-low-volume embedded cooling channels



These technologies in combination would potentially lead to

1. volumetric power density of >50 kW/L
2. cost of $6/kW, and
3. 2X improvement in motor life

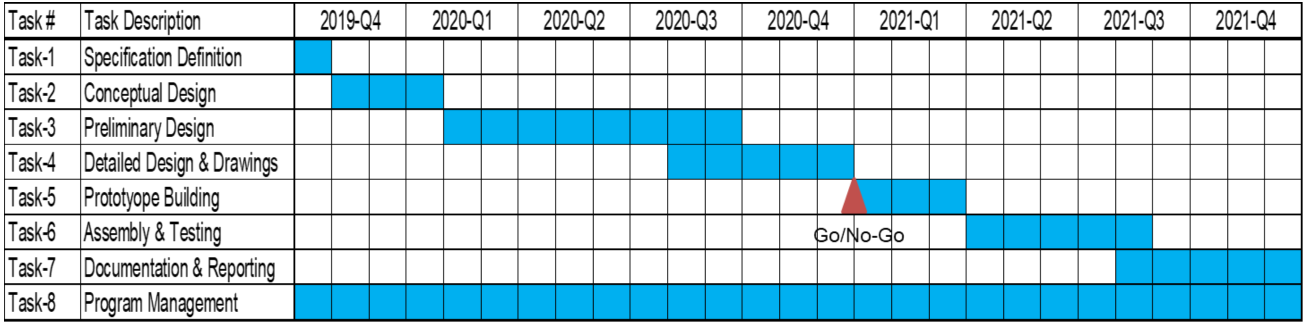
Project Approach

Proposed Approach for this project includes the following

- Electromagnetic design space evaluation: Identify an appropriate motor topology with in the suitable maximum fundamental frequency, winding architecture, materials, and key dimensions while applying assumptions, such as,
  - Segmented stator for higher slot fill factor
  - Slot-pole selection for maximum fundamental frequency to 2000 kHz
  - Low core losses by using high Silicon steel at high frequencies
  - Move loss density from core to copper losses
- Thermal management: Co-design methodology implemented to assess down-select EM configurations to evaluate the power density & cost
- Sectional stator prototype during BP-2 to reduce key in-slot cooling risks

Project Timeline & Milestones

Project Timeline



- Delays in contract negotiations along with personal end of year vacations delayed the start of the project
- BP-1 Milestone: Preliminary design (125 kW) with its performance variables compared with target metrics – Due end of Sept 2020
- BP-1 Milestone: Detailed sectional stator with in-slot cooling – Due end of Dec 2020 – Go/No-Go Review
- BP-2 Milestone: Build, test and validate sectional stator to validate in-slot cooling as function of current density – Due Dec 2021

Project Milestones & Status

Milestone #	Milestone	Type	Description
1.1	Target performance metrics	Technical	UTRC in collaboration with John Deere shall develop a comprehensive target performance metric to be achieved during the duration of the proposed project by month-1
2.1	Identify optimal operating speed and thermal management approach	Technical	UTRC team shall develop conceptual design of the motor and identify optimal operating speed (> 20,000 RPM) and suitable cooling mechanism by month-4
3.1	Preliminary design meeting target performance specifications	Technical	Preliminary density of the in-slot cooled 125kW motor with its performance comparison against target power density of 50 kW/l and cost target of $6/kW by month-12
4.1	Detailed design drawings for sectional stator	Technical& Go/No Go	Detailed design and drawings for a sectional prototype with in-slot cooling to validate slot fill factor and in-slot cooling performance by month-15. This is also a Go/No-Go decision point for the proposed project
6.1	Experimental validation	Technical	Experimental results and validation of model prediction of optimal current density for a given maximum hot spot temperature by month 23
8.1	Reporting	Technical	Quarterly and final reporting as per DOE requirements.

85% complete. Delays in contract negotiations with Deere

80% complete. Delays in project start.

Plan to Start by June 2020

Plan to Start Sept 2020

Accomplishments Till Date

Electric Machine Design

- Evaluated the design space for two different operating speeds (20,000 RPM, 24,000 RPM)
- Key machine parameters such as machine OD, current density and slot fill factor is considering for high level design space
- For each key parameter space, design optimization of in-plane motor parameters is performed to capture the optimal design with highest volumetric power density
- Down-selected the design space for thermal modeling and evaluation

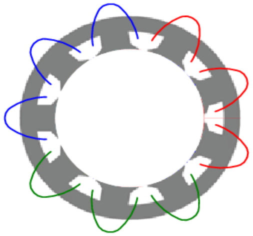
Thermal Management

- Capture each down-select design and performed in-plane, in-slot thermal model to estimate the hot spot temperatures with and without in-slot embedded cooling channel
- Provide feedback to EM team to capture the optimal slot current density, fill factor and stator OD

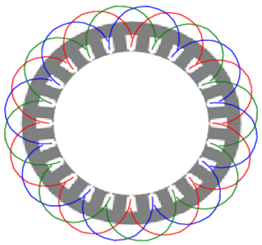
Motor Design Accomplishments

Stator Configurations Considered

Fractional Slot

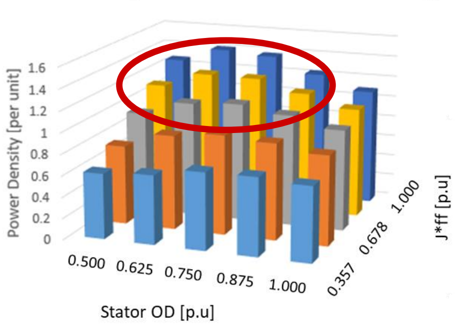


Integrated Slot

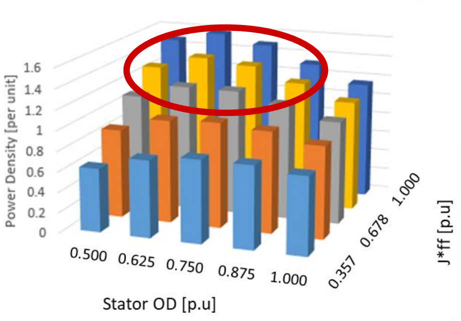


Design Space Exploration – Per Unit Power Density

@ 20k RPM



@ 24k RPM



Select Slot-Pole Configurations

Frequency	2000	Hz	
Speed	Poles	Winding Type	
[RPM]	[-]	Concentrated	Distributed
20000	12	Not Feasible	Feasible, tooth saturation
24000	10	Feasible	Feasible, good option
30000	8	Low Winding Factor	Feasible, good option
40000	6	Unbalanced Forces	Feasible, Thick Backiron

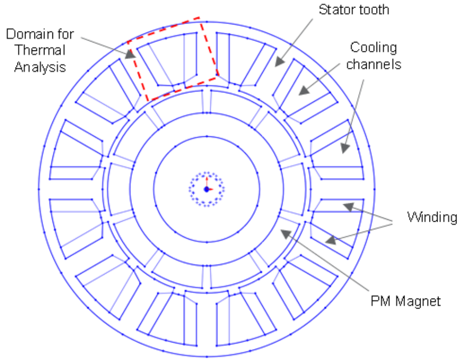
Speed	20000	RPM	
Frequency	Poles	Winding Type	
[Hz]	[-]	Concentrated	Distributed
2000	12	Not Feasible	Feasible, tooth saturation
1666.667	10	Feasible	Feasible, good option
1333.333	8	Low Winding Factor	Feasible, good option
1000	6	Unbalanced Forces	Feasible, Thick Backiron

- Two different winding patterns were considered. But concentrated winding design space was explored first
- Combined current density and fill factor for reduced design parameters
- Design space exploration was performed at 20kRPM and 24kRPM
- Select design meeting the target power density were down-selected to evaluate the thermal performance

Thermal Modeling Accomplishments

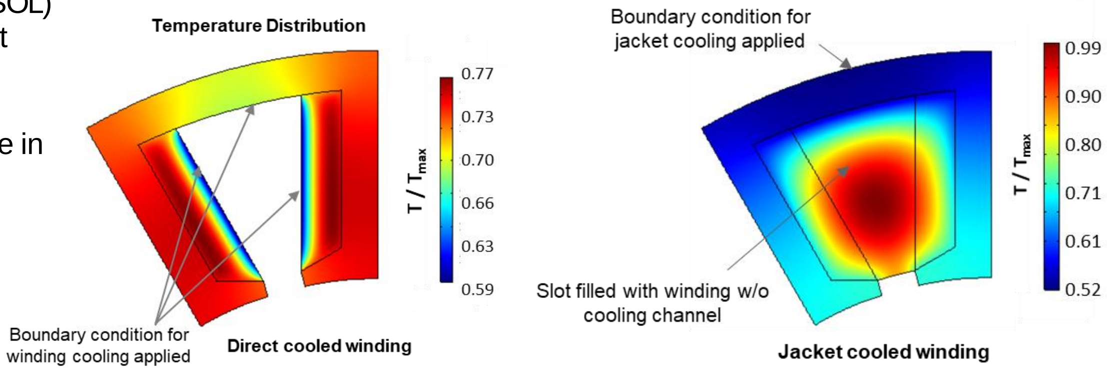
- Down-select design from EM design exploration were then considered for in-slot 2d modeling
- Thermal loads in the stator are copper and core losses
- Flow channel geometry for maximizing current density and heat transfer
  - Careful considerations for heat transfer coefficient determination[1]
  - Correlation reported in literature considered and modified

Electric Motor CAD from EM analysis



2D FEA model

- Thermal model developed using a FEA tool (COMSOL)
- Heat transfer in channel specified as a lumped heat transfer co-efficient
  - Coolant: 50/50 EGW at 50 °C
- Flow rates calculated for restricting temperature rise in coolant ~ 10 °C
- Uniform flow distribution in channels assumed
- Winding thermal conductivity ~ used conservative estimates as reported in literature[2]



Ref:

1. McHale, John P. and Garimella, Suresh V., "Heat Transfer in Trapezoidal Microchannels of Various Aspect Ratios" (2010). Birck and NCN Publications. Paper 1490
2. L. Siesing, A. Reinap and M. Andersson, "Thermal properties on high fill factor electrical windings: Infiltrated vs non infiltrated," 2014 International Conference on Electrical Machines (ICEM), Berlin, 2014, pp. 2218-2223.

Summary / Future Work during FY2020

- Complete the design space exploration for distributed winding architectures
- Evaluate the down-select design with thermal modeling and identify best suitable architectures based on thermal management solution
- Finalize the slot fill factor, current density and stator outer diameter for the conceptual design down-select
- Detailed understanding of thermal models for flow and heat transfer in unconventional channel geometries as applicable for the motor to maximized heat transfer performance
- Continue with header topology optimization exercise focusing on flow parameter optimization and fabrication
- Explore material for header and embedded cooling channel materials
- Initiate preliminary design by performing refinements considering the multi-physics aspects
- Perform detailed design for sectional stator and prepare for Go/No-Go review meeting