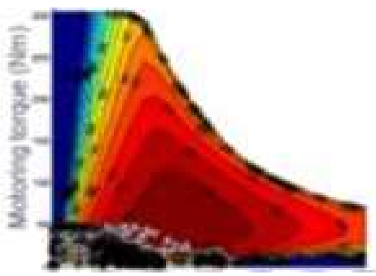
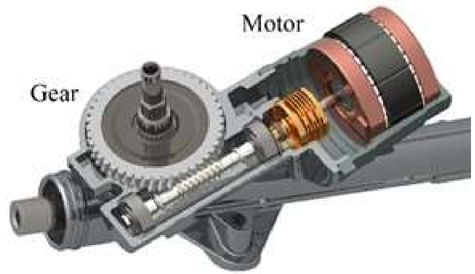
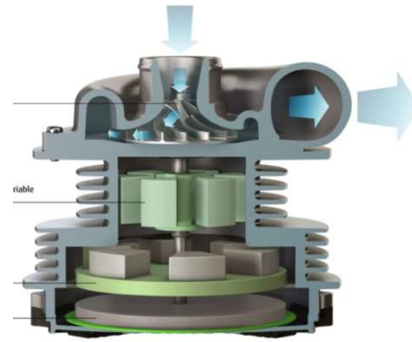


Efficiency optimization
Source: Burwell, et. al, Tokyo 2013



Electric power steering
Source: Nexteer



Electric supercharger
Source: Valeo

Hairpin winding
Source: Borg-Warner

Automotive motors: Recent accomplishments and challenges ahead

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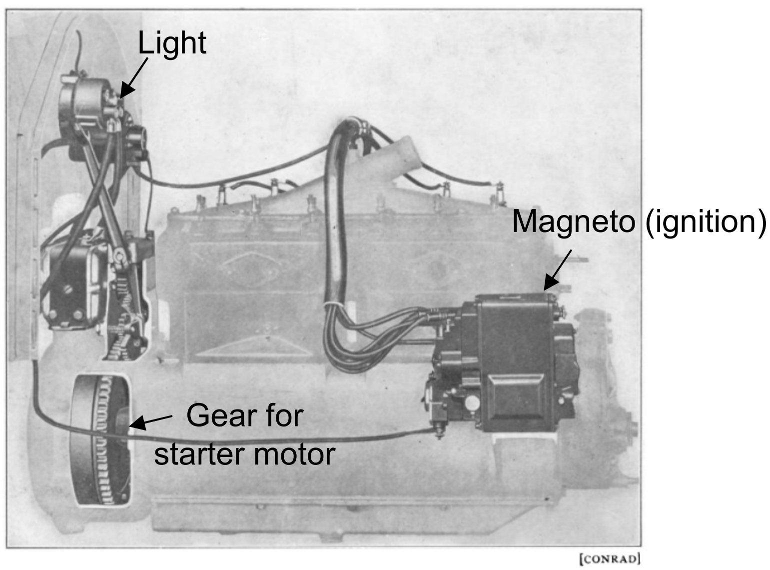
Introduction

- Hybrids and EVs get a lot of press – Well deserved, these are tremendous technical achievements

- There is however a much deeper groundswell of electrification throughout the automobile
  - Going to the origin of the automobile
  - Pushing technology forward



Source: Conrad, AIEE, 1913

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Automotive companies: At the forefront of motor technology?

- Example: Is integration of power electronics and motors cutting edge?

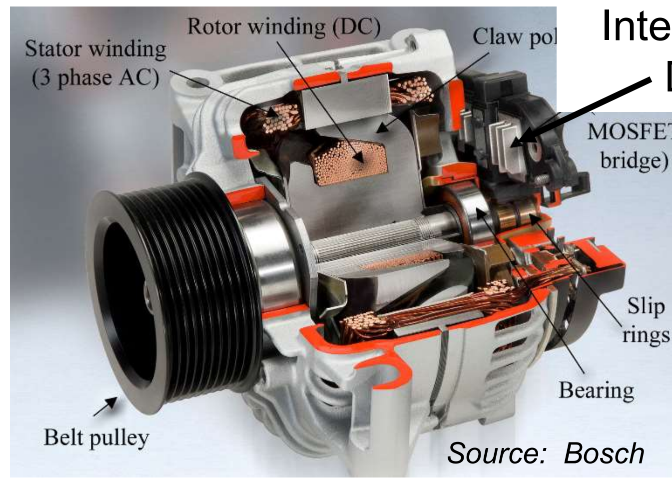
Enabling Technologies Thrust

Center for Power Electronics Systems /
U. of Wisconsin, 2016

Source: cpes.vtu.edu

Lundell motor

1950s



Source: Bosch

Integrated rectifier /
Diode bridge

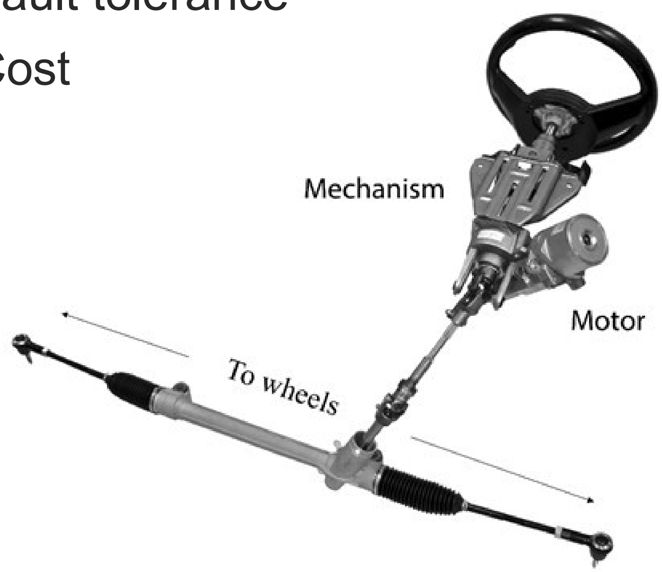
Source: intechopen.com

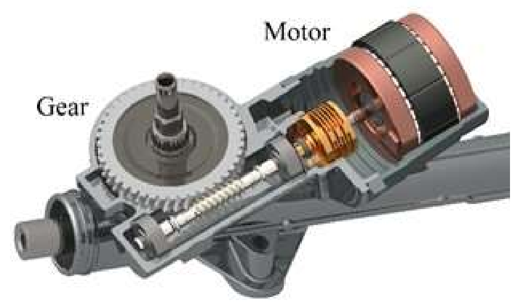
Presentation outline

- Power steering
- Accessory motors and concentrated windings
- High-speed motors
- Generators, starter-generators, and hybrid motors

Steering

- Best (recent) success story in automotive electrification
  - Electric power steering becoming standard
  - Provides power on demand: Significant fuel economy benefit (4%)
- Issues:
  - Torque ripple
  - Fault tolerance
  - Cost

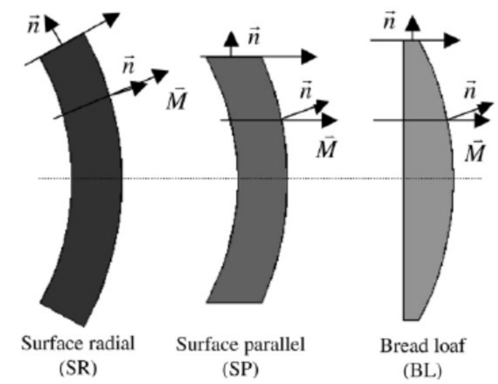




Source: Nexteer

Steering: Torque ripple

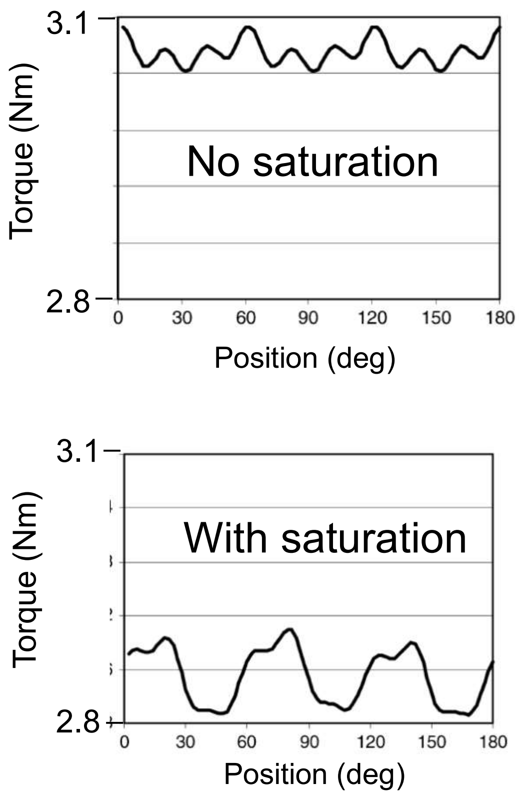
- Torque ripple felt by the driver on the steering wheel
  - Marketing issue (more than technical issue)
- Solution involved *all* aspects of motor and controller design and manufacturing:
  - Initial approach based on sinusoidal waveforms, current and flux
  - Motor:
    - Matching of magnet back-emf with current excitation (magnet shape, etc)
    - Magnet skewing, pole/slot design, etc

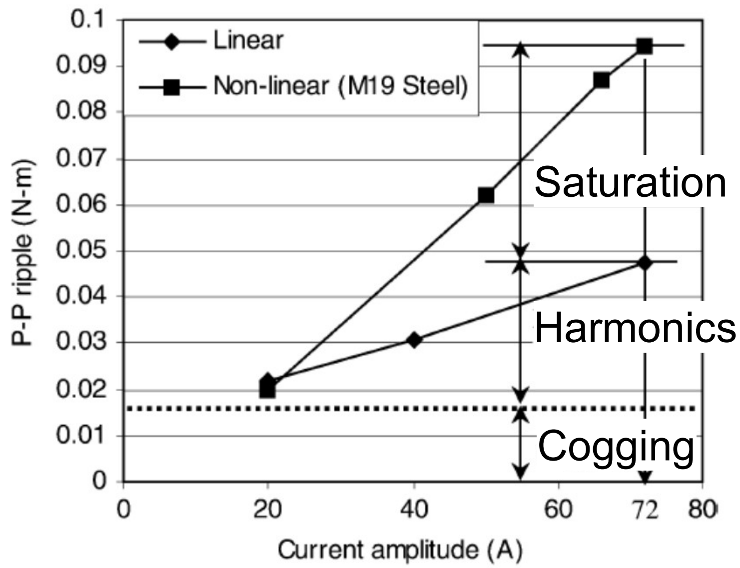


Source: Islam, et. al., IEEE T. IA, 2005

Torque ripple; Effect of saturation

- Saturation increases harmonic content
  - Can be evaluated with finite elements

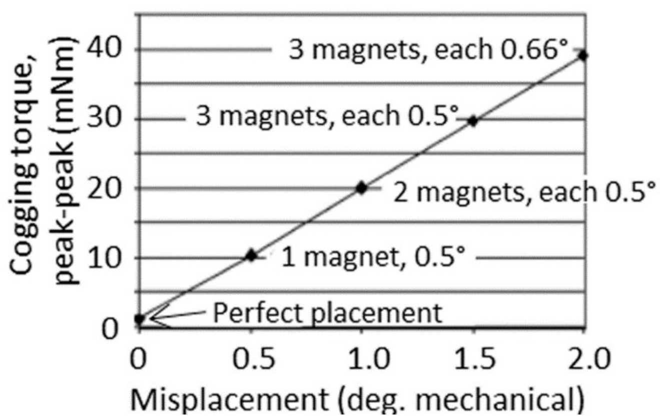




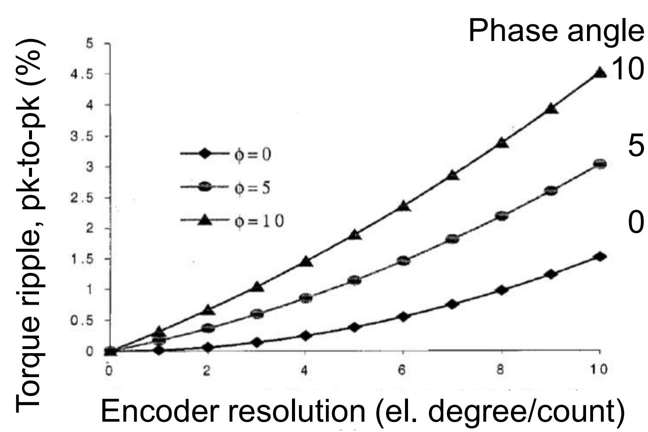
Source: Islam, et. al., IEEE T. IA, 2005

Torque ripple: Manufacturing issues

- Importance of Six Sigma methods to understand impact of build variations on performance
- Motor: Magnet misplacement, etc
- Controller:
  - Sensor positioning and accuracy
  - Switching frequency, delays



Source: Islam, et. al., IEEE T. IA, 2004



Source: Chen, et. al., IEEE T. IA, 2002

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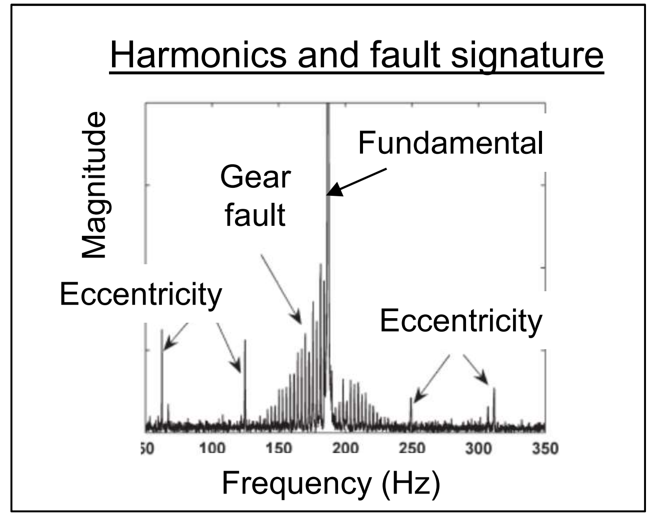
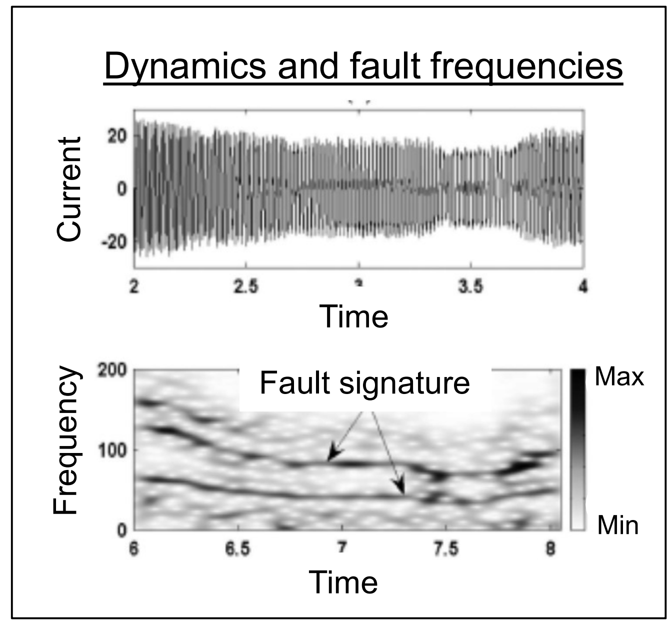
Steering: Fault tolerance

- Mechanical link to wheels kept, just in case
  - Last resort option
- Hardware solutions:
  - Minimize impact of fault (e.g., short circuit current)
  - Redundancy: Enough to be effective, not too much (FMEA)
- Software solutions:
  - Many faults have signatures in the current waveform
  - But, motor is always in dynamic situation
  - Alternatives to Fourier analysis needed
    - Wavelet, Wagnerville, windowed-Fourier…





Source: Rajagopalan, et. al., IEEE T. IA, 2006

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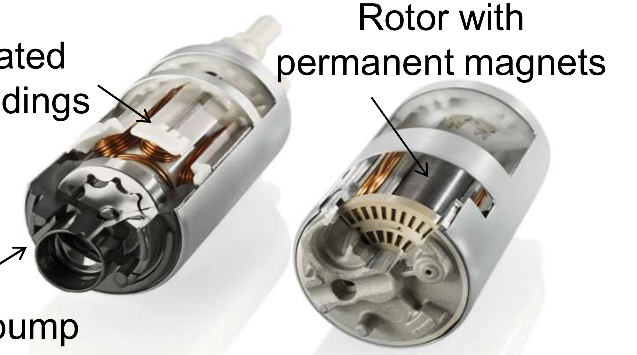
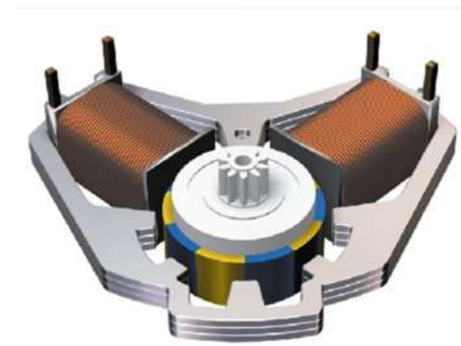
Accessory motors: Emergence of concentrated windings

Fuel pump



Source: Continental

Speed gauge actuator



Source: MMT

Crankshaft starter-generator

Mounted on flywheel (Honda 1999)

Source: wikipedia

- Developed first for 1) low cost and 2) short packages
- Performance on par with distributed windings

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Concentrated windings used on power steering

- Power steering, with the most stringent torque ripple spec, is going with concentrated windings!
- Proper combination of slot/poles, and shaping of magnets and slots critical

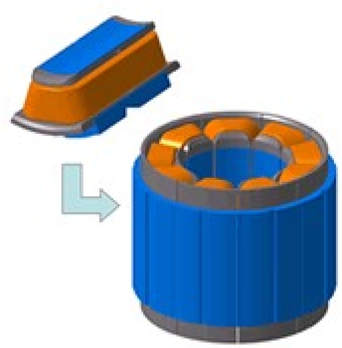
<u>1st generation</u>

- Distributed windings
- Ring magnet

Source: Nidec

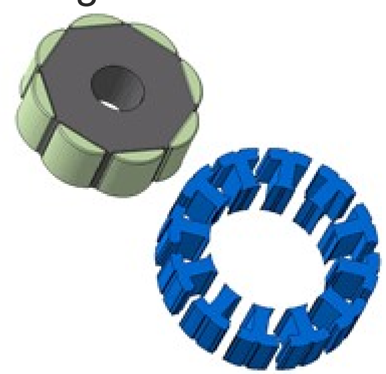
<u>2nd generation</u>

- Concentrated windings
- Ring magnet



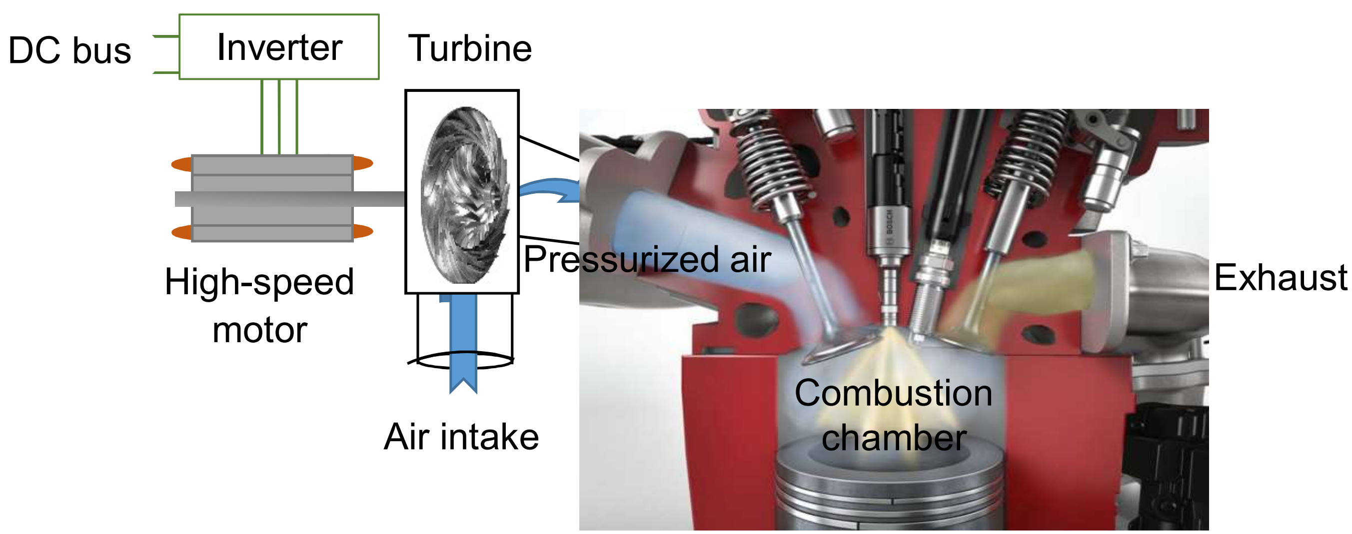
<u>3rd generation</u>

- Concentrated windings
- Segmented, shaped magnets



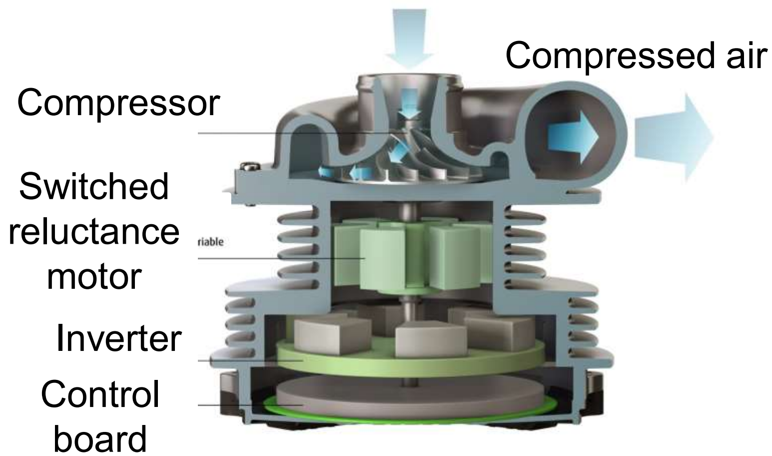
High-speed motors for supercharging

- Basic concept: Pressurize intake air to expand engine output
- Turbocharger: Uses exhaust pressure to run a turbine
  - Uses waste energy, but suffers from lag
- Supercharger: Direct actuation of pressurizing turbine
  - Mechanical (belt driven): Cheaper, simple, but limited speed not ideal for turbine
  - Electrical



Electric super-chargers

- Can go to very high speed (70 to 150 krpm for 1-2 kW)
  - Good for turbine
  - Can be done with motors, but a first for automotive
    - Issues of cost, controls, motor design from 12V
- First production-ready system (Valeo) uses switched reluctance motor
  - 70 krpm

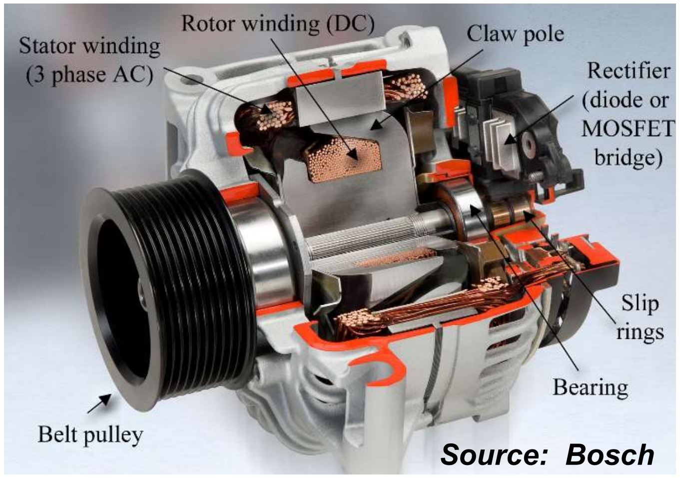


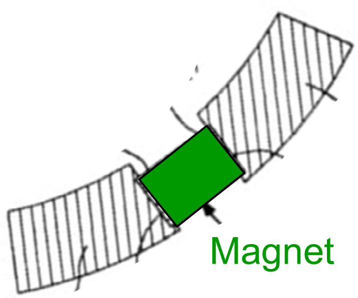
Source: Valeo

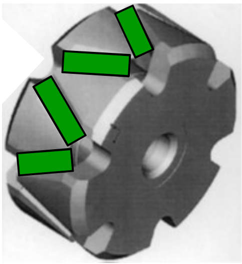
Generator: Steady improvements

- Lundell (claw pole) AC generator replaced DC generator in 50s
  - Low cost, hard to beat! But, low efficiency (50%)
- Improved with:
  - Magnets between claws
  - Water cooled
  - Active rectifier
    - Lower losses (resistive drop better than diode voltage drop)
    - Control of phase angle

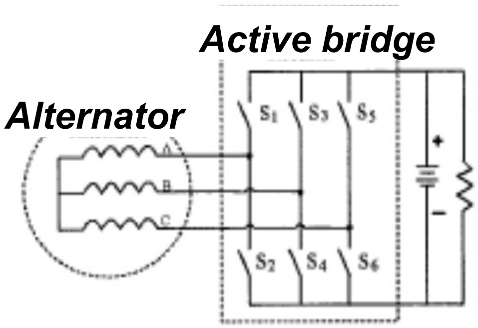
Lundell motor

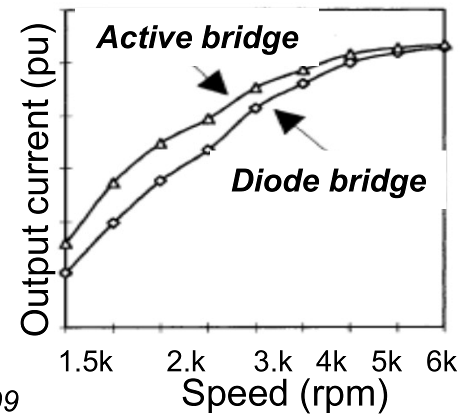






Source: Radomski (GM), US 4,959,577



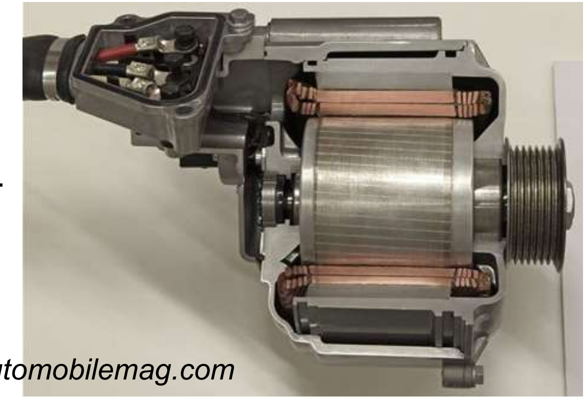


Source: Liang, Miller, Xu (Ford), T. IA, 1999

Starter-generator

- Starter motors are used for 30 seconds then “dead weight” during regular driving
- Starting needs high torque at low speed (0 to 200 engine rpm), generation power over a wide engine speed range (800 to 6,000 rpm)
- Combination starting to occur (finally) due to:
  - More and more power demand (specs merging)
  - Idle-off (stop-start) feature (4% fuel economy benefit)
- Belt-driven system offer good packaging
  - PM: Research level
  - Induction: GM eAssist (no magnet, wide speed range)
  - Lundell: Toyota Lexus 2003, GM Saturn Vue 2005 (lowest cost solution)

GM induction generator



Source: automobilemag.com

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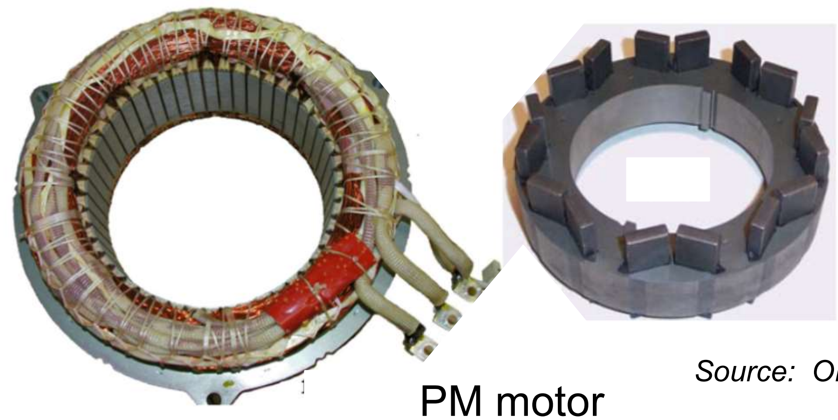
Hybrid/EV motors: New technologies

- Drive cycle optimization
- Winding
  - Need for higher fill factors
- Magnet supply issue
- Higher speeds
  - Materials and losses
- Torque ripple and noise
- Integration of magnetic and thermal models



Source: ORNL

PM motor
Toyota hybrid (Camry 2007)

Source: insideevs.com

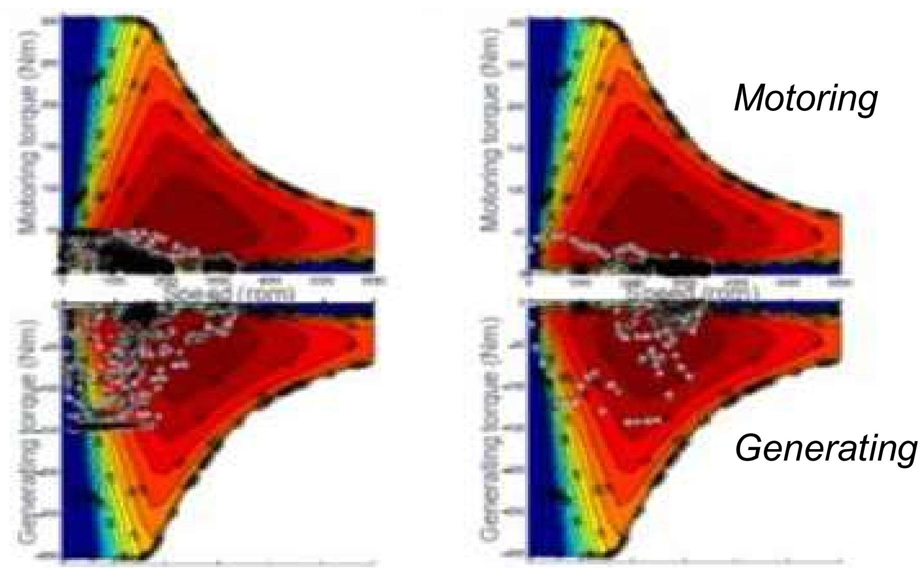
Induction motor
Tesla electric

Cycle optimization

- Importance of efficiency over actual cycles came to the fore in the early stages of hybrid and EV development
  - Top torque and speed are needed for emergency, passing, etc, but rarely used
- Some softwares now allow automatic calculations of desired/standard operating points

Efficiency maps
Dots indicate actual operating points based on standard drive cycles

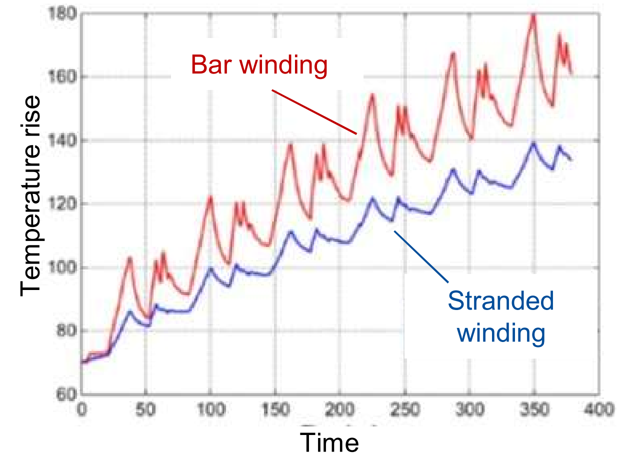
City driving (UDDS) Highway driving (HWFET)



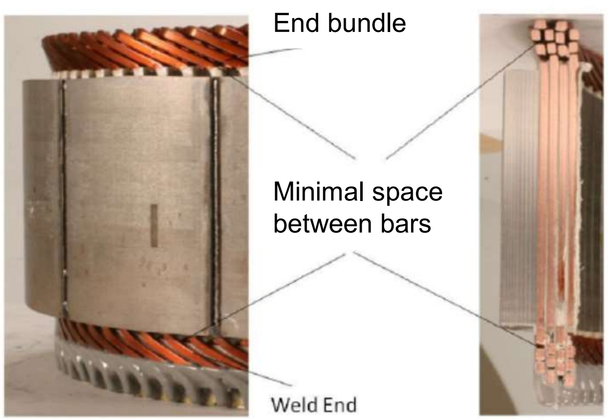
Source: Burwell, et. al, Tokyo 2013 (Int. Copper Association)

Bar winding

- Introduced on GM 2006 Tahoe (motor by then Remy)
  - Advantage of bars:
    - Higher fill factor (60%)
    - Shorter end turns
    - Easier cooling
    - Easier manufacturing
    - If inserted from end (hairpin), small slot opening
  - Advantage of round wires:
    - Can have more turns/slot (more flexibility in design)
    - Lower high frequency/speed losses



Source: Jurkovic, et. al, IEEE TIA 2015



Source: Rahman, et. al, IEEE TIA 2014

<u>Hairpin winding</u>

Source: Borg-Warner

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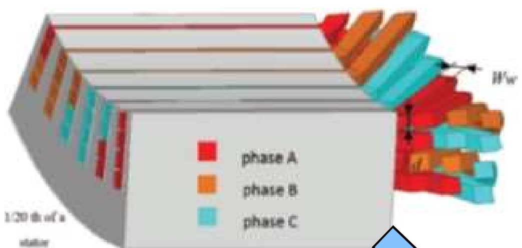
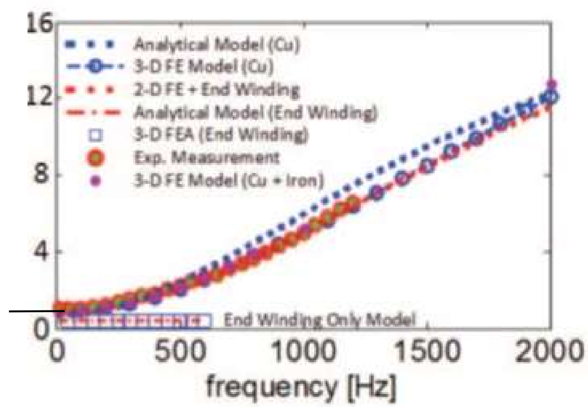
Bar winding: High speed

- Proximity losses in bar windings need careful consideration
  - AC resistance can be 10 times the DC resistance!
  - Zhang and Jahns, IEMDC 2015

<u>Traction motor, 4-bar winding</u>



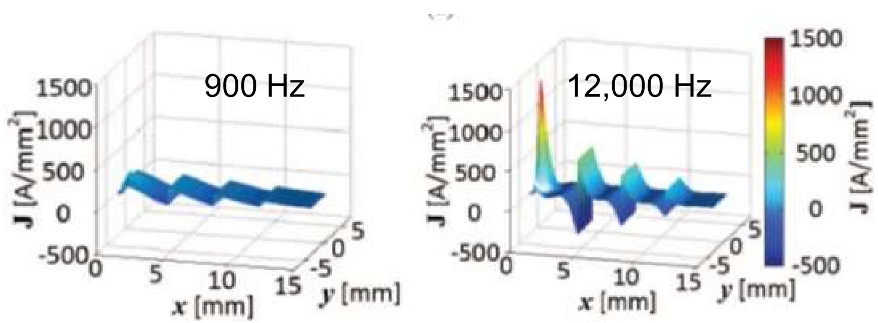
<u>Resistance versus frequency</u>



Base: DC

1

<u>Current density versus position within slot</u>



Source: Zhang and Jahns, IEMDC 2015

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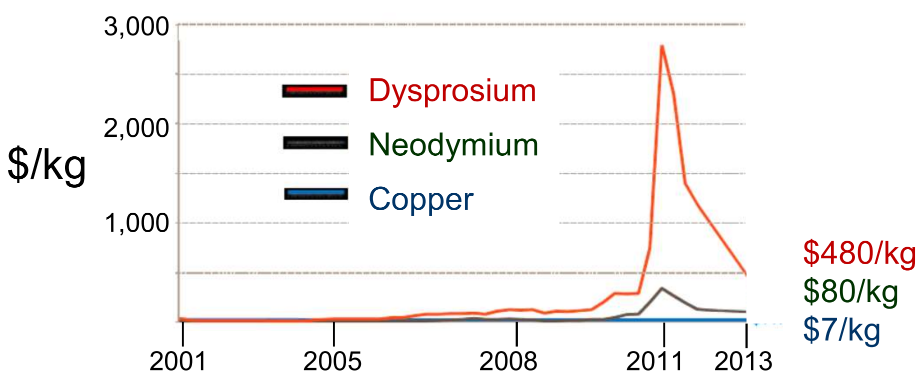
Magnet supply issue

- Rare-earth prices shot up sky high some 5 years ago
  - Speculation over, but demand still growing
  - Issue especially with "heavy rare earth" such as Dysprosium
- Research in new materials
- Strong argument for induction motors
- Dysprosium critical to prevent demagnetization under load at high temperature
  - Or is it? New grades with "boundary diffusion process" can circumvent problem



Source: metal-pages.com

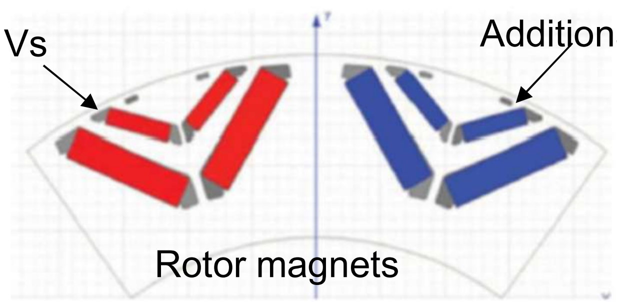
Honda Freed first hybrid vehicle
with magnet free of heavy rare earth
(Honda news, July 2016)

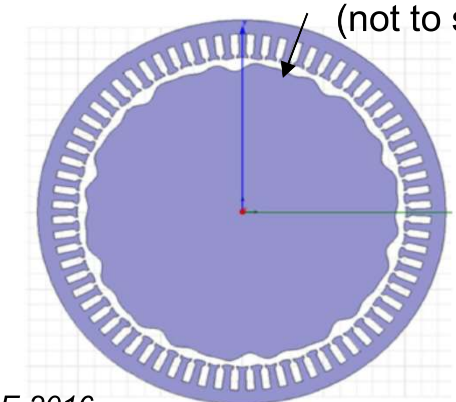
Source: world.honda.com, July 2016

Torque ripple and noise

- Electric machine #1 noise/vibration producer under the hood in EVs
  - Even for hybrids, engines are quieter, and motors have annoying higher-frequency pitch
- Solutions:
  - Magnet slot shape
  - Asymmetric North and South poles
  - Uneven rotor surface to cancel specific harmonics

GM Cadillac CT6 Plug-in hybrid

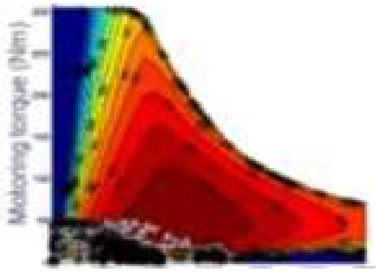




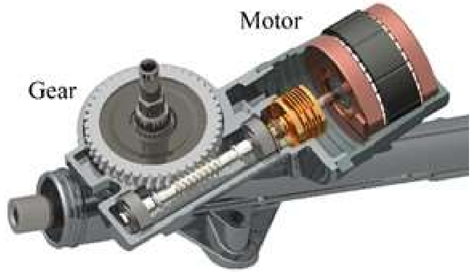
Source: Jurkovic, et. al., IEEE ECCE 2016

Conclusions

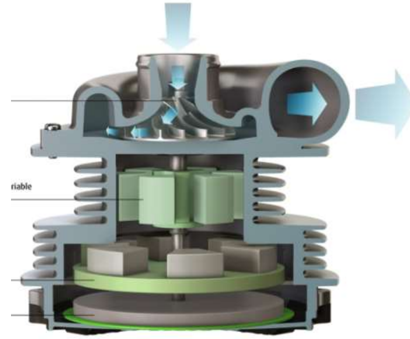
- Automotive applications have driven many innovations, will continue to do so
- Challenging environment (temperature, cost) with a variety of applications
  - Each with own needs (low torque ripple, efficiency, etc)
- Future development in:
  - Higher speed, from hybrid motor reaching upward of 15,000 rpm to superchargers at 70,000 rpm
  - Loss reduction at high speed, particularly in bar windings
  - Reduced use of heavy rare-earth
  - Integration of magnetic and thermal models for robust optimization
  - Noise reduction



Efficiency optimization
Source: Burwell, et. al, Tokyo 2013



Electric power steering
Source: Nexteer



Electric supercharger
Source: Valeo

Hairpin winding
Source: Borg-Warner

Thank you!

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