Automotive Electric Motor Drives and Power Electronics

Iqbal Husain
Distinguished Professor
Department of Electrical and Computer Engineering
North Carolina State University

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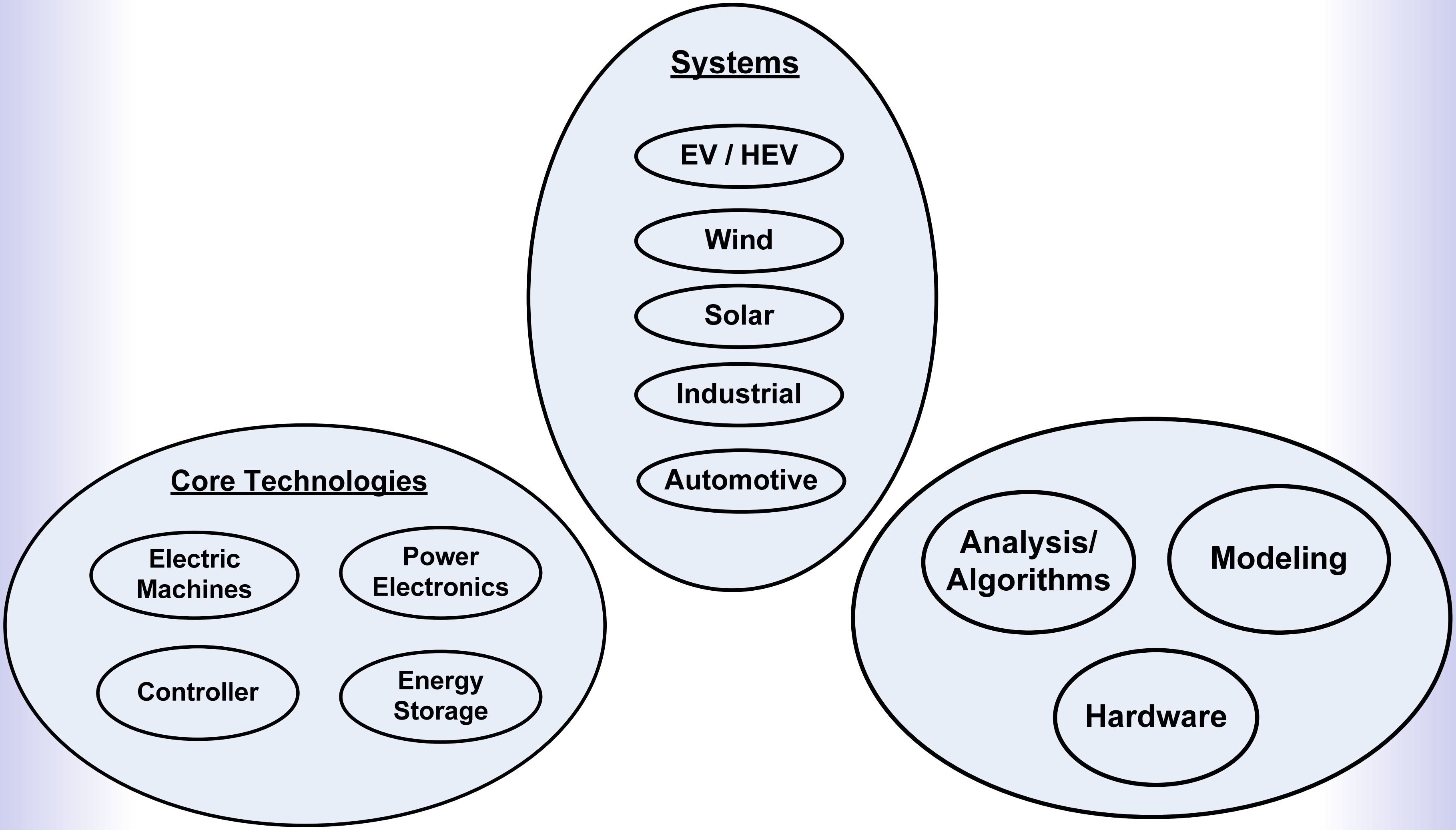
Overview

- Systems and Technologies
- Electric and Hybrid Vehicles
- Electric Machines and Drives: Different Types
- Power Electronics in EV/HEVs
- Electric Motor Drives for Automotive Systems
- Technology Trends

Systems and Technologies



Systems

- EV / HEV
- Wind
- Solar
- Industrial
- Automotive

Core Technologies

- Electric Machines
- Power Electronics
- Controller
- Energy Storage

- Analysis/ Algorithms
- Modeling
- Hardware

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Electric and Hybrid Vehicles

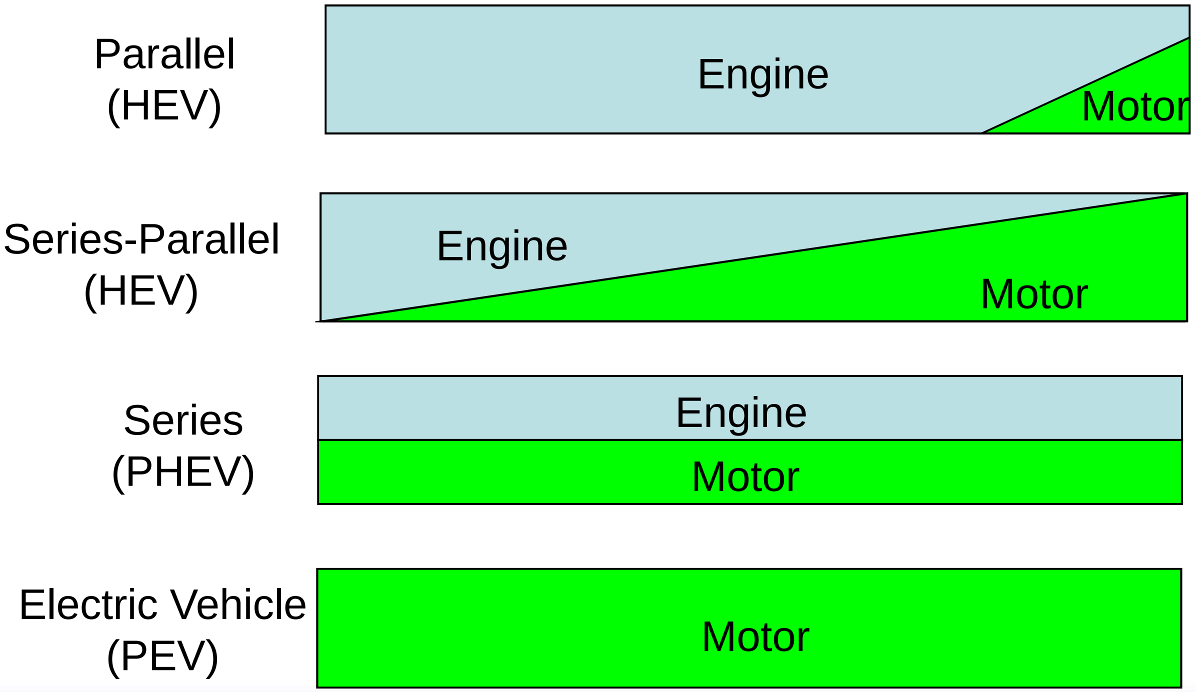
Electric/Hybrid Vehicles

- Electric Vehicles
  - The energy source is portable and electrochemical in nature.
  - Tractive effort is supplied only by an electric motor.
    - Battery Electric Vehicle
    - Fuel Cell Electric Vehicle

- Hybrid Vehicles
  - A vehicle in which at least one of the energy sources, stores or converters can deliver electric energy.
  - The propulsion energy during specified operational missions is available from two or more kinds or types of energy stores, sources or converters, of which at least one store or converter must be on board.
    - Charge Sustaining HEV
    - Plug-in HEV (PHEV) or Charge Depleting HEV

Series/Parallel/Split/EV

- Plug-in Hybrid Vehicles designed with series architecture
- Production hybrid passenger vehicle architectures are of series/parallel combination type; also known as split
- From parallel to only electric => electric motor contribution increases
- Key enabling technology for EV/HEVs is the Electric Motor Drive



Parallel (HEV): Engine, Motor

Series-Parallel (HEV): Engine, Motor

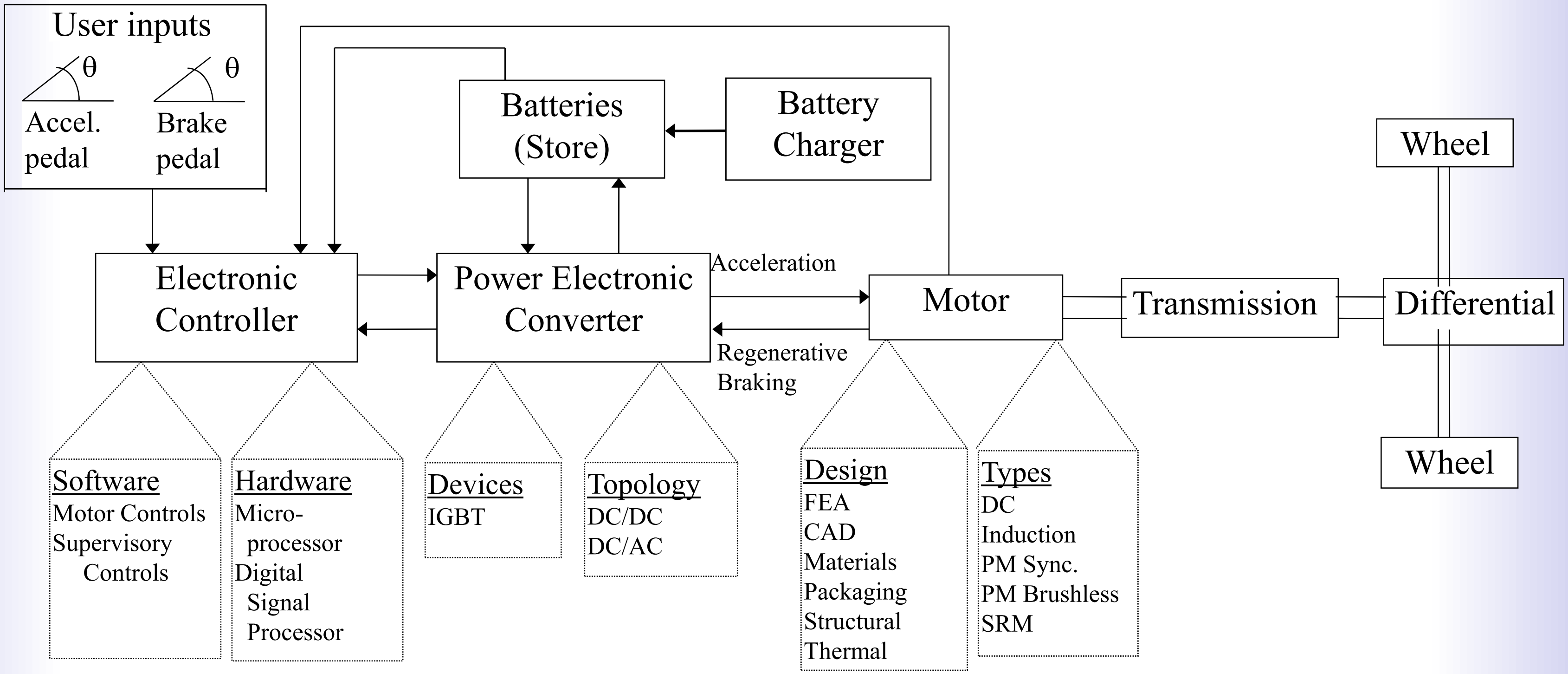
Series (PHEV): Engine, Motor

Electric Vehicle (PEV): Motor

Fuel Economy Increase in Hybrids

- Engine Downsizing
- Engine Operating Point Optimization
- Engine Idle-off
- Electric Only Operation
- Regenerative Braking

EV Transmission Path



User inputs
θ
θ
Accel. pedal
Brake pedal

Batteries (Store)

Battery Charger

Wheel

Electronic Controller

Power Electronic Converter

Acceleration

Motor

Transmission

Differential

Regenerative Braking

Wheel

Software
Motor Controls
Supervisory Controls

Hardware
Micro-processor
Digital Signal Processor

Devices
IGBT

Topology
DC/DC
DC/AC

Design
FEA
CAD
Materials
Packaging
Structural
Thermal

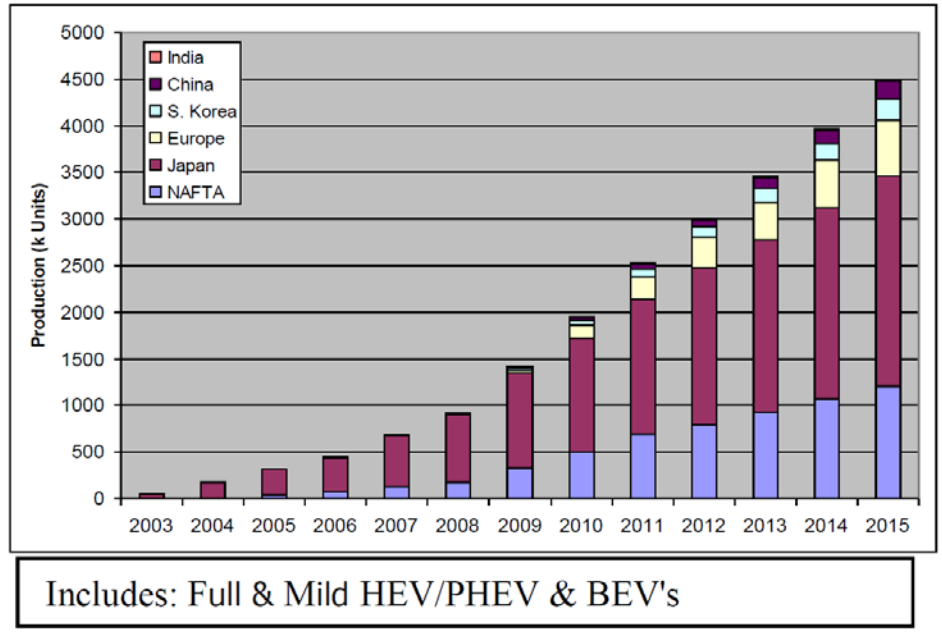
Types
DC
Induction
PM Sync.
PM Brushless
SRM

- ➢ Maximize performance and efficiency
- ➢ Driver inputs continuously and consistently satisfied

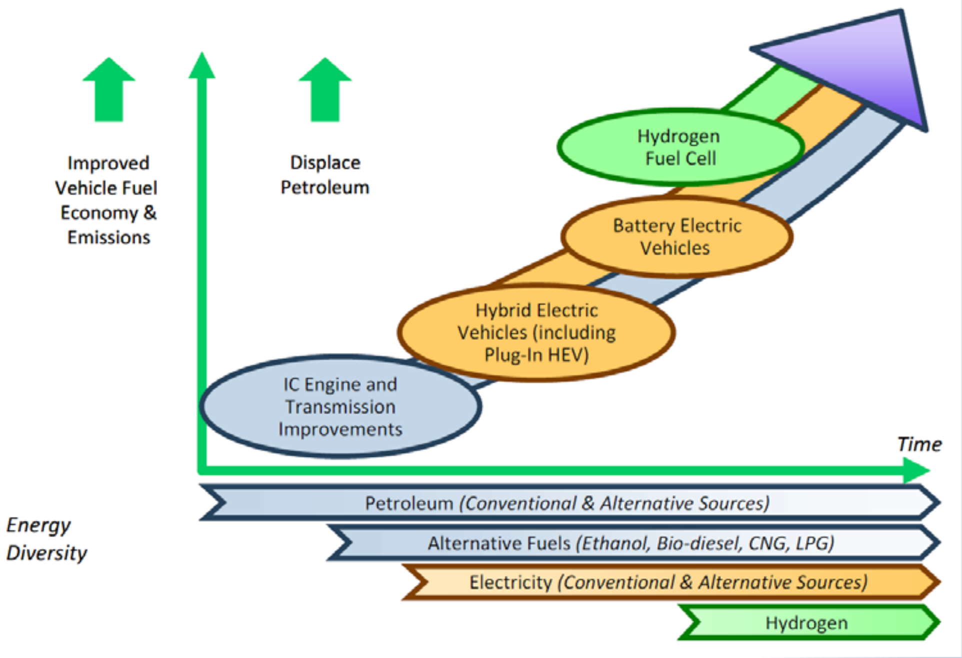
Goals and Challenges of Alternative Vehicles

- Goals:
  - ✓ Reduction of fuel consumption
  - ✓ Reduction of well-to-wheel energy consumption
  - ✓ Reduction of emissions
  - ✓ Diversification of energy sources
  - ✓ Enhanced customer acceptability
- Challenges
  - ✓ Quality and Reliability
    - ❖ Multidisciplinary area
    - ❖ Harsh environment
  - ✓ Size and Cost
  - ✓ Efficiency and Performance
  - ✓ Standardization of safety and diagnostic requirements
  - ✓ Development of trained engineers

EV/HEV Growth and Energy Diversity



Includes: Full & Mild HEV/PHEV & BEV's



Source: SAE 10CNVG-0048, Power Electronics Optimization through Collaboration

DOE/GM Student Vehicle Competitions

- *Challenge X* and *EcoCar* Competitions
  - University of Akron selected for *Challenge X* between 2004 and 2008
  - North Carolina State University selected for *EcoCar1* between 2008-2011 and for the ongoing *EcoCar2*.
- Objective: Reengineer a GM Vehicle into an Alternative Vehicle

Competition and Program Goals

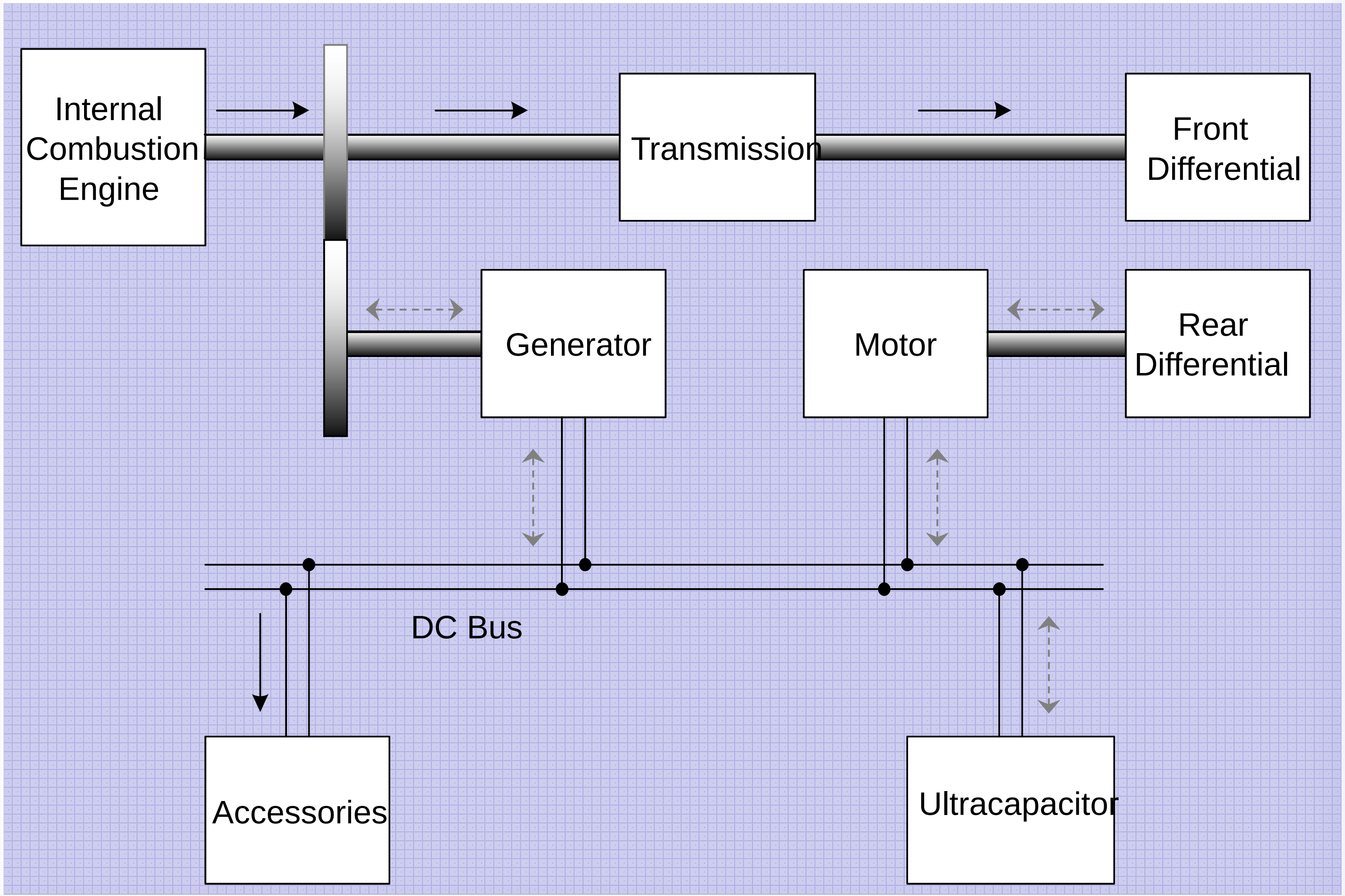
Competition Goals:

- ✓Meet Vehicle Technical Specifications (VTS) set by GM
- ✓Increase in fuel economy
- ✓Significantly reduce well-to-wheel energy consumption
- ✓Reduce criteria tailpipe emissions
- ✓Maintain or enhance customer acceptability

Program Goals:

- ✓Develop trained engineers
- ✓Learn processes of automotive vehicle development
- ✓Build awareness of energy and environmental issues in automotive transportation

Series-Parallel 2×2 Architecture



UA Diesel-Hybrid Electric Vehicle

Cargo Space

Entertainment/Display

Supervisory Controller

Ultracapacitor Bank

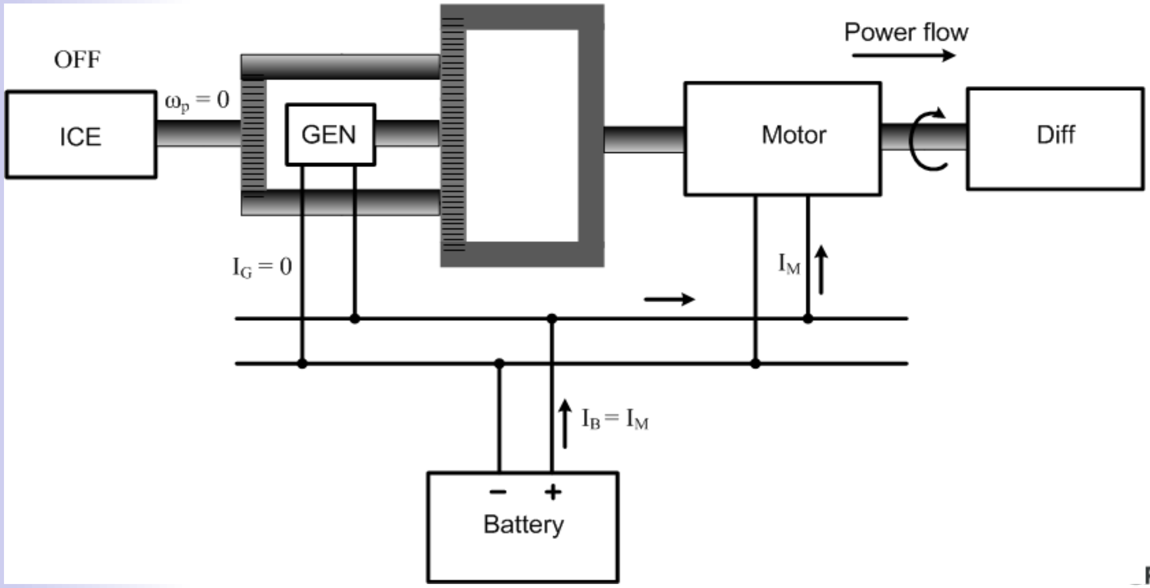
1.9L Diesel Engine

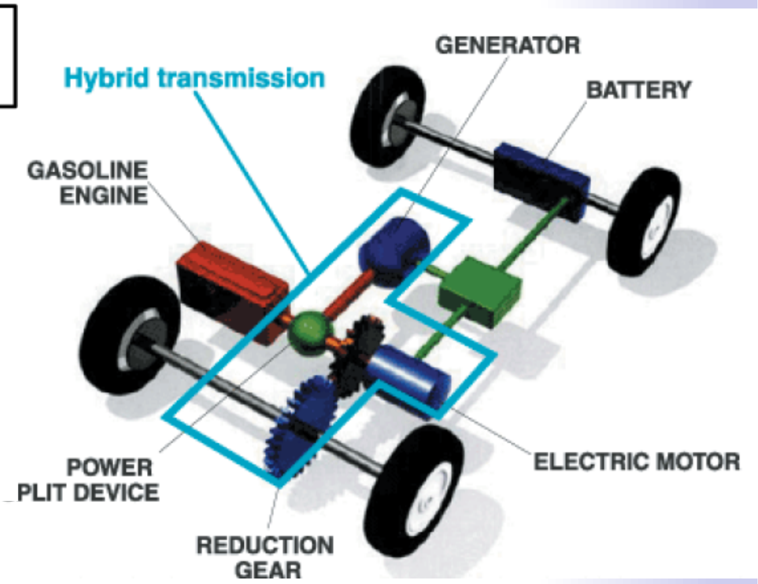
65kW Traction Motor

20kW PM Starter/Generator

Toyota Hybrid Architecture

Toyota Hybrid Power Split Series/Parallel Architecture

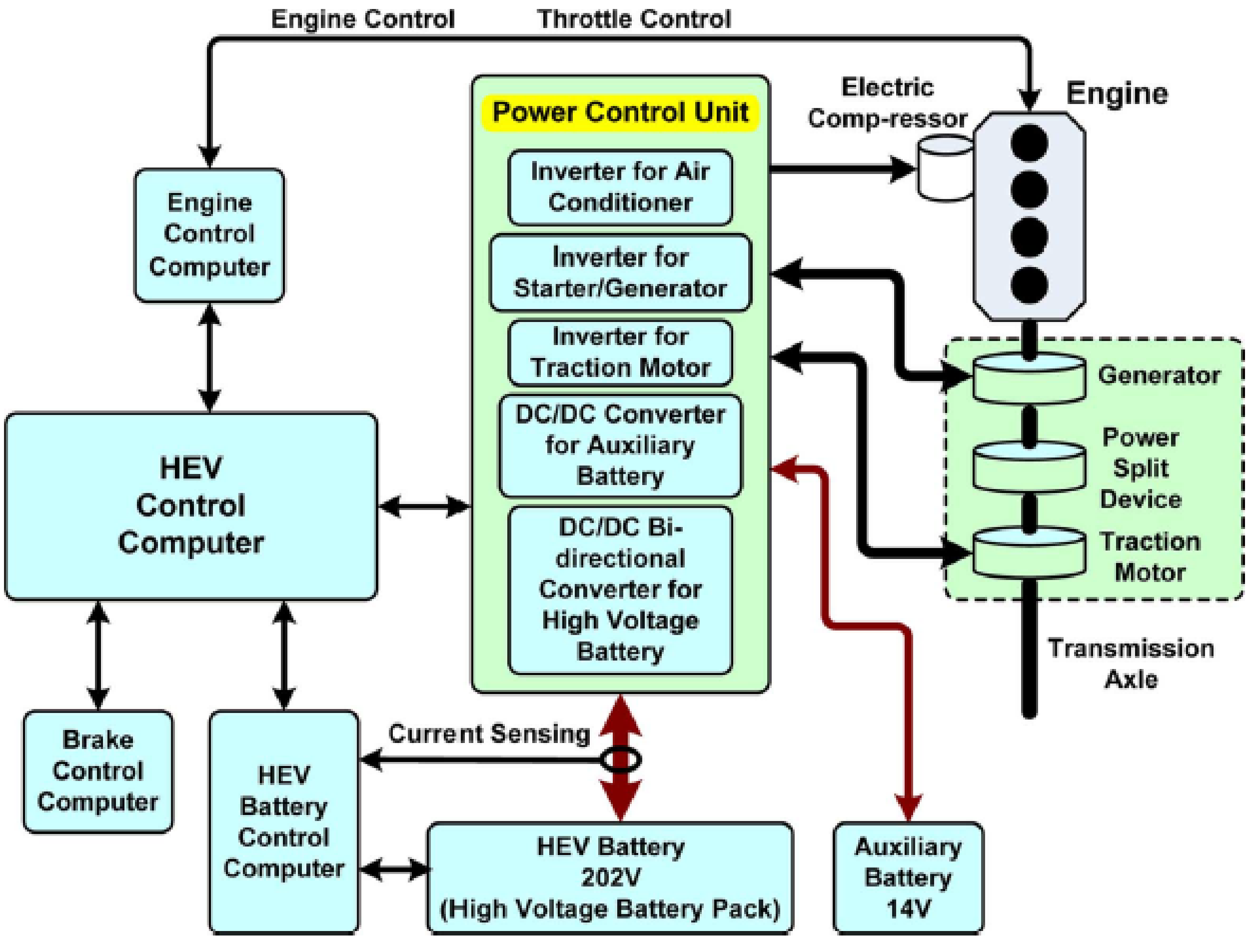




Source: *Electric and Hybrid Vehicles Design Fundamentals*, I.Husain Taylor and Francis, 2010

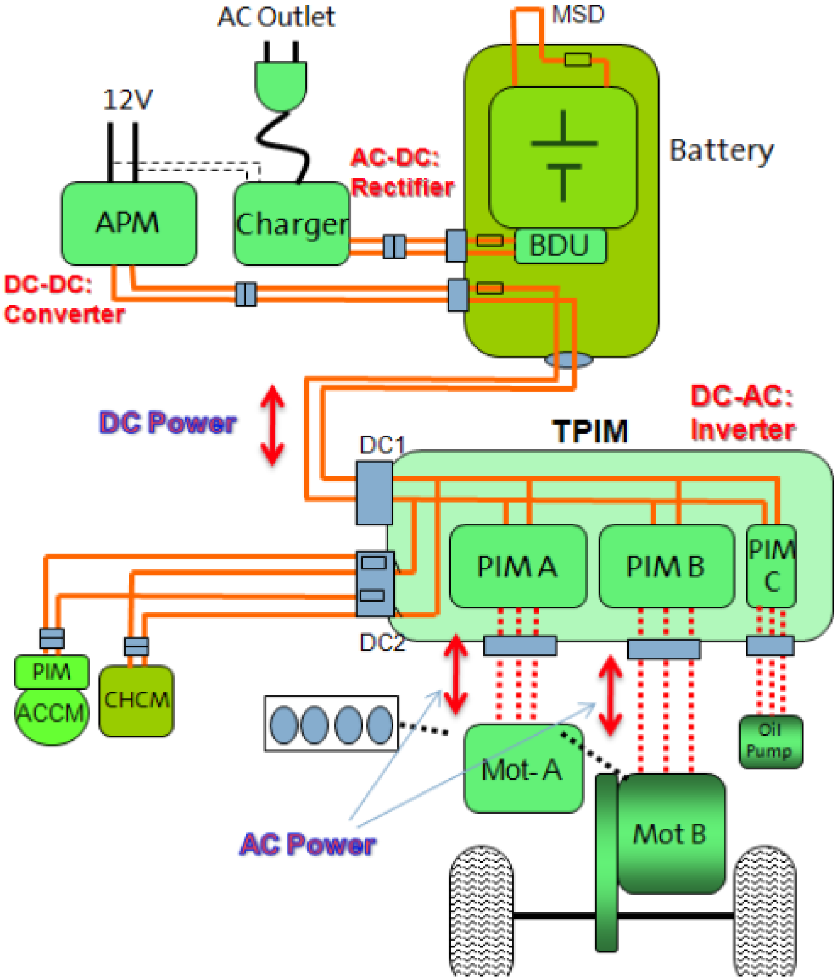
Source: Toyota Hybrid System THS II document

Toyota Hybrid Controls



Source: A. Emadi et al., *IEEE Tran. On Industrial Electronics*, Vol. 55, No. 6, June 2008

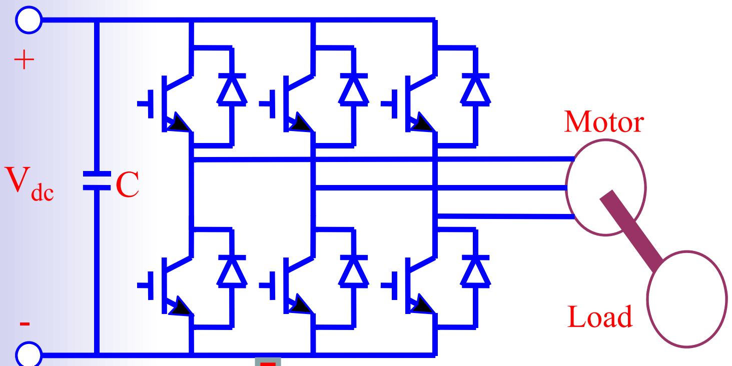
GM Chevy Volt Architecture



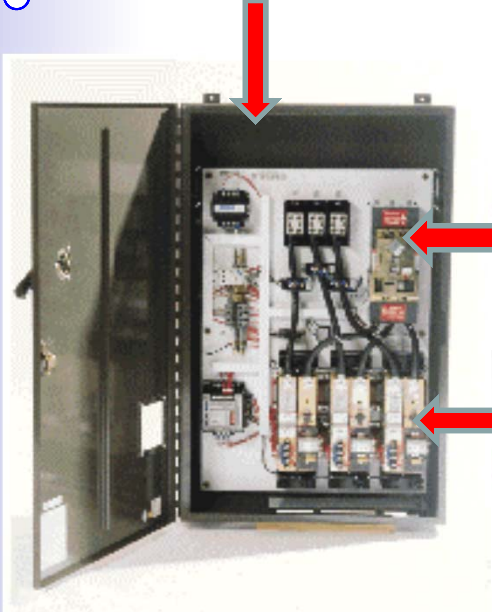
Source: SAE 11PFL-0948, The Voltec 4ET50 Electric Drive System

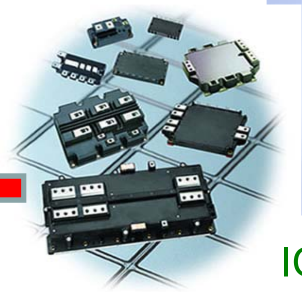
Electric Machines and Drives

Electric Motor Drive Components



Electric Machine





IGBTs

Electronic Controller

Gate Drive Board

Power Electronic Converter

General Principles of Operation

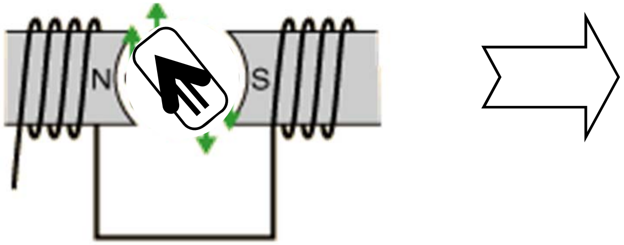
- Biot-et-Savart law:
  - Wire and PM

    B_r from PM

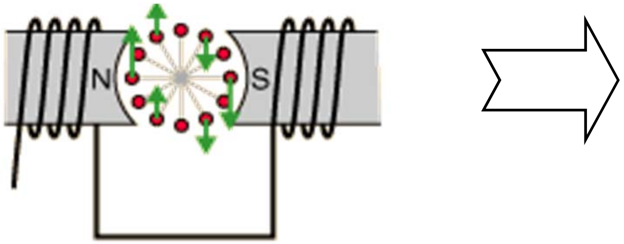
    B_s from wire with I
  - Wire and wire

    B_s from one wire

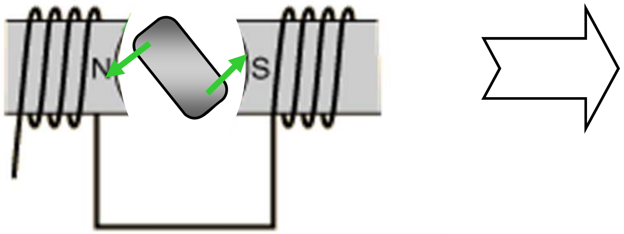
    B_r from other wire
  - Need for rotating field
- Minimum reluctance law



PM



Induction



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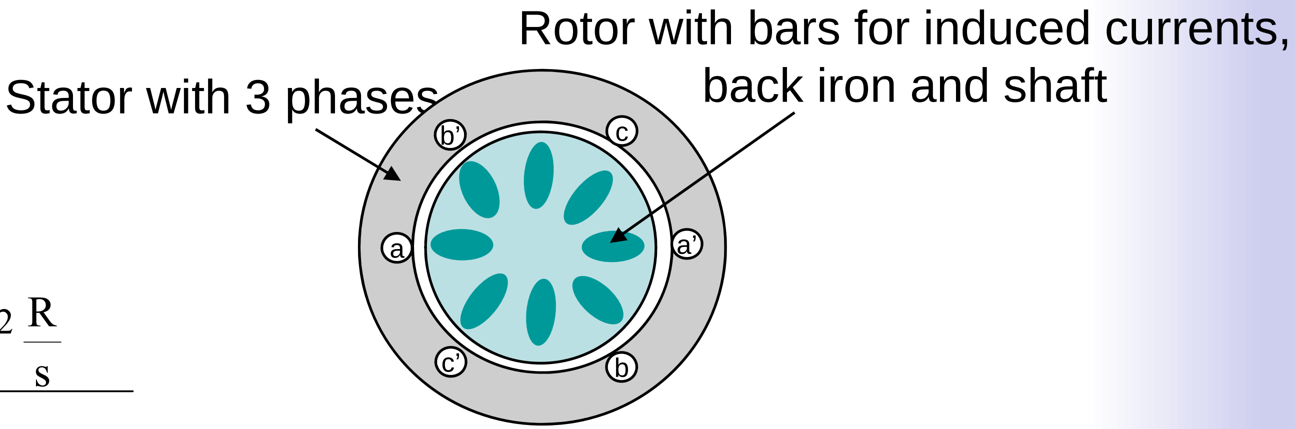
Induction Machines

- Rotating field created by 3 phases
- Rotating field generates its own field by inducing current in rotor bars
  - (makes is own magnets on the fly)
- Currents in rotor bars follow rotating field



- Torque: $$T = \frac{p}{\omega}\frac{V^2\frac{R}{s}}{\left(\frac{R}{s}\right)^2 + L^2\omega^2}$$

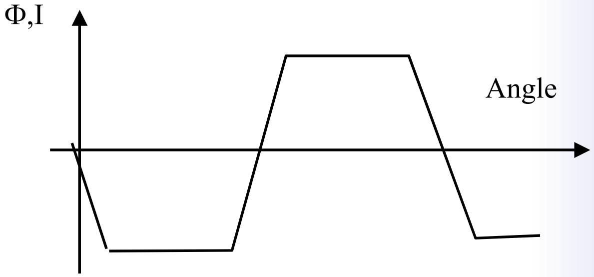
V = voltage; R,L =resistance, inductance; p = number of pole pairs; ω = speed

s = slip, or speed difference between rotor speed and rotating field speed

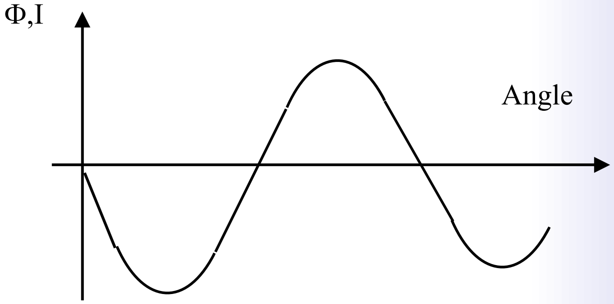
Permanent Magnet Machines

Magnetization shape and current excitation:

- Trapezoidal (PMBLDC): Magnet flux (Φ) trapezoidal; current (I) square
- No rotating field
  - Simpler
  - Most common
  - EPS, brakes, etc.

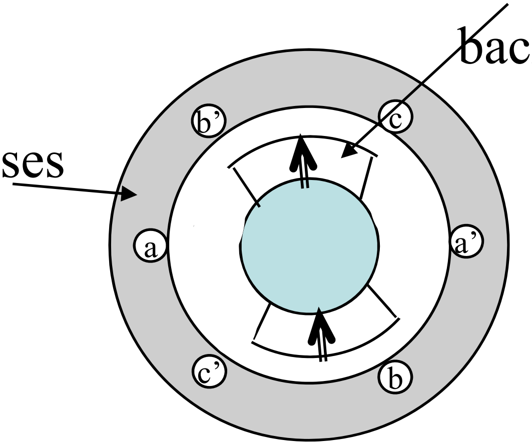


- Sinusoidal (PMSM): Magnet flux (Φ) and current (I) sinusoidal
  - Smoother torque
  - Needs a high resolution sensor
  - EVs, HEVs, EPS



PM Synchronous Machine (PMSM)

Rotating field created by 3 phases; magnets follow rotating field



Rotor with magnets, back iron and shaft

Stator with 3 phases

Advantages of PM Machines:

- Loss-free excitation, useful for small machines
- High power density
- No brushes and slip rings required

Disadvantage of PM Machines:

- Magnet cost and availability

PM Synchronous Machine Types

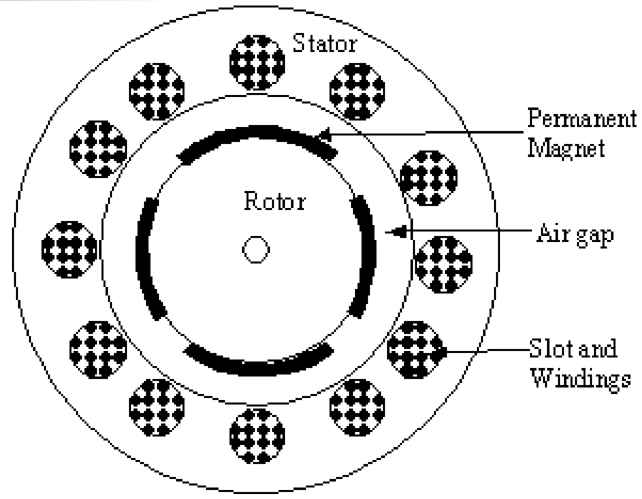
PMSM Magnet construction:

Surface: Most common in automotive applications

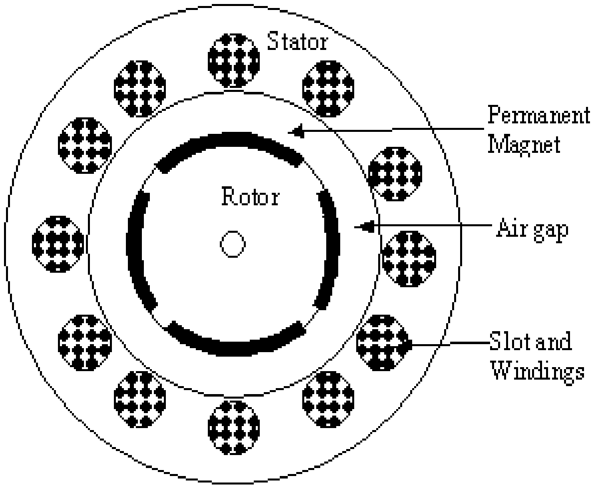
Inset: PM inserted at rotor surface, $L_d \neq L_q$ limited speed range

Interior: Wide constant power speed range, more expensive, requires larger machine (starter-generator, EV, HEV)

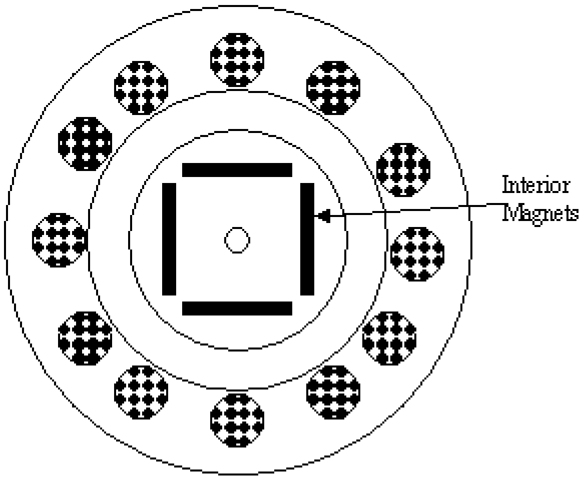
Surface mounted



Inset



Interior/IPM



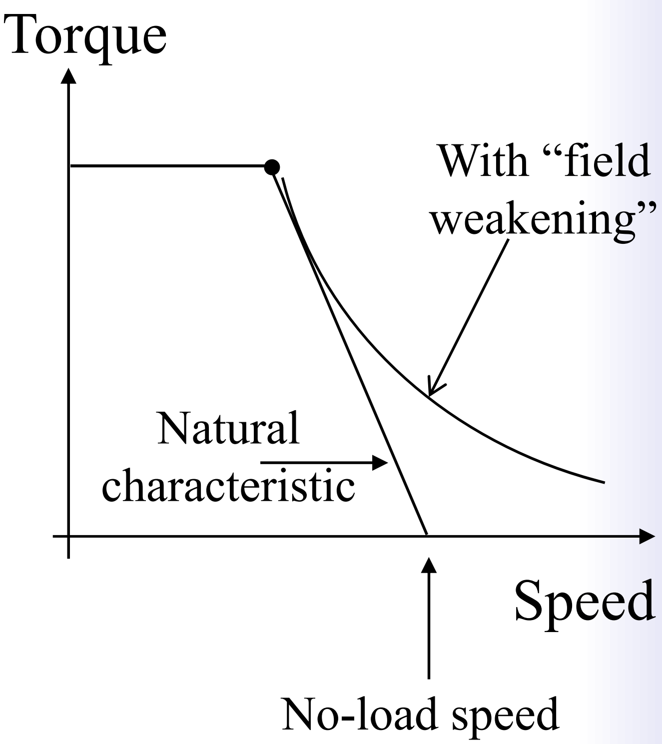
PMSM: High Speed Control

- Magnet flux is fixed, imposes top speed

Magnet flux

$$V = N\frac{d\Phi}{d\theta}\omega$$

- Field weakening techniques possible
    - Require current excitation from stator
- Techniques well known, but:
    - Require higher resolution sensor
    - Efficiency advantage lost at high speed, light loads
- Interior/Buried magnets preferable



Technology Trends

Strong Hybrid System Components

- Toyota leads industry in electric machine power density → nearing 4 kW/kg

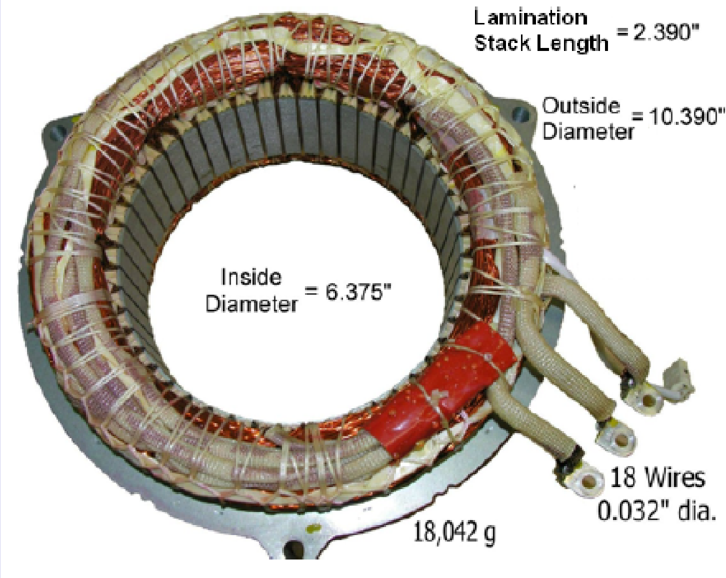
Component	Units	Prius THS-I	Prius, THS-II	RX400h	GS450h	Camry
System	V	274	500	650	650	650
MG2	kW	33	50	123	147	(50)
	rpm	1040-5600	1200-1500	4500	5600-13,000	
	Nm	350	400	333	275	
	rpm	0-400	0-1200	0-1500	0-3840	
	Rpm	**5600**	**6500**	**12,400**	**14,400**	**14,500**
MG1	kW	12	29	109	134	(30)
	Rpm	**6000**	**10,000**	**13,000**	**13,000+**	**13,000**
Max Pwr	kW	**73**	**78**	**191**	**254**	**140**
Retention		Conventional Permanent Magnet Retention Method			New Magnet Retention Method	

→ The key to high power density is design for significantly higher speeds!

Source: Dr. John Miller's Presentation to Challenge X 2006

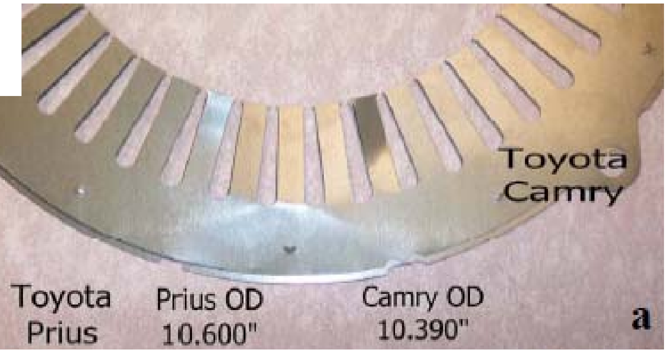
Hybrid Vehicle IPM

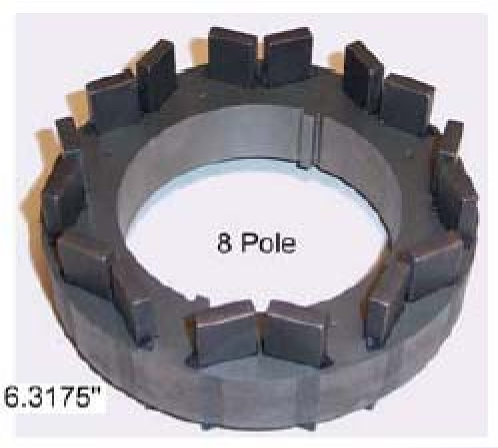
Interior Permanent Magnet (IPM) Machine is the design choice for production hybrid vehicles



Camry Stator

Stator Laminations





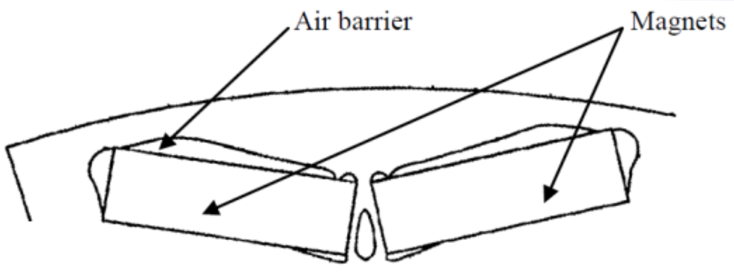
Camry Rotor

Source: Evaluation of 2007 Toyota Camry Hybrid Synergy Drive System, DOE Report ORNL/TM-2007/190, 2008.

GM Chevy Volt PHEV IPM

- Both machines in Volt are IPM AC Synchronous type
- Air pocket (barrier) introduced on top of magnet to:
    - ✓ Reduce airgap magnet flux thereby reducing iron loss
    - ✓ Reduce harmonics in the airgap further reducing iron loss
    - ✓ Increase *d*-axis inductance, and thus increases saliency
    - ✓ Reluctance torque increase due to increased saliency offsets loss of mutual torque due to airgap flux reduction
    - ✓ Impact of air pocket on peak torque is small

Chevy Volt Motor Stator and Rotor

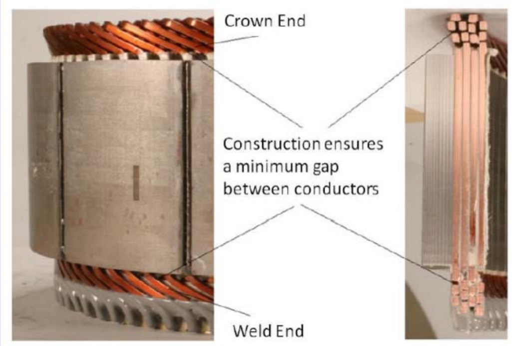


Rotor Geometry

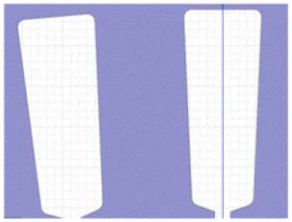
Source: SAE 11PFL-0948, The Voltec 4ET50 Electric Drive System

GM Hybrid Vehicle IPM

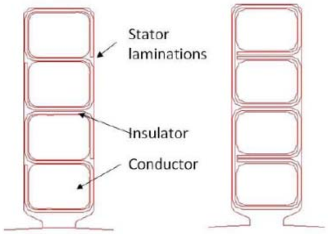
- Bar wound construction instead of stranded type with advantages of
  - ✓ Higher slot-fill
  - ✓ Shorter-end turn
  - ✓ Improved cooling performance
  - ✓ Fully-automated manufacturing process
  - ✓ Improved high voltage protection
- “Hairpin”s of bar-wound conductors are formed outside and then inserted in slot
  - ✓ Twisted end-turns welded together to form a wave-winding pattern



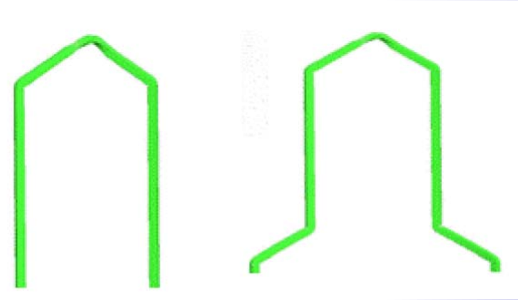
End-turn, weld-end of conductors



Stranded pattern



Bar-wound pattern



Hairpin before and after twisting

Source: SAE 11PFL-0948, The Voltec 4ET50 Electric Drive System

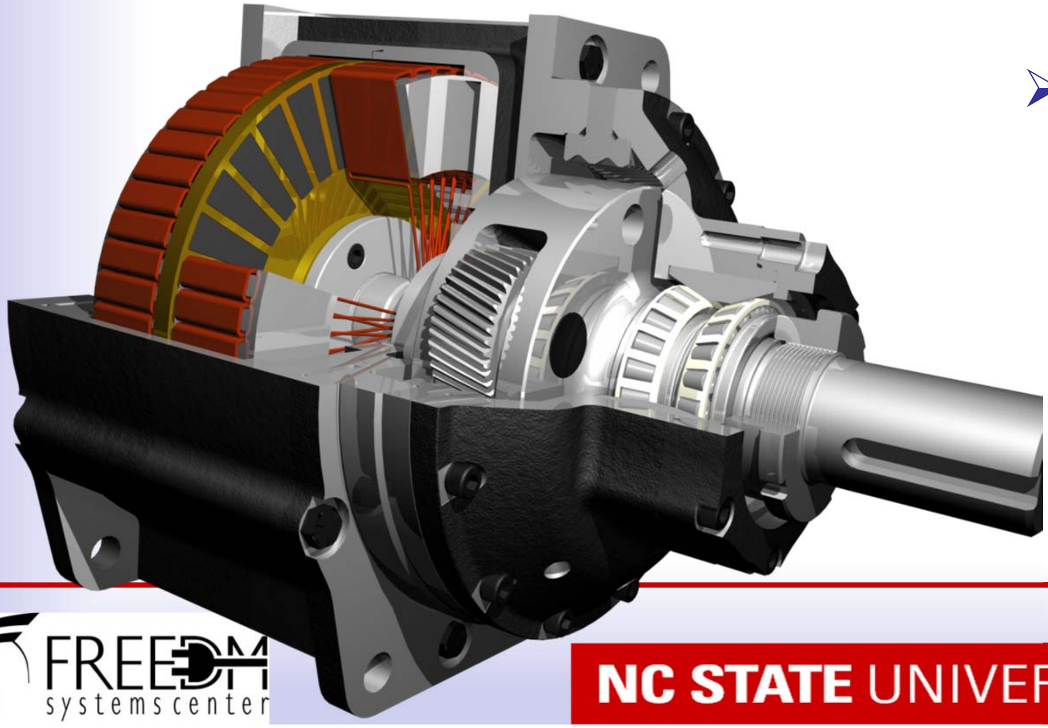
Axial Flux Motor

- Torque is a function of shear stress in the air gap times the air gap area times the moment arm

$$T = 2\pi r^2 L\sigma$$

$$\sigma = B_g A$$

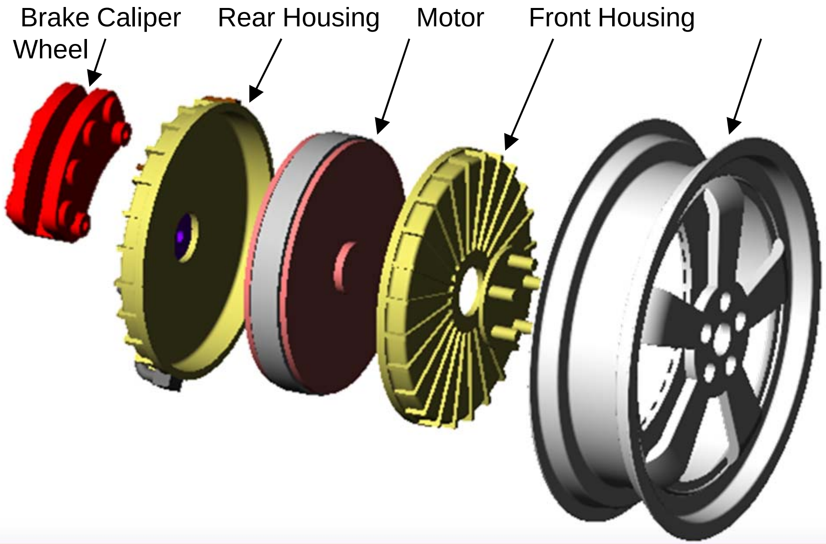
- Torque is produced over a continuum of radii, not a single radius
- Torque density advantage of axial flux increases as pole count increases.
- The utilization factor (specific torque) of the axial flux motor core is approximately twice that of the radial flux.



- Many options exist
  - Single Stator Single Rotor
  - Dual Stator Single Rotor
  - Single Stator Dual Rotor
  - Dual Stator Dual Rotor
  - Multiples of above

Axial Flux Motor Applications

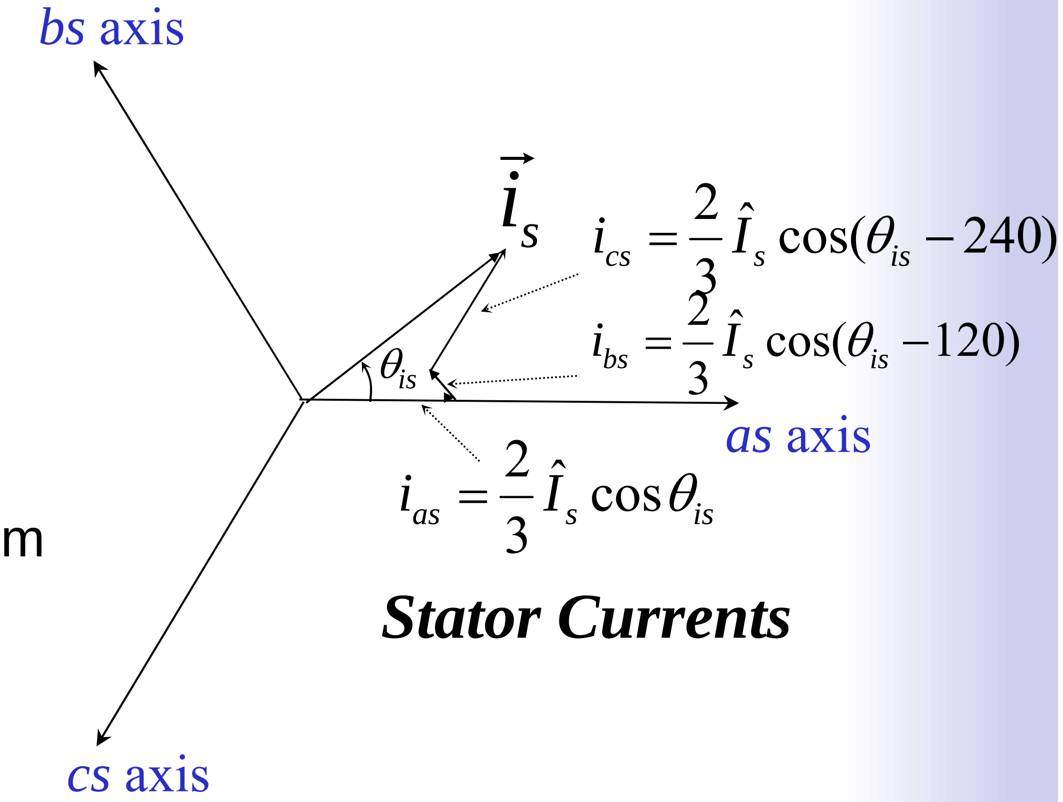
- Axial flux wheel motor and propulsion motor technology tested in automotive applications
- PM Motor characteristics apply, including speed range limitations.
- Axial flux machine technology would be a good candidate for gearless wind power generation system.



Source: General Motors

Space Vector Representation

- A simple and efficient way of representing sinusoidally space distributed variables
- Similar to the use of phasors
- Gives a compact way of representing machine equations
- Facilitates the conversion from a 3-phase system to a 2-phase system



$$i_{cs} = \frac{2}{3}\hat{I}_s \cos(\theta_{is} - 240)$$

$$i_{bs} = \frac{2}{3}\hat{I}_s \cos(\theta_{is} - 120)$$

$$i_{as} = \frac{2}{3}\hat{I}_s \cos\theta_{is}$$

Stator Currents

$$\vec{f}_{abc}(t) = \left(f_a(t) + f_b(t)\angle 120 + f_c(t)\angle 240\right)$$

dq Modeling

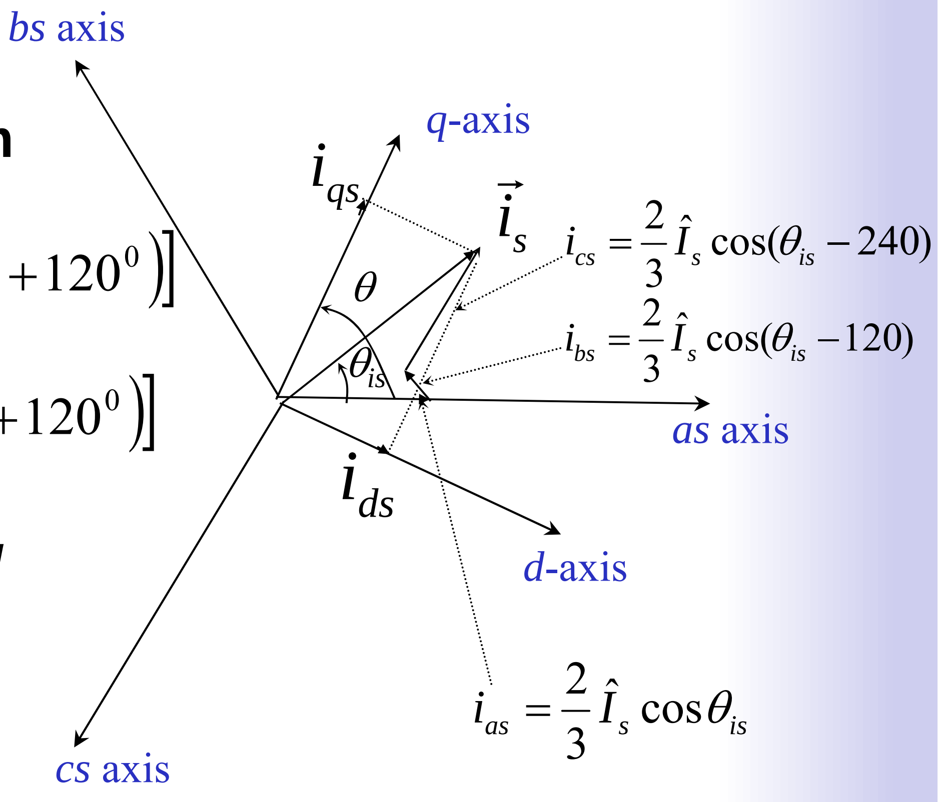
dq: From 3-phase to 2-phase system

$$f_q = \frac{2}{3}\left[f_a \cos\theta + f_b \cos\left(\theta - 120^0\right) + f_c \cos\left(\theta + 120^0\right)\right]$$

$$f_d = \frac{2}{3}\left[f_a \sin\theta + f_b \sin\left(\theta - 120^0\right) + f_c \sin\left(\theta + 120^0\right)\right]$$

Transformation between *abc* and *dq* variables through space vector:

$$\vec{f}_{qd}(t) = \frac{2}{3} e^{-j\theta} \vec{f}_{abc}(t)$$



Vector Control

- Vector control refers to both magnitude and angle control.

- Vector control in AC Machines emulate the separately excited dc motor or the PM brushless dc-motor.

- DC Machine torque: $T_e = k_T \lambda_f i_a$

- Induction Machine: With the reference frame rotating at synchronous speed with rotor flux, the torque is

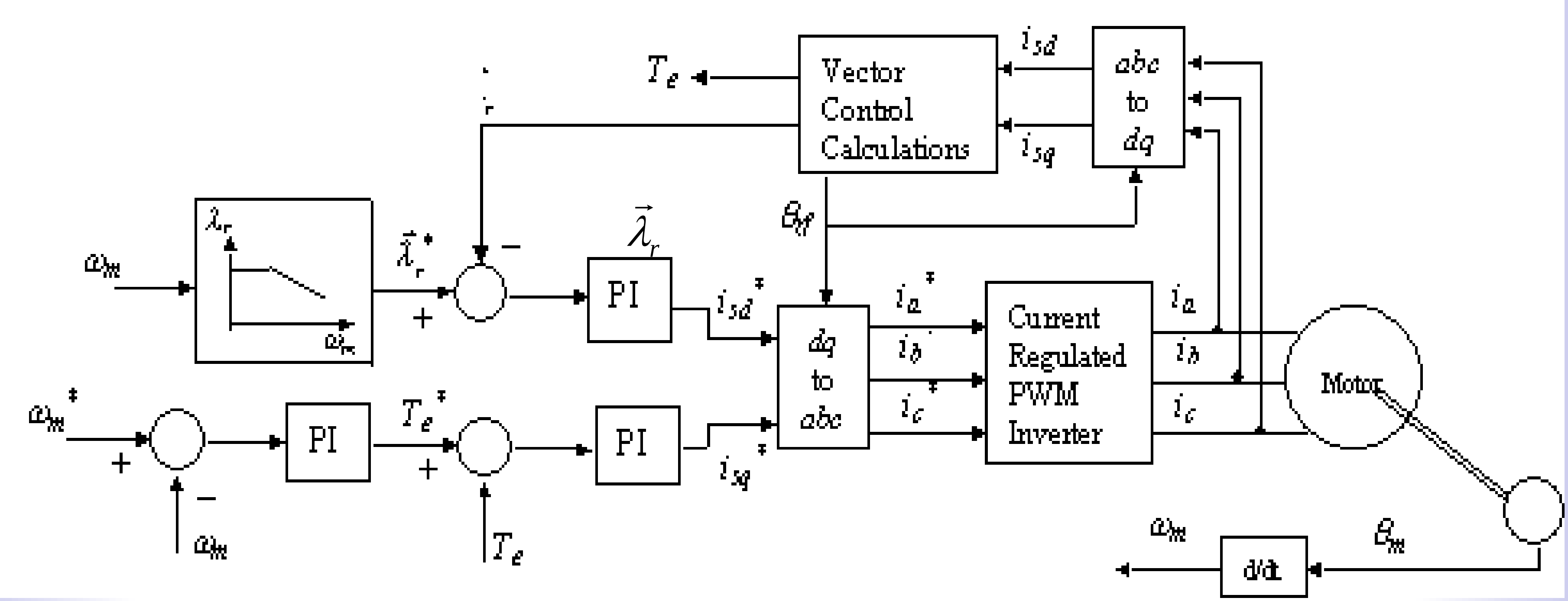
$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr} i_{qs}$$

- Vector control in PMSMs is simpler than in induction motors.

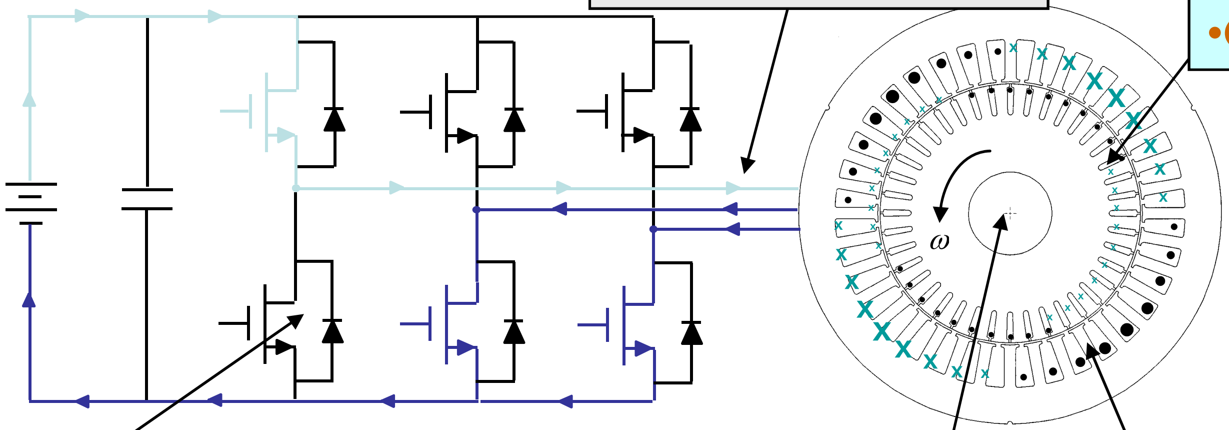
PMSM Torque: $T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_f i_q + (L_d - L_q) i_d i_q\right]$

Implementation of Vector Control

❑ The transformation of the variables into a rotating reference frame facilitates the instantaneous torque control of an AC machine similar to that of a dc machine.



Induction Motor Drive Implementation



Connection: 3 cables

Rotor currents:
- Generate heat

Inverter:
- Standard 6 switches
- Diodes in parallel with Mosfets/IGBTs
- Power shoot-through if short-circuit

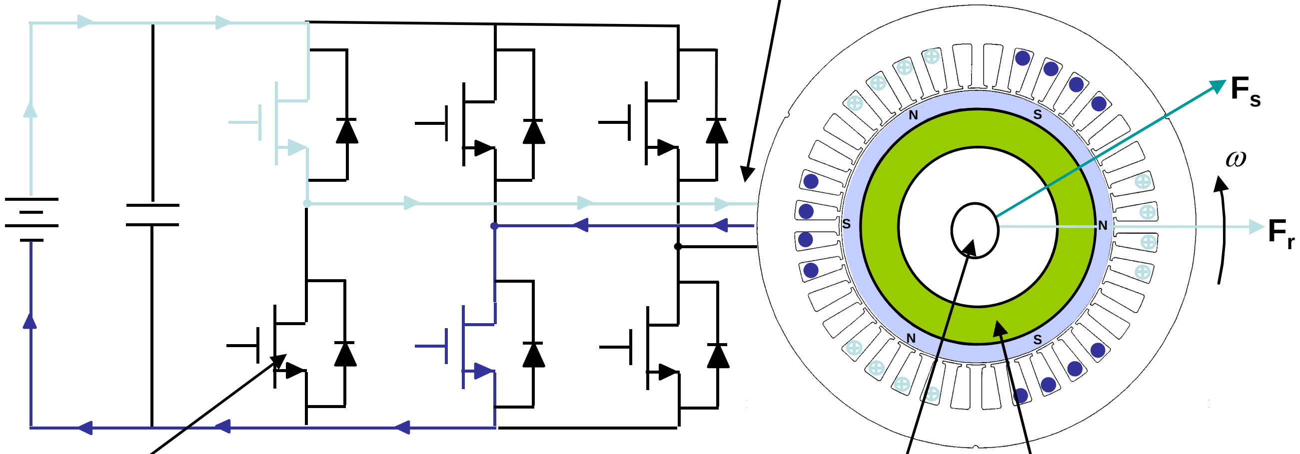
Excitation:
- Comes from stator
- Efficiency (-)
- Small airgap (-)

Motor position sensor:
- Incremental, Resolver

Controller: Well known

- **95% of world motors are induction**
  - **Large body of knowledge**

PM Drive Implementation



Connection: 3 cables

Inverter:
- Standard 6 switches
- Diodes in parallel with Mosfets/IGBTs
- Power shoot-through if short-circuit

Magnets:
- Material cost (-)
- Motor assembly issues (-)
- Larger airgaps (+)

Controller:
- Trapezoidal: Simple switching scheme
- Sinusoidal: Well known
- High Speed Control

Motor position sensor:
- Trapezoidal: Low resolution
- Sinusoidal: High resolution

PMSM: High Speed Control

- Magnet flux is fixed, imposes top speed

Magnet flux

$$V = N\frac{d\Phi}{d\theta}\omega$$

- Field weakening techniques possible
  - Require current excitation from stator
- Techniques well known, but
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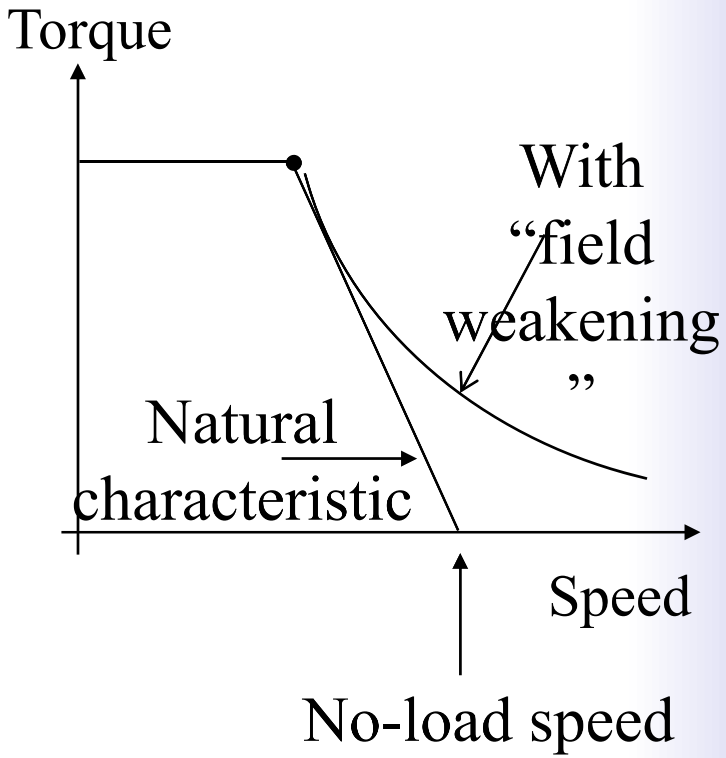
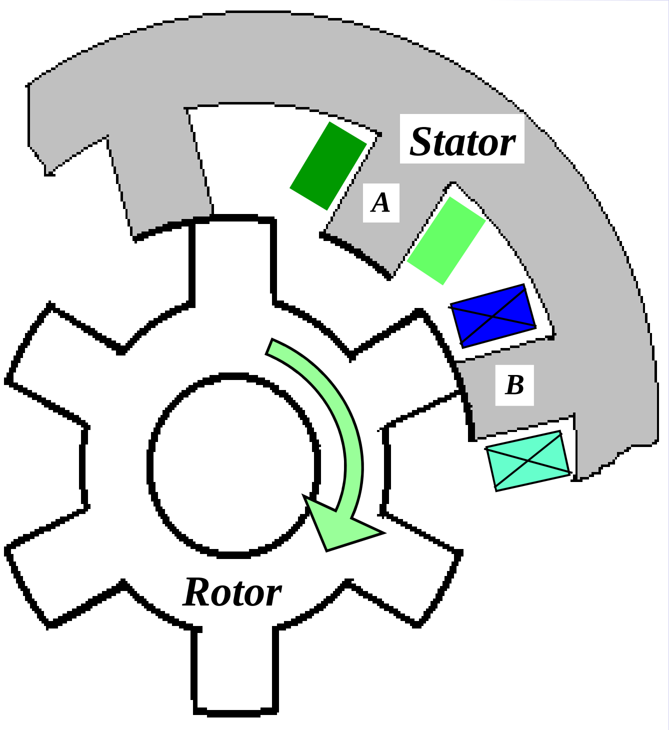
  - Efficiency advantage lost at high speed, light loads
- Interior/Buried magnets preferable

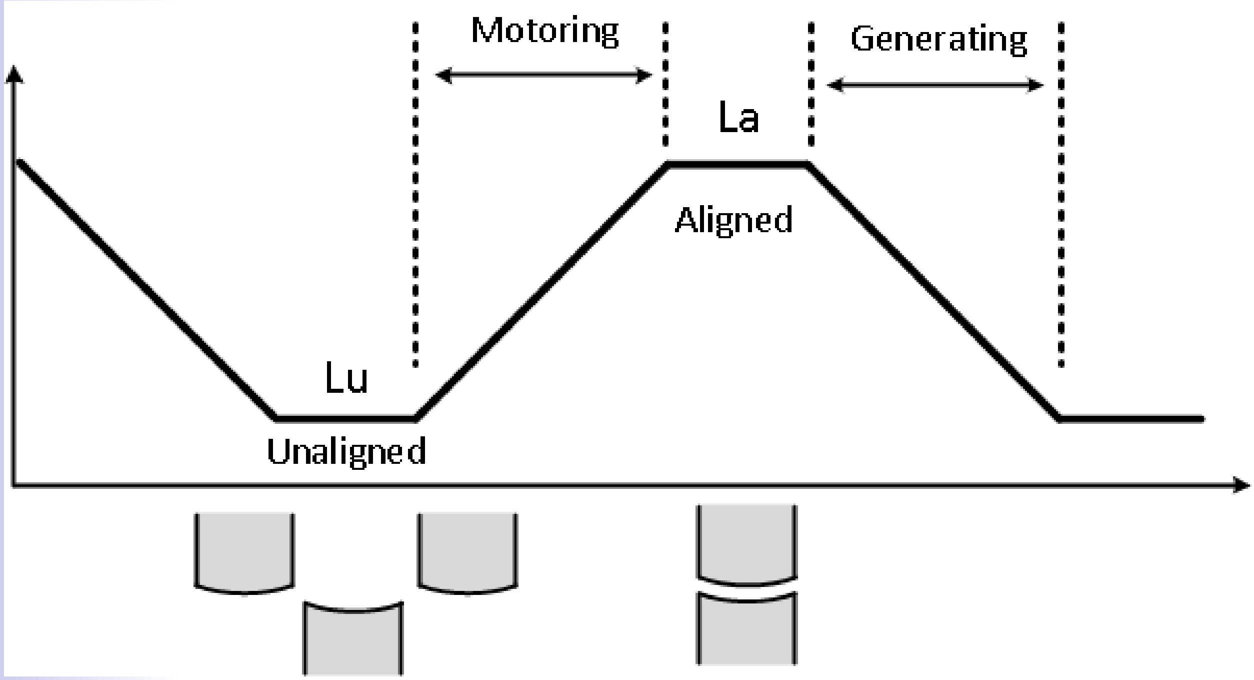


Reluctance Principle

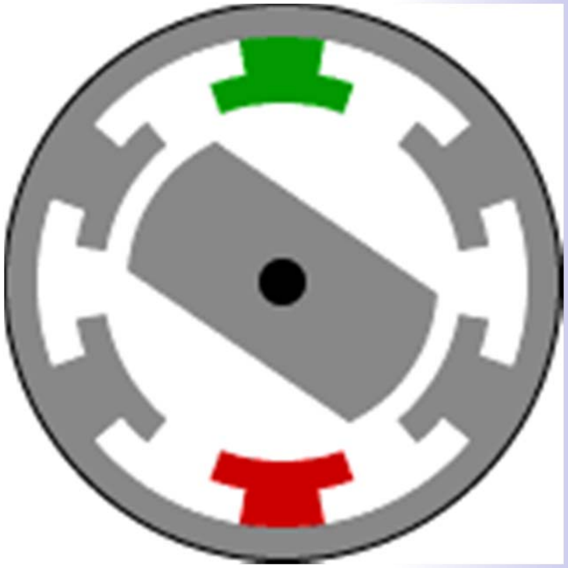
- Each phase excited one at a time
  - Phase B, then A…
- No rotating fields per se
  - Sequential excitation along the periphery
- Each phase independent of the other ones
  - Machine acts like engine with separate cylinders
- Common constructions:
  - 4 phases: smoother torque, better starting torque
  - 3 phases: higher speed, cheaper



Basic Principles of SRM



Inductance profile of SRM

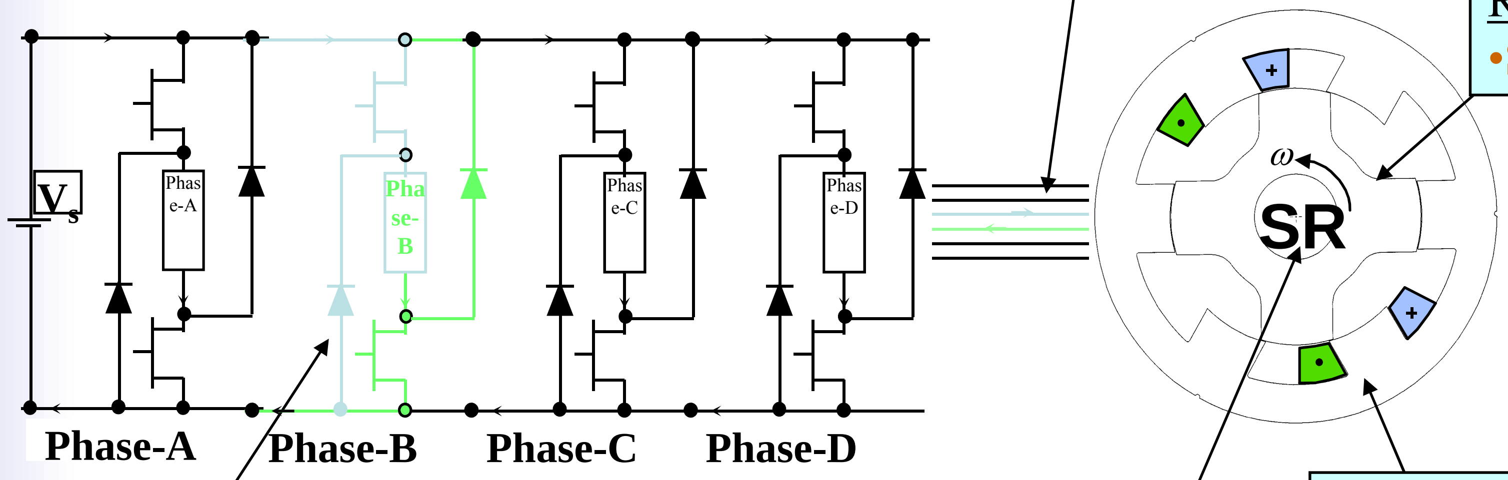


- Commonly used SRM configurations are 3 phase 6/4 , 12/8, 18/12 and 4-phase 8/6, 16/12.
- The torque equation is

$$T_e = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

- During the positive dL/dθ we get the motoring torque

Switched Reluctance Motor Drive



Connection: 6 or 8 cables

Rotor:
- Simple

Excitation:
- Comes from stator
- Small airgap (-)
- Simple coils

Inverter:
- Non standard
- Diodes not in parallel with Mosfets/IGBTs
- Power shoot-through impossible

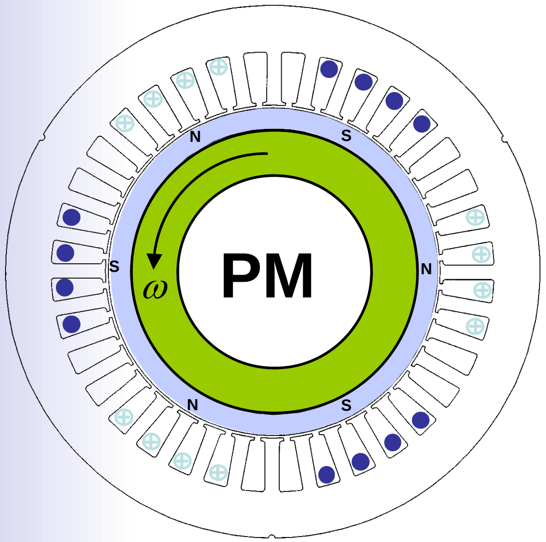
Motor position sensor:
High resolution

Controller:
- Careful design needed

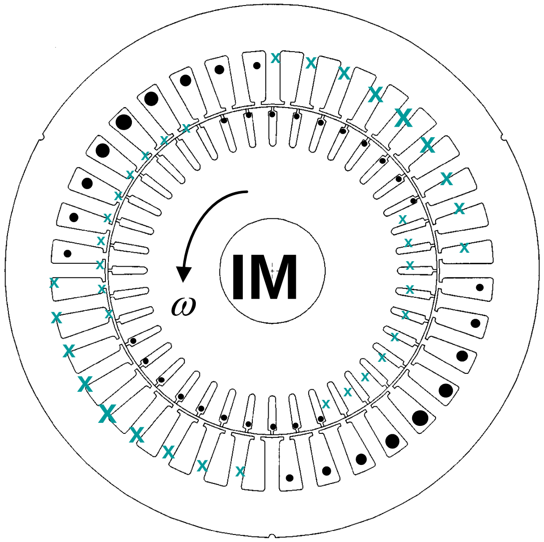
Comparison of SRM with PMSM

Comparison	PMSM	SRM
Torque density	High	Medium
Torque ripple	Excellent	Poor
Acoustic Noise	Excellent	Poor
Cost	High	Low
Controller cost	Moderate	High
PM Material	Yes	No
Position sensor	Required	Required
Fault tolerant	Poor	Excellent
Winding	Depends on slot/pole Configuration	Around the tooth Winding
Reliability	Medium	High

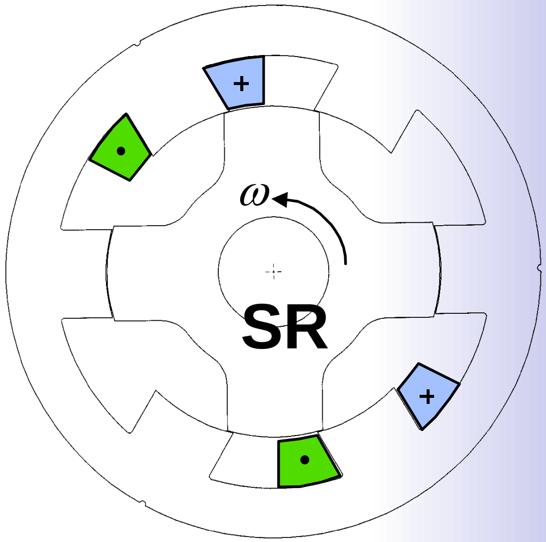
Cooling Comparison



PM Motor



Induction Motor



SR Motor

- **Distributed winding easy to cool**
- **Magnet temperature < 150^{o}C**

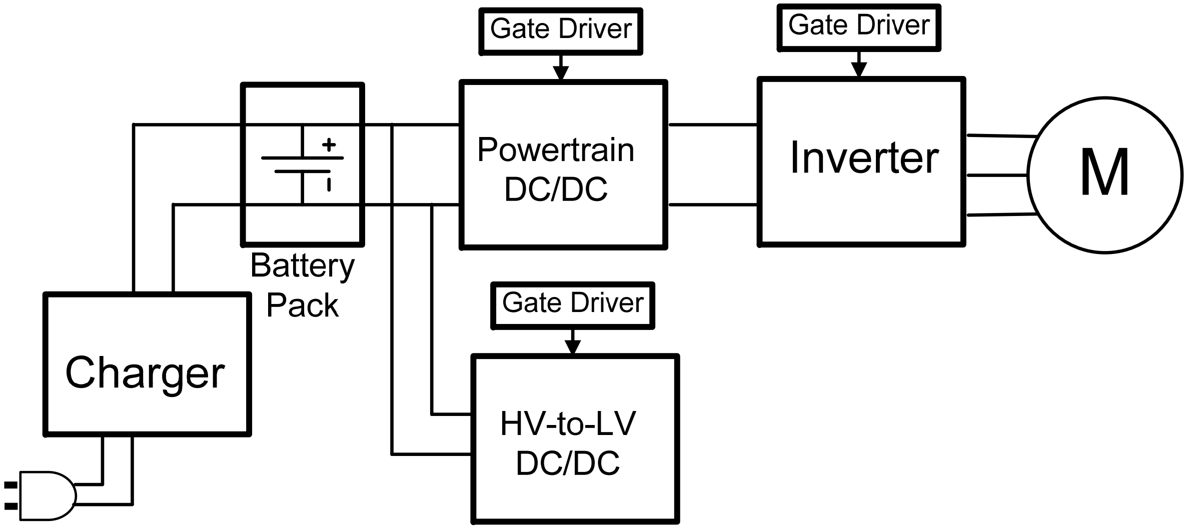
- **Distributed winding easy to cool**
- **Rotor currents constant source of heat**

- Rotor losses due to hysteresis, windage (at high speed)
- **Concentrated windings harder to cool**

Power Electronics in EV/HEVs

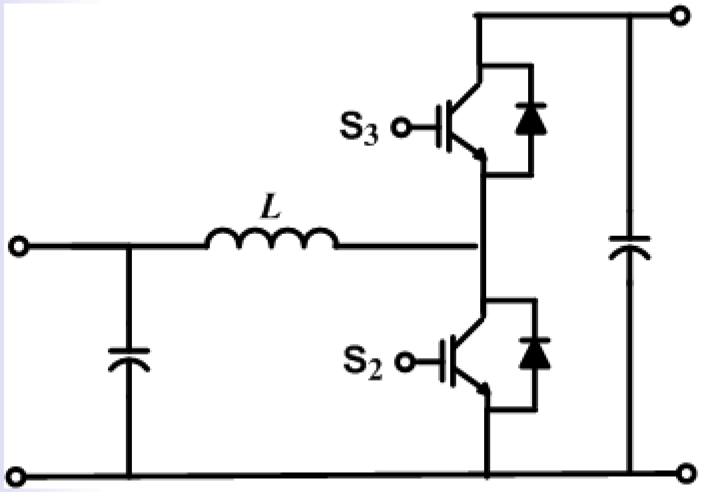
Power Converters in EV/HEVs

- Power Converters needed for:
  - Powertrain DC/DC converter
  - HV-to-LV DC/DC Converter
  - Battery charger
  - BMS of battery packs may also use DC/DC converters

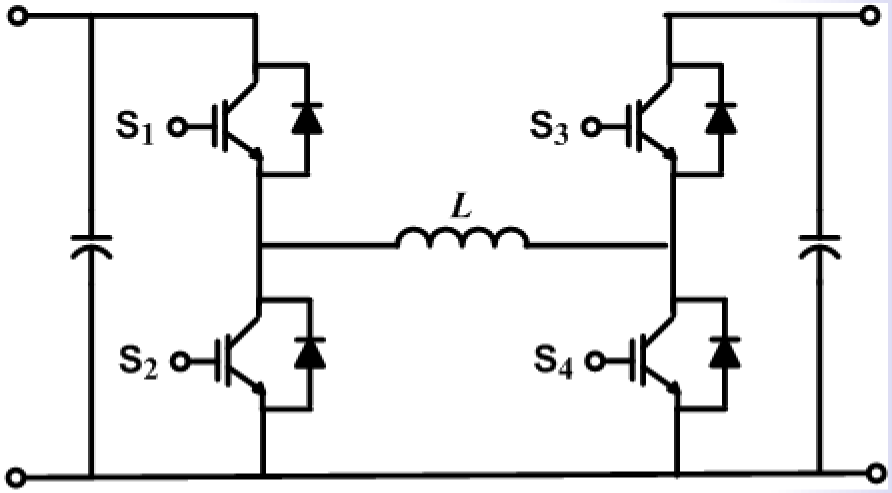


HV DC/DC Converter

- Designed for bi-directional power flow between DC bus and HV battery system
- Non-isolated type
- Design required for appropriate sizing, input/output filters and mechanical interface



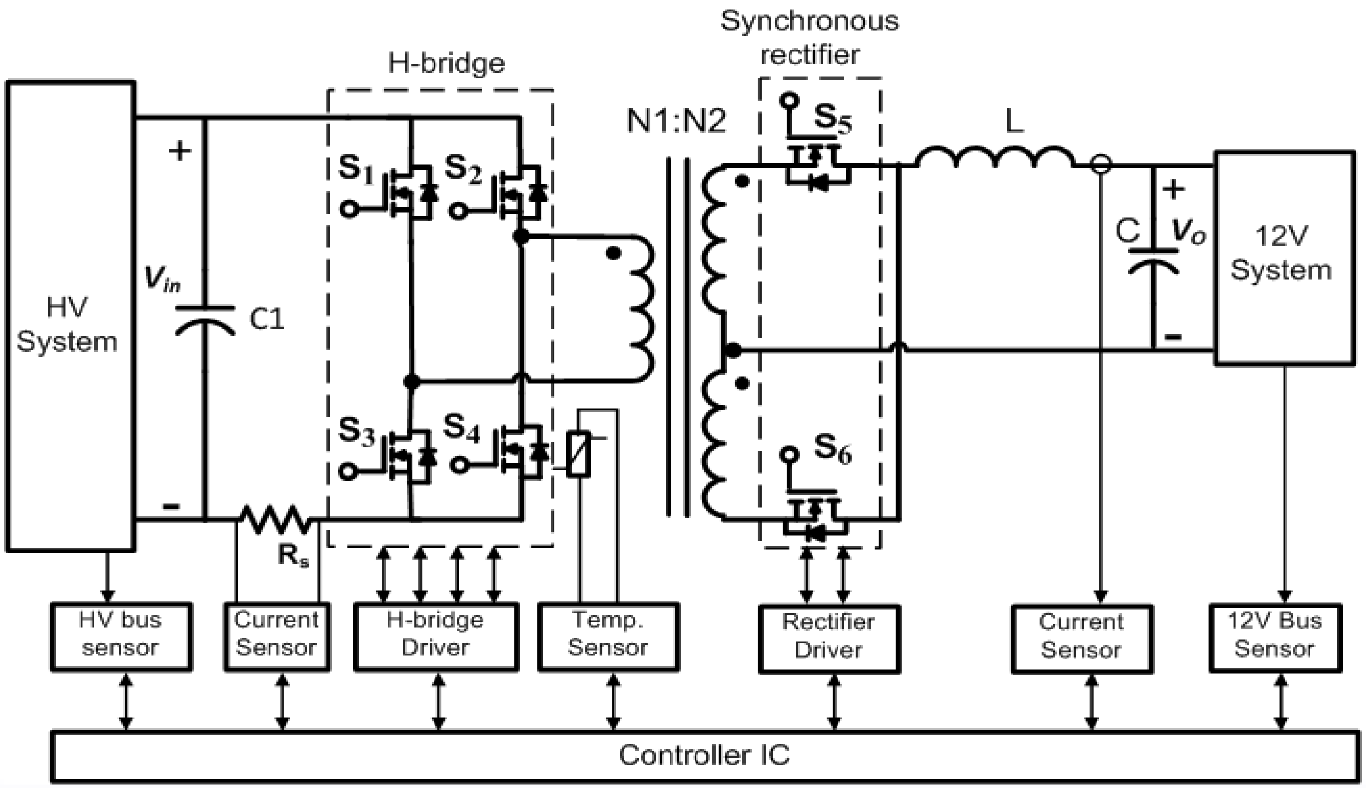
Boost-buck cascaded half- bridge topology



Boost-buck cascaded full- bridge topology

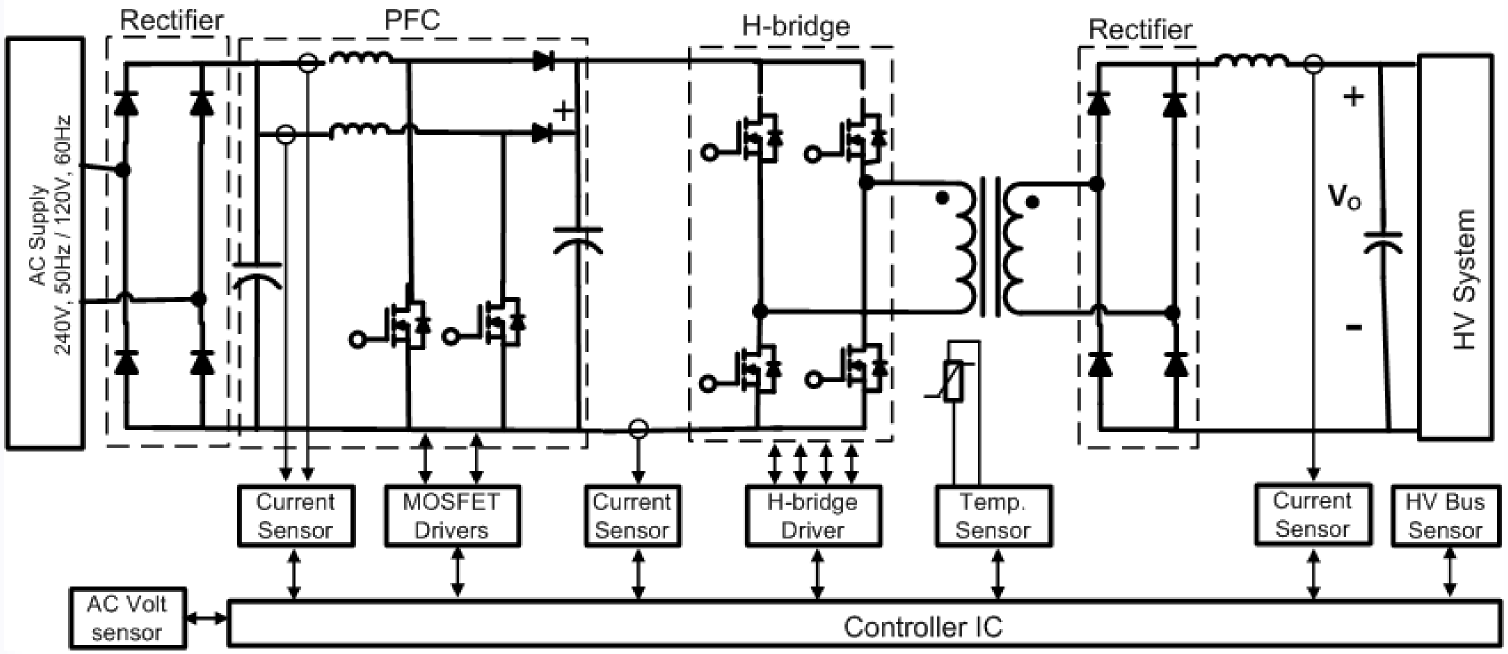
HV/LV DC/DC Converter

- Isolated type
- Full-bridge topology used
- Higher frequency devices

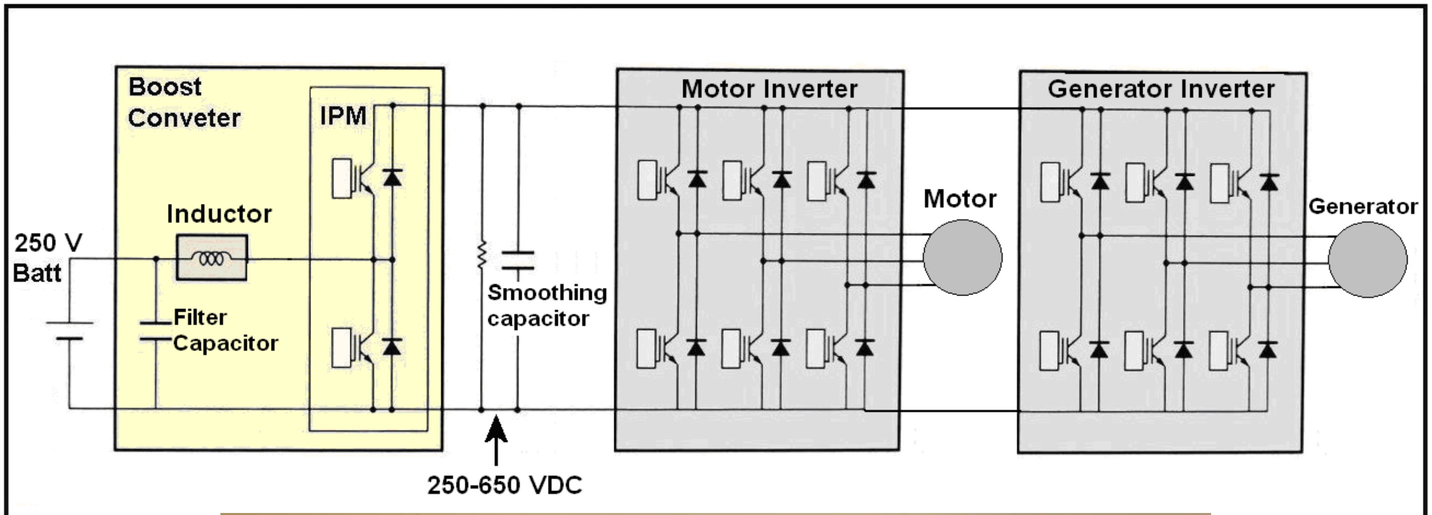


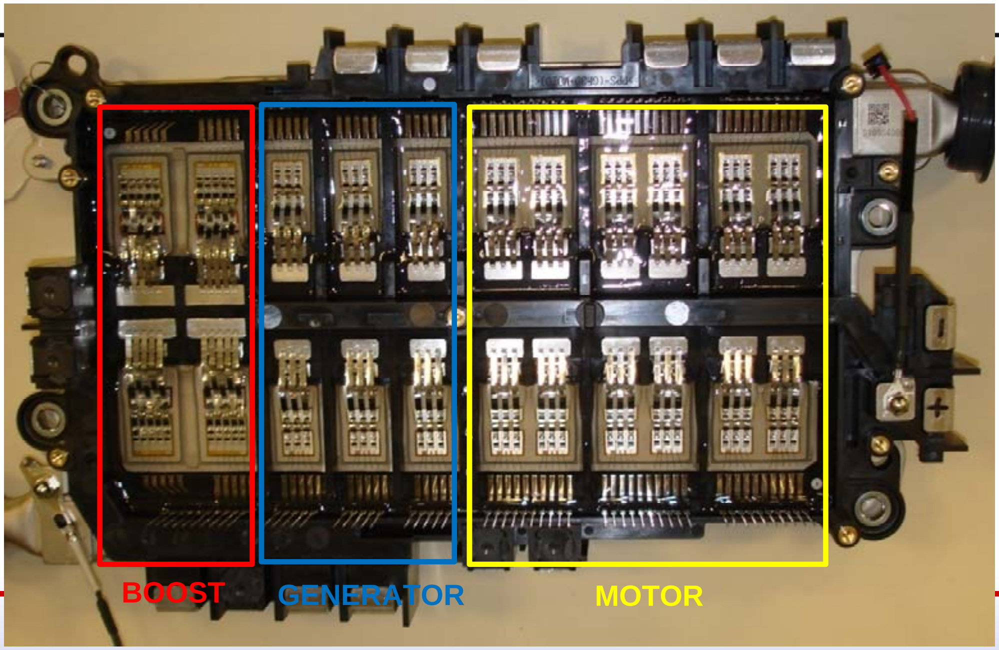
Battery Charger

- Charger Design Trends
  - Fast chargers
  - Off-board charger
  - Wireless charger



2010 Prius Power Electronic Schematic





Source: Evaluation of 2007 Toyota Camry Hybrid Synergy Drive System, DOE Report ORNL/TM-2007/190, 2008.

Power Electronics Challenges

- ✓ ***Quality & Reliability***
  - ✓ Life Expectancy
  - ✓ PE Multidisciplinary
  - ✓ Harsh Environment

- ✓ ***Size & Cost***
  - ✓ Low cost low mass
  - ✓ Silicon Technology
  - ✓ Power Stage Topology
  - ✓ System Understanding
  - ✓ Customer Usage Profile

- ✓ ***Efficiency & Performance***
  - ✓ Peak-to-Average Current Ratio
  - ✓ Increased Functionality
  - ✓ Silicon Characteristic Optimization

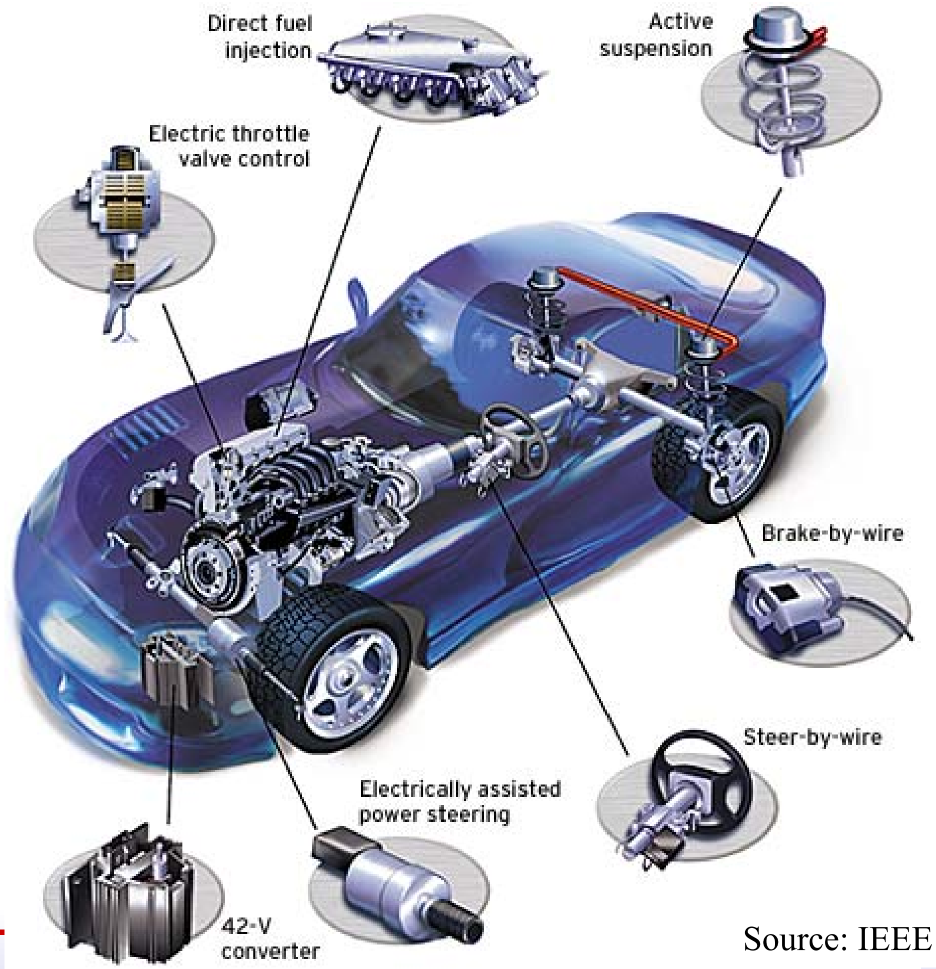
- ✓ ***Safety & Fault Protection***
  - ✓ Shutdown Unacceptable
  - ✓ Complex Failure Mechanism
  - ✓ On-Board-Diagnostic

- ✓ ***Lower Warranty Cost***
- ✓ ***Reach Scalable Common Parts***
- ✓ ***Standardize Safety and Diagnostic Requirement***

Automotive Motor Drive Systems

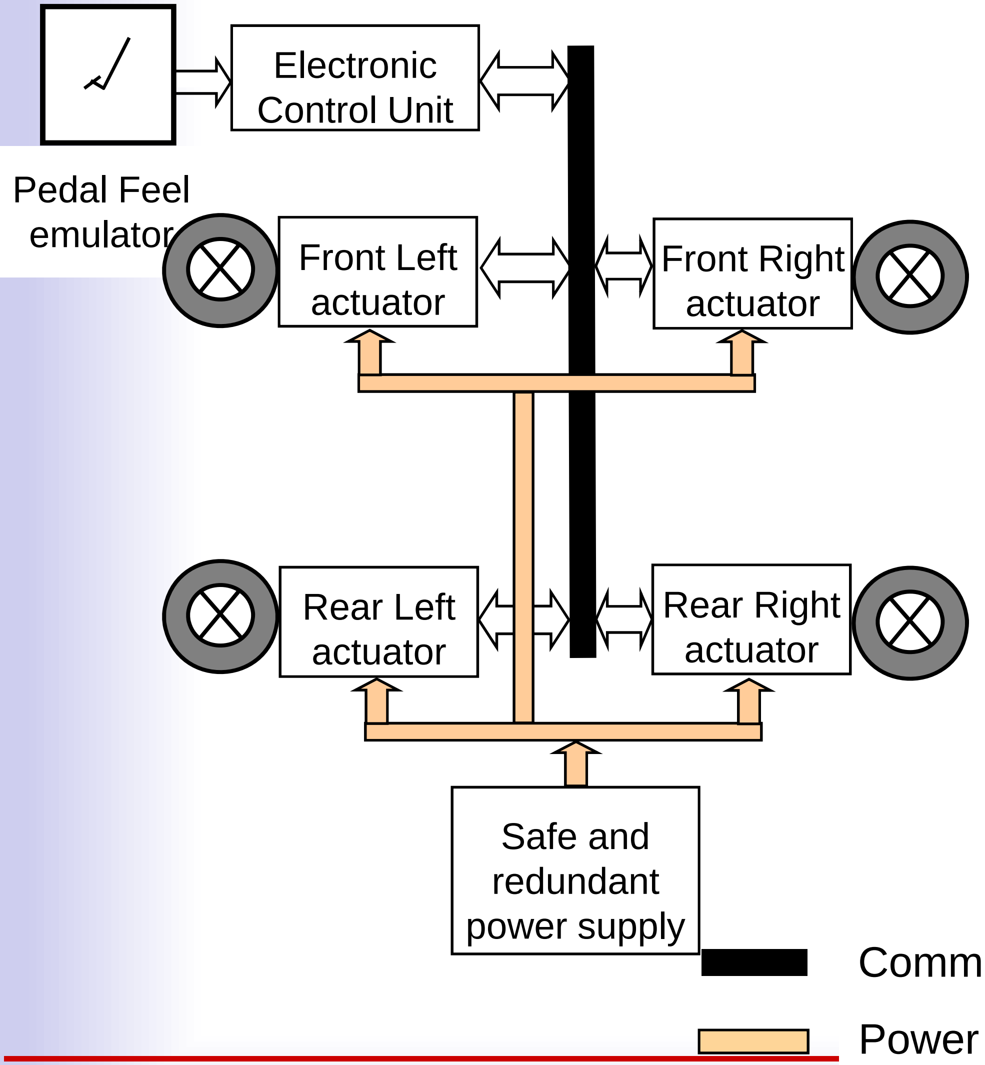
X-by-Wire Cars

Performance and safety will improve as mechanical systems in cars give way to electromechanical systems



Source: IEEE Spectrum

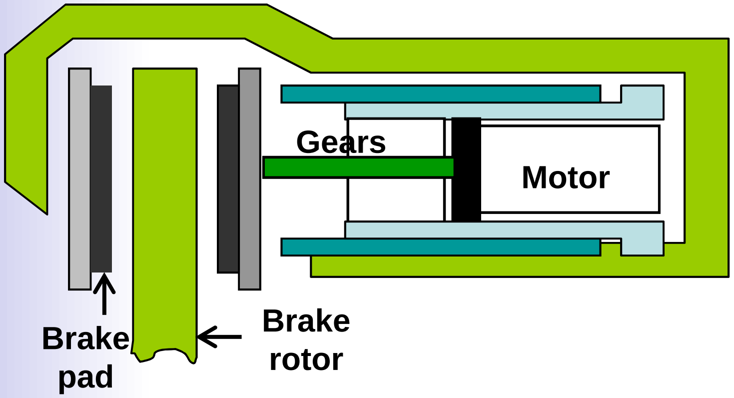
Electromechanical Brake System: Motivation and System Structure



- Can support all the functionalities of the conventional hydraulic brakes, PLUS:
- Advantages:
  - Improved packaging and easier assembly, no need for hydraulic pumps, eliminates brake fluid
  - Potential improvement in fuel economy due to less drag
  - Faster dynamic response
  - Easy to incorporate safety and stability related functionalities
- Could be all 4-corner electric brakes or could be front hydraulic and rear electric (hybrid)

Typical EMB operation and control

EMB unit



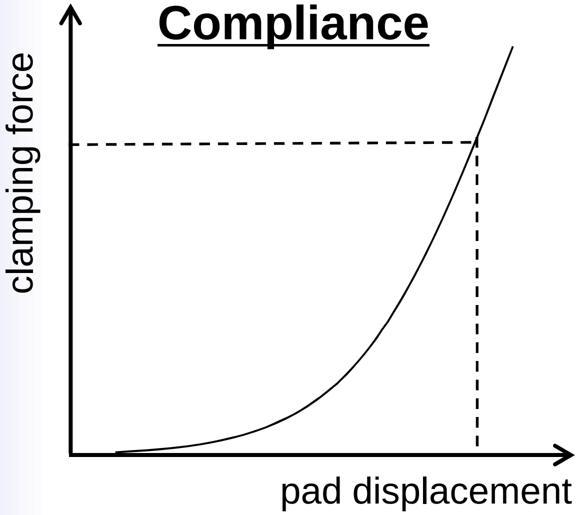
Gears

Motor

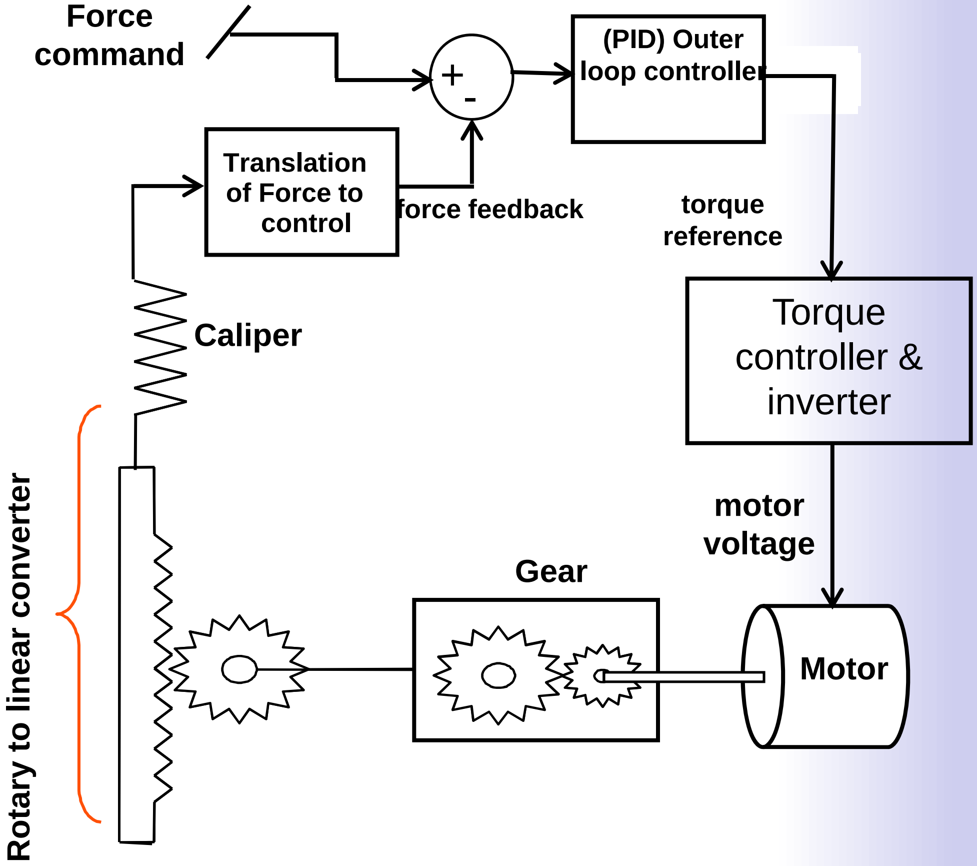
Brake pad

Brake rotor

Compliance



EMB control system



Force command

+

-

(PID) Outer loop controller

Translation of Force to control

force feedback

torque reference

Torque controller & inverter

Caliper

motor voltage

Gear

Motor

Rotary to linear converter

Gen 1 and Gen 1.75 SRM EMB

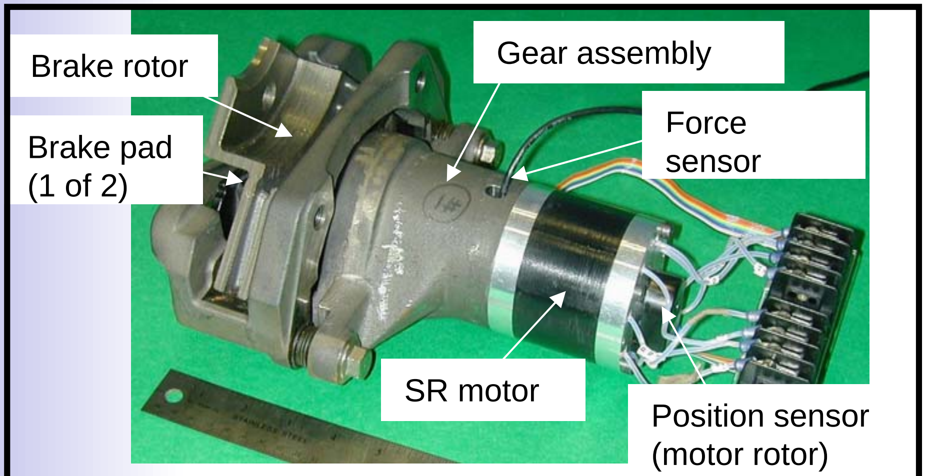
Calipers

Gen 1 (Front 42 V)

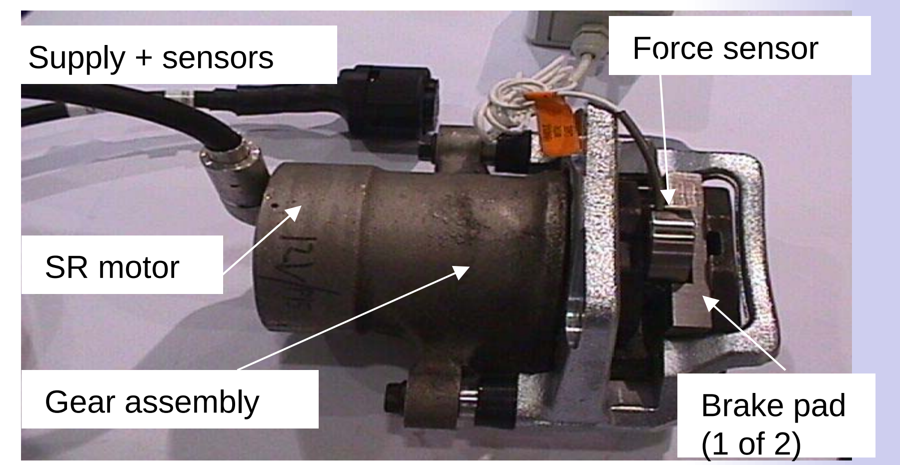
◆ Max clamping force = 27 kN
◆ Motor not integrated.

Gen 1.75 (Rear 14 V)

- Max clamping force = 20 kN
- Motor integrated.



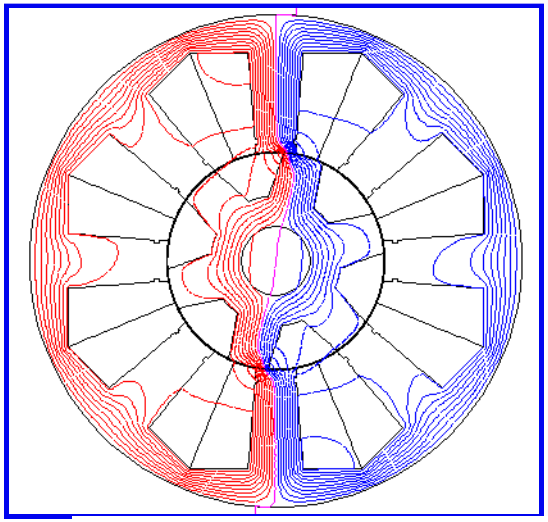
Photograph of Electric Caliper System (Gen 1)



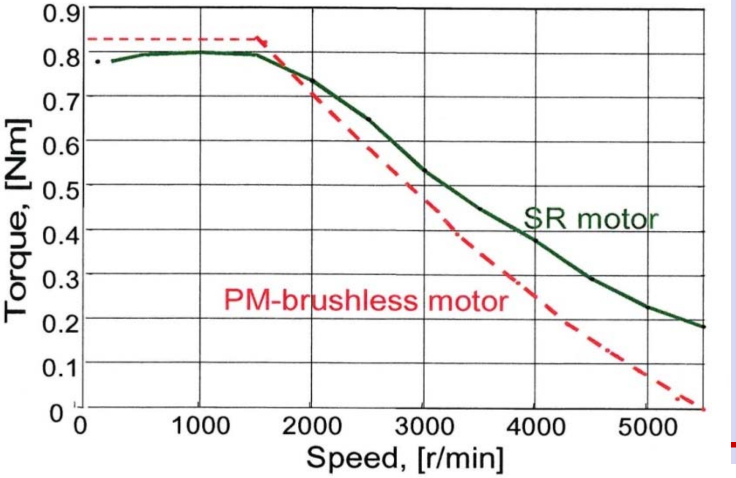
Photograph of Electric Caliper System (Gen 1.75)

Comparison of SRM and PM EMB Systems

- SRM Drive developed at University
- Comparable PM drive developed by Industry
- Motor design
  - <u>Packaging constraint</u>: outer diameter was limited; there was flexibility in choosing the length
  - <u>PM</u>: concentrated winding with sinusoidal back emf and trapezoidal excitation
  - <u>SR</u>: 8/6 design, optimized for maximum torque per ampere
- Static curves measured on dyno showed similar T-ω characteristics
- To achieve similar characteristics, the SR motor had to be 22% longer and needed 15% higher dc bus current



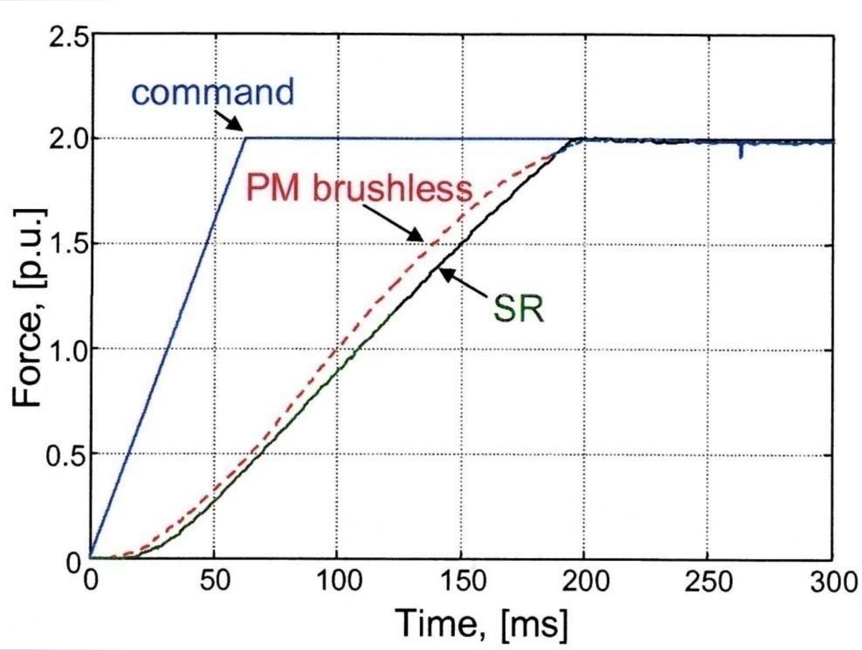
SRM FEA results



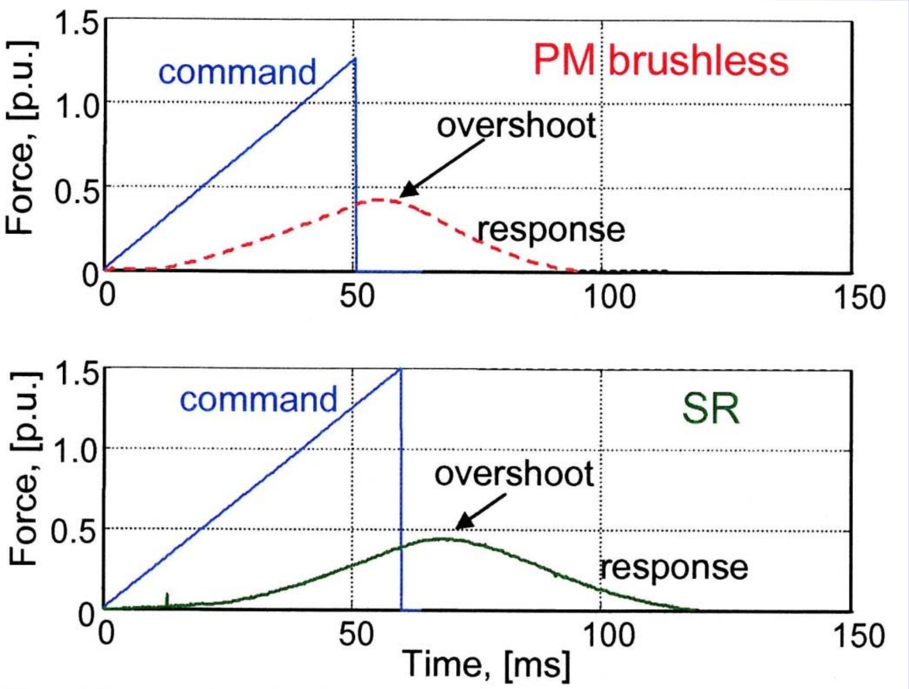
Measured static characteristics (dyno)

Dynamic Performance

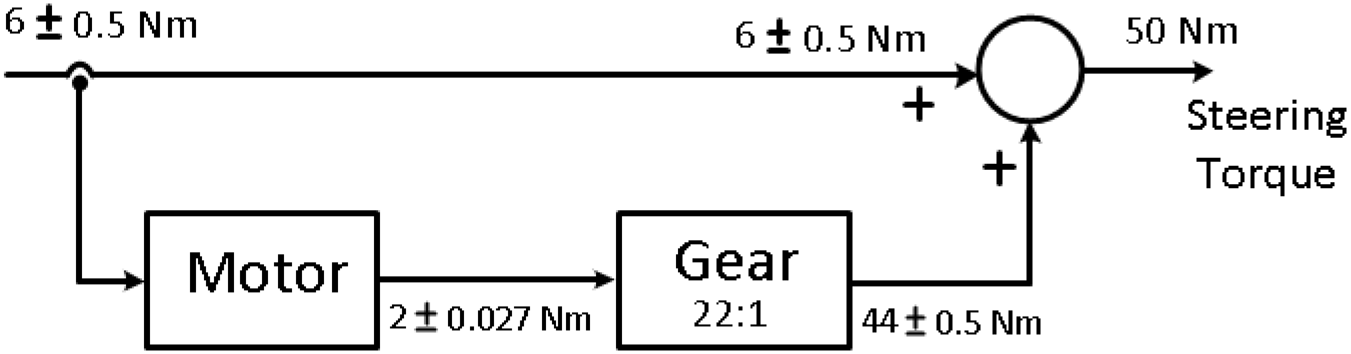
Brake apply



Brake apply-release



EPS System



6 ± 0.5 Nm

6 ± 0.5 Nm

50 Nm

+

+

Steering Torque

Motor

2 ± 0.027 Nm

Gear 22:1

44 ± 0.5 Nm

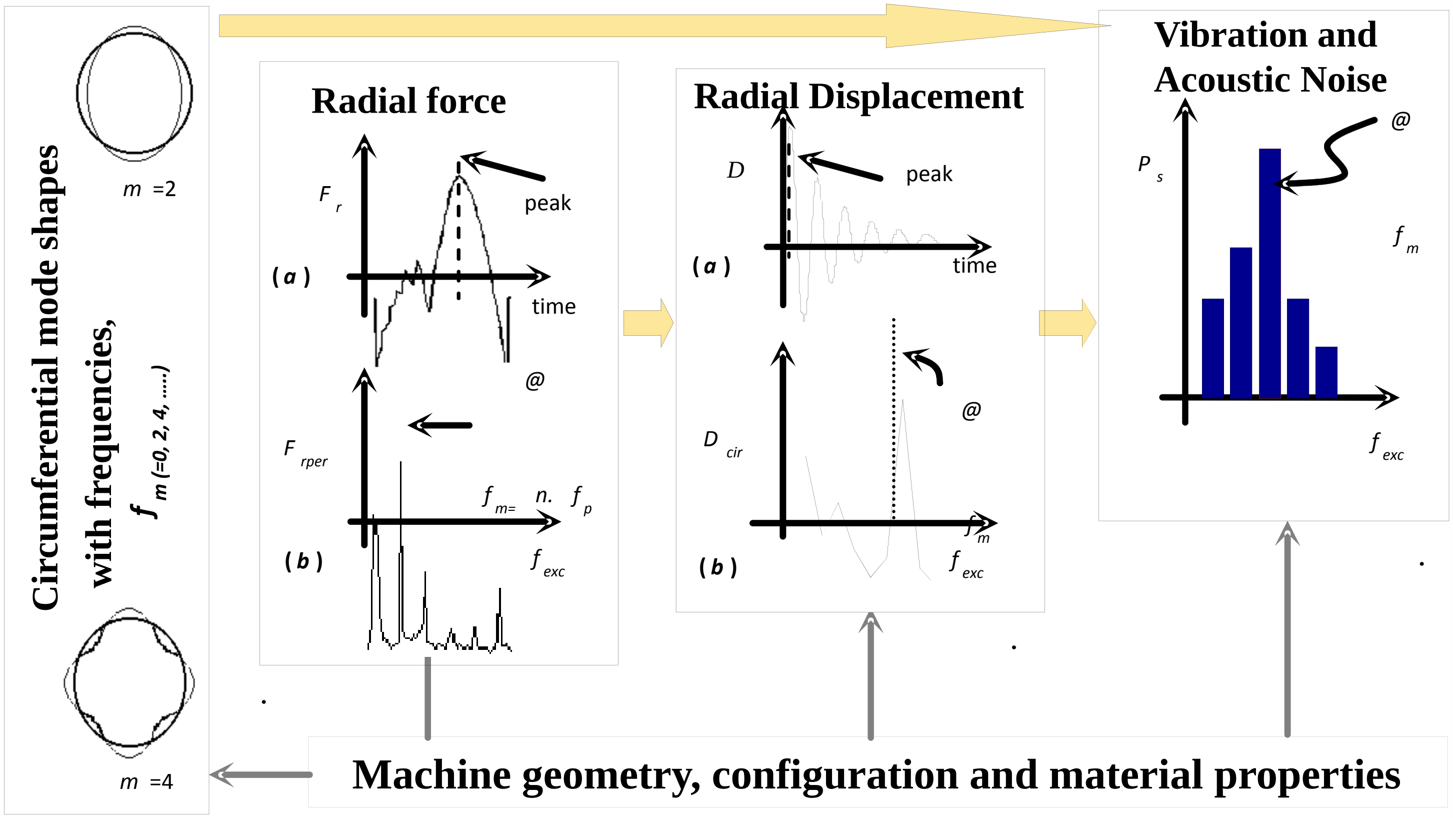
PMSM Design and Analysis for EPS

- Objective: Find the root cause of electromagnetic noise and vibration in PMSMs

  Design a PMSM with vibration and torque ripple minimization for electric power steering
- Four Different Geometries Analyzed
  - 12/10, 12/8, 9/6, and 27/6 slot pole combinations
  - Output dimensions and torque/power specifications are the same
- Outcome: Analytical Model for predicting noise and vibration in PMSMs

  Theoretically and experimentally verified design

Noise and Vibration Modeling in Machines



Circumferential mode shapes with frequencies, $f_{m\,(=0,2,4,\ldots)}$

Radial force

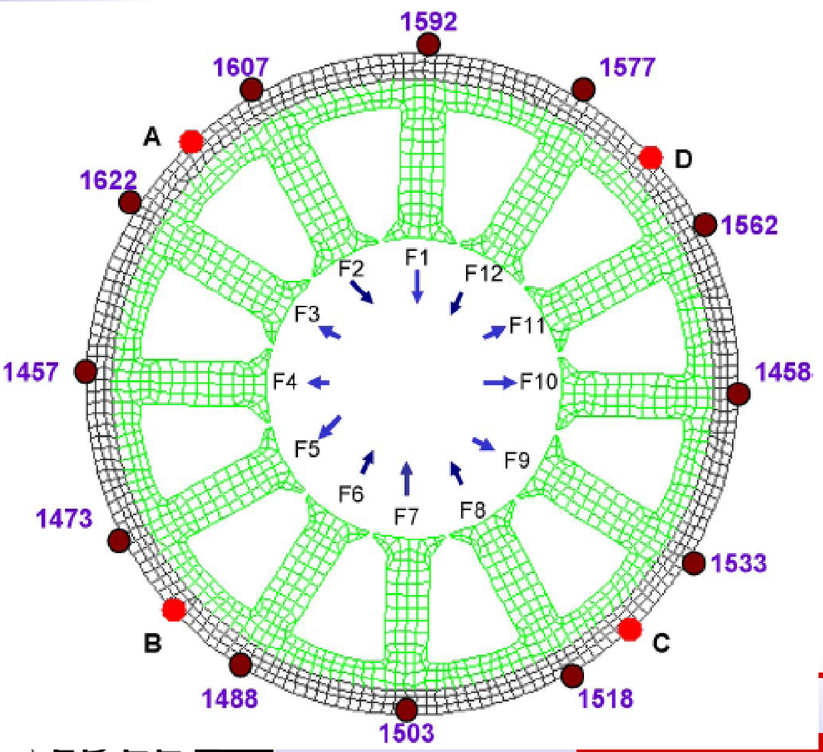
Radial Displacement

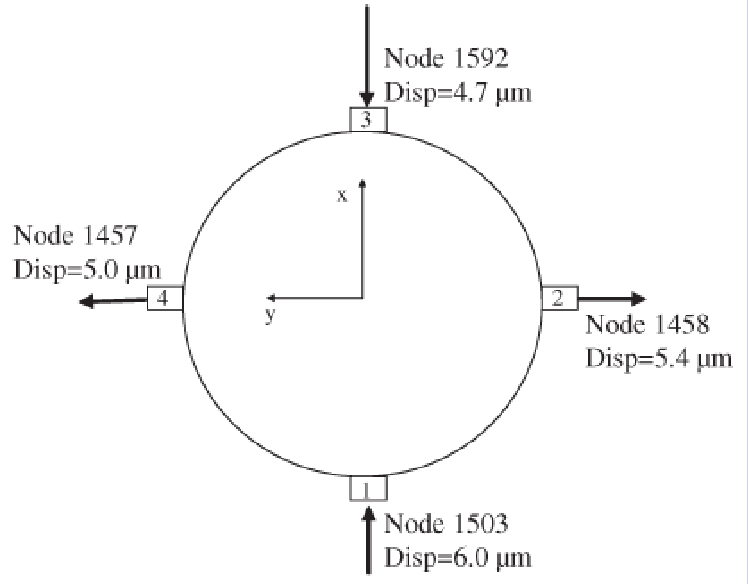
Vibration and Acoustic Noise

Machine geometry, configuration and material properties

Radial Displacement: Structural FEA and Experimental Results

- **Structural**
  - ✓6-pairs of radial forces
  - ✓Used in structural FE model (ANSYS)
- **Experimental**
  - ✓Experimental results taken at 4-nodes. Magnitude similar to structural FEA





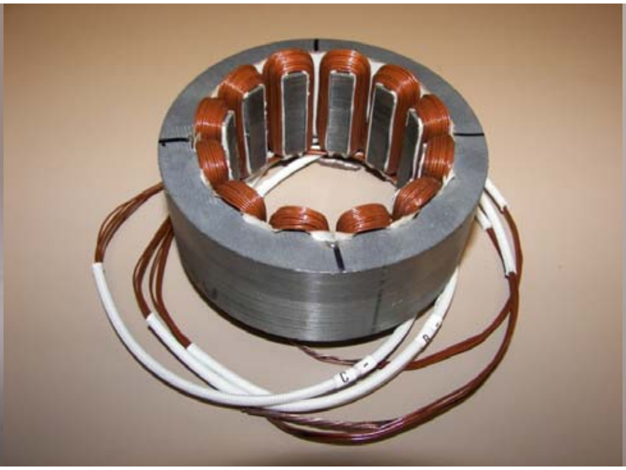
COMPARISON AMONG ANALYTICAL, FEA, AND TEST RESULTS

Displacement in 12s10p PMSM, mm			
Analytical model	Node #s	Structural FE (max)	Test
4.10e-3	1592	5.59e-3	4.7e-3
	1457	5.34e-3	5.0e-3
	1458	5.62e-3	5.4e-3
	1503	6.36e-3	6.0e-3

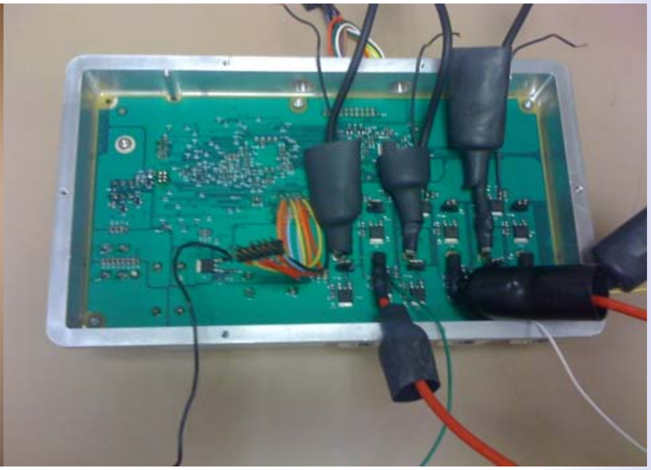
SRM Based EPS System

- SRM design for EPS with minimized torque ripple
- 12/8   Three phase SRM
- DSP based controller

Rotor



Stator



Controller

Conclusions

- Systems level perspective is essential in all projects
- Theoretical analysis based on the fundamentals leading to modeling and further analysis
- Analytical models to be verified or complemented with computational tools
- Experimental verification is essential