Multi-Speed Range Electric Motor R&D

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Overview

Timeline

- Start – FY15
- End – FY17
- 17% completed

Barriers

- Efficiency: With single speed range motor, it is difficult to reach 2022 EDT efficiency target of 94%

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY14: $ 0K
- Funding for FY15: $ 250K

Partners

- ORNL team members:
  - Tim Burress
  - Curt Ayers

Project Objective and Relevance

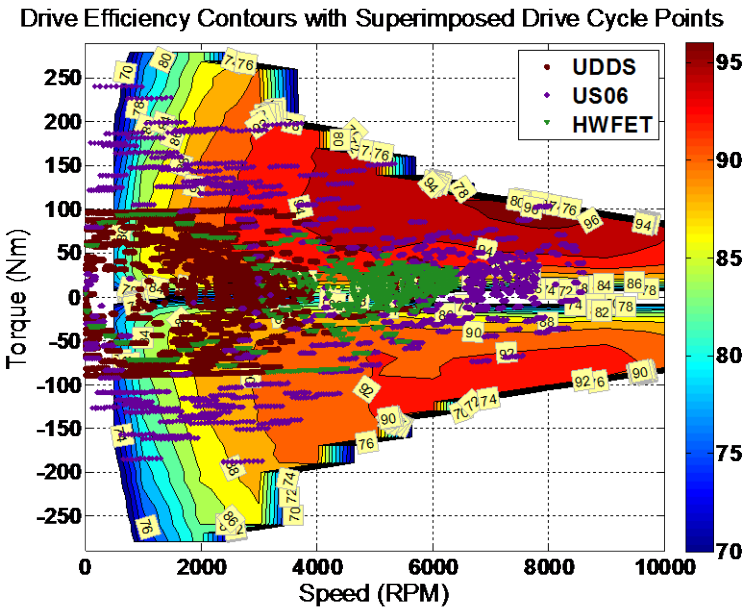
- Overall Objective
  - Designs and strategies will be developed to achieve multi-speed range (MSR) operation in order to provide
    - Higher drive cycle efficiencies
      - Solutions address inverter, motor, and combined efficiencies
    - Increased power density and specific power
    - Reduced system cost
- FY15 Objectives
  - MSR technique development, simulation, and comparison studies to find out the best MSR design
  - Verify in simulation that the MSR design can reach EDT 2022 efficiency target
  - Benchtop MSR component fabrication/evaluation to verify modeling results

Milestones

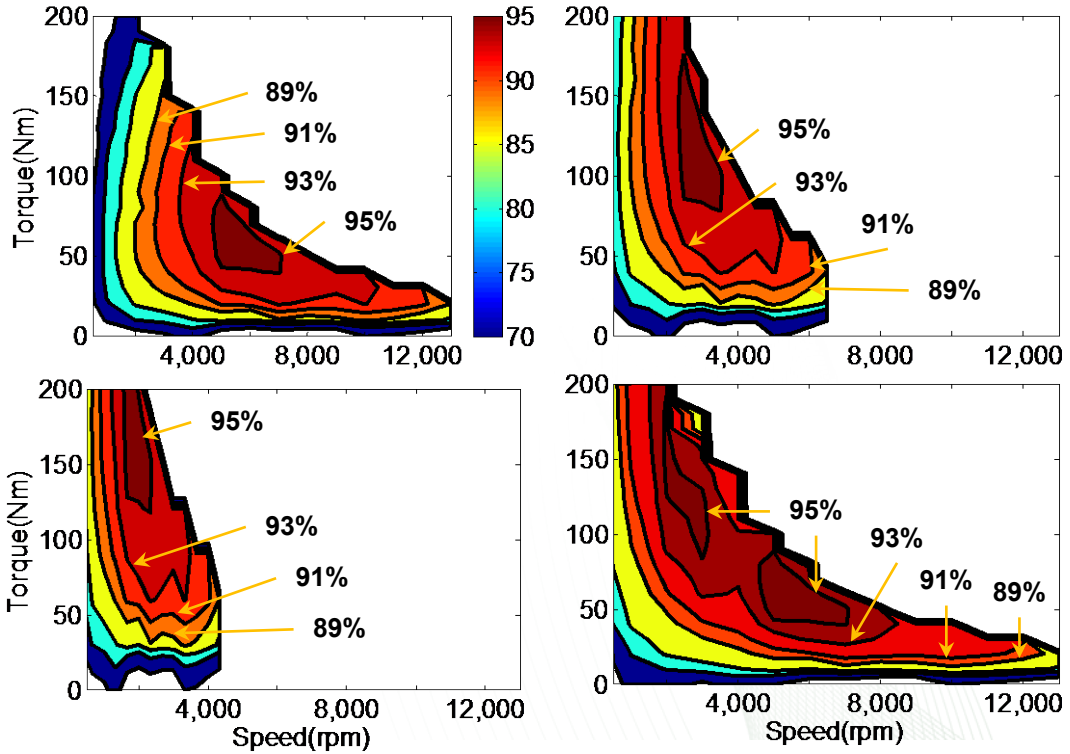
Date	Milestones and Go/No-Go Decisions	Status
2014	New start	
2014	New start	
June 2015	Go/No-Go decision: Determine if at least one MSR motor concept is feasible to achieve 2022 EDT efficiency target, then conduct benchtop testing.	
Sept. 2015	Milestone: Compare various MSR concepts based on simulation results and perform benchtop measurements for at least one concept.	**On track**

Problem to be Addressed

- HEVs and EVs with only one motor speed range have the following problems:
  - **Low motor efficiency points in low-to-moderate torque and speed operation regions are frequented**
  - **Peak power and high efficiency regions of the motor are infrequently used in normal driving conditions**
  - **Complex clutches and gear arrangements are required to address these issues above**



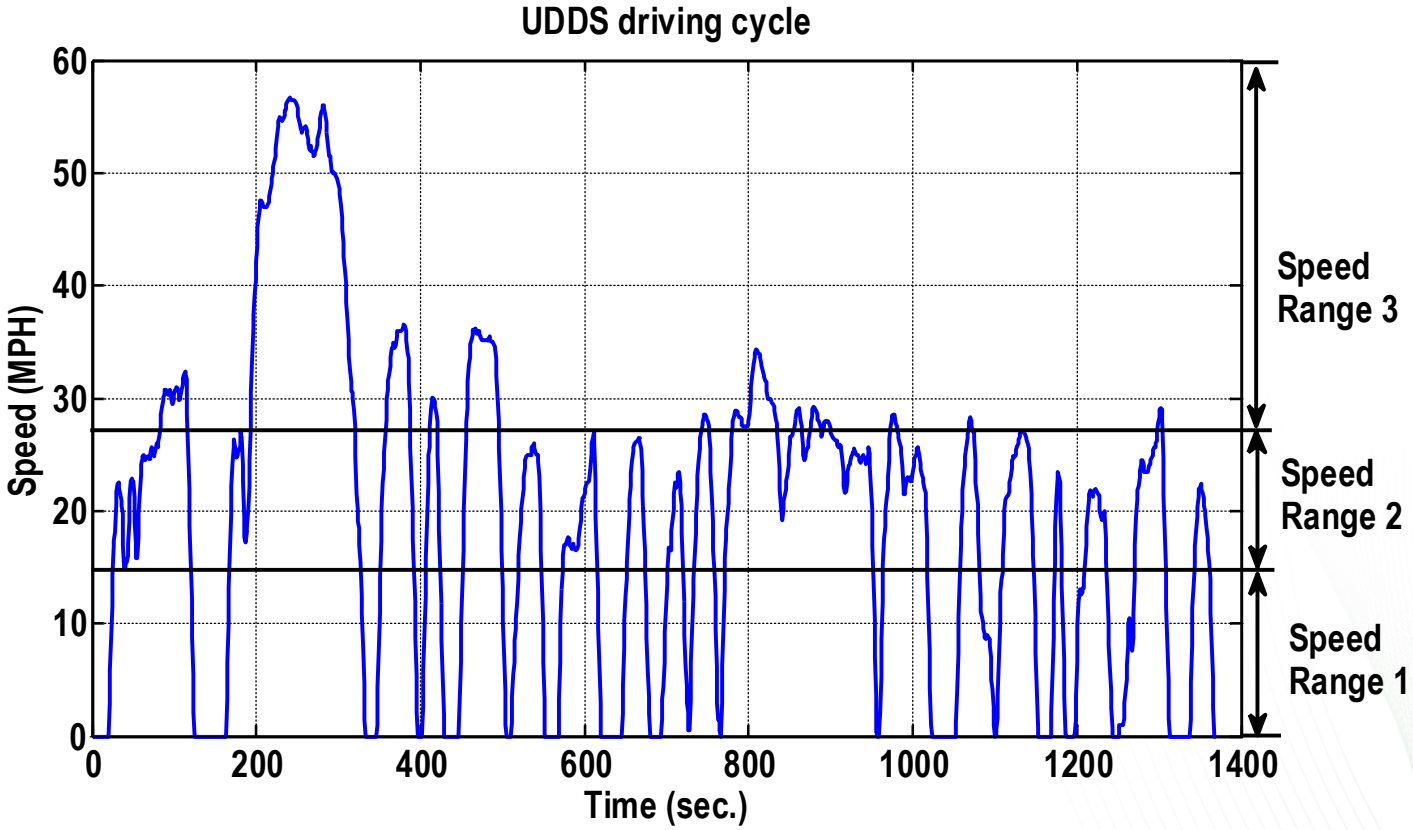
Overlay of drive cycle data points on efficiency map



Efficiency maps of a PM motor at different speed ranges (ideal case without switch losses).

Approach
Strategy to Address Limitations of SOA

- Implementation of MSR operation and the number of available speed ranges will vary depending on the method used
- Basic example of using three-speed range operation.

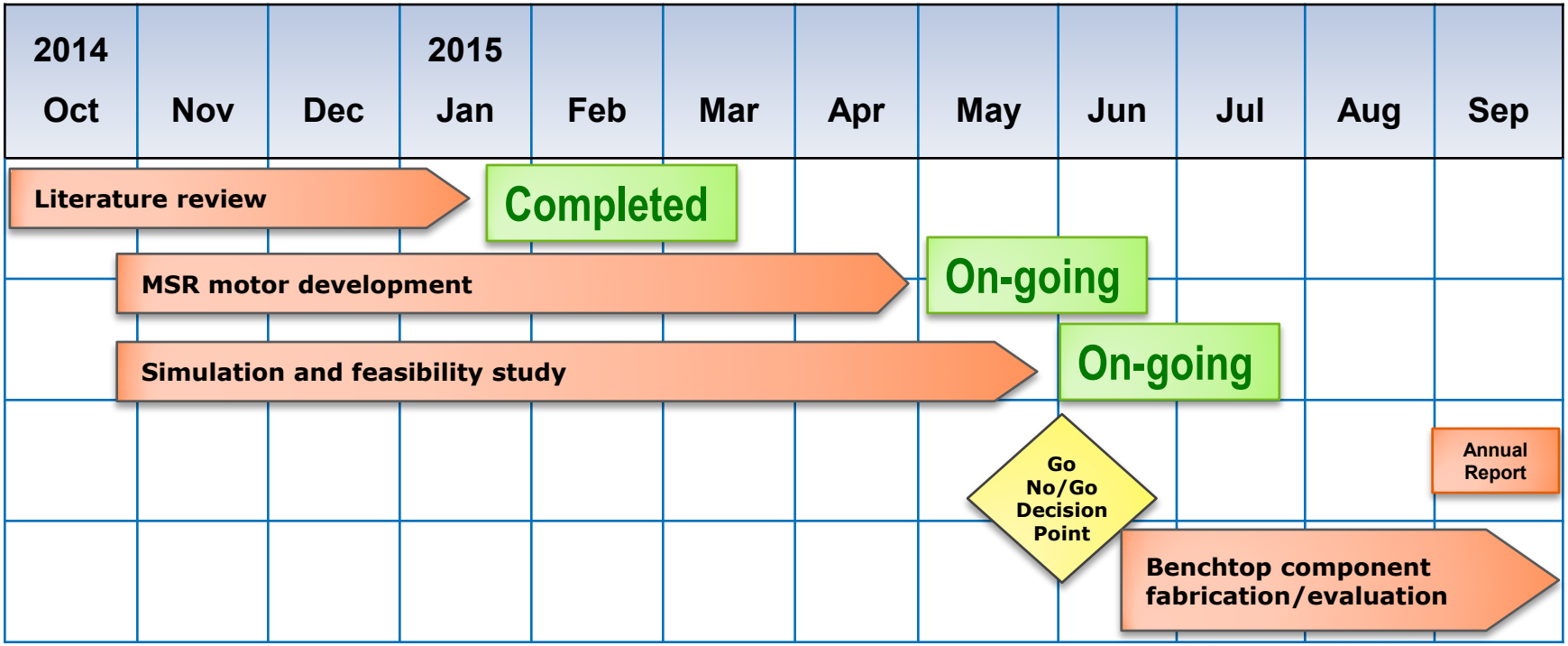


Implementation of MSR operation

Approach
Strategy to Address Limitations of SOA

- Designs and strategies will be developed to achieve MSR operation with higher drive cycle efficiencies, higher power density/specific power, and lower cost
- MSR motors can accomplish these goals through innovations in
  - Electric motor designs
  - Winding arrangements (e.g. reconfigurable windings)
  - Power electronics integration
  - Control techniques

Approach FY15 Timeline



Go No/Go Decision Point: Determine if at least one MSR motor concept is feasible to achieve 2022 EDT efficiency target, then conduct benchtop testing.

Key Deliverable: Annual report that includes literature review, feasibility studies and benchtop tests.

Technical Accomplishments FY 15 (1)

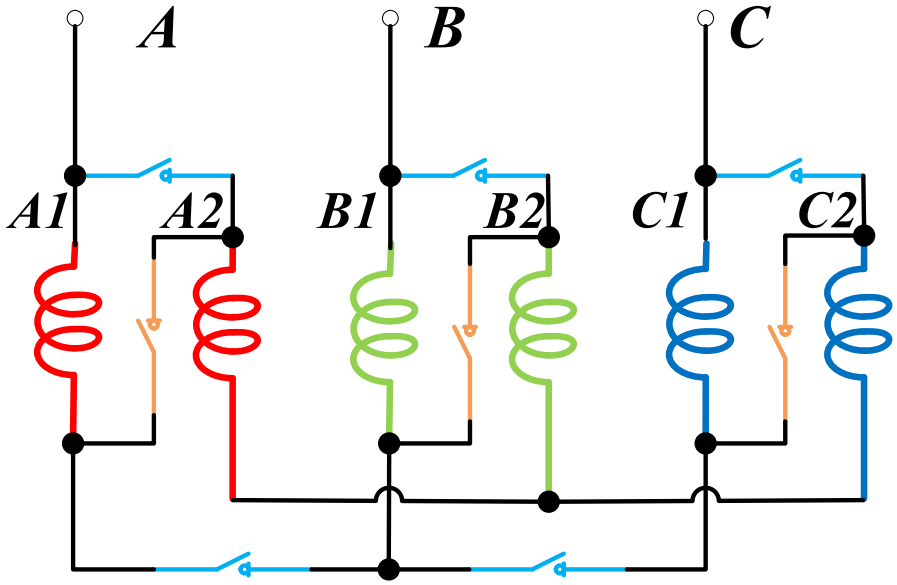
Literature review completed

- No commercial MSR motor products on the market yet
- Some MSR research targets low power applications such as electric scooter, electric bike, etc…
- Majority of MSR techniques reported utilize reconfigurable windings
  - Additional power switches are needed to change stator winding configurations
  - AC contactors and/or solid-state AC switches are used
  - Switching winding configuration in a MSR motor generates torque and current transients

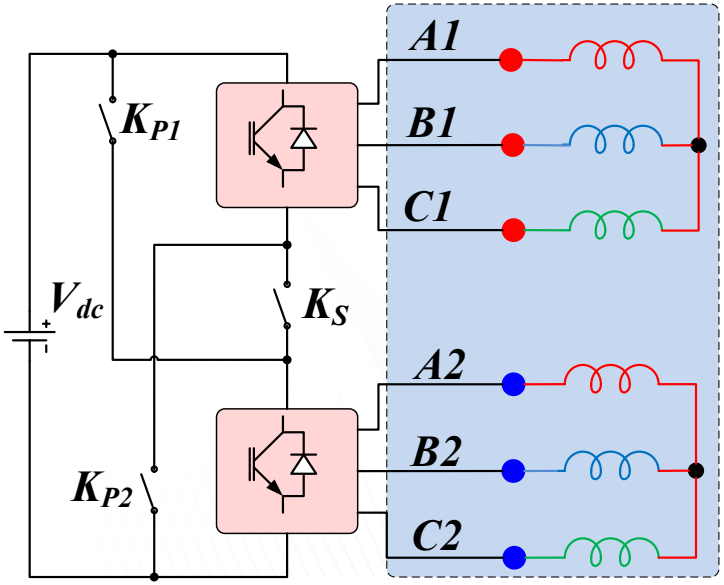
Technical Accomplishments FY 15 (2)

Literature review - important patents

- Patent A uses 8 switches to achieve two speed range operation
- Patent B only uses 3 switches to achieve two speed range operation
  - Switches on the dc bus increase stray inductance; not suitable for high power electric vehicle applications
  - Possible short-circuit in case of accidental turn on of switches (K_S, K_{P1} and K_{P2}); additional short-circuit protection is required
- During speed range change, undesirable torque interruption occurs



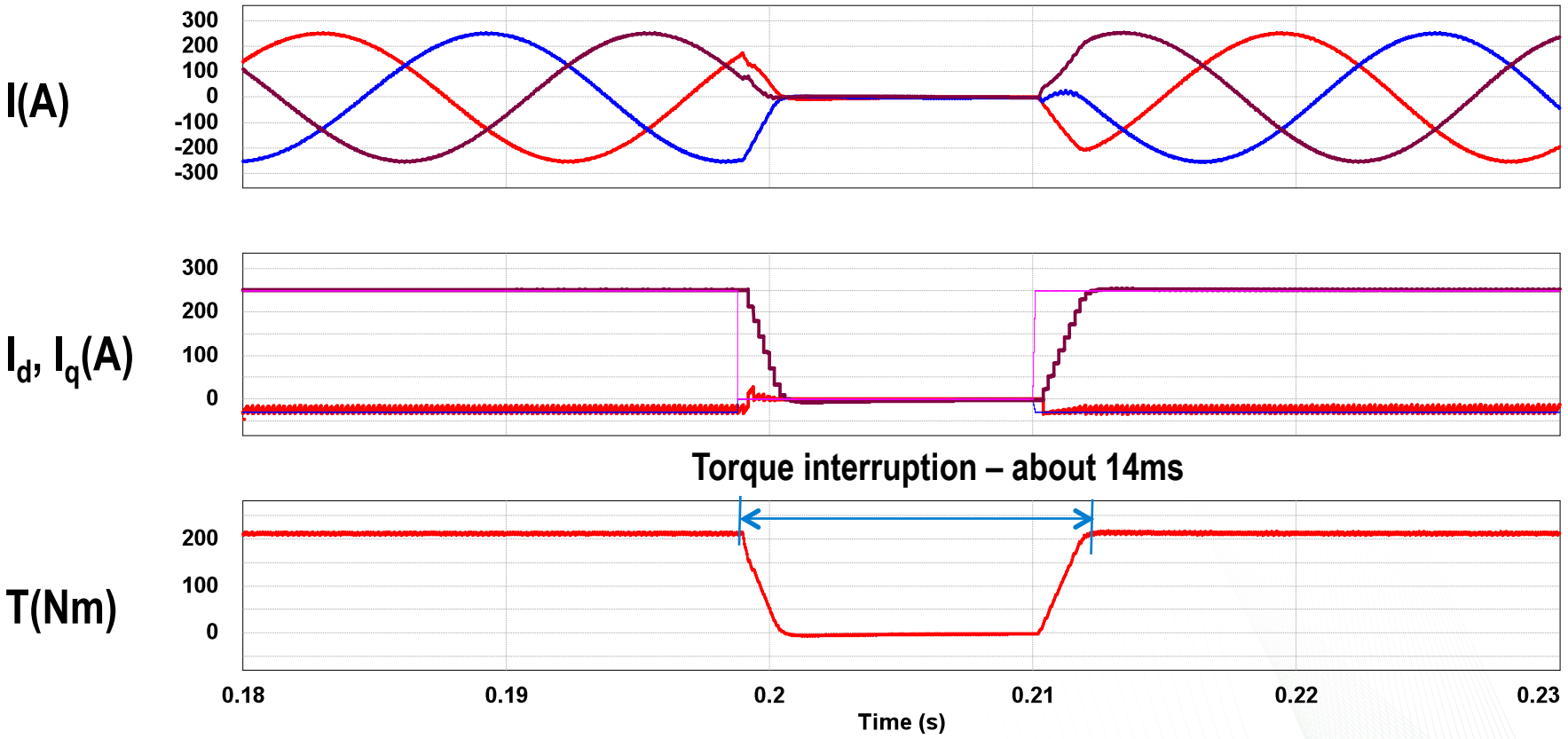
Industry patent A - US8415910 B2
published in 2013



Industry patent B - US20120086380
published in 2012

Technical Accomplishments FY 15 (3)

Demonstration of torque interruption by simulation



- Simulations using a typical traction drive motor showed a 14 ms torque interruption
- New designs have the potential to mitigate torque transient

Technical Accomplishments FY 15 (4)

Simulation and feasibility study - important efficiency improvement achieved with MSR operation

- **By using different strategies to actively re-locate high efficiency regions to lower speed/power regions, it is confirmed that the average drive cycle efficiency can be increased by roughly 5~6% with option 2 system (ideal case: without switch conduction losses).**

	US06 (Aggressive)	UDDS (City/stop-go)	HWFET (Highway)	Combined
2013 Prius Motor only	86.9	80.7	89.9	84.7
2013 Prius Inverter only	91.8	81.0	95.95	87.6
2013 Prius System	**81.7**	**69.1**	**86.6**	**76.7**
Option 1 System	**83.6**	**75.5**	**87.5**	**81.5**
Option 2 System	**86.3**	**78.7**	**87.8**	**83.0**

Average drive cycle efficiencies show MSR improves efficiencies

Option 1 - Two-speed approach

Option 2 - Three-speed approach

Technical Accomplishments FY 15 (5)

Simulation and feasibility study - MSR reduces drive cycle energy losses by 24% - modeling results

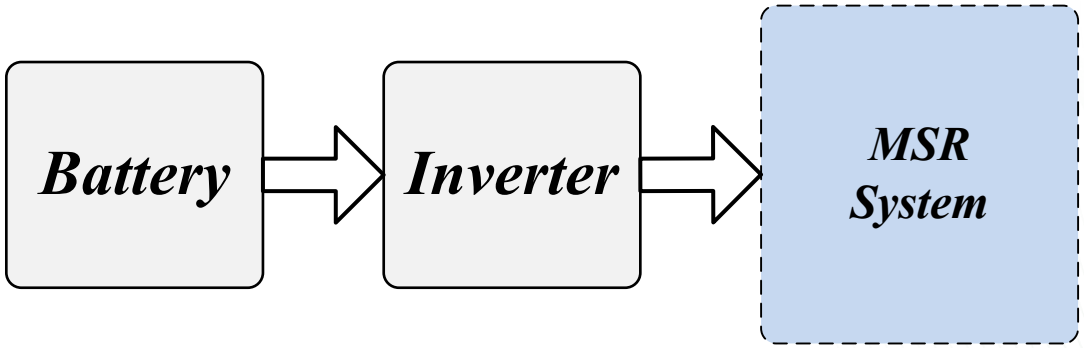
- The drive cycle total energy loss can be reduced by roughly 30% in US06 and UDDS drive cycle simulations (ideal case: without switch conduction loss)
- In combined drive cycle (US06 + UDDS + HWFET), the energy reduction is 23.6%

	US06 ($X10^6$ Joules)	UDDS ($X10^6$ Joules)	HWFET ($X10^6$ Joules)	Combined ($X10^6$ Joules)
2013 Prius System	1.374	1.621	0.803	3.798
Option 2 System	0.966	1.167	0.766	2.899
Loss Reduction (%)	29.7	28.0	4.61	23.6

Technical Accomplishments FY 15 (6)

Designed a novel MSR system called MSRS (under review for patent application)

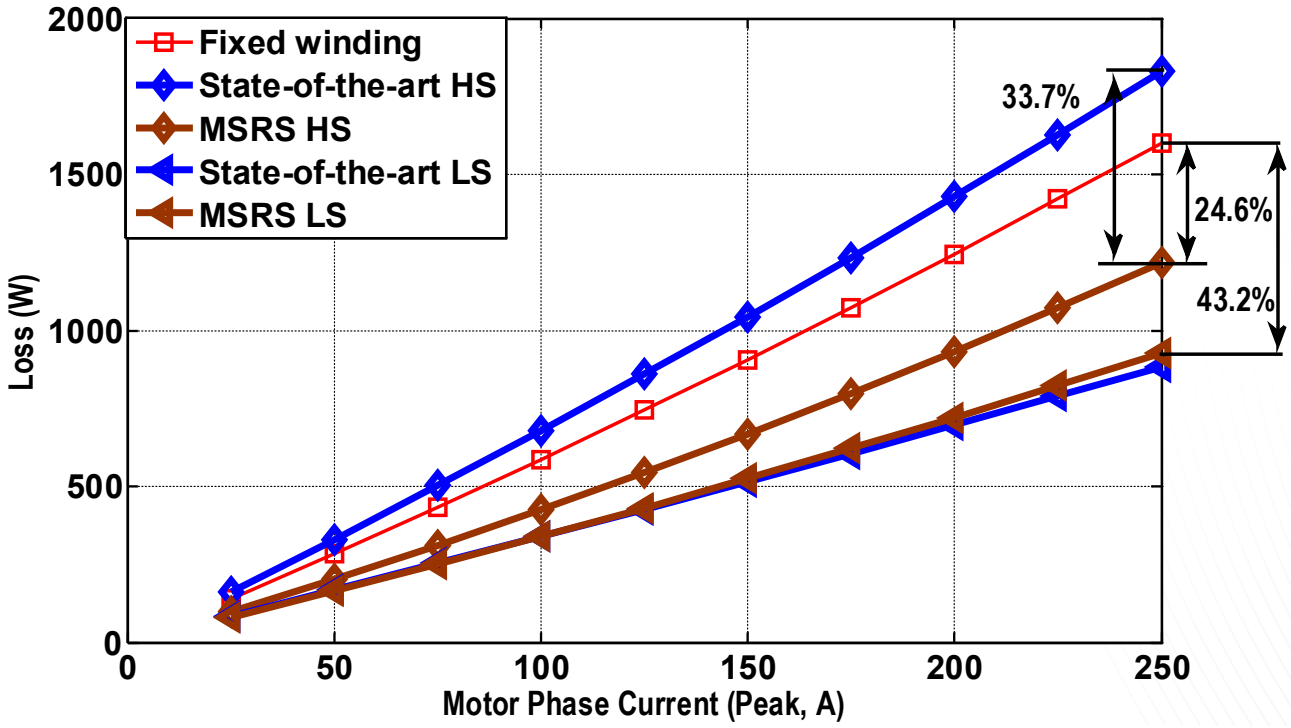
- Uses fewer solid state switches to change speed range — less added cost/weight
- Does not insert switches in dc bus – will not increase dc bus stray inductance and potentially electromagnetic interference.
- Does not have a battery short circuit failure mode



Technical Accomplishments FY 15 (7)

MSR system development, simulation, and feasibility study

- Compared to the conventional (fixed winding) case
  - 24.6% reduction in losses at high speed (HS: above 1000 rpm) operation
  - 43.2% reduction in losses at low speed (LS: below 1000 rpm) operation
- Compared to the state-of-the-art (SOA) case
  - 33.7% reduction in losses at HS operation
  - Similar losses at LS operation



Technical Accomplishments FY 15 (8)

MSRS simulation and feasibility study – significant loss reduction achieved (losses in solid state switches considered)

- At low speed, the loss reductions of MSRS and SOA are similar
- At high speed, using the SOA system, losses increase by 14%
  - However, using the MSRS, the losses decrease by 24.6%
- MSRS uses fewer solid state switches than SOA system

	Fixed winding Motor loss (W)	SOA system loss (W)	MSRS loss (W)
Maximum current in LS mode	1620	890	**920**
Maximum current in HS mode	1620	1840	**1220**
Loss change over fixed winding motor(LS/HS)		- 45% (LS) **+ 14% (HS)**	**- 43.2% (LS)** **- 24.6% (HS)**

Loss comparison – proposed MSRS reduces losses in both modes

Partners/Collaborators

- New start
- Actively seeking partners at this time.

Remaining Challenges and Barriers

- Cost of additional parts (e.g. extra rotor or switches/controls)
- Complexity of motor geometries and assemblies required to achieve MSR

Proposed Future Work

- Remainder of FY15
  - Feasibility studies and benchtop tests of MSR motor components
    - Develop, simulate and compare different MSR techniques
    - Fabricate/evaluate benchtop components
- FY16
  - Simulation, optimization, and testing of the benchtop prototype
    - Continue feasibility study on different MSR technologies
    - Perform simulation/optimization on the benchtop prototype
    - Build/test the benchtop prototype
- FY17
  - Select the final approach, system modeling, optimization and testing of final prototype
    - Select final design
    - Perform system modeling/optimization on the final prototype
    - Build/test the final prototype

Summary

- Relevance: This project targets drive cycle efficiency, weight, and improvement in performance and lifecycle
- Approach: MSR motors can accomplish these goals through winding arrangements (e.g. reconfigurable windings), power electronics integration, control techniques, and electric motor designs
- Collaborations: Actively seeking collaborations in motor industry partners to facilitate transition to industry
- Technical Accomplishments:
  - Literature review shows most MSR research are still under R&D
  - MSR motor reduces drive cycle loss by about 24% in a combined drive cycle
  - Proposed MSRS concept uses fewer solid state switches and does not have a battery short circuit failure mode
  - MSRS achieves significant loss reduction over a fixed winding motor
- Future Work:
  - Drive cycle loss analysis and components fabrication/evaluation (FY15)
  - Build/test benchtop prototype (FY16) and final prototype (FY17)
  - Commercialization plan: In-depth discussions will be held with automotive OEMs to maintain awareness of the advancements made on ORNL's motor project