Electric traction machine choices for hybrid & electric vehicles

Presented for:

FLORIDA INTERNATIONAL UNIVERSITY

by

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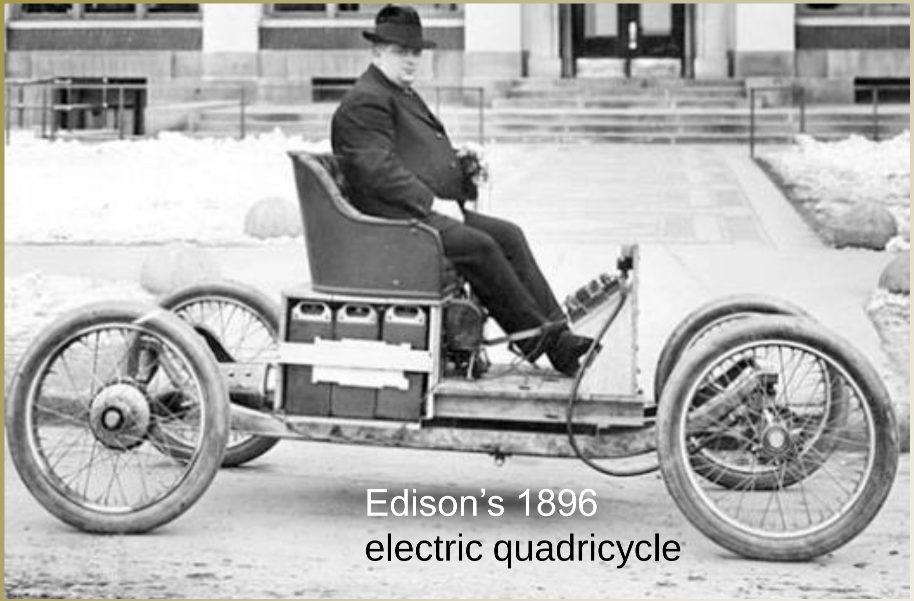
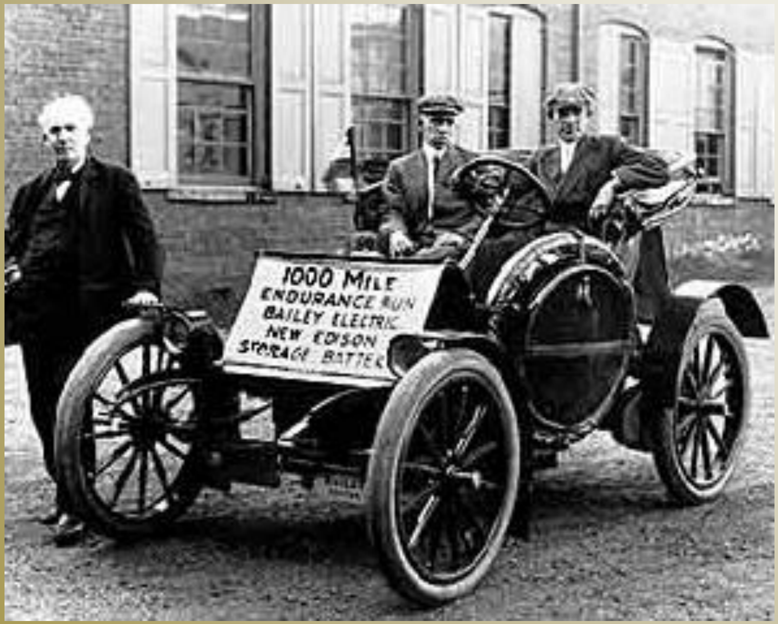
Edited by. Prof. Dr. Ernie Freeman

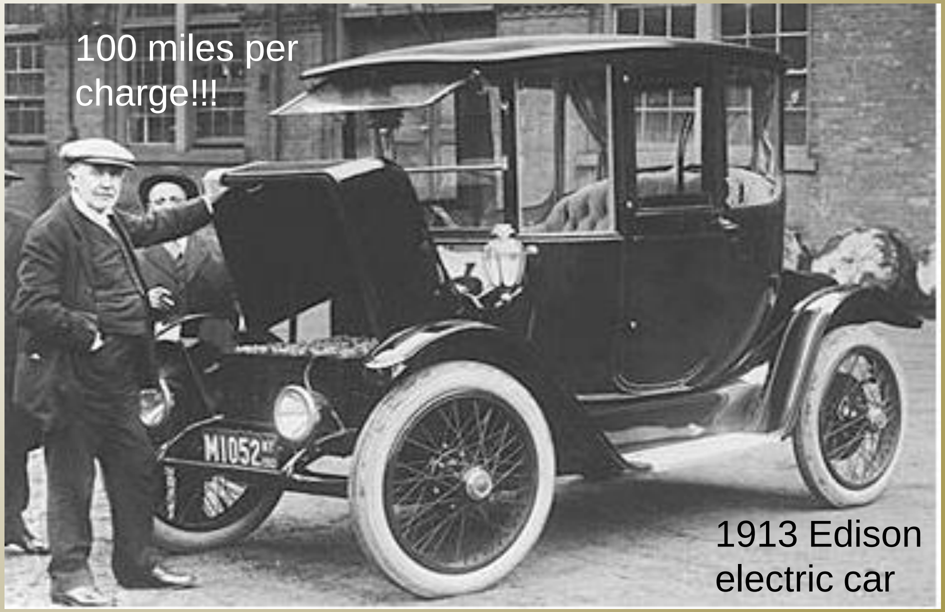
Early electric cars in USA



Edison's 1896 electric quadricycle

Allison driving early Ford-Edison car

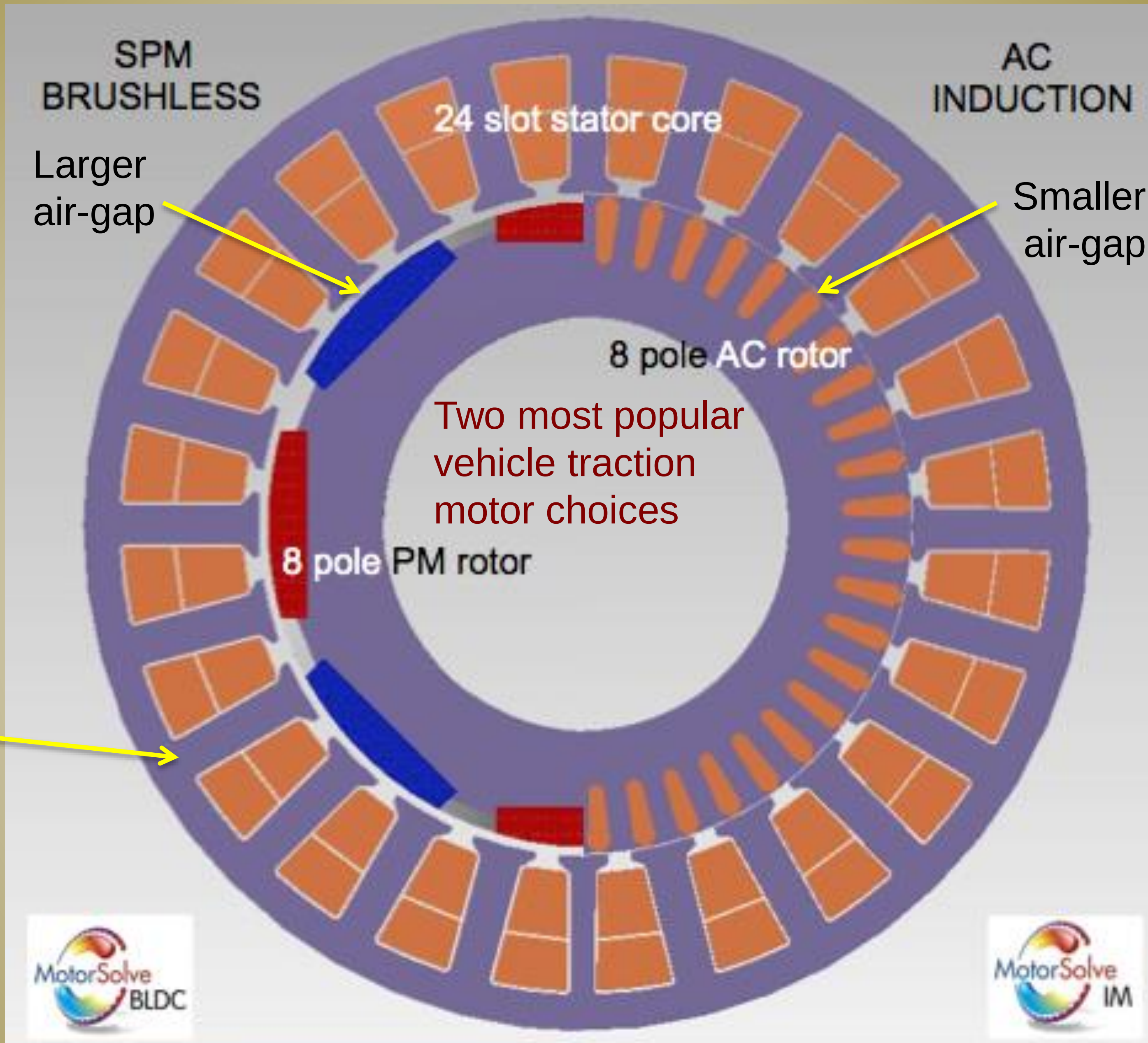




100 miles per charge!!!

1913 Edison electric car

As we approach 2015 there are a bunch of Hybrids or plug-ins being produced around the world with many more to come



Larger air-gap

Smaller air-gap

Two most popular vehicle traction motor choices

Brushless stator design typical of an AC Induction machine

Abstract:

"Electric traction machine choices for hybrid & electric vehicles"

How and why did the design engineers decide which electric machine type to develop for modern hybrid & pure electric vehicles? Similar machine types seem to be used in all hybrids. The all electric vehicles have been developed using a different machine topology. This presentation reviews the Toyota Prius Hybrid vehicle and many that followed to gain insight to this question.

It is the author's desire the engineers interested in vehicle traction motor design and selection will come away with a clear understanding of the choices, some tradeoffs and a starting place in mind for their own efforts.

Many photographs and details are presented for the drive train of nearly every such vehicle currently in production. Knowledge of what has been done before makes sure that re-invention is avoided.

"In order to be a creator of progress It is better to stand on the shoulders of those before you to enable you to see over their heads into the future"

Paraphrased from Isaac Newton"

17 years have now passed now since Toyota came out with the first Prius
(One year after the GM EV-1)

General Motors came out with the first production electric vehicle in 1996

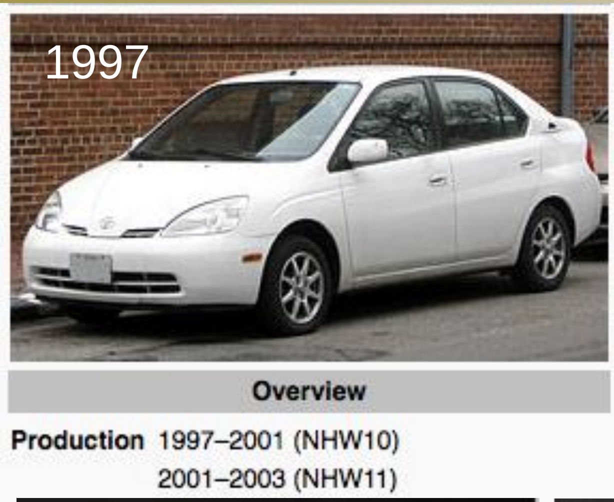
Going back further, Thomas Edison came out with an electric car in 1895

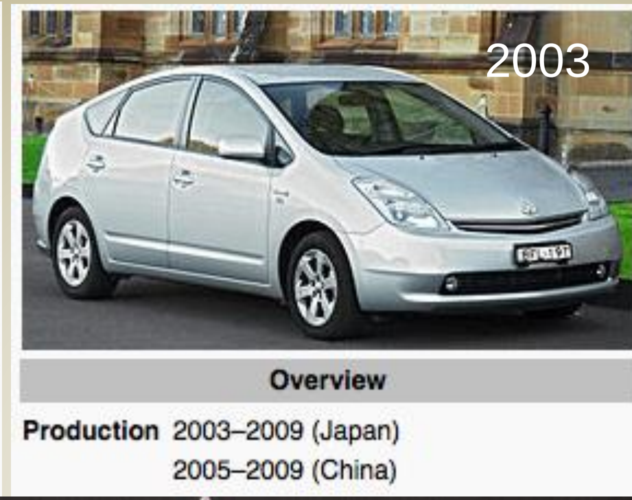
Interesting results since 1996 (date of first Prius)

Only production car using an AC Induction motor for traction is the TESLA
GM Volt rumored to use both an IPM and and AC induction motor for VOLT
All other hybrids and electric cars in production use IPMs

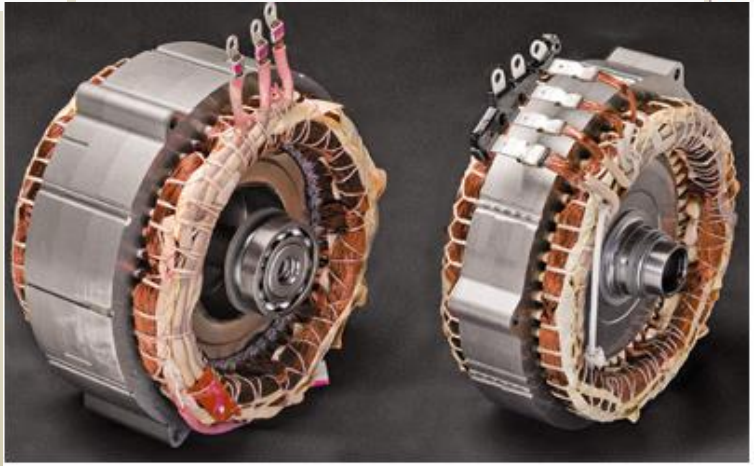
So my advice to you all is "don't re-invent any old motor concepts but only useful modifications of them or better still, new designs. Therefore we must have a quick look at the current electric cars and/or their electric motors to see what has already been done to make sure you drive on the right road !!

Toyota Prius (3,166,000 sold from1997 through mid 2013)

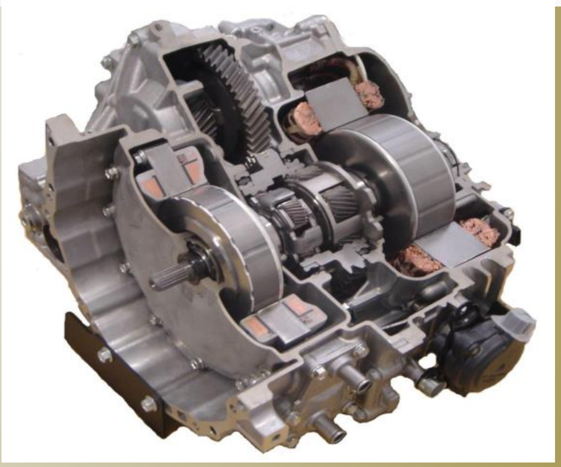




Rated 33 kW @ 4500 rpm
Max motor speed = 5600 rpm
Battery voltage = 288 VDC
DC to DC boost to 500 VDC
Peak torque = 350 Nm



Rated 50 kW @ 1200 to 1540 rpm
33 kW 1040 to 6,000 rpm max.
Battery voltage = 201.6 VDC
DC to DC boost to 500 VDC
Peak torque rating = 400 Nm



Rated 60 kW @ ?? rpm
Max motor speed =13,500 rpm
Battery voltage = 201.6 VDC
DC to DC boost to 650 VDC
Peak torque rating = 207 Nm

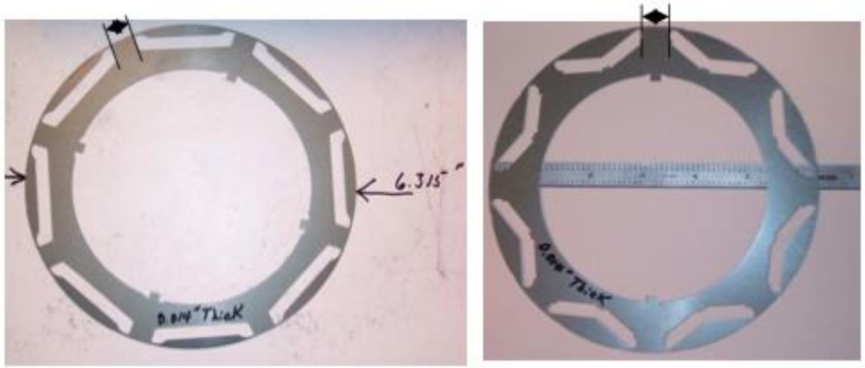
Comparison of Toyota, 2010 Prius, LS600 Lexus, Camry and 2004 Prius

Table 2.9. 2010 Prius, LS600h, Camry, and 2004 Prius generator design characteristics

Parameter	2010 Prius	LS 600h	Camry	2004 Prius	Comments
Lamination Dimensions					
Stator OD, mm	246.0	263.9	Same as LS	236.2	
Stator ID, mm	152.7	162.1	Same as LS	142.6	
Stator stack length, cm	2.7	7.07	3.58	3.05	
Rotor OD, mm	151.3	160.5	Same as LS	140.72	
Rotor lamination ID, mm	90.0	~87.0	95.63	85.09	
Lamination thickness, mm	0.305	~0.30	0.31	0.33	
Mass of Assemblies					
Rotor mass, kg	3.93	9.70	5.19	4.01	Includes rotor shaft
Stator mass, kg	8.58	20.50	12.09	9.16	
Stator Wiring					
Number of stator slots	12	48	48	48	
Number of wires per phase (number in parallel)		28 (14)	18 (9)	12	
Wire size, AWG	~15	20	20	20	

OAK RIDGE National Laboratory

Toyota has used such FEA simulation techniques to constantly improve their IPM designs for their Hybrid cars. Some examples shown below:



2003 **2004**

Fig. 4. Prius rotor punchings.

The width of bridges that contain the mechanical stresses holding the PMs against the centrifugal force has been optimized. A narrow bridge can reduce the leakage flux across the bridges and consequently can improve the motor performance.

Both the synchronous torque produced by the PM and the reluctance torque affect the final shape of the total torque. Figure 5 shows these torques components along with the resultant total torque of the 2004 motor.

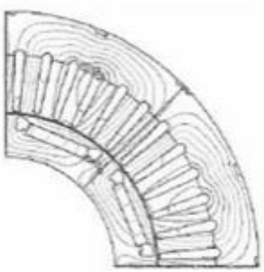


Figure 12
Torque Simulation by Electromagnetic Analysis

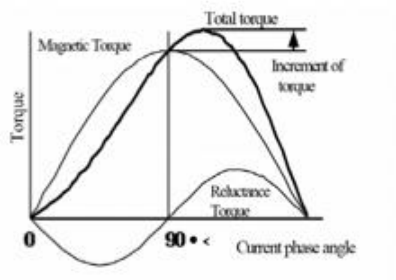


Figure 13
Torque-Current Phase Angle Characteristic

Fig. 5. Additional reluctance torque of Toyota Prius hybrid THS II motor.

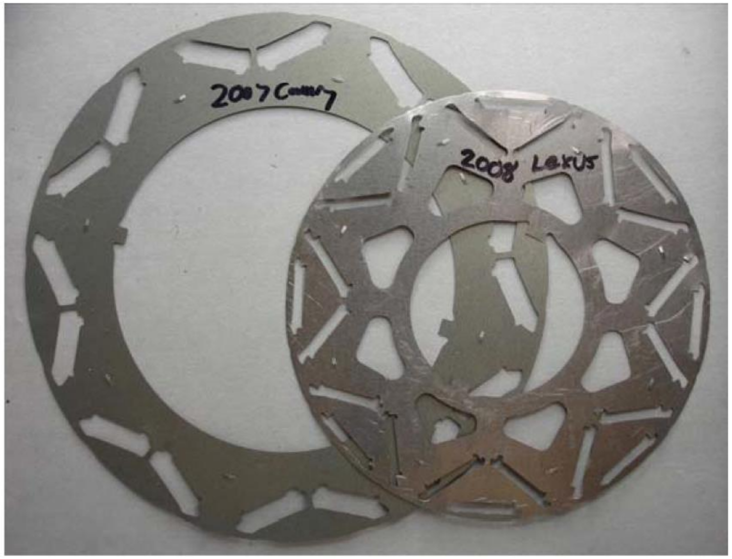
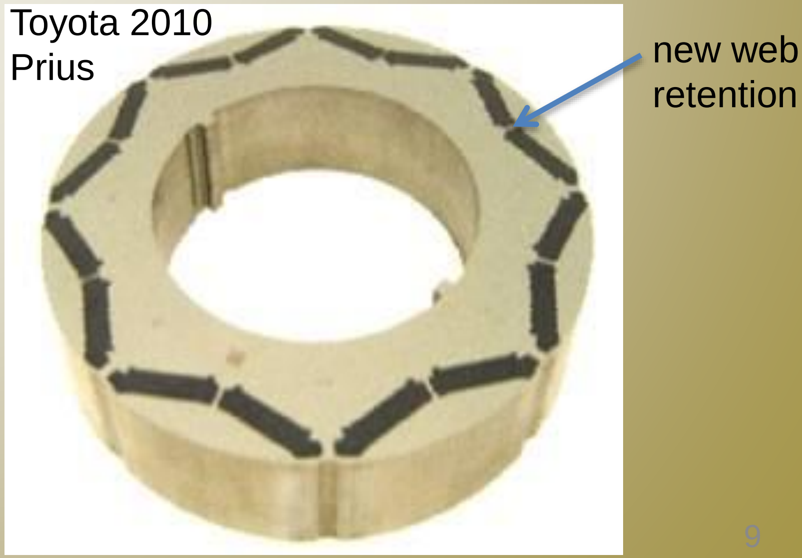


Fig. 2.69. Comparison of motor rotor laminations, Camry (left) vs. LS 600h (right).



Traction motor	3 phase AC Induction, aluminum rotor
Motor speed	0 to 7000 rpm
Rated output power	102 kW (137 hp)
Torque from 0 to 7 krpm	149 Nm (110 lbf-ft

Fixed gear ratio with no transmission
Original batteries “Deep cycle lead acid”, 312 VDC, 100 mile range
Delco-Remy “NiMH batteries”, 343 VDC, **160 mile** range
Acceleration 0 to 60 mph = 8 sec (Max speed 80 mph)

Toyota rotor & stator lamination cross section evolution

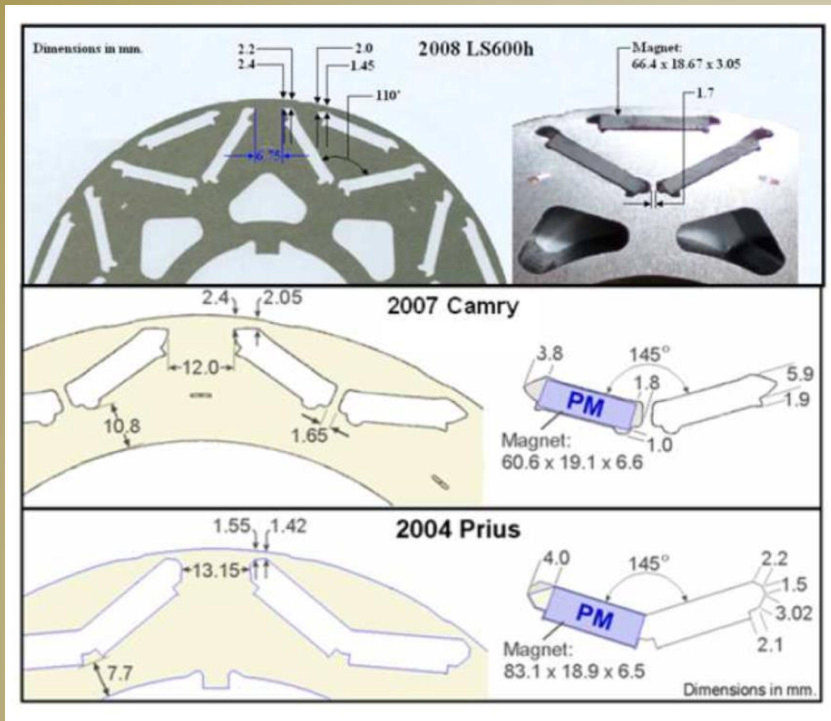
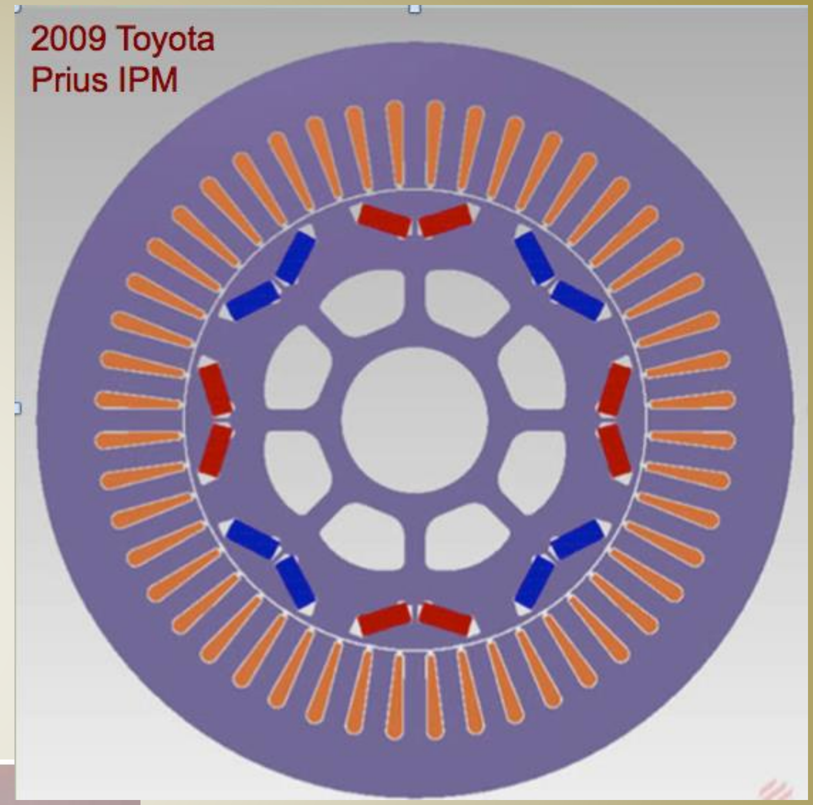
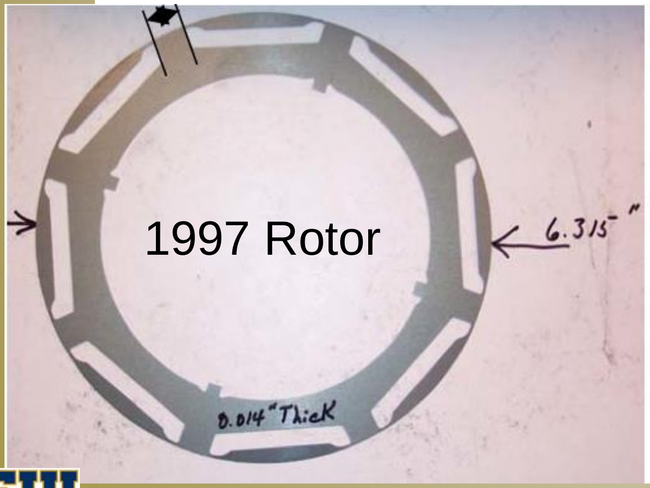
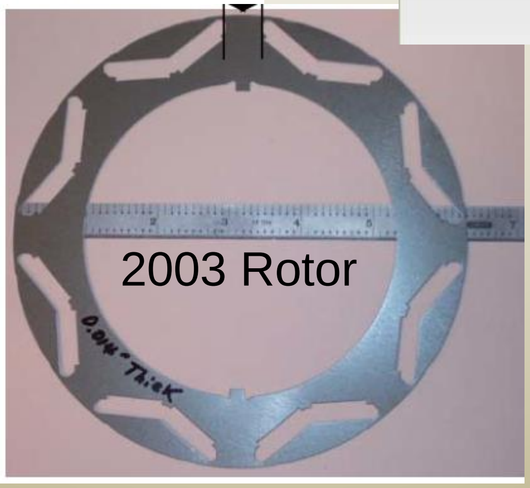


Fig. 2.70. Comparison of motor rotor lamination dimensions.

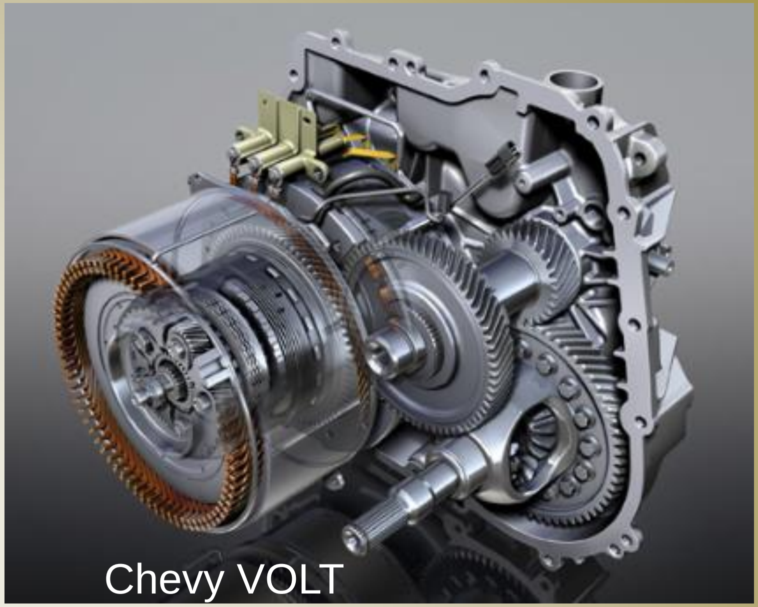


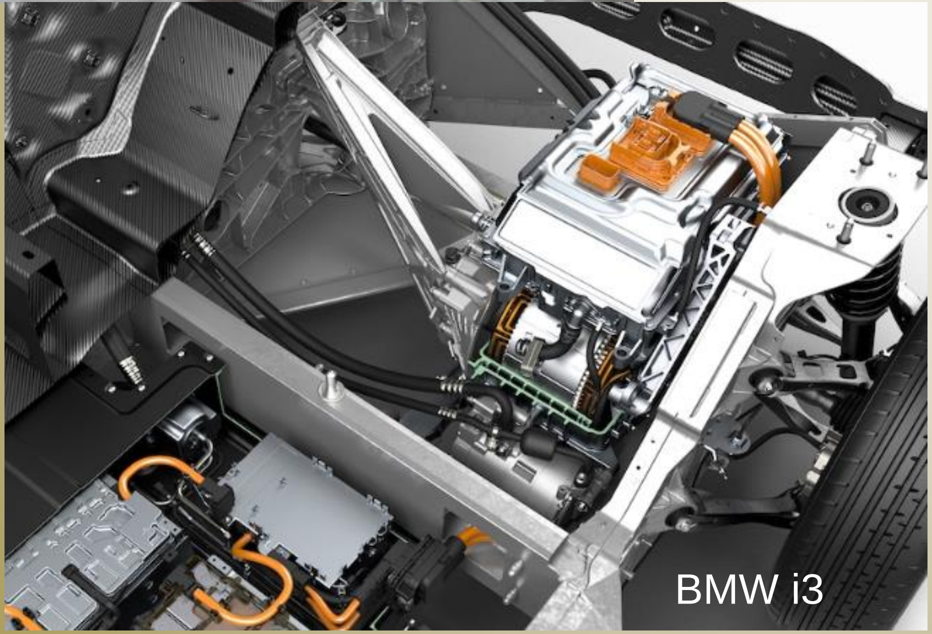




Notice the magnet design changes & center retention webs in 2007 Camry, 2008 Lexus & 2009 Prius.
(Very good design reasons)

Lets have a peek at some of these unique motor designs





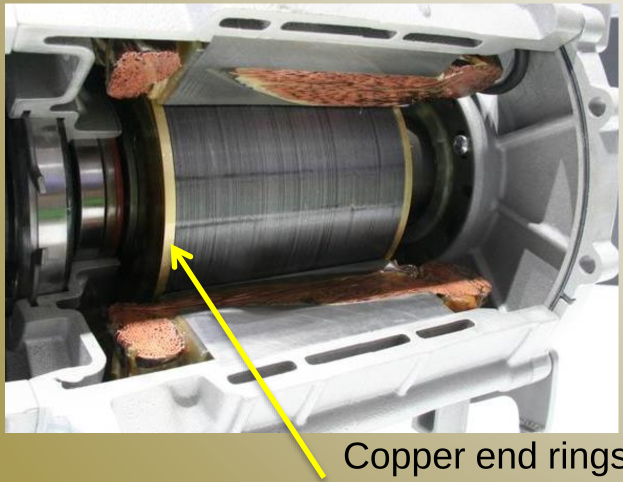
Note:

It appears that many automobile manufactures have elected to design their motors and drives in house rather than working with existing electric motor companies.

Ford electric traction motor details (Escape, Focus or Fusion?)

8

Ford Focus 123 HP (92 kw)



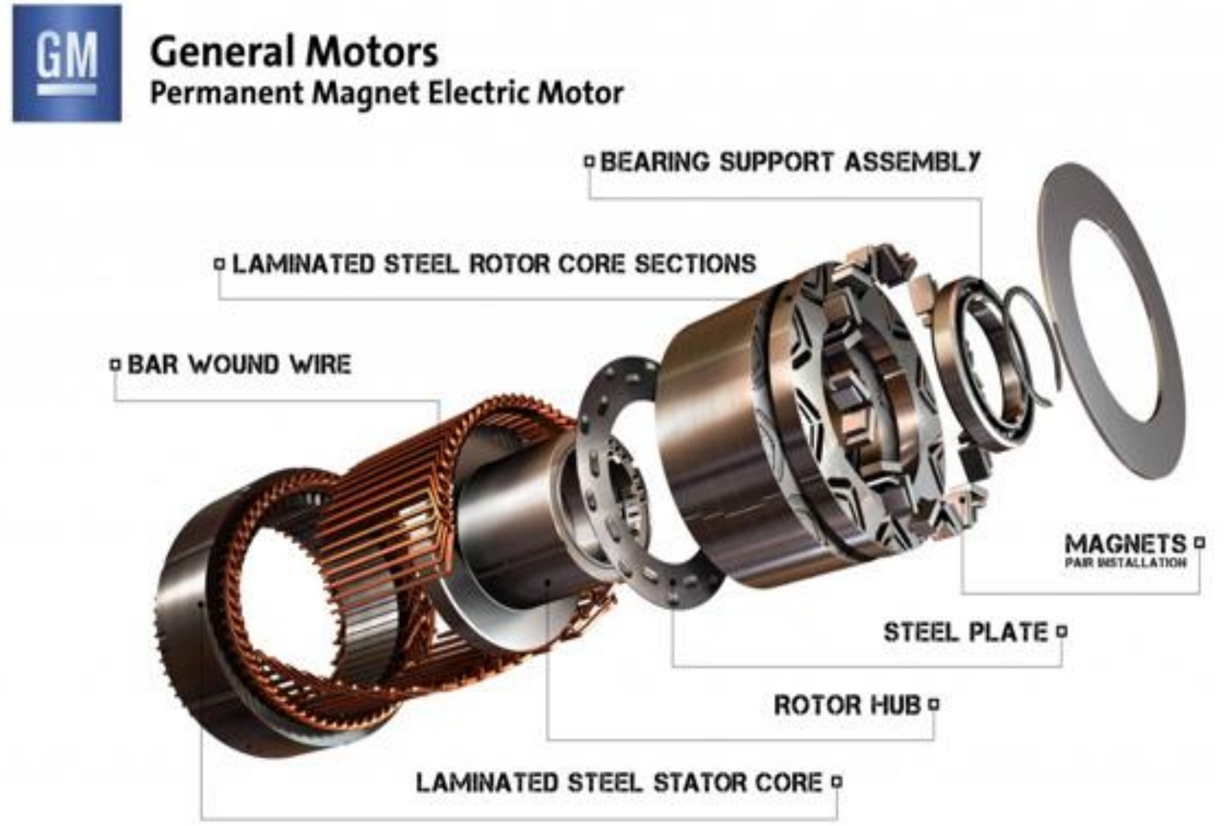
Copper end rings
or balance rings??

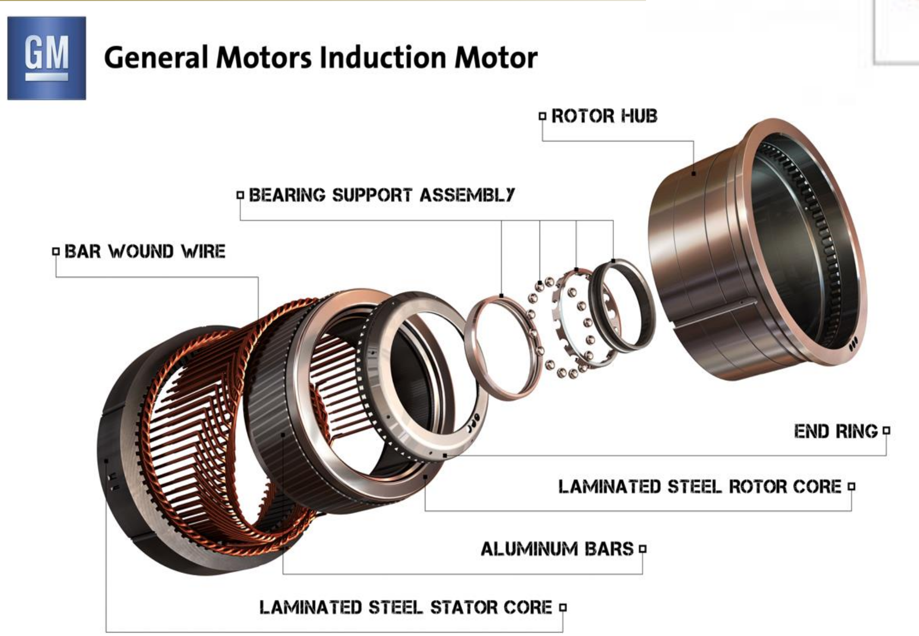
(8) Pole IPM Rotor

Hi slot fill (70%)

GM VOLT originally used the REMY 10 pole double layered IPM motor with a hairpin wound stator

voltage = 700
Output torque = 170 Nm
Output power = 150 kW
Max speed = 10,000 rpm

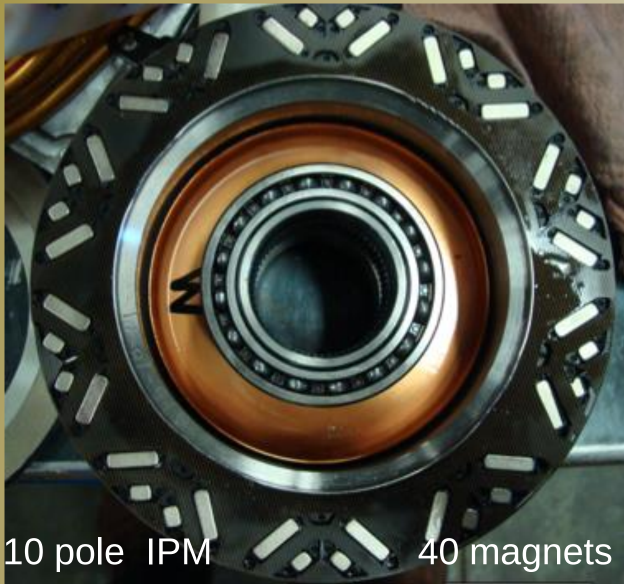


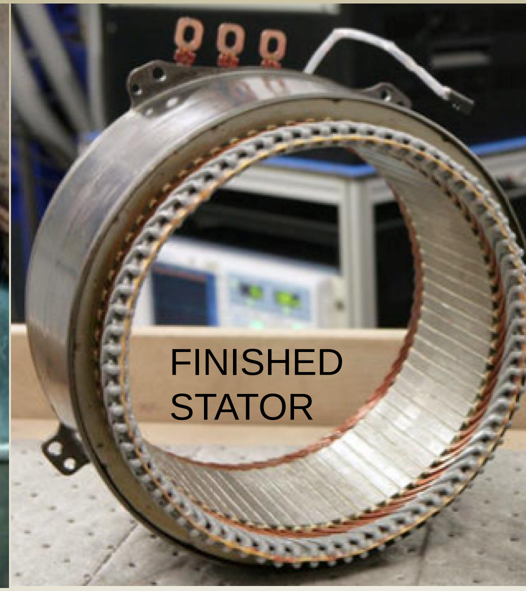


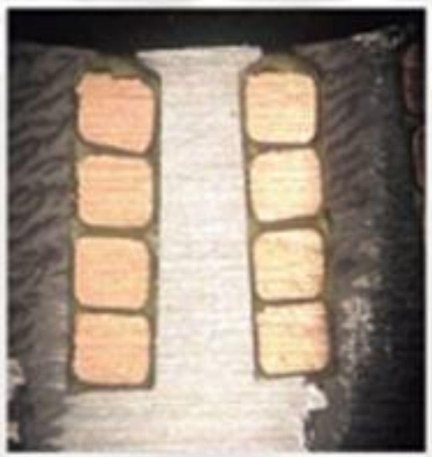
There is also an aluminum rotor AC Induction motor used in the Volt

Work continues by REMY & GM to convert its rotor to a copper rotor

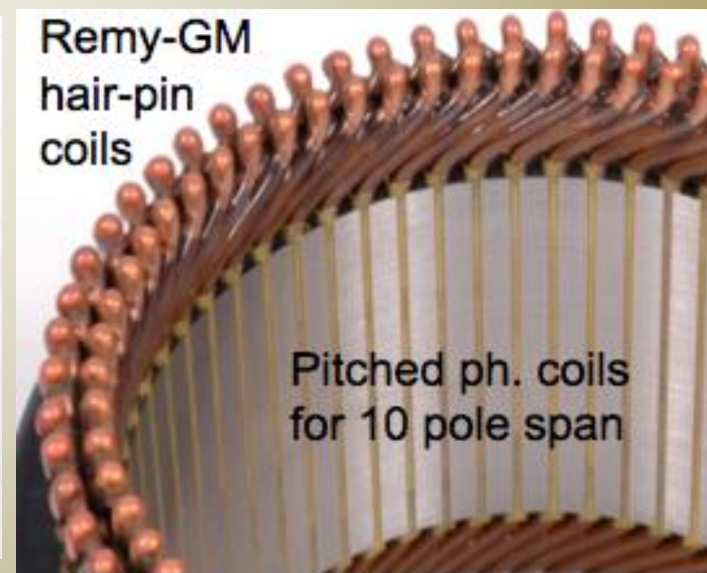
Chevy VOLT electric traction motor details



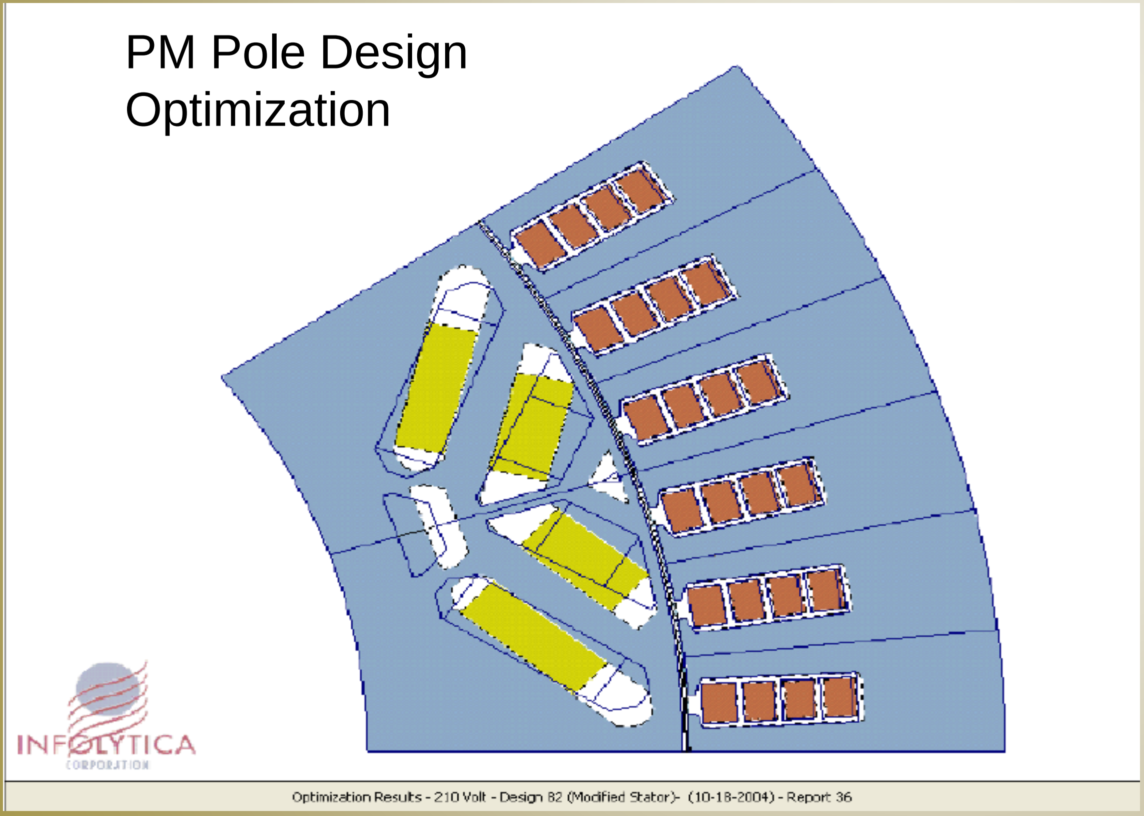


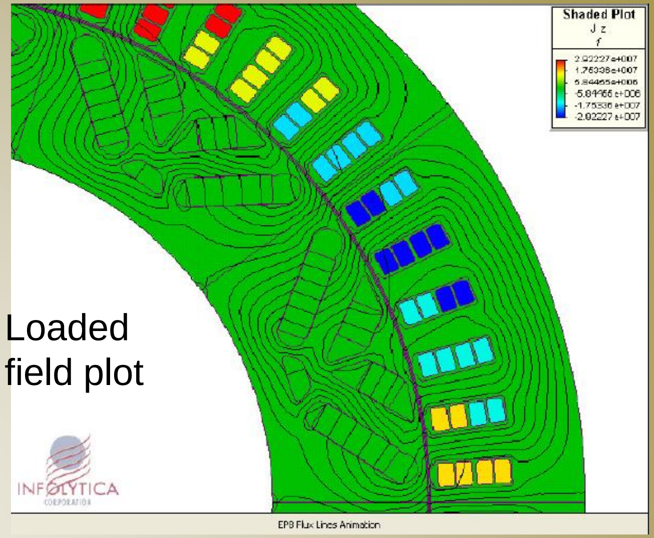


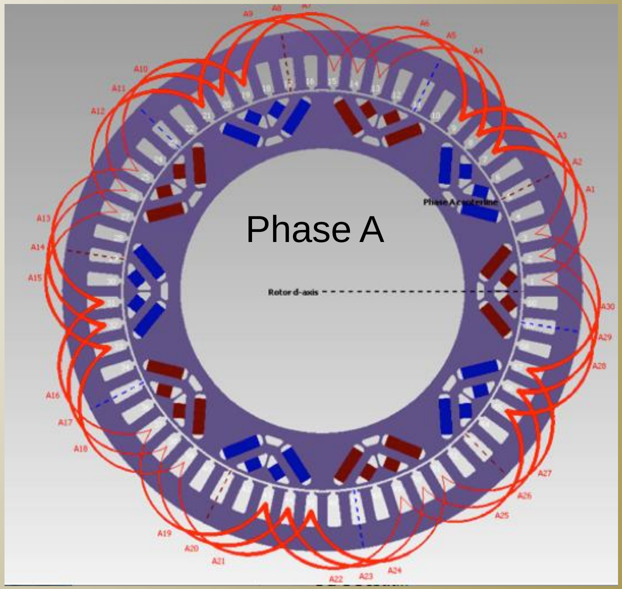
Hi slot fill using square wire



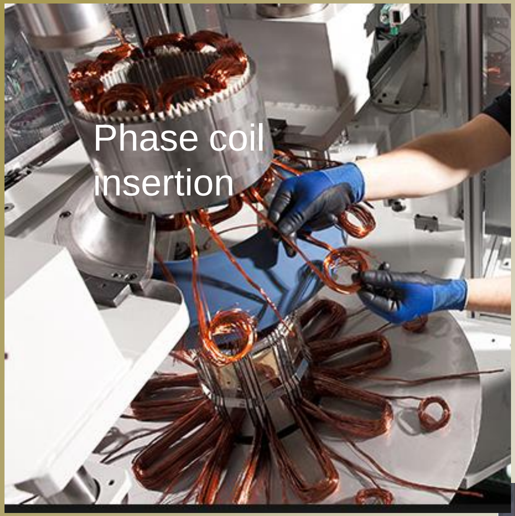
According to both REMY & GM, the 60 slot stator with hair-pin windings can be used with either the IPM or the Caged rotor

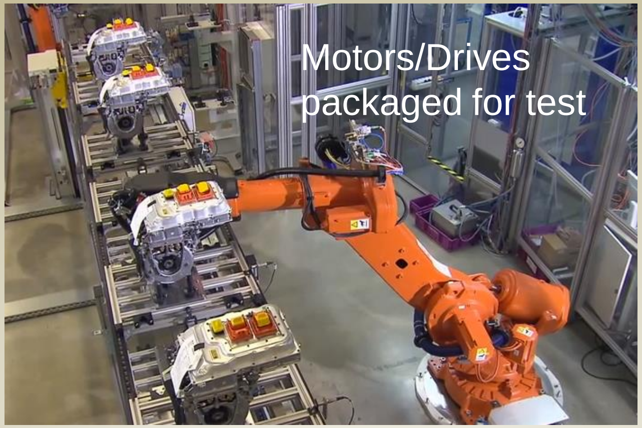


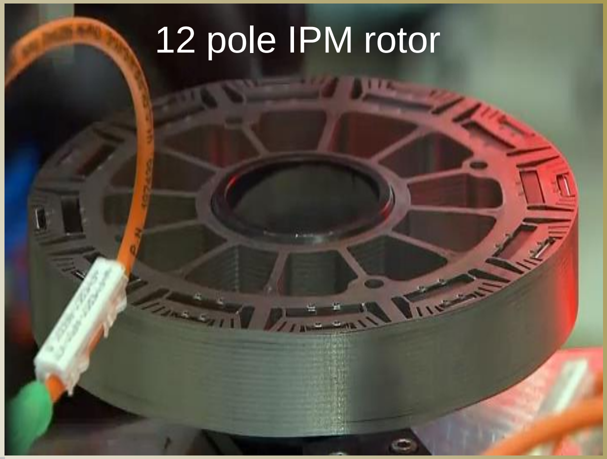


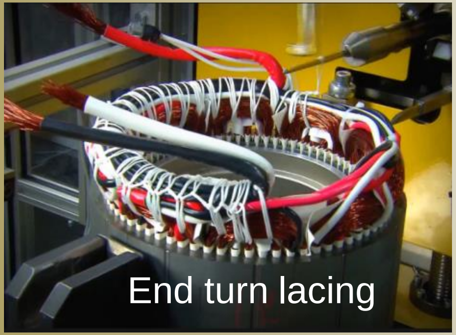


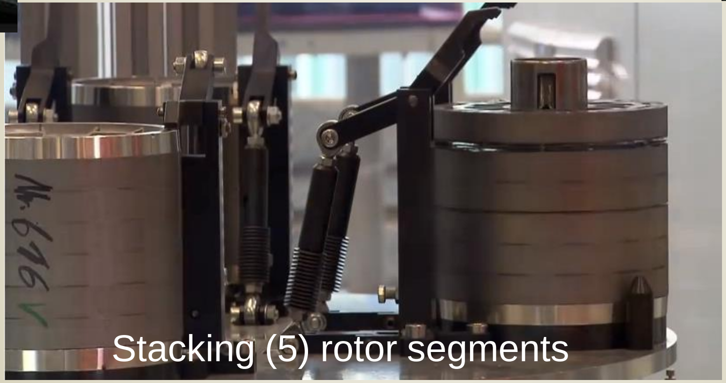
BMW i3 electric traction motor details (Landshut Germany)

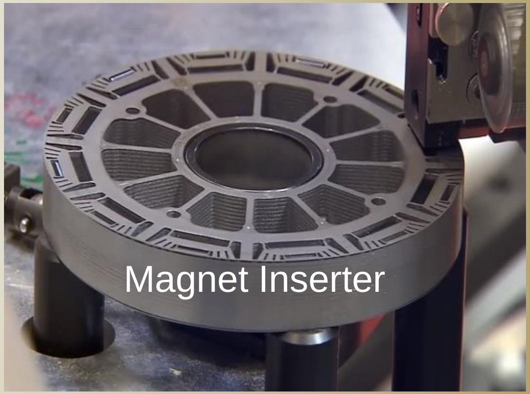


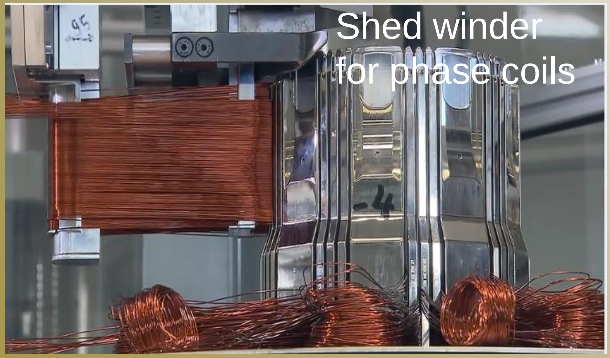


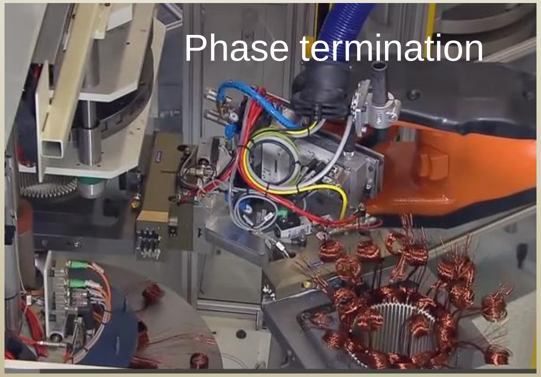


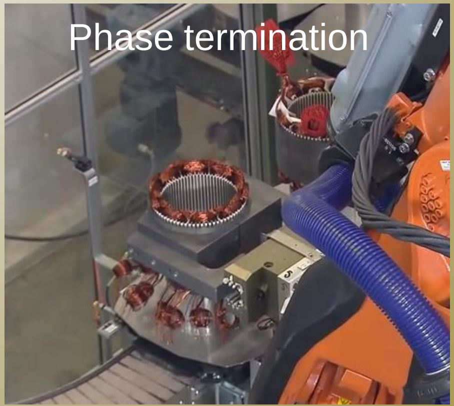






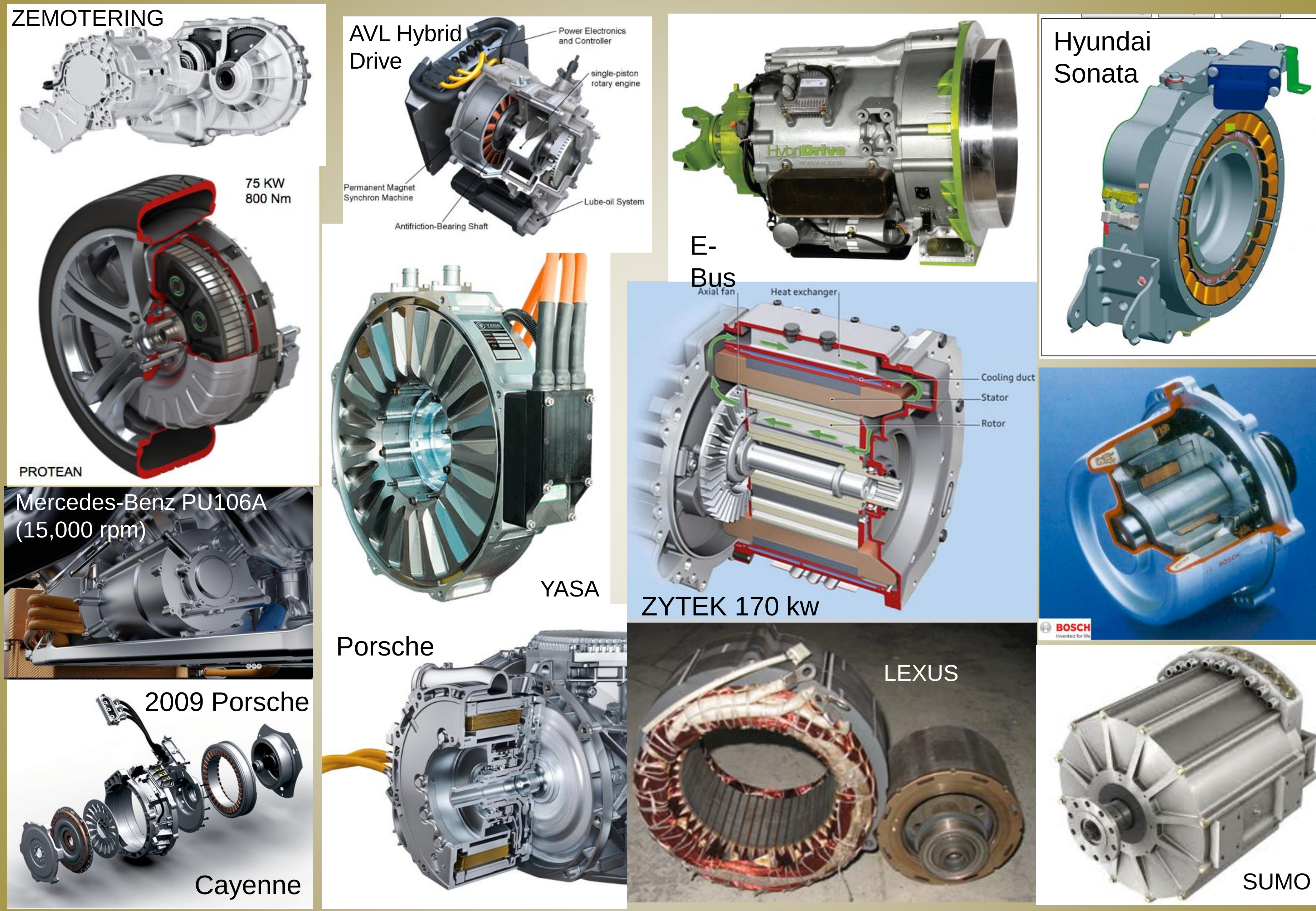






BMW patent application Nº 2012/0267977

Quick view of various motors intended for vehicle traction



Two SPM traction motors

SEGWAY stator cut-A way

Motors by Danaher
(Pacific Scientific)

New people movers with one or two wheels

Increasing the number of poles (all machines)

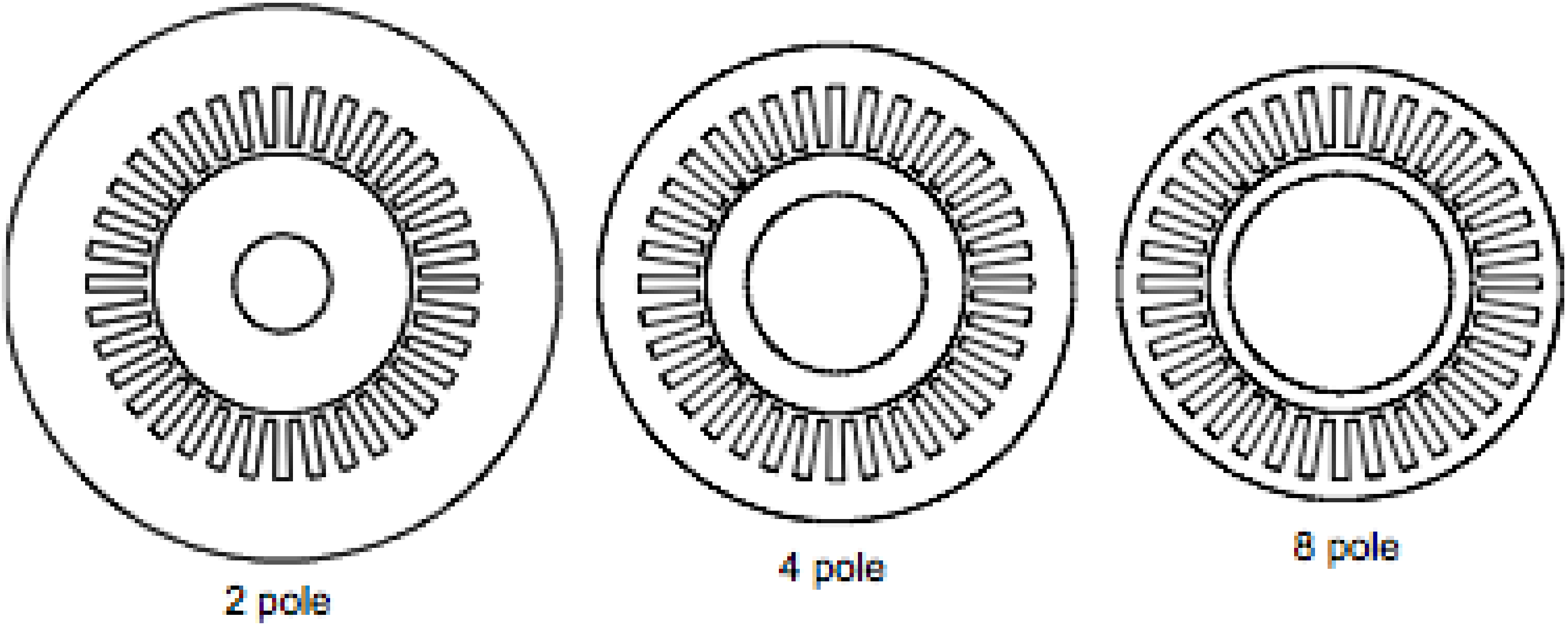
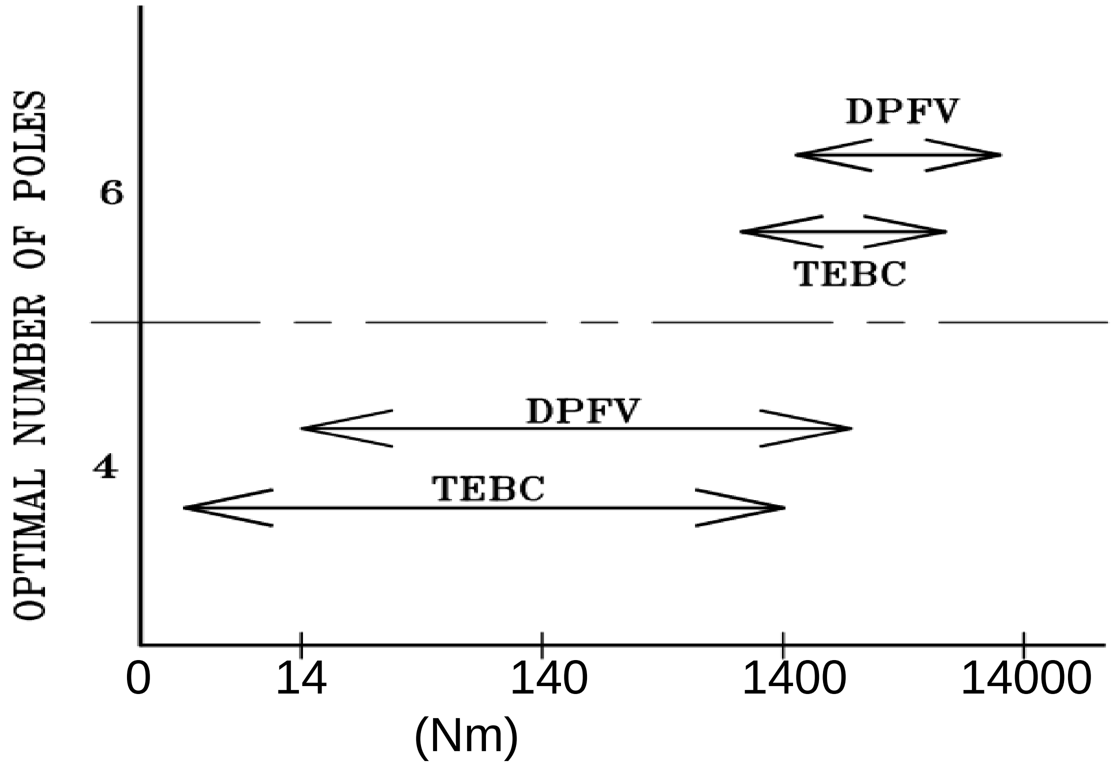


Fig. 4. The effect of changing the number of poles on the stator outer and rotor inner diameter for fixed values of stator slot inner and outer diameter, with a stator slot ratio of 0.7 and $B/B_y = 1/2.65$

Increasing the number of poles decreases the motor OD and mass (assuming rotor O.D. does not change)

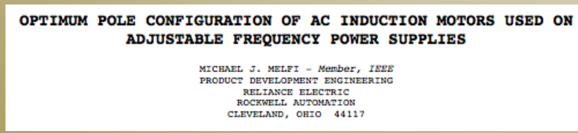
Optimum pole number for AC inverter driven machines



Optimal pole numbers for AC inverter driven motors

For most all traction motors the optimum number of poles = 4 resulting in lowest leakage reactance, highest power factor and efficiency

IPMs do not have this limitation so all IPM traction motors are 8, 10 or 12 poles
IPMs should be smaller and lower in mass than AC inductance machines



OPTIMUM POLE CONFIGURATION OF AC INDUCTION MOTORS USED ON ADJUSTABLE FREQUENCY POWER SUPPLIES

MICHAEL J. MELFI - *Member, IEEE*
PRODUCT DEVELOPMENT ENGINEERING
RELIANCE ELECTRIC
ROCKWELL AUTOMATION
CLEVELAND, OHIO 44117

The Tesla traction motor is a 4 Pole design.

The IPM – AC brushless machines are synchronous motors with high poles

The Switched reluctance motor is a synchronous machine with high poles

The Reluctance Synchronous motor is sort of in between, although it is a synchronous machine the pole number can be 4, 6 or 8 for traction.

Each machine has their pros and cons which we will not discuss here. Suffice to say that all types of motors with no magnets are on the table

Same stator with three rotor choices

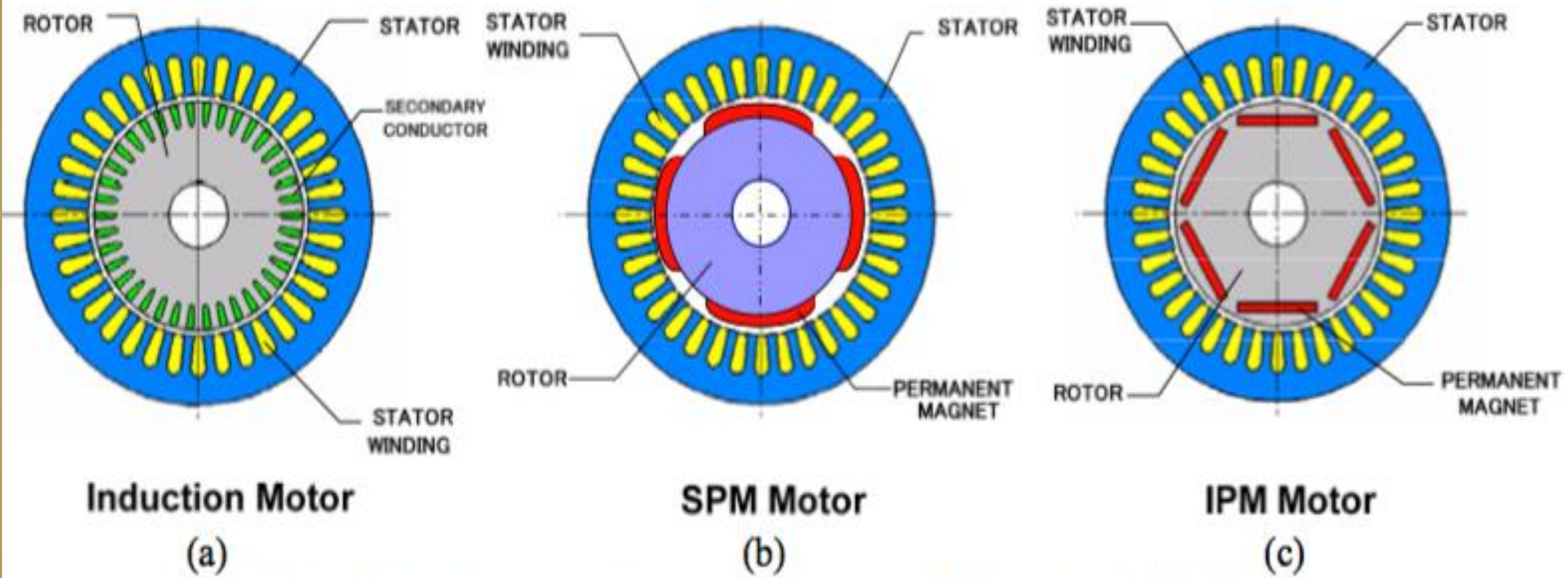
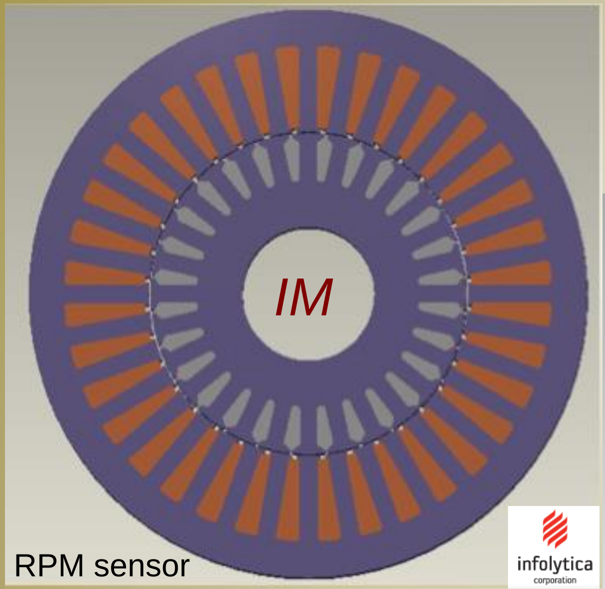
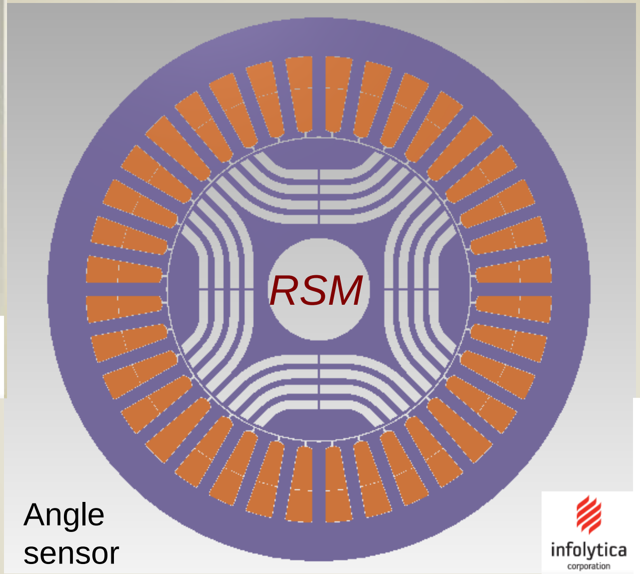


Fig. 5 – Rotor structures of induction motor, SPM motor, and IPM motors

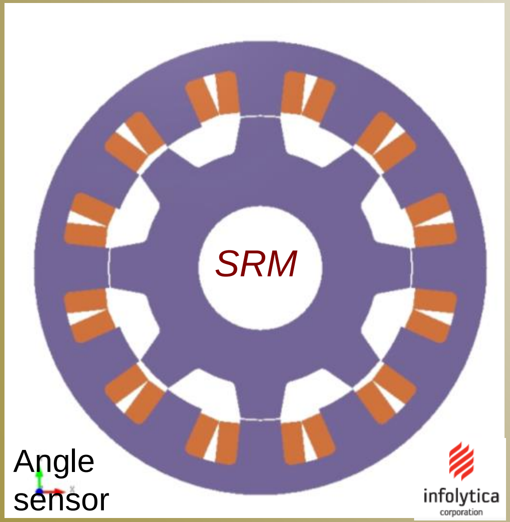
YASKAWA

Three rotor configurations using similar stators and windings.

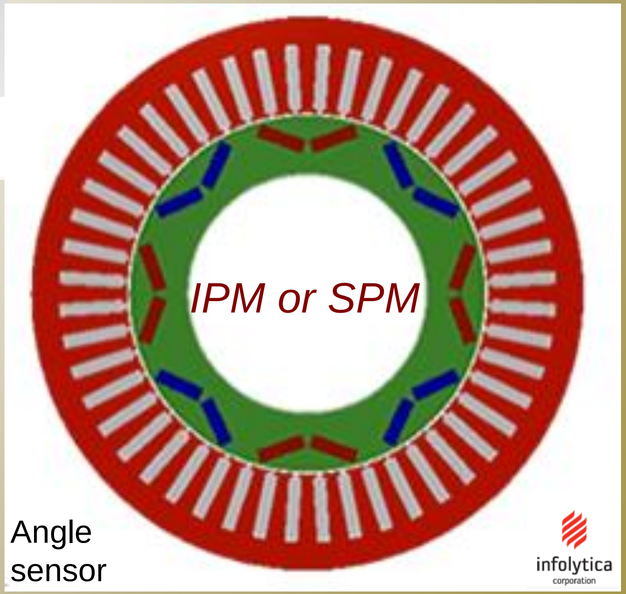




All three machines are Inverter fed for most specific requirements



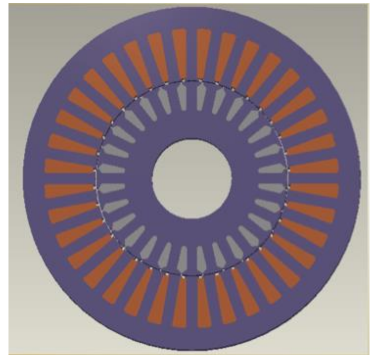
SR machines require, new stators & windings plus new half-bridge inverter/control technology



A comparative graphic of electric machine choices for vehicle traction & accessory motors (Besides brushed PM DC)

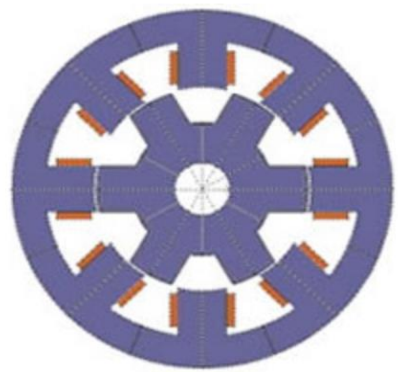
** NO RARE EARTH MAGNETS NEEDED

** AC INDUCTION

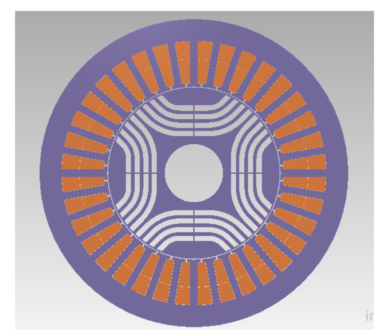


PM-AC SYNCHRONOUS

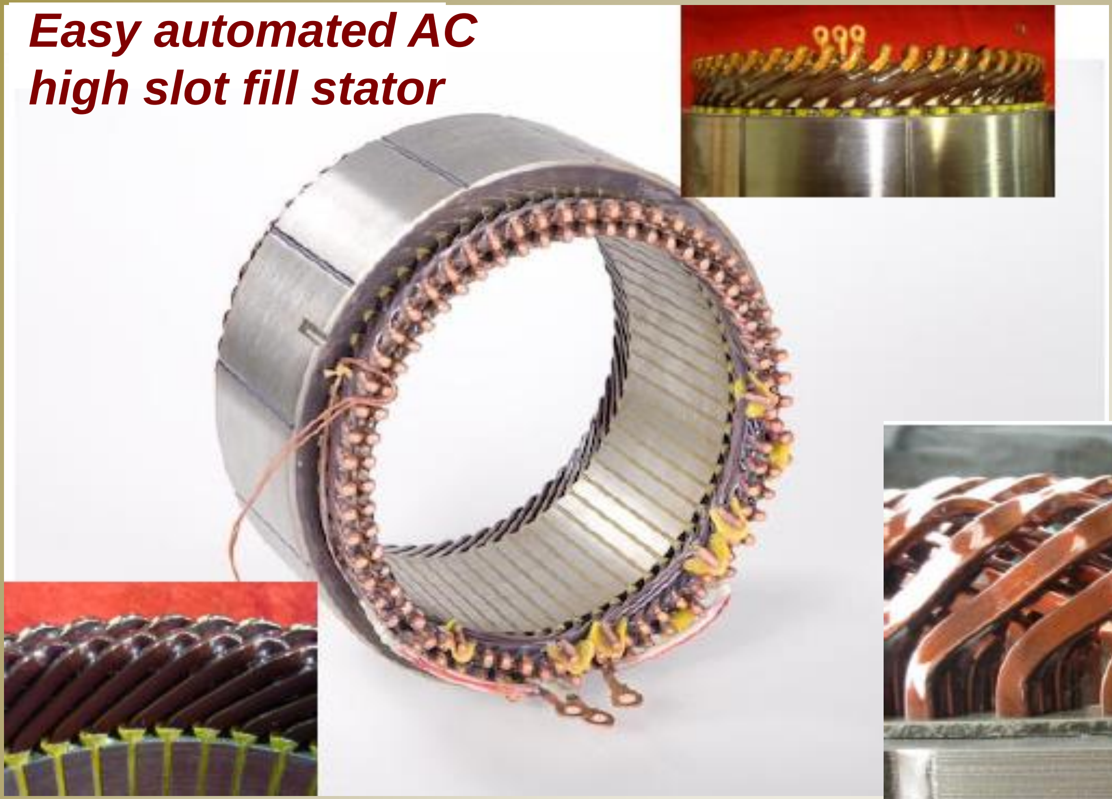
* *SWITCHED RELUCTANCE



** RELUCTANCE SYNCHRONOUS

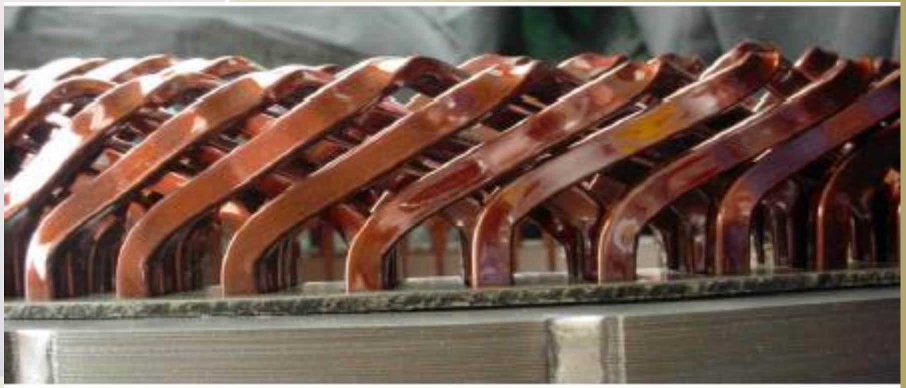


Easy automated AC high slot fill stator



Hair-pin stator automated winding with high slot fill. (Can be round or rectangular)

Applicable to all three machine types except SR



Doubly salient pole reluctance machines called Switched Reluctance (SRM) (Some have called the SRM, *"the good, bad & ugly"!!)*

GOOD !

The SRM is one of the oldest electric machines dating back to the middle 19th century but not practical until the development of the transistor.

Very simple in construction and low cost to manufacture

SRMs are very robust and reliable with decent fault tolerance

BAD !

Tricky to control & requires custom half bridge power switching circuits

Requires double number of connections as other machines

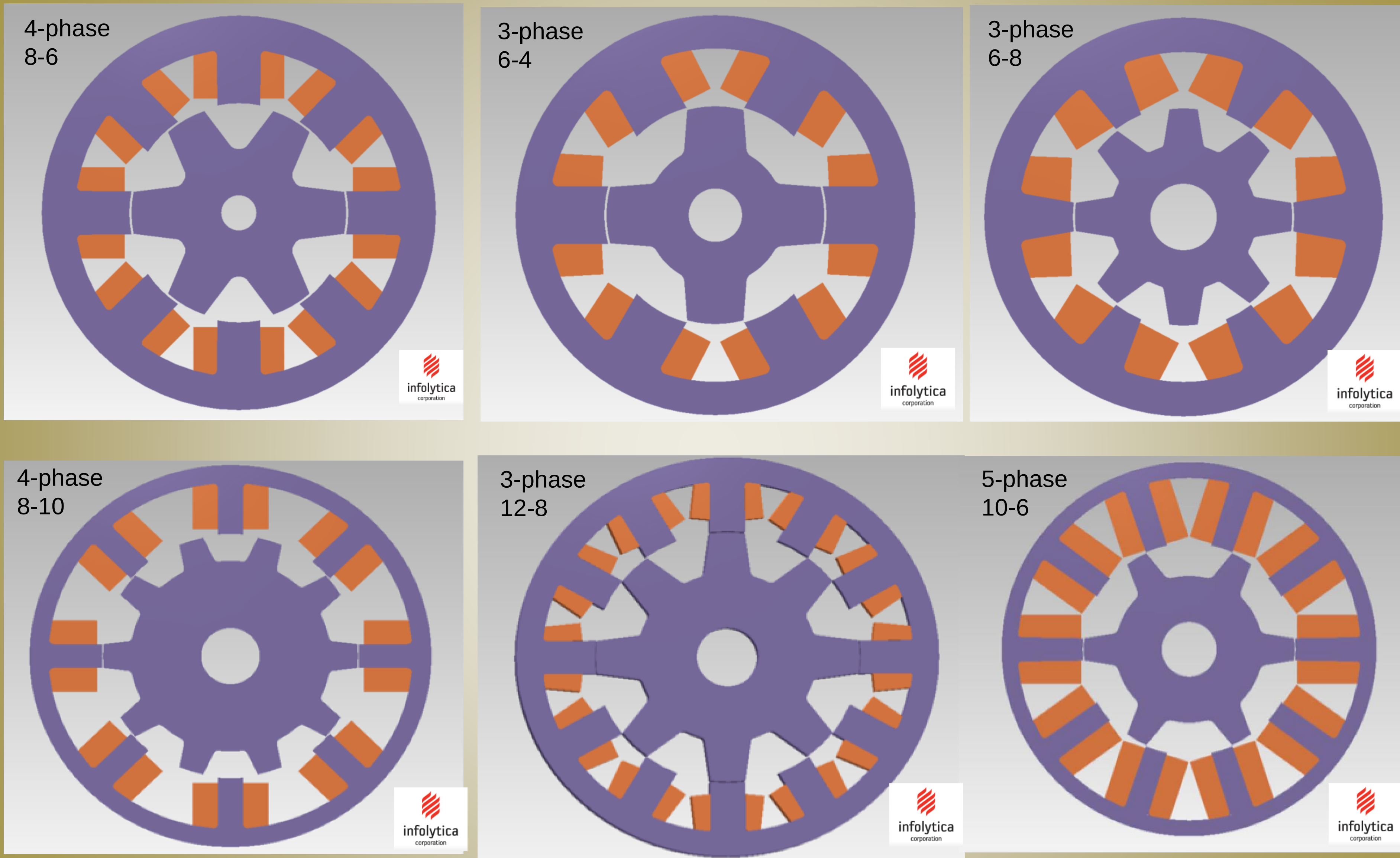
Requires double the number of power switching devices of other machines

Ugly !

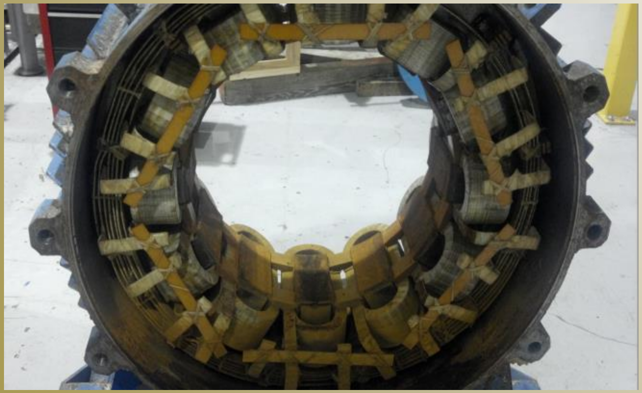
Tends to be noisy without special attention to design

Requires careful commutation to minimize torque ripple

Examples of 3, 4 & 5 phase SR machine cross sections



Photos of 200 KW SR motor design by Dr. Sergie Kolomeitsev for direct drive pump application, prototyped by a US company.



(3) phase 12-8 SR
Stator OD = 770
Rotor OD = 467

Stator coil details

(8) tooth rotor

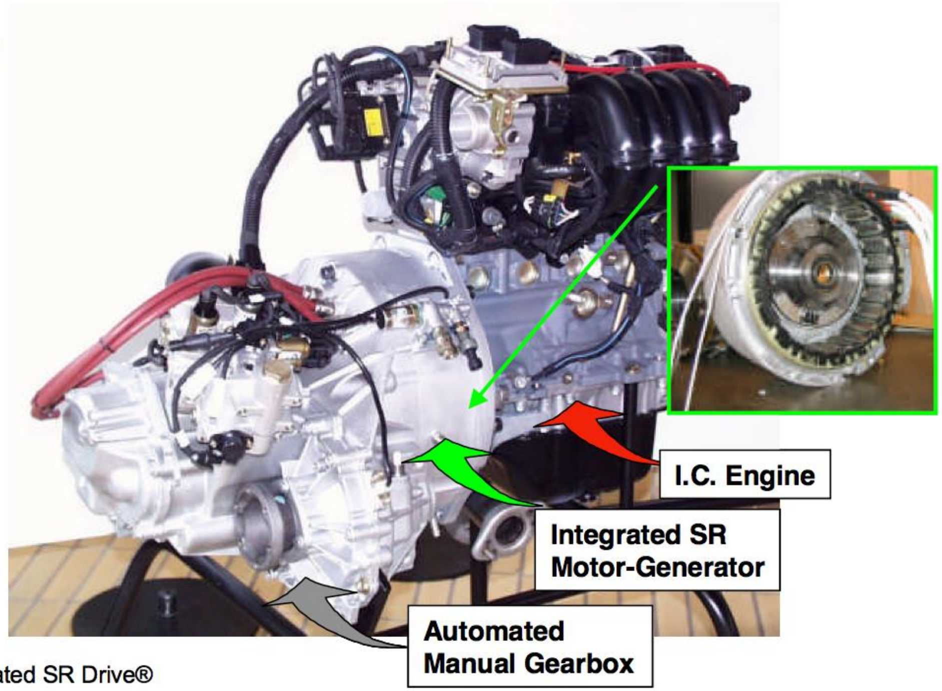
Case Study – Fiat Auto
Mild Hybrid Drive – The Solution

- 15kW SR Drive® motor/generator provides up to 120Nm torque assist during launch.
- 25% cost saving compared to other technologies.
- Anticipated 10% improvement in fuel efficiency.

EMERSON Motor Technologies

SR DRIVES®

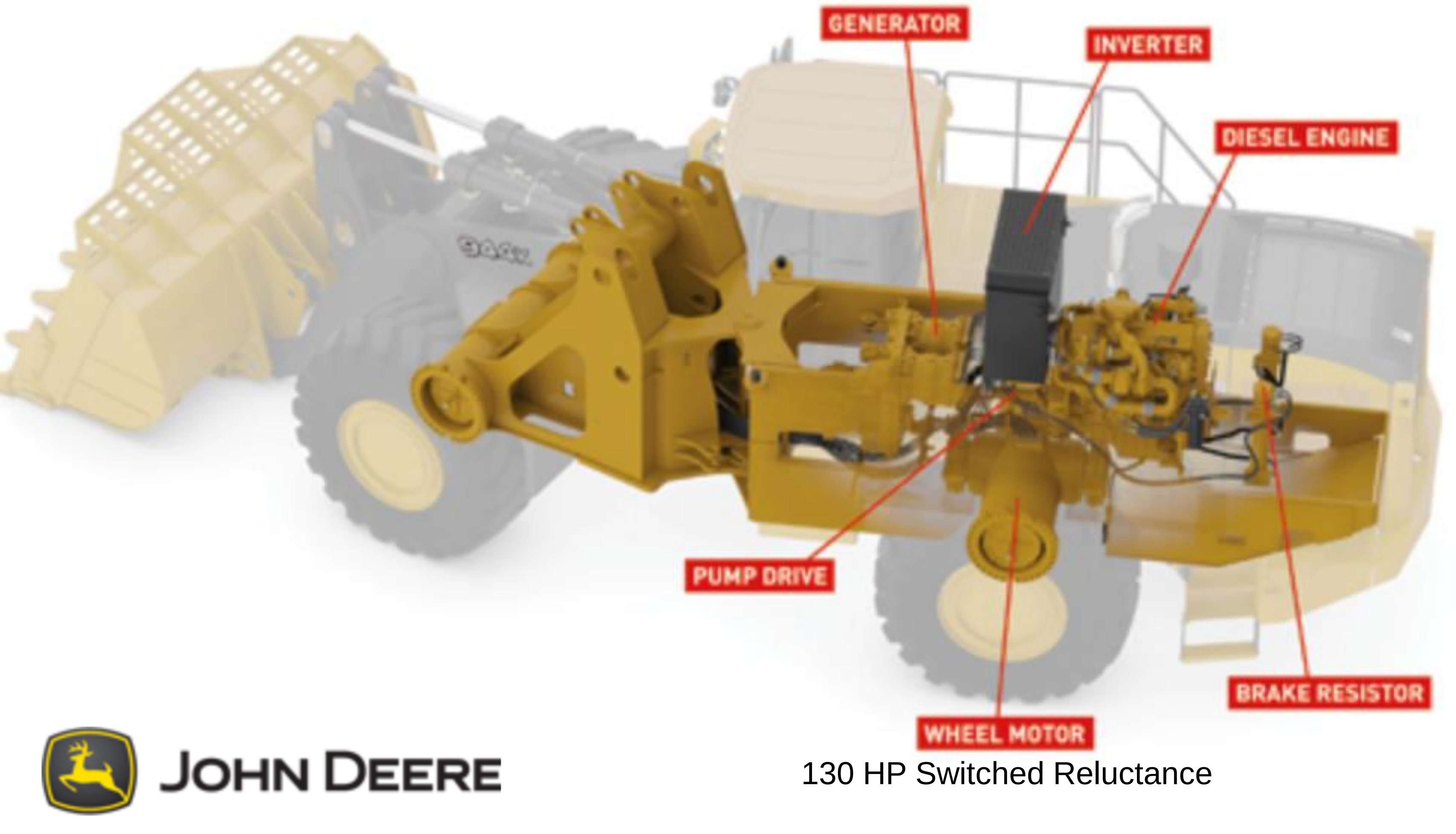
SR DRIVES® Manufacturing



ICE and drive train showing integrated SR Drive® Motor Generator.

John Deere 944 hybrid Loader (5900 liter capacity) with (4) SR traction motors

270 HP Switched Reluctance



130 HP Switched Reluctance

Delivering responsive torque and dependable traction

LeTourneau's product range includes the largest front-end loader in the world

LeTourneau Inc, the Longview, Texas-based company, employs SR Drive® technology in its latest 50 Series 'digital' loaders. The L-1350 electric-wheel loader is the first machine of its type to be fitted with SR Drive® systems that provide independent traction for each wheel.

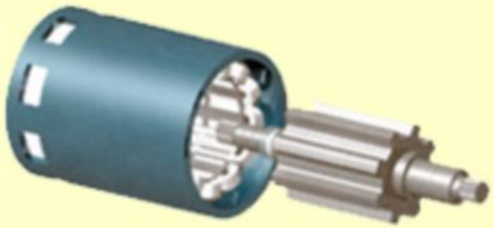
LeTourneau invented the electric-drive wheel loader more than forty years ago, and has been refining the concept ever since. Today, its range of loaders represents the industry standard and includes the largest front-end loader in the world. The L-1350 stands 6 metres high from ground to cab roof and more than 16 metres long. It weighs over 180 tonnes and its 21m³ rock bucket handles a 38 tonne payload.

Application Overview

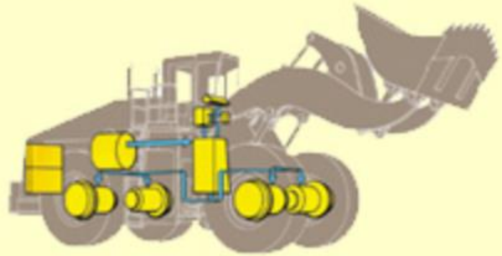
MANUFACTURED UNDER LICENCE • NIDEC SR DRIVES LTD •

LeTourneau, Inc.

Independent all-wheel electric drive for advanced wheel-loader.



LeTourneau's B40 SR Drive® motor.



LeTourneau's SR Drive® motors, electric power conversion and control system.

Nidec

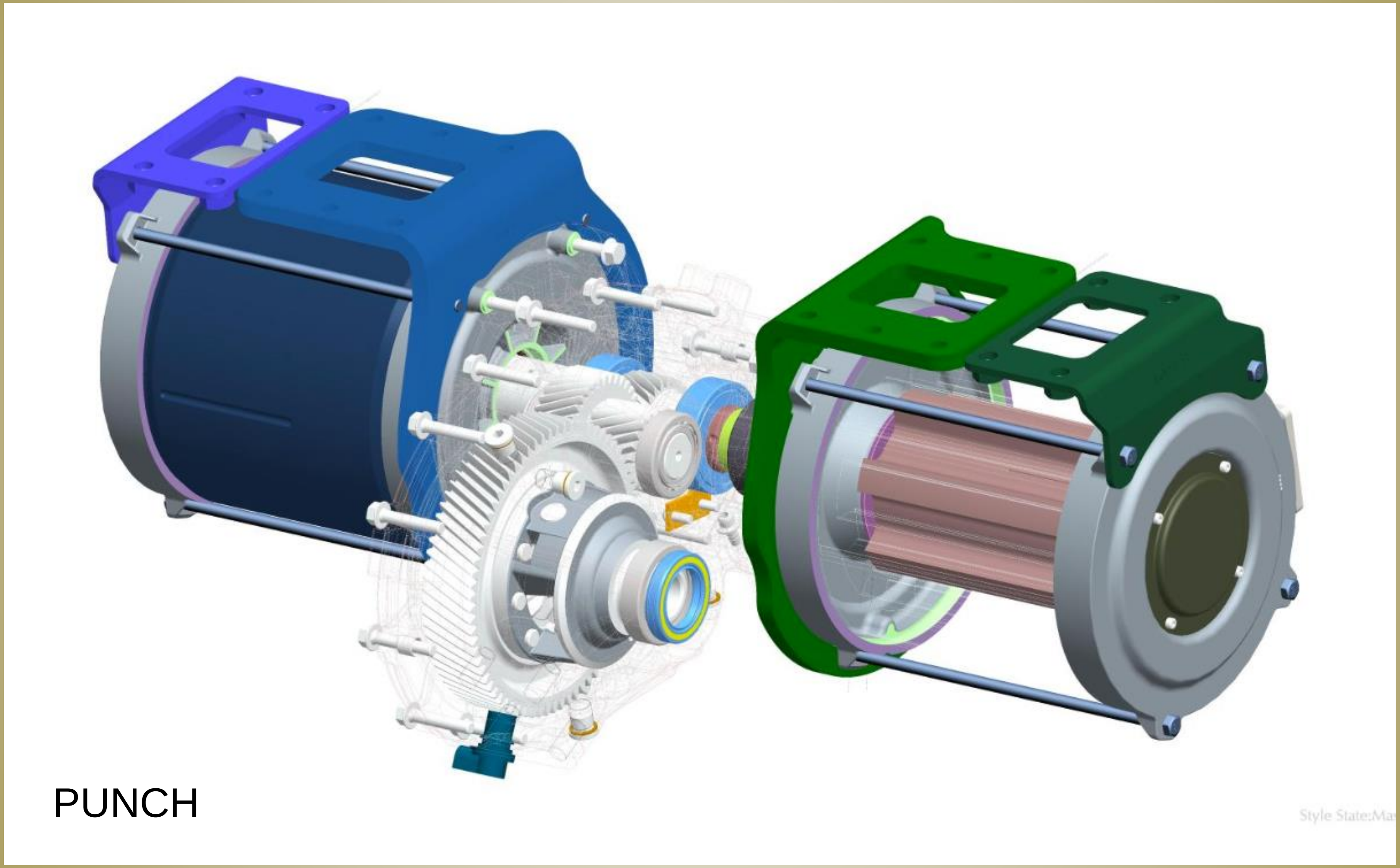
Hi performance Switched Reluctance IC engine generator

CAT Electronics

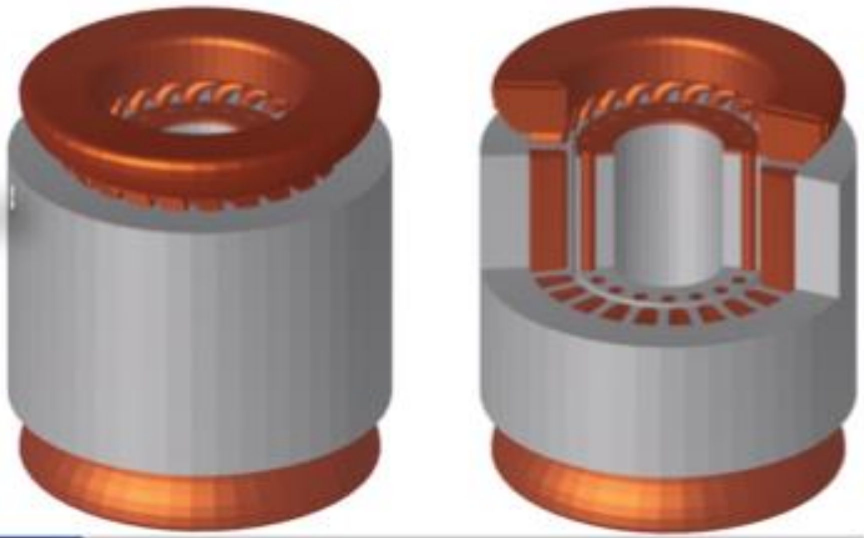
Component	MorElectric Generator	Heavy Duty Alternator
Length	212 mm (8.3")	208 mm (8.2")
Diameter	177 mm (7.0")	167 mm (6.6")
Weight	22 kg (48.5 lb)	12 kg (26.5 lb)
Efficiency	79-83%	40-60%
Power	7.3 kW	2.3 kW

PAT # US 7755308

Water Cooled SR traction drive tested by VOLVO



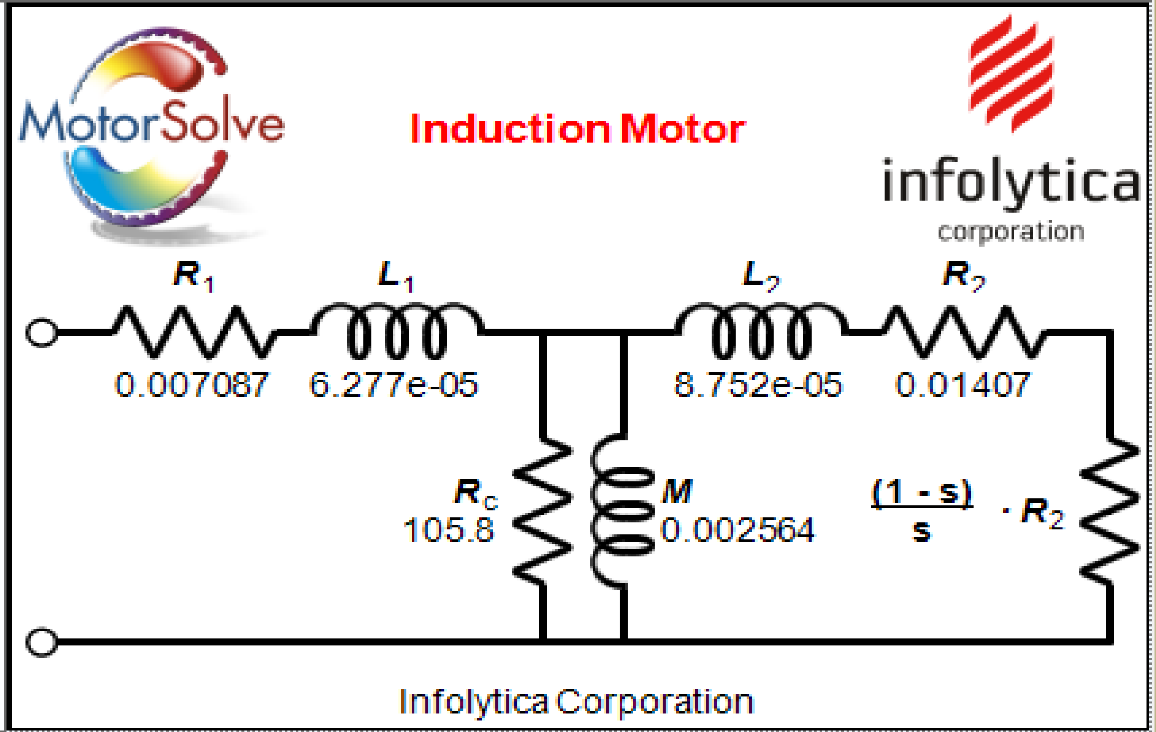
Examples of High performance AC induction machines



Rotor and Stator components of a high torque density AC induction machine design
(A und E of Switzerland)

1-High slot fill stator
2-Copper rotor

AC Induction machine is most elegant motor of all, *Rotating Transformer*

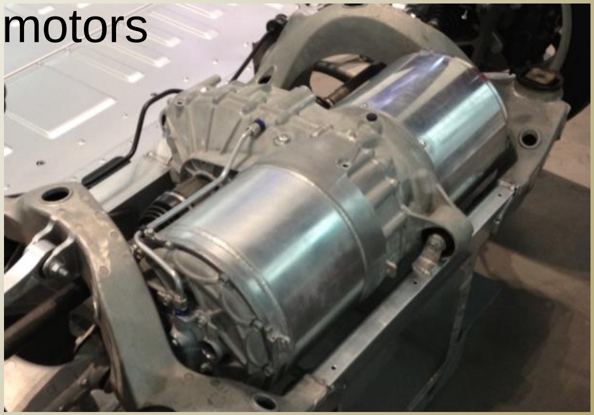
	Aluminum Bars
Equivalent circuit	
Values	
R1	0.00708717
R2	0.0140671
Rc	105.766
L1	6.27683E-05
L2	8.75207E-05
M	0.00256378

AC Induction motors for vehicle traction

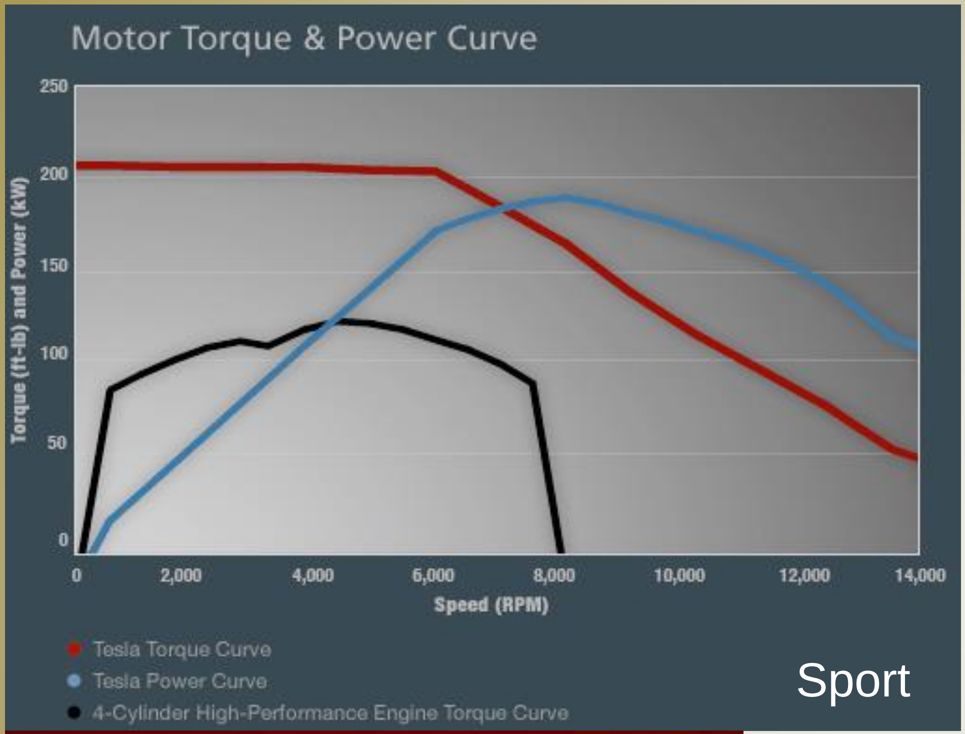
Tesla Sport

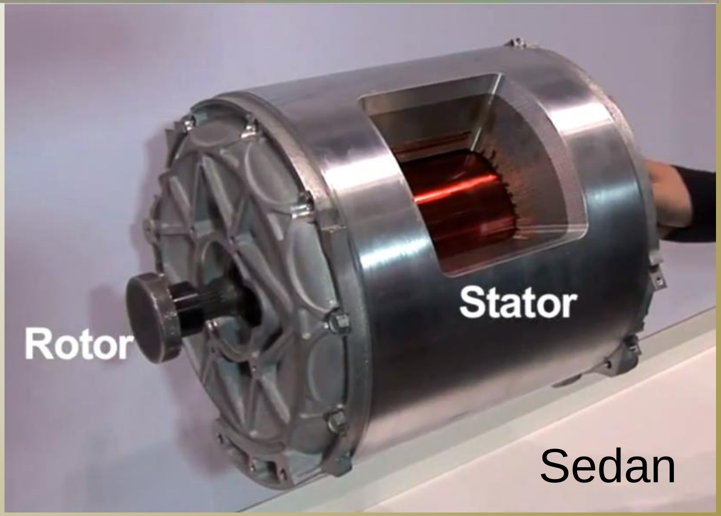
4 Pole AC Induction motors

Tesla Sedan

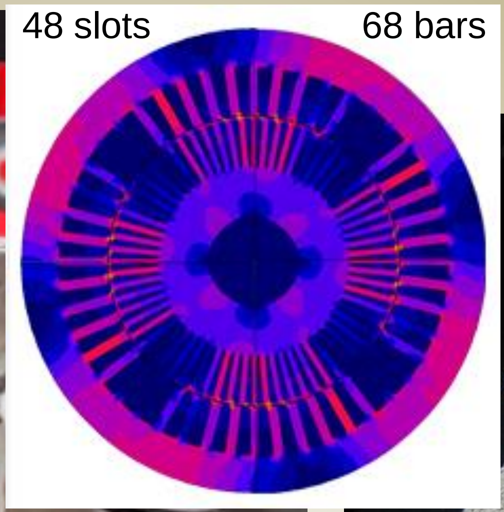


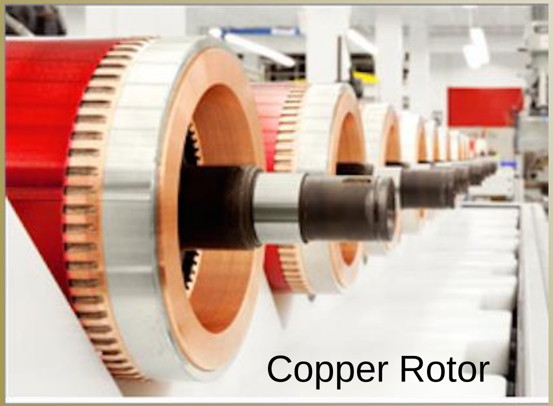
Some details regarding the AC Induction motor used by TESLA





Tesla electrics using AC Induction traction motors




Copper Rotor

Rated output power = 288 HP
Peak Torque = 300 lbf-ft
(0 to 5000 rpm)
Max speed = 14,000 rpm


Tesla Model S
Traction Motor

AC Propulsion

0 to 60 mph, 2.9 sec
AC Propulsion motor
6000 laptop batteries

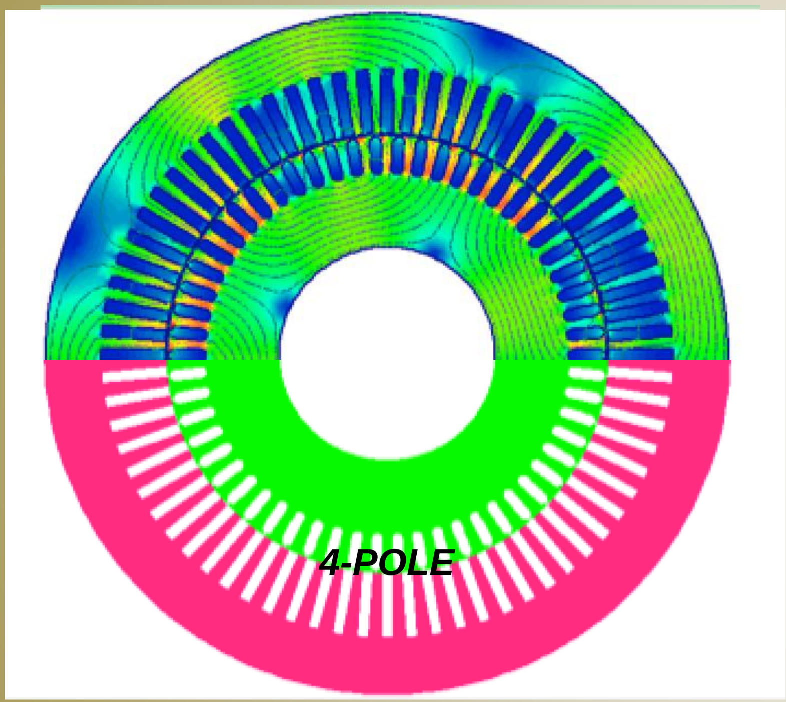
Figure 1 – AC-75 Motor shown with cooling shroud.

Specifications – Copper Rotor Motor
Outline dimensions: 305 mm dia. x 250 mm long
Weight: 34 kg (75 lbs.)
Voltage: 247 VAC nominal (line-line rms)
Current: 250A rms max, 80A continuous
Torque: 122 Nm (0 to 6000 rpm)
Base speed: 6000 rpm
Maximum speed: 13,000 rpm
Power: 75 kW (100 hp) max, 27 kW (36 hp) conti

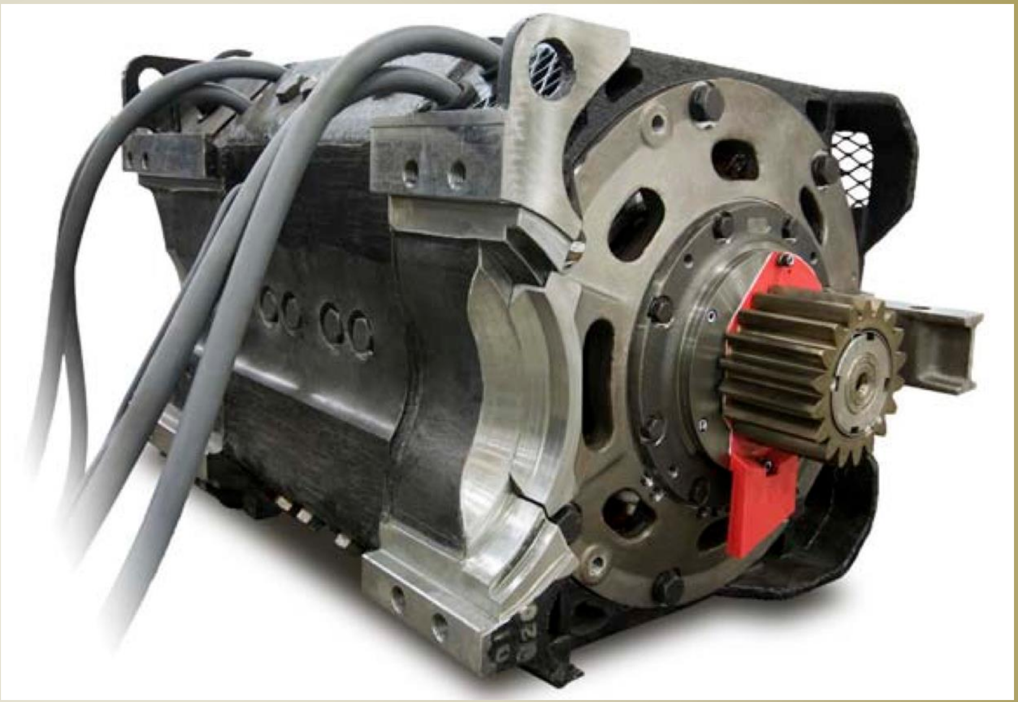
- Peak Power: >150 kW
- Continuous power: 40 kW
- Max torque: > 225 Nm
- Max speed: 13,000 rpm
- Over-temperature protection
- Integrated speed sensor and temperature sensor
- Class H, double insulated
- Zero motor back-EMF when excitation removed
- Forced air-cooled

AC PROPULSION

Powerful AC Induction motor used for Rail traction drives



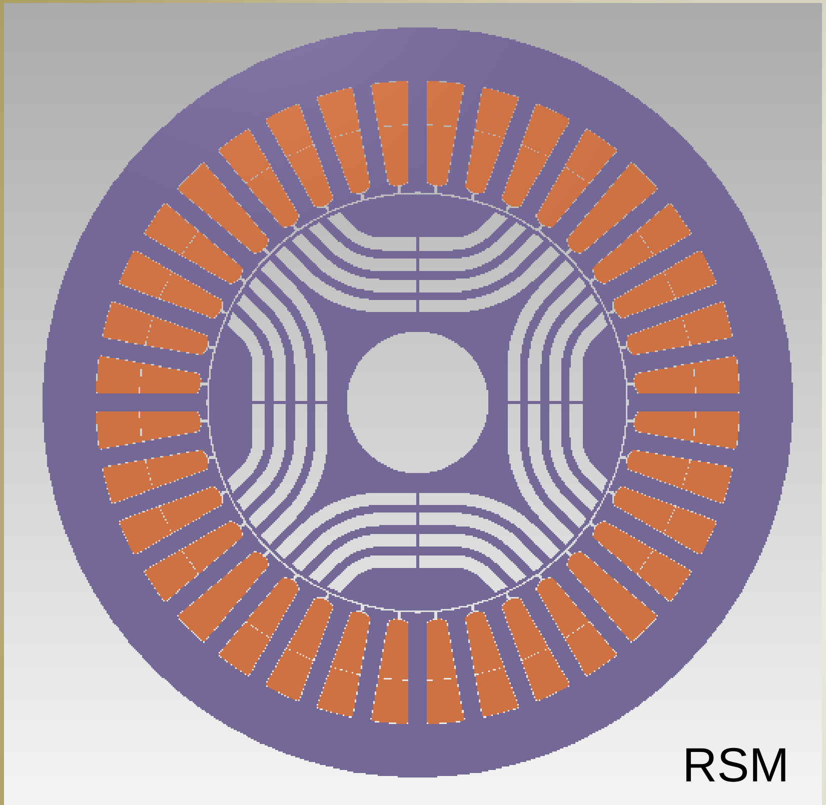
Asynchronous rotor-stator intended replacement

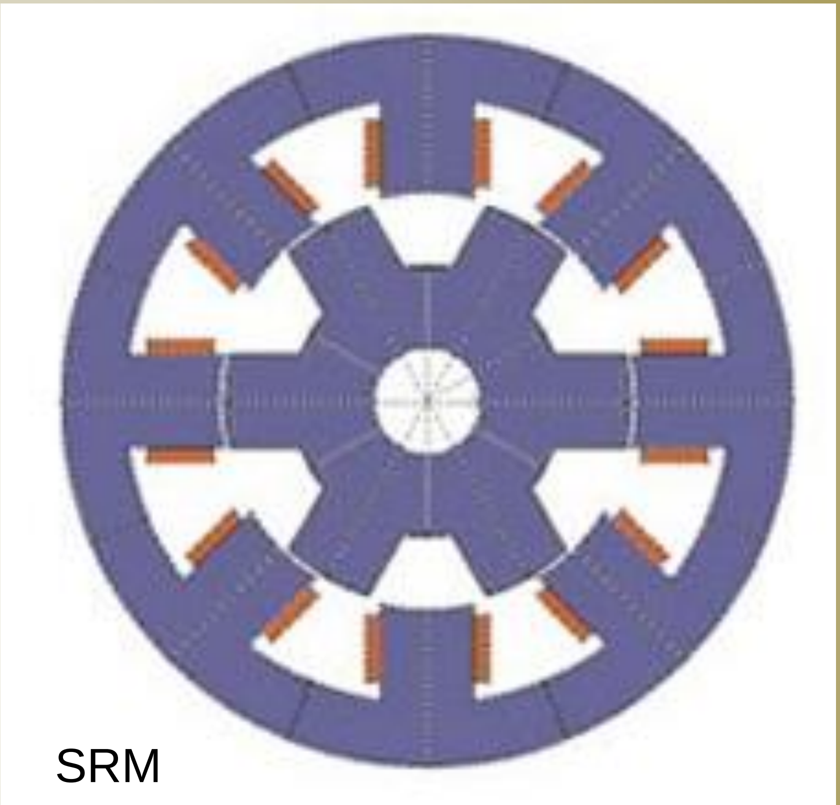


Typical open frame air cooled machine

Designed by JR Hendershot for American Traction Systems

Reluctance motors and generators types, RSM, single salient pole & SRM dual salient pole





RSM (Reluctance-Synchronous) uses

standard Induction stator and special

salient pole ro... tions

RSM (synchronous-Reluctance) types have salient poles in both rotor and stator at air gap like gear teeth. Phase coils are normally placed around each stator tooth.

Attractiveness of RSM for tram, Rail, car and truck traction

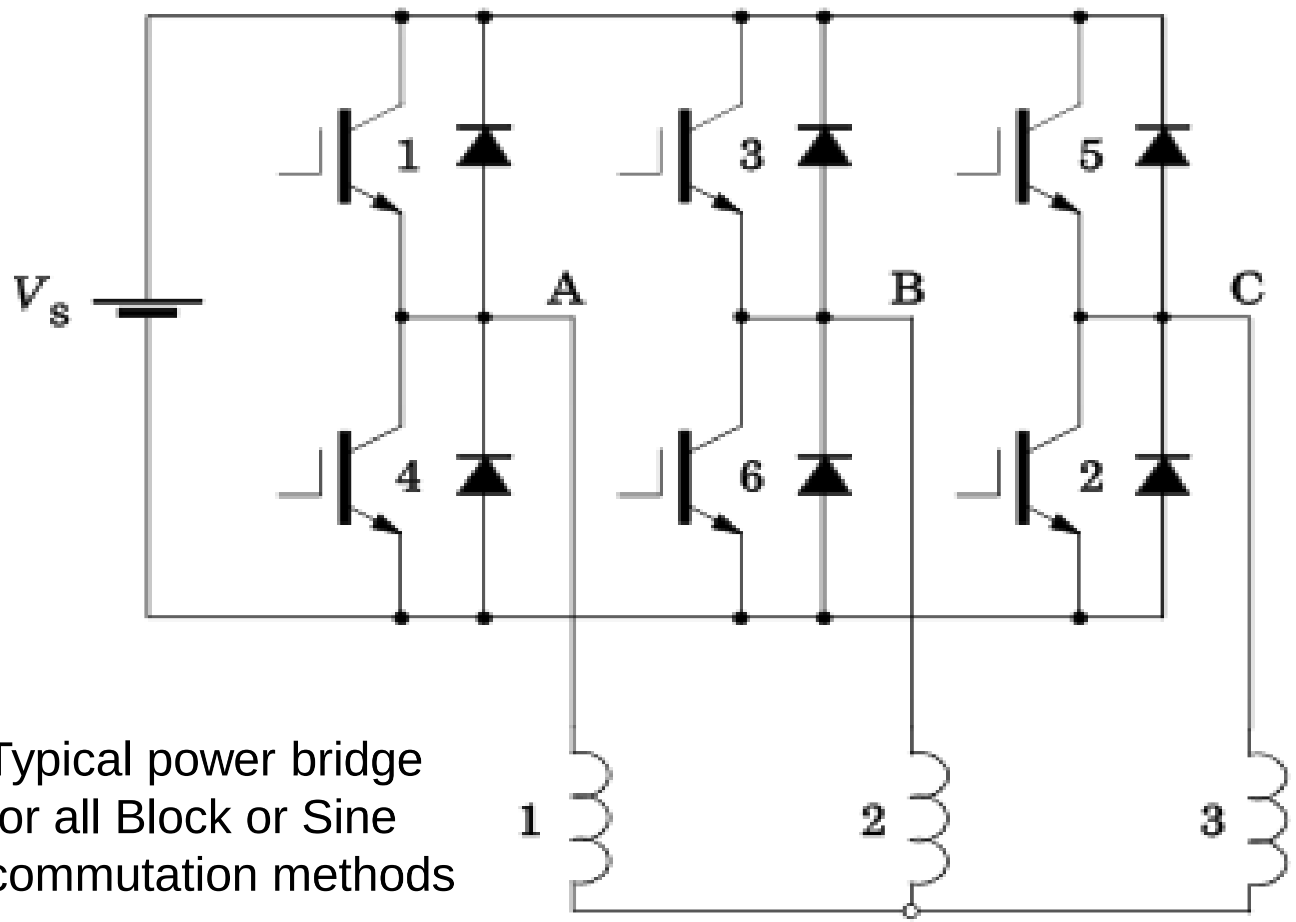
Low cost investment to change from Asynchronous machine with slip to a Synchronous machine with zero slip

- Use same frames, shafts, bearings and cooling system
- Use same stators for induction machines (maybe change turns?)
- Use same inverters with slight change in software

Unknown issues to ponder??

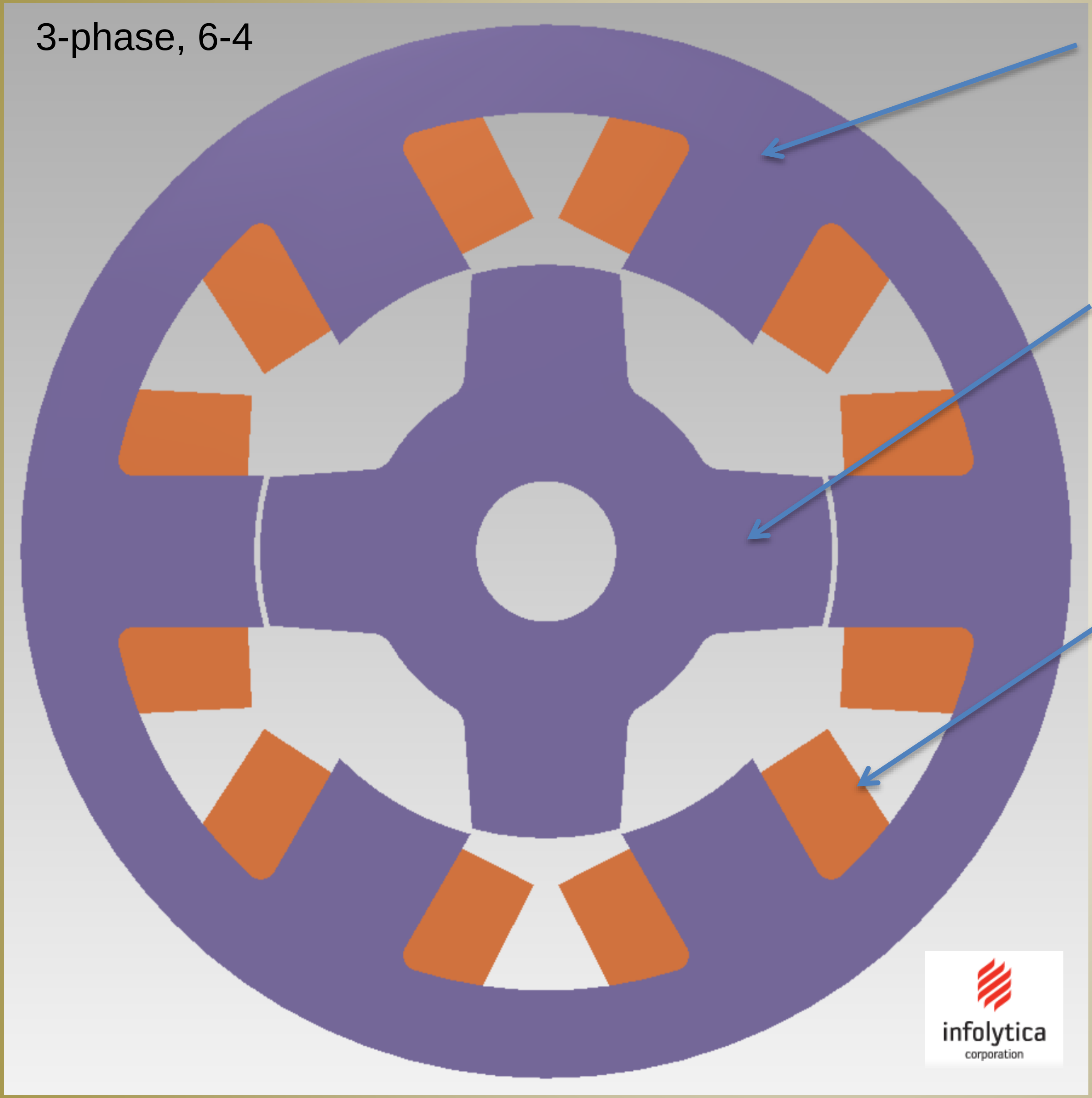
- New design only of simple salient rotor seems the only major task?
- Can a motor made up of flux barriers and flux carriers be designed with sufficient mechanical integrity for rail duty?
- Can the rotor saliency ratio be high enough to match of exceed the torque density and power factor of the Asynchronous machine??

Well recognized power bridge circuit for AC Induction, Reluctance Synchronous and Brushless DC, PM-Asynchronous drives.



Typical power bridge for all Block or Sine commutation methods

Another reluctance machine made from completely different components



Stator core from stamped electrical steel laminations

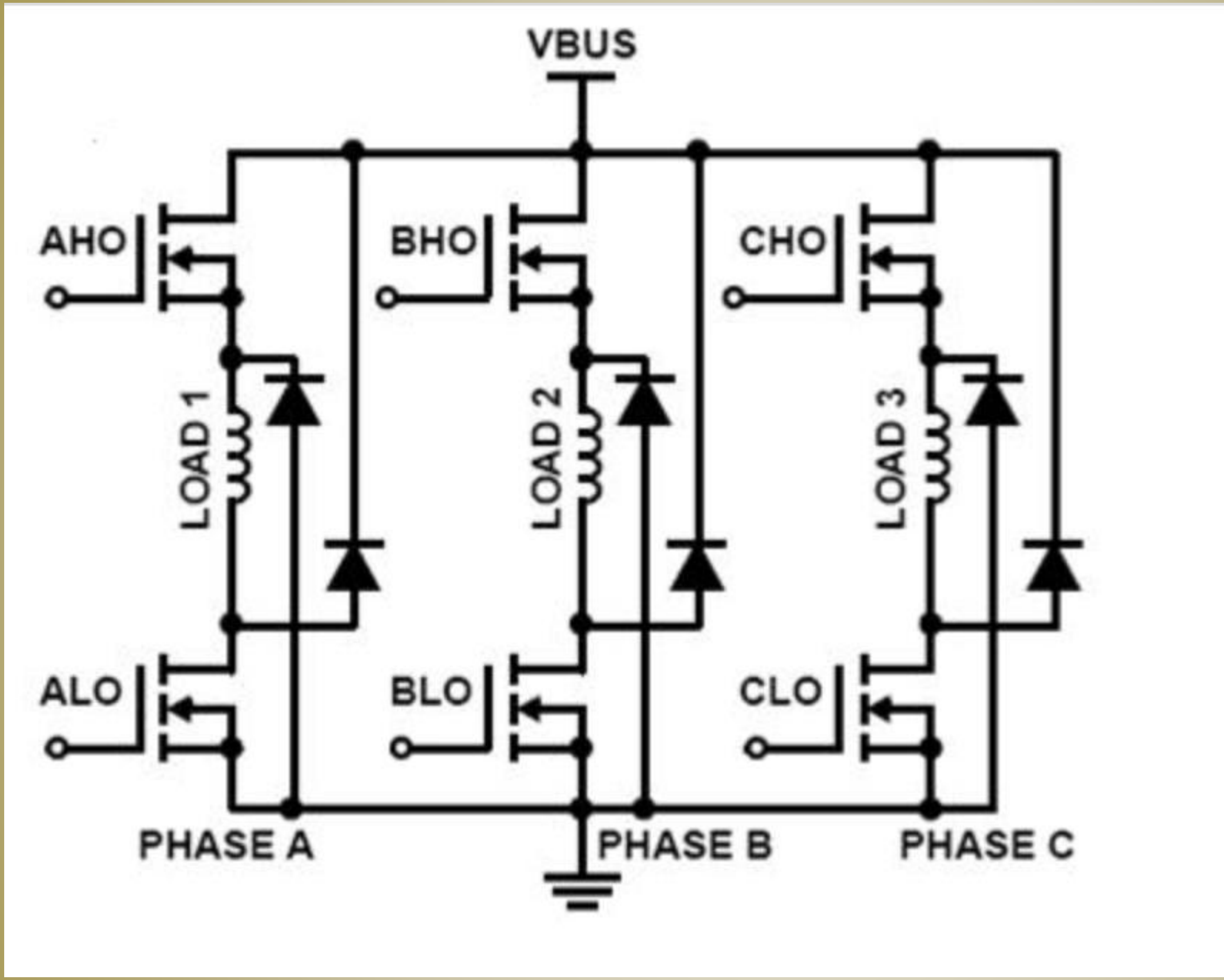
Rotor core from stamped electrical steel laminations

Layer wound coils fitted around each stator tooth

Very robust and low cost cost machine with high fault tolerance

(No magnets required!)

Half Bridge power circuit required for switched reluctance drives



Each load connects to a stator phase with two connections

All phases are in parallel between the DC rails and are controlled separately

Precise phase firing angles are required for efficient operation

At high speeds the use of continuous current conduction is very useful.

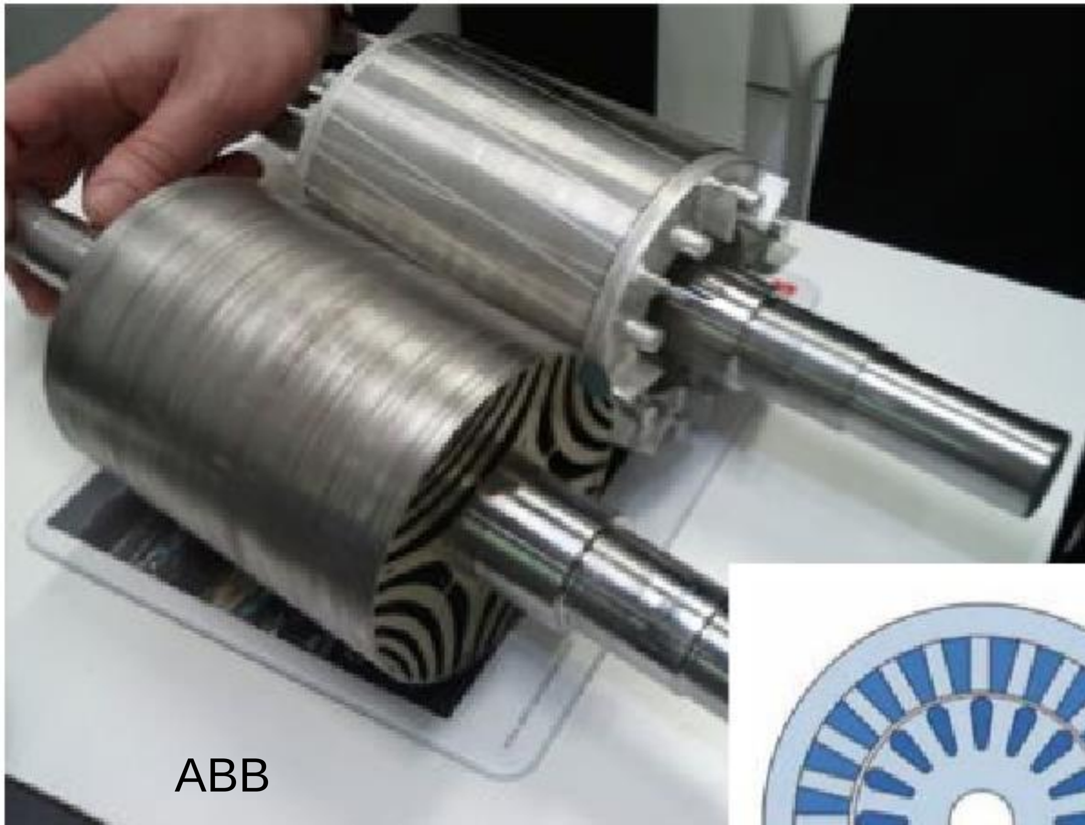
Three phase circuit shown, add a dual transistor half bridge for each additional phase

ABB Reluctance Synchronous motor & Inverter new product line 5 KW to 320 KW *(SynRM)*

4 poles
39 stator slots
32 flux barriers
34 flux carriers

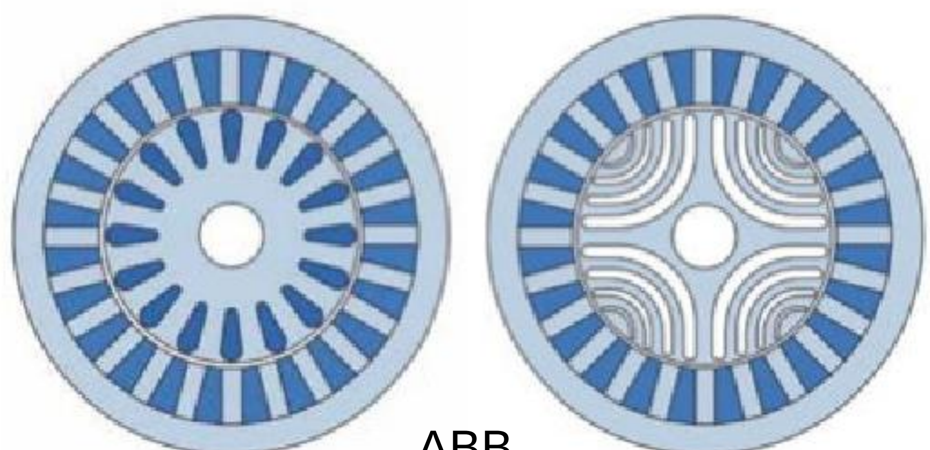
End view of ABB RSM rotor showing Flux barriers & carriers

Reluctance Synchronous machines (RSM)



Uses AC induction stator, phase windings & inverter.

New rotor design required to turn Asynchronous machines into a synchronous machines without magnets or windings in the rotor.



ABB

Rotor requires "*saliency*"
(High *q* & *d* inductance ratio)

RSM Reluctance Synchronous machines

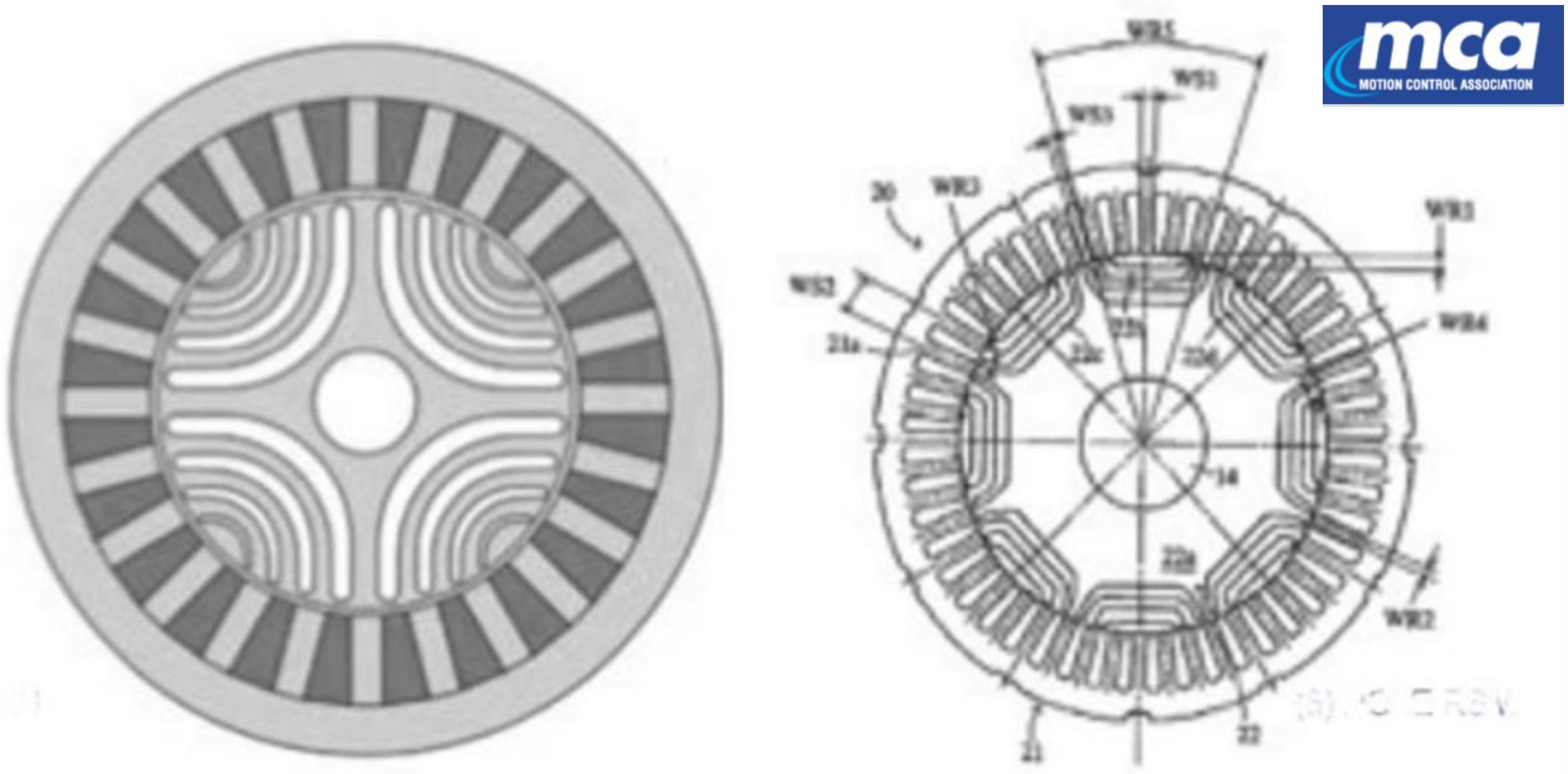
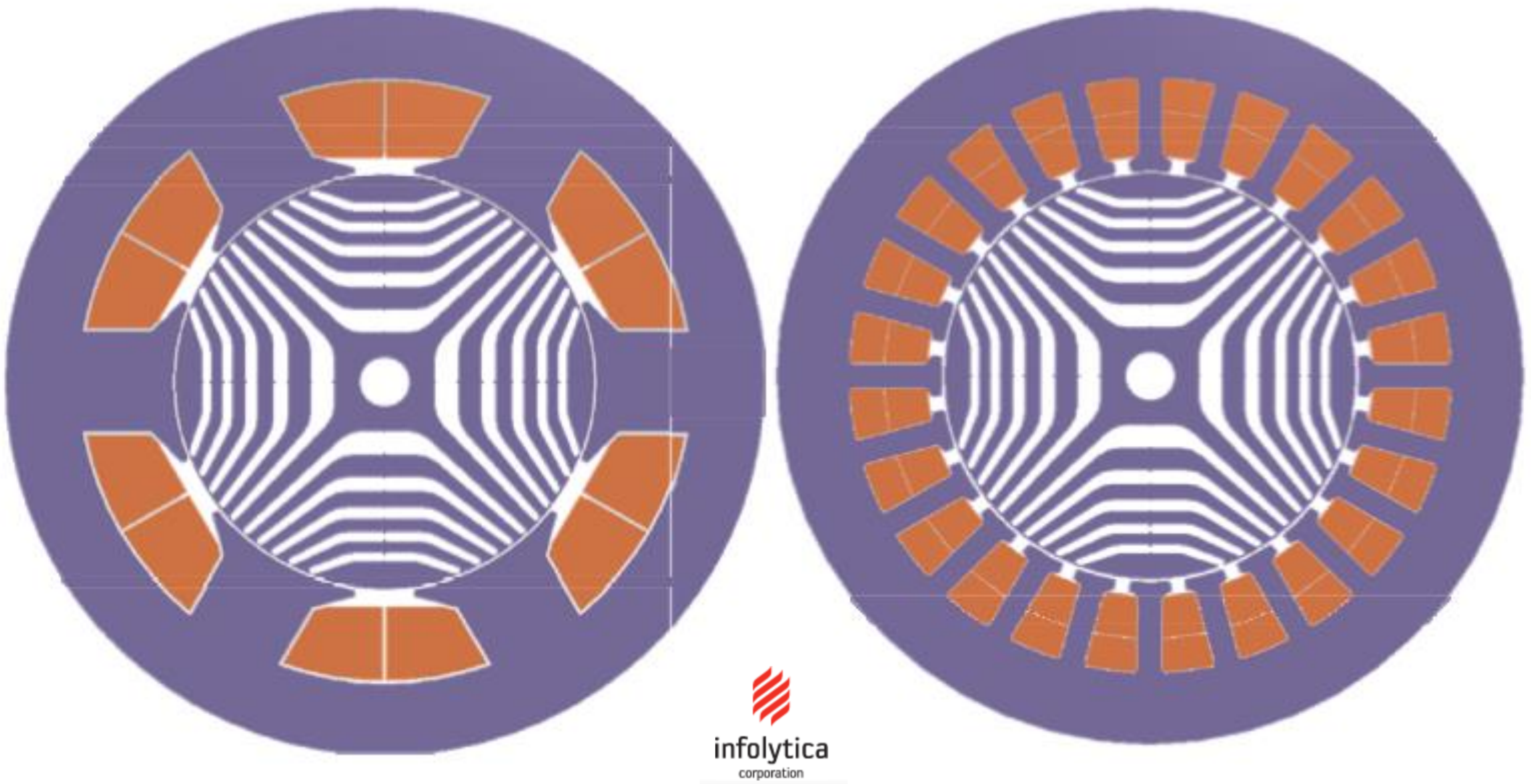


Figure 4: Cross section shows a six-pole RSM (left). The six sets of U-shaped grooves are the flux barriers that focus the flux (right). *(Courtesy of Jim Hendershot)*

Simple RSM (4) pole rotor

Complex RSM (8) pole rotor

RSM Rotor with concentrated phase winding & distributed phase windings



4-Pole RSM with 6 stator slots
two concentrated coils/phase

4-Pole RSM with 24 stator slots
eight distributed coils/phase or
four single layer coils/phase

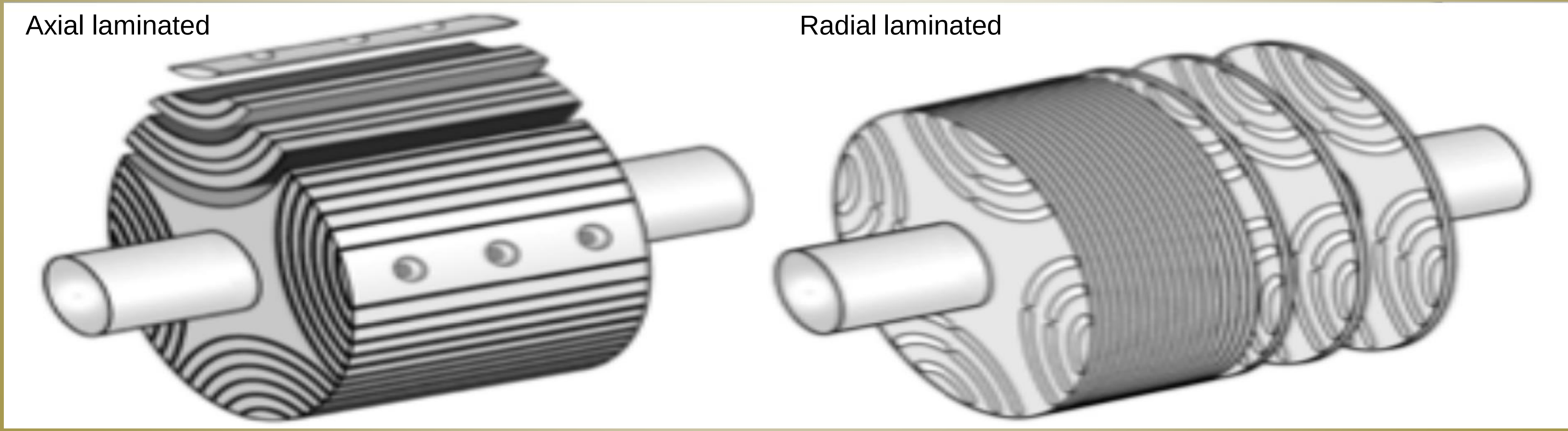
ABB has recently launched a very broad RSM product line (Trade-marked as SynRM) according to IE4 from 11 KW to 315 KW. (Perhaps all 4 pole motors)

Big advantages with this machine:

- Uses standard low cost Asynchronous stator and mfg. infrastructure
- Assembled in standard Asynchronous frame parts
- Use standard AC inverters with slight software modifications
- Only new requirement is a new rotor design with maximum saliency
- Synchronous machine with no slip
- Almost zero heat losses produced in rotor. (Only stator cooling req'd)

Principal design and development task:

- Maximize the Q axis inductance and minimize the axis inductance by creating a rotor magnetic design with a saliency ratio greater than 7



Classic research paper for optimizing RSM saliency ratio

Rotor Design Optimization of Synchronous Reluctance Machine

IEEE Transactions on Energy Conversion, Vol 9, No. 2, June 1994

Takayoshi Matsuo, *Student Member, IEEE*   Thomas A. Lipo, *Fellow, IEEE*

University of Wisconsin-Madison

Fig. 2 Power factor vs. saliency ratio κ (=L_{ds}/L_{qs}) of a synchronous reluctance motor when the motor is controlled with the maximum power factor control scheme.

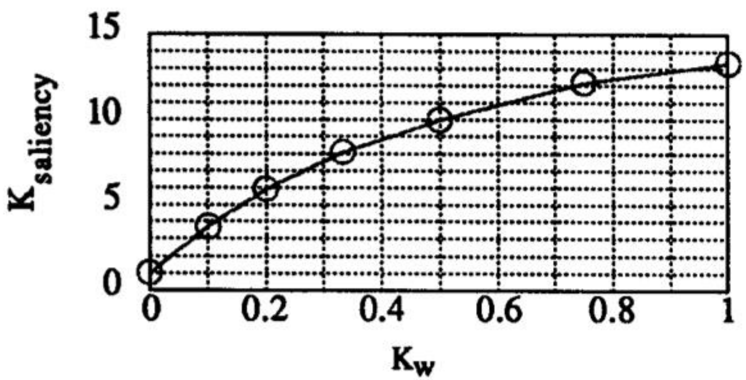
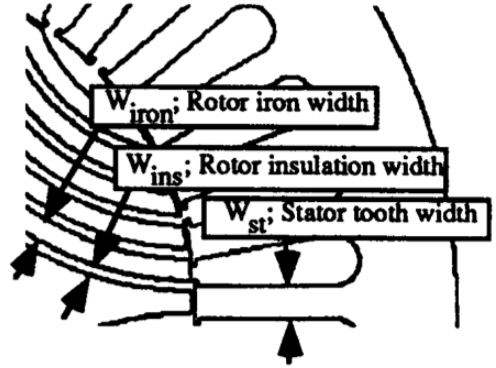


Fig. 7 Saliency ratio $K_{saliency}$ vs. K_w (rotor insulation width/ rotor iron width) resulting from the finite element study of a synchronous reluctance motor with 24 stator slots.



$$W_{st} = (W_{iron} + W_{ins}) \times n$$

where n; integer

Fig. 4 The relation of the stator tooth width W_{st}, the rotor iron width W_{iron} and the rotor insulation width W_{ins} for the rotor lamination design of a synchronous reluctance motor.

$$K_w = W_{ins}/W_{iron} \quad (11)$$

Clearly, when K_w =0, the rotor is assumed to be completely made of iron, (i.e., no saliency). When K_w = 1 the rotor is constructed of lamination segments in which the air space and lamination segments are equal.

Kw ~ 0.5 has been proven optimum

Gary Horst of Emerson Electric-NIDEK validated these findings with actual tested motor samples

Saliency ratio of axially vs. radially laminated RSM rotors

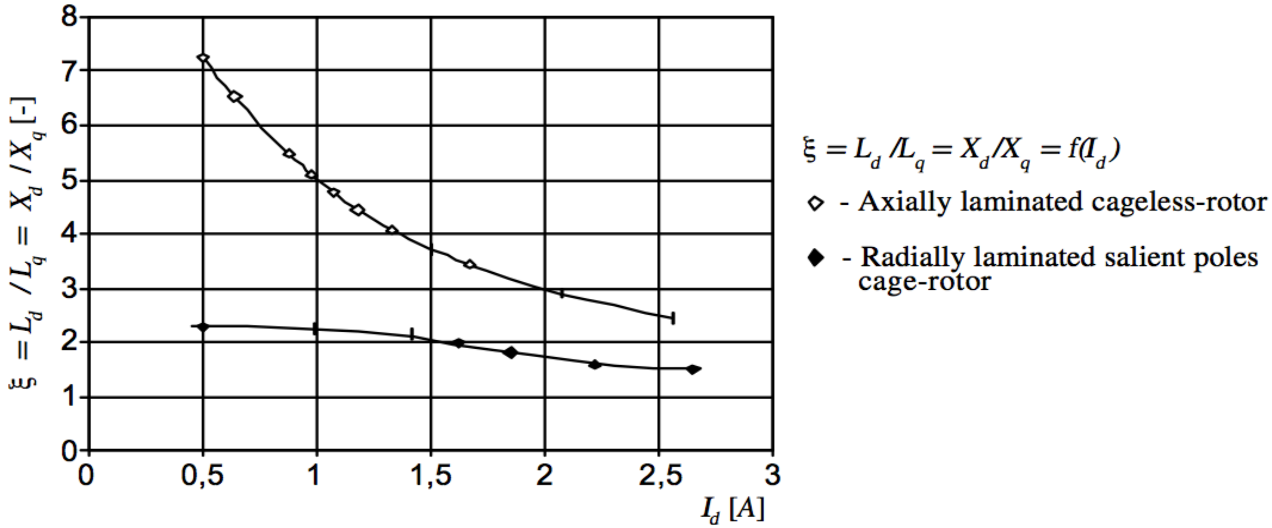
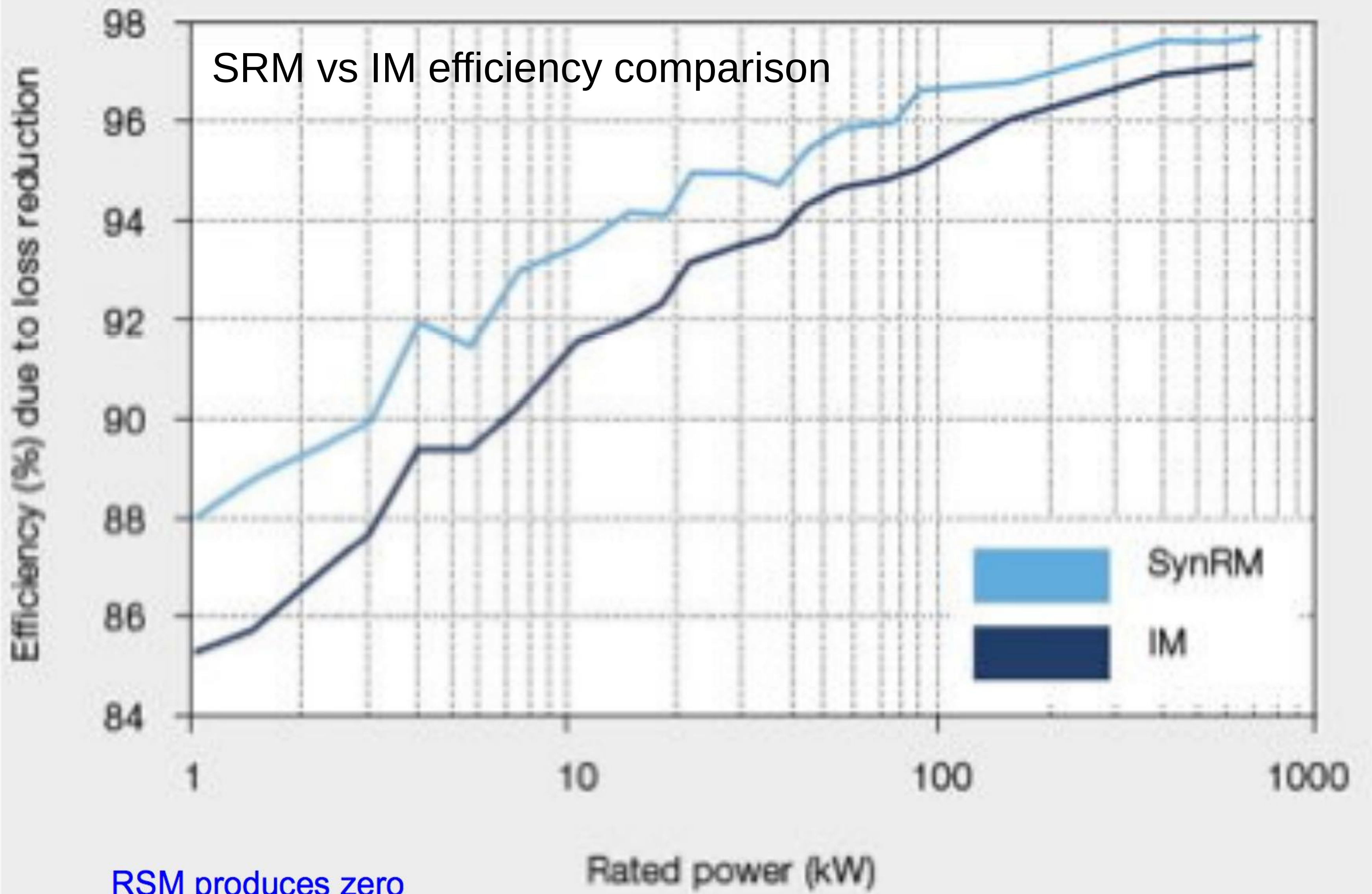


Fig. 6.1. Dependence of the saliency ratio $\xi = L_d / L_q$, if $I_d = I_q$

Tab. 6.1.

	Original radially laminated rotor	New axially laminated rotor	
	$2A$	$2A$	$1{,}5A$
Apparent input power [VA]	1320	1320	998,6
Input active power [W]	585	960	584
Power factor [-]	0,442	0,709	0,585
Output power [W]	392,5	706	392,5
Efficiency [%]	67	73,6	67,2

Valeria Hrabovcová – Pavol Rafajdus – Ladislav Janoušek – Peter Hudák
University of Žilina, Faculty of Electrical Engineering, Moyzesova 20, SK– 010 26Žilina
Jozef Mihok
Technical University of Košice, Faculty of Mechanical Engineering,
Letna 9, SK – 042 00 Košice



RSM produces zero
ohmic losses in rotor

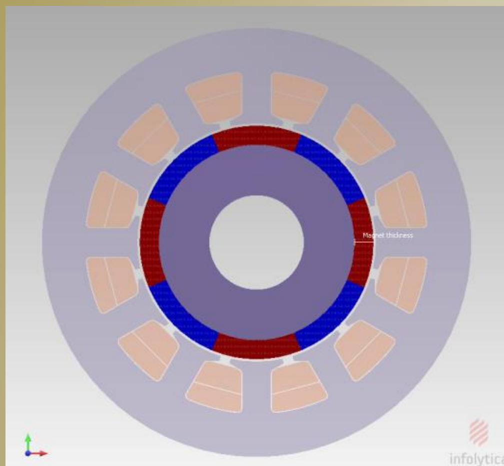
Data by ABB

RSM rotor examples

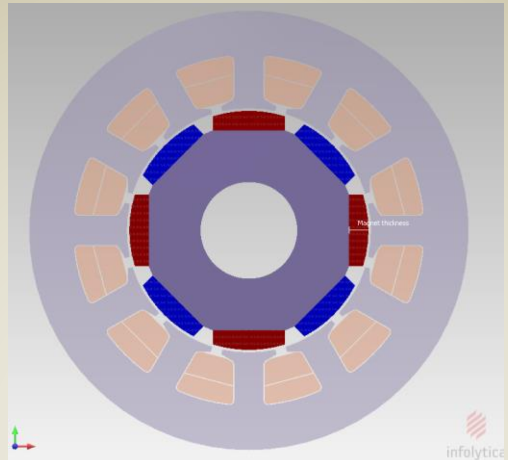
PM brushless motor configurations

Inside Rotors

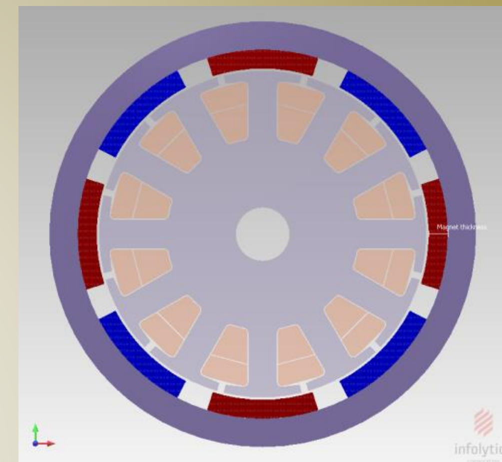
Outside Rotors



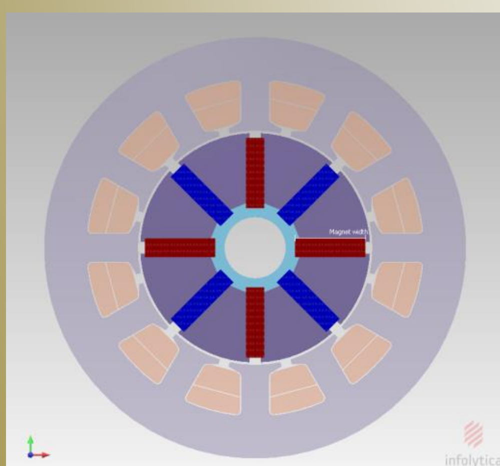
Radial or ring SPM



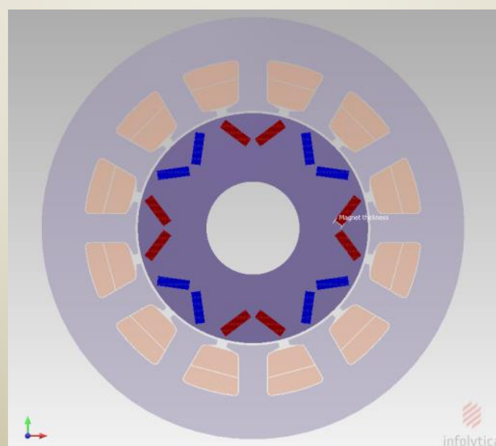
Bread-loaf SPM



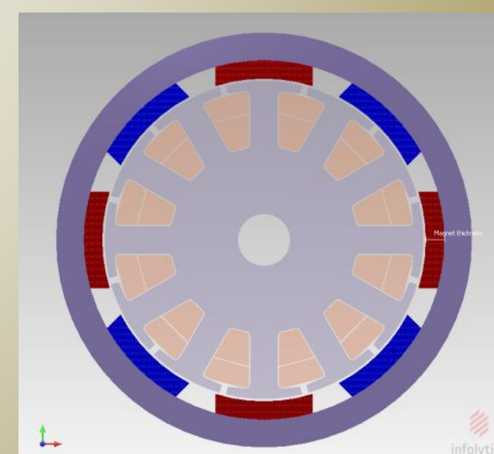
Radial



Spoke IPM

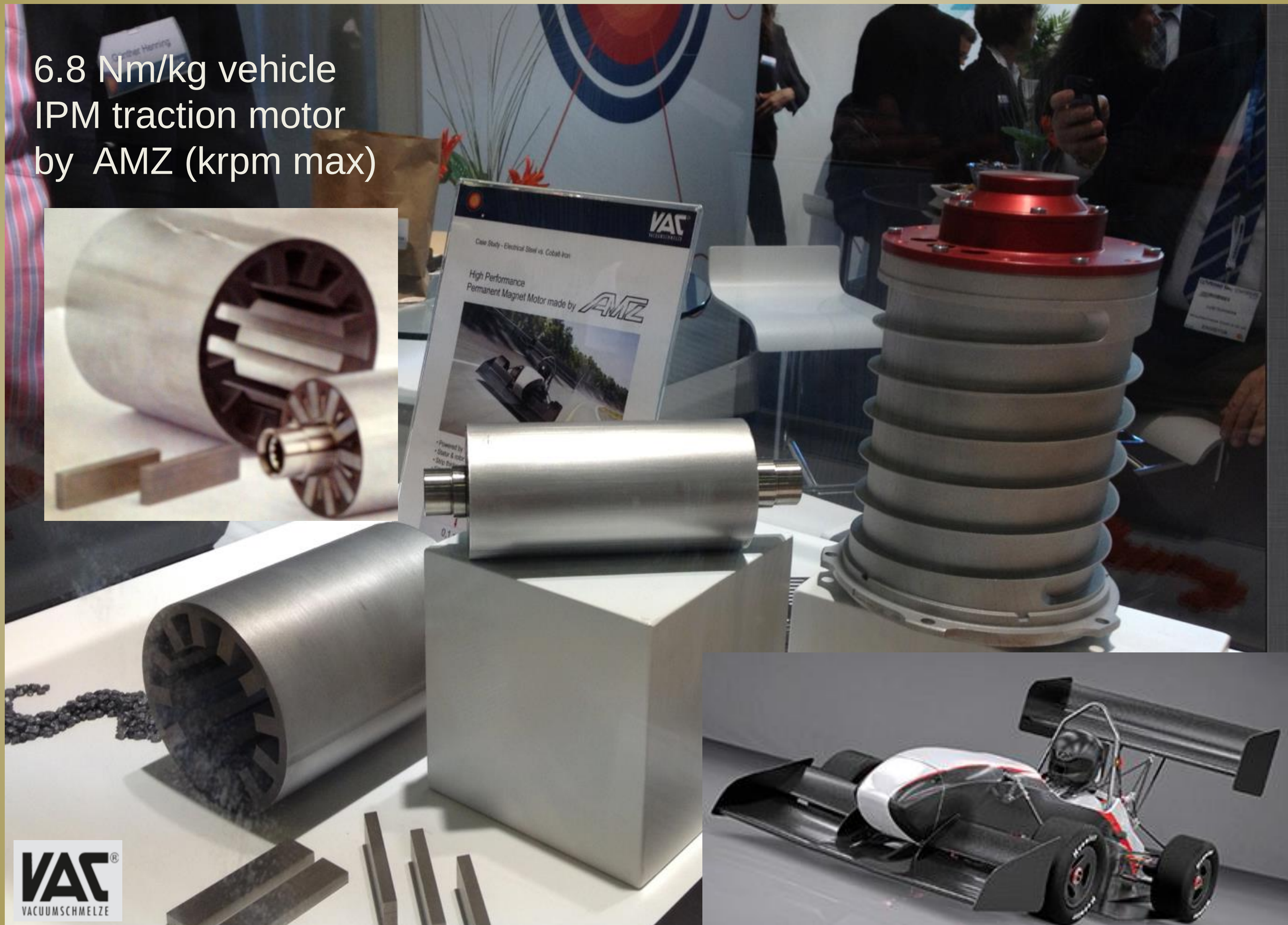


V-Pole IPM

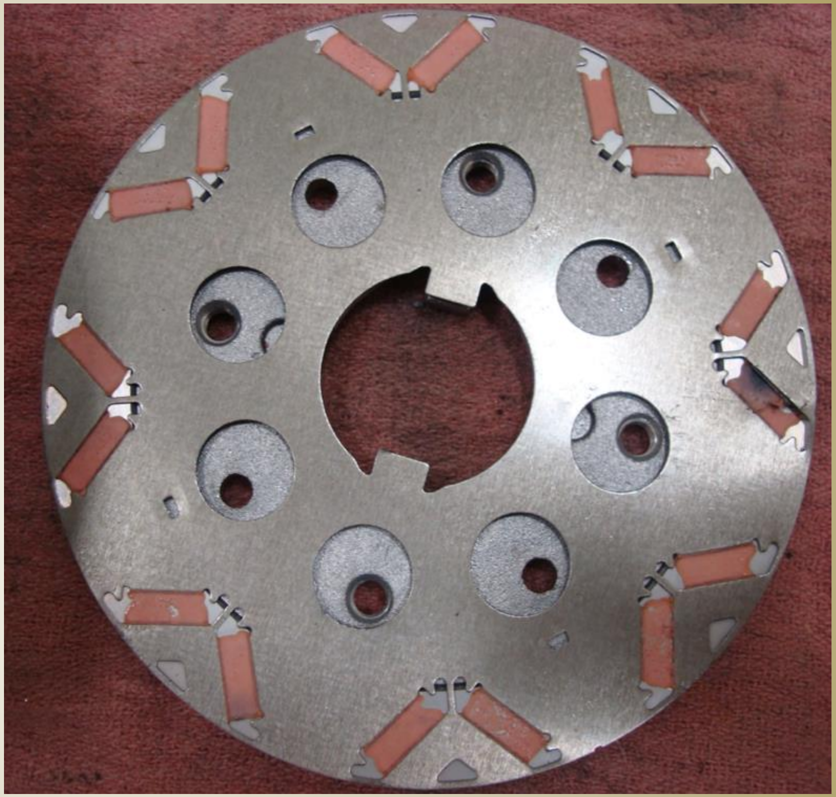


Parallel

10 Pole IPM Spoke race car traction motor, (High torque density)



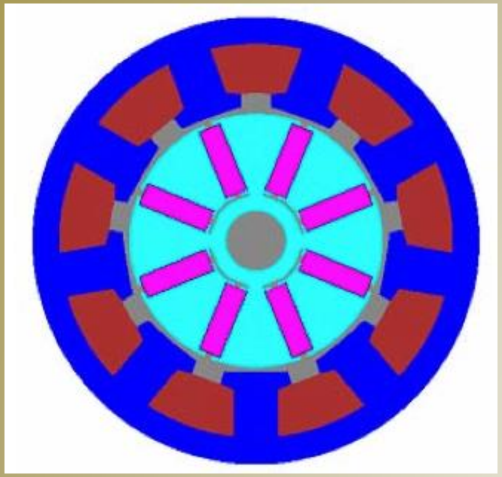
IPM rotor examples (for traction)



Ten pole IPM, dual layer V

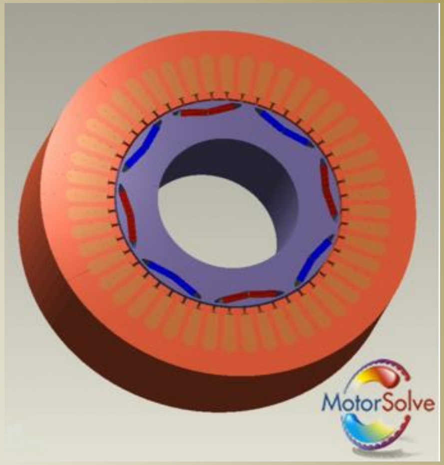
Eight pole IPM, single layer

IPM Rotor Configurations

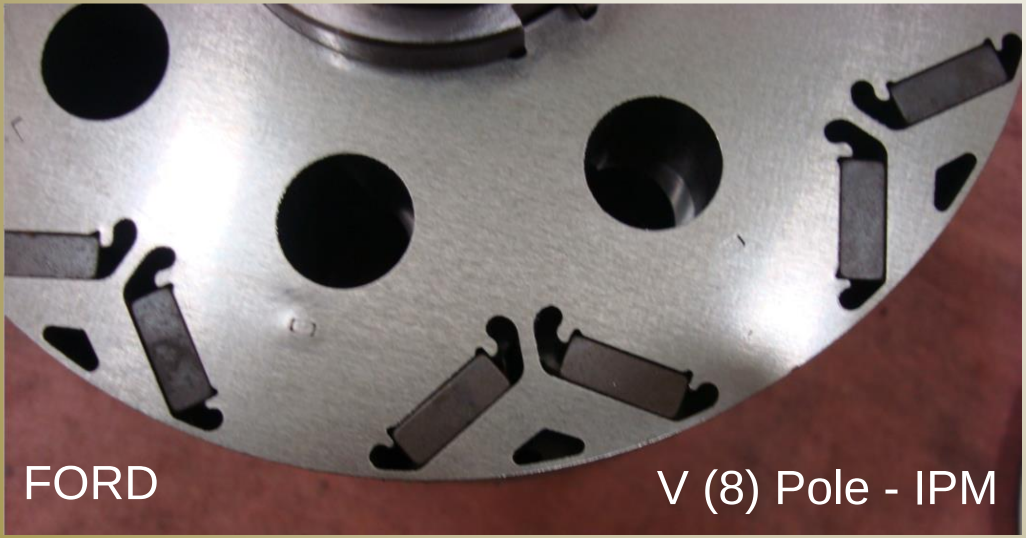


Spoke IPM*

No Saliency



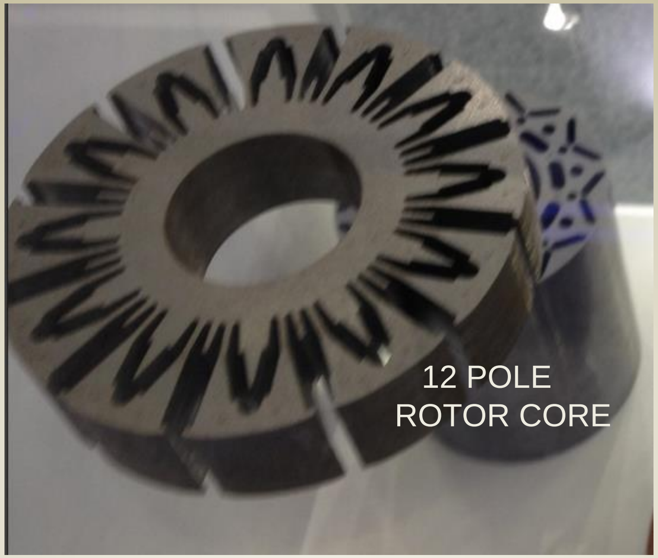
V (8) Pole – IPM*

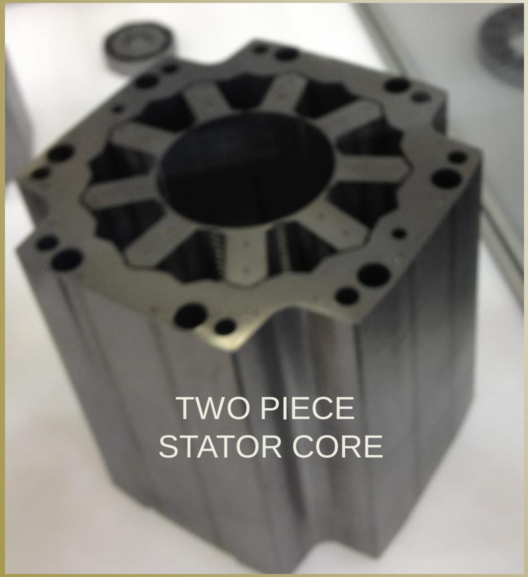


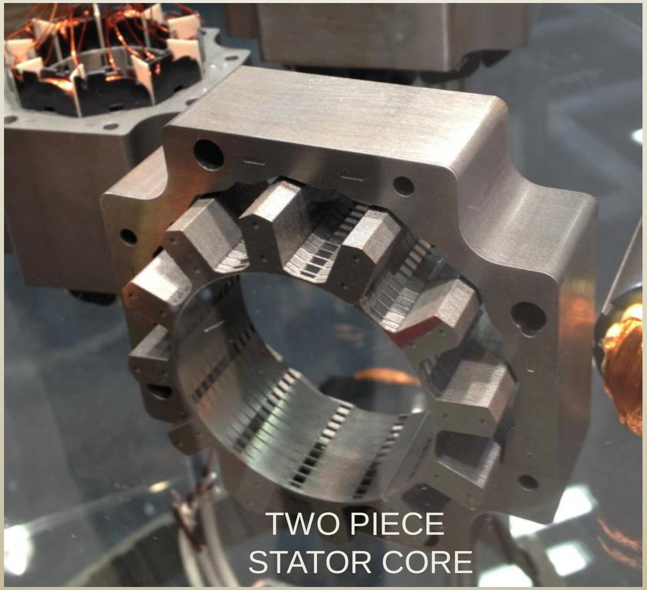
Toyota Prius

*Rapid Simulation of Permanent Magnet Drives
Praveen Kumar1 Peter van Duijsen2 - Pavol Bauer

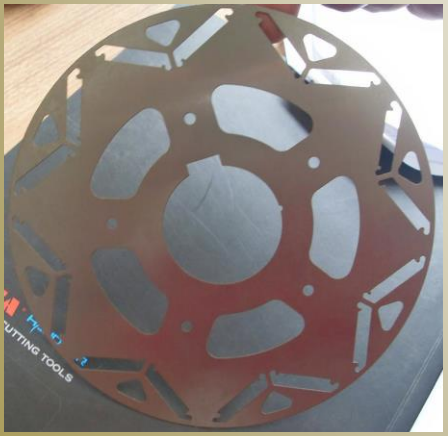
Photos of some of the new IPM spoke parts.



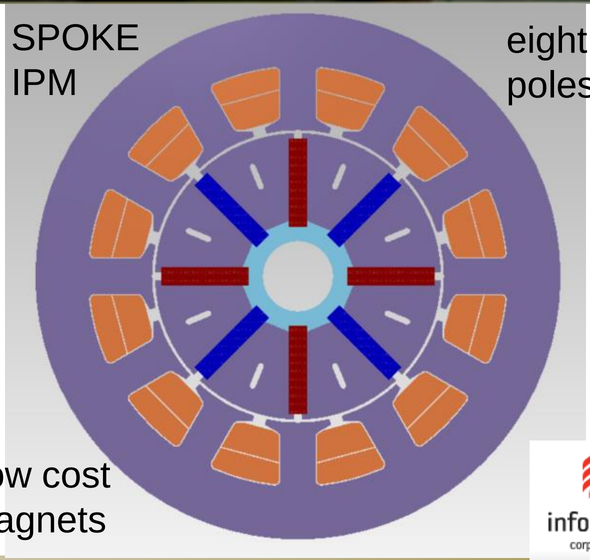




IPM rotor configurations



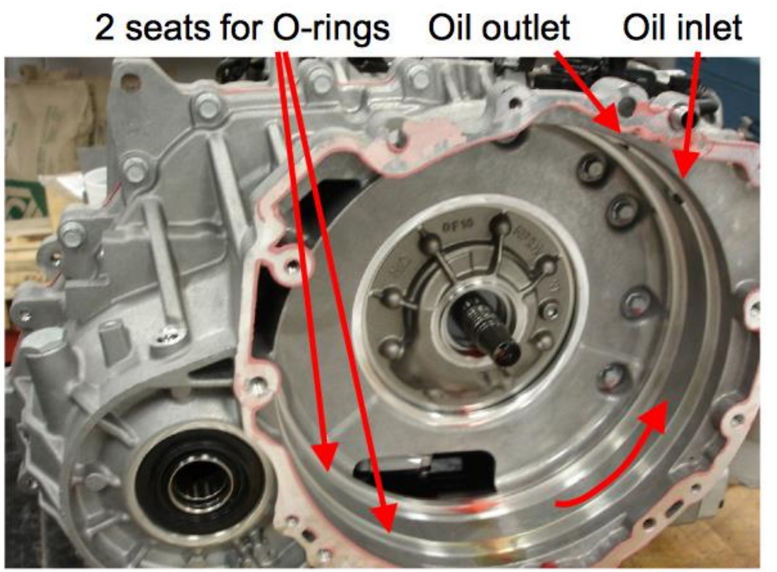
Examples of IPM-AC high performance rotors

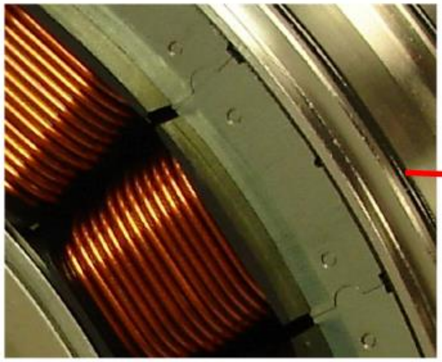


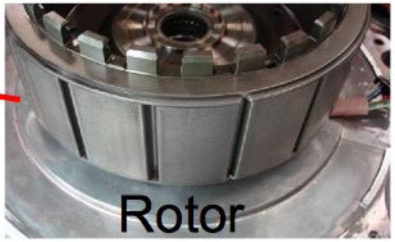
Low cost
magnets

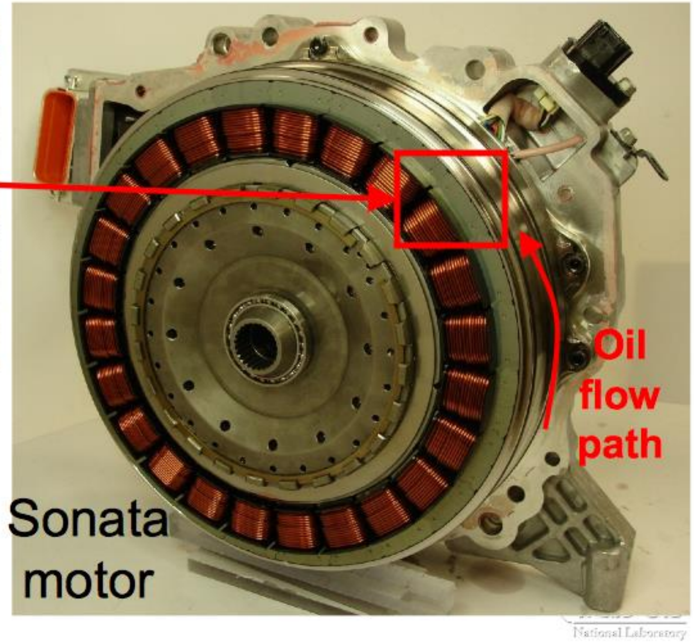
infolytica corporation

- **Sonata transaxle/transmission**
  - Conventional 6 speed transmission
  - Motor replaces torque converter
    - But not simply interchanged
  - Primary motor: 205 Nm and 30 kW ratings
    - Approximate corner speed: 1400 rpm
    - Motor very similar to Honda hybrids
    - 24 stator teeth and 16 rotor poles
  - Resolver similar to Toyota/Honda
  - 3-phase oil pump
  - Clutch integrated into motor rotor
  - Oil cooling path around stator



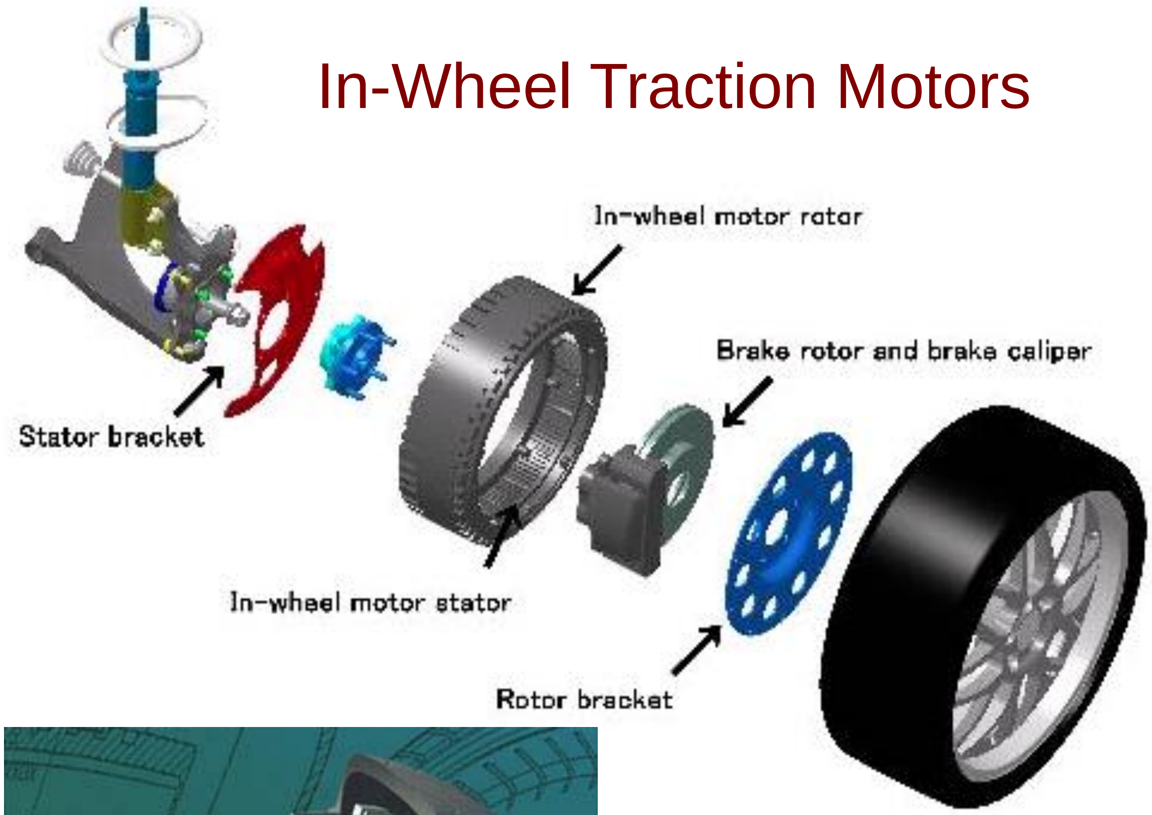


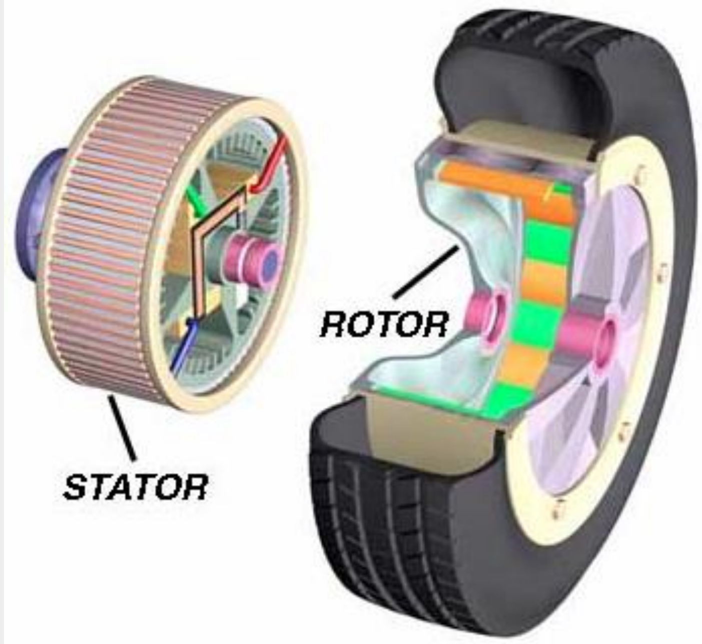


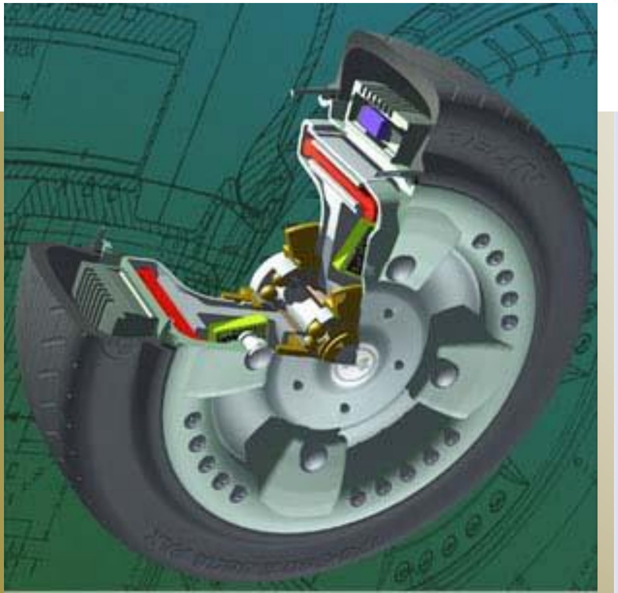


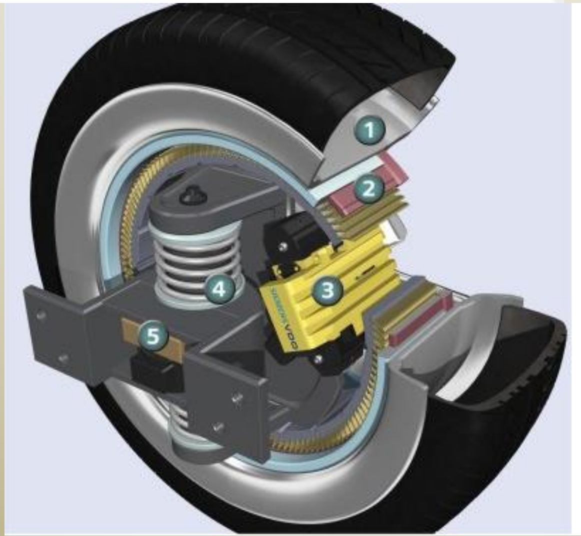
2010 Toyota Prius PM Synchronous Generator

In-Wheel Traction Motors



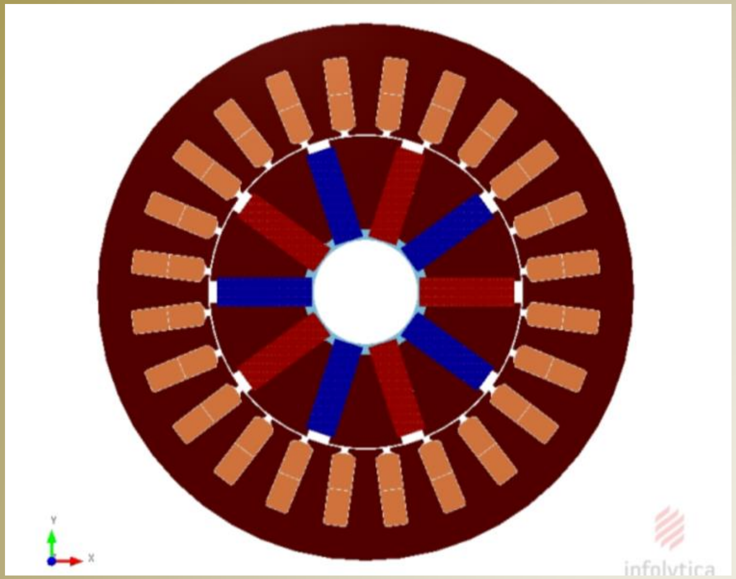


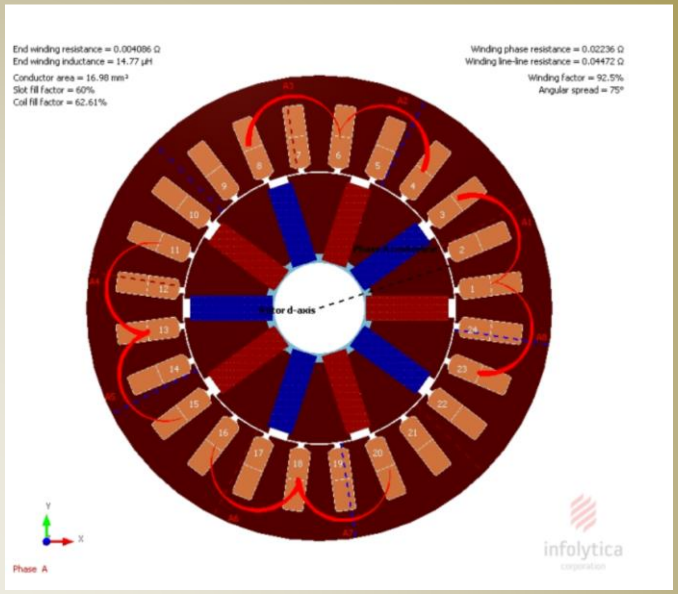


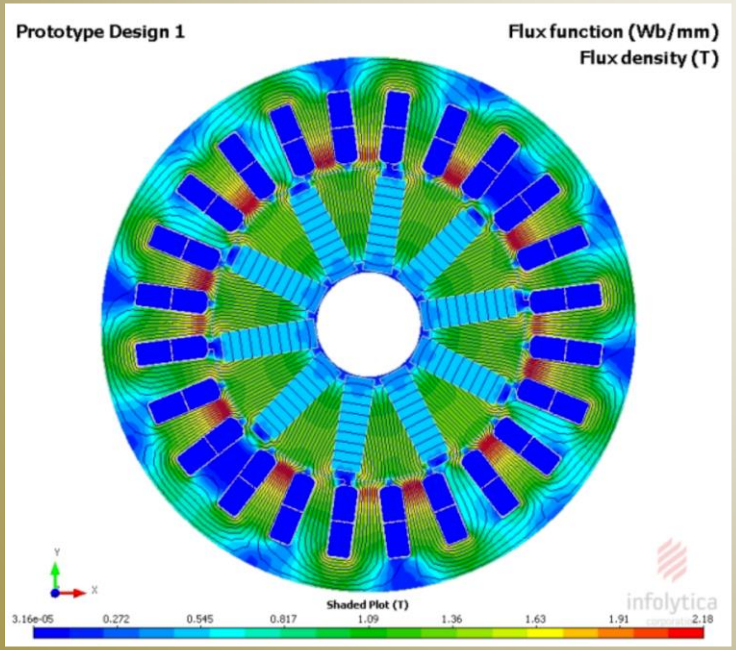


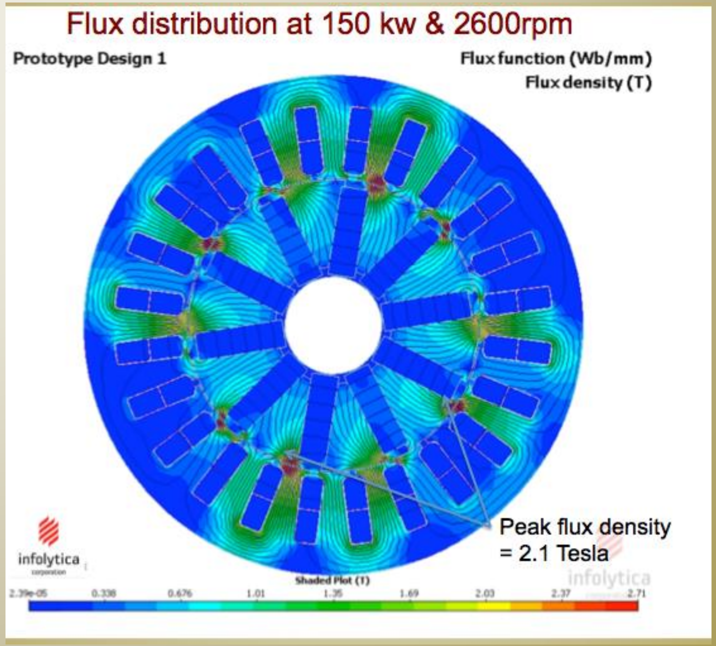
In-wheel motor (on Colt EV)

24 slot, 10 IPM spoke traction motor rated @ 150 Kw @ 2600 rpm









No matter which machine you choose for vehicle traction, it’s torque density is limited by two important magnetic materials.

1-Hard materials (permanent magnets) can produce a maximum flux density of ***1.4 tesla***

2-Soft materials (electrical steels) become saturated at maximum flux densities in the range of *2.1 to 2.4 Tesla*

I offer each of you a challenge to invent new materials

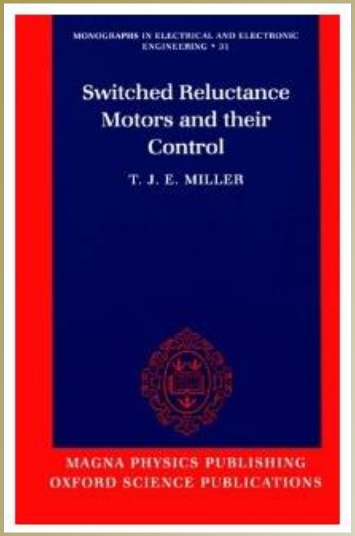
A new material with a *negative permeability* would be a good start

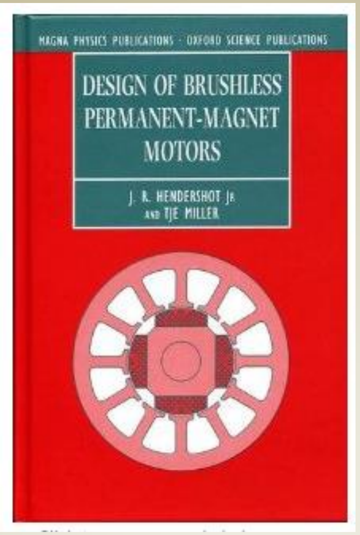
I sincerely hope some of my remarks have stimulated your creativity and provided some insight on electric machine selection for vehicle traction applications.

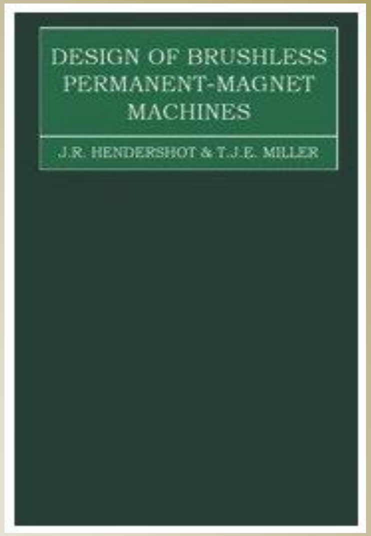
I further encourage you to invent some new machine types for vehicle traction applications.

Thank you very much for your attention and participation,

Jim Hendershot, Life Fellow IEEE
October 2014







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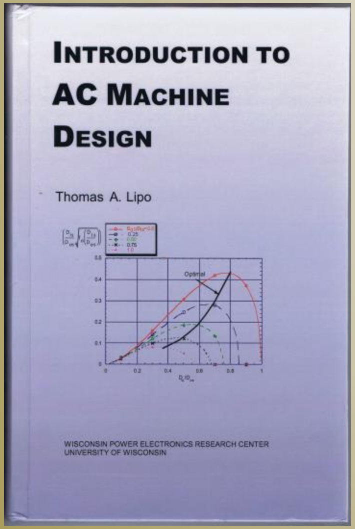

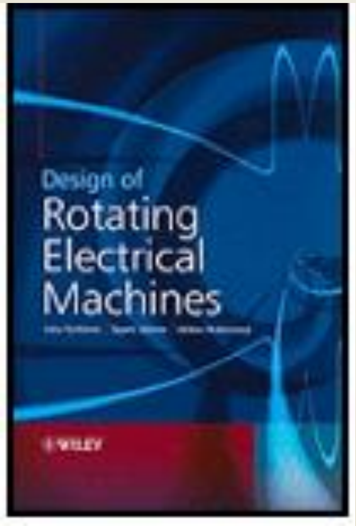

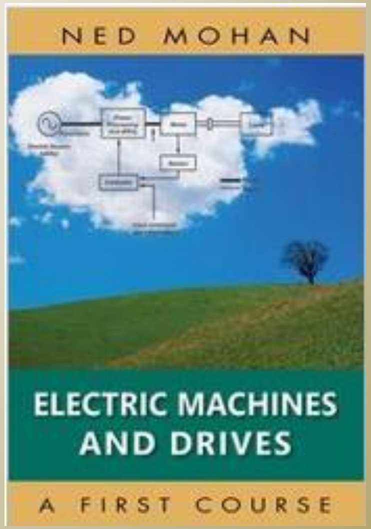

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