Electric Motor Research

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Oak Ridge National Laboratory

Industry Engagement Meeting
VTO EDT Program

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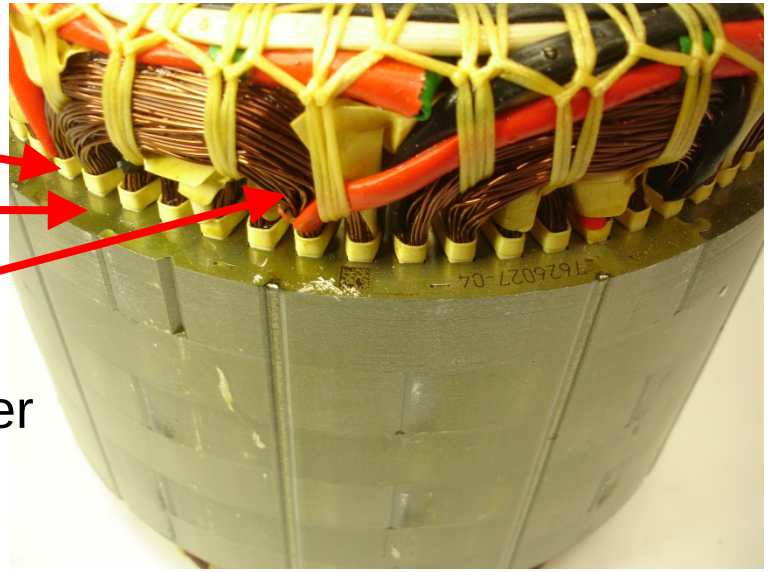
Overview

- Comparison of motor types
- Roles and trends of electric machines
- Motor design considerations for non-rare earth or reduced rare earth PMs
- Performance improvements - Reconfigurable windings
- Materials
  - Slot liner (improve or eliminate)
  - High efficiency steel
  - Winding
    - High purity copper and unconventional conductors
- Motor optimization with HPC/Supercomputer



Comparison of Motor Types

Must consider system impacts

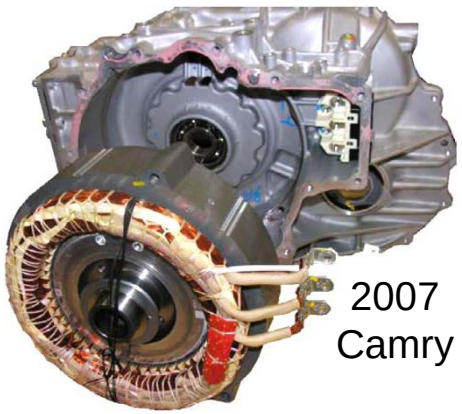
	RE Permanent Magnet Motor	Non - RE Permanent Magnet Motor	Synchronous Reluctance	Induction Motor	Switched Reluctance Motor
Cost ($/kW)	$$$	$ - $$	$	$$	$
Power density (kW/L)	High	Moderate - High	Moderate	Moderate	Moderate
Specific power (kW/kg)	High	Moderate - High	Moderate	Moderate	Moderate
Efficiency (%)	High	Moderate - High	Good	Good	Good
Noise and vibration	Good	Good	Good	Good	Challenging
Manufacturability	Mature/Costly	Assembly Mature Magnet not mature Net shape /Costly	Simple	Not Mature/Costly	Simple
Potential for technical improvement for automotive applications	Moderate	Significant	Significant	Significant (Rotor)	Significant

Not one particular machine is the solution

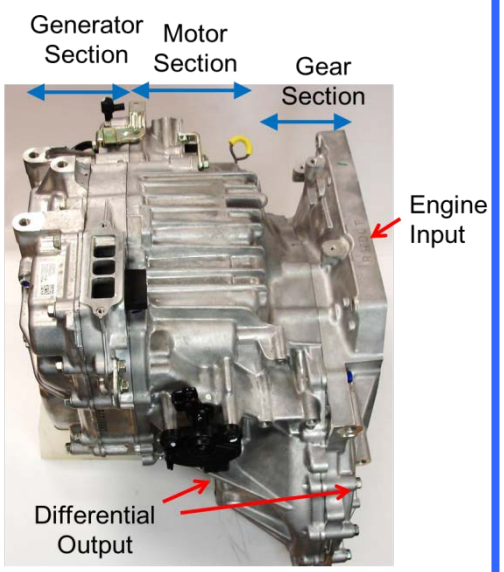
Induction
P4 – no disconnect clutch
Squeeze casting Al

Various Roles of Electric Machines

Full Hybrid FWD

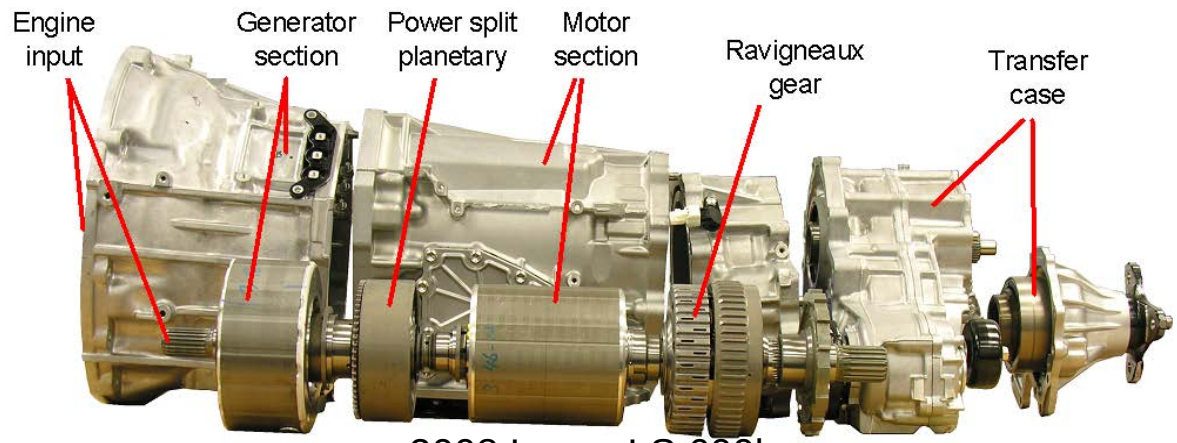


2007 Camry



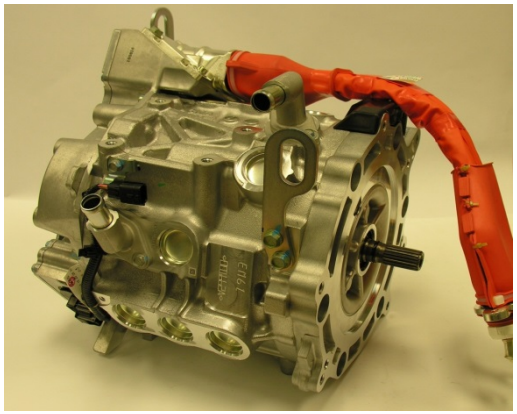
2014 Accord

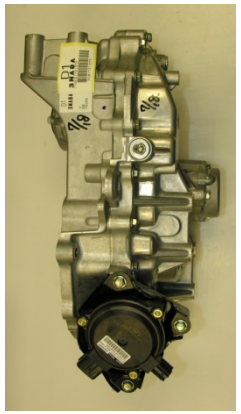
Full Hybrid RWD/AWD



2008 Lexus LS 600h

Full EV



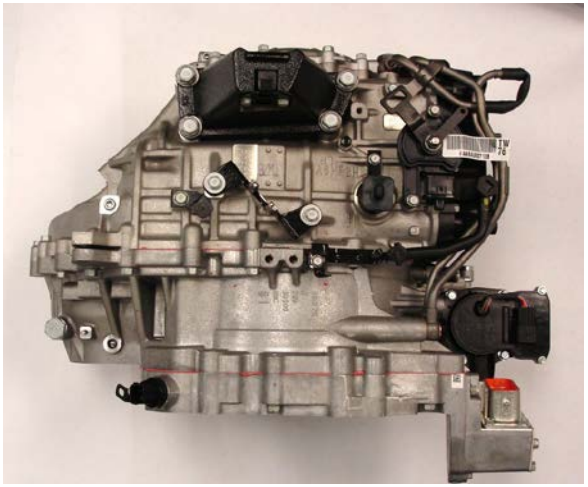


2012 Nissan LEAF

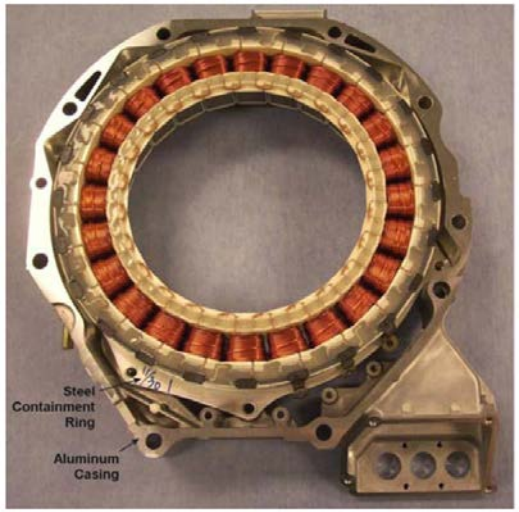
Various Roles of Electric Machines

- Examples of mild hybrids
  - Drive motor often replaces torque converter in conventional automatic transmission, e.g., Hyundai Sonata attached to front end of 6 speed automatic transmission
  - Start-stop requires heavy-duty starter

Mild Hybrid FWD

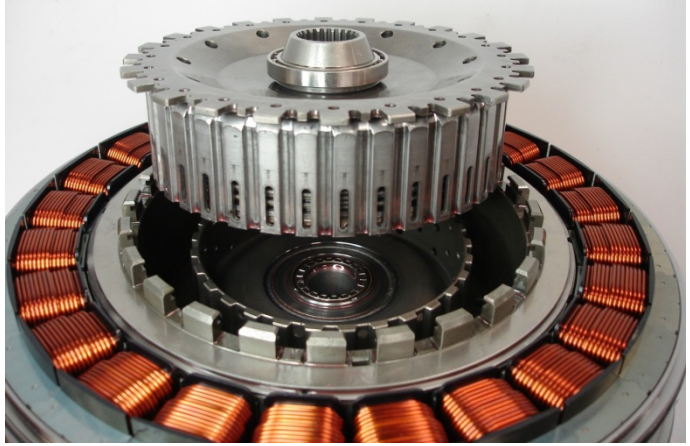


2012 Sonata Transmission



2007 Accord

Clutch integrated into rotor



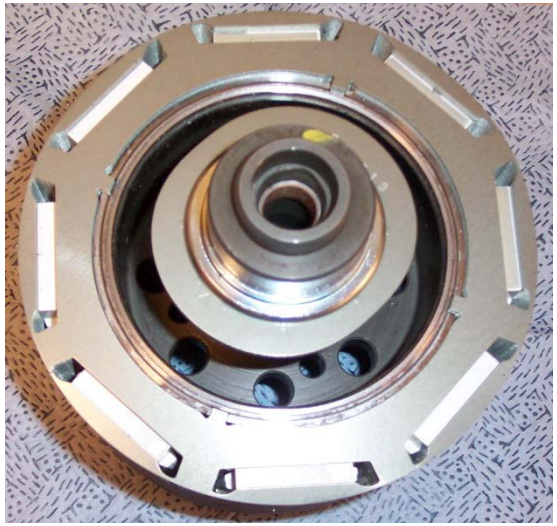
2012 Sonata Motor

2012 Sonata Starter-Generator

Trends of Toyota Prius Machine Designs

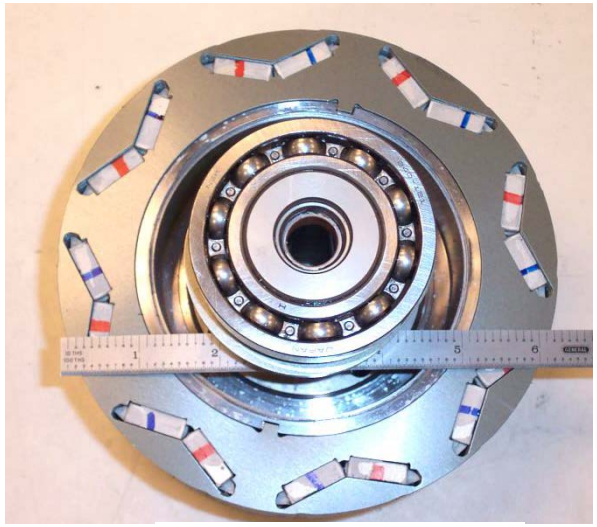
2002 Prius - 3.5” stack

33 kW, 274VDC, 6000 RPM



2004 Prius - 3.3” stack

50kW, 500VDC, 6000 RPM



2010 Prius - 2” stack

60kW, 650VDC, 13000 RPM

’02,’04, and ’10 stator laminations have very similar OD/ID with 48 slots

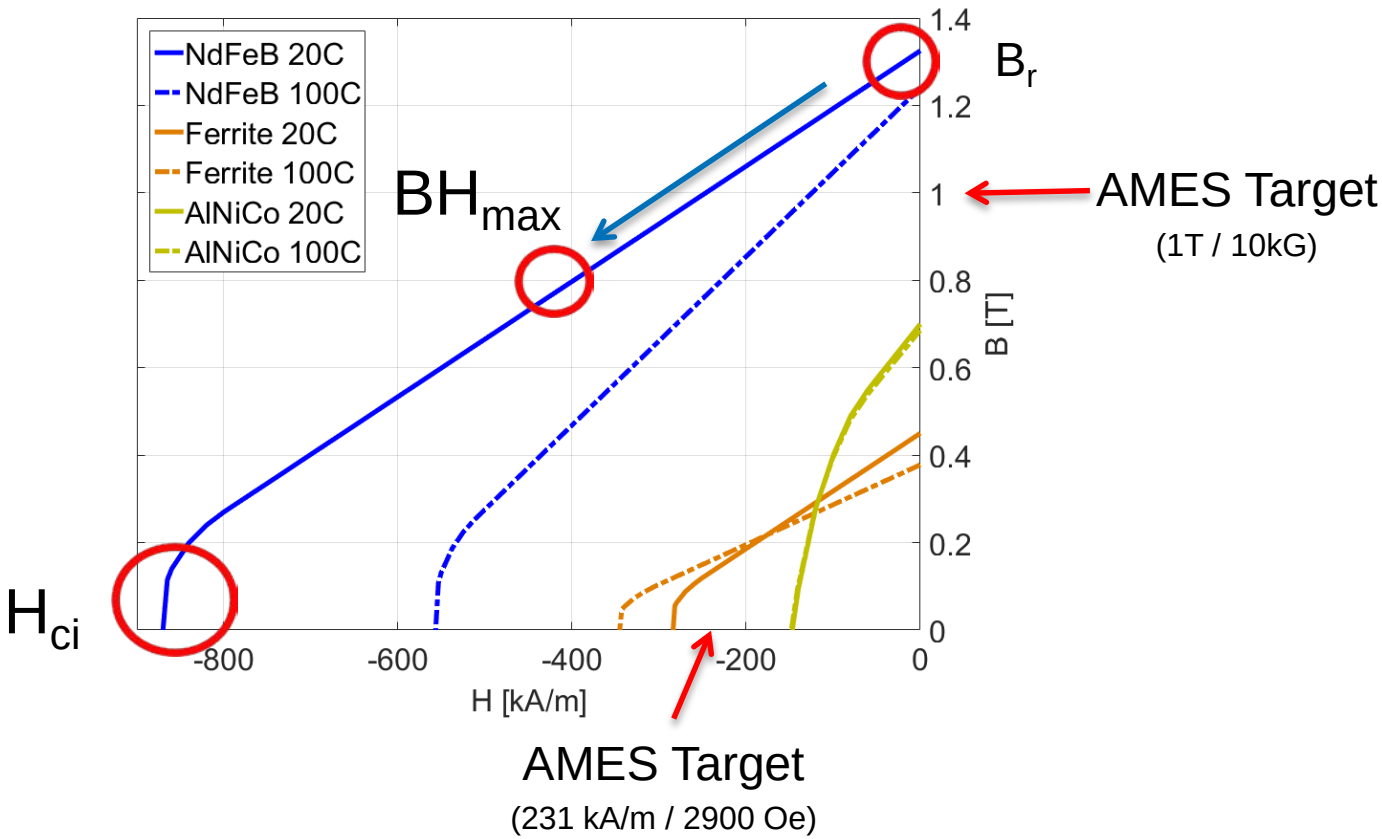
Note: speed reducer required for ‘10 speed level

Increase of voltage, speed, and design quality yielded significant power density (kW/L) and specific power (kW/kg) improvements.

Key Magnet Properties

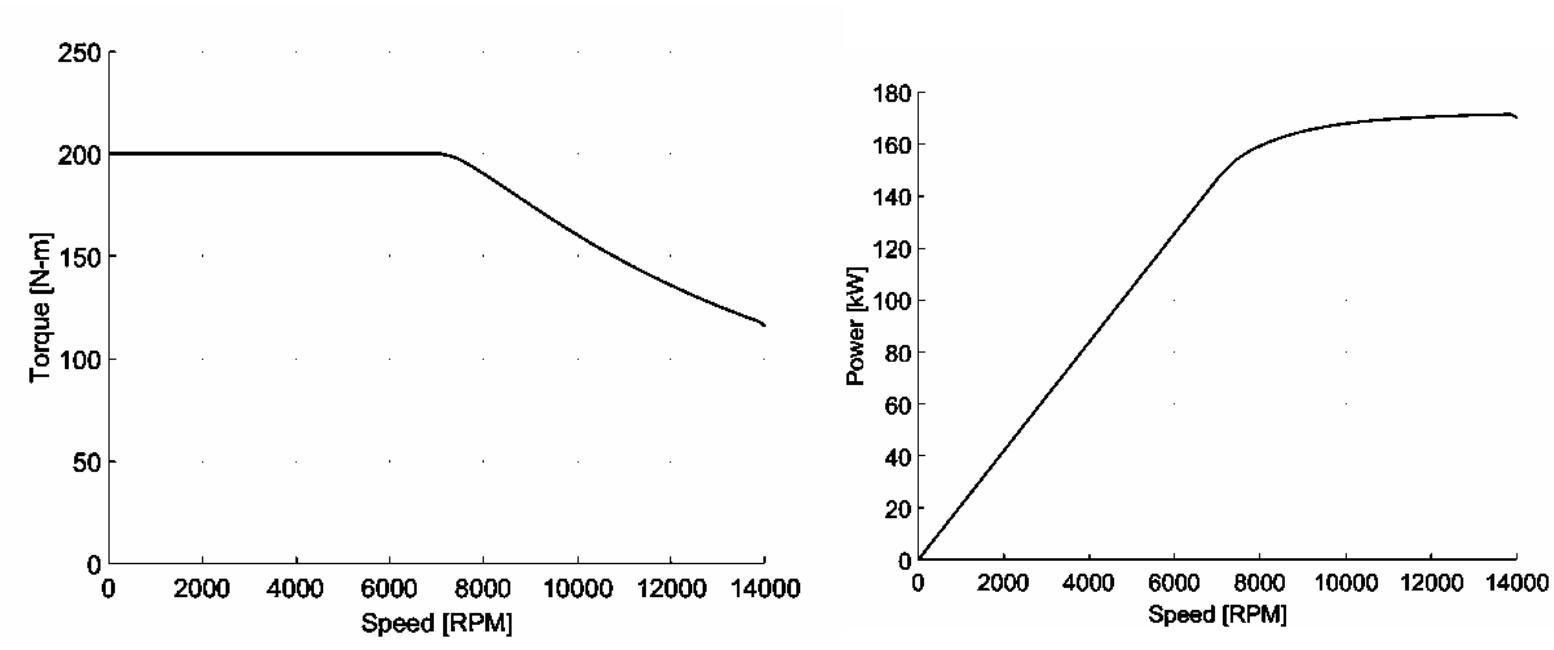
- B_r - Remanent flux density – Amount of flux density with no opposing field applied
- H_{ci} – Intrinsic coercivity – Relates to how readily a magnet is demagnetized
- BH_{max} – Maximum Energy Product –Representative of overall magnet strength

Comparison of various magnet B-H properties



Motor Design With Limited Magnet Performance

- If torque requirements are most important, high H_{ci} is priority
- If power requirements are most important, high B_r is priority
- Must consider magnet conductivity - Lower resistivity increases eddy current heating, which can lead to demagnetization

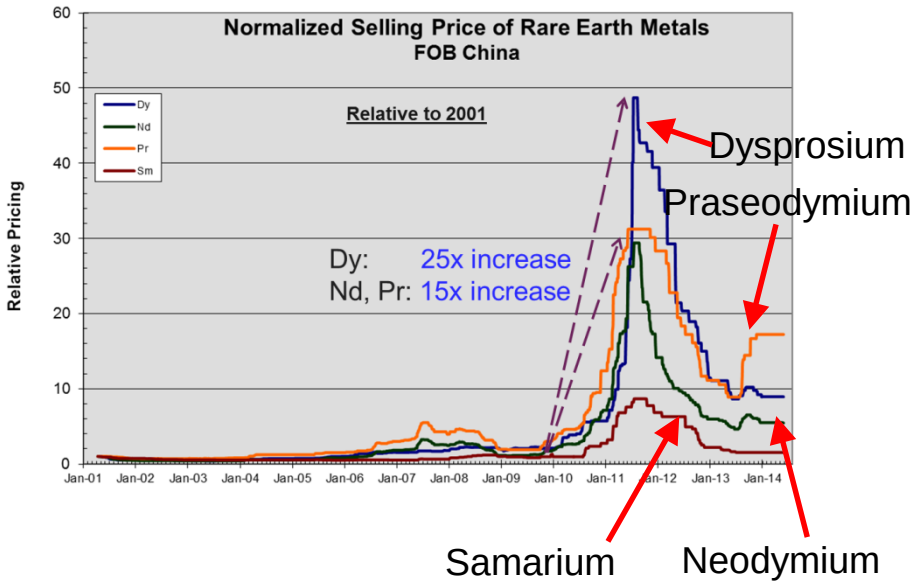


Initial torque and speed calculations using anticipated AMES Alnico magnet characteristics.

Magnet Cost

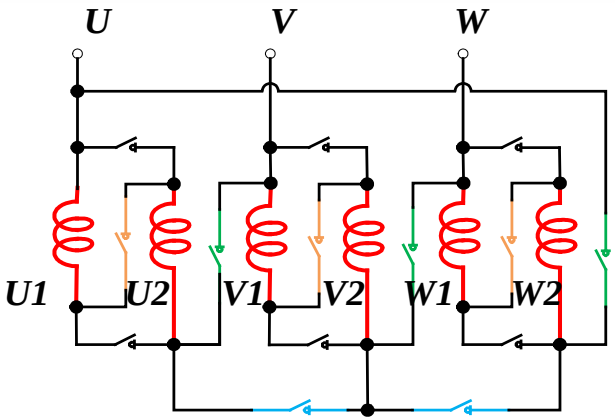
- Cost greatly impacted by magnet processing steps (grinding, etc.)
  - Researching processing methods
  - Ways to achieve net-shape magnets, design motors that aren't susceptible to wide range of tolerances
- Reduced or non-heavy rare earth: still Neo
  - Honda's non-heavy rare earth
  - Grain boundary diffusion

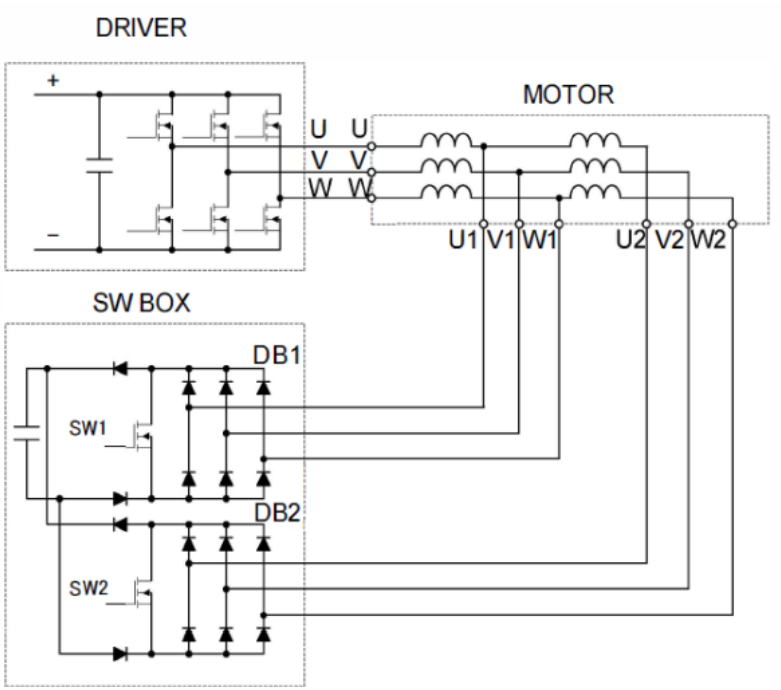
Source:
Steve Constantinides
Arnold Magnetics

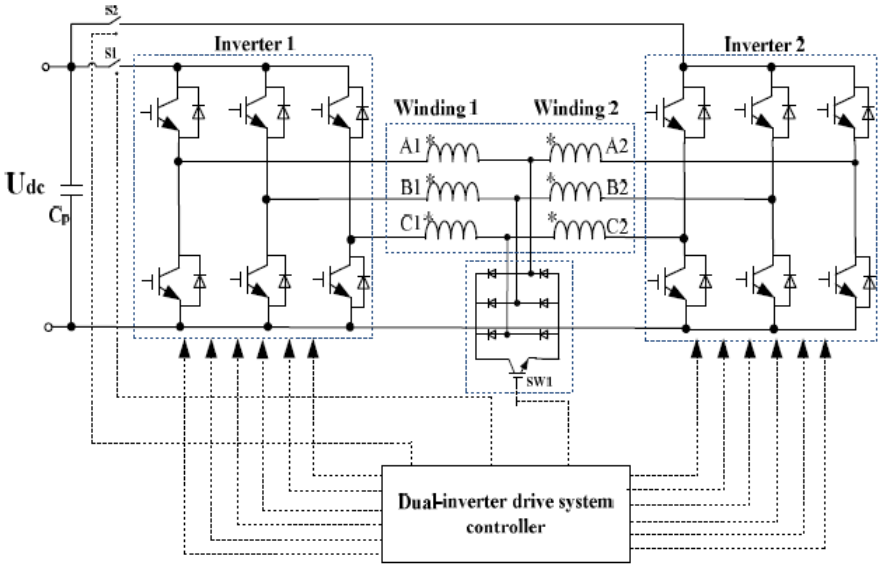


Performance Improvements

- Examples of reconfigurable winding approaches
- Approaches range from slow to fast switching requirements – Low device conduction losses particularly important for slow switching
- Switches desirably located close to motor to reduce cost, complexity, etc.

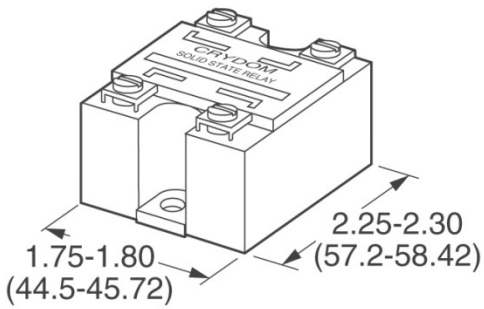






Switch Selection for Reconfigurable Windings

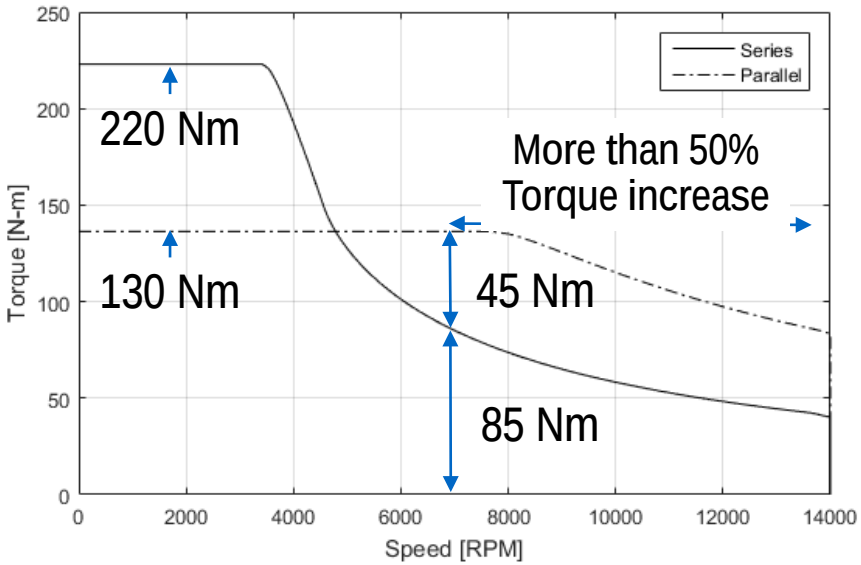
- Although IGBTs and MOSFETs can be considered,their high cost is a limiting factor.
- Further, two IGBTs must be connected in anti-series mode to provide reverse-blocking capability, adding up the conduction loss.
- IGBTs with reverse-blocking capability could be used; however, the forward voltage drop of a reverse-blocking IGBT is higher than that of a normal IGBT, and their market availability is limited at this time.
- Off-the-shelf solid-state switches are available, with costs as much as ~$100 for a switch with 660V/120A rms ratings (showing right), and its footprint is 1.8”X 2.3”
- Selected anti-parallel thyristors modules with similar rating (1200V/135A rms) as the solid-state AC switches due to low cost and smaller footprint(1.1”X 1.6”)
- Thyristors cost $24.87/each and can go further down to about $15 each (Qty > 1500), extra PCB and gate drive circuits are needed



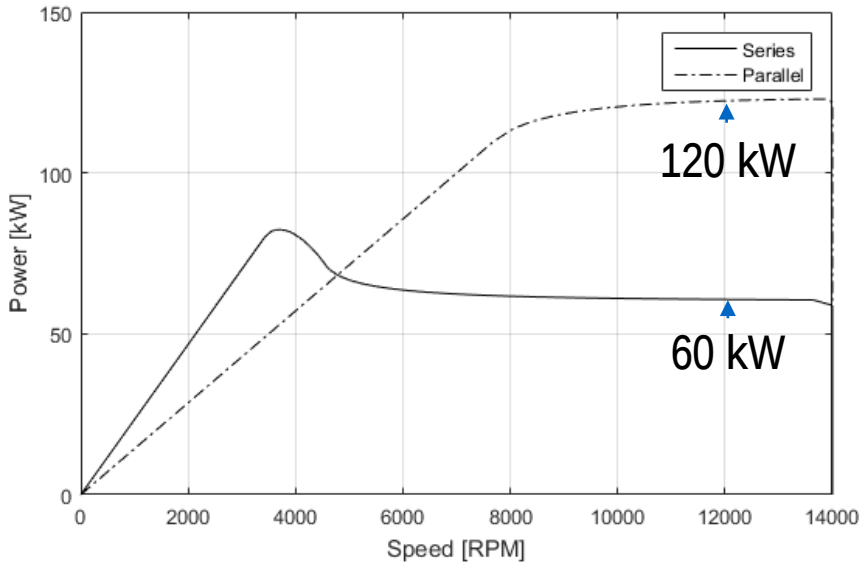
- High costs
  - IGBT
  - MOSFET
  - AC contactor
- Large size
  - AC contactor

Performance Improvements

- Reconfigurable winding example study
  - Example has the same size as 2013 Prius
  - Same peak inverter currents in both serial and parallel modes
  - Two times peak power (120 kW) is produced when in parallel mode
  - Peak efficiency region shifts as well



Torque vs. speed characteristics

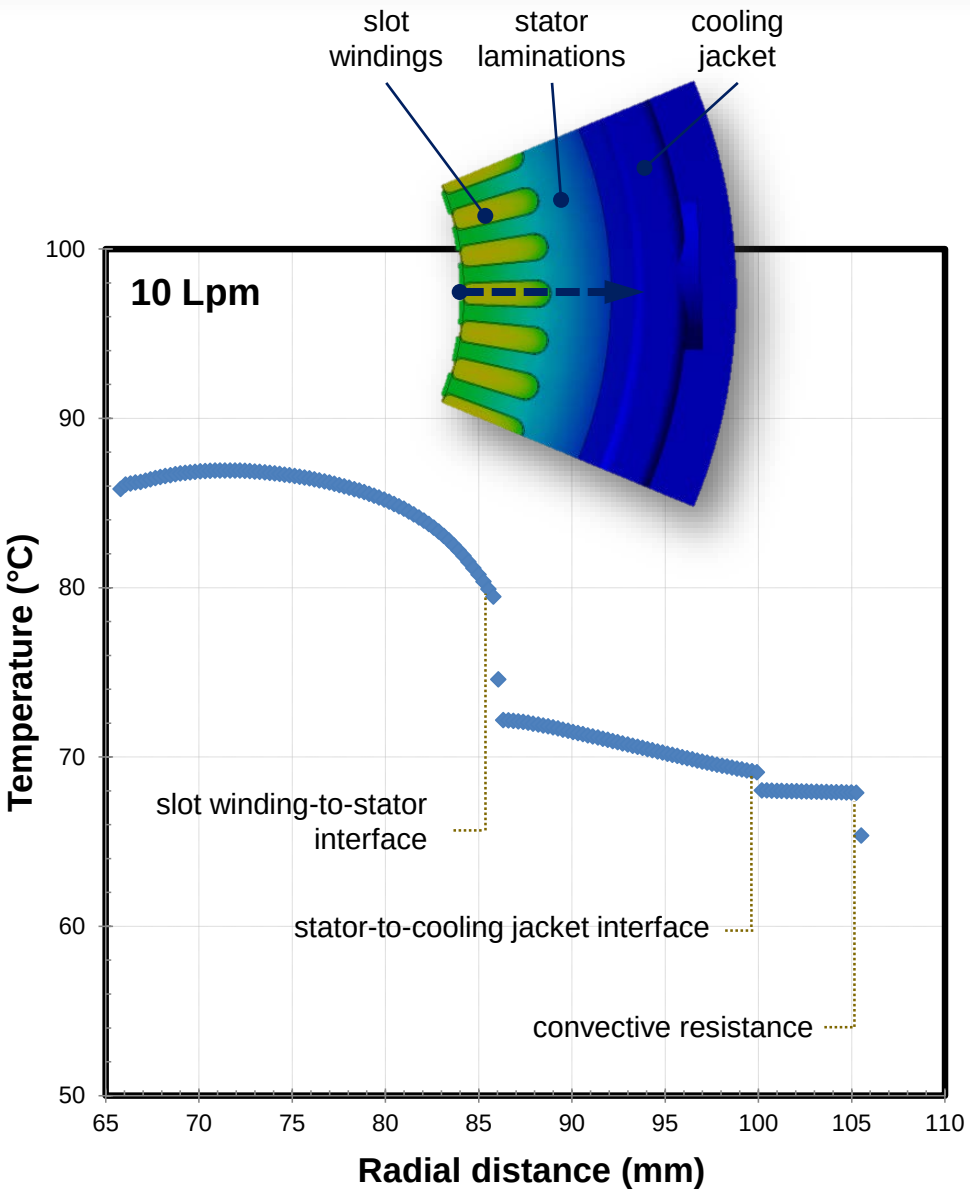


Power vs. speed characteristics

Stator Temperature Profile

NREL Thermal Analysis of LEAF Motor:
Gilbert Moreno, Kevin Bennion, et. al.

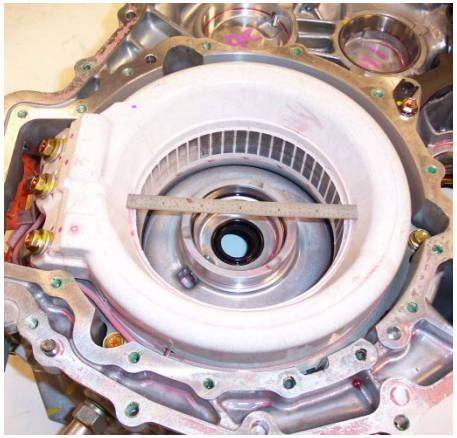
- Used the model to create a temperature profile from the inner stator surface to the coolant channel
- Demonstrated that ~98% of the temperature drop occurs through the passive stack
- Identified the slot winding-to-stator interfaces as the single largest thermal resistance (~33% of the total temperature drop)

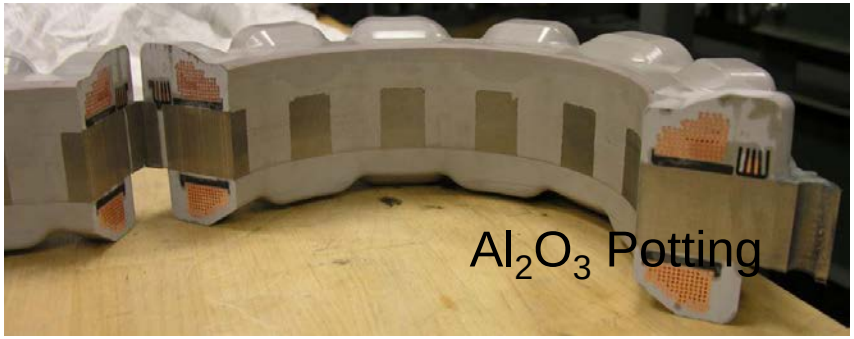


Slot liner replacement

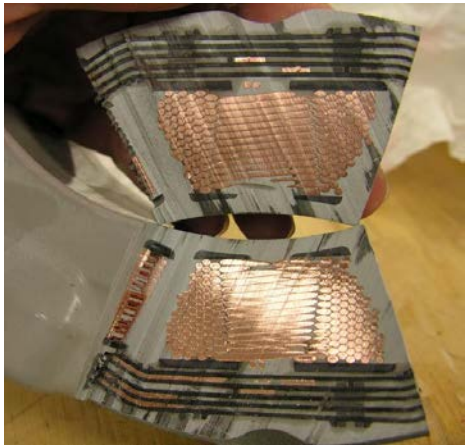
- Potting compounds can reduce vibration, add thermal mass, facilitate new manufacturing techniques, and reduce thermal resistance to cooling medium.
- Not easily implemented with some winding approaches (e.g. stranded mush windings)
- Electrostatic deposition widely used on small motors, for large motors, obtaining uniform deposition thickness is challenging.

2003 Prius





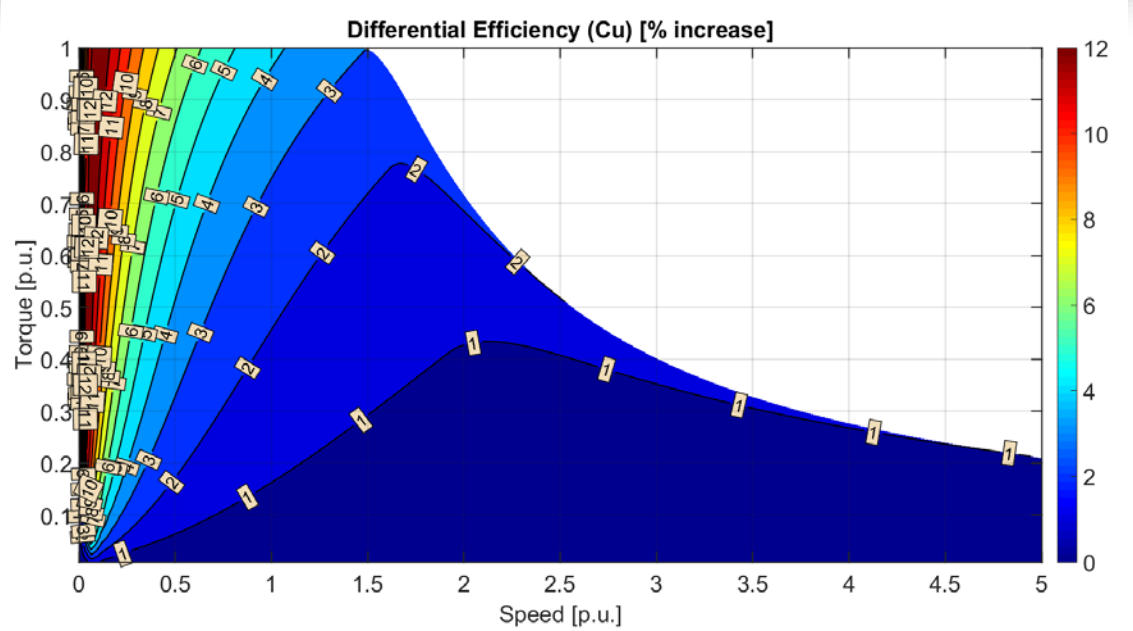
2013 Prius

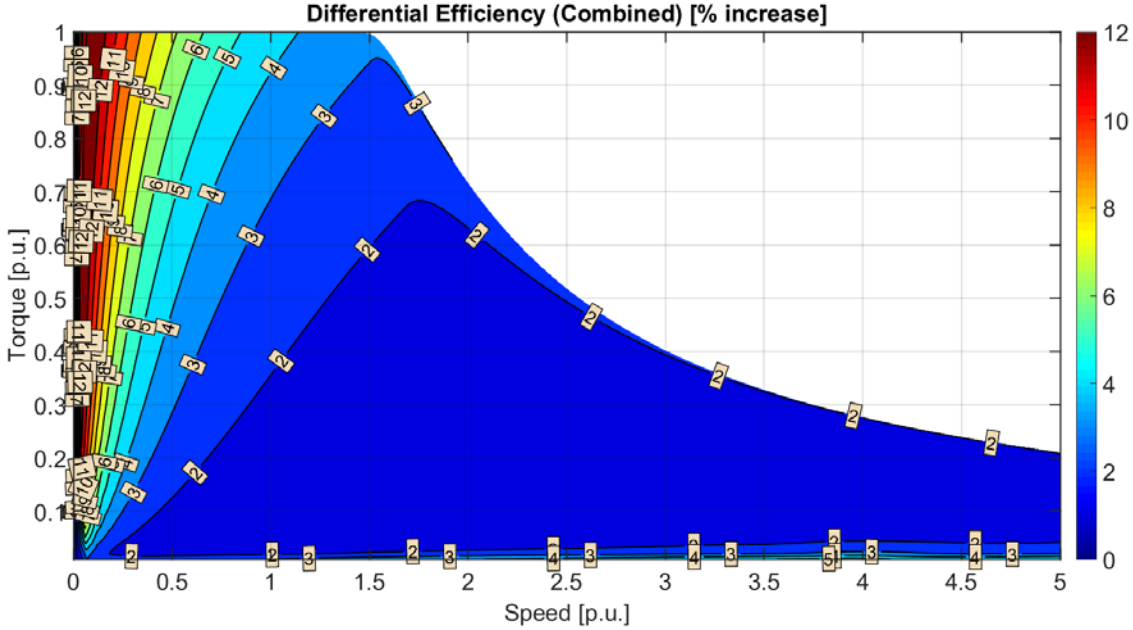


Materials

- Conductor improvement
  - Bar windings
  - High purity copper
  - 30 to 50% increase in conductivity
- High efficiency steel
  - 6.5% Si Steel
  - Other possibilities
  - Up to 40% efficiency improvement

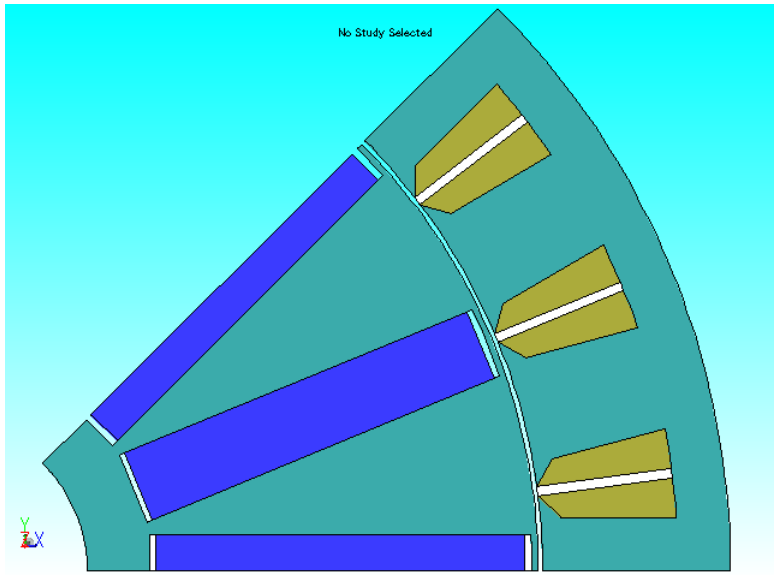
Prototype rolled samples of 6.5% Si Steel

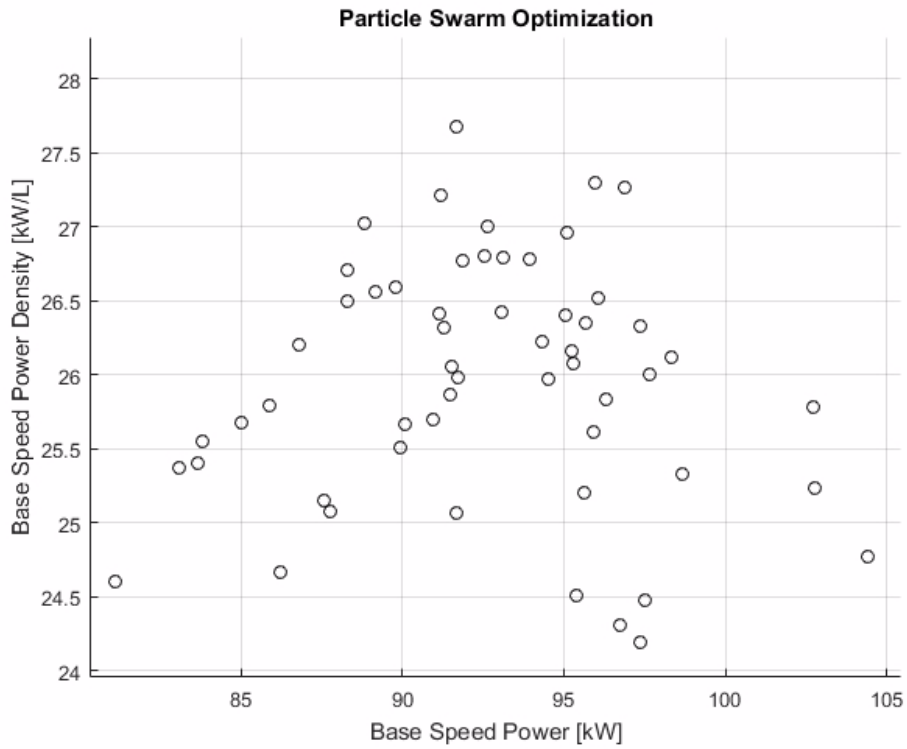




Motor Design With HPC/Supercomputer

- Optimization of motor lamination, magnet, winding properties, etc. with respect to
  - Electromagnetic performance (power, torque, and efficiency)
  - Mechanical stress
  - Heat generation/cooling performance
  - Acoustic noise





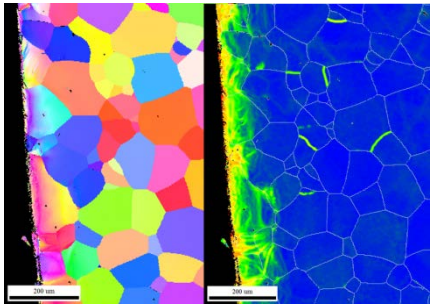
Animation of particle swarm optimization process

Motor Design Tool for HPC/Supercomputer

Development of Advanced FEA Modeling Method With Detailed Magnetization/Loss

Stress Distribution

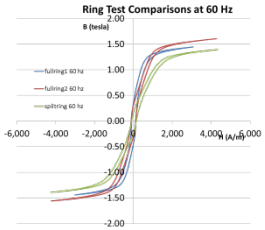
- Function of cutting/stamping method
- Influenced by mechanical fastening
- Impacted by rotation and other forces

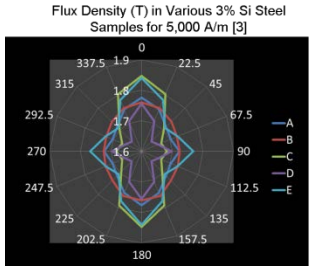


Advanced FEA Modeling Tool

Bulk Characterization

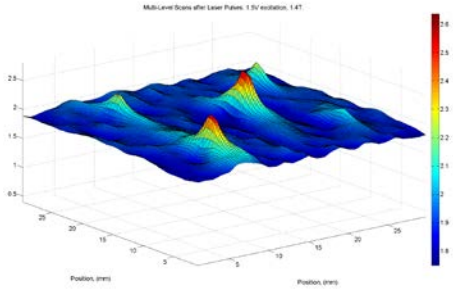
- Traditional Epstein and ring specimen testing at various temperatures
- Custom analysis of rotational losses, anisotropic magnetization/loss, PWM, etc.





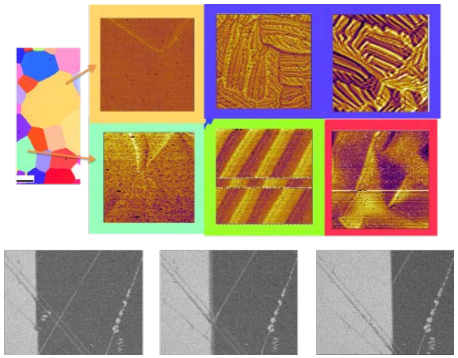
Localized Magnetic Properties

- Function of stress distribution
- Magnetization and loss characteristics are not homogeneous



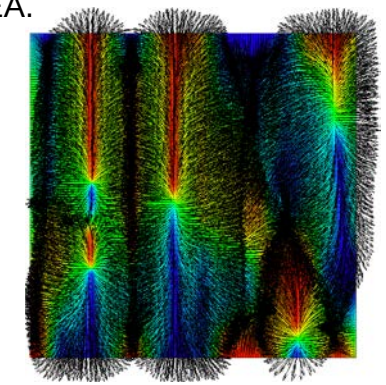
Empirical Magnetic Domain Analysis

- Traditional Epstein and ring specimen testing
- Impacts of stress, pinning, etc. upon domain wall movement, and ultimately magnetization/loss properties.



Theoretical Magnetic Domain Analysis

- Fundamental theory to confirm and supplement empirical findings.
- Indirect link to FEA - too computationally intensive for direct use in FEA.



Questions?

Power Requirements in HEVs/EVs - backup

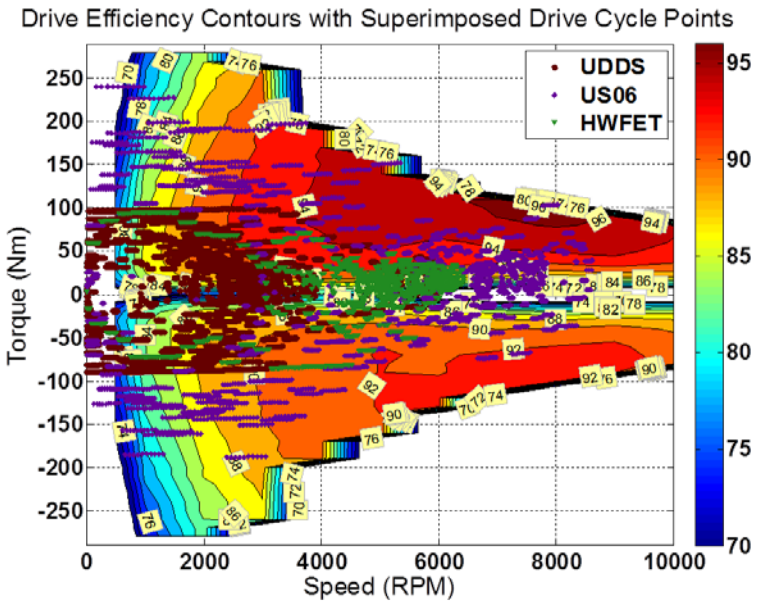
Example of Peak Power Scenarios

	LEAF		Mid-Sized Sedan		Mid-Sized SUV	
	Curb Weight (3300 lbs)	Gross Weight (4200 lbs)	Curb Weight (3300 lbs)	Gross Weight (4600 lbs)	Curb Weight (3800 lbs)	Gross Weight (5500 lbs)
70-80 mph in 5 seconds (0% grade)	70 kW	85 kW	65 kW	90 kW	85 kW	110 kW
70-80 mph in 5 seconds (3% grade)	85 kW	105 kW	80 kW	110 kW	100 kW	135 kW
60-80 mph in 5 seconds (0% grade)	110 kW	130 kW	105 kW	150 kW	135 kW	185 kW
60-80 mph in 5 seconds (3% grade)	135 kW	160 kW	130 kW	170 kW	150 kW	220 kW

Example of Continuous Power Scenarios

	LEAF		Mid-Sized Sedan		SUV	
Continuous Condition	Curb Weight (3300 lbs)	Gross Weight (4200 lbs)	Curb Weight (3300 lbs)	Gross Weight (4600 lbs)	Curb Weight (3800 lbs)	Gross Weight (5500 lbs)
33% grade at 35mph	80 kW	100 kW	76 kW	108 kW	90 kW	130 kW
5% grade at 80 mph	50 kW	60 kW	45 kW	60 kW	61 kW	80 kW
10% grade at 80 mph	80 kW	94 kW	71 kW	95 kW	91 kW	120 kW

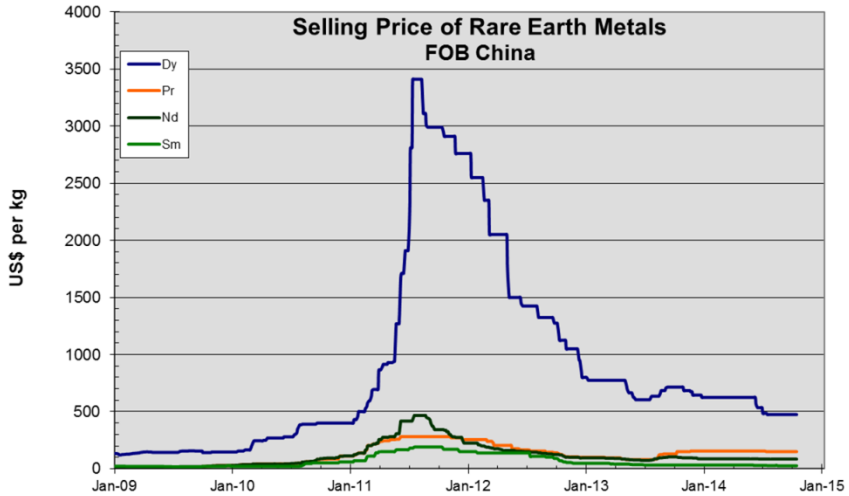
LEAF

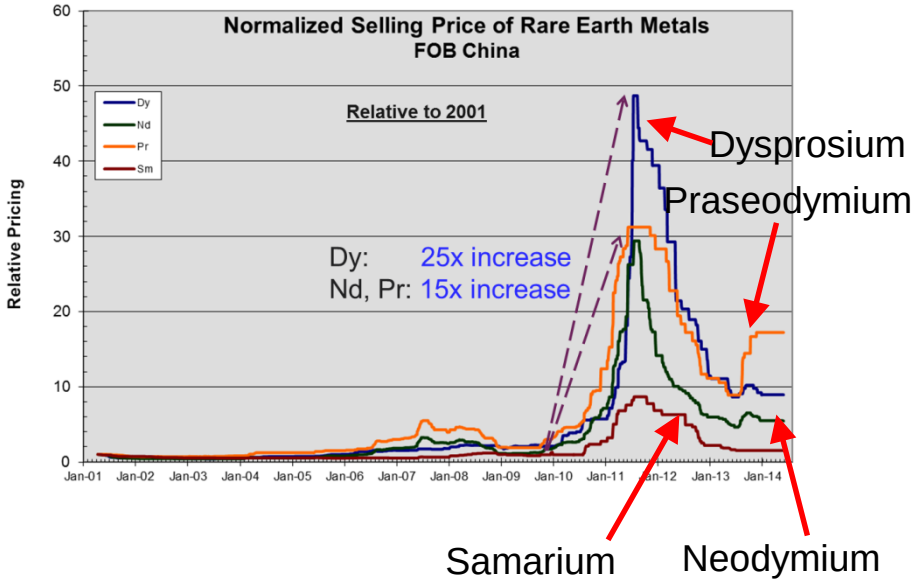


The electric motor is an excellent match for driving requirements due to the high torque capability at low speeds, and constant power range at elevated speeds.

Rare-Earth Material Costs - backup

- RE elements in PMs contribute up to 78% of the total DOE EDT 2020 electric motor cost target
  - Currently 30-50% of actual cost
- Uncertainty in RE material availability and the likelihood that metallurgical separation processes for heavy RE mean that pricing will remain high over the near term and longer





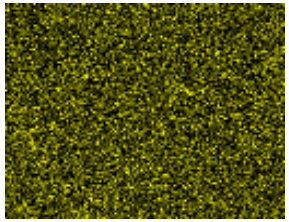
Source: Steve Constantinides, Arnold Magnetics

‘04 Prius Magnet Composition Mapping - backup

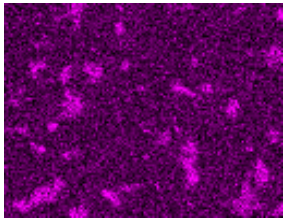
- Recent rare earth price fluctuations facilitated new approaches to reduce cost
  - Dysprosium grain boundary diffusion
  - Segmented magnets
  - Electromagnetic design

Element	Range in Various HEV/EV Magnets (% by mass)	Cost of Bulk Material ($/kg)
Fe	31-48%	0.13
Nd	11-24%	85
Dy	3.4-6.2%	475
Pr	0.64-4.31%	150
Cu	0.8-3%	6.8

Cu



Nd



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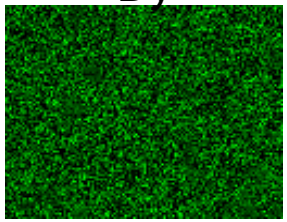

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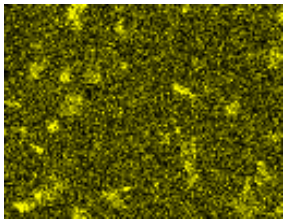
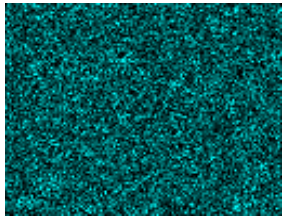


Gd



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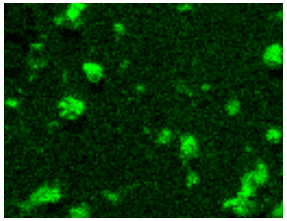

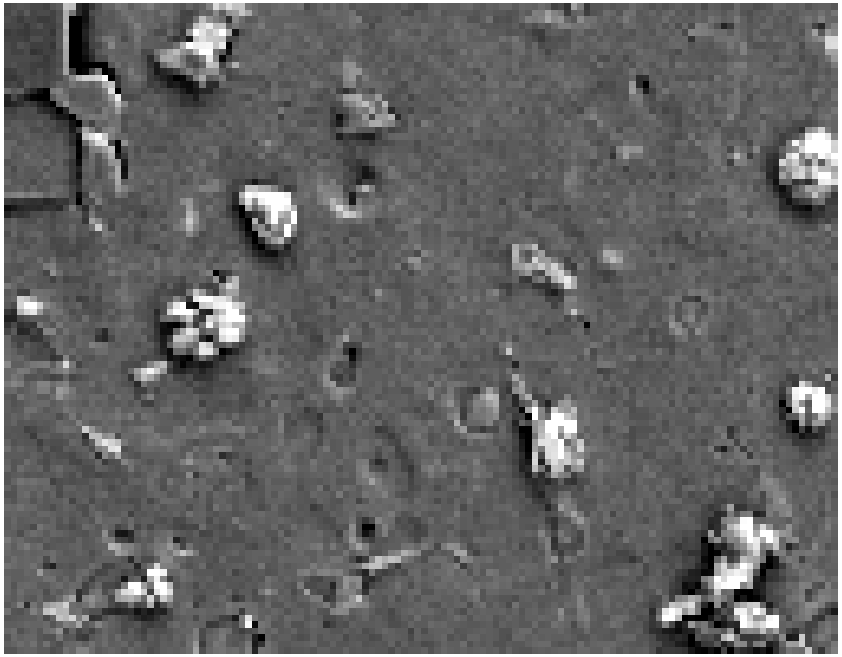

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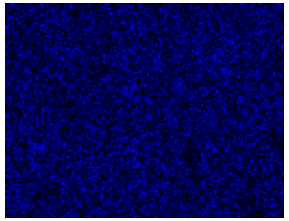

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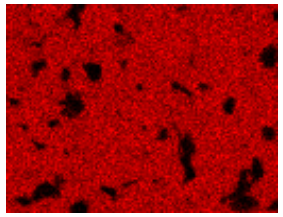

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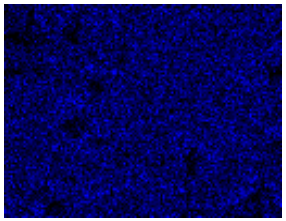
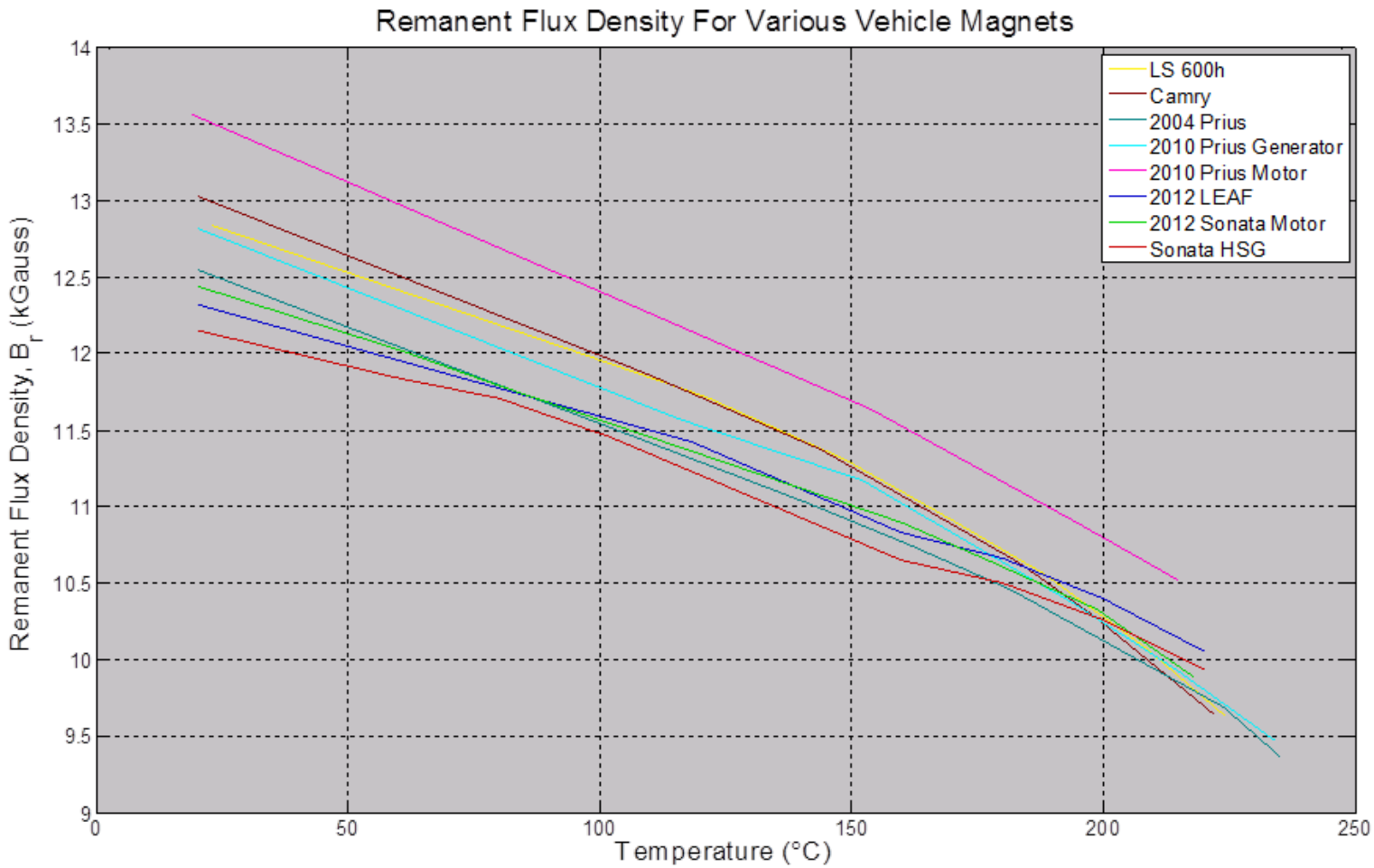
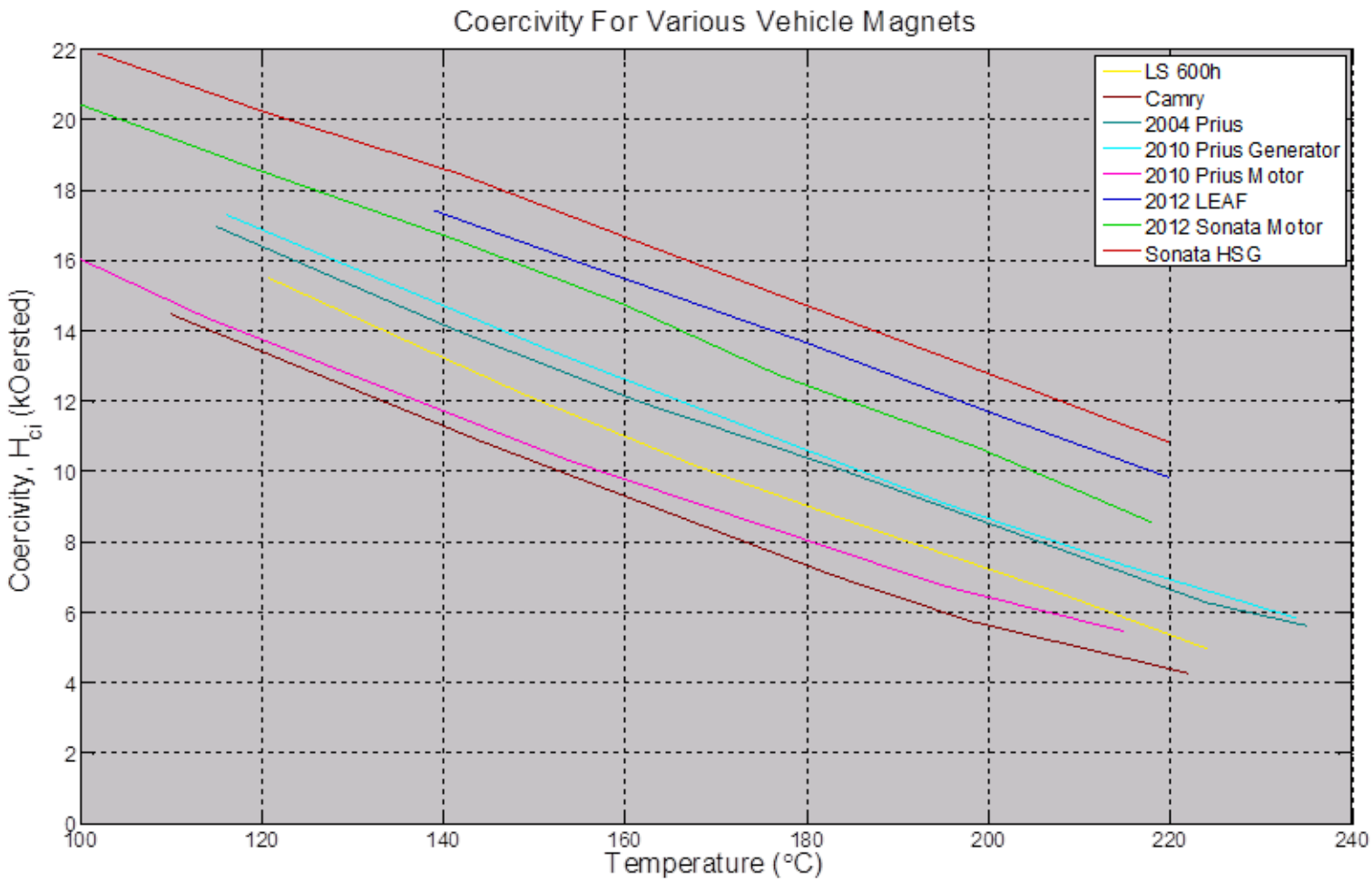


Magnets – BH Properties



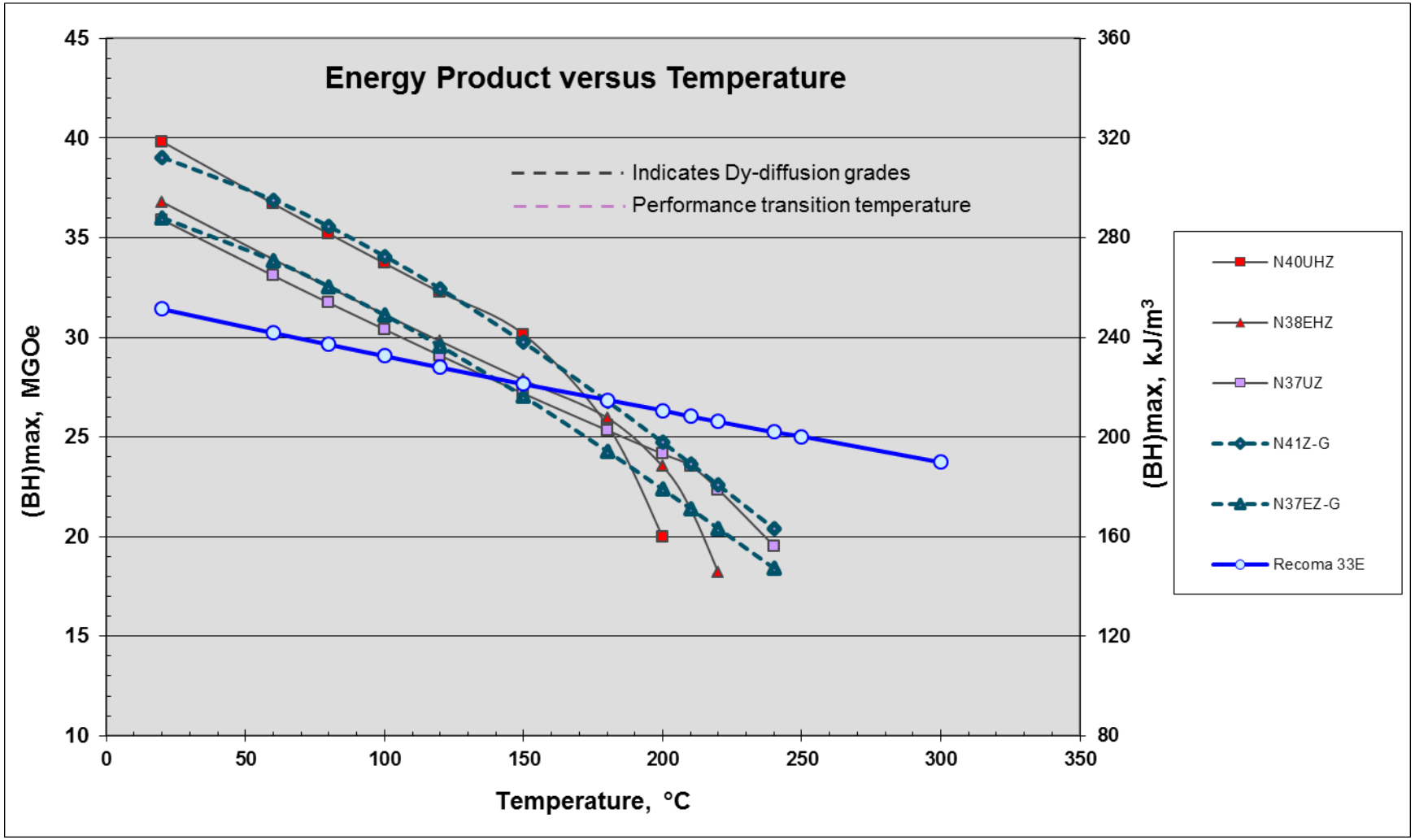
Modeling magnet temperature is crucial for accurate performance simulations.

Magnets – BH Properties



Modeling magnet temperature is crucial for ensuring no demagnetization.

Magnet Performance Versus Temperature – backup



Source: Steve Constantinides, Arnold Magnetics

Magnet Cost Comparison

		Relative Price					
		x-China Manufacture			China Manufacture		
Material	**BHmax** typ 20 °C, MGOe	**Relative to ferrite=1**	**per MGOe at 20 °C**	**per MGOe at 150 °C**	**Relative to ferrite=1**	**per MGOe at 20 °C**	**per MGOe at 150 °C**
Ferrite (flexible)	1.5	1	0.65	1.20	1	0.65	1.20
Ferrite (sintered)	3.5	4	1.30	2.35	2	0.70	1.25
La-Co Ferrite (Sintered)	5.5	5	0.95	1.75	6	1.00	1.85
Neo (injection molded)	5.5	25	4.50	6.10	19	3.50	4.75
Alnico 5-7	5	35	6.95	7.15	22	4.35	4.45
Sm_2Co_{17}	32	36	1.10	1.25	35	1.10	1.20
Alnico 9	9.5	36	3.85	4.05	18	1.90	2.00
$SmCo_5$	22	40	1.80	2.05	37	1.65	1.90
NdFeB (N40SH)	40	53	1.35	1.85	36	0.90	1.25
NdFeB (N33EH)	33	74	2.25	3.05	48	1.45	2.00

Sorted by

Material prices of 1-Jun-2014

Source: Steve Constantinides, Arnold Magnetics

Magnet Cost Comparison Sorted W.R.T. 150C

		Relative Price					
		x-China Manufacture			China Manufacture		
Material	**BHmax** typ 20 °C, MGOe	**Relative to ferrite=1**	**per MGOe at 20 °C**	**per MGOe at 150 °C**	**Relative to ferrite=1**	**per MGOe at 20 °C**	**per MGOe at 150 °C**
Ferrite (flexible)	1.5	1	0.65	1.20	1	0.65	1.20
Sm_2Co_{17}	32	36	1.10	1.25	35	1.10	1.20
La-Co Ferrite (Sintered)	5.5	5	0.95	1.75	6	1.00	1.85
NdFeB (N40SH)	40	53	1.35	1.85	36	0.90	1.25
$SmCo_5$	22	40	1.80	2.05	37	1.65	1.90
Ferrite (sintered)	3.5	4	1.30	2.35	2	0.70	1.25
NdFeB (N33EH)	33	74	2.25	3.05	48	1.45	2.00
Alnico 9	9.5	36	3.85	4.05	25	2.60	2.75
Neo (injection molded)	5.5	25	4.50	6.10	19	3.50	4.75
Alnico 5-7	5	35	6.95	7.15	22	4.35	4.45

Sorted by

Material prices of 1-Jun-2014

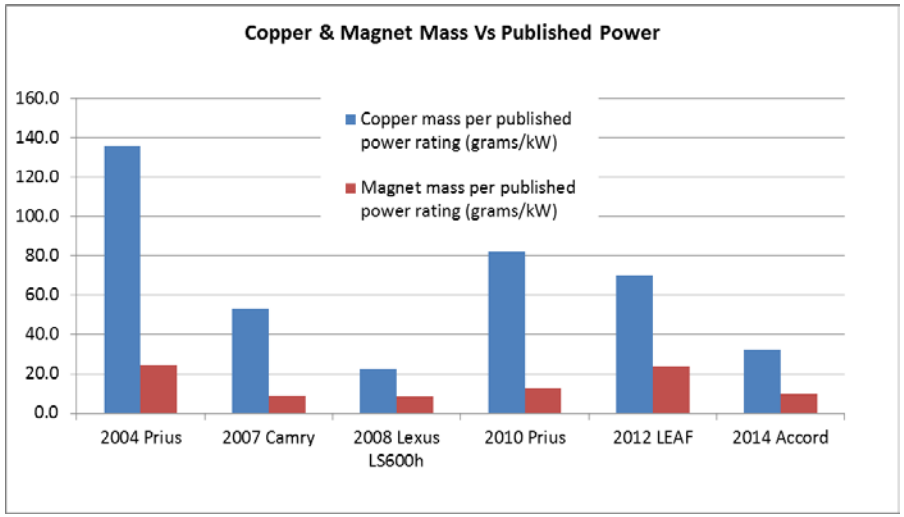
Source: Steve Constantinides, Arnold Magnetics

Comparison of Various Magnet Design Specifications - backup

Note the impact of roles on cost and sizing metrics

- E.g. Impact of 2010 Prius short stack/end turns on effective copper usage

Parameter	Accord G	Accord M	LEAF	2010 Prius	LS 600h	Camry	2004 Prius	Comments
Published Rating (kW)		124	80	60	160	105	50	
Magnets (neodymium iron boron [NdFeB])								
Magnet dimensions, mm	26.5x6.28x ~37.62	26.5x6.28x ~61.7	21.3x8.34x2.29 and 28.9x8.36x3.79	49.3×17.88× 7.16	66.4×18.7×3 .05	60.6×19.1×6 .6	83.1×18.9×6. 5	
Magnet volume, cm^3	6.26	10.27		6.31	3.78	7.63	10.2	
Magnet mass, grams	~47.2	77.50		48	28.1	58	77	
Total mass of magnets, kg	0.755	1.24	1.895	0.768	1.349	0.928	1.232	Entire magnet mass in rotor.
Magnet mass per published power rating (grams/kW)		10.0	23.69	12.8	8.43	8.84	24.64	
Copper mass per published power rating (grams/kW)			70.2	82.2	22.4	53	136	



Implementation Considerations
Switch Selection

- Semi-conductor solid-state relays and AC contactors are often used for re-configurable winding motor
- Semi-conductor solid-state relays are faster(< 1~2 ms turn on/off time) than the AC contactor(~10 ms), which are desirable
- Due to mechanical parts, AC contactors have limited operating cycles(million cycles)
- However the voltage drop of relays is higher (around 1~2 V vs <1V), so more heat is generated