# **Electric Motor R&D**

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# Overview

### Timeline

- Start Oct. 2012
- Finish Sept. 2015
- 22% complete

### Budget

- Total project funding
  - DOE share 100%
- Funding for FY13: \$900K

### **Barriers**

- Cost is an over-arching concern
- Electric traction motors are on ~3.5% learning curve, power electronics ~7% means 2020 Traction Drive System (TDS) target will not cross \$8/kW goal until ~2028
- Instability in rare earth (RE) magnet pricing demands close attention to non-RE motor designs
- Inconsistent definition of efficiency Targets Addressed
- System
  - Improve efficiency over DOE 2020 target of 94%

### **Partners/Collaborators**

- **ORNL Team Members:** Curt Ayers, Tim Burress, Randy Wiles, Andy Wereszczak, Balasubramaniam Radhakrishnan
- NREL collaboration: Kevin Benion
- ORNL Materials Science and Technology Division (MSTD) epoxy matrix composites (funded by DOE VTP Propulsion Materials Program)
- ORNL Computer Science and Mathematics Division (CSMD) low loss lamination materials
- Ames Laboratory magnets



# **Project Focus**

 Develop non-rare earth traction motor designs that will meet DOE 2020 targets



# **Objectives**

### Overall

- Develop efficient and low cost non-RE electric motors that take advantage of lower loss materials enabled by new processing methods.
- Meet DOE 2020 cost and performance targets for electric motors.

### • FY13

- Develop candidate, non-RE, motor (induction and switched reluctance, and in future, synchronous reluctance) designs suited to 55 kW peak, 30 kW continuous power.
- Deliver electrical models to APEEM traction drive systems team for computer simulation and performance validation.
- Employ material and process innovations that facilitate meeting DOE 2020 motor efficiency goal.



# **Milestones**

Date	Milestones and Go/No-Go Decisions	Status
Sept- 2013	Milestone: New start for non-RE motor designs that meets DOE 2020 cost and performance targets.	Completed induction motor design, BOM cost and performance model Completed 2012 IPM comparator model
Sept- 2013	Go/No-Go Decision: Motor design meets DOE 2020 specific cost (\$4.7/kW)	Analysis shows this metric can be met
Sept- 2014	Milestone:Down select promising traction motor candidate and fabricate short stack prototype.Go/No-Go Decision:Prototype motor meets performance and efficiency goals over combined drive schedules (CDS)	

BOM: Bill of materials IPM: Interior permanent magnet



# **Approach/Strategy**

- Development performance and cost assessment for candidate electric traction motors.
  - Use 2012 NISSAN LEAF® All Electric Vehicle (AEV) traction motor as the baseline comparator
  - Analysis to show present traction motors, power electronics, and traction drive system (TDS) will not meet 2020 target until ~2028 (given 2010 metric initial conditions)



Historical trend in automotive traction motor speed, a surrogate for cost, indicates that by 2020 motors would benefit from operating at higher speed.



## Approach (contd.)

- Development performance and cost assessment for candidate electric traction motors.
  - Project RE-based motor designs out to higher speeds, using optimized RE content at ~\$77/kgRE, to show potential benefits of higher speed are lost when RE content dominates motor cost.



Charting the cost of IPM traction motors with speed (5,000 rpm to 23,000 rpm) shows that an inflection point has already been crossed at which point the historical learning curve transitions to a shallow slope and 2020 target \$4.7/kW can no longer be achieved when RE is involved.



## Technical Accomplishments and Progress - Overall

- FY13 Motor R&D candidate motors identified.
- Comparisons based on DOE 2020 targets for specific power (SP), power density (PD), specific cost (SC), and efficiency).
  - Candidate designs include induction (IM), switched reluctance (SRM), and in FY14, the synchronous reluctance (Sync-Rel) motors
  - More package efficient motor designs (i.e., smaller) are more challenging thermally. This prompted closer collaboration with NREL.
- Developed more package efficient traction motor that analysis shows can meet DOE 2020 targets.
  - Minimizes material content,
  - Benefits from low loss steels, and
  - Improved thermal management materials



- Mass and cost calculations show baseline IPM traction motor will be challenged to meet DOE 2020 targets.
  - RE magnets are a small fraction of total mass, but very large fraction of cost
  - IPM designs are close, or at, their rotor structural stress limits so moving to much higher speeds will be challenging



Meets 2015 SP Target 1.4kW/kg Specific power (SP): 1.43 kW/kg 2020 target: SP=1.6 kW/kg



**EXAMPLE 1 EXAMPLE 1 EXAMP** 

- Low loss material (present)
  - JFE Super Core, chemical vapor deposition (CVD) process is energy intensive, slow, and expensive (6x conventional steel)
  - Recent literature (2011) shows China now exploring lower cost high-silicon iron processing
  - ORNL is developing low cost process

CVD (siliconizing) Process Concentration distribution control diffusion process Uniform diffusion process JNHF-Core Gradient high-silicon steel sheet with low silicon content at the center portion **JNEX**-Core and 6.5% silicon near the outer surface areas 6.5% silicon steel sheet. (A high-silicon steel sheet with a uniform silicon content of 6.5% throughout the sheet)

JFE Super Core Production Process

Graphic used with permission: Kanematsu USA & JFE



#### ORNL low loss material

- ORNL performance evaluation of low loss electrical steel in FY12 demonstrated substantial improvement in core loss reduction in IPM test motors.
- Development of potential low cost processing technology is underway at ORNL and collaborators based on a metallurgical process with potential for significant cost reduction.





- Hybridized motor/generator
  - Field controlled permanent magnet (PM) work explored novel method of flux weakening
    Open Circuit Voltage Output for Hybrid Ferrite Generator
  - Experimental open circuit voltage:



 Motor size (mass & volume) optimization: torque (m) and speed (n).



Motor optimization methodology consists of finding the smallest motor (mass & volume) as speed increases. In this illustration both motors A&B deliver the same power, but motor B is smaller than motor A (i.e., area(A) = area(B))



Identified candidate motor technologies: IM, SRM, SyncRel

Attribute	Baseline: Interior Induction Motor/ PM Motor Asynchronous (IPM) (IM)		Switched Reluctance Motor (SRM)	Synch-Rel or PM Reluctance (Synch-Rel)	
Representative design			Stator Rotor		
Date of 1 <sup>st</sup> concept	1986	1889	1900	1923	
Electromagnetic torque, m <sub>em</sub> =	$\frac{3P}{22} \left\{ \lambda_{pm} I_{qs} - \left( L_{ds} - L_{qs} \right) I_{ds} I_{qs} \right\}$	$\frac{3}{2} \frac{P}{2} \frac{L_m^2}{L_r} I_{ds} I_{qs}$	$\frac{1}{2}I_{z}^{2}\frac{dL(\theta)}{d\theta}$	$\frac{3}{2}\frac{P}{2}(L_{ds}-L_{qs})I_{ds}I_{qs}$	
Power Factor (PF)	<del>→</del> 1.0	<1.0	<<1.0	$PF_{Sync\ hRel} = \frac{\frac{L_{ds}}{L_{qs}} - 1}{\frac{L_{ds}}{L_{ds}} + 1}$	
Suitable for HS	0	+	++	0	
Efficiency	++	+	+	+	
Cost		++	++	+	



- Identified baseline motor: 2012 NISSAN LEAF® Interior Permanent Magnet (IPM) with RE magnets
- Comparison of high speed (HS) induction motor to commercial AEV motor



(E 400)

Stator O.D.: ~ 19.812 cm (7.8")



- Motor dimensions
  - Stator OD: 198.12 mm
  - Stator bore: 130.96 mm
  - Stator stack: 151.38 mm
  - Rotor OD: 129.97 mm
  - Rotor stack: 151.16 mm
  - Rotor mass: 16.45 kg (with magnets)
  - Magnet only mass: 1.895 kg
- Winding design
  - 48 slots, 8 pole, 3 phase, SPP=2
  - NIH = 20 of #20 AWG

	(5.12")		LEAF Motor		HS Induction
		Maximum speed	(rpm)	10,300	23,000
		Stack length	(mm)	151.3	106.8
		Rotor OD	(mm)	130	87.2
		Rotor mass	(kg)	16.432	5.602
		Rotor volume	(dm <sup>3</sup> )	2.008	0.638
		Rotor Inertia	(kg-m <sup>2</sup> /rad)	0.0347	0.00533
		Gear ratio for inertia balance	(#)	1.0	2.55
		Gear ratio to match n <sub>mx</sub>	(#)	1.165	1.92
		Shaft diameter	(mm)	44.45	34



- Developed Induction traction motor
  - BOM based mass and cost



Meets targets Specific power: 3 kW/kg 2020 target: 1.6 kW/kg



#### Meets targets Specific cost: \$3.1/kW

2020 target: \$4.7/kW









#### Induction Motor (18.26 kg, 55 kW)

# **Collaboration and Coordination**

Organization	Type of Collaboration/Coordination
Industry: Solepoxy, Tempel Steel, JFE Corp.	Powder coated slot lining, Epstein tests, lamination materials and assembly
National Renewable Energy Laboratory (NREL)	Thermal materials, motor thermal modeling, and thermal management
ORNL Material Science and Technology Division	Thermal conducting materials and mechanical properties
ORNL Computer Science and Mathematics Division	Alternative to expensive CVD processing of Fe6.5%Si lamination steel
Ames Laboratory	Advances in non-RE magnet materials and permanent magnets for traction motors





JFE









# **Proposed Future Work**

#### Remainder of FY13

- Perform 2<sup>nd</sup> iteration on IM stator design and update BOM mass & cost
- Perform spin tests of FY12 IPM motors with different lamination materials and winding potting (loss characterization).
- Simulate IM over drive cycles and share loss data with NREL for thermal design and feedback any concerns that influence motor design
- Complete 1<sup>st</sup> iteration of switched reluctance motor (SRM) design

#### • FY14

- Finalize IM design and commission prototype fabrication of short stack
- Move into phase II of Fe6.5Si low loss lamination material directional solidification processing
- Kick-off 1<sup>st</sup> iteration of synchronous reluctance motor design
- Coordinate with wide bandgap inverter development project and NREL partners

### • FY15

- Down select from candidate non-RE and one reduced RE motor design and fabricate full scale prototype.
- Mate to wide bandgap full rated inverter for system dynamic test in ORNL vehicle systems hardware-in-loop facility



# Summary

- **Relevance:** This project focuses on motor technology best suited to meet all DOE 2020 targets when matched to wide band gap power inverter.
- Approach: The approach pursued addresses traction motor designs and materials
  - Development of advanced low loss core materials and their processing,
  - Improved thermal materials and higher rate cooling designs,
  - Designs that will accommodate innovations in non-RE and alternative material magnets
- Collaborations: Collaborations with industry material providers and sister national laboratories necessary to maximize the impact of this work.
- Technical Accomplishments:
  - Identified alternative to low loss Fe6.5%Si lamination steel processing than approach followed in FY12
  - Close collaboration with industry and copper association on copper rotor induction motor.
  - Completed assessment of comparator RE traction motor mass and cost survey and contrasted to copper rotor induction motor.
- Future Work: Continue development of copper alloy rotor induction traction motor, improved switched reluctance motor, and determine potential of synchronous reluctance motor having alternative material, and reduced content, rotor magnets.



### **Technical Back-up Slides**



### Approach (contd.)

- Assessment of state-of-the-art in electric traction motor performance and cost.
  - 2012 NISSAN LEAF® 80 kW IPM traction motor
  - Water-ethylene-glycol WEG Liquid cooled, rated to 10,300 rpm





Metric	Units	2020 Target	2010 Prius	2012 LEAF	2011 Sonata
Peak Power	(kW)	55	60	80	30
Inverter	SP (kW/kg)	14.1	16.7 (5.9*)	4.94	6.9
	PD (kW/liter)	13.4	11.1 (6.9)	5.14	7.3
Motor	SP (kW/kg)	1.6	1.6	1.43	1.1
	PD (kW/liter)	5.7	4.8	4.21	3.0
System	SP (kW/kg)	1.44	1.46 (1.25)	1.1	0.95
	PD (kW/liter)	4.0	3.35 (2.8)	2.3	2.13
Sys Eff	(peak %)	>94%	~95	~94	93



- Induction traction motor
  - Model data when n<sub>b</sub>=8846 rpm taken as rating point (e.g., corner point)
  - P<sub>pk</sub> ~ 55 kW, P=4 poles, m<sub>1</sub>=3 phase design with U<sub>d0</sub>=720Vdc



$$m_{bd} = \frac{m_1 U_{th}^2}{\omega_m \left[ r_s + \sqrt{r_s^2 + (\omega_s L_{lk})^2} \right] 2}$$



