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Subcontract Report:

Final Report on Assessment of Motor Technologies for Traction Drives of Hybrid and Electric Vehicles

Subcontract No. 4000080341

Prepared for:

Oak Ridge National Laboratory

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Submitted to:

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Susan A. Rogers, Technology Development Manager

March 2011

OAK RIDGE NATIONAL LABORATORY

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Raymond R. Fessler
BIZTEK Consulting, Inc.

Publication Date: March 2011

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Final Report

on

Assessment of Motor Technologies for Traction Drives of Hybrid and Electric Vehicles

Subcontract No. 4000080341

to

UT Battelle, LLC
Oak Ridge National Laboratory

by

Raymond R. Fessler
BIZTEK Consulting, Inc.

Mitch Olszewski, Program Manager
Oak Ridge National Laboratory

March 2, 2011

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EXECUTIVE SUMMARY

Currently, interior permanent magnet (IPM) motors with rare-earth (RE) magnets are almost universally used for hybrid and electric vehicles (EVs) because of their superior properties, particularly power density. However, there is now a distinct possibility of limited supply or very high cost of RE magnets that could make IPM motors unavailable or too expensive. Because development of electric motors is a critical part of the U.S. Department of Energy (DOE) Advanced Power Electronics and Motors activity, DOE needs to determine which options should be investigated and what barriers should be addressed. Therefore, in order to provide a basis for deciding which research topics should be pursued, an assessment of various motor technologies was conducted to determine which, if any, is potentially capable of meeting FreedomCAR 2015 and 2020 targets.

Highest priority was given to IPM, surface mounted permanent magnet (SPM), induction, and switched reluctance (SR) motors. Also of interest, but with lesser emphasis, were wheel motors, multiple-rotor motors, motors with external excitation, and several others that emerged from the assessment.

Cost and power density (from a design perspective, the power density criterion translates to torque density) are emerging as the two most important properties of motors for traction drives in hybrid and EVs, although efficiency and specific power also are very important.

The primary approach for this assessment involved interviews with original equipment manufacturers (OEMs), their suppliers, and other technical experts. For each technology, the following issues were discussed:

- The current state-of-the-art performance and cost.
- Recent trends in the technology.
- Inherent characteristics of the motor – which ones limit the ability of the technology to meet the targets and which ones aid in meeting the target.
- What research and development (R&D) would be needed to meet the targets.
- The potential for the technology to meet the targets.

The interviews were supplemented with information from past Oak Ridge National Laboratory (ORNL) reports, previous assessments that were conducted in 2004, and literature on magnet technology.

The results of the assessment validated the DOE strategy involving three parallel paths:

(1) there is enough of a possibility that RE magnets will continue to be available, either from sources outside China or from increased production in China, that development of IPM motors using RE magnets should be continued with emphasis on meeting the cost target.

(2) yet the possibility that RE magnets may become unavailable or too expensive justifies efforts to develop innovative designs for permanent magnet (PM) motors that do not use RE magnets. Possible other magnets that may be substituted for RE magnets include samarium-cobalt (Sm-Co), Alnico, and ferrites. Alternatively, efforts to develop motors that do not use PMs but offer attributes similar to IPM motors also are encouraged.

(3) New magnet materials using new alloys or processing techniques that would be less expensive or have comparable or superior properties to existing materials should be developed if possible.

IPM motors are by far the most popular choice for hybrid and EVs because of their high power density, specific power, and constant power-speed ratio (CPSR). Performance of these motors is

optimized when the strongest possible magnets – i.e., RE neodymium-iron-boron (NdFeB) magnets – are used.

Currently China controls the supply of RE mining, processing, and magnet production. Whereas China previously supplied RE metals to other countries for magnet production, China has recently decided to vertically integrate to include magnet production and even motor production. It is projected that China will soon consume virtually all of their RE production for internal use. The demand for RE magnets is further exacerbated by the growth of wind power, which is projected to consume a significantly greater share of RE magnets than hybrid vehicles. One possible solution would be to reactivate the MolyCorp mine in Mountain Pass, California, which has a significant reserve of RE ores, but which ceased mining operations for economic and environmental reasons. Restarting mining operations would require a significant investment. However, renewed operation at Mountain Pass could supply the RE needs of North America for a decade or more.

Doubling or even tripling the magnet cost might not justify a shift from RE magnets to weaker magnets or other technologies; system costs must be considered including the hidden costs of increased volume or weight. The use of weaker magnets would require significant design changes for any new design. Although most manufacturers are assuming that RE magnets will continue to be available, they also recognize the importance of developing backup technologies.

If NdFeB magnets are not available, the following alternatives may be considered:

- Sm-Co have similar magnetic properties to NdFeB magnets, have better high-temperature stability (up to ~300ºC), but are very costly.
- Alnico has somewhat lower cost but very low coercivity (resistance to de-magnetization).
- Ferrites are the least expensive but also are the weakest magnets. They have good thermal stability between -40ºC and 250ºC.
- New alloys yet to be developed.

Temperature tolerance is extremely important with respect to wiring and magnets.

SPM motors have relatively high specific power but restricted CPSR. The speed of these motors is limited due to challenges of magnet retention. Essentially, they have no advantage over IPM motors.

Induction motors have lower power density compared with IPM motors but also cost less. They are robust and have a medium CPSR. Being a mature technology, they are reliable but have little opportunity for improvement. Most manufacturers consider induction motors the first choice if IPM motors are not available.

SR motors are durable and low cost, and they contain no magnets. Their efficiency is slightly lower than that of IPM motors at the sweet spot, but the flatter profile of SR motors can give higher efficiency over a typical drive cycle. The torque density is much better than that of induction motors. They require different power electronics (PEs) compared to IPM motors. Significant concerns about SR motors are torque ripple and acoustic noise. Efforts are currently being directed to solve those problems through rotor design, modified electronics, and stiffening of the case.

Motors with external excitation are currently being studied at ORNL. They would contain no magnets, but serious concern about cost, manufacturability, and durability need to be addressed.

Other motor designs including wheel motors, multiple-rotor motors, and synchronous reluctance motors were mentioned in the interviews but are considered low priority and do not justify research at this time.

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ACKNOWLEDGEMENTS

The author is grateful for the support and participation of Mitch Olszewski, who participated actively in the interviews and provided valuable technical guidance and advice, and for the financial support of Susan Rogers, manager of the U.S. Department of Energy's Advanced Power Electronics and Electrical Machines activity.

ACRONYMS AND ABBREVIATIONS

Ac	alternating current
Al	aluminum
APEEM	Advanced Power Electronics and Electric Machines
BDCM	brushless direct current motor
BEV	battery electric vehicle
Co	cobalt
CPSR	constant power-speed ratio
CVT	continuously variable transmission
dc	direct current
DOE	U.S. Department of Energy
EETT	Electrical and Electronics Technical Team
emf	electromagnetic field
EREV	extended-range electric vehicle
ETS	electric traction system
EV	electric vehicle
FCV	fuel cell vehicle
FEA	finite-element analysis
FSCW	fractional-slot concentrated windings
GM	General Motors
HEV	hybrid electric vehicle
ICE	internal combustion engine
IGBT	insulated gate bipolar transistor
IMMD	integrated modular motor drive
IPM	interior permanent magnet
kg	kilogram
kW	kilowatt
L	liter MMF
	magnetic motive force
NdFeB	neodymium-iron-boron
Ni	nickle
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PE	power electronic
PHEV	plug-in hybrid electric vehicle
PM	permanent magnet
PMSM	permanent magnet synchronous machine
PNGV	Partnership for a New Generation of Vehicles
R&D	research and development
Sm-Co	samarium-cobalt
SPM	surface mount permanent magnet
SPP	slot-per-phase-per-pole
SR	switched reluctance
SRM	switched reluctance machine
USCAR	U.S. Council for Automotive Research
UW	University of Wisconsin

INTRODUCTION

As part of its project management activities, the Advanced Power Electronics and Electric Machines (APEEM) activity of the Vehicle Technologies Program occasionally solicits assessments of technologies that are critical to the program in order to obtain guidance in project selection. Electric motors represent a significant portion of the extra cost, weight, and volume of hybrid and electric vehicles (EVs) compared with conventional internal combustion engine (ICE) vehicles and therefore are an important research area in the APEEM activity.

For the past several years, the interior permanent magnet (IPM) motor has been considered the obvious choice for electric traction drive systems. However, with the rapidly increasing costs of magnets and the possibility of a future shortage of rare-earth (RE) metals[1], the use of IPM motors may not continue to be economically or technically feasible.[2] Therefore, it is timely to consider other options for motor types. The purpose of this assessment is to determine, for various motor technologies, which if any, is *potentially* capable of meeting FreedomCAR 2015 and 2020 targets, and what further technological developments are necessary to do so. The results will be used by the U.S. Department of Energy (DOE) to guide their selection of projects to be funded.

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[1] S. Constantinides, "Status of the Chinese Magnet Industry and its Likely Impact on Western Magnet Users," presentation to the Electrical and Electronics Technical Team (EETT), April 2009.
[2] "IGBT and Rare Earth Market Conditions and Projections," presentation to EETT February 2009.

APPROACH

Most of the material for this assessment came from interviews with technical experts at the original equipment manufacturers (OEMs), their suppliers, consultants, and researchers. Relevant technical reports from the Oak Ridge National Laboratory (ORNL) also were reviewed. Table 1 lists the organizations and individuals that contributed to this assessment. Some of the consultants and researchers supplied written reports on various issues. Portions of those reports have been incorporated into this document, as noted in footnotes. The entire reports from Jim Nagashima, John Miller, and Jim Hendershot are attached as Appendices A, B, and C respectively.

Table 1. Interviews that provided the basis for this assessment

OEMs	**Consultants**
Chrysler	Duane Hanselman
Ford	Jim Hendershot
General Motors (GM)	Tom Jahns
Deere	John Miller
	Jim Nagashima
Suppliers	**Researchers**
Arnold Magnetic	Ames
Delphi	Iver Anderson
Emerson	Bill McCallum
General Electric	ORNL
MolyCorp	Tim Burress
UQM	John Hsu

For each technology, the following topics were addressed:

- The current state-of-the-art performance and cost.
- Recent trends in the technology.
- Inherent characteristics of the motor: which ones limit the ability of the technology to meet the targets and which ones aid in meeting the targets.
- What research and development (R&D) would be needed to meet the targets.
- The potential for the technology to meet the targets.

TYPES OF MOTORS FOR ASSESSMENT

The assessment considered traction motors that could be suitable for full hybrids, including hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), and all-EVs including battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). Extended-range PHEVs (EREVs) – PHEVs with a significant all-electric range – will have requirements similar to those for BEVs and FCEVs. PHEVs that are designed for blended operation—operating for only brief periods without the ICE—will have requirements similar to those for HEVs.

As is shown in Fig. 1, there are many types of motors that could be considered or HEVs or EVs.[3] Figure 2 illustrates the magnetic structures of the major types of motors.[1]

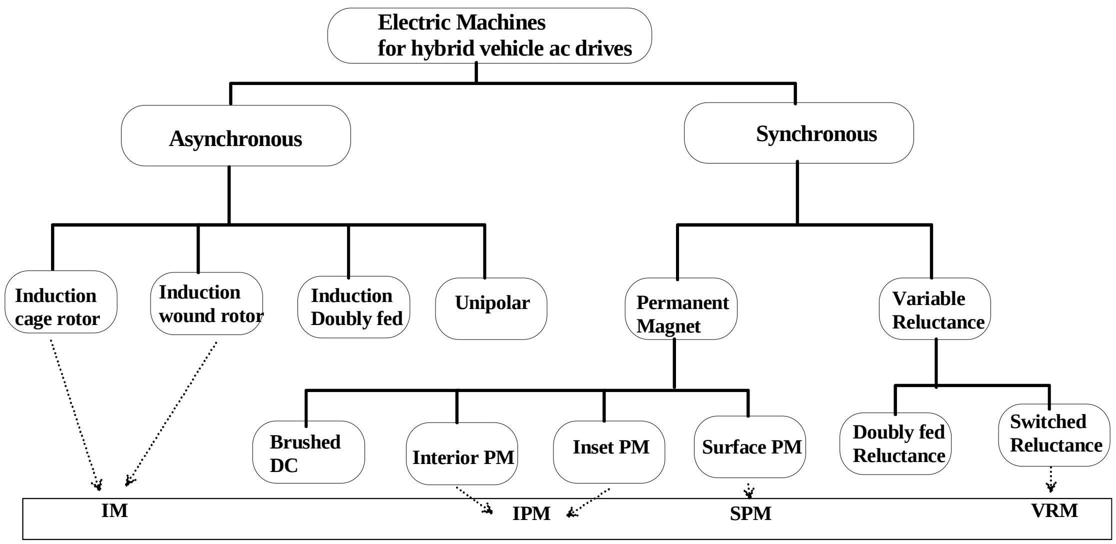

Fig. 1. Types of motors that could be considered for HEVs or EVs.

[3] Based on input from John Miller.

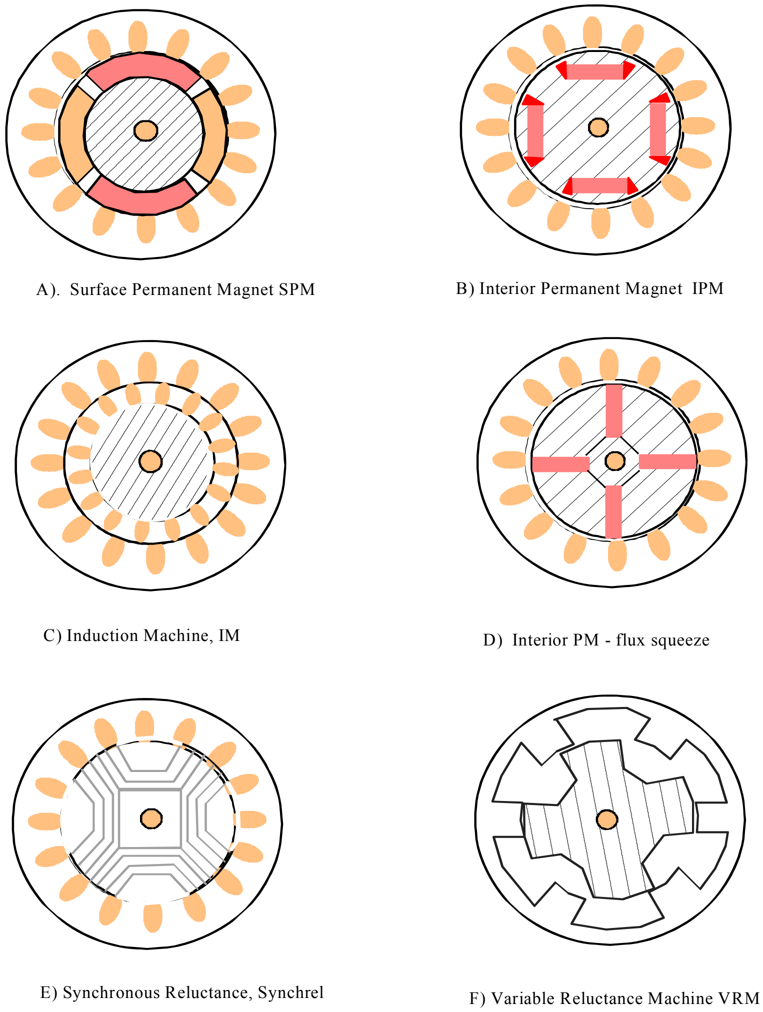

Fig. 2. Magnetic structures of the major types of motors.

In order to focus this assessment on the most important types of motors that should be considered, only brushless motors are included and the following types are emphasized:

- Permanent magnet (PM) motors:
  - IPM – These were treated in detail and formed the baseline against which other types of motors were compared.
  - Surface-mounted permanent magnet (SPM) – These were treated only briefly, because they have no advantage over IPM motors.
  - Wheel motors – These were treated only briefly because they are not a high priority in the current program.
  - Multiple-rotor motors – These were treated only briefly because previous research indicated that there are significant challenges that would require extensive R&D with a questionable probability of success.
- Motors without PMs:
  - Induction – Although having inferior performance to IPM motors and being a relatively mature technology, these were treated in detail because they are relatively inexpensive and they had been considered seriously before the introduction of IPM motors.

- Switched reluctance (SR) – Although there are problems with torque ripple and acoustic noise with this type of motor, it was considered in detail because it is rugged and relatively inexpensive.
- Motors with external excitation – These were considered in detail because it is a relatively new technology with unknown but possibly exciting potential.
- Other concepts that might have emerged during the assessment. Synchronous reluctance motors and direct current (dc) motors were mentioned briefly.

BACKGROUND

HISTORICAL PERSPECTIVE[4]

For most of the history of electric motors, the machines of choice were either the dc brush motor or alternating current (ac) induction motor. The dc motor offered good performance but needed a commutation block with brushes, which required regular service and replacement. The ac induction motor was brushless, needed no inverter, and was used in applications where ac line power was available. Its construction was simple, and it offered excellent performance. The induction motor uses the rotating ac field in the stator to induce an ac in the rotor. The rotor current creates a magnetic field that interacts with the stator current and creates torque. This torque is proportional to the difference between the rotating electrical field speed and the rotor mechanical speed, or "slip." Since most machines were line connected, motor speed was determined by line frequency and the pole number so it was suitable for fixed speed operation like pumps, blowers, etc. When variable speed operation was required such as a spindle drive, the motor was driven by an inverter, usually a voltage source inverter, which provided a variable frequency and variable voltage source.

In the Sixties, General Motors Research Laboratories developed a high-flux magnet material using RE materials. Patented by MagnaQuench, neodymium-iron-boron (NdFeB) magnets had almost an order of magnitude greater flux than other types of PMs of the day. This created a revolution for many products that needed small high-flux magnets, including speakers, hard drives, etc. It was a logical application to use RE magnets in an electric motor in the 80's. The PMs could be mounted on the rotor to create the magnetic field. This would eliminate the rotor bar losses compared to the induction motor, thus improving overall motor efficiency. Also there was no need for "slip," and the motor would be synchronous with the electrical speed. It all depended on the cost of these magnets, and there were significant price reductions after the MagnaQuench patent expired in the 90's. Most of the production of RE magnets moved from the U.S. to Japan. However, Japan has no naturally occurring RE resources and imported the raw materials from other countries such as China, the United States, and Canada. At the turn of the century, China saw an opportunity to gain market share by undercutting the competition in raw materials. It was aided by low wages, non-existent environmental laws, a supportive government, and cheap mining operations. This enabled China to produce RE material at prices others could not match. Finished magnets were selling for under $16 per kilogram (kg). The effect of this undercutting was to drive competitors out of the market and leave China with a 90%+ market share and effectively establish a monopoly on RE magnets. The price of RE magnets has steadily increased and prices have hit as high as $60/kg. Considering that a single automotive traction motor may use 1–1.5 kg of magnets and there are usually two motors per vehicle times several million cars, then the quantities are staggering. China has recently announced their intention to limit exports on RE materials in order to supply their own needs and to bolster their position on the value chain as a supplier of magnets and motors. This has driven everyone to examine the role of PMs in electric machines and try to figure out topologies and technologies that either eliminate or reduce the amount of magnets.

TECHNICAL TARGETS

The technical targets for 2015 and 2020 for the entire traction system are shown in Table 2; they are appropriate for an HEV application. For other applications, the targets may be adjusted on a case-by-case basis. Selecting the HEV application that has a power level near the low end of the range is appropriate for this program because that is where the challenge of meeting the specific power and power density targets would be greatest. Meeting the targets for more powerful systems should be somewhat

[4] Based on input from Jim Nagashima.

easier because some of the “overhead” items (e.g., connectors) would not have to be entirely proportional to the power.

Table 2. Technical targets for electric traction system (ETS)

	2015	2020
Cost, $/kilowatt (kW)	<12	<8
Specific power, kW/kg	>1.2	>1.4
Power density, kW/liter (L)	>3.5	>4.0
Efficiency (10–100% speed at 20% rated torque)	>93%	>94%

Although the technical targets have been established at the system level, an approximate allocation of the targets between the motor and the power electronics (PEs) is useful as guidance for projects that address one or the other. The values in Table 3 estimate how much can be achieved with improvements to the motor and, along with comparable numbers for the PEs, are consistent with the system-level targets.

Table 3. Approximate technical targets for motors

	2015	2020
Cost, $/kW	<7	<4.7
Cost, kW/$	>0.143	>0.213
Specific power, kW/kg	>1.3	>1.6
Power Density, kW/L	>5.0	>5.7

It is important to note that certain motor designs may have an impact on the weight, volume, and cost of other parts of the vehicle. For example, a design that minimizes the back-electromagnetic field (emf) might eliminate the need for a boost converter, while a design that involves higher speeds might require the addition of a gear box. Whenever a new concept is compared to the targets, it will be essential to clearly state and consider those effects including any special cooling system that might be required.

Although many vehicle architectures require two electrical machines, one as a motor and another as a generator, some architectures make use of a single machine for both purposes. The targets in Table 3 refer to one machine.

INTERIER PM MOTORS

An IPM motor is a hybrid that uses both reluctance torque and magnetic torque to improve efficiency and torque. These motors are created by adding a small amount of magnets inside the barriers of a synchronous reluctance machine. They have excellent torque, efficiency, and low torque ripple. They have now become the motor of choice for most HEV and EV applications. [5]

IPM machines have high power density and maintain high efficiency over the entire drive cycle except in the field-weakening speed range where there are losses in motor efficiency. This translates into a challenge to increase the constant power speed range without loss of efficiency. Other major issues are failure modes and the high cost of the motor. These machines are relatively expensive due to the cost of the magnets and rotor fabrication. Major challenges are to develop bonded magnets with high energy density capable of operating above 200^{o}C and motor designs with high reluctance torque. This may result in reducing the magnet cost. Other challenges include thermal management and the temperature rating of the electrical insulation.

MAGNETS FOR IPM MOTORS

As will be explained in more detail later, there are four main classes of commercial PMs:[6]

- NdFeB magnets. These are the strongest magnets, but are subject to corrosion and have a limited useful temperature range.
- Samarium-cobalt (Sm-Co) magnets. These are the next strongest magnet material and are more temperature stable and corrosion resistant than the RE magnets. They are widely available and samarium is in a relatively good supply condition.
- Alnico magnets – the main constituents being aluminum (Al), nickel (Ni), and cobalt (Co). They are tough, corrosion resistant, and extremely temperature stable. They have intermediate magnetic strength and a moderate price.
- Ferrite magnets. These are relatively weak but very inexpensive, very corrosion resistant, and widely available.

The strengths of the various types of magnets, as they developed over time, are compared in Fig. 3.

[5] Based on input from Jim Nagashima.
[6] Based on presentation to the EETT by Steve Constantinides of Arnold Magnetic Technologies, April 2009.

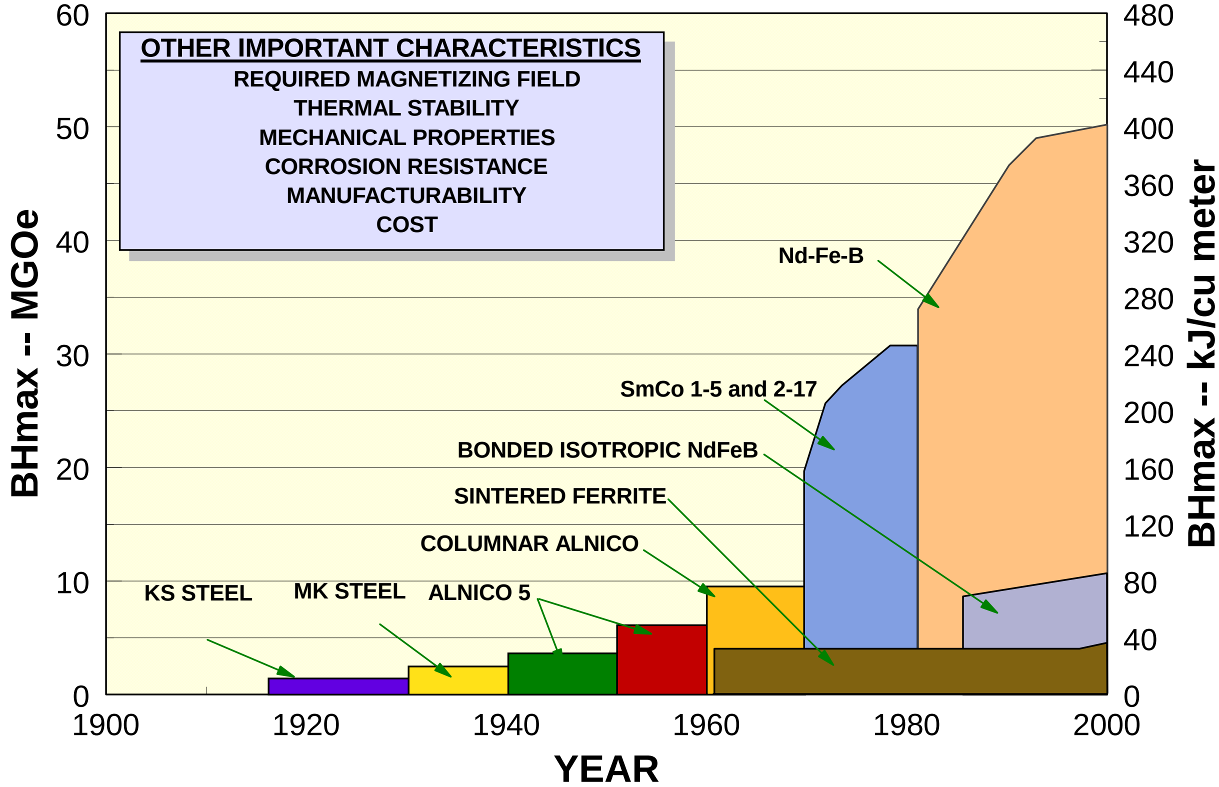

Fig. 3. Improvements in magnet strength over time.

Properties of Magnets

Every PM material can be characterized by a demagnetization curve that plots the material's flux density *B* (on the vertical y-axis) against its coercive force *H* (on the horizontal x-axis) in the second quadrant of the *B*-*H* plane. This quadrant of the demagnetization curve is particularly important since this is where the magnet material typically operates in any practical electric machine application with positive *B* and negative *H*. The actual operating point can be determined with reasonable accuracy in most cases by finding the position of the magnet's load line (sometimes referred to as its air gap line) which is dependent on the details of the magnetic structure in which the magnet is placed.[7]

Although the derivation will not be presented here, it can be shown that the magnet load line has a slope given by:

$$-\frac{A_g}{A_m}\frac{l_m}{l_g}\mu_o \qquad (1)$$

where A_g is the air gap area, A_m is the magnet area, l_g is the air gap length, l_m is the magnet length (in the direction of magnetization), and μ_o is the permeability of air. When this load line is plotted together with the magnet's demagnetization curve, the intersection determines the operating point of the magnet. When the stator current is zero, the load line passes through the origin in the B-H plane, but as the stator current increases, the load line moves to the left in the plane without changing slope intersecting the *H* axis at:

[7] Based on input from Tom Jahns.

$$\frac{-N_{eq}I}{l_g} \tag{2}$$

where $N_{eq}I$ is the armature reaction magnetic motive force (MMF).[8] An example of such a load line is shown in Fig. 4. The slope of the load line is called the permeance coefficient. Fortunately this demagnetization is completely reversible (within limits) as the armature reaction is reduced, allowing the operating point to move back and forth along the magnet's demagnetization curve as the machine's armature reaction MMF is changed.[49]

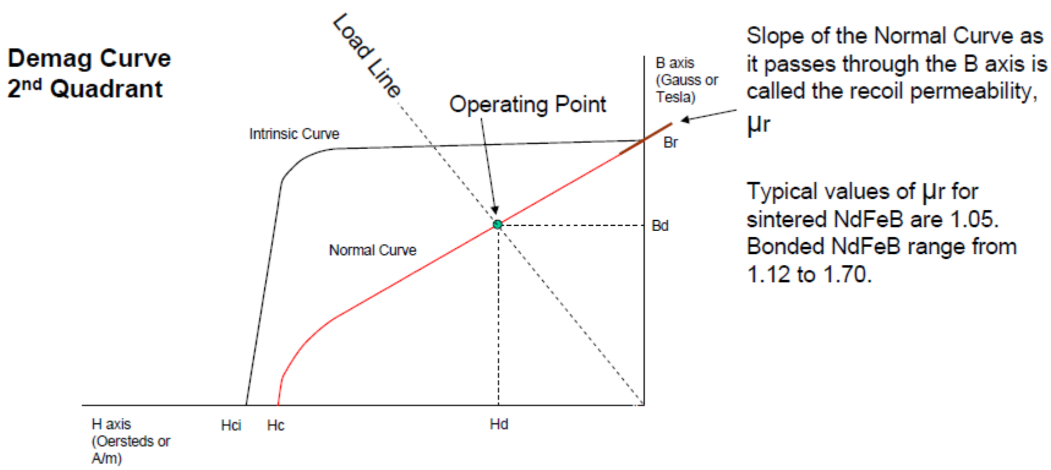

Fig. 4. Schematic demagnetization curve with load line.

The limits of this reversible demagnetization is reached when the armature reaction MMF is increased so high that the load line intersects the magnet's demagnetization curve beyond the "knee" of the curve identified as H_{ci}. If this condition occurs, reduction of the armature reaction will cause the magnet to recoil along a new demagnetization curve that is parallel to the original curve, but positioned to its right, reflecting the irreversible demagnetization that the magnet has suffered due to the excessive armature reaction MMF that was applied due to either an overload current or fault condition.[5]

The properties of various PMs are listed in Table 4.[6] The industry compares various grades of PMs based on their maximum energy product of remnant flux density B_r and coercive force H_c at a permanence coefficient that falls on the magnet recoil line. The better grade of PM for electric machines will have recoil permeability approach that of air (=1.0) which is why the best motor magnets are the RE neodymium types such as NeoMax 27H.

[8] Based on input from Tom Jahns.
[9] Input from John Miller.

Table 4. Properties of various PMs

Type	Remanence, Br, (T)	Coercivity, Hc (kA/m)	Energy (MGOe)	Recoil Perm. (#)
Alnnico 5	1.35	58.9	7.5	17
Alnico 6	1.05	62	31	13
Alnico 9	1.06	119.3	9	7
Ceramic 5	0.38	190.8	3.4	1.1
Ceramic 6	0.32	190.8	2.5	1.1
Ceramic 8	0.40	222.6	4.1	1.1
Magnequench I	0.68	390	9.8	1.22
Magnequench II	0.8	517	13	1.15
Magnequench III	1.31	979	42	1.06
NeoMax 27H	1.1	811	28	1.05
NeoMax 35	1.25	882	36	1.05

- Conversion H_c in A/m ÷ 79.6 = Oerstead, Oe.
- Conversion Br in T × 10^4 =Gauss, G.

As stated earlier, the RE magnets are clearly superior to other types, but there is a danger that they might become too expensive or even not available. Therefore, other types of magnets need to be considered.

Both ferrite and RE magnets are resistant to irreversible demagnetization and this is reflected in the fact that the H_{ci} knee values of their corresponding *B-H* curves lie in the third quadrant, as is shown in Fig. 5 (i.e., negative *B* values), indicating that large armature reaction MMFs are required to actually reverse the direction of the magnetic flux density in the magnets before irreversible demagnetization occurs.

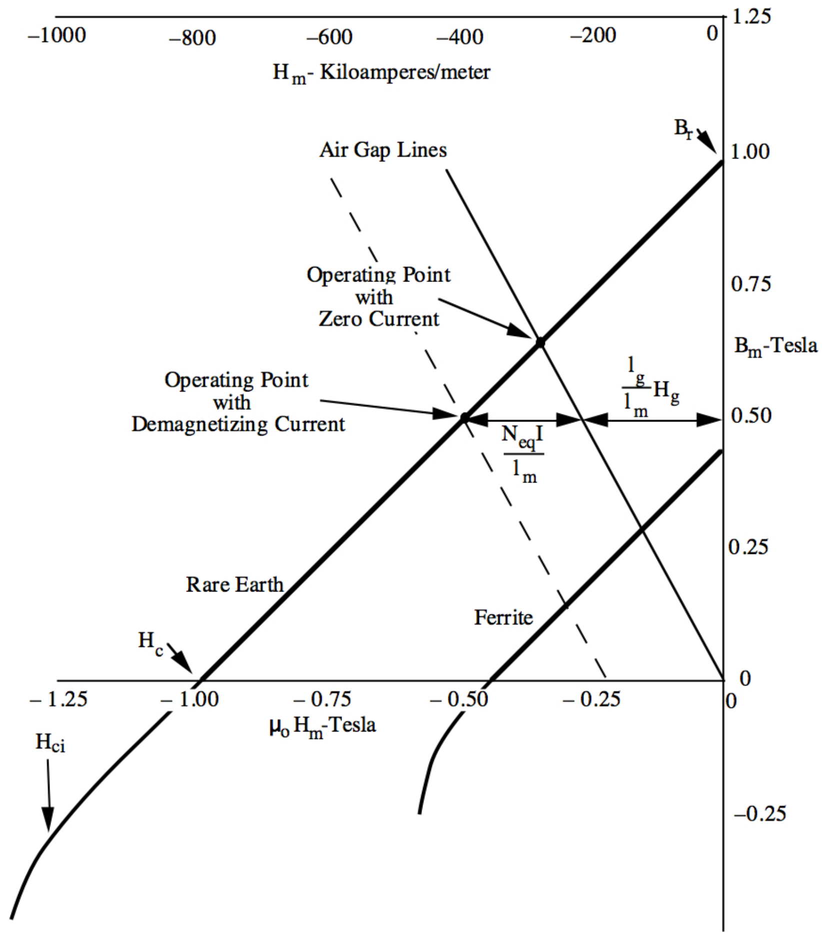

Fig. 5. PM demagnetization curves and air gap magnet load line for RE and ferrite magnets.
(Courtesy of D.W. Novotny and T.M. Jahns, University of Wisconsin(UW)-Madison)

The vulnerability of the magnets to irreversible demagnetization increases significantly for other types of magnets such as Alnico. A simplified plot of the demagnetization curve for Alnico is shown in Fig. 6 showing that the value of H_{ci} is much lower, causing the knee of the B-H curve to fall well inside the second quadrant of the B-H demagnetization curve when the flux density values are still quite high in the positive direction. The magnet load line plotted in Fig. 6 for the case without any armature reaction MMF is drawn much steeper in order to insure that the intersection with the magnet's demagnetization curve falls to the right of the H_{ci} knee. As the armature reaction MMF is increased, shifting the load line to the left, the magnet would suffer substantial irreversible demagnetization for the particular situation illustrated in Fig. 6 where the new intersection with the demagnetization curve has been forced well beyond the H_{ci} knee.

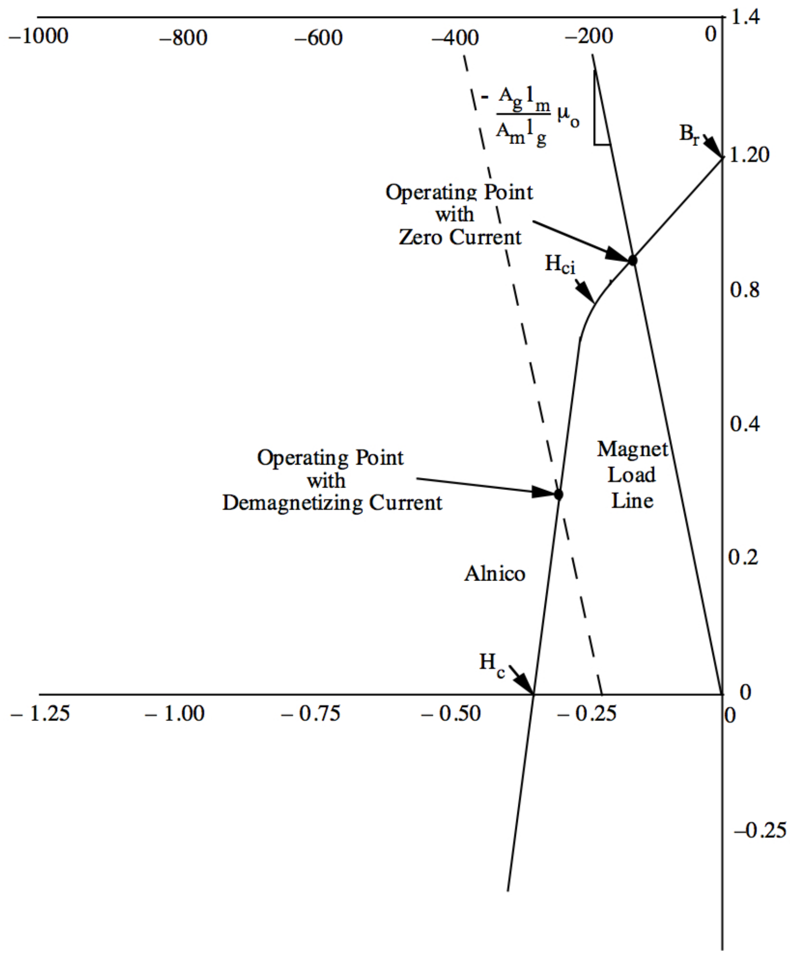

Fig. 6. PM demagnetization curves and air gap magnet load line for Alnico magnets.
(Courtesy of D.W. Novotny and T.M. Jahns, UW-Madison)

Alnico in fact was viewed as a potential high flux PM that could find application in future electric machines were it not for its very low coercivity. The low coercive force of Alnico has precluded its use in electric machines, save as the flux source in D'Arsonval meter movements.[10]

As is shown in Fig. 7,[11] elevated temperatures have the undesirable effect of reducing the H_{ci} values and the impact can be sufficiently large at high temperatures to move the knee of the B-H demagnetization curve into the second quadrant under these extreme conditions. This has the effect of making the magnets much more vulnerable to irreversible demagnetization under these conditions. Magnet manufacturers have developed techniques for retarding this negative impact of high temperatures by adding small amounts of additional elements such as dysprosium in the case of NdFeB magnets. Unfortunately the cost of the magnets is raised in the process and in some cases substantially for high-temperature magnet materials.[12]

[10] From John Miller.
[11] Based on presentation to the EETT by Steve Constantinides of Arnold Magnetic Technologies, April 2009.
[12] Based on input from Tom Jahns.

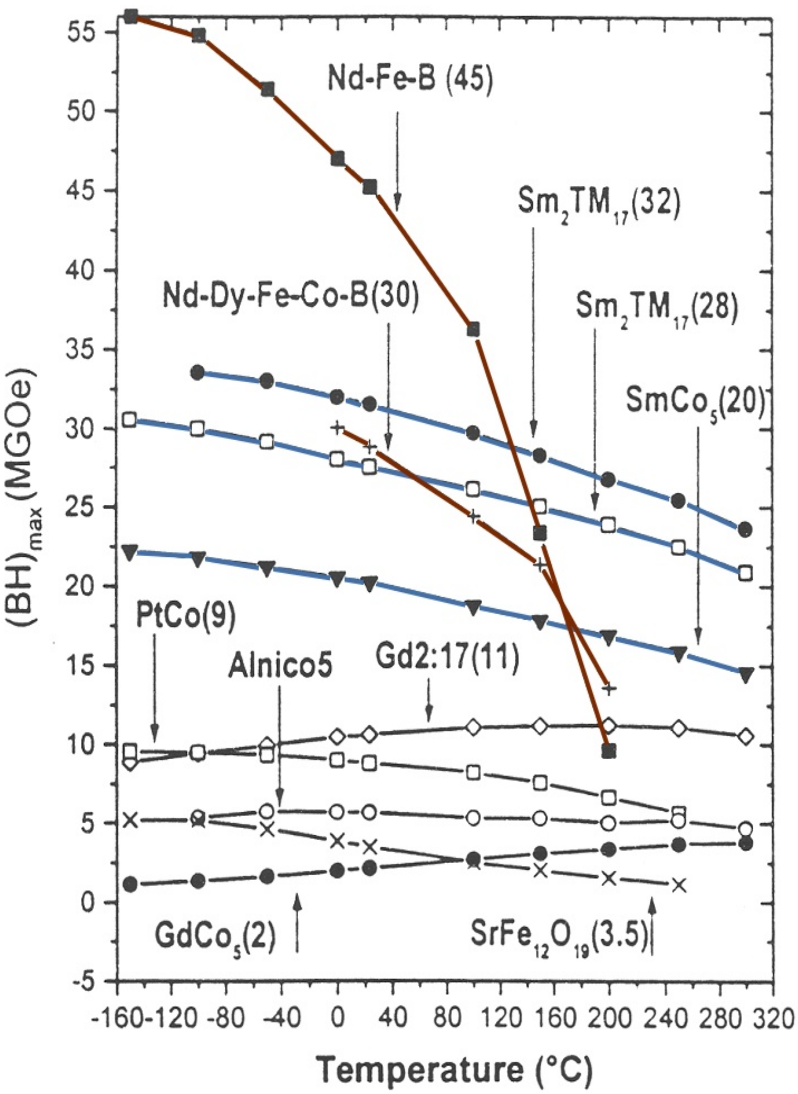

Fig. 7. Effect of temperature on the strength of magnets.

As is shown in Fig. 8,[13] the resistance to demagnetization, as measured by coercivity, also decreases with increasing temperature for almost all magnet materials except ferrites.

[13] Based on presentation to the EETT by Steve Constantinides of Arnold Magnetic Technologies, April 2009.

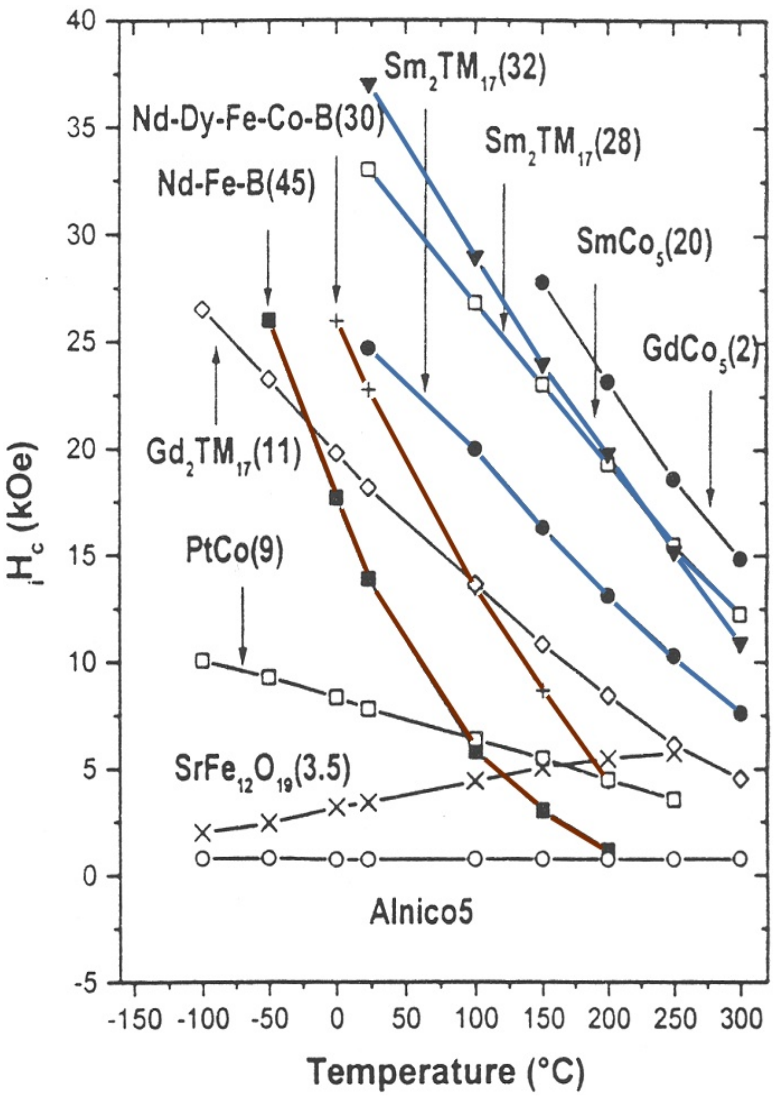

Fig. 8. Effect of temperature on coercivity of various magnet materials.

When the temperature of a ferrite magnet drops, the intrinsic coercivity drops. It is not necessary for intrinsic coercivity to reach 0 for the magnet to be non-functional in an application, only that its intrinsic coercivity be low enough that the presence of demagnetizing forces, such as in a motor or generator, are large enough to demagnetize or reverse the magnetic field in the magnet. Automotive use of ferrite is extensive, but the “rule of thumb” is to design for a minimum temperature of -40 ºC (-40ºF). For example, the knee of the curve for Ceramic 8 occurs at a permenance coefficient of 0.75 at -40ºC. Historically, it was expected that leading and trailing edges of magnets would lose about 10% of their flux output as a result of partial demagnetization. At the high end of the operating temperature spectrum, ferrite loses flux output (Br drops) at the rate of ~0.2% per ºC, so at 150ºC (130 degrees above room temperature) Br has dropped by 26% (130 × 0.002). So the practical use range for ferrite is -40–150ºC.[14]

[14] Private communication, Steve Constantinides.

Magnet Materials

NdFeB Magnets

Because of their superior magnetic properties, NdFeB magnets are the clear choice for IPM motors. A typical composition of the alloy, along with a cost structure as of April 2009, is shown in Table 5.[15]

Table 5. Composition and cost structure for sintered NdFeB magnets

Composition #1		**38UH**		
Material	**Weight%**	**Raw Matl $/kg**	**$ per kg**	**%**
Nd	20.5%	18.00	3.69	
Dy	8.0%	147.00	11.76	
Pr	2.0%	17.00	0.34	
Y	0.0%	41.00	0.00	
SubTot	30.5%			
Fe	64.4%	1.60	1.03	
Co	2.0%	34.16	0.68	
Zr	0.0%	25.00	0.00	
Nb	0.1%	25.00	0.03	
SubTot	66.5%			
B	1.0%	4.00	0.04	
Al	0.1%	2.88	0.00	
Ti	0.0%	23.00	0.00	
C	0.1%	0.50	0.00	
Other	1.8%	0.00	0.00	
Total	100.0%		17.57	60.0%
Melt/Alloying cost			5.00	17.1%
Total Processing per kg			5.85	20.0%
Total Cost per kg			$ 29.27	
Margin		40%	$ 19.52	
Price per kg			$ 48.79	

Dysprosium additions to the alloy are needed to retain adequate coercivity at elevated temperatures. However the amount of dysprosium must be limited because, as is shown in Fig. 9, the increase in coercivity is accompanied by a decrease in remanence.[16] In addition, as Table 5 shows, dysprosium also is the most costly alloying element.

[15] Based on presentation to the EETT by Steve Constantinides of Arnold Magnetic Technologies, April 2009
[16] Based on presentation to the EETT by Steve Constantinides of Arnold Magnetic Technologies, April 2009

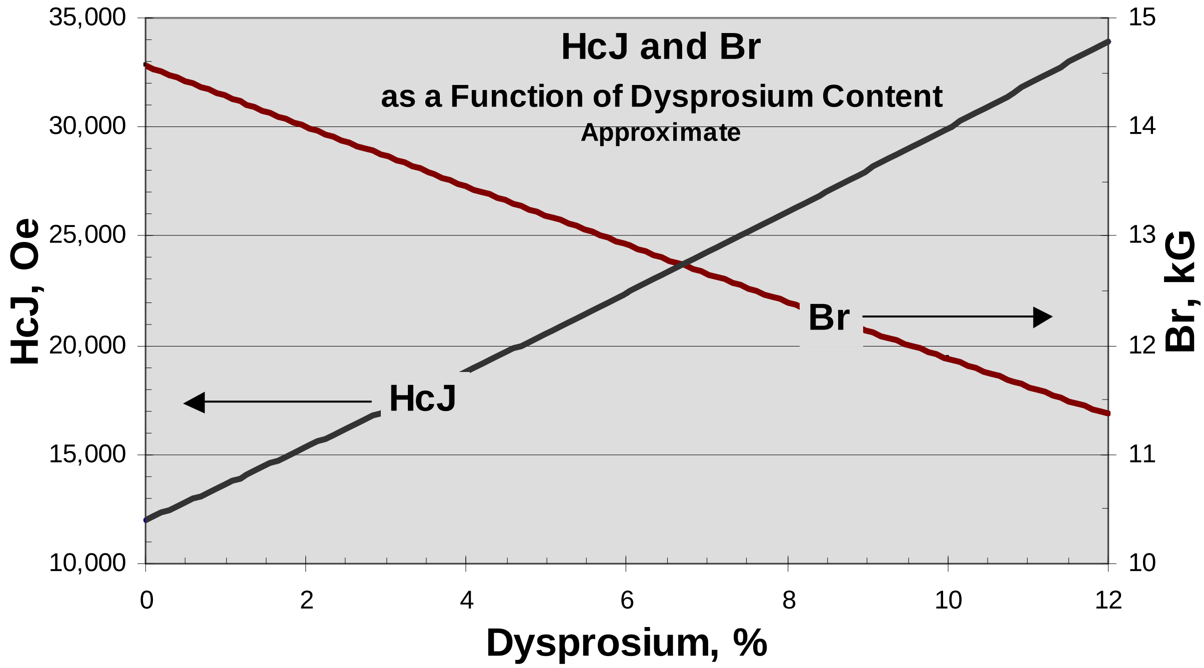

Fig. 9. Effect of dysprosium on magnetic properties of NdFeB magnets.

As was mentioned earlier, there are serious concerns about the future availability and cost of RE magnets. As is shown in Fig. 10, China furnishes most of the RE metals, but China's internal need for REs is expected to equal their capacity by about 2012 and they may not be willing to export those materials at that time. That pending shortfall also is allowing them to raise the price substantially, as shown in Fig. 11.[14]

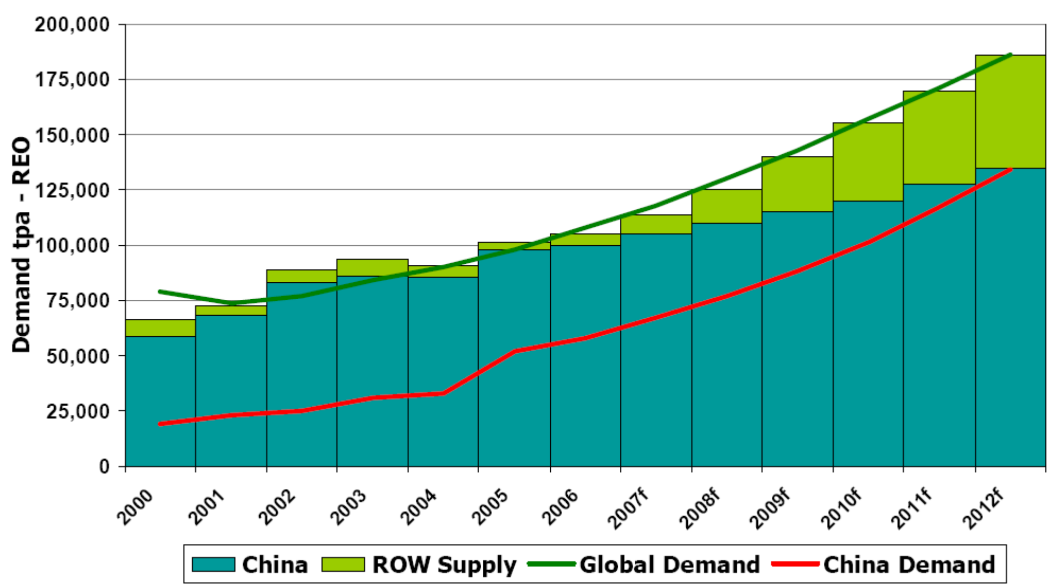

Fig. 10. Supply and demand for RE metals.

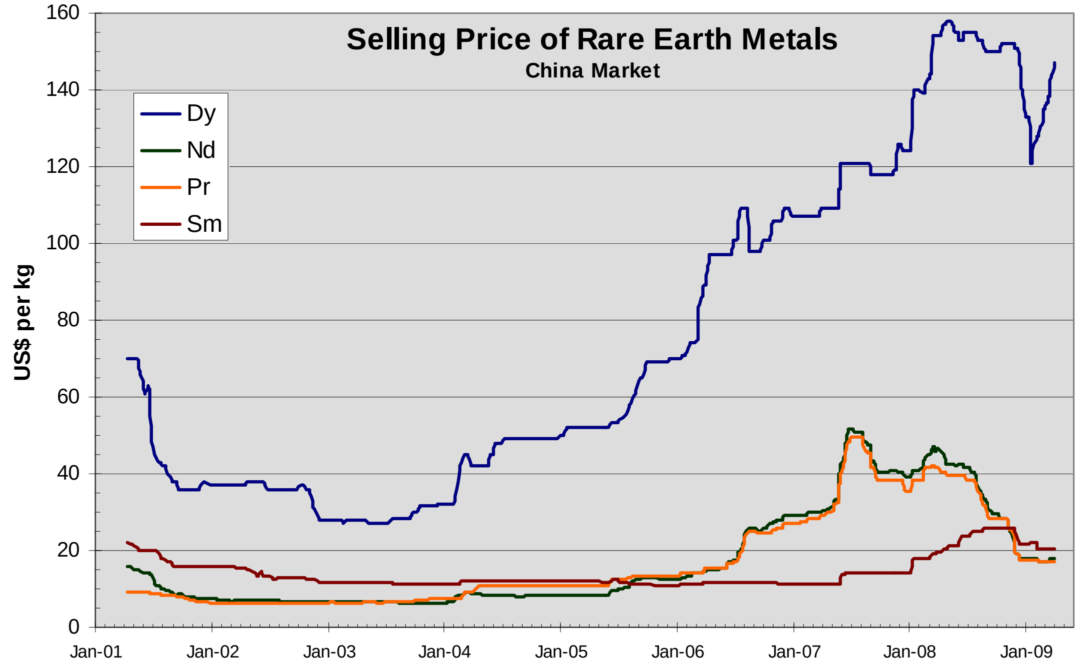

Fig. 11. Recent trends in the price of RE metals.

The increasing price of REs may make it economically feasible to tap deposits outside of China. The most promising possibility is the re-opening of the Mountain Pass operations by MolyCorp. They hope to do that by 2012.

Sm-Co Magnets

Sm-Co was the first widely used RE PM type starting with the 1–5 composition in the early ’70s and switching mostly to the 2–17 type in the 1990s. It is second only to NdFeB in magnetic output. It has excellent high-temperature performance with grades available for use to 550ºC. Its corrosion resistance is superior to that of NdFeB but coatings are generally advisable.

When RE ore is mined, all the REs become available in the refining process including cerium, lanthanum, misch metal (a combination of REs), praseodymium, neodymium, dysprosium, and samarium. As NdFeB usage goes up, more samarium is also mined and available for magnet production. Capable Western sources are available in addition to Chinese vendors. Although samarium is a relatively abundant resource with large proven reserves, if Sm-Co magnets were to be designed into a major application such as hybrid vehicle traction motors, the demand would quickly exceed supply causing shortages and price increases.

Co not only is used in Sm-Co magnets making up between 35 and 50% of the formulation (by weight), it is also used in many NdFeB magnet grades to improve the high-temperature capability, improve corrosion resistance, and reduce reversible temperature coefficients of induction; it is an important constituent of Alnico magnets representing 10–38% by weight of those materials; and it has many uses besides magnet materials. As illustrated in Fig. 12, Co has experienced considerable price volatility and it also is subject to political instability in producing countries.

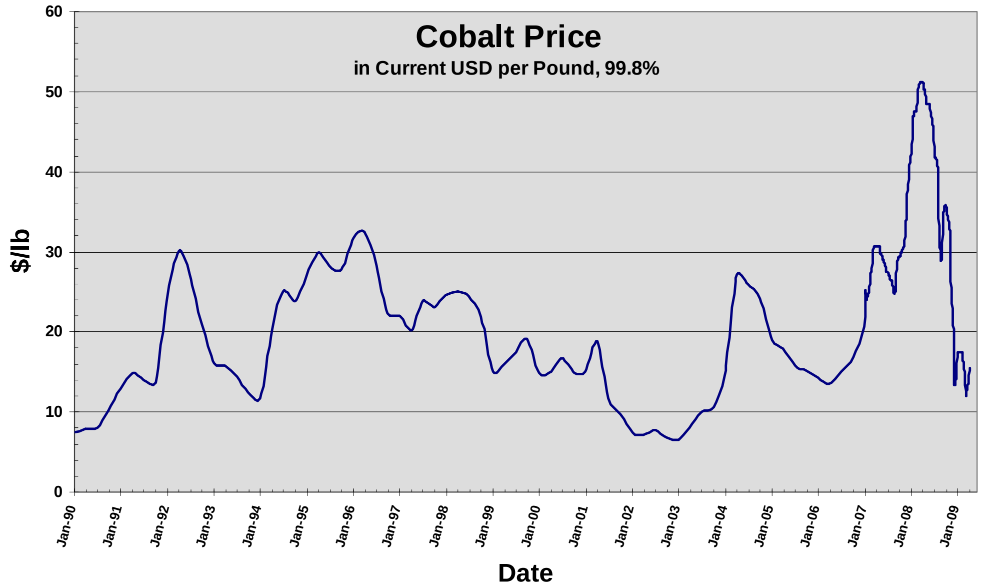

Fig. 12. Volatility in the price of Co.

Sintered and hot formed fully dense anisotropic neodymium magnets are superior to Sm-Co below 180°C. There needs to be solid technical justification such as corrosion resistance and very high temperature (approaching 300°C) to justify the expensive Sm-Co magnets.

Alnico Magnets

Alnico magnets were the first type used in electric machines. This is because of their high flux, which approximated the fields possible in shunt-wound dc motors of the day. However, because of very low coercive force of Alnico magnets, these early electric machines used novel pole magnetic structures such as soft iron pole pieces adjacent to the armature or soft iron pole pieces bonded to the Alnico magnet and machined to the arc of the rotor (armature of dc motor). With soft iron pole shoes of this design, the Alnico magnet motor could operate at up to six times the normal armature current of Alnico only before demagnetization. Even if the Alnico did become demagnetized, it would be an easy matter to simply re-magnetize it using coils designed just for this purpose as was done in these early days. With the availability of higher-performance and low-cost ceramic magnets, the Alnico magnet was displaced from use in electric machines but remained useful in electronic meters as noted earlier.

Ferrite Magnets

Among the commercially available PMs, ceramic ferrites have low magnetic properties (Br, Hc), but are lowest in cost and have good temperature stability to >250°C and corrosion resistance. Ceramic magnets made from strontium ferrite yield at least 0.4 Tesla at $4.00–$6.00 per kg as compared to RE magnets that cost at least 10 times that much for a flux density of about 3 times that of the ceramic or 1.2 T. In addition, the low-cost ceramic magnet grade will not rust and it will not demagnetize as easily as RE magnets, so if it can be designed in a configuration where a large surface area can be used, it can be very cost effective. The temperature coefficient of the Bm for the ceramic magnets is about the same as for RE magnets, but the Curie temperature is much higher for the ceramic and the coercivity of the ceramic magnet grades increases with elevated temperature. In addition, it is not scarce and the U.S. has significant capacity to manufacture.[17]

[17] Based on input from Jim Hendershot.

A company called QM has developed a unique PM brushless motor design that can produce high torque and power densities using the low-cost ferrite magnets. Their design is called a parallel flux path brushless motor. The parts can be volume produced using magnetic powdered metal technology with minimal machining and the magnets can be low-cost ceramic magnets used on the outside part of the circuit. These magnets can have large surface areas because the flux is naturally focused into the circuit for the same flux densities as is possible using expensive RE magnets. If the surface area of the flat-slab ceramic magnets is three to four times the area required for RE magnets, the same air gap flux can be achieved with these low-cost ceramic magnets. A concept illustration of this PM brushless motor is shown in Fig. 13.[10]

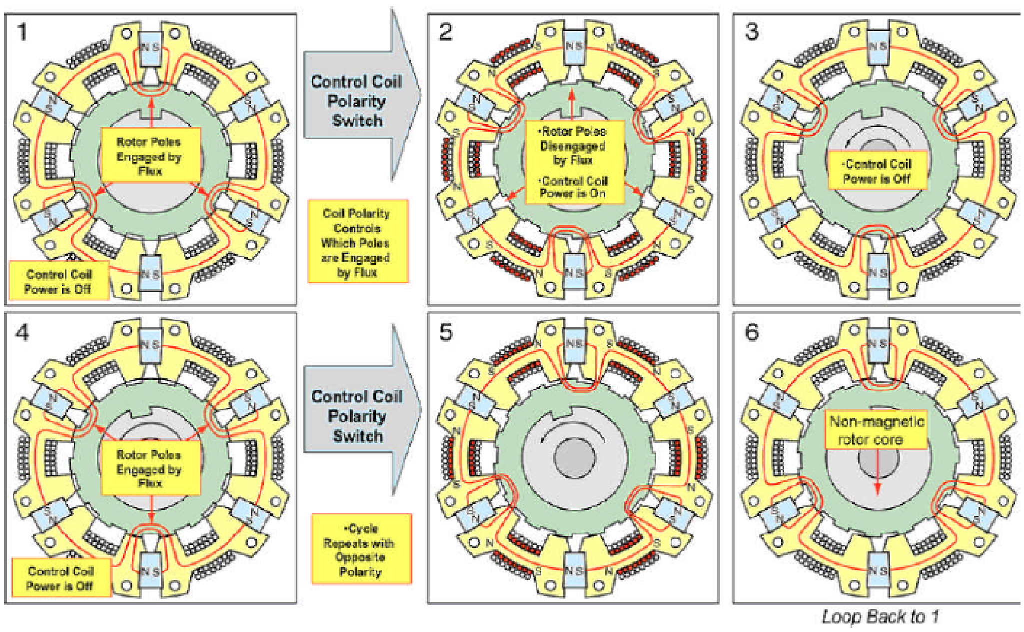

Fig. 13. Six magnet motor flux sequence (CCW) by QM.

Another PM brushless design that can use ferrite magnets is the “Spoke Type" IPM made famous by Fanuc in Japan. The original designs used Sm-Co magnets made by General Electric, but the Fanuc versions utilized the low-cost flat-slab strontium ferrite ceramic magnets. After Fanuc configured their spoke magnet rotors with 8 poles, the surface area of each magnet was 3.5–4 times the surface area of the radial soft iron poles they fed, so the gap flux was about 0.9 Tesla. This enabled a low-cost ceramic brushless motor to achieve as high gap flux as any RE IPM or SPM motor ever developed to this day. Fanuc found that this design is not effective with less than eight poles to yield the flux focusing required depending on the rotor diameter. This IPM motor design is used for machine tool servomotor applications as one of the highest volume servomotors ever produced. They are driven by ac sine drives like most IPM machines. Further development of this type of IPM may be useful for modern vehicle traction to reduce motor cost and to avoid the use of RE magnets.

Hitachi in Japan has recently developed a new ceramic magnet grade with better thermal properties and higher flux densities. This new ceramic grade is called **NMF-12 SERIES** and is made by replacing some of the strontium with lanthanum. It is called Lanthanum Strontium Cobalt Ferrite.

Nevertheless, attaining the motor size and weight targets while delivering acceptable low-end torque will be a challenge unless the system concept is to accept low torque production and make up for it with additional gearing in the drive train. Reportedly Hitachi Ltd. has developed a motor that uses "ferrite magnets," made up of the cheaper and easier-to-procure ferric oxide.[18] Its magnetic force was 50% weaker than the RE-based model, but Hitachi succeed in improving a motor structure around the rotator so as to magnify the force. As a result, the prototype can achieve largely the same performance as the RE-based model with 10% less electric power consumption. In two years, Hitachi plans to adopt the new motor in such products as air conditioners.

DESIGN CONSIDERATIONS

Having observed these trends in Figs. 5 and 6, the engineering question naturally arises asking what can be done in the design of the electric machine to reduce, if not eliminate, the risk of irreversible demagnetization. Increasing the negative slope of the magnet load line will help to reduce the risk. Inspecting the equation for the load line slope in Eq. (1), one of the most typical actions that is taken by designers in PM machines to limit (but not eliminate) the risk of irreversible demagnetization is to increase the length of the magnets, l_m, in comparison to the air gap length, l_g. This creates a classic engineering tradeoff since increasing the magnet length almost always results in increasing the magnet mass and its associated cost.[19]

Further inspection of the slope formula in Eq. (1) also suggests that decreasing the magnet area A_m in relation to the air gap area A_g will also have the effect of increasing the negative slope amplitude. Unfortunately, this action is typically less useful in PM machines because reductions in the magnet area nearly always result in lowering the total flux linkage contributed by the magnets, thereby reducing the contribution of the magnets to the machine's performance. In many cases, this effect is unacceptable.[17]

A more subtle but important insight into possible approaches for reducing the risk of demagnetization comes from recognition that it is the leftward shift of the load line due to the armature reaction MMF that poses the greatest threat of triggering irreversible demagnetization. The amplitude of the motion is inversely proportional to the air gap length l_g as indicated in Eq. (2), suggesting that increases in the air gap length will help to soften the impact of armature reaction MMFs. Unfortunately, this beneficial effect is partially offset by the fact that increasing l_g also has the effect of reducing the negative slope of the load line in Eq. (1), posing an engineering tradeoff that must be evaluated in each design case.[18]

Perhaps one of the most intriguing possibilities for reducing the threat of irreversible demagnetization for vulnerable magnet materials such as Alnico is only hinted at by the preceding discussion. More specifically, the question arises whether there is any way to design the machine so that the magnet material is not directly exposed to the demagnetizing impact of the armature MMF. That is, are there any engineering approaches to PM machine design that might keep the magnet material "out of harms way" so that it can contribute its magnet flux without being placed in series with the armature reaction MMF in the machine's magnetic circuit. There are some clues that the answer may be affirmative for some specific machine design, at least in part if not completely. If so, this may prove to be one of the most promising strategies for enjoying the benefits of high remanent flux density values offered by magnet materials such as Alnico while avoiding the pitfalls posed by its low H_{ci} characteristics.[18]

Another approach, which is being pursued at Ames, is to attempt to develop new magnet materials that do not contain RE metals but have desirable magnetic properties. Their first attempts will involve iron-Co based alloys and alloy additions to the basic Alnico composition.

[18] The Nikkei September 10, 2010 morning edition.
[19] Input from Tom Jahns.

STATOR WINDING DISTRIBUTIONS[20]

Concentrated vs. Distributed Stator Windings

The nature of the stator winding distribution in an ac machine has a significant impact on the machine's performance characteristics. The stators of conventional induction machines, wound-field synchronous machines, and some PM machines are built with distributed windings so that the end winding of coils overlap with each other [see Fig. 14(a)]. As a result, the production of such windings typically requires expensive specialized winding equipment to "sew" the windings into the stator slots. Alternatively, the coils can in some cases be wound separately from the stator and then inserted as groups into the stator slots either manually or by machine. Significant manufacturing equipment investments and production costs are involved either way.

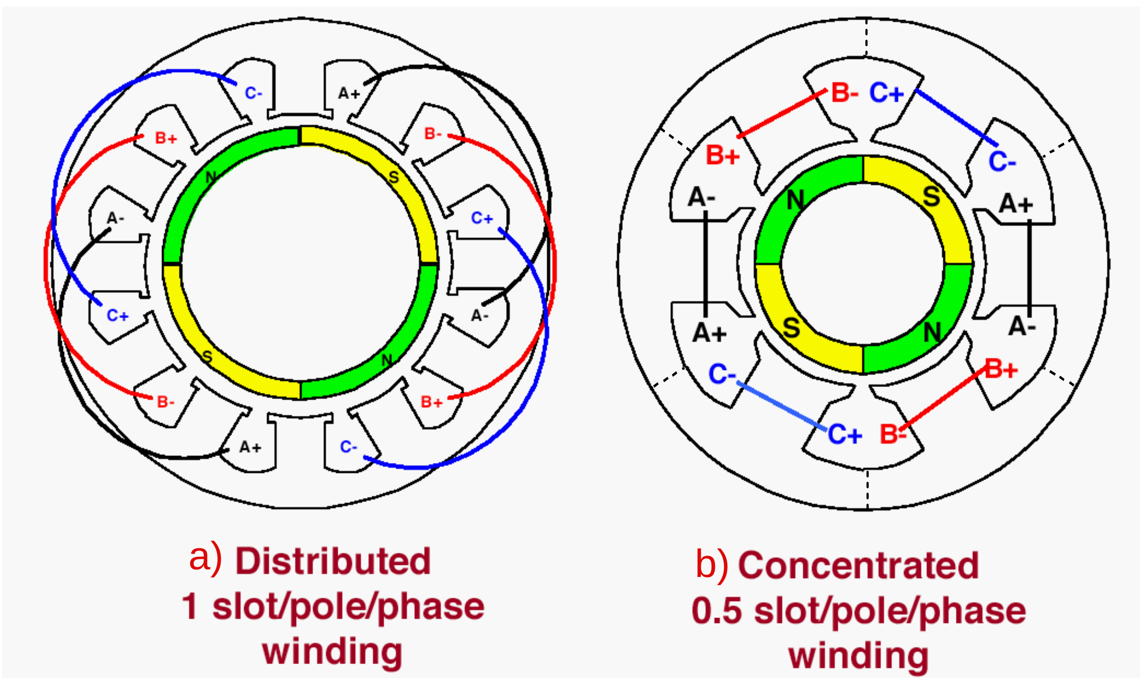

Fig. 14. Two types of stator winding configurations: (a) distributed windings; and (b) concentrated windings.

The adoption of distributed windings also has the undesirable effect of limiting the percentage of each stator slot that can be filled with the stator windings. Typical values of the slot "fill factor" are in the vicinity of 35%, meaning that over half of the area of each stator slot is a combination of insulation and non-magnetic filler (typically air or epoxy varnish). This low stator slot fill factor has a significant effect on limiting the maximum torque and power densities that can be achieved with these ac machines. More specifically, the performance metrics are typically dominated by thermal limitations linked to the total amount of stator current that flows through each slot (i.e., the number of wires in the slot multiplied by the current in each wire).

An alternative to conventional distributed windings is the adoption of concentrated windings in which each coil surrounds only a single stator tooth, eliminating any overlap between the end windings of adjacent coils [see Fig. 14(b)]. An immediate benefit of concentrated windings is a reduction in the total length of the machine because of the elimination of end winding overlaps. Another tangible benefit of

[20] Based on input from Tom Jahns.

eliminating end-winding overlaps is the near-elimination of opportunities for turn-to-turn shorts between different phase windings, an advantage discussed further later in this section.

Concentrated Winding Advantages

The adoption of concentrated windings has some significant effects on the electromagnetic design and performance of the associated ac machine in comparison to conventional distributed-winding machines. Major technical progress has been made during recent years towards understanding the performance implications of concentrated windings, particularly in association with PM machines. This work has demonstrated that the high performance of the PM machine can be retained while reducing the number of concentrated windings for a given number of rotor poles, resulting in "fractional-slot" concentrated windings. The term "fractional-slot" refers to stator windings with slot-per-phase-per-pole (SPP) values less than one. For example, the 4-phase SPM machine with concentrated windings shown in Fig. 14(b) has an SPP value of 0.5 because there are 6 slots, 3 phases, and 4 poles (i.e., $6 \div 3 \div 4 = 0.5$).

This introduction of fractional-slot stator windings provides a combination of performance and manufacturing advantages to the machine. Advantages include the reduction of cogging torque with careful choice of the winding SPP value. In addition, these concentrated windings make it possible to segment the stator into individual tooth pieces [note the dotted lines in Fig. 14(b)]. Each of these teeth can then be wound individually using a much simpler winding machine to produce a solenoidal winding. A valuable benefit of this approach is that the solenoidal coils can be wound very tightly so that the slot fill factors can be doubled from values in the 30–40% range to much more attractive values in the 70–80% range. Such large fill-factor improvements can be employed to significantly increase the torque-densities and power densities of the resulting machines.

In addition, fractional-slot concentrated windings (FSCW) open opportunities for reducing the manufacturing cost of the machines. Although quantitative numbers are difficult to obtain, there is strong circumstantial evidence that such opportunities are real since they have been adopted in mass-produced PM machines manufactured by major manufacturers including Honda, Toyota, Mitsubishi, and Yaskawa. Two examples are shown in Figs. 15(a) and 15(b).

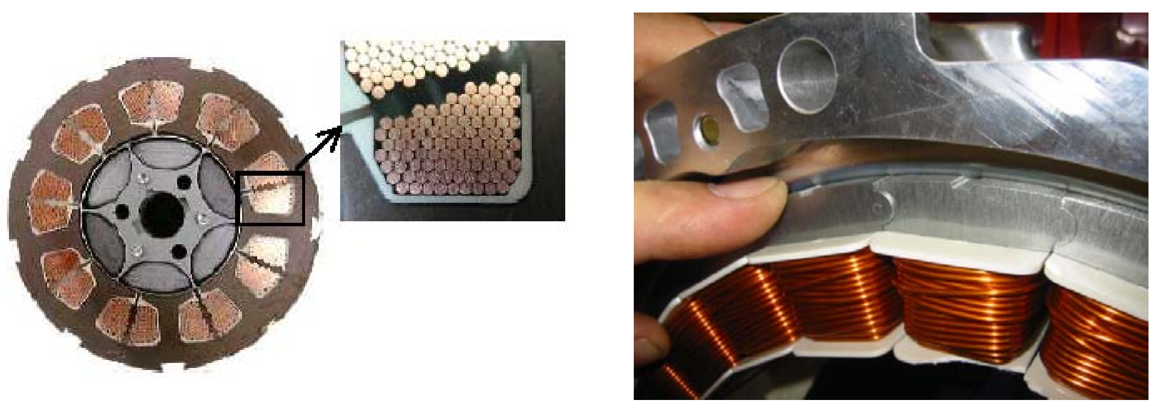

Fig. 15. Two commercially-produced machines with concentrated windings and segmented stators: (a) Mitsubishi compressor surface PM machine; and (b) Honda hybrid Accord IPM machine.

It has subsequently been demonstrated that optimal flux weakening operation is achievable in surface PM machines by properly designing the machine's stator windings using FSCW. These windings can be designed to significantly increase the machine inductance in order to meet the conditions for optimal flux weakening while simultaneously delivering near-sinusoidal back-emf waveforms and low cogging torque. Demonstrator surface PM machines have been built and tested at UW-Madison with ratings of 6 kW and 30 kW (continuous) that meet the conditions for delivering constant power operation over a 10:1 speed range.

One additional attractive feature of concentrated windings that is worth noting is the opportunity that they open for modular and fault-tolerant ac machines. For example, the integrated modular motor drive (IMMD) concept that is being pursued in a joint project at ORNL and UW-Madison breaks the stator into a finite number of segmented stator poles with concentrated windings. Each of these stator modules has its own dedicated PEs and controller mounted immediately adjacent to the windings on one of the module axial ends. Combined together into an annular structure, these independent stator modules provide the basis for a highly modular and fault-tolerant machine-plus-drive configuration. The fact that none of the stator end windings overlap with each other further reduces the risk of phase-to-phase short-circuit faults.

Concentrated Winding Challenges

Despite these attractive features, concentrated windings present some challenges to the machine designer that require careful design attention to minimize. One of the most important of these challenges is the risk of additional losses in the machine due to the rich mixture of spatial harmonic flux density distributions that are generated in the air gap of the machine because of the FSCW. The same spatial harmonic flux-density components that help to boost the inductance of the machine to improve the flux-weakening capabilities can also aggravate eddy-current loss mechanisms in the iron core, the rotor magnets, and the stator windings themselves (i.e., ac proximity losses). The problems tend to be most severe if the machine is designed for high-speed (>10,000 rpm) with a high pole count, since the eddy currents scale as the square of the frequency. A variety of techniques have been developed to significantly reduce the magnitude of these additional losses in high-speed machines, including segmentation of the rotor magnets, transposition (i.e., twisting) of the stator windings, and the use of thinner stator laminations.

Another challenge introduced by the FSCW is the detrimental impact of the widened stator teeth on the machine's magnetic saliency. This effect is caused by reducing the winding SPP value to less than one, thereby widening that stator poles so that they behave as spatial magnetic "filters" in the air gap. The wide stator teeth tend to average out the reluctance saliency that would otherwise appear if the stator teeth were narrower. This effect is not harmful for some machine types such as surface PM machines that do not use reluctance torque, or for SRMs that depend on reluctance torque but typically have low numbers of narrow rotor poles. However, other types of ac machines including IPM and synchronous reluctance machines are vulnerable to this undesired side effect of FSCW. Careful choice of the SPP and winding configuration details can be used to counteract this effect, but it remains an important issue that requires careful machine design tradeoffs if significant amounts of reluctance torque are desired.

A model to predict the performance of an IPM motor with concentrated windings was developed in an ORNL project in 2008.[21] For the design that they used for their simulation, the efficiency was very high at low speeds, but very high speeds were required to fully negotiate standard driving cycles and such high speeds resulted in losses of efficiency as well as severe design challenges. These issues need to be considered in future designs.

An ORNL study was conducted to determine if electric motor configurations using IPMs can benefit from using FSCW instead of distributed windings in EV or HEV traction drives. Compared with the baseline IPM with distributed windings, the cost, specific power, and efficiency with concentrated windings were better at speeds up to 18,500 rpm, but this benefit was lost because of a reduction in shaft

[21] J. W. McKeever and P, J. Otaduy, "Application of Concentrated Windings to Electric Motors without Surface-Mounted PMs," 2008 ORNL Annual Report.

power between 18,500 and 33,460 rpm. Because concentrated windings make better use of copper, more copper was used; to offset the increased copper costs, the savings from simplified fabrication must be more than the 2% assumed in this study.

Stator Windings in a Post NdFeB World

An obvious question that arises from this winding discussion relating to the purpose of this study is: what importance do concentrated windings take on for future machines that use either no or significantly less NdFeB magnet material than today's PM machines? This question can only be answered hypothetically at this stage since the answer depends on what PMs are eventually available as substitutes for today's NdFeB magnets. If, for example, a new class of Alnico magnet were to appear that has high remanent flux density (B_r) but relatively low coercive force (H_C), then thicker rotor magnets would be required to reduce the machine's vulnerability to demagnetization. As noted earlier in this section, the availability of FSCW makes it possible to boost the machine inductance to offset, at least partially, the inductance reduction caused by the thicker magnets.

Of course, the manufacturability and modularity advantages offered by segmented stators using concentrated windings may be desired regardless of the types of magnets that are available, or even in the absence of any magnets. In that case, the consideration of concentrated windings as an alternative to conventional distributed windings takes on an importance as a design issue that is relatively insensitive to the detailed scenario for future NdFeB magnet availability. There is good reason to expect that both concentrated windings and conventional distributed windings will continue to find broad applications in different segments of the electric machine universe regardless of what happens to NdFeB magnets.

SELECTABLE STATOR WINDINGS

Traditional approaches to extend the speed range of PM motors is to weaken the magnetic flux of the rotor as the speed increases, thus decreasing the magnitude of the back-emf and allowing higher electric currents to circulate in the stator windings. The drawback inherent to this approach is that the linked rotor field is suppressed, and additional current and complexity in the drive system and/or stator are needed. In addition to the current invested to suppress the rotor's field, extra current is needed to compensate for the rotor's field in order to attain the same torque.

A promising alternative way to produce more torque in the low-speed operating region and to extend the operating speed range is to change the effective number of turns involved in the electrical-to-mechanical energy transformation. Increasing the number of turns increases the torque produced with the same amount of current, which is of particular interest in the low-speed region. Reducing the effective number of turns in the stator windings reduces the back-emf without expending stator current to weaken the magnitude of the linked rotor's field. As a result, higher currents can be reached at a given speed with the same terminal voltage limit. This extends the operating speed region by allowing torque generation at higher speeds without having to boost the terminal voltage.

A motor with the capability to change the number of turns continuously in one step for optimal performance can be simulated readily, but consideration of added cost, complexity, and energy losses associated with the switches may not justify the performance gains. Instead, considering that the stator coils are often made with several wires bundled together and welded at the ends instead of a single thicker wire, the simplest implementation of turn-changing appears to be by factors of 2 or more. A factor of 2 is the most feasible, since it can be accomplished by splitting the wires in each phase into two groups and connecting their ends in parallel or in series to have N or 2N turns per phase, respectively, depending on the motor's speed and load demand. At low speeds, having twice the number of turns doubles the torque for the same current limit and decreases the need for voltage regulation. At high speeds, switching back to the reduced number of active turns reduces the back-emf for the same speed, thus increasing the speed-range of operation. Adjustment of the number of stator turns up and down appropriately should result in better performance with better copper and battery voltage utilization over the whole range of operation.

ORNL recently completed a research project on the viability of changing the effectively active number of turns in the stator windings of an IPM electric motor to strengthen or weaken the magnetic fields in order to optimize the motor's performance at specific operating speeds and loads.[22] Analytical and simulation studies were complemented with research on switching mechanisms to accomplish the task. The simulation studies examined the power and energy demands on a vehicle following a series of standard driving cycles and the impact on the efficiency and battery size of an electrically propelled vehicle when it uses an IPM motor and turn-switching capabilities. Both full driving cycle electric propulsion and propulsion limited starting from zero to a set speed were investigated. Stator turn reconfiguration showed clear benefits over the traditional design with a fixed number of turns. For all 8 driving cycles with a particular IPM motor with 9–18 turn-switching, whether the motor was used as the only prime-mover as in fully electric propulsion or to provide propulsion from vehicle start to a set speed as in hybrid configuration, available voltage was better utilized; stator currents were lower; motor efficiency was higher; efficiencies of PEs, battery, and cabling were higher; overall vehicle system efficiency was higher; battery life and cost were reduced; and power demand was met everywhere along all cycles. For the EV configuration, the vehicle with the stator turn-switching IPM motor consumed between 3.6–26.9% less energy and required between 5.1–19.6% less peak power than the vehicle with the conventional 9-turn IPM motor. For the HEVs, the vehicle with the stator turn-switching IPM motor consumed between 13.5–23.4% less energy and required between 16.1–38.9% less power than the vehicle with the conventional 9-turn IPM motor.

LAMINATIONS

It should be noted that there have been some recent developments in Japan in improvements for electrical steels used for motor laminations. The optimization of the steel can be determined by the electrical grade, the thickness, and the core plate used for interlamination insulation against eddy current losses.

SOFT MAGNETIC MATERIALS

ORNL recently conducted a four-step evaluation of the potential for soft amorphous or nano-crystalline core materials to improve the efficiency radial-gap IPM motors. The study focused on amorphous Metglas®. The material costs of the Metglas was 4.5 times that of M-19 laminated silicon steel and there is no known way to produce bulk pieces of Metglas at a reasonable cost for radial-gap motor stators and rotors. A comparison of the performance of a baseline IPM with a standard M-19 core and the same motor with a Metglas motor showed there was no gain in efficiency at 2,500 rpm or 6,000 rpm at maximum current.[23]

COMMENTS FROM OEMS AND SUPPLIERS

The IPM motor is strongly preferred by the automakers. In general, they exhibited a high level of confidence that RE magnets would continue to be available for their needs. Plans to reactivate the MolyCorp mine in Mountain Pass, California, may be a solution. It has a significant reserve of RE ores but mining operations were discontinued for economic and environmental reasons. MolyCorp has plans

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[22] P. J. Otaduy, J. S. Hsu, and D. J. Adams, *Study of the Advantages of Internal Permanent Magnet Drive Motor with Selectable Windings for Hybrid-Electric Vehicles*, ORNL/TM-2007/142, November 2007.
[23] J. W. McKeever, "Amorphous Core Material Evaluation," FY 2008 Progress Report.

for restarting mining operations even though that would require a significant investment. However, renewed operation at Mountain Pass could supply the RE needs of North America for a decade or more. The only other near-term source of RE metals outside of China is the Lynas mine at Mt. Weld, Australia. It also has been reported that China is willing to increase production to meet the increasing world-wide demand.

Because of the hidden costs that would be involved with designing for larger motors that would not contain RE magnets, the OEMs may continue to use IPM motors with RE magnets even if the cost of the magnets doubles or triples. Nevertheless, they were supportive of the APEEM research into other types of motors.

SPM MOTORS

The SPM motor uses magnets attached to the rotor surface. Since the torque is proportional to magnet flux, an SPM motor uses the highest amount of magnet material but has the highest torque density and efficiency. However, SPM motors need significant field weakening at high speeds, which reduces the overall efficiency for a traction drive. Using low-cost magnets would increase both mass and volume.

The performance of SPM motors with FSCW was investigated in two projects several years ago.[24,25]

The SPM motor is inferior to the IPM motor in virtually all respects. Therefore, it will not be treated further in this document.

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[24] P. B. Reddy and T. M. Jahns, *Final Report on Control Algorithm to Improve the Partial-Load Efficiency of Surface PM Machines with Fractional-Slot Concentrated Windings*, Final Report ORNL/TM-2007/048, 2007.

[25] N. Patil, J. S. Lawler, and J. McKeever, *Control of Surface Mounted Permanent Magnet Motors with Special Application to Motors with Fractional-Slot Concentrated Windings,* Final Report ORNL/TM-2007/007, 2007.

WHEEL MOTORS

The Michelin Active Wheel System shown in Fig. 16 is scheduled to be available on at least one car for in wheel traction. The motor has a mass of 42 kg and a rated output power of 30kW and a peak power of 120 kW.[26]

Fig. 16. The Michelin Active Wheel System.

None of the OEMs or suppliers expressed an interest in wheel motors at this time. Disadvantages include the requirement for four inverters and concerns about fault tolerance. Therefore, no additional effort was directed toward this topic. Likewise, the current APEEM research program does not contain any projects on this subject.

[26] Input from Jim Hendershot.

MULTIPLE-ROTOR MOTORS

Several years ago, ORNL initiated a project to design a machine that would combine the motor and generator into one unit with the potential to be used as a continuously variable transmission (CVT) as well as other applications that require two electric machines. It involved a totally new and unique technology whereas secondary rotor would work in conjunction with a PM rotor. It was anticipated that additional torque coupling between the two rotors would produce more wheel torque and that it would provide a less costly CVT. A design was demonstrated in simulations that resulted in a 30% effective power increase with only a 15% increase in weight compared with a conventional IPM motor. However, because of budgetary constraints in 2008 and concerns about costs, manufacturability and durability the project was not continued.[27]

[27] D. J. Adams and J. S. Hsu, *Uncluttered Rotor PM Machine for a CVT Design*, ORNL FY2008 Annual Report.

INDUCTION MOTORS

The induction motor was invented by Nicola Tesla in 1882 and is the most widely used type of electric motor. Mostly because of its ability to run directly from an ac voltage source without an inverter, it has been widely accepted for constant-speed applications. In the past 30 years low-cost inverters have made variable-speed operation possible for traction drives. Induction motors have the advantages of being the most reliable; they require low maintenance, have high starting torque, and are widely manufactured and utilized in the industry today. These machines offer robust construction, good CPSR, low cost, and excellent peak torque capability.[28]

A paper by Michael J. Melfi indicates that the only way to increase the power density of an ac induction motor used for vehicle traction is to increase the speed. This is probably why many ac traction drives run at high speeds of 12,000 rpm and even 15,000 rpm at maximum vehicle speeds. This use of high motor speeds always results in smaller, light-weight traction motors, but it requires a high-ratio gear box that also has a mass and losses.

One of the earliest EV design in recent times was the GM EV1 which was powered by an ac induction motor made by the General Electric company but was designed by Dr. Ahmed El Entably from GM. It was a conventional four-pole motor with an Al die cast rotor that was driven by a flux vector drive designed and fabricated by the Hughes Division of GM. The principle engineer who was responsible for the drive on that car now works for Tesla Motors, and perhaps this is why the Tesla traction motor use four-pole ac induction motors as well. However the Tesla motors use die cast copper rotors for superior performance over the Al die cast rotor. The perfection of the die casting of copper was a significant technological advancement.[29]

Depending upon the size of the motor, the use of copper can increase the efficiency of an ac induction motor by one to three percentage points. In order to calibrate the significance of this small improvement, consider a 50 kW ac induction traction motor like the rating of the IPM motor used in the Prius. If an Al rotor were used and the motor efficiency turned out to be 93% and by the use of copper if it increased to 94%, the decrease in rotor losses would be about 570 watts. This copper rotor would be much easier to cool, and the extra 1% would improve the battery driving distance. A copper rotor that was die cast is shown in Figs. 17 and 18. [27]

Fig. 17. A copper die cast rotor.

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[28] Based on input from Jim Nagashima.
[29] Based on input from Jim Hendershot.

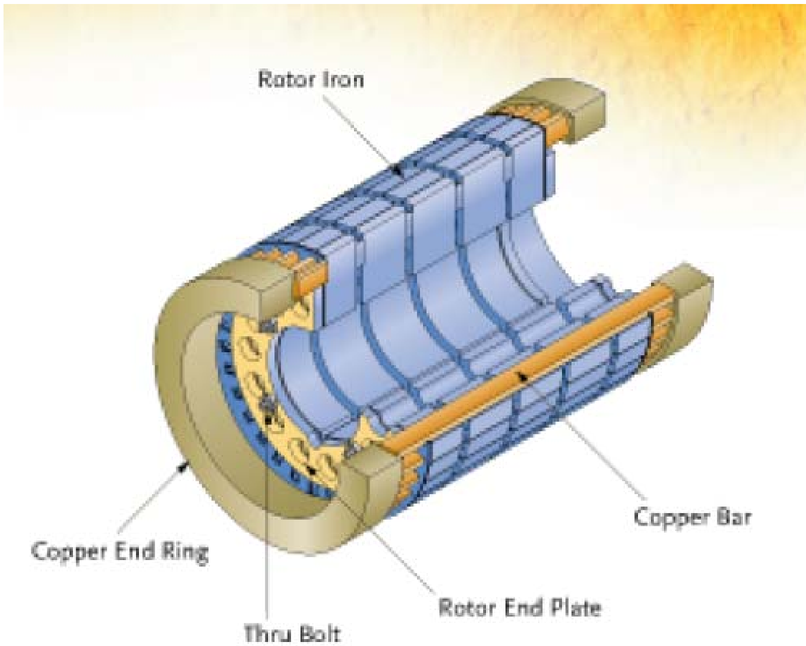

Fig. 18. Copper rotor cut-a-way with cooling channels.

The ac induction motor has been studied to determine the effect of different pole numbers, and it has been shown in several studies by Allen Bradley, Reliance Electric, General Electric, and Siemens that the optimum pole number for ac induction machines below 1,000 NM is four poles. Increasing the pole numbers for smaller machines reduces the power factor, but is the torque density is increased in the same frame size by increasing the number of poles. For ac induction motors driven by inverters, the number of poles should be increased from 4–6 for motors above 1,000 NM torque.[30]

The most difficult problem to deal with when using an ac induction motor is to extract the heat generated by the rotor conductors. The use of the lower-resistance copper over Al can be beneficial two ways. The first is to reduce the ohmic losses in the rotor conductors, thereby reducing the heat that must be extracted to achieve high power and torque densities. The second possible advantage of using copper rather than Al in the rotor conductors is that the cross section of the conductors can be reduced for the same ohmic losses due to the lower resistively of copper compared to Al so that higher rotor magnetizing flux can be permitted, which can improve vehicle traction by increasing the starting torque.[31]

Induction motors are not as efficient as PM machines, usually 3–10% lower, due to rotor bar losses. Furthermore, they cannot meet the FreedomCAR cost, power-density, and efficiency targets. Because of the mature nature of this technology, the likelihood of achieving the required additional improvements in efficiency, cost, weight, and volume is low. Therefore, they are not included in the research portfolio. However, if IPM motors become infeasible for reasons of cost or availability, induction motors would be the next choice, so they should not be forgotten.

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[30] Based on input from Jim Hendershot.
[31] Based on input from Jim Hendershot.

SR MOTORS

The SR motor uses a doubly salient structure with toothed poles on the rotor and stator. Each set of coils is energized to attract a rotor pole in sequence so it acts much like a stepper motor. With current technology, SR motors have inherently high torque ripple. In addition, the high radial forces can create excessive noise levels if not carefully designed. These machines are best suited in high-speed applications where ripple is not an issue. [32]

In comparison with mature motor technologies such as the ac induction machine, dc shunt motor, and even the more recent brushless PM synchronous machine (PMSM), the SR machine (SRM) offers a competitive alternative to its counterparts despite the relatively young age of SRM technological advancement. Although the basic concept of the SRM has been around for about 170 years, advances in PEs, digital control, and sensing technologies have completely reinvigorated the capabilities of the SRM and provide an immense amount of novel design opportunities which are better suited for vehicle propulsion.[33]

Unlike most other motor technologies, both the rotor and stator of the SRM comprise salient teeth such that torque is produced by the tendency of its rotor to move to a position where the inductance of an excited stator winding is maximized and reluctance is minimized. This condition generally occurs when the corresponding stator tooth is fully aligned with a rotor tooth. The non-steady state manner in which torque is produced in the SRM introduces the requirement of a sophisticated control algorithm which, for optimal operation, requires current and position feedback. In addition to non-steady state operation, the SRM often operates with the rotor and stator iron in saturation, increasing the difficulty of optimal control and making the machine very difficult to accurately model without the aid of computer processing and modeling techniques. Therefore, since the SRM is very technologically demanding in terms of design, modeling, and control, the evolution of SRM technology has been limited until these demands were adequately addressed. Furthermore, the progression of other motor technologies such as the induction motor and PMSM have not been as limited by the state of other technologies.[31]

Since the torque of an SRM is based on reluctance as opposed to a Lorentz force, no excitation is required from within the rotor, making it more simple, mechanically resilient, and cost effective than that of other motor technologies. The absence of PM material, copper, Al, or other artifacts in the rotor greatly reduces the requirement of mechanical retention needed to counteract centrifugal and tangential forces. This causes the SRM to be especially well suited for rugged applications or high-speed applications wherein high power density is desired. As there are no conductors in the rotor, only a low amount of heat is generated therein, and most of the heat is generated in the stator, which is easily accessible in regards to thermal management. In addition to having low material costs, the simplicity of the SRM facilitates low manufacturing costs as well.[32]

Having much lower material and manufacturing costs, the SRM presents a competitive alternative to the PMSM. Although the power density and efficiency of the PMSM will probably not be surpassed, the SRM comes close to matching these characteristics. Various comparison studies have shown that the efficiency and power density of the SRM and ac induction machine with copper rotor bars are roughly equivalent, while the ac induction machine with Al rotor bars falls slightly behind these two types of motors.[34]

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[32] Based on input from Jim Nagashima.
[33] Based on input from Tim Burress.
[34] Based on input from Tim Burress.

In regards to mass-transportation vehicle propulsion, the primary problems with SRM technology are the torque ripple and acoustic noise that is associated with the fundamental manner in which torque is produced. When current is supplied to the coil of an SRM stator tooth with proper respect to rotor position, torque is created until the nearby rotor tooth is fully aligned with the stator tooth. Thereafter, torque is created in the opposite direction if the rotor continues to rotate and if current is still supplied to the coil. Therefore, it is typically desirable to reduce the current to zero prior to generating an undesirable torque. However, the inductive behavior of the coil and corresponding magnetic path prevent rapid evacuation of current in the coil, and thus a torque transient occurs and provokes the issue of acoustic noise and torque ripple. Nonetheless, various methods have been developed to address this issue.[32]

Perhaps the second most significant problem with the conventional SRM is that it cannot be driven with the conventional three-phase power inverter. Nonetheless, a unipolar inverter for a three-phase SRM contains three diodes and three switching elements, as is the case with the conventional three-phase power inverter. If a particular SRM converter design is placed into mass production, the unfamiliarity and unavailability of the converter design will not be an issue. Although the volt-amp requirement of the SRM converter for a given power rating is typically somewhat higher than that of the conventional drive system, the layout of this inverter is such that the risk of catastrophic dc rail-to-rail failure is eliminated.[32]

While the absence of PM material in the rotor provides design and cost benefits, the lack of a passive magnetic excitation source effectively leads to the need of inducing magnetic flux in the rotor, which is typically achieved by the utilizing stator windings to do so. This is one factor that causes the efficiency of the SRM and ac induction machine to be lower than that of the PMSM machine.[33]

In addition to more adequately addressing the demands of the conventional SRM, improved PEs, digital control, and computational tools introduce an opportunity for development of novel machine geometries and control techniques that are more advantageous than those of conventional SRMs. There are various methods to reduce torque ripple and acoustic noise, but they often bring about important sacrifices of efficiency and/or power density. In the conventional SRM, only about 25–33% of the air gap is used at one instant, and torque ripple is indirectly influenced by this fact. Efforts are being made at ORNL to improve the percentage of air gap being used at each instant, while maintaining efficiency and even improving power density. Since torque production in the SRM depends on variation of reluctance and thus saliency of the rotor and stator teeth, it is difficult to increase the amount of active air gap without decreasing the saliency of each tooth as a result of leakage between adjacent teeth. Nonetheless, promising progress has been made in this area thus far.[35]

Figure 19 illustrates the qualitative relationship between estimates of power density (kW/L) and cost ($/kW) for current SRM, PMSM, and induction motor technologies as well as the ORNL SRM currently under development.[33] These values vary considerably with size, approach, packaging, and thermal management system characteristics and are best interpreted in a nonspecific and relative perspective. As indicated, the PMSM surpasses all other machines in regards to power density, but also entails the highest cost due to the presence of PM material and manufacturing complexity. The induction motors have comparable power densities with the conventional SRM, but have higher costs due to additional copper and manufacturing complexity. It is anticipated that the ORNL SRM will achieve a higher power density than that of the conventional SRM, but will not match that of the PMSM. However, it is expected that the low cost of the conventional SRM will be maintained in moving to the ORNL SRM. A comparison of specific power (kW/kg) for these machines is reasonably similar to the comparison of power density. It is anticipated that the characteristics of the ORNL SRM will meet the following criteria:

[35] Based on input from Tim Burress.

- Power density between 5 kW/L and 7.5 kW/L.
- Specific power between 1 kW/kg and 2.2 kW/kg.
- Motor cost between $6.5/kW and $9.5/kW.

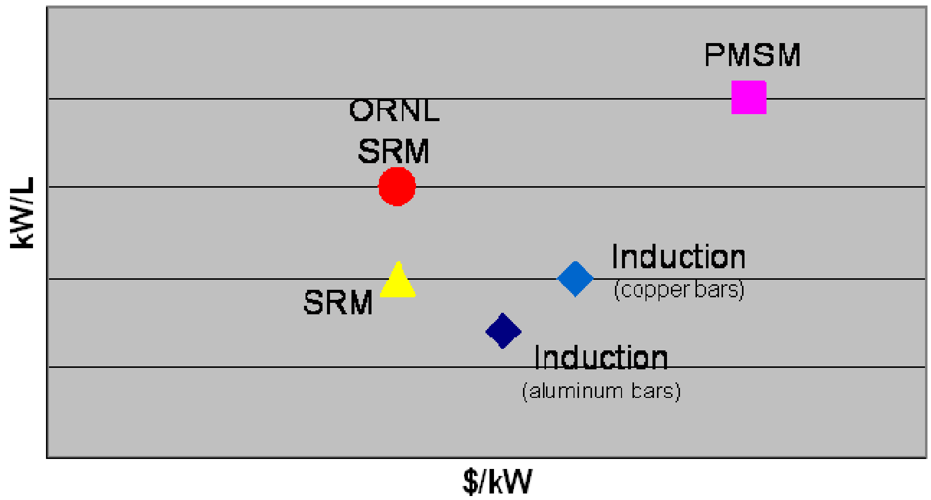

Fig. 19. Qualitative comparison of SR motor power density and cost with other motor types.

DESIGN CONSIDERATIONS FOR SRMS

The phase topology for the SRMs is totally different from the six-transistor bridge connections for the IPM and ac induction motors. The SR motor phases are connected in parallel between the dc voltage bus with a transistor on each leg of the phase winding and also a diode. Therefore, the standard transistor bridge modules used for ac induction and IPM motors cannot be utilized. Special configurations of discrete components are usually required, except for some custom drive modules made for special applications. The typical SR phase drive topology is shown in Fig. 20 with the location of the fly-back diodes such that the ones included with most transistors connected from the emitter to the collector cannot be utilized.

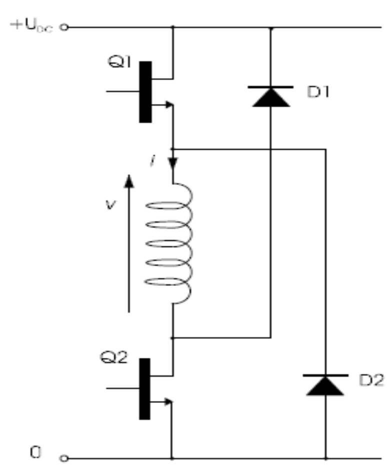

Fig. 20. Half-bridge phase leg for a SRM.

The capacitor requirements are more severe for the SR inverter, and the commutation control accuracy is very strict to achieve the maximum output torque at all speeds. To further complicate the optimization of the SRM, the back-emf is not fixed nor is it near sine shaped. The selection of the number of phases determines the torque ripple for most common designs. It should be noted that a two-phase SR motor cannot be electrically reversed but is single directional. In addition, the single-phase SR motor is becoming quite popular for fans, pumps, blowers and certain appliances that are single directional. The reason for this is its simplicity and low cost for the inverter, which requires only 4 transistors rather than 6 for the 3 phase, 8 for the 4 phase and 10 for the 5 phase. However in order to make these two-phase SR motors useable, a special design trick must be used to eliminate the dead spots and minimize their torque ripple. Many of these ideas are being developed and patented. Normally the torque produced by each phase covers only 180 electrical degrees of rotor rotation. In order to produce continuous torque with no dead spots or low starting torque rotor positions, the motor lamination geometry must be modified to assure torque production for each phase greater than 180 electrical degrees. The best design exhibits the largest angles with steep torque rise from zero.

Comments from OEMs and Suppliers

Because considerable research efforts to eliminate or sufficiently reduce the torque ripple and noise problems have not been successful to date, most of the industry people that were interviewed are highly skeptical that those problems will ever be solved in a cost-effective manner. However that opinion is not universal. In a study of design strategies to meet or exceed Partnership for a New Generation of Vehicles (PNGV) goals, PM motors, SR motors, and induction motors were compared.[36] It concluded that SR motors have been overlooked by many designers, particularly in the U.S. because of their reputation for noise and excessive torque ripple. They state that if an SR motor is designed to optimize efficiency and specific power, which they generally have not been, the inherent physics of modern SR motors enables them to outperform other motor types including PM motors in efficiency, power density, and specific power along with overload capability, ruggedness, controllability, form-factor flexibility, simplicity, and cost.[37]

Switched Reluctance Drives Ltd. and Nidec Motor Corporation have developed SR motors for several automotive and heavy-duty applications.[38] These include:

- A 15kW (continuous) motor/generator for a mild hybrid power train, which costs 25% less than alternative systems.
- A 30kW (continuous) Caterpillar starter/generator to provide a direct-drive capacity to start the engine and also to generate the required power for electrical auxiliaries on highway trucks.
- A 55kW (continuous) drive motor and a 160kW (peak), 130kW (continuous) drive motor for hybrid traction drives for urban buses.

[36] T. C. Moore and A. B. Lovins, "Vehicle Design Strategies to Meet and Exceed PNGV Goals," SAE Paper No. 951906, SAE Conference, Costa Mesa, California, August 4, 1995.
[37] J. R. Hendershott, "A Comparison of AC, Brushless & Switched Reluctance Motors," *Motion Control*, pp. 16–20, April 1995.
[38] www.srdrives.com

MOTORS WITH EXTERNAL EXCITATION

A wound field motor uses no magnets and is separately excited using a field coil driven by a circuit that controls the excitation flux. It can be designed with the field coil in the rotor or in the stator.

ROTOR FIELD COIL

An example is an alternator or Lundell claw-pole motor. It consists of a rotating coil with slip-ring brushes and a set of rotor pole pieces. Issues include brush wear, limited speed due to the rotating coil, low efficiency of claw poles, and poor thermal dissipation of the coil. However, the issues with high speed might be mitigated with good mechanical design. Rotor cooling can be improved with oil spray cooling. Better rotor electrical design can improve overall efficiency. Since this uses slip rings, brush wear is much longer than a commutation block. The advantages of variable field excitation and no magnets make this a good candidate for future development.[39]

STATIONARY FIELD COIL

As stated previously, the high power density of the IPM motor makes it the favorite of the auto makers. IPM motors have the three torque production capabilities: the magnet torque, the reluctance torque, and the third-harmonic synchronous torque (through shaping the total air gap flux for voltage limit manipulation and through the interaction between 3rd harmonic currents and flux). This unique three-torque feature of IPM motors cannot be matched by other types of motors such as induction and SR motors. [40]

In order to retain these three-torque production capabilities without PMs, a novel brushless synchronous motor with external excitation is being developed at ORNL. The motor is based on the uncluttered rotor principle that has been successfully validated through the previously funded DOE projects (i.e. the 16k-rpm IPM project and the 6,000-rpm IPM project). To reduce the volume of the motor, the field winding of this PM-less synchronous motor is wound on the inner side of the end brackets facing the ends of rotor. The end brackets of the conventional IPM motors are made of Al for supporting the bearings. The end brackets of the ORNL PM-less synchronous motor are made of magnetically conducting material such as mild steel for supporting the bearings as well as for conducting magnetic fluxes. These dual function end brackets help to limit the overall dimensions. However, because mild steel is denser than Al, this creates an unfavorable weight issue for the PM-less motor. Fortunately the weight is a less serious problem than the volume for acceptance. Furthermore, it is possible to increase the speed further than what the IPM motor can reach by putting mechanically reinforcing components inside the grooves vacated by the PMs. A higher-speed machine can reduce both the volume and the weight.[41]

The ORNL PM-less synchronous motor would be expected to reduce the motor cost by not having PMs; only common materials such as mild steel, core laminations, and copper are used. This helps to meet the DOE 2020 motor cost target.[38]

The ORNL PM-less synchronous motor retains the three torque production capabilities (magnetic torque, reluctance torque, and 3rd harmonic related torque) of the IPM motor. The permissible temperature of the ORNL PM-less synchronous motor can be increased without the PM temperature limitation. Consequently power density can go up, or cooling cost can go down. The permissible speed of the ORNL

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[39] Based on input from Jim Nagashima.
[40] Based on input from John Hsu.
[41] Based on input from John Hsu.

PM-less synchronous motor can go up by using the space vacated by the PMs for mechanically reinforcing components. This helps to meet the power density target. Due to the adjustable field capability that the PM machines do not have, the performance of the motor such as the power factor, constant power speed ratio, etc can be improved.[38]

When a hybrid vehicle is cruising on a highway, the engine normally runs at its highest efficiency, and the IPM motor can be switched off, but it still rotates and produces a significant amount of core loss at high speed due to the PMs that cannot be switched off. This PM-less machine does not have that problem. Also, during highway driving, the, the voltage of the open-circuit stator winding of an IPM motor may be too high and require an artificial short-circuit of either the upper or lower coils to lower the back-emf to prevent the insulated gate bipolar transistor (IGBT) and insulation breakdown. Having an adjustable field, this PM-less machine does not have this problem. In addition, the ORNL PM-less motor can totally cutoff of the field increase the drive-cycle efficiency and to prevent burning if there is an insulation defect, but an IPM motor cannot.[38]

One problem with the PM-less motor is that the few amps of dc that are needed for producing the flux through the additional field excitation would cause copper loss. However, the loss of efficiency needs to be evaluated for the full drive cycle. For example, no field excitation is required when the motor is not in use at cruising; hence no high-frequency loss would be produced. Also, the material used for bringing the externally excited flux to the air gap adds to the weight and volume.

Although there will be extra cost associated with the excitation coils, it is anticipated that the cost will be more than offset by the elimination of the cost of the magnets in an IPM motor. Furthermore, making the end brackets carry the excitation flux as well as the bearing supporter reduces the volume. Also, by raising the permissible temperature of the motor and by increasing the speed, the power density of the motor can go up. Additionally, with the adjustable field excitation, the system cost can be reduced by the elimination of the boost converter.

OTHER MOTORS

ALTERNATOR OR LUNDELL CLAW-POLE MOTOR

As was mentioned in the section on Motors with External Excitation, the advantages of variable field excitation and no magnets make the alternator or Lundell claw-pole motor a good candidate for future development.[42]

SYNCHRONOUS RELUCTANCE MOTOR

These machines operate on reluctance torque due to the ratio of d-axis inductance to q-axis inductance. They create saliency with air barriers placed in the rotor lamination or by axial laminations. No magnets are needed. These motors have a sinusoidal stator field, so torque ripple is relatively low. The problem with this topology is saturation of the rotor, which reduces the saliency. Another issue is the poor mechanical strength of the punched lamination. Axially laminated motors have better mechanical strength but are very difficult to manufacture. The potential for this type of motor to be successful is only fair because of the limits of B_{max} of current lamination steels, and they have lower torque density compared to PM motors. If a steel can be found that does not saturate at high flux levels, then the saliency ratio will not drop, reducing the torque.[39]

DC MOTOR

The oldest type of electric motor, dating back to its invention in 1832 by Michael Faraday, dc motors require no inverter, but consist of a wound rotor with a commutator block and brushes. This reverses the armature magnetic field in synchronization with rotor speed to produce torque. The stator magnetic flux can be created by either a wound field or PMs. The dc motor provides good torque and excellent field weakening, but it suffers from limited speeds due to the commutator block, poor thermal cooling of the rotor coil, and low power density due to the additional space required by the brushes.[39]

[42] Based on input from Jim Nagashima.

COMPARISON OF MOTOR TYPES

Table 6 provides a qualitative summary of the most important features of the principal motor types that are being considered.[43]

Table 6. Advantages (green) and disadvantages (red) of the major motor types

Motor Design		CPSR	Cost	Peak Power to Weight Ratio	Peak Power to Volume Ratio	Lifetime
Induction (natural field weakening)		4	$	Low	Low	Higher
PM (can't modulate the flux)	SPM motor [brushless dc motor (BDCM)] low inductance	11	$$	High	High	High
	SPM motor with concentrated windings (higher inductance)	Theoretically, infinity, but allow for rotational losses	$$	High	High	High
	IPM motor	Theoretically, infinity, but allow for rotational losses	$$$	Highest	Highest	High
SR	Non-linear solenoid type force	Discontinuous control	$	Low	Low	Higher

[43] Extracted from material supplied by Richard Smith of ORNL.

DOE APEEM APPROACH FOR TRACTION DRIVE MOTOR R&D FOR HEVs AND EVs

Because of the importance of motors to the future of HEVs and EVs, motor R&D has always been an important part of the APEEM portfolio. In the recent past, the primary emphasis has been on PM motors. However, with the recognition of the uncertainty in the future price and supply of RE magnets, the scope of the DOE motor R&D has been expanded to include three parallel paths for dealing with various economic and technical possibilities that might develop in the future. Those paths include the following:

1. *Continued development of IPM motors using RE magnets* – This activity is to develop technologies for IPM motors that will enable them to meet the technical targets. Possible innovations could result in lower magnet content in the motor. In addition, manufacturing improvements are being pursued to lower cost. This path addresses the possibility that domestic production of RE metals will be reactivated.

2. *Develop innovative designs for PM motors that do not use RE magnets.* This includes the possibility of substituting non-RE magnets, which tend to have weaker flux-producing properties, in traditional or innovative motor topologies and new topologies that do not use PM material.

   2.1 Possible other magnets that may be substituted for RE magnets include
   - Sm-Co, which is the next strongest magnet material and is more temperature stable and corrosion resistant than the NdFeB magnets. However, the cost depends on the price of Co, which tends to be high and very unstable.
   - Alnico, which is somewhat weaker, but it is corrosion resistant and extremely temperature stable.
   - Ferrite, which is widely available and inexpensive, but is considerably weaker than other types. However, it may be possible to compensate for the lower strength through novel design concepts.

   2.2 An alternative potential solution pathway is to develop motors that do not use PMs but offer attributes (e.g., power density, specific power, etc.) similar to IPM motors that use RE magnets. For example, modify the design of SR motors to eliminate the problems of noise and torque ripple that are the main drawbacks to a motor that is extremely rugged and inexpensive. Also pursue innovative topologies that utilize flux generated via electromagnets.

3. *Develop new magnet materials using new alloys or processing techniques that would be less expensive or have superior properties compared with existing materials.* The following approaches were initiated in FY2010:

   - Continue development of a RE material in which yttrium has been substituted for neodymium. This material has better high-temperature tolerance and is less expensive than the NdFeB alloy. It was originally developed in the form of isotropic spherical powder for injection molding. In that form, it is easier to incorporate into a motor, but it sacrifices some of the magnetic strength.

     - One approach is to develop the material with an anisotropic crystal structure such that it will have improved magnetic properties.
     - The second approach is to develop a process for producing it in a sintered aligned form, which will optimize the magnetic properties but increase the cost somewhat.

- Develop a new magnet material that does not contain RE metals. The approach will be to search for inter-metallic compounds that contain iron and Co but have better magnetic properties than Alnico. This will involve some very fundamental research as well as process development.

TOPICS FOR FUTURE RESEARCH

There was general agreement among most of the people who were interviewed that the DOE strategy as described above and the specific projects that fit that strategy represent a reasonable distribution of available human and monetary resources. If additional resources become available, some of the following topics could be considered.

Several people mentioned the importance of thermal control for motors. Ultimately, the peak power of the motor is determined by the maximum temperature of the winding, and, if it can be kept below the insulation-rated temperature, higher peak power densities could be achieved. Thermal control of motors is receiving increased attention in the FY2010 and FY2011 project portfolios. It is being covered in a separate assessment of thermal control to be completed in FY2011.

SUGGESTIONS FROM JIM NAGASHIMA

In this author's opinion, motor technology has much room for improvement and has been overshadowed by semiconductor technology. The electric traction power-train is only as good as the weakest link, and that is moving towards the motor and gearbox. We need more research into better materials to achieve the DOE goals and make hybrids and EVs cost competitive and viable.

Stator/Rotor Poles

It is well known that torque density improves as the number of poles increases, up to a point. Increasing the pole count improves the winding utilization. If the pole count is increased too far, there is no room for the windings, and power density starts to decrease. The machine designer has to do several finite-element analyses (FEAs) to determine the optimal pole number for a specific application. There are also many papers on general machine sizing equations that can help to determine the right pole number.

Phase Number

Most traction drives use three-phase ac as this is the most efficient phase number. Recent studies have shown that multi-phase systems may have an advantage in the mid speed region above base speed when coupled with harmonic current injection. This is currently being examined by other DOE investigators.

Inner Rotor vs. Outer Rotor Construction

Since torque is proportional to the radius of the air gap, it follows that any machine topology that moves the effective air gap towards the outer diameter will increase torque. One example is to reverse the rotor and stator positions in a SPM motor. By placing the magnets on the inside of a rotor drum and moving the stator to the inside, the air gap radius increases and significantly increases torque for a given motor diameter. Of course this complicates rotor mounting and stator cooling, but can be used effectively in certain applications. Another method is to change from a radial gap to an axial gap. This will move the effective air gap radius to the geometric diameter of the rotor disk.

Soft Magnetic Materials

The great need now is a low cost lamination steel that has a high saturation flux to prevent saturation at high torque levels. It is well known that the addition of Co can improve B_{max} but at a cost nearly tenfold. More research is needed to find ways to improve the alloy content without the use of rare elements. Much research has been done on soft magnetic composites which are powdered magnetic metals mixed with a non-magnetic binder. This material can be molded or extruded into final shape using dies. Since each grain is isolated, there is high bulk resistivity and laminations are not needed. It presents the possibility of 3D shapes and transverse flux paths to improve flux utilization. However, it has lower saturation flux compared to lamination steels and poor mechanical strength so it cannot be used for rotors.

Bar Windings

Using wire with a rectangular cross-section instead of round wire is an excellent way to increase fill factor. The extension of this is to use heavy gauge bars that are pre-formed and inserted into the slots and welded on each end to form the turns. This has the advantage of machine forming, high fill, and effective cooling when combined with oil spray cooling. Several types of production hybrid motors use this type of construction. This is an excellent alternative to concentrated windings with the advantage of a solid yoke and back iron.

High Speed Motors

It is known that power for a given size can be increased with speed. Currently the motors we use for traction are rated for 6,000–12, 000 rpm. The issue with very high motor speeds is the gearbox. The motor speed eventually has to be reduced to an axle speed of approximately 1,200 rpm by the gearbox or transmission. A practical gear ratio limit for a single stage is 5:1, so that a 12,000 rpm motor requires two stages. If we want to design a small 50,000 or 100,000 rpm motor, we would need 3 or 4 stages which presents higher gear losses, complexity, and a larger gearbox. The increase in gearbox size generally offsets the reduction in motor size. In addition, designing a gearbox with a high-speed input shaft is a very special design that uses very high-speed, expensive bearings. The trade-off has to be done at the system level. The breakthrough would be for a high ratio gearbox with low losses and standard bearings.

SUGGESTIONS FROM JOHN HSU

Magnet-Wire Insulation

Research on high-temperature magnet-wire insulation materials would help significantly for meeting the 2020 coolant goal (either 105ºC or 85ºC). If one can make the Camry motor 40ºC hotter, the 2020 target is roughly met except the cost. Therefore, raising the permissible temperature of the motor would be a useful approach.

Third-Harmonic Flux and Currents for Torque and Voltage Manipulation

Utilization of third-harmonic flux and currents is beneficial to a wide range of motors with or without PMs. The high-power-density motors are magnetically very saturated; the air gap flux is flattened and contains very high third harmonics. A five-phase motor is one way to use the third harmonics; ORNL has some alternative proprietary methods for the utilization of third harmonics.

Manufacturing Technology

Research on topics such as how to wind the motor windings with less labor, how to increase the copper fill factor in the slots, and how to build the rotor with ziplocks are examples of research that would help in producing a final product that meets the 2020 targets.

SUGGESTION FROM JIM HENDERSHOT

Designs That Use Ferrite Magnets

It would seem that if PM brushless machines must be used for vehicle traction because of power and torque density advantages over all other types of motors and generators the use of these ceramic magnets should be investigated by using similar concepts to the QM design and the Fanuc design.

CONCLUSIONS

The results of the assessment validated the DOE strategy involving three parallel paths:

(1) There is enough of a possibility that RE magnets will continue to be available, either from sources outside China or from increased production in China, that development of IPM motors using RE magnets should be continued with emphasis on meeting the cost target.

(2) Yet the possibility that RE magnets may become unavailable or too expensive justifies efforts to develop innovative designs for PMs motors that do not use RE magnets. Possible other magnets that may be substituted for RE magnets include Sm-Co, Alnico, and ferrites. Alternatively, efforts to develop motors that do not use PMs but offer attributes similar to IMPs are also encouraged.

(3) New magnet materials using new alloys or processing techniques that would be less expensive or have comparable or superior properties to existing materials should be developed if possible.

IPM motors are by far the most popular choice for HEVs and EVs because of their high power density, specific power, and CPSR. Performance of these motors is optimized when the strongest possible magnets – i.e., RE NdFeB magnets – are used.

Doubling or even tripling the magnet cost might not justify a shift from RE magnets to weaker magnets or other technologies; system costs must be considered including the hidden costs of increased volume or weight. The use of weaker magnets would require significant design changes. For any new design, temperature tolerance is extremely important with respect to wiring and magnets. Although most manufacturers are assuming that RE magnets will continue to be available, they also recognize the importance of developing backup technologies.

If NdFeB magnets are not available, the following alternatives may be considered:

- Sm-Co magnets have similar magnetic properties to NdFeB magnets, have better high-temperature stability (up to ~300ºC), but are very costly.
- Alinco has somewhat lower cost but very low coercivity (resistance to de-magnetization).
- Ferrites are the least expensive but also are the weakest magnets. They have good thermal stability between -40ºC and 250ºC.
- New alloys yet to be developed.

SPM motors have relatively high specific power but have restricted CPSR. The speed of these motors is limited due to challenges of magnet retention. Essentially, they have no advantage over IPM motors.

Induction motors have lower power density compared with IPM motors but also cost less. They are robust and have a medium CPSR. Being a mature technology, they are reliable but have little opportunity for improvement. Most manufacturers consider induction motors the first choice if IPM motors are not available.

SR motors are durable and low cost, and they contain no magnets. Their efficiency is slightly lower than that of IPM motors at the sweet spot, but the flatter profile of SR motors can give higher efficiency over a typical drive cycle. The torque density is much better than that of induction motors. They require different PEs compared to IPM motors. Significant concerns about SR motors are torque ripple and noise. Efforts are currently being directed to solve those problems through rotor design, modified electronics, and stiffening of the case.

Motors with external excitation are currently being studied at ORNL. They would contain no magnets, but serious concern about cost, manufacturability, and durability need to be addressed.

Other motor designs including wheel motors, multiple-rotor motors, and synchronous reluctance motors are considered low priority and not justifying research at this time.

APPENDIX A. REPORT FROM JIM NAGASHIMA

Assessment of Motors/Magnets to Address Rare Earth Materials Issues

September 3, 2009

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OBJECTIVE

The purpose of this report is to provide to ORNL technical information and research and development needs for selected motor technologies to DOE's Vehicle Power Electronics and Electric Machine program in assessing motor technologies that are critical to its VT mission.

TASK

The Oak Ridge National Laboratory is currently assessing motor technologies to determine their applicability to meet motor cost and performance targets established for the DOE Freedom CAR Program. The consultant, Nagashima Advanced Technology Consulting (NATC), shall assist in this assessment by providing technical information and research and development needs for selected motor technologies.

Nagashima Advanced Technology Consulting (NATC) will serve as subject matter expert to assess motor technologies and/or technical information and participate in an initial interview with ORNL, Mitchell Olszewski, and its contractor Ray Fessler of BIZTEK, Inc. lasting approximately four (4) hours. This Interview was conducted at the National Transportation Research Center in Knoxville TN on August 24, 2009. This report provides documentation of the verbal data supplied in the interview and providing additional information as identified in the interview.

BACKGROUND

For most of the history of electric motors the machines of choice were either the DC brush motor or AC induction motor. The DC motor offered good performance but needed a commutation block with brushes which required regular service and replacement. The AC induction motor was brushless, needed no inverter, and used in applications where AC line power was available. Its construction was simple and it offered excellent performance. The induction motor uses the rotating AC field in the stator to induce an AC current in the rotor. The rotor current creates a magnetic field that interacts with the stator current and creates torque. This torque is proportional to the difference between the rotating electrical field speed and the rotor mechanical speed, or "slip". Since most machines were line connected, motor speed was determined by line frequency and the pole number so it was suitable for fixed speed operation like pumps, blowers, etc. When variable speed operation was required such as a spindle drive the motor was driven by an inverter, usually a voltage source inverter, which provided a variable frequency and variable voltage source.

In the Sixties, General Motors Research Labs developed a high flux magnet material using rare earth materials. Patented by MagnaQuench, Neodymium Iron Boron, NeFeB, magnets had almost on order of magnitude greater flux than other types of permanent magnets of the day. This created a revolution for many products that need small high flux magnets including, speakers, hard drives, etc. It was a logical application to use rare earth magnets in an electric motor in the 80's. The permanent magnets could be mounted on the rotor to create the magnetic field. This would eliminate the rotor bar losses compared to the induction motor, thus improving overall motor efficiency. Also there was no need for "slip" and the motor would be synchronous with the electrical speed. It all depended on the cost of these magnets and there were significant price reductions after the MagnaQuench patent expired in the 90's. We saw most of the production of rare earth magnets move from the U.S. to Japan. However, Japan has no natural occurring rare earth resources and imported the raw materials from other countries such as China, United States, and Canada. At the turn of the Century, China saw an opportunity to gain market share by undercutting the competition in raw materials. It was aided by low wages, non-existent environmental laws, a supportive government, and cheap mining operations. This enabled China to produce rare earth material at prices others could not match. Finished magnets were selling for under $16 per kilo. The effect of this undercutting was to drive competitors out of the market and leave China with a 90%+ market share and effectively establish a monopoly on rare earth magnets. The price of RE magnets has steadily increased and prices have hit as high as $60/kg. When you consider that a single automotive traction motor may use 1-1.5 kg of magnets and there are usually two motors per vehicle times several million cars, then the quantities are staggering. China has recently announced their intention to limit exports on rare earth materials in order to supply their own needs and to bolster their position on the value chain as a supplier of magnets and motors. This has driven everyone to examine the role of PMs in electric machines and try to figure out topologies and technologies that either eliminate or reduce the amount of magnets.

MOTOR TOPOLOGIES

There are many different motor topologies that can be examined and new ones are being published each month. This report cannot do any in-depth examination of each type of electric motor, but we can look at the primary classes of machines and do a qualitative estimate of its potential to reduce or eliminate magnet content. For the evaluation of motor topologies I will examine the following criteria:

- Magnet Content: High, Low, None. For a 50kW motor, High >1.5 kg of magnets, Low < 1.5 kg.
- Cost Impact: What is the impact on future traction motors if this topology is accepted
- Barriers: What technology is needed to make it practical.
- Potential: What are the chances that improvements in this motor will make it suitable for traction.

Surface PM motor. This motor uses magnets attached to the rotor surface. Since the torque is proportional to magnet flux, it uses the highest amount of magnet material but has the highest torque density and efficiency. However, SPM motors need significant field weakening at high speeds which reduces the overall efficiency for a traction drive. Using low cost magnets will increase both mass and volume.

- Magnet Content: High
- Cost Impact: Motor cost will rise as magnets become more expensive.
- Barriers: High cost of rare earth magnets.
- Potential: Low, unless a cheap magnet is found.

Wound field motor. This ac motor uses no magnets and is separately excited using a field coil driven by a circuit that controls the excitation flux. It can be designed with the field coil in the rotor or in the stator.

1. **Rotor field coil**. An example is an alternator or Lundell Claw pole motor. It consists of a rotating coil with slip-ring brushes and a set of rotor pole pieces. Issues include brush wear, limited speed due to the rotating coil, low efficiency of claw poles, poor thermal dissipation of the coil.
   - Magnet Content: None
   - Cost Impact: Future costs of motors may be reduced.
   - Barriers: Need better long life brushes.
   - Potential: Good. I believe the issues with high speed can be mitigated with good mechanical design. Rotor cooling can be improved with oil spray cooling. Better rotor electrical design can improve overall efficiency. Since this uses slip rings, brush wear is much longer than a commutation block. The advantages of variable field excitation and no magnets make this a good candidate for future development.

2. **Stationary field coil**. This is a separately excited machine, however the coil is stationary. There are no brushes to wear out and the coil can be easily cooled. Additionally, the flux can be tailored to the operating point to maximize torque, power factor, and efficiency. One example is Dr. John Hsu's Uncluttered Machine which uses excitation coils placed at each end of the motor. Flux travels through the shaft, hub, rotor, stator, then back to the end bracket. The disadvantage is multiple air gaps, difficult construction, and complex flux paths.
   - Magnet Content: None
   - Cost Impact: None to increased cost.
   - Barriers: A cleaver way to couple the field coil flux to the rotor.
   - Potential: Fair. The added complexity of moving the excitation coil to the stator side brings more parts, difficult assembly, and added cost. This will either offset the cost of magnets or increase the cost of the motor.

Synchronous reluctance motor. These machines operate on reluctance torque due to the ratio of d-axis inductance to q-axis inductance. They create saliency with air barriers placed in the rotor lamination or by axial laminations. No magnets are needed. These motors have a sinusoidal stator field so torque ripple is relatively low. The problem with this topology is saturation of the rotor which reduces the saliency. Another issue is the poor mechanical strength of the punched lamination. Axially laminated motors have better mechanical strength but are very difficult to manufacture.

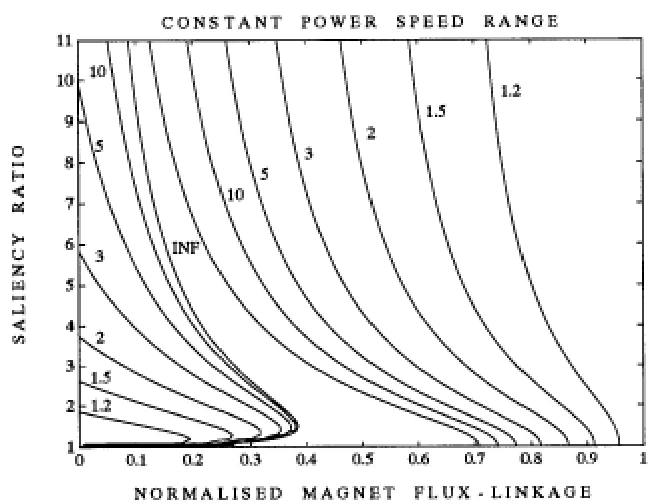
- Magnet Content: None
- Cost Impact: Motor costs may be reduced.
- Barriers: Lamination steels with Bmax.

- Potential: Fair. Although these motors have lower torque density compared to PM motors, they have no magnets. If we can find a steel that doesn't saturate at high flux levels, then the saliency ratio won't drop which reduces torque.

SR motor. This motor uses a doubly salient structure with toothed poles on the rotor and stator. Each set of coils are energized to attract a rotor pole in sequence so it acts much like a stepper motor and has inherently high torque ripple. In addition, the high radial forces can create excessive noise levels if not carefully designed. These machines are best suited in high speed applications where ripple is not an issue.

- Magnet Content: None
- Cost Impact: Motor cost may be reduced.
- Barriers: Noise, torque ripple due to the nature of the topology.
- Potential: Low. The stepper-like torque of this machine is not fundamentally good for traction. Poor utilization of the poles leads to lower torque production.

Interior PM motor. An IPM motor is a hybrid that uses both reluctance torque and magnetic torque to improve efficiency and torque. These motors are created by adding a small amount of magnets inside the barriers of a synchronous reluctance machine. Dr. Wen Soong in his PhD dissertation [1] introduced the IPM plane and showed that a IPM with a nominal saliency ratio of 4 to 5 needs a magnetic torque contribution of 25-30% to achieve an infinite constant power speed range.



Since magnetic flux is low there is very little field weakening required at high speeds and efficiency over a drive cycle is improved. So good performance over a broad speed range can be achieved with a small quantity of magnets. These motors have excellent torque, efficiency, low torque ripple. They have now become the motor of choice for most hybrid and EV applications.

- Magnet Content: Low to Moderate.
- Cost Impact: Motor cost will rise as magnets become expensive.
- Barriers: Low cost magnets are needed.

- Potential: Good. Since IPMs use a small amount of magnets, they are a candidate for using other magnet types such as Alnico, ferrite, etc. This would increase the motor size slightly (maybe 10%) with a small cost impact.

Induction Motor. The induction motor was invented by Nicola Tesla in 1882 and is the most widely used type of electric motor. Mostly because of its ability to run directly from an ac voltage source without an inverter, it has been widely accepted for constant speed applications. In the past 30 years, low cost inverters have made variable speed operation possible for traction drives. These machines offer robust construction, good CPSR, low cost, and excellent peak torque capability. They are not as efficient as PM machines, usually 3-10% lower, due to rotor bar losses.

- Magnet Content: None
- Cost Impact: Motor cost may stay the same or be reduced.
- Barriers: Copper costs, tooling for rotor bar casting.
- Potential: Fair. It is unlikely that a new design for an induction motor will be invented anytime soon. It is known that copper rotor bars can improve efficiency but with a penalty of increased tool wear due to the high temperatures involved.

DC motor. The oldest type of electric motor, dating back to its invention in 1832 by Michael Faraday. These motors require no inverter, but consist of a wound rotor with a commutator block and brushes. This reverses the armature magnetic field in synchronization with rotor speed to produce torque. The stator magnetic flux can be created by either a wound field or PMs. The dc motor provides good torque, excellent field weakening. It suffers from limited speeds due to the commutator block, poor thermal cooling of the rotor coil, and low power density due to the additional space required by the brushes.

- Magnet Content: None
- Cost Impact: Higher costs
- Barriers: Commutator Block and brushes
- Potential: Low. This is a good motor but the brush block severely limits life and speed. It also takes up a lot of space on the rotor.

Homopolar Motor. Like a dc motor, a homopolar machine uses dc current and magnets, but no commutation block. Instead, brushes provide current to a rotor. Since these motors use low voltage at high currents, they are not suitable for traction drives.

- Magnet Content: High
- Cost Impact: Motor cost will increase
- Barriers: High magnet cost, high currents
- Potential: Low. The combination of brushes, high cost magnets, and high currents make this a poor candidate.

A summary of evaluation criteria for the motor topologies:

Summary of Motor Topologies				
Motor Topology	**Magnet Content**	**Cost Impact**	**Barriers**	**Potential**
Surface PM	High	Increase	Magnet cost	Low
Wound Field-Rotating Coil	None	Decrease	Brushes	Good
Wound Field-Stationary Coil	None	Increase	Mechanical design	Fair
Synchronous Reluctance	None	Decrease	Magnetic steels	Fair
SR	None	Decrease	Construction	Low
Interior PM	Low	Increase	Magnet cost	Good
AC Induction	None	None	Rotor bars	Fair
dc Motor	None	Increase	Brush Block	Low
Homopolar	High	Increase	Magnets, brushes	Low

MACHINE DESIGN ISSUES

Stator/Rotor Poles. It is well known that torque density improves as the number of poles increases, up to a point. Increasing the pole count improves the winding utilization. If the pole count is increased too far then there is no room for the windings and power density starts to decrease. The machine designer has to do several FEAs to determine the optimal pole number for a specific application. There are also many papers on general machine sizing equations that can help to determine the right pole number.

Phase Number. Most traction drives use three phase ac as this is the most efficient phase number. Recent studies have shown that multi-phase systems may have an advantage in the mid speed region above base speed when coupled with harmonic current injection. This is currently being examined by other DOE investigators.

Inner rotor vs. Outer rotor Construction. Since torque is proportional to the radius of the airgap, it follows that any machine topology that moves the effective air gap towards the outer diameter will increase torque. One example is to reverse the rotor and stator positions in a surface mount PM motor. By placing the magnets on the inside of a rotor drum and moving the stator to the inside, the airgap radius increases and significantly increases torque for a given motor diameter. Of course this complicates rotor mounting and stator cooling, but can be used effectively in certain applications. Another method is to change from a radial gap to an axial gap. This will move the effective air gap radius to the geometric diameter of the rotor disk.

Magnetic Materials. The great need now is a low cost lamination steel that has a high saturation flux to prevent saturation at high torque levels. It is well known that the addition of

Co can improve B_{max} but at a cost nearly tenfold. More research is needed to find ways to improve the alloy content without the use of rare elements. Much research has been done on Soft Magnetic Composites which are powdered magnetic metals mixed with a non-magnetic binder. This material can be molded or extruded into final shape using dies. Since each grain is isolated, there is high bulk resistivity and laminations are not needed. It presents the possibility of 3D shapes and transverse flux paths to improve flux utilization. However, it has lower saturation flux compared to lamination steels and poor mechanical strength so it cannot be used for rotors.

Magnets. Rare earth magnets are a blessing and a curse. They have improved so many of the products we use every day and made new products possible. The wide acceptance and low cost drove high demand world-wide and now the limited resources (real or imaginary) are driving the cost of RE magnets higher than anyone expected. Since traction motors use kilograms of magnets, the effect of PM motors in hybrids and electric vehicles would be to deplete the world supply rather quickly. The U.S. government would be wise to develop and subsidize the domestic production of rare earth materials in the national interest of our economy. Reliance on Chinese sources, in view of their own growth, would be short sighted. The alternative is to fall back on other types of magnets which can be made domestically at lower cost and lower performance. The application into interior PM motors would appear to be the best candidate.

Concentrated Windings. Recently we have seen much progress in the area of segmented windings to replace traditional distributed windings. This technology uses individual coils wound on a stator pole piece that is later joined to form a complete stator. An example is the Honda hybrid motor. The advantage is much greater winding fill ratio and the ability to machine wind each pole. To use this technology, designers had to overcome the non-sinusoidal flux distribution, low structural rigidity of the stator, poor air gap alignment, multiple coil connections, and cooling issues. They have used some very cleaver processes to make it a high production rate motor. We will see more motors of this technology in the future.

Bar Windings. Using wire with a rectangular cross-section instead of round wire is an excellent way to increase fill factor. The extension of this is to use heavy gauge bars that are pre-formed and inserted into the slots and welded on each end to form the turns. This has the advantage of machine forming, high fill, and effective cooling when combined with oil spray cooling. Several types of production hybrid motors use this type of construction. This is an excellent alternative to concentrated windings with the advantage of a solid yoke and back iron.

Thermal. All motors share a thermal system as a common denominator. For traction applications, liquid cooling is the preferred method as it provides excellent power dissipation and is well understood in the vehicle. In the future we will see more applications that use direct cooling, such as oil spray or dielectric fluid sprays which directly cool the motor (especially the winding) through conduction or phase change. For in the end, the motors peak power is determined by the maximum temperature of the winding, and if we can keep it below the insulation rated temperature then we can achieve higher peak powers.

High Speed Motors. The last topic is to examine high speed motors. It is known that power for a given size can be increased with speed. Currently the motors we use for traction are rated for 6,000 to 12, 000 rpm. The issue with very high motor speeds is the gearbox. The motor speed eventually has to be reduced to an axle speed of approximately 1200 rpm by the gearbox or transmission. A practical gear ratio limit for a single stage is 5:1, so that a 12,000 rpm motor requires two stages. If we want to design a small 50,000 or 100,000 rpm motor, we would need 3 or 4 stages which presents higher gear losses, complexity, and a larger gearbox. The increase in gearbox size generally offsets the reduction in motor size. In addition, designing a gearbox with a high speed input shaft is a very special design that uses very high speed , expensive bearings. The trade-off has to be done at the system level. The breakthrough would be for a high ratio gearbox with low losses and standard bearings.

Future Technologies. Fundamental research into materials will bring about the biggest changes in electric motors. The dream of many designers is to have room temperature super-conductors to eliminate copper losses, high flux steels that won't saturate when driven hard, high coercivity magnets that are good over a wide temperature range, and low cost bearing and sensors. Any improvement in these areas will bring about change in a positive direction. Of course, motor topologies will enable the application of improved materials. In this authors' opinion, motor technology has much room for improvement and has been overshadowed by semiconductor technology. But the electric traction power-train is only as good as the weakest link and that is moving towards the motor and gearbox. We need more research into better materials to achieve the DOE goals and make hybrids and EV's cost competitive and viable.

Ref;

[1]. Design and Modelling of Axially Laminated Interior Permanent Magnet Motor Drives for Field-Weakening Applications, Wen Liang Soong, PhD Thesis, University of Glasgow, September 1993.

APPENDIX B. REPORT FROM JOHN MILLER

John M. Miller/J-N-J Miller, P.L.C.

Assessment of Motors

Address Rare Earth Materials and Issues

JNJ Miller PLC
9/18/2009 to 10/3/2009

Overview and Summary of Initial Meeting

At this writing we have the announcement made by China MIIT[44] Ministry of Industry and Information Technology of strict limits and ban on certain rare earth minerals of the type used in the manufacture of rare earth permanent magnets (PM) (Neodymium) and catalytic converters (Palladium). This action generated considerable uneasiness in the respective industries, and of particular relevance here, to the future of vehicle traction motors. This announcement followed almost exactly one week after our 13 August 2009 initial meeting. At this meeting discussion started in fact with China holding roughly 70–73% of the world RE magnet market and in fact, China exports approximately 95% of the world's rare earth (RE) materials. It is also becoming clear that China intends to master the electric machines market in much the same fashion as Japan dominated the power semiconductor industry and vehicle traction inverter technology.

General guidelines for completion of this assessment report. United States Department of Energy (DOE) national laboratories have various projects in place to develop advanced materials for use in PMs (Ames Lab), for novel electric machine architectures [the Oak Ridge National Laboratory (ORNL)/National Transportation Research Center (NTRC)], for advanced PEs (ORNL/NTRC) and thermal management materials and systems [National Renewable Energy Laboratory (NREL)]. Discussion covered other magnet materials such as barium and strontium titanate ceramics and Alnico. Alnico in fact was viewed as a potential high flux PM that could find application in future electric machines were it not for its very low coercivity. The low coercive force of Alnico has precluded its use in electric machines, save as the flux source in D'Arsonval meter movements.

On the topic of PMs we can say that ceramic ferrites have low magnetic properties (Br, Hc), but are lowest in cost too, have good temperature stability to >250°C and corrosion resistance. Sintered and hot formed fully dense anisotropic neodymium magnets are superior to samarium-cobalt (Sm-Co) below 180°C. There needs to be solid technical justification such as corrosion resistance and very high temperature (approaching 300°C) to justify the expensive Sm-Co magnets. Alnico magnets were the first type used in electric machines. This is because of their high flux which approximated the fields possible in shunt wound dc motors of the day. However, because of very low coercive force of Alnico magnets these early electric machines used novel pole magnetic structures such as soft iron pole pieces adjacent to the armature or soft iron pole pieces bonded to the Alnico magnet and machined to the arc of the rotor (armature of dc motor). With soft iron pole shoes of this design the Alnico magnet motor could operate at up to six times the normal armature current of Alnico only before demagnetization. Even if the Alnico did become demagnetized it would be an easy matter to simply re-magnetize it using coils designed just for this purpose as was done in these early days.

With the availability of higher performance and low cost ceramic magnets the Alnico magnet was displaced from use in electric machines but remained useful in electronic meters as noted earlier. The industry compares various grades of PMs based on their maximum energy product of remnant flux density B_r and coercive force, H_c at a permeance coefficient that falls on the magnet recoil line. The following table lists magnetic properties of magnets.

[44] http://www.cars21.com/content/articles/2009-08-26-china-to-ban-exports-of-ev-metals.php
http://www.terramagnetica.com/ for a follow-up to this announcement

Table 1 Permanent magnet properties

Type	Remnant Br (T)	Coercive Hc (kA/m)	Energy (MGOe)	Recoil Perm. (#)
Alnnico 5	1.35	58.9	7.5	17
Alnico 6	1.05	62	31	13
Alnico 9	1.06	119.3	9	7
Ceramic 5	0.38	190.8	3.4	1.1
Ceramic 6	0.32	190.8	2.5	1.1
Ceramic 8	0.40	222.6	4.1	1.1
Magnequench I	0.68	390	9.8	1.22
Magnequench II	0.8	517	13	1.15
Magnequench III	1.31	979	42	1.06
NeoMax 27H	1.1	811	28	1.05
NeoMax 35	1.25	882	36	1.05

- Conversion H_c in A/m ÷ 79.6 = Oerstead, Oe.
- Conversion Br in T × 10^4 =Gauss, G.

The better grade of PM for electric machines will have recoil permeability approach that of air (=1.0) which is why the best motor magnets are the RE neodymium types such as NeoMax 27H. The following figure illustrates this situation for RE magnets.

In summary we can say the following about PMs:

- Alnico for highest temperature stability.
- Ceramic for best energy at lowest cost.
- Sm-Co for compactness and good thermal stability.
- Neodymium iron boron for compactness, robustness and low cost (until now that is).

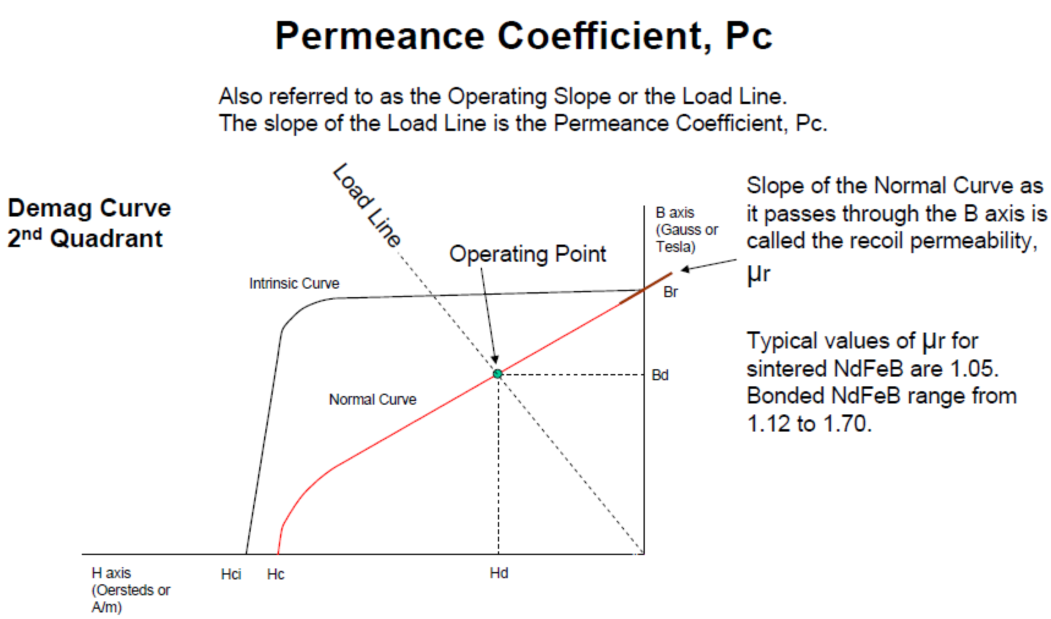


Fig. 1. PM intrinsic and normal characteristics with load line (Arnold Magnetics).

Electrically conductive materials are the next essential parts of any electric machine. Typically copper for armature, stator and wound field windings and Al (or copper) for cast rotor cage windings in induction machines. Since electric machines will operate normally up to 160°C, the resistance of these conductors will have increased by 50% over their room temperature resistance.

In the next sections we take a closer look at the torque production mechanisms of electric machines of any design and from this build a picture of where electric machine technology is today. Then we'll return to the topics of what the issues are and where research and development (R&D) can take us in the quest for lowering cost/kW and getting closer to DOE's 2015 power density targets as represented in the following figure.

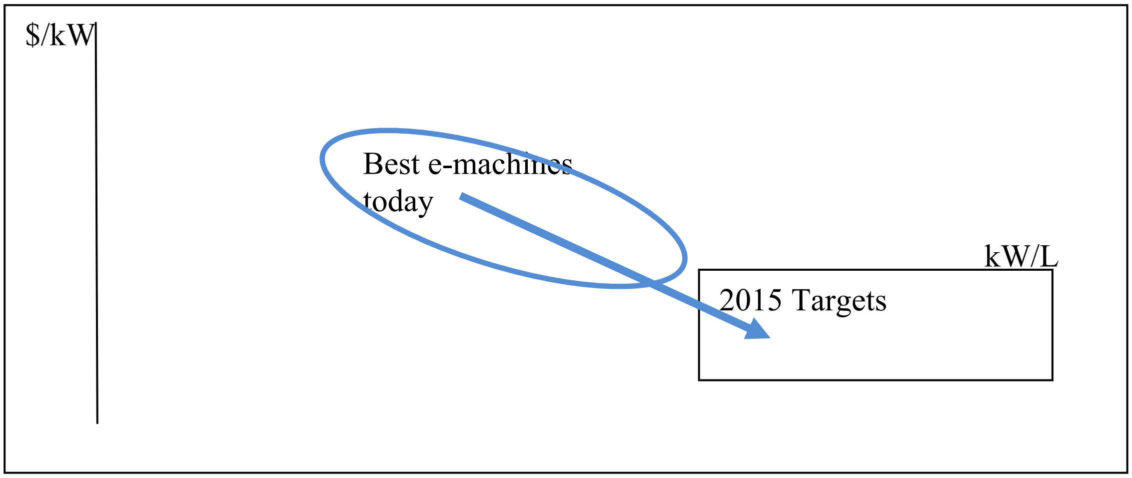


Fig. 2. Technology today and 2015 targets.

Specific Turning Force of Electric Machines

For any electric machine, or electromechanical energy conversion device, one can say the following are inherent features:

- The electric machine develops torque through the electromagnetic interaction of electric currents and magnetic flux at the air gap.
- The resulting Lorentz force is normal to the plane of current and flux and acts at a lever arm producing a mechanical couple.
- A consequence of rotating mass at some radius from its rotational center is the presence of polar inertia. Inertia requires torque input to accelerate or decelerate and therefore constitutes a response limitation on the machine.

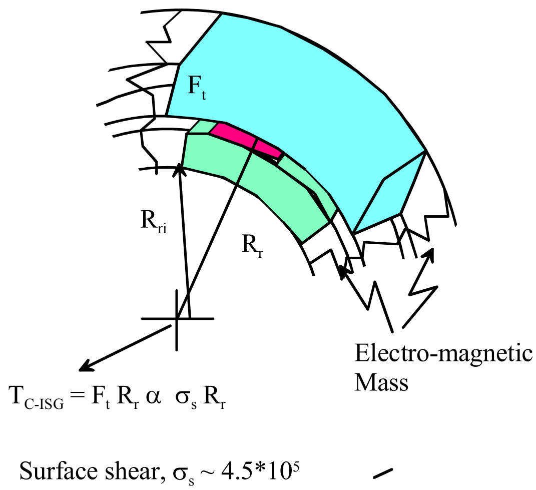


Fig. 3. Illustration of electric machine turning force.

At the level of magnetic materials and currents being conducted in wires the tangential force, Ft, can be seen to result from the vector cross product of current with magnetic flux as shown in Fig. 4. In this illustration stator currents flow in the direction of "I" which is also the physical length axis of the machine, L. Flux is normal to the currents with the result that force production is normal to both the direction of current and of flux (i.e., the current-flux plane).

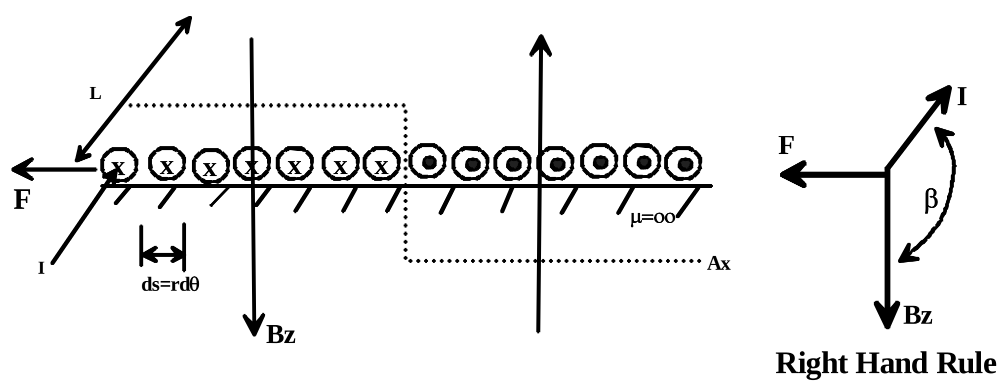


Fig. 4. Depiction of force production in the electric machine.

Regardless of the specific type of electric machine, there must be magnetic flux, B, a current or currents, and special displacement of the two in order to produce an electromagnetic force (emf) (1).

$$emf = \oint (vxB) \bullet dl$$

Take as an example a drum wound electric machine and let:

Z=2I = At/m, Amp-turns of conductor in armature or stator,
Ax = electric loading of the conductors (A-turn/m), and
Sr = surface area of the rotor, m^2
F=net turning force, N, on the rotor surface at radius, r.

$$A_x = \frac{Z}{2\pi r}$$

$$S_r = 2\pi rL$$

$$\Upsilon \qquad \sigma_s = A_x B_z \sin(\beta) = \frac{B_z Z}{2\pi r}\sin(\beta) \qquad (2)$$

$$\Upsilon \quad F = \sigma_s S_r = \frac{B_z Z}{2\pi r}\sin(\beta)\, 2\pi r L$$

$$F = B_z Z L \sin(\beta)$$

Where angle β = relative displacement of machine surface current Ax and normal flux Bz resulting from a vector cross product. The result is a force that is normal to both Ax and Bz, at least to the degree that β=90°. In the brushed dc machine (BDCM), the commutator acts to hold the armature Amp-turns at 90° to the PM field flux, or in wound field machines to the resultant field flux. In all electric machines there must be special displacement between flux and current. In the dc commutator machine as just mentioned this is implemented mechanically. In a PM brushless dc machine, BDCM, a set of flux sensors determine where the magnets are and also feedback this information to the current regulator PEs that injects currents into stator windings at the appropriate special position. Because rotation is the goal in any electric machine a secondary requirement is to control the injected currents such that the currents have the proper special and temporal alignment in the stator.

Therefore we can summarize the essential turning force generation normalized to machine mass, M, in any electric machine as a ratio of torque production, m, to mass:

$$\frac{F}{M} = \frac{m}{r * M} \qquad (3)$$

Where **F** (N), the net turning force developed at the air gap surface as a result of current and flux interaction relative to mass is the most fundamental aspect of an electric machine. In terms of torque production, m, the effect of rotor radius must be taken into account. A measure of a motor's ability to develop a shearing force at the air gap surface with an economic usage of material, such as steel, copper or Al and PM material is the ratio of the net air gap force F to the total mass M (kg) of the machine[45].

Since mass and force are fundamental quantities this ratio is a true metric of electric machine performance. <u>Nominal values of the ratio are: 90<F/M<180 (N/kg).</u>

Consider an automotive integrated starter alternator of induction and variable SR designs. Both machines are designed to fit the same transmission package space of approximately 50mm length and 300mm diameter.

Table 2: Electric machine ultimate force/mass figure of merit.

---

[45] Note: A measure of force per unit mass, in units of N/kg, is <u>not</u> a function of the air gap radius. A measure of torque per unit mass, in units of Nm/kg, however, <u>is</u> a function of the gap radius, and would artificially reward structures with larger diameters, and could mask the performance measure of machines with poor ability to produce motoring shear at the gap.

Machine type	Peak Force (N)	Electromagnetic Mass (kg)	F/M
Asynchronous/induction integrated starter-generator (ISG)	2,438	20.75	117.5
Variable/SR ISG	1,656	16.4	101
UDLP Series 85	12,592	240	52
GDLS RST-V	*	*	88

The last two rows in Table 2 are for military ground vehicle traction motors designed to have extremely high torque production and also to be very robust[46]. Note: compared to very high torque density automotive designs that these more robust machine designs will have roughly half the turning force. This is mentioned because regardless of what metric is used to make comparisons there will be some aspect of the design that forces mass to be higher or force lower than anticipated, mainly for reasons of peak to continuous duty. In fact, and for thermal reasons, the peak normalized turning force listed in Table 2 for the ISG's will only be 30% the value listed under continuous duty.

Summary:

The following conclusions can be drawn from the analysis in this section.

- Electric motors produce a shearing force at the air gap on the rotor surface.
- A measure of a motor's ability to produce shearing force with economic usage of materials is the ratio of the net air gap force F to the motor mass M.
- A (practical) maximum attainable value of F/M for a motor is approximately 90–180 N/kg.
- Some existing traction motors approach this maximum attainable value of F/M.

[46] Data excerpted from: Dr. Pat McCleer , McCleer Power, Inc. Jackson MI. Hybrid Electric & Aux Power Systems Workshop, TACOM, Warren, MI 1/14/04.

Comparative Analysis of Machine Types

Before proceeding into some machine type comparisons it may be insightful to contrast the automotive ISG and military ground vehicle traction motor ultimate turning force to that of an industrial grade induction motor. In this case, a totally enclosed fan cooled, TEFC, induction machine having the following ratings is evaluated for F/M:

Table 3 Industrial TEFC induction motor: 4P, 3f, 230V, 50Hz, delta connected

Rated voltage, U_r	230 Vrms	Rated speed, n_r=120f/P	1500rpm
Rated current, I_r	37.5 A	Angular frequency, $\omega_m=2\pi n_r$	157.1
Stack length,h	210mm	Rated power, kW	11 kW
Rotor outer dia., D_{ro}	131.27mm	Stator slot depth, d_{s1}	41.18mm
Air gap, g	0.6mm	Stator back iron, d_{os}	43.76mm

For this industrial motor the electromagnetic mass calculates out to approximately M = 60.9kg, assuming cast Al cage rotor. Taking peak torque as 250% of rated conditions yields a peak value of m = 175Nm. From this the turning force computes to F = 2,667N. For these values the peak normalized turning force is:

$$\frac{F_{pk}}{M} = \frac{2667}{60.9} = 43.8 \tag{4}$$

And at rated condition for continuous operation the value in (4) reduces to F/M = 17.5 (N/kg). This example puts use of this metric into perspective by highlighting the fact that although peak ratings can be quite impressive, it is the continuous thermal limited rating that matters.

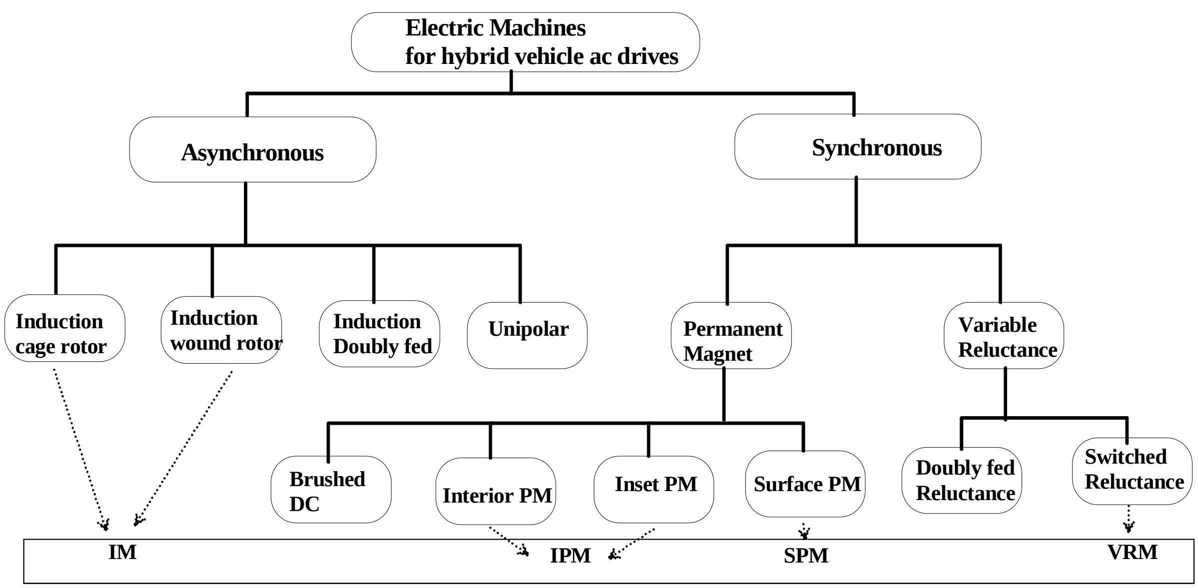


Fig. 5. Taxonomy of electric machines.

The machine structures illustrative of the major machine types listed in figure 5 are shown here in Fig. 6. In these illustrations the electromagnetic designs include PM types across the top row and right hand second row. The induction machine has slotted stator and rotor as do the two classes of reluctance machines, the sync-rel and the variable reluctance.

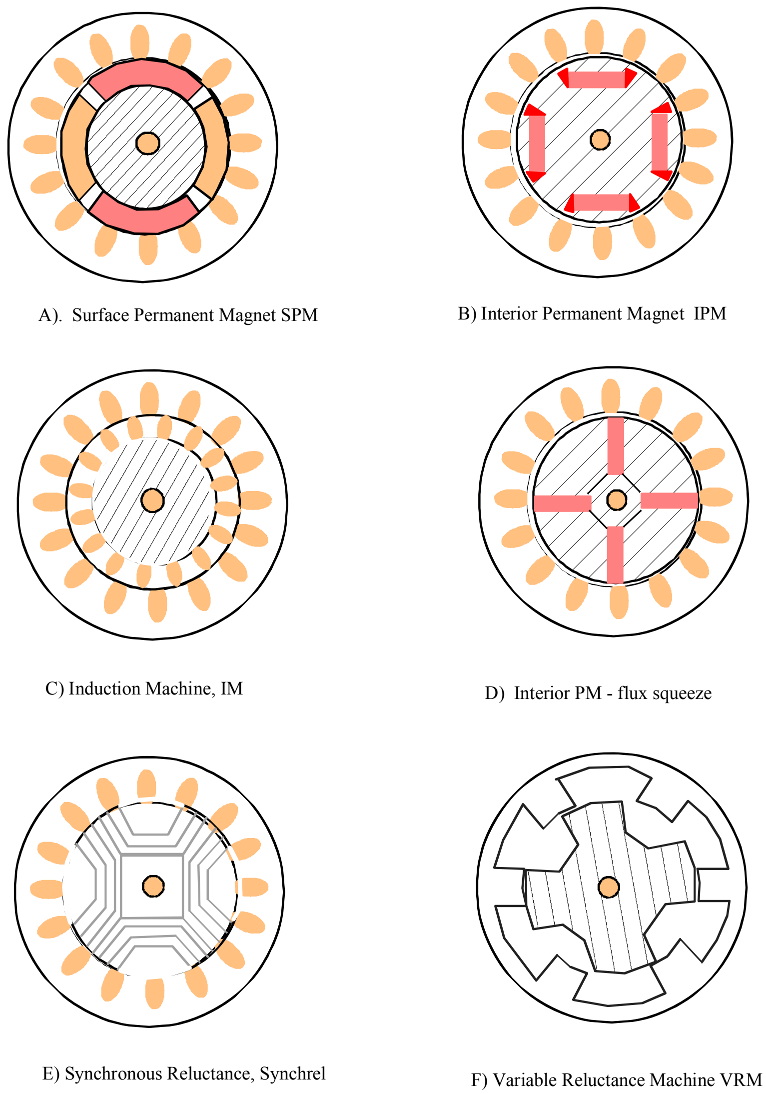


Fig. 6. Electric machine magnetic structures.

In the next two subsections we take a closer look at some of these machine types, specifically PM and reluctance. For the machine types shown in Fig. 6 the following key points summarize their performance.

- SPM: surface magnet PM. Highest specific power, but most restricted constant power speed
- IPM: interior PM. High specific power and highest constant power speed range, CPSR, but at the expense of somewhat larger size.
- IM: Induction (asynchronous) machine. Very robust, good specific power, medium CPSR.
- VRM: Variable reluctance machine. Comparable to IM, but with lower rotor inertia.

It is worthwhile furthermore to insert some commentary on the ubiquitous automotive alternator, the Lundell or claw-pole wound field synchronous generator. Facts:

- Specific power of 0.3kW/kg.
- Survival speed = 20,000 rpm.

- Relatively high frequency during generation due to P=12 pole, m=3 phase wave winding and spiral punched stator laminations.

$$P_e = U_d I_d = \frac{m L_m}{2 L_r} \lambda_{dr} \lambda_{qs} \tag{5}$$

Equation (5) provides insights into this wound field synchronous machine that can be contrasted to the same machine with PMs:

- The power responds at the rotor time constant, Lr/Rr, and is therefore slow at approximately 280ms nominal. This is why load dump is so critical. A rapid loss of load results in over voltage lasting 4 rotor time constants at a significant energy level.
- A PM version of Lundell alternator has a rotor time constant of 360ms, so even slower than the wound field version.
- Furthermore, the PM Lundell has problems with inverter field weakening control at high speed because it is very difficult to maintain constant power at high efficiency and high power factor.
- Lastly, with PM there is the ever present concern with uncontrolled generation under an inverter fault.

Investigators have prototyped wound rotor synchronous machine ISG designed for 42V electrical systems. Parameters of this machine are:

- Package ϕ257 × L53mm and 214mm stator bore, 3ϕ, 12 pole.
- Efficiency >80%, stable power factor: PF>0.94 over full operating range.
- Capable of operation to 250°C.
- Generates P=8kW at 42Vdc to 6,000 rpm.
- Torque of 170Nm @ 400Arms.

As another example a variable reluctance, VR, machine was compared to a PM machine.

- PM machine is a fractional slot winding (q=1/2) 3-phase, 6-pole, 9-slot.
- VR machine is a conventional 4-phase, 6/4 design.
- Both are designed to automotive 12V system requirements.

In order to match torque-speed plane performance the VR machine requires a 22% larger stator stack than the PM machine otherwise high speed performance is compromised. Moreover, the dc link current in the VR machine is 15% higher than the PM machine. This however is offset at high temperature because of the reduction in remanence flux in NdFeB of 0.1%/°C. For nearly identical dynamic response time the VR machine speed is lower.

Radial designs versus axial designs.

Primary objections to radial or axial machine designs in automotive tend to center on their bearing systems. Radial designs require very tight tolerance to maintain close tolerance physical air gaps, especially in reluctance and induction machines. Natural resonances must be avoided as must cantilevered bearing designs. Axial machines are more sensitive to axial movement of their axle, for example a VR ISG directly mounted to an ICE must have air gap tolerance, or a spline joint, to tolerate up to 50μm of axial movement of the engine crankshaft. Lets consider the design equations for both types of electric machine:

V_t = rotor tangential velocity, m/s
R_{r0} = rotor outer radius, m
R_{ri} = rotor inner radius, m (for axial design)
L = machine stack, m
K = effective surface current in stator/armature, A/m
B = machine flux density, Wb/m^2 or T

For both designs:
0.2 < B < 0.8T in the air gap
20kA/m < K < 30kA/m of electric loading in the stator/armature (~2A/mm^2 in conductors)
V_t < 200m/s for virtually all electric machine rotor designs and materials. This means rotor outside diameters to survive 20,000rpm overspeed D_{ro}<0.191m.

$$P_{radial} = \frac{\pi}{4} K B D_{ro}^2 L \omega \tag{6}$$

Equation (6) is the familiar relationship that electric machine power increases linearly with speed for given electric loading and magnetic loading and with the stated bore volume, D^2L.

$$P_{axial} = \pi K B R_{ro}^2 \left(1 - \left(\frac{R_{ri}}{R_{ro}}\right)^2\right) \omega \tag{7}$$

Power production in the axial design is very dependent on the rotor geometry. Other than that the same linear relation with speed is observed for the same electric and magnetic loading of the copper/Al and steel respectively. In this regard radial or axial designs are more a matter of packaging choice.

There may be some advantage in the axial design to extract stator heat because the conductor end turns are outside the inner and outer radius. This is more likely mitigated by the fact that mechanical requirements, mounting for example, favor a radial design.

Designed for High Speed Performance: e-Turbo

Potentially the most revealing electric machine comparison appears in this comparison of electric machine types that are most suitable to a very high speed electrically driven automotive turbocharger. The design requirement is 0 → 120,000rpm but spin up normally starts at the idle condition of 20,000 rpm and target ramp times are <200ms. Also, in this application the rotor will experience at least one, if not two, critical speeds over its full speed range. The lower one generally designed to be below the idle condition.

At this writing Honeywell announced the availability of a very low inertia conventional turbocharger having a speed capability to 140,000rpm. Whether this meets requirements for spin-up in <200ms is not certain.

In the table to be presented for three different PM designs (radial-slotted, radial-slotless, axial), two induction machine designs (copper-cage and solid iron rotors) and one variable reluctance type the following design features are held constant:

Table 4 Electric machine comparisons for high speed application, same design requirements

Power rating	6.28kW	Operating temperature	105C
Rated speed	60,000rpm	Idle speed	20,000rpm
Rotor gap/slot fill	0.5mm/60%	PM designs	NdFeB (in Titanium for axial design)
Pole count/base freq	2 to 6-pole/6kHz at max speed	Inverter kVA ratings	Stated values for rated speed and voltage

Table 5 Comparison matrix of the machine types, inverter rating and issues

Type	Pole Number	Stator design	Rotor design	Stator bore (mm)	Stack length (mm)	Inverter kVA	Issues
PM	2	Slotted	NdFeB glass	30.4	33.3	8.9/17.8	Overvoltage at high speed& high kVA
PM	2	Slotted	SM-Co stainless	28.6	44.5	8.8/17.6	High rotor surface loss
PM	2	Slotless	NdFeB glass	45	48	6.9/13.8	PM's all have high kVA needs at high speeds
PM	2	Slotless	SM-Co stainless	34.1	77.4	7.8/15.6	
PM	6	Axial	SM-Co titanium	60	-	6.8/13.6	Same high kVA requirement due to PM
IM	2	Slotted	Copper cage	28	42	7.5	High temperature excursions
IM	2	Slotted	Copper cage	28	76	8.0	
IM	2	Slotted	Solid iron	28	42	9.7	Reasonable dimensions and kVA
VR	6/4	Salient	Laminated	28	40.5	20.3	Very excessive kVA needs & high peak currents

As can be seen in Table 5 all the PM machines require a double inverter rating to meet voltage requirements at top speed. Also, magnet retention is an issue with glass or other bonding needed and in one magnets are embedded into titanium.

Therefore, the induction machine with solid iron rotor was selected for this application. This provides very compact size, on the order of the PM machines and with reasonable pole count. The design used 2 pole but anywhere from 6–8 poles can be used provided the inverter can deliver the high base frequencies under six step square wave, SSSW drive.

This is a very convincing case favoring induction machines over both PM or VR types. The IPM machine is not even considered due to the very high speeds. Also, constant power speed range is limited to that of the IM to approx 3:1.

Technology Gaps and Recommendations

There are three major conclusions to be drawn from this exercise and review of electric machines:

- The comparison of electric machines should be based on performance. For example, the same dynamics over torque-speed requirements for same response speed.
- The most applicable comparison metric is rotor turning force, or ultimate force that is normalized to machine electromagnetic mass. Using F/M (N/kg) eliminates rotor radius from unfairly biasing the comparison when a torque metric is used. This metric also goes directly to the selection criteria seen in Table 5 that resulted in selection of a solid iron rotor induction machine.
- Induction and reluctance machines are about on par in terms of performance, dynamics and ultimate force generation.

Recommendations for future R&D

This report has shown that regardless of application (alternator, ISG, pump/fan drive, or e-Turbo) that induction machines compete very favorably with reluctance and PM types. What is also evident from the early discussion and a topic of discussion at the kick-off meeting is that Alnico magnets should be put into the R&D mix. There has only been sporadic treatment of Alnico magnet use over the years with some fairly recent work using soft iron pole shoes and mounting structures that limit the tendency for demagnetization. However, these geometries have not been adequately explored nor have more novel machine geometries that would accommodate this stable, high temperature and inexpensive magnet material been explored.

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APPENDIX C. REPORT FROM JIM HENDERSHOT

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July 25, 2009

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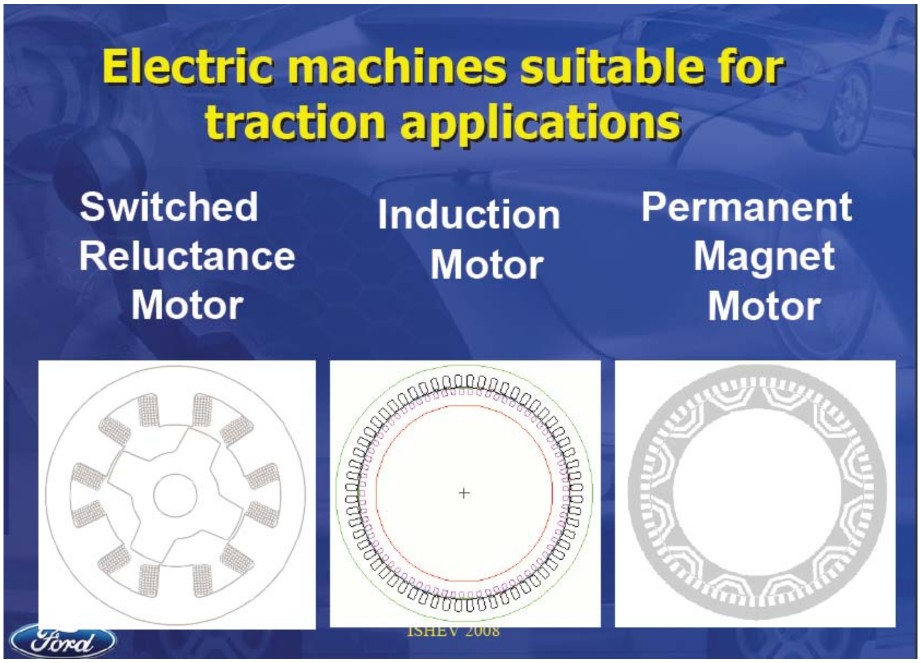
Subject: ELECTRIC TRACTION DRIVE MOTORS FOR AUTOMOBILES
IPM & SPM AC BRUSHLESS SYNCHRONOUS, AC INDUCTION &
SWITCHED RELUCTANCE

Ref: ORNL P.O. # 4000081347

INTRODUCTION:

The three principle motor types in this study will be defined as follows:
(AC) a-synchronous machine known as *induction motor*
(IPM) internal PM brushless ac motor
(SR) switched reluctance motor



The three basic types of motors discussed in this study have been compared many times in the past from a number of sources over the past 20 years in terms of their relative cost to manufacture, cost to power and control, relative efficiency and power density. Over those same 20 years there have been some significant changes in the some of the materials available for these motors and in addition many new motor design variations have been developed. This study will attempt to reflect the impact of two significant material changes on the performance and cost of two of the three machine types. (The Neodymium magnets for the IPM machine and die cast copper rotors for the ac machine) The SR motor type has not benefited by any recent material changes.

In addition to the two material changes there have been many new design configurations that have come forth over the past 20 years. The PM brushless motor type has seen more variations than any other. Even the IPM itself is an example of a new design and was not included in most previous studies of these three motors types in the past. The ac induction motors are currently configured the same as they have been for the past 100 years. However rather than grid powered they are now powered from very smart electronic drives using Flux vector control. This has greatly effected their capabilities and performance. The SRM has experienced a couple of new designs (like 2, 3, 4 or 5 phase configurations along with some new control strategies).

These new developments certainly have affected the power density comparisons, efficiency comparisons and perhaps their costs as well.

MOTOR COMPARISONS STATED IN SOW

The statement of work for this project asks for a comparison of efficiency, $/kW and kW/kg for the three motor types. These comparisons require some definition understanding from the outset of this report.

First of all electric motors convert electrical power (current times voltage) to a torque or a tangential moment of force in the air gap between the rotor and stator. The speed (rotor rpm) at which this torque is produced in the air gap determines the mechanical power at the shaft. For the SR and the IPM the voltage applied to the motor determines that rotor rpm. (The SR and IPM machines are commonly thought to be *synchronous* machines but in fact they are *self-synchronous* machines because their respective commutation frequencies are a result of the rpm not the control factor of rpm like a true synchronous machine). For the ac Induction machine which is an A-synchronous machine the rotor rpm is controlled by the frequency and slip. In all cases the current determines the torque converted in the air gap. Therefore the use of KW in these machine comparisons is very misleading and does not provide a true comparison of the different motor types unless the speed is the same for all motor compared. I would suggest that these should be compared as $/Nm ($/unit of torque), Nm/kg Unit of torque/kg and Nm/L (Unit of torque/volume) rather than using output power that would only be comparable if all machine types are compared at the same rpm. For example a comparison of the kw/kg of a 50 kw motor inside the wheel of a car running at about 600 rpm without gearing would have a significantly lower kw/kg power density and a much higher $/kg than the same motor type running at 12,000 rpm with significant gearing to the wheels. The differences in the results would be about 20 to 1 if the cost and machine density is proportional to the speed and torque differences. One could attempt to eliminate this disparity by keeping the rotor speed the same for all three machine types for comparison purses using output power. This does not seem practical because the three different machine types adapt differently to various speeds and configurations. For example many studies have confirmed that an axial flux machine with a lot of poles produces the highest output torque per unit volume or weight of any motor configuration presently known by a significant margin. Since these type of machines are arguably best suited for packaging as wheel motors when used for traction without gearing or minimal gearing their power per unit volume is noy so impressive because the produce torque at such low rpms. Using torque criteria for machine comparison yields a much more useful comparison of motor types and configurations.

The final and absolute performance limit of any electric machine type that converts electro-magnetic forces into mechanical forces in the air gap producing shaft torque depends upon the saturation level of the magnetic materials and the max heat allowed as allowed by the cooling method. (*Shaft torque* = rotor radius times the total tangential air gap force and *Shaft power* = shaft and shaft power = shaft rpm X shaft torque)

There are some basic facts that influence machine power density that can be summarized for all three machines in the chart provided below.

1-Power density KW/L & KW/kg are increased by increasing speed because the machines becomes smaller.

2-Power density KW/L & KW/kg are increased by increasing the torque density.

3-Power density KW/L & KW/kg are increased by allowing higher operating temperatures and better cooling such as forced air or glyco-water.

4-Power density KW/L & KW/kg are increased by the use of PMs in one of the two magnetic circuits, (rotor or stator).

5-Power density KW/L & KW/kg are increased by using the lowest resistance conductors (such as copper rotor for ac motors) and lower core loss magnetic core materials.

A-The torque density of PM brushless (including IPM) machines in increased by increasing the number of poles. The torque density is somewhat improved for ac Induction machines and slightly improved for SRMs when the pole number is increased.

B-The torque density for all machines is improved by the use of improved cooling methods.

C-The torque density for IPM and all types of PM motors and generators is improved by the use of higher flux PMs.

D-Using small magnetic air gaps between the rotor and stator somewhat improves the torque density of both the ac and the SR motors.

E-The use of copper rotors rather than aluminum rotors improves the torque density of ac motors somewhat.

F-The optimization of copper, electrical steel and magnets can improve the torque density up to the max possible. Certain PM motor configurations are more affected by this than others such axial flux machines.

COMPARISON OF TWO TOYOTA TRACTION MOTORS

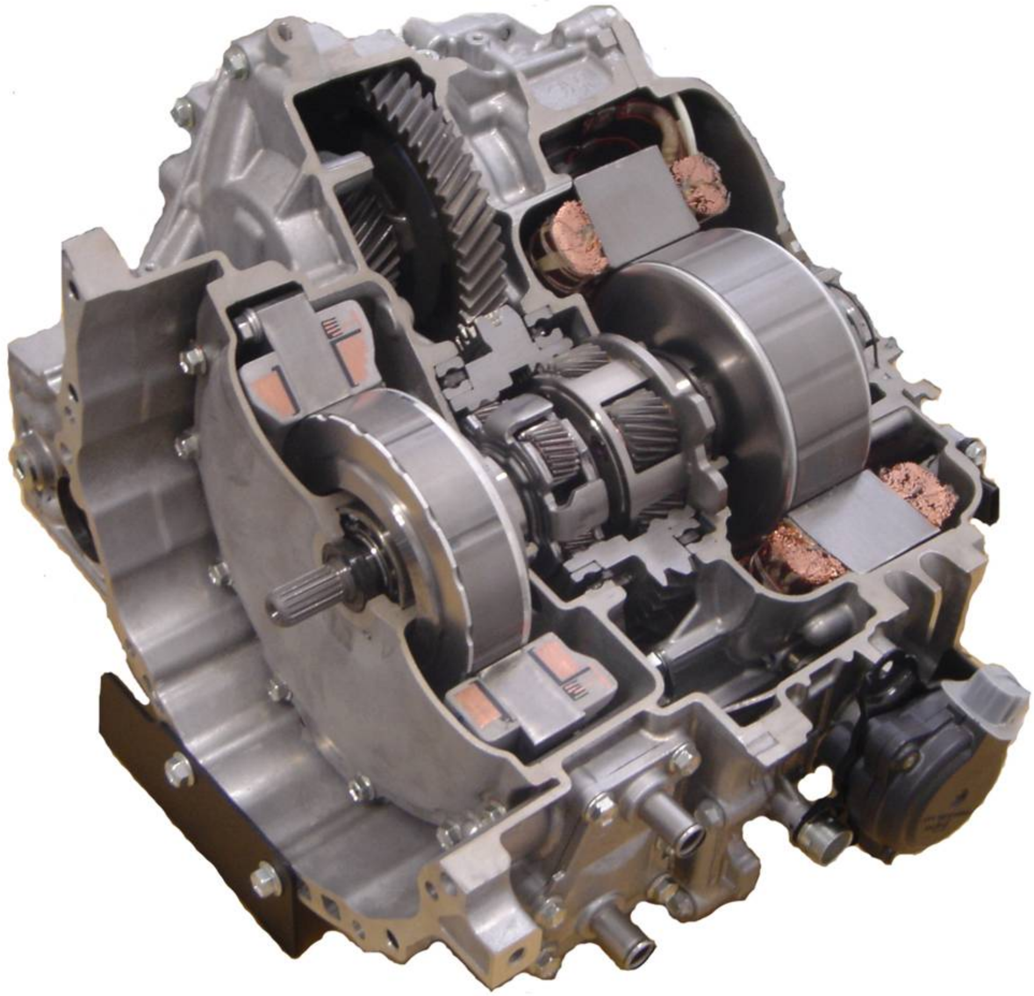
Two of the Toyota hybrid traction motors that were studied by ORNL and reported on included the 2004 Prius 50KW 8 pole IPM and the 2008 Lexus 110KW 8 pole IPM. The detailed performance data including the rotor & stator mass and size (including the shaft but excluding the cooling system and frame) can be reviewed with respect to their respective output power vs. volume & mass and output torque vs volume & mass. The 50 KW rating of the Prius motor was at 6000 rpm and peak torque was 400 NM. The 110 KW rating of the Lexus motor was at 10,230 rpm and the peak torque was 300 NM. The data in the ORNL reports used the volume of the housed machines but in this comparison only the volume and mass of the active magnetic components was used for comparison. The torque per unit volume and mass is a more realistic method of comparing electric machines and removes the unrelated custom mechanical packaging variations from one motor installation to another. One of the most important parameters used to compare one motor to another is the phase winding current density. Unfortunately there is not enough information from the ORNL reports for either of these motors to make this comparison. It seems that the RMS phase current was never measured during their tests. The Motor constants Kt & Ke seem not to have been measured as well as the air gap stress (torque/rotor rad/swept air area in PSI). These are very important parameters to use to equate one PM motor design (IPM or SPM) to another for the study of both torque and power density of electrical machines. The PSI gap stress is also an important parameter to compare motors to determine how hard a particular motor is working. This parameter was not included in the can be calculated from the data in the ORNL reports but the data to calculate the gap stress in PSI is reported and the results are included below.

The following chart lists the comparison between the Prius and the Lexus IPM machines.

Paramater	Units	2004 Prius	2008 Lexus
Peak Power	kw	50	110
Peak Power	hp	67	148
Peak Torque	Nm	400	300
Peak Torque	lb-ft	296	222
Max Speed	rpm	6000	10,230
Power/Mass	kw/kg	1.39	3.58
Power/Mass	hp/lb	0.84	2.18
Torque/Mass	Nm/kg	11.08	9.77
Torque/Mass	lb-ft/lb	3.73	3.29
Power/Volume	kw/L	10.52	21.7
Power/Volume	hp/cu-in	0.19	0.4
Torque/Volume	Nm/L	84.18	59.1
Torque/Volume	lb-ft/lb	0.85	0.6
Active Mass	kg	36	30.7
Active Mass	lb	79.2	67.3
Peak Gap Stress	psi	17	12
Magnet Mass	kg	1.232	1.349

It should be clear from a review of this data that if these two motors are compared on the basis of their power density alone with respect to the active magnetic components that convert electro-magnetic energy into mechanical energy the Lexus machine would be considered the superior machine by a small margin. However the Lexus machines requires about 10% more magnets than the Prius and it only produces 75% of the torque of the Prius machine. The total active mass of the Prius machine is 17% greater than the active mass of the Lexus machine. The difference between these two machine can be attributed to the speed difference of 6000 rpm for the Prius motor and 10,300 rpm for the Lexus motor. If the peak output torque per unit volume is very close to being the same for both machines even though the power/unit volume is quite different. The main advantage with designing the motor for higher rpms and using gearing ratios to provide the torque required at the vehicle wheels is the motor gets smaller or if about the same size it has a higher rated to peak torque ratio and it will not run as hot. For example in order for the Prius motor to produce the 400 NM peak torque the gap stress comes out to 17 psi which is very high and can only be maintained for a short time as the ORNL data shows. The Lexus motor requires a gap stress of only 12 psi at its peak torque.

The illustration below is a picture provided to me by a Toyota design Engineer of their new gear box assembly including the generator and traction motor used in their 2010 PRUIS.



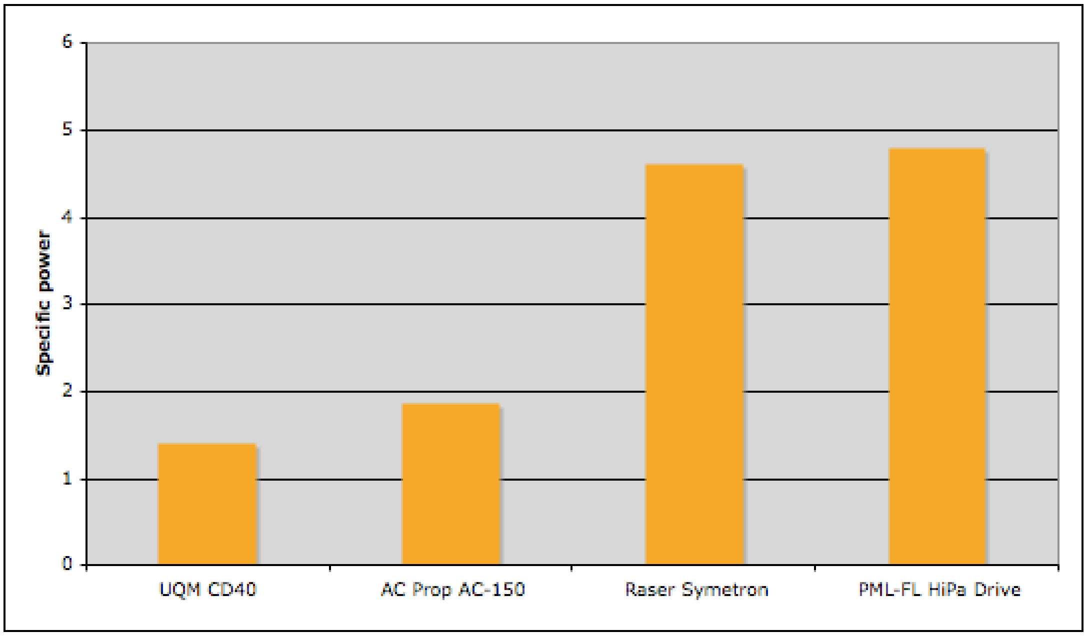
REVIEW OF SOME OTHER PM BRUSHLESS TRACTION MOTORS

Various companies around the world report the results of their developments for traction motors for electric cars and hybrid vehicles. Some of these reviews report their respective power densities and some report their respective torque densities. In order to get a snapshot of the power and torque densities that represent the current machine developments a few of these are discussed in this section.

In October 2007 from FutureDrive at WorldPress the following chart was published which lists the power density reported by 4 of the 5 motor companies reported on. The PML-FL is an *axial flux* motor.

	Type	Power (kW)	Mass (kg)*	Power/mass	Peak Efficiency	Load Efficiency
UQM CD40	Brushless DC	150	106.9	1.4	n/g	n/g
AC Prop AC-150	AC induction	150	80	1.875	91%	86%
Raser Symetron	AC induction	373	80.6	4.62	92%	85%
PML-FL HiPa Drive	Brushless DC	120	25	4.8	n/g	n/g
Tesla	AC induction	185	32kg+controller	n/g	n/g	80%

*Includes mass of controller
n/g= not given



The SAE published a report (960256) in 1996 comparing ac Induction, PM brushless , IPM and SRMs. Some manufactured machines were listed. The results comparison is listed below from that report. As Toyota has shown, the developments and improvements of IPM machines has been significant during the past 13 years but little improvements have been made for the SR and ac induction technologies. It is worth noting that the SRM reported in that SAE report produced the highest specific torque in Nm/kg and that was the 40 kw SR motor purchased by ORNL from Magna Physics. The Toyota IPM designs are of the same order of magnitude while the ac induction machine is much lower. The ac induction motor produced the highest power density because it was the highest speed (more than twice the speed of the SR) but its specific torque of the ac induction was about one third of the SR.

Table 6: Original and Scaled Drive Specifications

		Induction Motor Drive	DC Brushless PMM Drive	IPM Induction Motor Drive	S.R. Drive
Original Specifications					
Max. Torque	N-m	195	145	117.4	680
Max. Power	kW	59.5	30.6	54.6	40.1
Speed Range	RPM	0-13,000	0-8,000	0-11,000	0-5,600
Drive Weight	kg*	82.7	58.7	82.1	83.6
Powertrain Wt.	kg**	125.1	88.7	141.3	103.6
Transmission/Speed Reducer Data					
Type		Reducer	Reducer	2-Speed Auto.	Reducer
Reduction Ratio		12.18	6.9	21.19 & 10.5	3.08
Scaling Factors					
Speed		1.0	1.0	1.0	1.0
Torque		0.76	1.47	0.82	1.12
Scaled Specifications					
Max. Torque	N-m	148.2	213.2	96.3	761.6
Max. Power	kW	45.22	45.0	44.8	44.9
Wheel Torque	N-m	1805.1	1471.1	2040.6	2345.7
Speed Range	RPM	0-13,000	0-8,000	0-11,000	0-5,600
Drive Weight	kg	62.9	86.3	67.3	93.6
Powertrain Wt.	kg	105.3	116.3	126.5	113.6
Sp. Torque	Nm/kg	2.36	2.47	1.43	8.14

* Motor and power electronics weight
** Motor, power electronics and transmission/speed reducer weight

The Michelin Active Wheel System is scheduled to be available on at least one car for in wheel traction. The motor has a mass of 42 kg and a rated output power of 30kw and a peak power of 120 kw. To compare this power density of the Michelin motor with the other motors described herein including the two Toyota we would use the published peak power for 2.857 kw/kg. A photo of the wheel assembly is shown below.

The propulsion motors used for ships are also interested in high torque density. For example a company called DRS Electric Power Technologies in Hudson MA (who is probably the former KAMAN Corp.) has been developing high torque density machines for many years for the Navy and for commercial ships. These motors used for propulsion are usually much larger than those used for vehicle traction but their methods and results of machine type comparisons are useful for our purposes of comparison. Mr. Peter Mongeau of this company published an article entitled
High Torque Density Propulsion Motors in which he explained the understanding of the constituent mass elements that comprise an electric machine and their scaling relationships. He summarizes the current torque density of PM liquid cooled machines at 8 lb-ft/lb being double what it was a few years ago.

Mr. Mongeau breaks down the *Constituent Elements of Torque Density* into three groups.

1-Electro-magnetic mass, which includes the cores, windings and magnets.
2-Structural mass, which consists of the frame, end flanges and shafting.
3-Service mass. This category includes the bearings, seals, cooling system cables, connectors and plumbing.

The magnetic scaling parameters are summarized in Table 1 from his publication.

Constant per unit pole parameters	*Conserved quantities*	*Elements that can/will vary with scale size*
• Pole pitch • Slots per pole • Slot depth • Slot fraction • Backiron thickness • Current density • Gap speed • Gap field	• Current loading • Magnetic shear stress • Coil/tooth stress • Losses per unit circumference • Electrical frequency • Flux density in steel • Force per unit magnetic mass	• Shaft speed • No. of poles • Gap radius • Gap length

Table 1: Magnetic Scaling Parameters

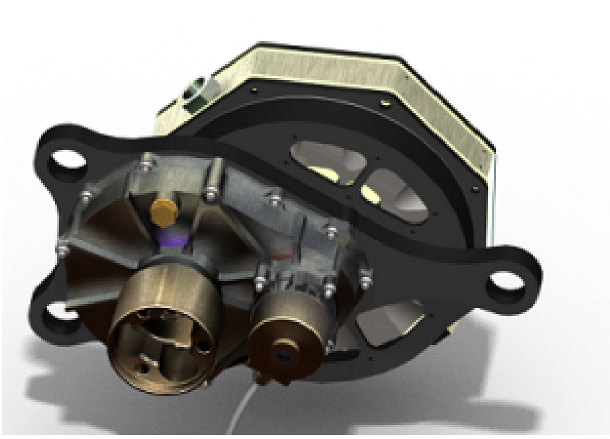
A summary of the torque density trends are shown on Table 2 of his report.

Generation	*Technology*	*Torque density (ft-lbs/lb)*
1st	Air-cooled induction, Field-excited synchronous	3.5
2nd	Liquid-cooled permanent magnet	8
3rd	advanced PM, HTS	16
4th	Advanced materials	>20

Table 2: Motor Torque Density Trends

Dr Malcolm McCulloch of the University of Oxford in the UK has developed a very high peak torque per unit mass configuration. It is a 130 Nm motor with a peak power of 50 kw like the Prius machine and has a torque density of 10Nm/kg which is right in between of the Prius and the Lexus. He claims he is developing a similar motor for an electric car with a 500 Nm peak torque and a mass of 25 kg for a torque density of 20Nm/kg. A brief description is included below.

The Oxford Invention



A new topology of motor featuring a segmented armature and the novel use of materials has been designed and developed by the Electronic Power Group within the Engineering Department at the University of Oxford. The key features of this design applicable to motor and generator applications are:

- Greatly reduced weight – the use of iron and copper is reduced
- High efficiency (up to 97%) through the intelligent use of new materials
- Excellent manufacturing possibilities
- The design allows for the use of novel combinations of materials even for large machines
- Reduced torque ripple due to multi phase winding
- Improved cooling characteristics due to segmented design
- Scalable for large generators such as those used in renewable energy (e.g. low speed wind and tidal) applications.

There are a number of axial flux machines that have been carefully summarized by the University of Wisconsin a few years ago as outlined in their research report # 2004-10. The report identifies several different configurations of axial flux motors but they all have certain advantages over radial flux motors. Axial flux motors seem to use their occupying space and materials more efficiently than radial flux motors. This material usage advantage of the axial flux motor yields significantly higher torque-per-unit-volume and torque-per-unit-weight numbers. They also seem to package very well for in wheel motors integrated with the brakes and suspension systems. A separate motor can be installed in each wheel. Two front wheel motors are very effective for battery charging during braking. Radial flux SR motors or ac induction motors appear not to package as well as axial flux machines for use as in wheel motors. Currently as far as can be determined no practical axial flux SR or Induction machines have surfaced for use as in wheel traction motors. This might be a very good for future development to take advantage of the axial flux torque density advantage over radial flux machines and thereby avoid the use of Neo magnets.

General Motors has funded a significant amount of engineering study and development of axial flux PM brushless motors for in wheel traction drives due to their superior torque density. The added un-sprung mass of the in wheel motors complicates the vehicle suspension design. One disadvantage to the axial flux SPM machine is a relatively high magnet mass required as compared to the IPM motors, which exhibits a reluctance torque component due the inductance difference between the direct axis and the quadrature axis.

A very high power density axial flux machine had been developed by Protean Electric in the UK offers their HI-PA Drive which is an axial flux PM brushless traction motor as described in their literature shown below. These motor exhibit output power densities of 2.22, 3.81 & 4.0 kw/kg for the three sizes shown in their literature from their web site as shown below.

Hi-Pa Drive

Key Features:~

- Full regenerative braking down to very low speed
- Full holding torque at zero speed
- Wide speed range
- Built in brake resistor (for full charge regeneration situations)
- Hand / parking brake option available
- Heavy duty bearing system

Hi-Pa Drive is a literal revolution in motor technology. It represents both the culmination of 4 years development and the global state of the art today.

Hi-Pa Drive is an integrated motor and drive electronics in one unit.

Hi-Pa Drive is ultra high power density - 20 times more than conventional systems

Hi-Pa Drive is ultra reliable – 20 times more reliable than conventional systems

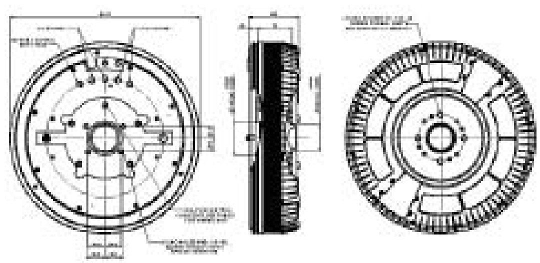
Providing high torque in a lightweight flat motor package, Hi-Pa Drive is ideally suited to vehicle in wheel drives, where its impact on suspension dynamics is minimal.

For more information, contact PML at: enquiries@pmlflightlink.com
Or telephone: +44 (0) 1420 594140

	HPD40	HPD35	HPD30
Torque (max)	750Nm	500Nm	350Nm
Speed (max)	2000rpm	2000rpm	2000rpm
Power (max)	120kW	80kW	40kW
Mass	25kg	21kg	18kg

Connections

Inputs	
+ve power	400vdc max 200A
Uv power	
Throttle input	pwm 20khz
Brake input	pwm 20khz
TC Input	pwm 20khz
Forward	digital 24v pos true
Reverse	digital 24v pos true
Enable	digital 24v pos true
CanBus	

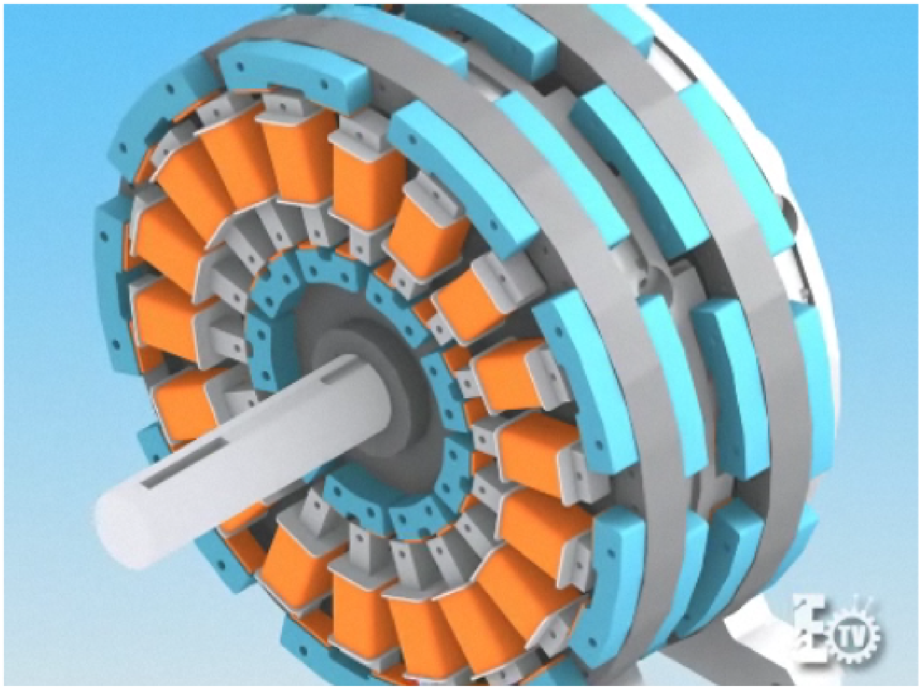


Outputs

Speed	A quad B simulated encoder 5v 1000ppr
Fault	Open collector sink = fault state

A company called EXRO Technologies has developed a transverse PM brushless technology for high torque density designs. These are currently funded for wind power applications but they also are well suited for vehicle traction drives. Due to their unique transverse magnetic circuit they yield high torque densities. (Their design is covered by U.S. patent # 7,081,696). The inventor claims that the use of many identical components for the motor configurations allows tooling and high volume parts fabrication that can lower cost.

EXRO TRANSVERSE FLUX GENERATOR



Another company that has developed a unique PM brushless motor design is called QM. Their design is called a parallel flux path brushless motor. The parts can be volume produced using magnetic powdered metal technology with minimal machining and the magnets can be low cost ceramic magnets used on the outside part of the circuit. These magnets can have large surface areas because the flux is naturally focused into the circuit for the same flux densities as is possible using expensive rare earth NEO magnets. If the surface area of the flat slab ceramic magnets is three to four times the area required for Neo magnets the same air gap flux can be achieved with these low cost ceramic magnets. A concept illustration is shown below of this PM brushless motor that can produce high torque and power densities using the lowest cost magnets on earth.

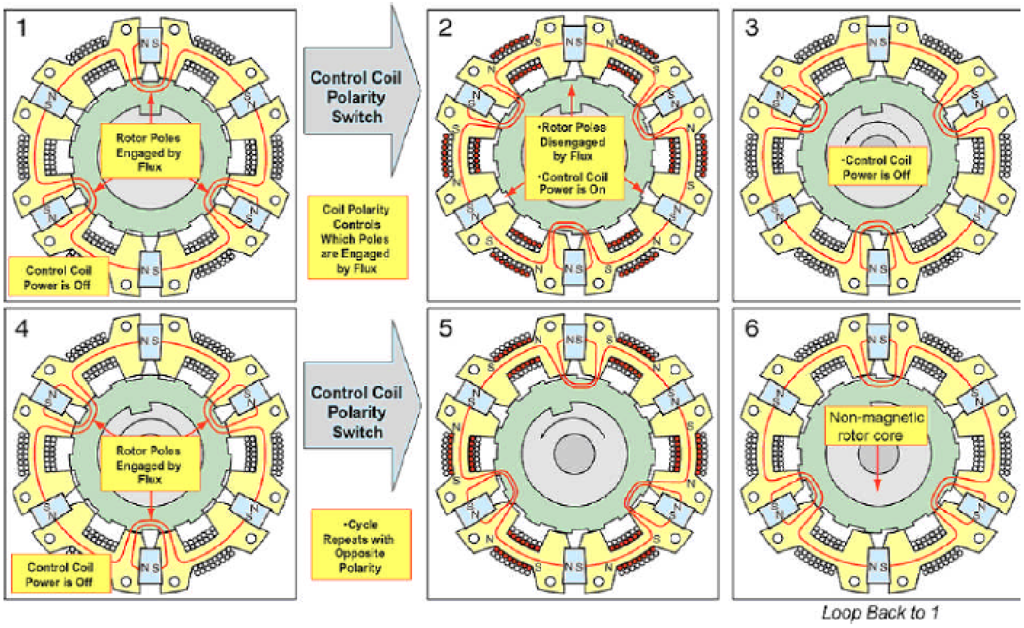


Fig 3. Six Magnet Motor Flux Sequence (CCW) by QM

Ceramic magnets made from Strontium Ferrite yield at least 0.4 Tesla at $4.00 to $6.00 per kg as compared to Neo that cost at least 10 times that much for a flux density of about 3 times the ceramic or 1.2 T. In addition, the low cost ceramic magnet grade will not rust and it will not demagnetize as easily as Neo so it is if it can be designed in a configuration where a large surface area can be used it can be very cost effective. The temperature coefficient of the Bm for the ceramic magnets is about the same as for Neo but the curie temperature is much higher for the ceramic and the coercivity of the ceramic magnet grades increases with elevated temperature. In addition it is not scarce and the USA has significant capacity to manufacture. It would seem that if PM brushless machines must be used for vehicle traction because of power and torque density advantages over all other types of motors and generators the use of these ceramic magnets should be investigated by using similar concepts to the QM design and the Fanuc design. (see page 14.)

Hitachi in Japan has recently developed a new ceramic magnet grade with better thermal properties and higher flux densities. This new ceramic grade is called **NMF-12 SERIES** and is made by replacing some of the strontium with Lanthanum. It is called *Lantanum Strontium Cobalt Ferrite*

Environmental Systems *Products*

Piping & Infrastructure *Products*

Tooling, Tool Steel, Mold & Die

Metal & Plastic *Manufacturing Devices*

Aviation, Space & Nuclear *Industry Materials*

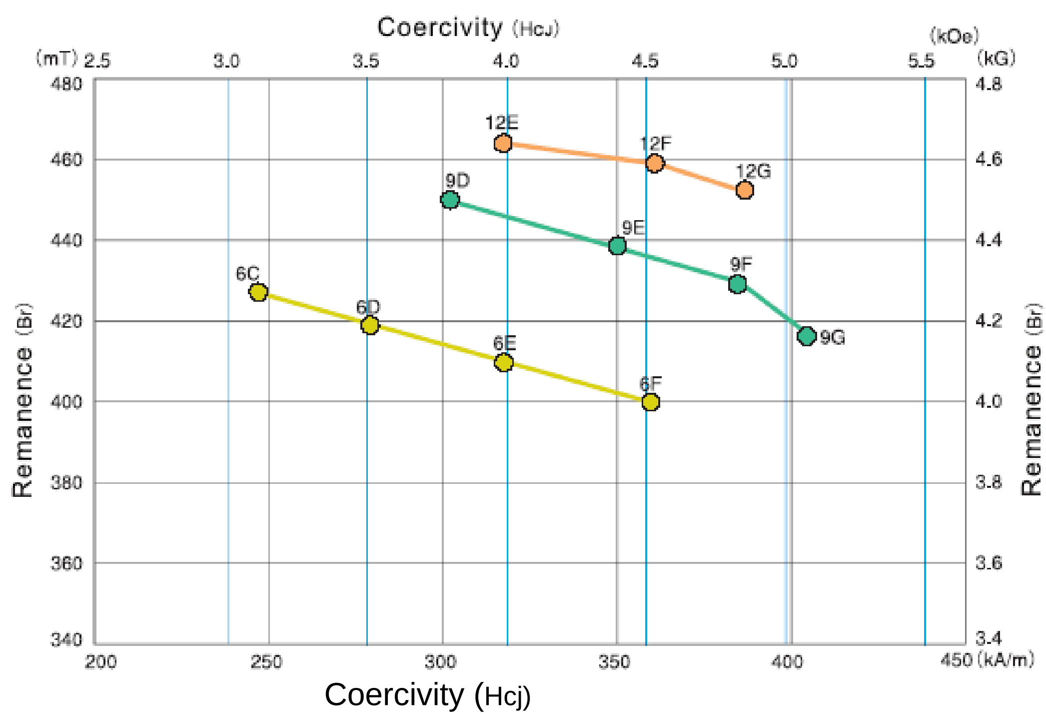
Construction & Plant *Materials*

Product Range Overview

The ferrite magnet that previously had the best magnetic characteristics was also developed by Hitachi Metals in 1998.This was the Lanthanum-Cobalt (La-Co) substituted strontium (Sr) ferrite magnet (9 series). The company's new ferrite magnet (12 series) is greatly superior to this earlier product. Among ferrite magnets, it provides the world's best magnetic characteristics.

Material Code	Remanence (Br)		Coercivity (HcJ)	
	SI (mT)	CGS (kG)	SI (kA/m)	CGS (kOe)
NMF-12E	460—480	4.6—4.8	≥310	≥3.9
NMF-12F	450—470	4.5—4.7	≥342	≥4.3
NMF-12G	440—460	4.4—4.6	≥382	≥4.8

Magnetic Properties



A very excellent PM brushless design that is quite old as a matter of fact is the "Spoke Type IPM made famous by FANUK in Japan. This motor design was originally design by Dr. Eike Richter of GE for aircraft generators and also about the same time by Sam Noodleman at Inland Motors for industrial servo motors. The original designs used samarium cobalt magnets mad by GE but the Fanuc versions utilized the low cost flat slab Strontium Ferrite ceramic magnets. After Fanuc configured their spoke magnet rotors with 8 poles the surface area of each magnet was 3.5 to 4 times the surface area of the radial soft iron poles they fed so the gap flux was about 0.9 Tesla. This enabled a low cost ceramic brushless motor to achieve as high gap flux as any Neo IPM or SPM motor ever developed to this day. Fanuc found that this design is not effective with less than 8 poles to yield the flux focusing required depending on the rotor diameter. This IPM motor design was and still used for machine tool servomotor applications as one of the highest volume servomotors ever produced. They are driven by ac sine drives like most all IPM machines. Inland motors and Pacific Scientific (both now owned by Danaher) also made these types of IPM motors for servo applications. A photo of a complete rotor and one of the eight a core sections with two adjacent ceramic magnets attached is shown below. (Taken from a brushless motor design book (1994) ISBN # 0-19-859389-9.) Further development of this type of IPM appears very attractive for modern vehicle traction to reduce motor cost and to avoid the use of Neo magnets.

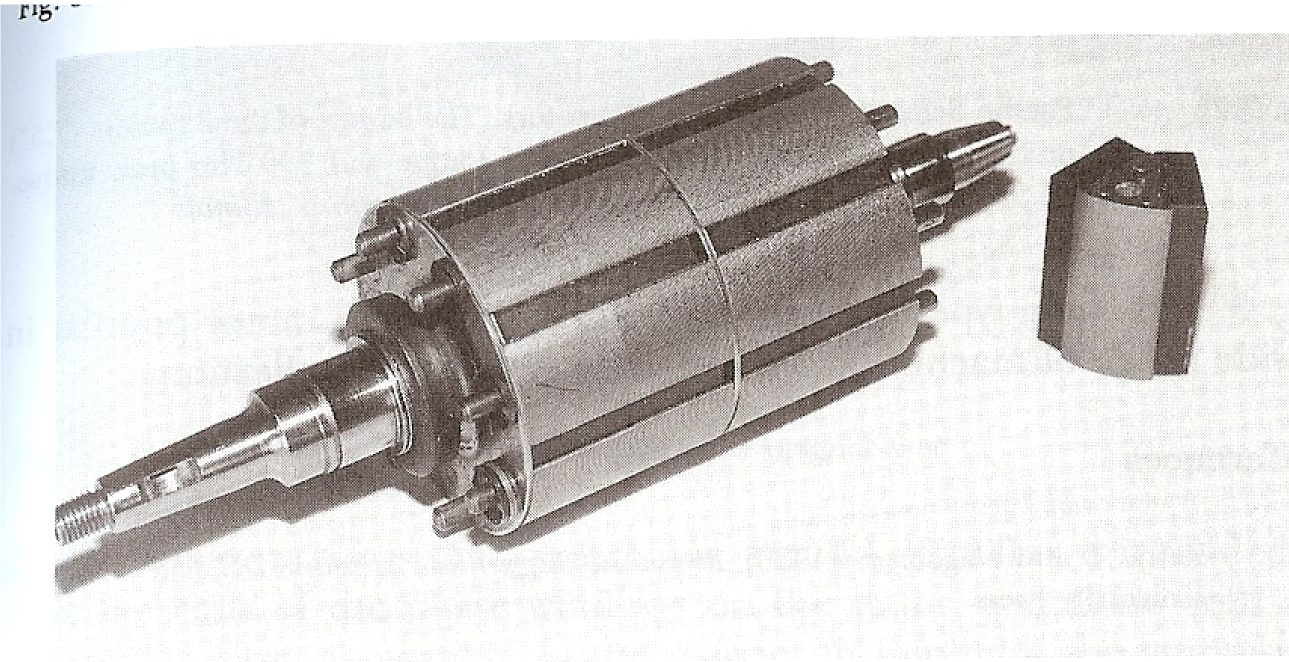


Fig. 3.25 8-pole spoke-type rotor (Pacific Scientific F40 Series). *Photo kindly supplied by Pacific Scientific, Rockford, Illinois*

3-73

Perhaps this IPM configuration of at least 8 poles using parallel slabs of low cost ceramic magnets between pole pieces made from triangle shaped laminated steel punched out from the stator lamination hole is the most cost effective IPM ac synchronous motor for traction of any design currently known. The preceding parallel path design might be as good but has not as yet been proven.

Project Seeks to Optimize Composition of Magnets for Traction Motors to Improve Economic Competitiveness

July 08, 2009

A research project currently underway at St. Pölten University of Applied Sciences (Austria), in cooperation with the University of Sheffield (UK), is exploring the ideal composition and structure for high-performance PMs intended for use in hybrid and electric car motors—specifically, how the proportion of dysprosium can be reduced without compromising the

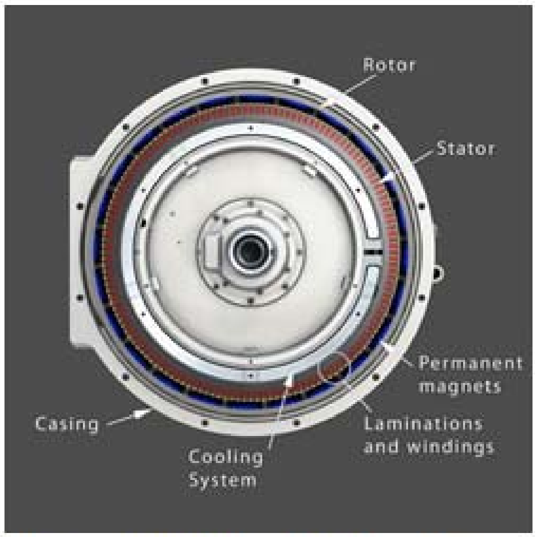
thermal stability of the magnets. By optimizing magnets, the researchers suggest, hybrid and electric cars can be made economically competitive.
Overall, an electric or hybrid drive contains around 2 kg (4.4 lbs) of magnetic material in their motors. At present, neodymium iron boron magnets form the basis of this. These have considerably less mass than conventional magnets, but deliver the same level of performance. In order to ensure the magnetic properties are retained even at high temperatures—such as those that occur within a car—the rare earth element neodymium is partially replaced by dysprosium, another rare earth element. This increases the coercive force of the magnet—its stability against demagnetization. However, notes Prof. Thomas Schrefl, project leader:

A leading motor and drive development company in Canada called *tm4 Electrodynamic Systems* (a spin-off of Hydro-Quebec in1998) seems to have made significant improvements in the power and torque density of PM brushless motors and drives. They also state they use IPM designs. A couple of pages from their web site is included below to show the their typical PM Synchronous motor cross section with an outside rotor of many poles which greatly improves the torque density.
In addition a finished motor is shown with the liquid tubes shown on the rear of the motor which improves the machine densities because higher air gap stresses can sustained with liquid cooling close to the coils as is indicated by the cross section. This finished motor is advertised as a 120 KW PM Brushless Traction motor that weighs a total of 26 kg. This works out to 4.6 kw.kg and with a continuous torque output of 170 Nm, the torque density is 6.54 Nm/kg.

The largest HPA axial flux motor described previously on page 10 produced a similar power density at 120kw/25kg = 4.8 kw/kg but the torque density was much higher at 750 Nm/25kg = 30 Nm/kg. These comparisons are interesting because in both cases the mass used includes the frames, shafts end flanges bearings and cooling fins or cooling channels. The previous densities from the Toyota motors included only the active magnetic components.

High Density Electric Machine

Compared to rotor centric permanent magnet motors, the inversed rotor topology (where the rotor rotates on the outside of the stator) has a larger magnetic field. The additional radius provides higher torque and power density and leads to better efficiency.



Cross section of a typical TM4 motor

TM4's PM motor technology results in:

- Higher efficiency level
- Higher power density

Technology

TM4 can customize its leading-edge technologies in permanent magnet motors and generators and compact power electronics to your specific hybrid or electric powertrain configuration.

Features

1. Patented winding
   - Controlled position of the rectangular copper wire
   - Reduced head winding length
   - Higher fill factor than round wire
2. Interior permanent magnets
3. Increased radius
4. Low cogging torque due to magnet shape
5. Patented lamination profile that eases manufacturing
6. Patented algorithm to minimize electric losses

Advantages

- Electric insulation improvement (1)
- Better heat management and improved cooling (1)
- Excellent retention of magnets in place (2)
- Superior power density (1, 3)
- Small volume: excellent packability for all types of vehicles (1, 2, 3, 5)
- Very smooth drive (4)
- Lower production cost (1, 3, 5, 6)
- High efficiency over a wide range of speeds (1, 6)

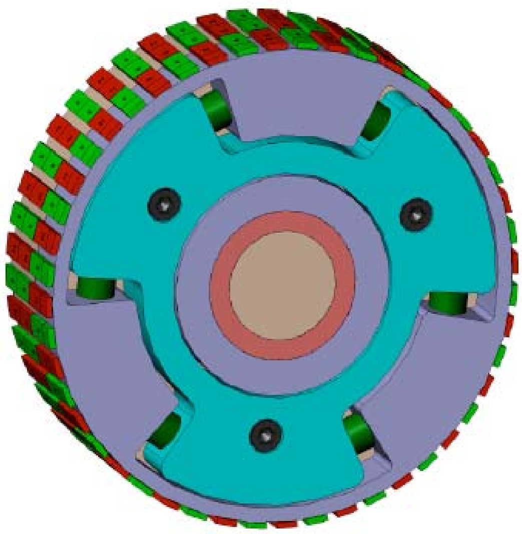
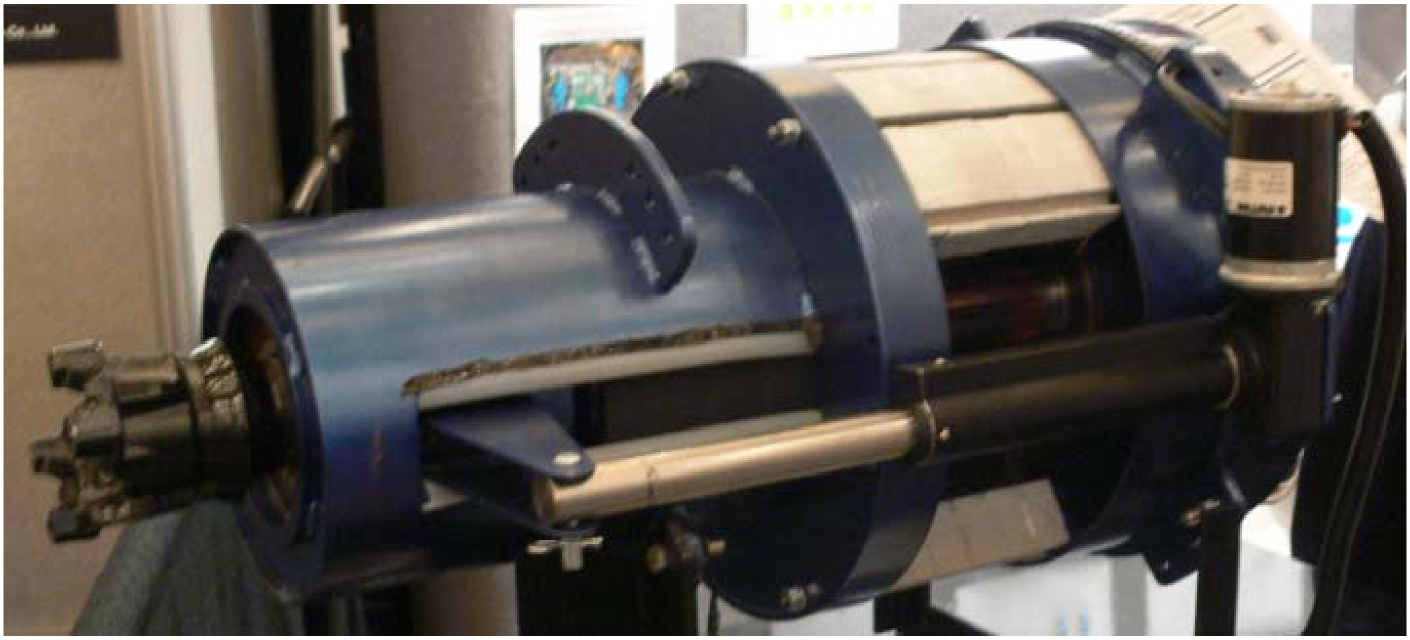


Figure 1

The rotor on the left is a so called axially split PM rotor for a SPM motor. The split concept could also apply to an IPM split the same way. If one half is rotated slightly during operation, the effect is field weakening due to a reduction of flux linkage as some of the flux leaks from one rotor half to the other rotor half as a function of the rotation angle. A suitable actuator is required of course but this design has been designed, developed and patented by a company called Innovatec Automation in Wauconda IL.

The traction motor on the right is an outside rotor motor using ceramic or neo magnets. The rotor is fixed to the inside of the wheel but the stator is fixed to a radial slide along the axial or shaft that permits the stator to slide in and out of the rotor to change the flux linkage for field weakening. This is a very clever design worth considering for radial flux rear wheel traction drives. The same vehicle might have axial flux PM motors on the front wheels to be used only for acceleration and as generators for battery charging during braking. This machine was designed in Japan for a solar vehicle race.

The next machine example is similar to the one above and has been developed by Larry Zepp and others (including yours truly) at Dura -Trak in Ft Wayne IN. The principle difference is that the rotor moves in and out of the stator axially along the rather the stator moving in and out of the rotor. This machine has no less than five issued patents on its concept, its manufacturing method and slide actuator. These machines are currently being used for battery powered school buses and airport Tugs. It is interesting to note that either of the two possible designs that can utilize low cost magnets as described on pages 12 & 14 could be field weakened by this method of moving the rotor in the stator.



AC INDUCTION MOTORS FOR TRACTION

One of the earliest EV design in recent times was the GM EV1 which was powered by an ac Induction motor made by the General Electric company but was designed by Dr. Ahmed El Entably from GM. It was a conventional 4 pole motor with an aluminum die cast rotor that was driven by a flux vector drive designed and fabricated by the Hughes Div of GM. The principle engineer who was responsible for the drive on that car now works for TESLA Motors and perhaps this is why the Tesla traction motor use 4 pole ac induction motors as well. However the Tesla motors use die cast copper rotors for superior performance over the aluminum die cast rotor. The perfection of the die casting of copper was a significant technological advancement. The most difficult problem to deal with when using an ac induction motor is to extract the heat generated by the rotor conductors. The use of the lower resistance copper over aluminum can be used two different ways. The first is to reduce the ohmic losses in the rotor conductors thereby reducing the heat that must be extracted to achieve high power and torque densities. The second possible advantage of using copper rather than aluminum in the rotor conductors is that if the cross section of the conductors can be reduced for the same ohmic losses due to the lower resistively of copper compared to aluminum, higher rotor magnetizing flux can be permitted which increases the starting torque capabilities which is very useful for vehicle traction.

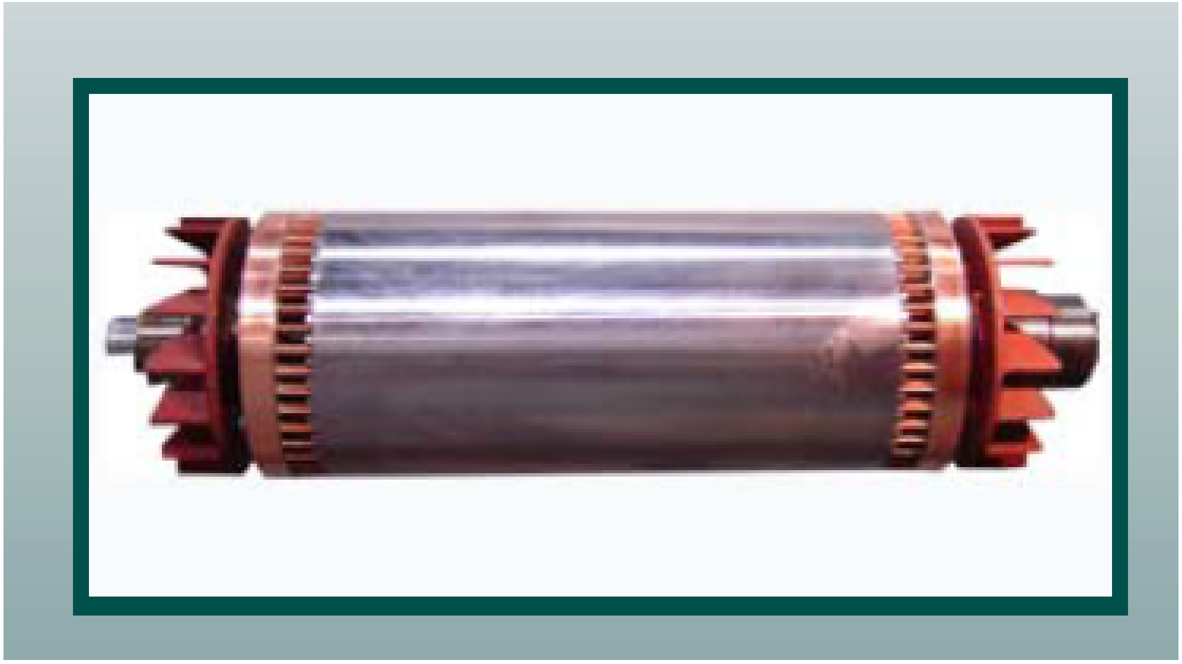
The development of the die casting of copper was perfected first by a French company but now there are several companies that can offer this rotor construction. There is a very excellent copper die caster in OHIO as well (RAMCO ROTORS). Depending upon the size of the motor the use of copper can increase the efficiency of an ac Induction motor by one to three percentage points. In order to calibrate the significance of this small improvement consider a 50 KW ac induction traction motor like the rating of the IPM motor used in the PRIUS. If a aluminum rotor were used and the motor efficiency turned out to be 93% and by the use of copper if it increases to 94% the decrease in rotor losses would be about 570 watts. This copper rotor would be much easier to cool and the extra 1% would improve the battery driving distance. A chart of ac motor sizes with efficiency improvements by replacing aluminum with copper has been furnished below.

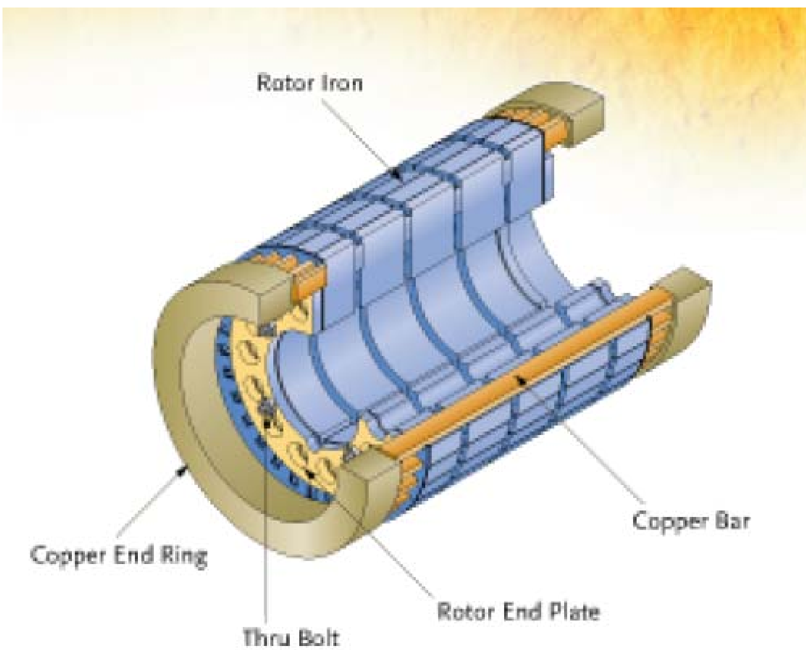
Motor Power (HP)	Motor Frequency (Hz)	Efficiency		Improvement in Efficiency (percentage points)	Percentage Reduction in Rotor Losses	Ref
		Aluminum Rotor	Copper Rotor			
2	50	78.0%	80.3%	2.3	53%	5
2	50	81.1%	82.5%	1.4	--	4
3	50	83.6%	85.9%	2.3	--	4
4	60	83.2%	86.4%	3.2	58%	1, 2
4	50	82.0%	84.1%	2.1	46%	6
4	50	81.8%	84.3%	2.5	53%	5
5	50	84.0%	87.1%	3.1	--	4
5	50	83.0%	86.0%	3.0	--	4
5	50	--	--	--	38%	1, 2
7.4	50	83.4%	84.3%	0.9	--	3
7.4	50	83.0%	84.3%	1.3	--	7, 8
7.5†	50	74.0%	79.0%	5.0	--	9
10	50	84.2%	87.4%	3.2	50%	6
10	50	86.1%	88.0%	1.9	52%	5
10	60	85.0%	86.5%	1.5	--	10
20	50	90.1%	91.0%	0.9	40%	11
40†	--	88.8%	90.1%	1.3	--	1, 2
120†	--	91.4%	92.8%	1.4	--	1, 2
270†	50	92.0%	93.0%	1.0	--	9

†Calculations rather than experimental measurements

Table 1.2.1.1: A summary of reports from the literature of efficiency improvements when aluminum rotors are replaced with ones die-cast from copper. Other than the change in the squirrel cage material, no other design changes were made to these motors (references are listed **here**

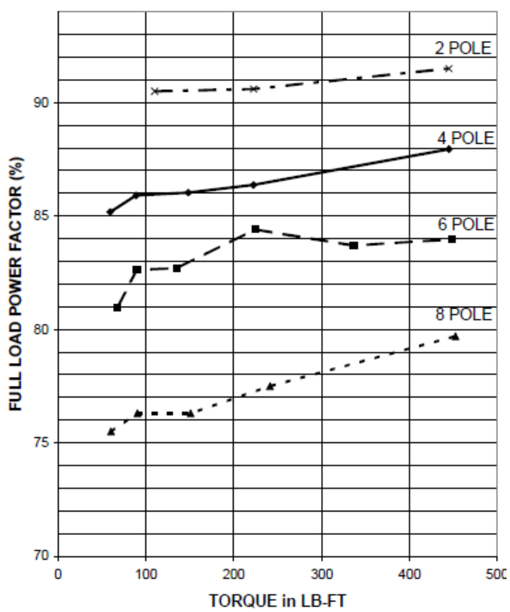
A copper rotor that was die cast is shown in the photo below.





COPPER ROTOR CUT-A-WAY WITH COOLING CHANNELS

The ac induction motor has been studied to determine the effect of different pole numbers and it has been shown by several studies by Allen Bradley, Reliance Electric, General Electric and Siemens that the optimum pole number for ac induction machines below 1000 NM is four poles. The reason is because when increasing the pole numbers for smaller machines the power factor is reduced. For example a study of a 200 LB-FT Reliance motor indicates a PF = 90.5% for a two pole version, PF = 86.3% for a four pole, PF = 83% for a six pole and the PF = 77% for the eight pole version each in the same frame. However the torque density is increased in the same frame size by increasing the number of poles just like the PM brushless and the IPM machines. For ac induction motors driven by inverters, the number of poles should be increased from four to six for motors above 1000 NM torque.



When matching ac induction motors to variable speed applications using adjustable frequency power supplies, there is a temptation to assume that 50 or 60 Hz will be the "base frequency," and therefore the "base speeds" achievable are those provided by varying the number of motor poles. That assumption not only limits the choices of base speeds, but also results in suboptimal performance from the motor. This paper will explain the physics of why the optimal choice of the number of motor poles is more a function of the motor torque (size), rather than the motor speed, when considering adjustable frequency applications. In fact, the exclusive use of a four pole configuration results in optimal performance for a significant range of ratings. The parameters which can be optimized via the correct choice of pole configuration include - torque density, speed range, efficiency, power factor, overload capability, and acoustic noise.

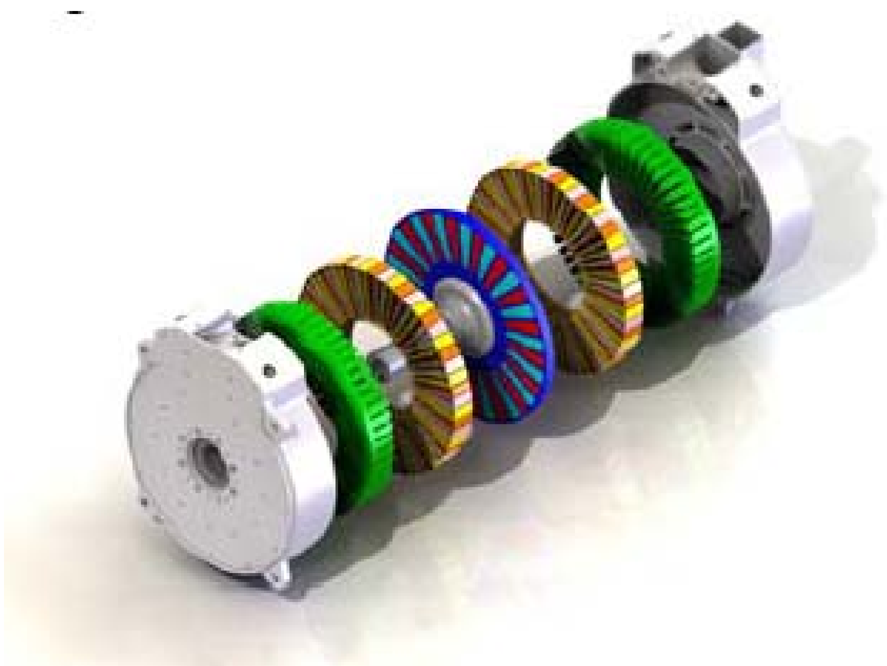
Data & Quote from Reliance Electric, by Michael J. Melfi

This article indicates that the only way to increase the power density of an ac induction motor used for vehicle traction is to increase the speed. This is probably why many ac traction drives run at high rpms of 12Krpm and even 15Krpm at maximum vehicle speeds. This use of high motor speeds always results in smaller light weight traction motors but it requires a high ratio gear box that also has a mass and losses.

As far as is known today the principle new technology that improves the chances of using an ac induction motor for traction applications is the use of a copper conductor rotor. Before the development of copper die casting copper rotor were very expensive because they required extensive hand labor to fabricate. Now the copper rotors can be die cast they are potentially as cost effective as aluminum die cast rotor with the main difference if cost attributed to the cost per kg of aluminum vs copper. Due to the assumed requirement for the optimum number of 4 poles for A-synchronous motors the torque and power density of the ac induction machine for vehicular traction will be considerably less than IPM or SPM Brushless and Switched Reluctance to some limited degree because they can use a higher number of poles.

The use of low core loss amorphous electrical which exhibit very low core losses might be useful in increasing the power and torque density of ac induction machines if suitable manufacturing techniques can be developed. This material commonly known as *Metglas* is supplied in ribbon form and is widely used in high frequency transformers. The principle motor application that can easily utilize the ribbon form of the material would be axial flux machines that could be packaged as traction wheel motors. An example is shown below, supplied by Light Engineering.

The amorphous stators are shown in green.



It should be noted that there has been some recent developments in Japan in improvements for electrical steels used for motor laminations. The optimization of the steel can be determined by the electrical grade, the thickness and the core plate used for interlamination insulation against eddy current losses. (**NIPPON STEEL TECHNICAL REPORT No. 87 July 2003)** The title and abstract is provided below along with a summary of typical vehicle traction motor types and some of their characteristics.

Electrical Steel Sheet for Traction Motors
of Hybrid/Electric Vehicles

Masao YABUMOTO*1 Chikara KAIDO*1
Takeaki WAKISAKA*1 Takeshi KUBOTA*1
Noriyuki SUZUKI*1
Abstract
Electrical steel sheet is used for core of traction motors of hybrid electric vehicles (HEV) and electric vehicles (EV), and affects performance of HEV/EV. In order to

make motors to be small, light, powerful and efficient, there are many demands to electrical steel sheet. To realize these demands, development of electrical steel sheets with suitable qualities, and suitable application techniques of electrical steel sheet are required as well.

NIPPON STEEL TECHNICAL REPORT No. 88 July 2003

Table 1 Types of EV traction motor and their characteristics [1,2]

	Motor type	DC	Induction	Synchronous (PM)	Switched reluctance
Motor properties	Max. efficiency (%)	△ 85-89	○ 94-95	◎ 95-97	△○ <90
	Efficiency (load 10%) (%)	○ 80-87	○ 79-85	◎ 90-92	○ 78-86
	Max. revolution (rpm)	△ 4,000-6,000	◎ 9,000-15,000	○ 4,000-10,000	◎ <15,000
	Cost/ torque ($/kW)	○ 10	○ 8-12	△ 10-15	◎ 6-10
	Costs of controller	◎ 1	△ 3.5	○ 2.5	△ 4.5
	Rigidness	○ Good	◎ Best	○ Good	○ Good
	Reliability	△ Good	◎ Best	○ Good	○ Good

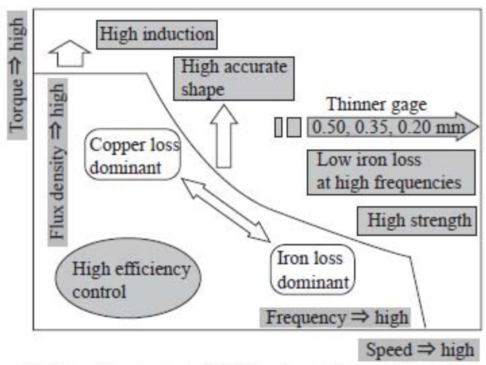


Fig. 1 Required performance of EV and requirements of electrical steel sheet for EV traction motor

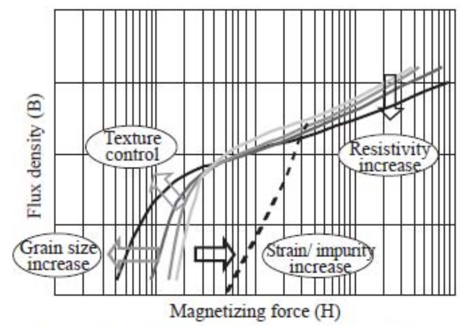
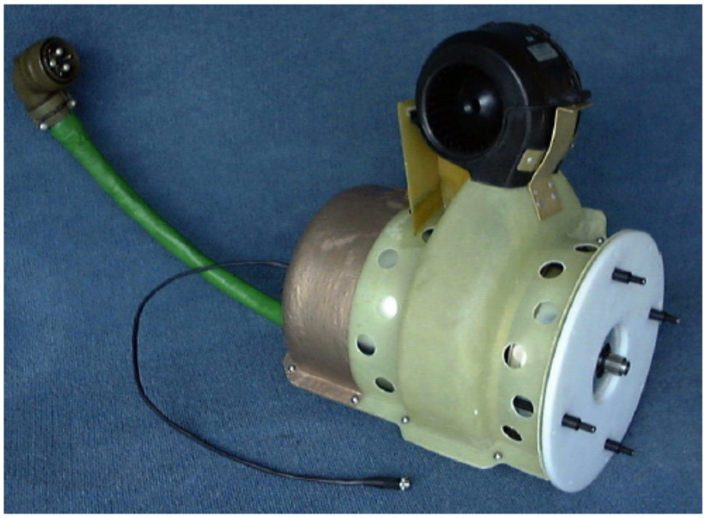


Fig. 2 Magnetizing characteristics of electrical steel sheet and principal influencing material properties

A California company called AC Propulsion has developed a liquid cooled high performance ac induction motor for traction with a copper rotor. They also offer an air cooled power converter for this 150 KW motor.

MOTOR



The AC-150 motor is custom designed for automotive application to maximize high power/weight ratio and efficiency over a broad range of speed and power. The three-phase induction motor has a patented copper rotor construction which allows extremely high power density and high efficiency. The motor weighs 50 kg (110lbs.) including its cooling system and produces 225 N-m (165 ft-lb) of torque from zero to 5000 rpm. Maximum speed is 12,000 rpm which is electronically limited. The air-cooled design provides for simplified installation and maintenance as well as weight savings and cost reduction. The motor houses a winding temperature sensor and an encoder that provides speed and direction information to the PEU. A variable speed blower is provided which is driven from the PEU. Power connector orientation and cable length are normally specified at time of order to suit the vehicle installation.

AC Propulsion, Inc. • 441 Borrego Court • San Dimas, CA 91773 • 909 592-5399

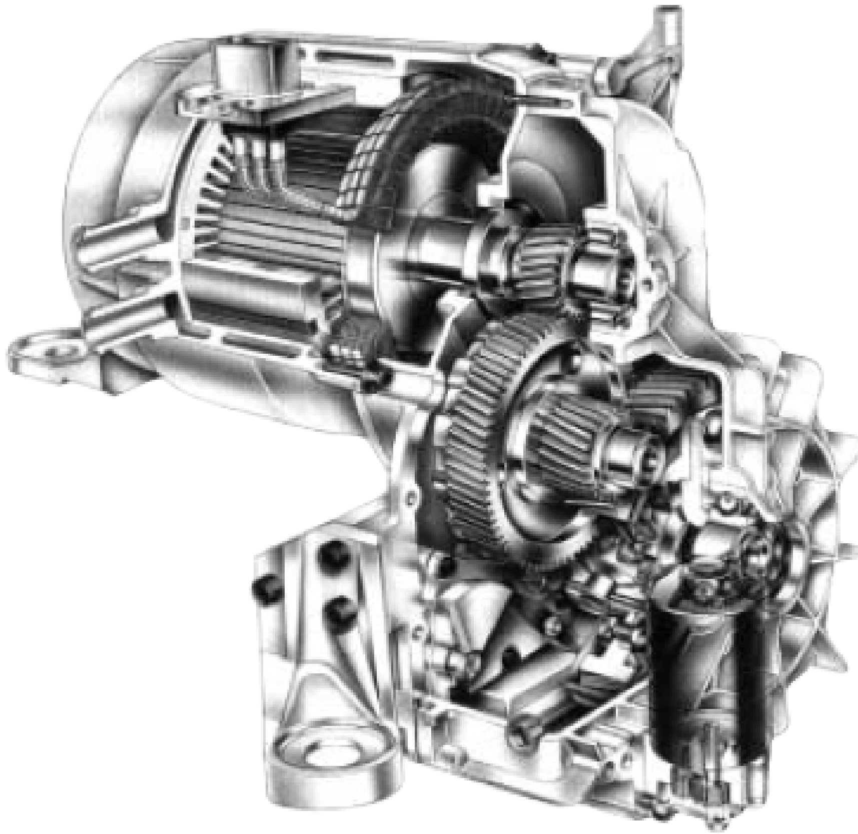
system can also pre-condition the cabin environment whilst the vehicle is charging. Power is taken from the recharge station and not the vehicle's batteries.

Pulse Width Modulation (PWM) control modules conserve energy in DC motor applications. With PWM, neer in the design team, the extreme requirements of EV1's propulsion system were met and exceeded. The unit had to be compact, light, highly efficient and able to deliver power levels comparable to other road vehicles. The result of the considerable efforts of the design team was the Delphi Drive Unit, a three-phase AC induction motor with integrated gear reduction. The drive unit motor is capable of than 13,000 RPM and only requires routine maintenance when it has covered more than 160,000 km. Rated at 103 kW peak, the unit features regenerative braking which extends the vehicle's range by up to 20 per cent.

Weight was the most vital factor in the design of every EV1 component especially the drive unit which weighs a mere 150 pounds - one third the weight of an equivalent four-cylinder petrol engine.

The drive unit has liquid cooling, oil lubrication and built-in temperature sensors and a gear mode switch. The parking brake can be applied by simply pressing a button in the cabin which operates a park/lock device in the unit. The unit is also very simple to use as forward, reverse and park are the only gear selections needed.

GM is already moving to production of the 2nd generation propulsion system which is lighter and has fewer moving parts. A third generation system, currently under development, sees the contents of the Power Electronics Bay reduced to the size of a shoe box.



The Delphi Drive Unit

DETAILS OD GM DELCO AC INDUCTION DRIVE UNIT USED IN THE VAUXHALL (2001)

SWITCHED RELUCTANCE TRACTION MOTORS

The phase topology for the SRMs are totally different from the 6 transistor bridge connections for both of the motors discussed so far. (IPM brushless and ac Induction). The SR motor phases are connected in parallel between the dc Voltage Bus with a transistor on each leg of the phase winding and also a diode. Therefore the standard transistor bridge modules used for ac Induction and IPM brushless cannot be utilized. Special configurations of discrete components are usually required except for some custom drive modules made for special applications not available for new applications. The typical SR phase drive topology is shown below with the location of the flyback diodes such that the ones included with most transistors connected from the emitter to the collector cannot be utilized.

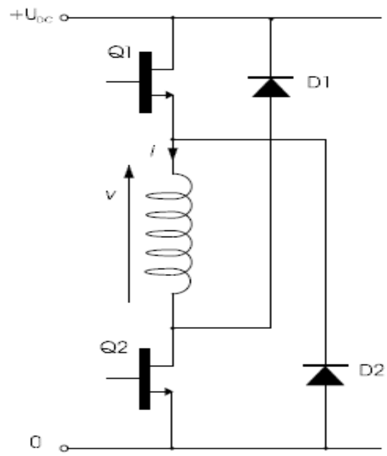
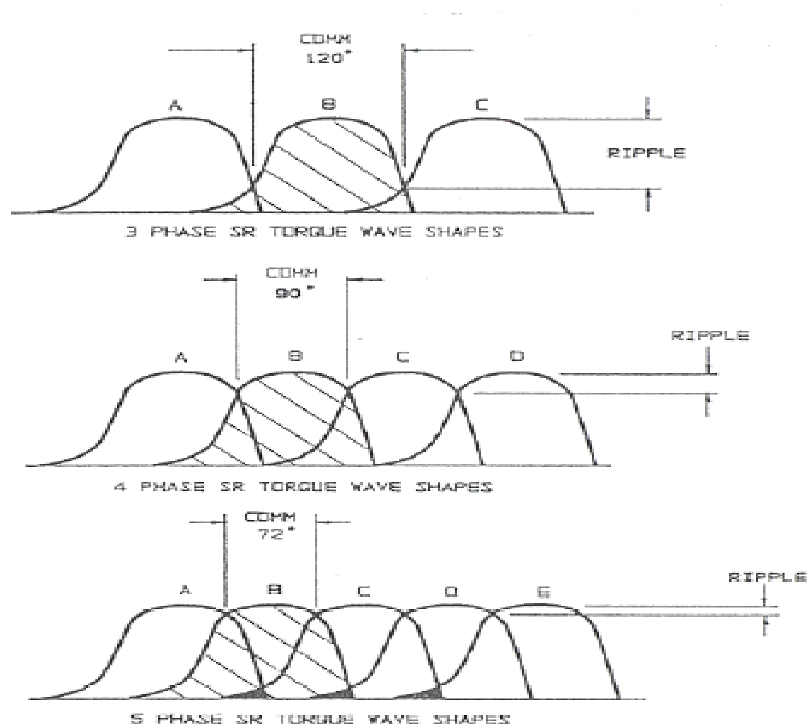
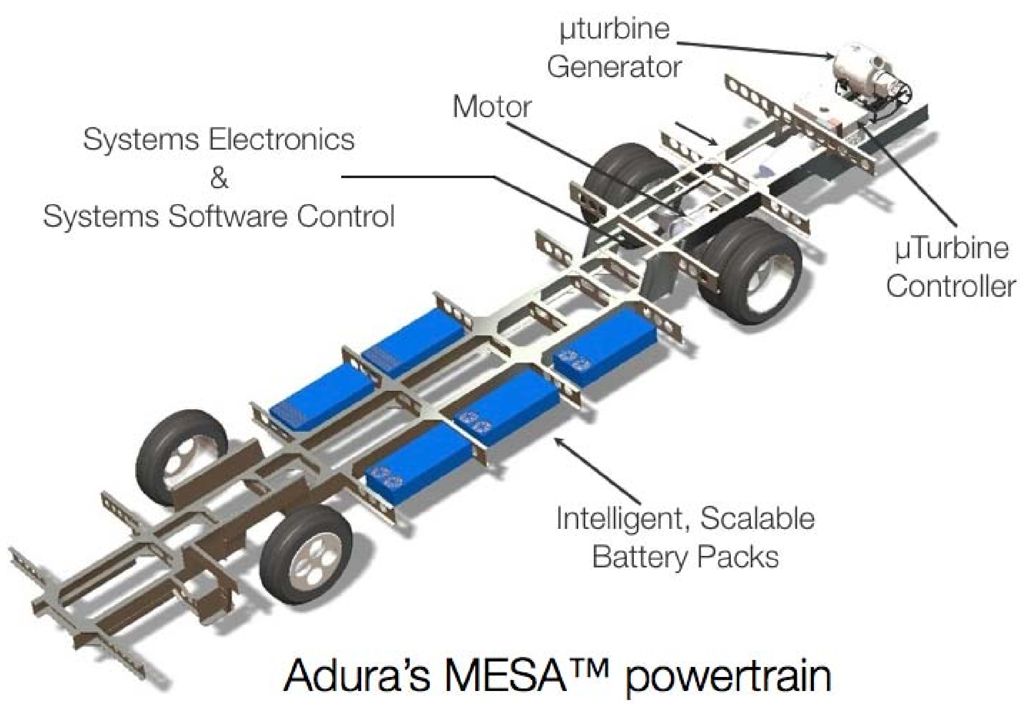


Fig. 2 Half-bridge phase leg for switched reluctance machine.

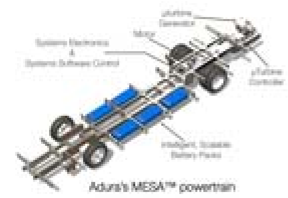
The capacitor requirements are more severe for the SR inverter and the commutation control accuracy is very strict to achieve the maximum output torque at all speeds. To further complicate the optimization of the SRM the back-emf is not fixed nor is it near sine shaped. The selection of the number of phases determines the torque ripple for most common designs. For example a two-phase SR motor has a 100% torque ripple with actual dead spots unless a special design is used. The inherent torque ripple can be summarized in the following example which is a plot of the torque vs rotor angle produced with constant current for each phase for different numbers of phases at a fixed current. Notice the rotor angle between the phases, 120 deg for the three phase, 90 deg for the four phase and 72 deg for the 5 phase. If a single phase is shorted or open there is a dead spot in the rotor location for the three phase, probably no dead spot for the four phase and for sure positive torque for the five phase if a single phase is open or shorted. It should be obvious that if two phases are used, the torque ripple is 100% assuming there is torque produced for 180 deg for each phase and also there is a large dead spot if on phase is shorted or open. It should be noted that a two phase SR motor cannot be electrically reversed but is single directional. In addition the single phase SR motor is becoming quite popular due for fans, pumps, blowers and certain appliances that are single directional. The reason for this is its simplicity and low cost for the inverter which requires only (4) transistors rather than (6) for the three phase, (8) for the four phase and (10) for the five phase. However in order to make these two phase SR motor useable a special design trick must be used to eliminate the dead spots and minimize their torque ripple. There are many of these ideas that are being developed and patented. Normally the torque produced by each phase covers only 180 electrical degrees of rotor rotation. In order to produce continuous torque with no dead spots or low starting torque rotor positions the motor lamination geometry must be modified to assure torque production for each phase greater than 180 electrical degrees. The best design exhibits the largest angles with steep torque rise from zero.





Adura's MESA Electric Powertrain Combines Controls, Switched Reluctance Traction Motor and MicroTurbine

Adura Systems, Inc. unveiled its new MESA (Modular, Electronic, Scalable Architecture) electric powertrain for use in series hybrid, all electric and fuel cell mass transportation buses, large utility vehicles and other automotives.



Components of the Adura MESA powertrain. Click to enlarge.

Adura's MESA powertrain features patent-pending, highly modular systems electronics, an innovative intelligent control software platform and the industry's first scalable, field installable energy storage system that can be configured, depending upon users' requirements, to provide 25, 50 miles or 100 miles of initial travel in pure electric mode with subsequent travel in hybrid mode.

VS TECHNOLOGY CORORATION

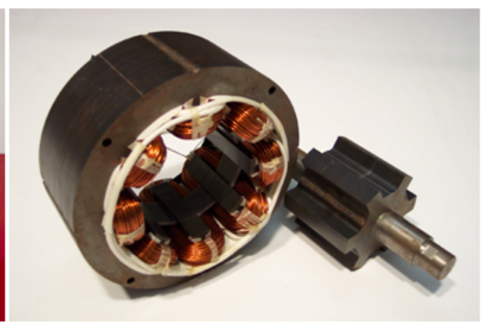
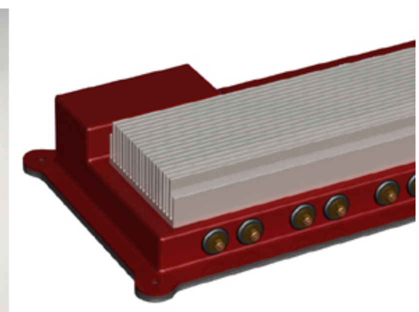
17170 Jordan Rd., Suite 106 - Selma, TX 78154 - 210-651-6868 - Fax: 210-651-9997

VS Technology Corporation is pushing the leading edge of electric motor and vehicle technology by developing and manufacturing Switched Reluctance Drives and drivetrains for small to large applicati

VST has been working in the advanced technology automotive field since 1990 and in 2007 acquired all of the advanced motor drive technology from Honeywell Corporation, expanding VST's technolog control and pulse width modulated controls.

VST also maintains numerous relationships with several prototype and high volume motor manufacturers and has long term agreements with expert motor and control consultants who have up to 40 ye respective areas.

Why Switched Reluctance Motors for Vehicles?

The SR traction motor drive shown above by VS Technologies is a four phase machine with eight stator poles and six rotor poles. This SRM type has very low torque ripple because of the 90 electric degree separation of the phases so there is considerable overlap as shown above in the static torque plots vs rotor angle. The drawback with this design is that since each phase requires two transistors and two diodes the four phase SRM requires 8 transistors and 8 diodes each about the same rating. The use of three phases reduces those components to 6 transistors and 6 diodes. However the torque ripple at starting the vehicle from a stand still is quite high even with careful phase overlap control of two adjacent phases.

Hewlett Packard was issued a very important patent (# 4647802) for three phase SR motors based upon the inventions of Karl F. Koneckny with 6 stator poles and 8 rotor poles. The purpose of this special design with tapered stator poles was to reduce the torque ripple. The effect of the tapered poles in the stator limited the pole saturation to the pole tips. The cross section showing the tapered stator poles is shown below in Fig 3 taken from the patent. Fig 7a shows the typical static torque of each phase spaced 120 electric degrees apart. The two torque transducer plots are from Hewlett Packard lab test data. The first one shows the 12 oz-in torque plot of a standard parallel sided stator tooth 2" diameter with 6 stator poles and 8 rotor poles. The lower curves are plotted from the torque of each phase from unaligned to aligned rotor to stator pole angles. The phase overlap can be observed and the very high torque ripple between phases with only one phase powered at a time from unaligned to aligned rotor to stator pole angles. The other plot on this first set of curves is the resultant torque ripple with two adjacent phases on at a time to reduce the torque ripple. Even when commutating for the maximum phase overlap as shown in the first plot, there is still a considerable amount of torque ripple.

The second plot is the torque transducer measured results for the same size SR motor but with the stator poles tapered like is shown in their patent to eliminate the stator teeth saturation at the current level for 12 oz-in (saturation occurs at the air gap portion of the teeth.) The result is a much wider torque profile for each phase resulting in a significant reduction in torque ripple without any phase current overlap. The patent on this design has expired now so I think this SR design feature is very important for incorporation into any SR traction drive motor.

The tapered stator poles and relatively thick yoke of the HP type design provide one of the most quite SR motors ever made because. The section modules of the teeth and intersection to the yoke provides a very still stator structure that resists deflections caused by rotor to stator passing during rotation due to the magnetic attraction pulses.

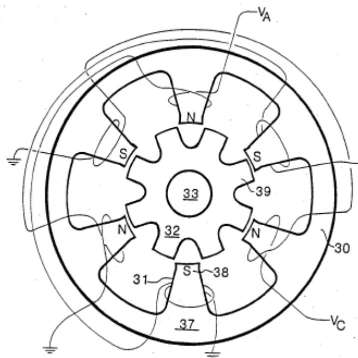


FIG 3

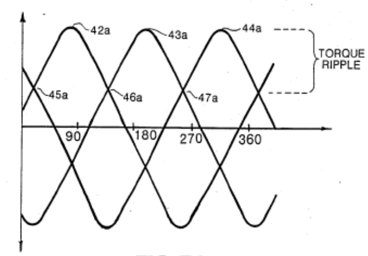


FIG 7A

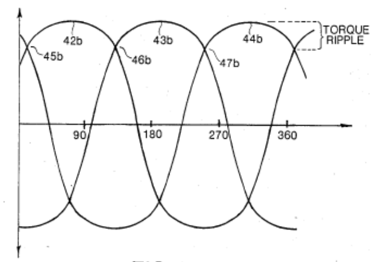
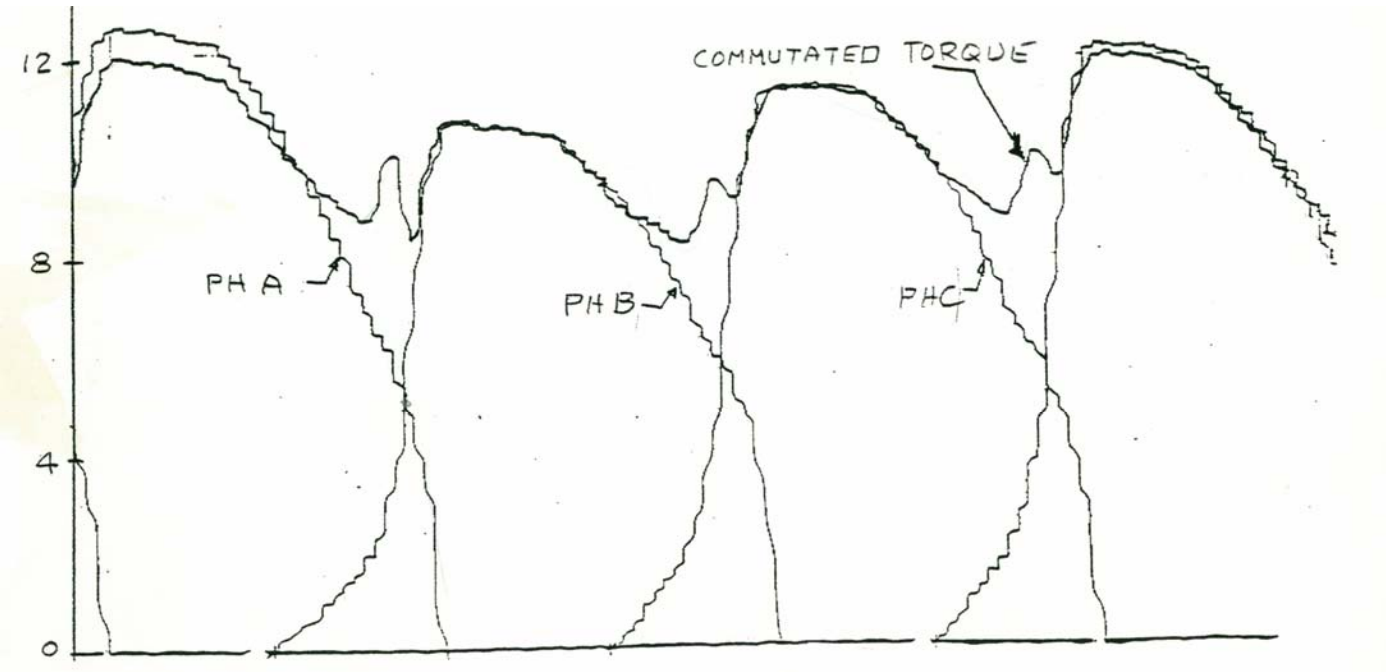
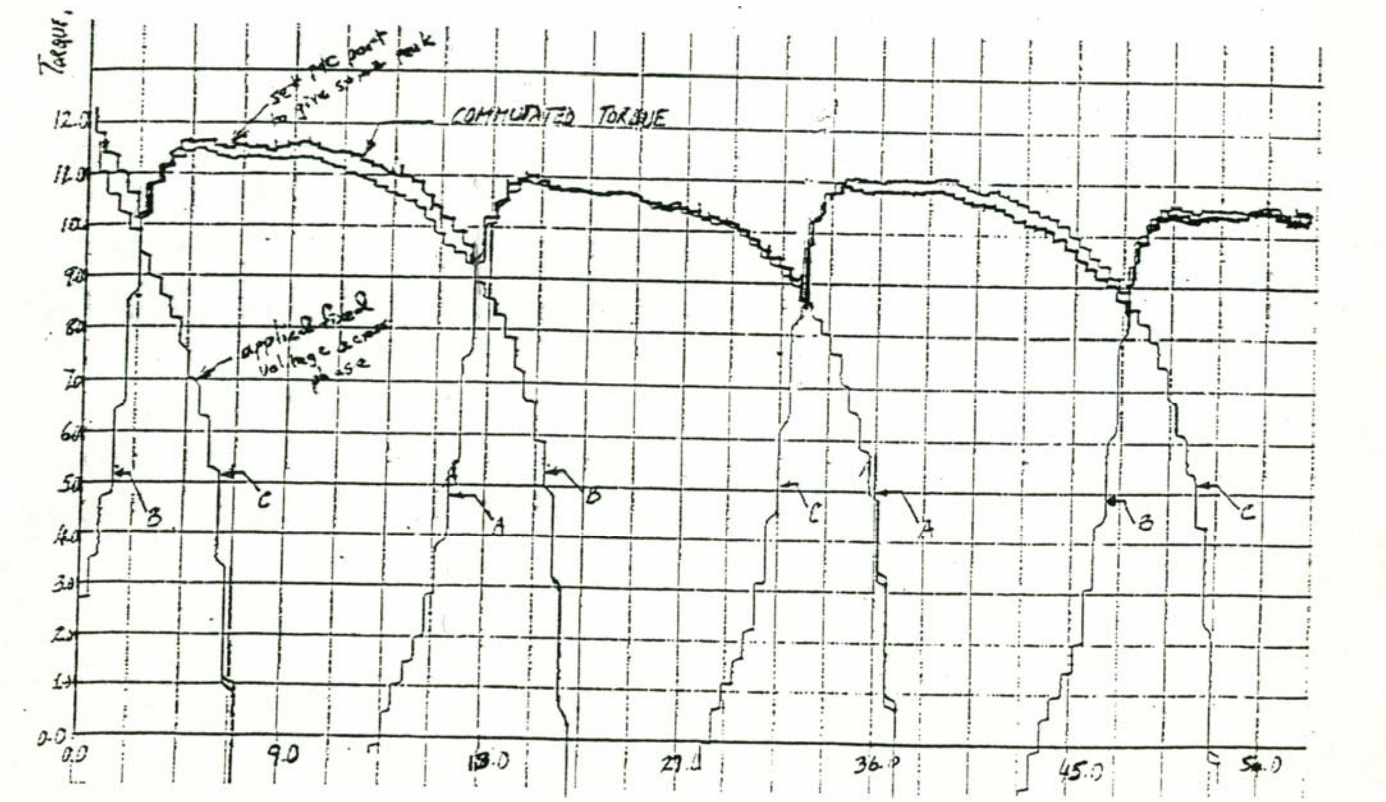


FIG 7B



12 OZ-IN TORQUE vs. ROTOR ANGLE HP 3 PH SR WITH PARALLEL STATOR TEETH



12 OZ-IN TORQUE vs. ROTOR ANGLE HP 3 PH SR WITH TAPERED STATOR TEETH

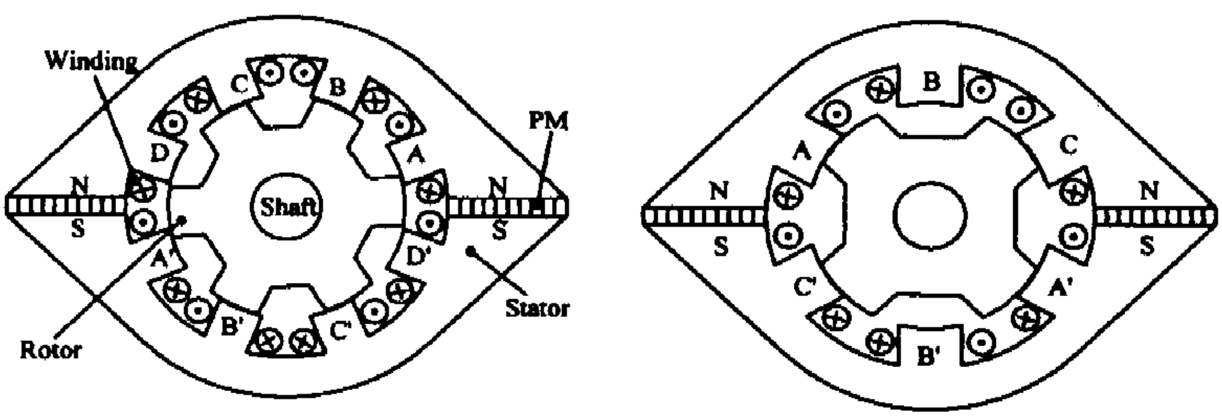
TWO PHASE SWITCHED RELUCTANCE MOTORS

Two phase SRMs have become very popular for fan, pump and vacuum cleaners plus other kitchen appliances because they are a very low cost solution to improve household motor efficiencies without requiring rare earth PMs and a minimum number of electronic components to drive them from rectified dc from the 60 Hz single phase grid. Since SRMs require two transistors per phase only 4 switching devices are required (plus 4 diodes). The limitation of the two phase SRM is single direction shaft rotation. Therefore it must be used for either cc rotation or ccw rotation but not both in the same application. Since IC engines cannot rotate in both directions so reversing gearing is required for driving backwards the two Phase single direction SR motor seems to be a low cost candidate for vehicle traction. The power density will not be as high as any other machine of any type but the cost to manufacture would be very low because there are only windings in the stator, the rotor is very simple like all SR motor rotors and there are no magnets. Having said that last statement there are designs and experiments that use magnets in the stator like the QM design described on page 12 and the one shown below.

Journal of Asian Electric Vehicles, Volume 3, Number 1, June 2005

Development of Doubly Salient Permanent Magnet Motors for Electric Vehicles

Ying Fan [1] and K. T. Chau [2]



(a) 8/6-pole (b) 6/4-pole

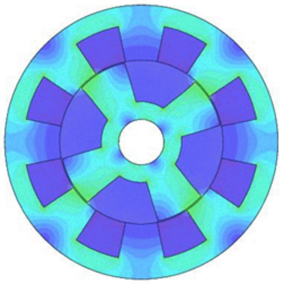
Fig. 2 Cross section of DSPM motors

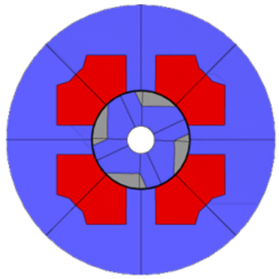
PROJECTS ON SWITCHED RELUCTANCE DRIVES

This centre and these projects have mostly moved to the Company Technelec Ltd, that was set up by Professor Pollock to exploit this technology

High Efficiency Switched Reluctance Drives

Research in the Department has resulted in the discovery that switched reluctance motors with an odd number of phase windings can be designed to operate with much higher efficiency than motors with an even number of phases. A five phase switched reluctance drive has now been designed with the full benefit of static and dynamic finite element analysis simulation software. This motor has been constructed in conjunction with a power mosfet power electronic controller. Efficiencies well above 80% have been recorded over a wide range of the motor's operating range with a full load drive efficiency of 87%.





One of the most interesting versions of the two phase SR motor with very low torque ripple and no dead spots is known as the *"Stagger Tooth SR Motor"* invented and patented by Wayne Pengov of Cleveland, Ohio. In addition to its large torque for each phase this design exhibits very low audible noise. The IEEE paper reference

A new low-noise two-phase switched reluctance motor
Pengov, W.; Hendershot, J.R.; Miller, T.J.E.
Electric Machines and Drives, 2005 IEEE International Conference on
Volume , Issue , 15-15 May 2005 Page(s):1281 - 1284
Digital Object Identifier 10.1109/IEMdc.2005.195887

Summary: *This paper presents a detailed analysis of a 2-phase switched reluctance motor in which a significant component of the acoustic noise (ovalization) is suppressed or neutralized by means of a flux-switching transition. The flux transforms naturally and smoothly without electronic control from a 2-pole to a 4-pole configuration before the phase current commutates, causing the ovalizing stress to be dispersed before the point of commutation. The unique asymmetrical geometry of the motor also produces low torque ripple, because the rate of change of inductance in each phase remains constant over a wide angle as the rotor rotates. Measurements and finite-element analysis show that this angle can approach 180 electrical degrees, which is exceptional for a 2-phase switched reluctance machine. With only two phases, the motor and drive connections are simplified; the component count is kept to a minimum, and the shaft-position sensing requirements are inexpensive. The paper describes the basic theory of the motor and presents test data together with new finite-element computations and insights*

[54] **STAGGERED POLE SWITCHED RELUCTANCE MOTOR**

[75] Inventor: **Wayne A. Pengov**, Hillsboro, Ohio

[73] Assignee: **Tridelta Industries, Inc.**, Mentor, Ohio

[21] Appl. No.: **09/216,449**

[22] Filed: **Dec. 18, 1998**

Related U.S. Application Data

[63] Continuation of application No. 08/545,085, Oct. 19, 1995, Pat. No. 5,852,334.

[51] **Int. Cl.**[7] **H02P 1/46**

[52] **U.S. Cl.** **318/701**; 318/254; 310/168; 310/269; 310/162; 310/179; 310/193; 310/261

[58] **Field of Search** .... 318/701, 254; 310/168, 166, 254, 261, 216, 193, 186, 269, 49 R, 162, 179, 191, 209; 340/815.64

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T. J. E. Miller; Switched Reluctance Motors and Their Control, 1993, pp. 2–3, 8–9, 14–15, 26–47, New York.

Primary Examiner—David Martin
Attorney, Agent, or Firm—Mark Kusner

[57] **ABSTRACT**

A switched reluctance machine includes a first element having a plurality of uniform poles and a second element having a first pole and a second pole. The first pole has a wide face and the second pole has a narrow pole face. The first and second elements are disposed for movement relative to each other such that the wide and narrow poles are moveable in spaced relation to the plurality of uniform poles.

13 Claims, 25 Drawing Sheets

0 DEGREES

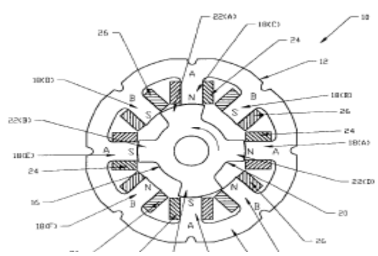
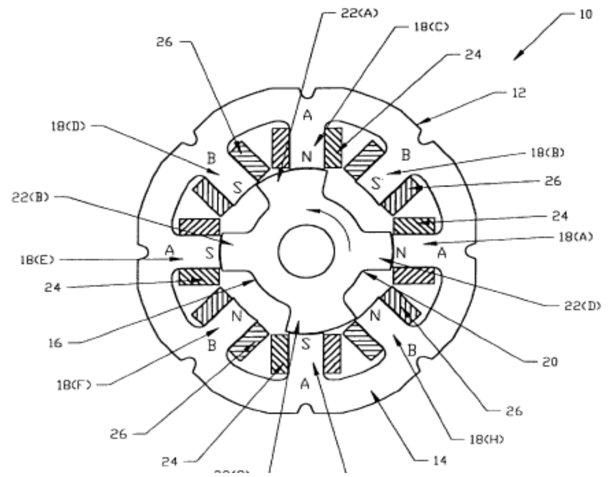
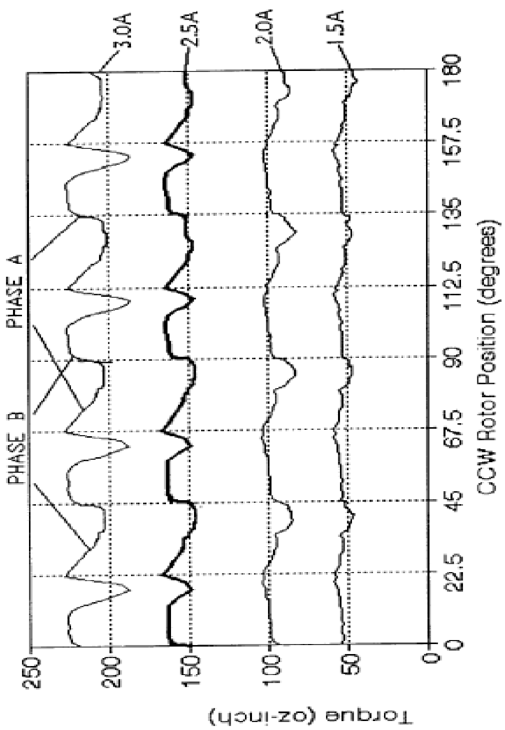


FIG. 1

0 DEGREES





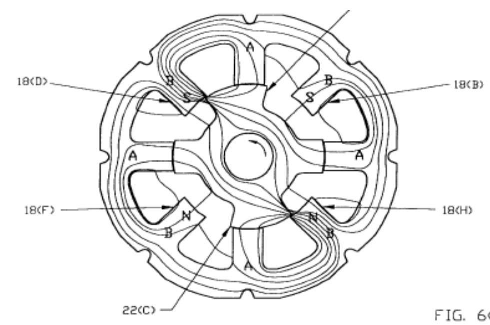


FIG. 6(A)
0 deg

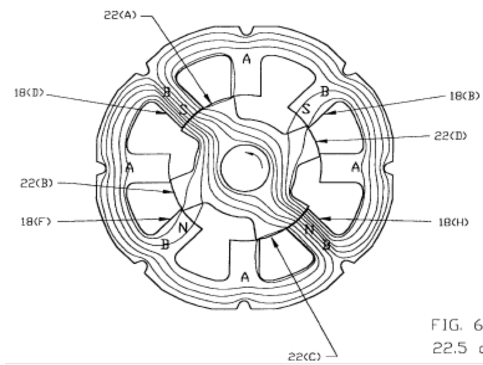


FIG. 6(B)
22.5 deg

The only transistor technology available for traction motors in the next few years is the IGBT and its assorted modules for 6 transistor bridges used for both the IPM and Ac induction machines. The SRMs will require new packaging into modules using IGBT technology. It seems the trend is to go for higher voltages as can be seen in the evolution of the Toyota traction machines. This trend is to be expected and is necessary to minimize the currents for low speed starting torques and still be able to achieve the highway speed for a wide constant power range. As the voltages increase a given transistor must operate at reduced currents and this is necessary due to the increased losses. The frequency has a lot to do with this so as we increase the number of poles to increase power and speed density of the motors to reduce their size the ratings of the switching devices must be reduced or the efficiency of the drive is trashed. The notable solution to this problem is multiple stage inverter. The three stage inverter is the future for vehicle traction drives as the frequencies and voltage increase. An example of a standard product from 5 to 500 HP is shown below.

P7 Drive, 5 - 500 HP

The P7 Drive: For industrial applications such as centrifugal fans and pumps, the P7 drive is an ideal choice. The drive is provided in Normal Duty ratings with 110% overload capability. V/f control mode, network communication options, and an array of input/output options are available.

The P7 is factory-programmed and ready to run. For operational simplicity and clarity, the LCD operator display has 5 lines x 16 characters. It can be set to any of 6 languages. The keypad is intuitive and includes parameter copying to move a chosen set of parameters from one drive to another. If the application requires programming, the P7 makes it easy. Parameters are grouped in easy to use sets; quick start and advanced. To enhance parameter and data management, DriveWizard software for the PC is available at no charge, for upload/download, trending, and graphing.

This drive is designed for tough industrial environments. It is rugged and reliable, with an MTBF of 28 years. A variety of enclosure options provide the right environmental protection. Providing the right power requirements is also easy with 208/240 and 480 volt ratings, built-in bus choke above 30 HP, common bus capability, and other energy savings options. Other features include motor auto-tuning and configurable options such as circuit breakers and fuses.

The P7 supports the industry's open architecture, open connectivity demands with network communications choices such as DeviceNet, Profibus-DP, and others. Drive coordination with other equipment is simplified with inputs and outputs for 4 to 20 mA, 0-10V, and an assortment of programmable contacts.

With an optional phase-shifting input transformer, the P7 dual-diode bridge can be operated in 12-pulse rectification mode, reducing input current harmonic distortion factor by over 90%. With lower EMI/RFI emission and lower total harmonic distortion contribution, the P7 meets or exceeds the generally accepted power quality standards. Inherent motor protection features resulting from low noise/low carrier technology provides for longer lead lengths without additional motor protection devices.

The optional P7/Bypass package is a 3-contactor style bypass, allowing motor operation from the drive or across the line. This facilitates drive maintenance while the motor continues to operate.

The P7 has been designed to provide the features and options commonly needed for fan and pump applications.

YASKAWA
The Drive for Quality™

P7 Drive

SUMMARY

The following in depth report is very important reading when considering the projected cost of IPM machines and comparisons to other motor technologies. If a copy is needed please let me know.

AMES LABORATORY
United States Department of Energy
Creating Materials and Energy Solutions

IS-5191

System Cost Analysis for an Interior Permanent Magnet Motor

August 2008

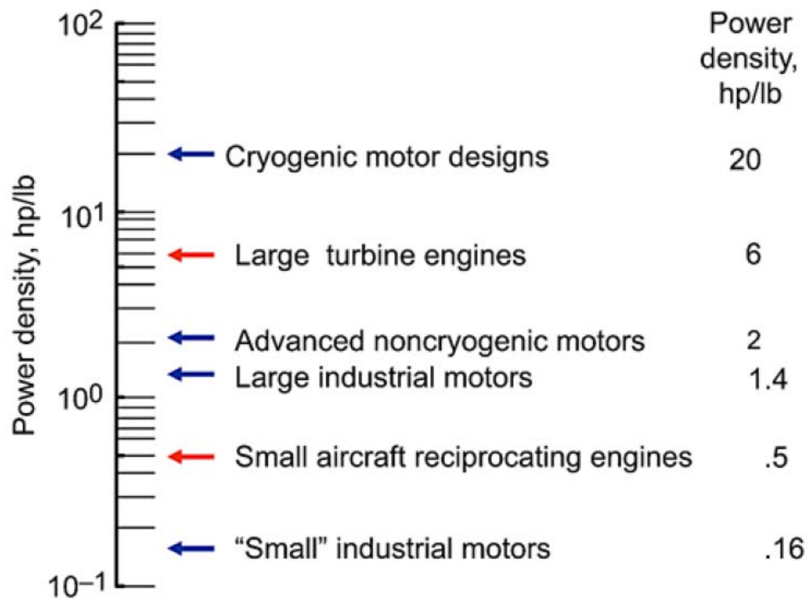
Peter Campbell
Consultant

Table 2: Comparison of active materials per motor in viable new designs

	New design, sintered NdFeB	New design, compression-molded NdFeB
Weight of magnets:	0.65 kg	1.39 kg
Total weight of active materials:	19.12 kg	19.09 kg
Peak power-to-weight ratio for active materials:	2.88 kW/kg	2.88 kW/kg
Cost of magnets:	\$59.26	\$54.45
Total cost of active materials:	\$172.92	\$163.68

Around the 160^{o}C temperature of interest, the grade of sintered NdFeB we selected has a greater safety margin with respect to its thermal stability than does the bonded NdFeB using anisotropic HDDR powder. However to do this, sintered NdFeB contains slightly more neodymium, much more dysprosium and

POWER
DENSITY
FOR
ELECTRIC
MOTORS
&
AIRCRAFT
ENGINES



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8. S. J. Boyd, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.
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