Rare-Earth Permanent Magnet Machines for Automotive Applications

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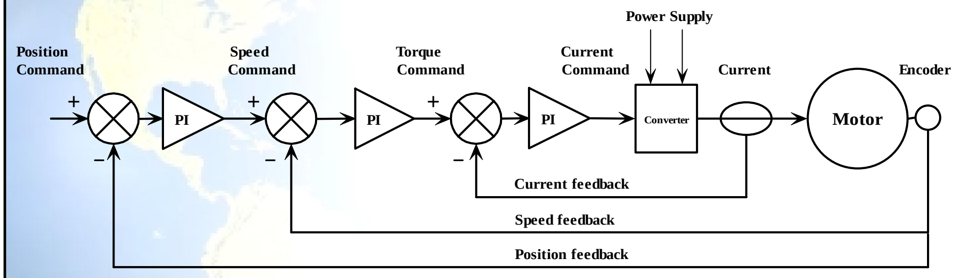
Motion Control



Course Outline

- Introduction
- Rare-earth PM material and its application
- PM machines and their applications
- Applications of PM machines in automobiles
- Practical issues of PM machines
- Speed and torque control of PM machines
- Practical issues associated with automotive applications
- Wrap up

Introduction

- **PM machines provide a unique set of advantages for modern control systems:**
  - Unsurpassed efficiency
  - Unit or leading power factor design
  - Increased reliability
  - High power density and low volume
  - Overloading capability and full torque capability at zero and low speeds
  - Braking or power feed-back at braking for many applications
- **Challenging in many ways**
  - Cost associated with PM material and power electronics unit
  - Sophisticated control algorithm
  - Assembly difficulties of magnets and increase of manufacturing cost
  - Temperature sensitivity
- **Requires expertise on both machines and power electronics**

Rare-earth Metals

- **What are rare-earths?**
  - Rare-earths are oxides of the **rare-earth metals**. They were once thought to be elements themselves. They are widely distributed in the earth's crust and are fairly abundant, although they were once thought to be very scarce.
  - Rare-earth metals are a group of metals including those of the lanthanide series (element number 57 to 71) as well as scandium(21), and yttrium(39) sometimes thorium(40).
  - Promethium(61), which is not found in nature, is not usually considered a rare-earth metal.
  - A subgroup of them, consisting of those with atomic numbers between 57 and 63 and ytterbium, is often called the cerium metals.
  - Neodymium(60) and Samarium(62) are most important ones to produce permanent magnets
  - The rare-earth metals usually occur together in minerals as their oxides (rare-earths) and are somewhat difficult to separate because of their chemical similarity.
  - Actinoids series (element number 89 to 103) are not usually considered as rare-earths

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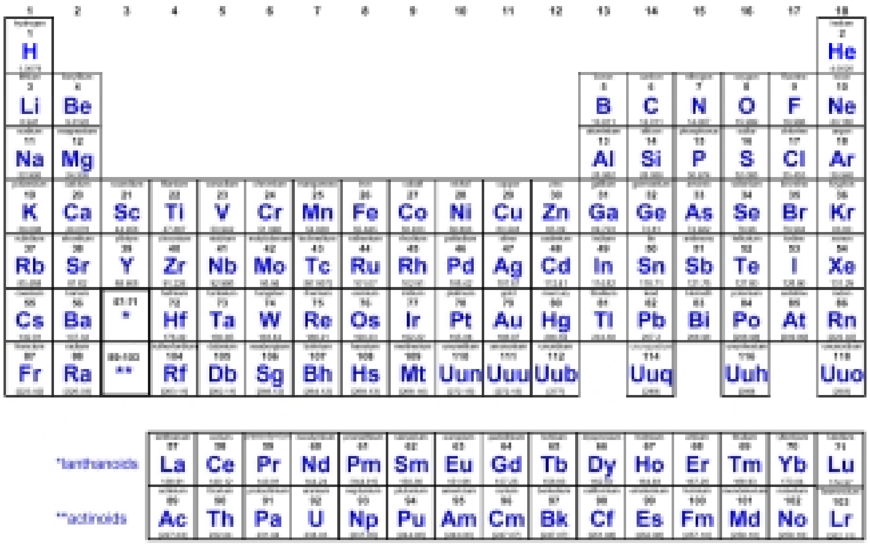
Periodic Element Table



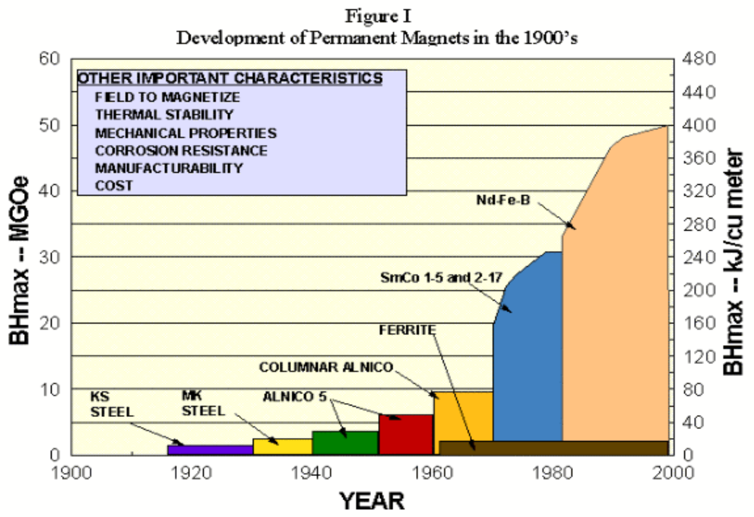
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71 *	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-102 **	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uuq		Uuh		Uuo

*lanthanoids	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**actinoids	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Application of Rare-earths

- **What to to with rare-earths?**
  - Mixed rare earths are used in glassmaking, ceramic glazes, glass-polishing abrasives, carbon arc-light electrode cores, and catalysts for petroleum refining.
  - Individual purified rare earths have many uses, e.g., in lasers and as color-television picture tube phosphors.
  - There are reports that rare-earth elements used in agriculture and curing diseases.
  - Misch metal is an alloy of the cerium metals often used in lighter flints, in alloys with other metals (especially magnesium), and to remove residual gases in the manufacture of vacuum tubes.
  - **Of course, making permanent magnets**
  - Important rare-earth minerals include bastnasite, cerite, euxenite, gadolinite, monazite, and samarskite.
  - Individual metals may be isolated as their compounds by ion exchange methods, solvent extraction, or fractional crystallization, and chemically or electrolytically reduced to the pure metal.

PM Material-a Brief History



AlNiCo Permanent Magnets

- **Properties and Design Considerations**
  - One of the oldest members magnets family, low priced
  - Alnico also has the lowest temperature coefficient of any commercial magnet material (.02% per degree centigrade) up to 1000F
  - Coarse-grained, hard and brittle, they cannot be drilled or conventionally machined
  - Can change magnetic orientation
  - High Br and low Hc compared to ceramic and rare-earth magnets
  - Magnetize after the magnet has been assembled with its pole pieces into the final magnetic circuit.
- **Application**
  - Electron tubes, radar, traveling wave tubes
  - Separators, holding magnets, coin acceptors, clutches and bearings
  - Magnetos, motors, generators, meters, instruments, controls, relays, watt-hour meters
  - Communications, receivers, telephones, microphones, bell ringers, musical instruments
  - Automotive sensors, loudspeakers

Ferromagnets (Ceramics)

- **Properties and Design Considerations**
  - High Hc and Hci compared to Alnico
  - Very fragile, require expensive tooling
  - Ceramics are good for simple shapes only
  - Demagnetization resistance, excellent corrosion resistance and low price
  - Temperature sensitive: 0.2% per degree centigrade. Coercivity, a measure of resistance to demagnetization, changes at a rate of about 0.27% per degree centigrade. As temperature rises, a ferrite magnet will increase in coercivity!
- **Application**
  - DC permanent magnet motors used in the automobile industry for blowers, window lifts, windshield wipers, etc. Many of the motors are out sourced by the auto companies. Separators to remove ferrous materials from liquid powder and bulk commodities
  - Magnetic Resonate Imaging, MRI
  - Magnetos used on lawnmowers, garden tractors and outboard motors
  - DC brushless motors with controllers for speed and direction

SmCo Magnets

- **Properties and Design Considerations**
  - Sintered samarium cobalt (SmCo) magnets available since 1970's. There are two types of composition in the Sm_1Co_5 and Sm_2Co_{14}
  - High Hc and Hci, high Br compared to other PM material
  - Very expensive
  - Outstanding thermal stability and excellent corrosion resistance
  - Can be used at up to 350ºC, with temperature coefficient at -0.030%, only higher than AlNiCo
  - Contains Cobalt as is in AlNiCo
- **Application**
  - Traveling wave tubes
  - Computer rigid disc drives
  - D.C. motors where temperature stability is vital, such as, Military use-satellite systems, small military motors, sensors, growing automotive applications and linear actuators
  - Pump couplings
  - Special cases where the magnet is required to operate at high temperatures, across a broad temperature range or in a corrosive environment

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Sintered NdFeB Magnets

- **Properties and Design Considerations**
  - Highest energy product of any PM material today (50 MGOe) and are available in a very wide range of shapes, sizes and grades
  - Less expensive than SmCo magnets but more expensive than AlNiCo and Ceramics
  - Corrosion that can result in loss of energy, protective coating is highly recommended (dip epoxy coating, dry electrostatic spray epoxy, nickel plating and combinations of these coatings)
  - Reversible temperature coefficient of .13%/ degree centigrade, Can be used only up to 150ºC
- **Application**
  - Voice coil motors (VCM's) in hard disk drives
  - High performance motors, (DC motors, synchronous motors, servo motors & automotive starters)
  - Magnetic separation
  - Magnetic resonance imaging (MRI),
  - Sensors and loudspeakers, microphones
  - Linear actuators and magnetic separators

Bonded NdFeB Magnets

- **Properties and Design Considerations**
  - Less energy product (10 MGOe) than sintered NdFeB
  - Can be made for different shapes and sizes with high dimension accuracy
  - May form together with other parts in one step to reduce cost
  - Free choice of magnetization direction best for multi-pole applications
  - High resistance to corrosion
- **Application**
  - Hard disk and CDROM drives spindle motors, printers
  - Mobile phones, loudspeakers, and microphones
  - Air conditioners and refrigerators
  - Sensors
  - Micro motors

Application of PM Materials

- **Automotive**
  - Permanent magnet starter / generator; sensors; electric fuel pumps; gauges; ZEV / LEV / HEV applications
- **Computer and Office**
  - Disk drive spindle and voice coil motors; printer and fax stepper motors copy machine rollers; CD-ROM drive spindle and pick-up motors
- **Consumer**
  - VCR and camcorders; cameras; speakers; headsets; microphones; pagers; watches; DVD players; telephones; microwave tubes; weighing systems
  - Toys and signs
- **Medical**
  - Nuclear magnetic resonance imaging devices (MRI); surgical tools; magnetic therapy
- **Appliance**
  - Portable tool motors; household appliance motors; microwave ovens
- **Industrial**
  - Robot motors; robot arms; magnetic coupling, pumps; servo motors

Permanent Magnet Machines

- **Permanent magnet electrical machines**
  - Commutator PM DC machines
  - Brushless PM synchronous generators
  - Line-start PM synchronous motors
  - Prushless PM DC motors

    Usually referred to PM motors that are fed with trapezoidal current
  - PM synchronous motors

    Usually referred to motors that are fed with sinusoidal current

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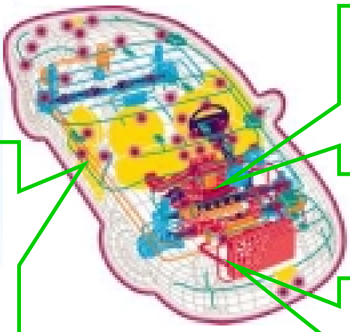
Automotive Applications



Body
- **Power lock**
- **Power window**
- **Power seat**
- **Power door**
- **Windshield wiper**
- **Air conditioner / Fan**
- **Radio antenna**
- **Suspension for magnetically**
- **levitated vehicles**

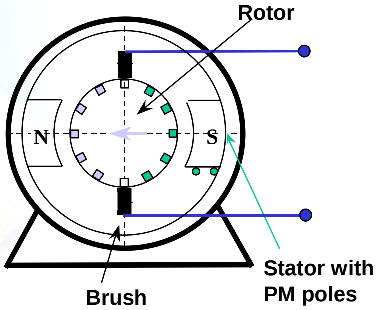
Chassis & Safety
- **Power steering**
- **Power brake**
- **Traction control**
- **Active suspension**

Powertrain
- **Alternator/Starter**
- **Integrated starter generator**
- **HEV generator / motor**
- **EV / LEV traction drive**

By-the-wire operation of modern vehicle!

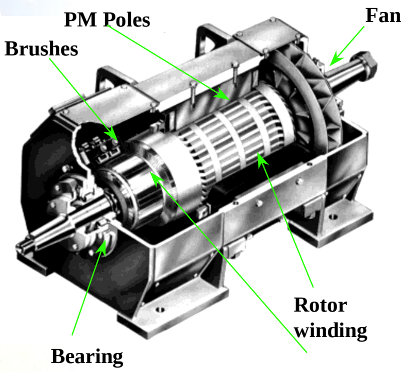
Commutator DC Machines

- **Configuration**
  - PM poles on stator and armature on rotor
  - Commutator needed
  - Used more as motors
  - Power ratings from a few watts to 100kW
  - Small PM DC motors magnets are magnetized after assembling while in larger PM DC motors, magnets are assembled after magnetization



Commutator DC Machines

- **Configuration**



Commutator DC Machines

- **Desirable control characteristics**
  - Constant torque operation
  - High efficiency compared to separately excited DC machines due to elimination of loss in field windings
  - Used in small DC motors/generators such as starters and alternators of vehicles
  - Light weight and less volume with the same power rating compared to DC excited motor/generators.
  - For battery operated machines, maximum constant torque can be achieve at starting up
- **Drawbacks**
  - High cost due to difficulty of manufacturing of rotor
  - A need for regular maintenance of commutators
  - Heavy rotor with high inertia
  - Restricted applications due to its open structure
  - Limited constant power speed range operation due to fixed airgap flux and armature reaction
  - For generators, it’s difficult to maintain desired voltage for different loads
  - Limitation on speed due to mechanical stress on commutators

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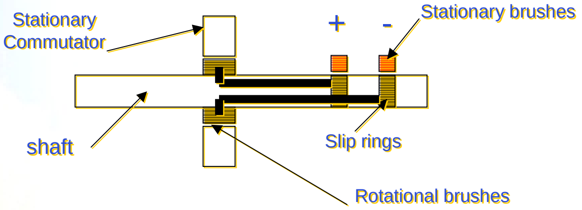
Commutator DC Machines

- **Inside out design**
  - Magnets are mounted on rotor and armature is stationary
  - Commutator is mounted on stator and brush are mounted on rotor shaft
  - Used for rare-earth PM machines to reduce material usage
  - One pair of stationary brush are needed to bring the current out, through the means of slip rings mounted on the rotor shaft



Brushless Synchronous Generators

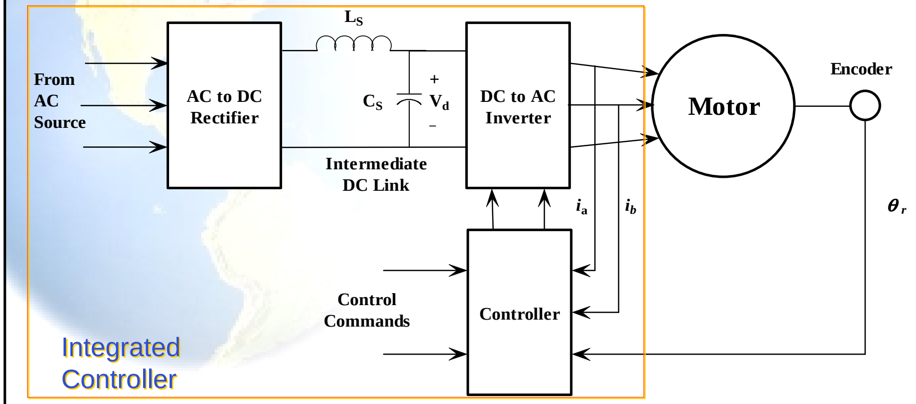
- **Configuration**
  - Inside rotor with magnets mounted
  - Stationary stator, single or three or multi-phase winding
  - Bridge rectifier to DC output or inverted back to fixed frequency and voltage AC
- **Inside out design**
  - Rotor is outside of stator, magnets are mounted on the inside of rotor
  - Used for applications such as small to medium gasoline generators
  - Increased security of magnets

Line-start PM Synchronous Motors

- **Configuration and characteristics**
  - Stator similar to that of a three-phase induction machines
  - Rotor contain inset magnets and squirrel cage for starting purpose
  - Motor running at synchronous speed, eliminating rotor loss
  - Increase power factor therefore reduced copper loss
  - Efficiency is usually 3-10% higher that an induction machine with the same power rating
- **Drawbacks**
  - Complicated rotor design make it difficult to manufacture
  - Huge starting current compared to induction machines
  - Oscillation torque during starting may damage the motor shaft
  - Pull-in torque is usually an issue
  - Used mostly for applications where there is no load at start or starting torque of the load is very light
  - Used for applications where frequent staring of machine is not common
  - Size of this category PM motor is usually small – up to 50kW

PM Synchronous Motors

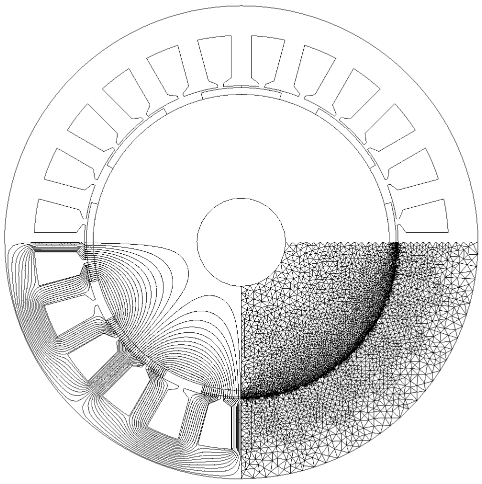
- **System components**
  - Rectifier and DC linker
  - Inverter and Control unit
  - PM motor
  - Position sensor (encoder)



From AC Source
AC to DC Rectifier
L_S
C_S
+ V_d –
Intermediate DC Link
DC to AC Inverter
Motor
Encoder
i_a
i_b
θ_r
Control Commands
Controller
Integrated Controller

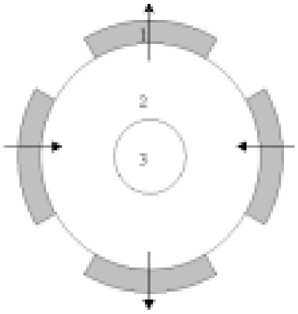
PM Synchronous Motors

- **Motor Configuration**
  - Stationary stator
  - Rotor with magnets



PM Synchronous Motors

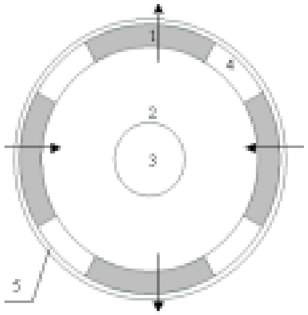
- **Surface mounted**
  - Simple and cheap construction
  - Magnet is glued on to the surface of rotor
  - Rotor is not secure
  - Magnet may fly away due to repeated centripetal force and corrosion of magnets
  - Magnets are actually made in cuboids to reduce manufacture cost



1. Magnets
2. Rotor laminations or solid steel
3. Shaft

PM Synchronous Motors

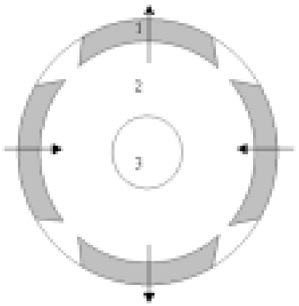
- **With sleeve rings**
  - Most secure
  - Resistance to breakage and corrosion
  - Costly to make sleeve ring for large PM machines
  - Non-magnetic material in inter-polar space
  - Rotor can be solid steel



1. Magnets
2. Rotor laminations or solid steel
3. Shaft
4. Non-magnetic material
5. Sleeve ring

PM Synchronous Motors

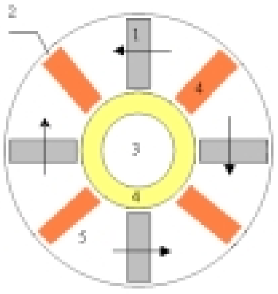
- **Inset magnets**
  - Increased security compared to surface mounted
  - Less expensive compared to rotors with sleeve rings
  - Rotor must laminated steel due to surface loss



1. Magnets
2. Rotor laminations non-solid steel
3. Shaft

PM Synchronous Motors

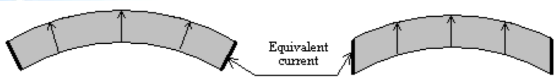
- **Circumferential magnets**
  - Flux concentration function, can significantly increase airgap flux
  - Suitable for 4 or more poles
  - Rotor must laminated steel due to surface loss
  - Very large quadrate synchronous reactance
  - Holes can be made at inter-polar space to balance direct and quadrate reactance
  - Magnetic bridge is kept for the integrated structure of lamination
  - Leakage flux through magnetic bridge is not negligible



1. Magnets
2. Magnetic bridge
3. Shaft
4. Non-magnetic material
5. Rotor laminations

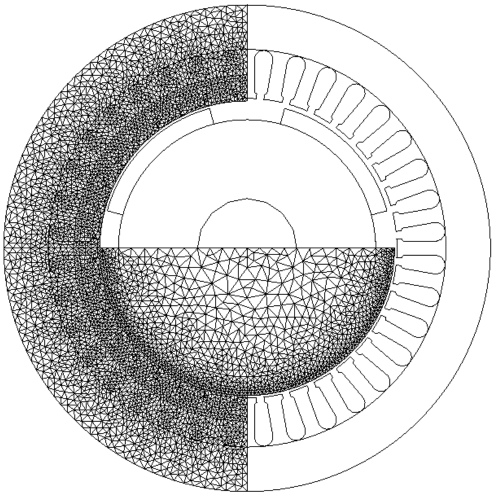
PM Synchronous Motors

- **Magnetization of magnets**
  - Magnetization is usually after assembly for rare-earth magnets
  - Parallel magnetization
  - Radial magnetization



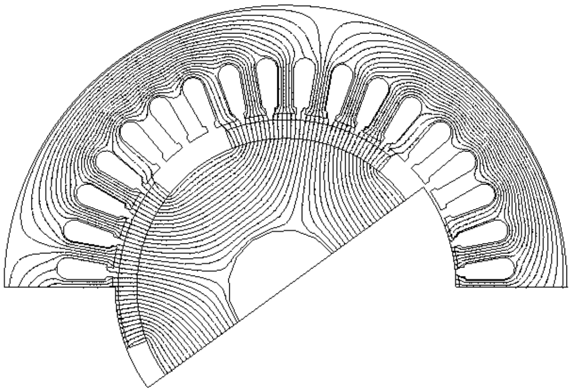
PM Synchronous Motors

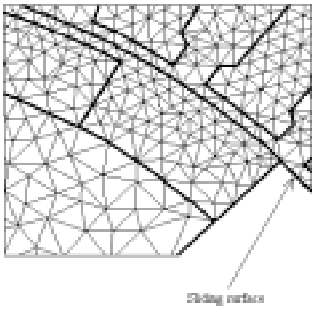
- **Finite element analysis**



PM Synchronous Motors

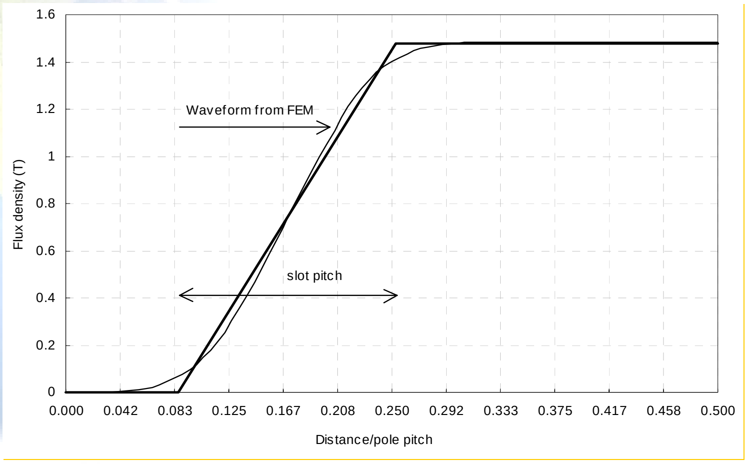
- **Finite element analysis**

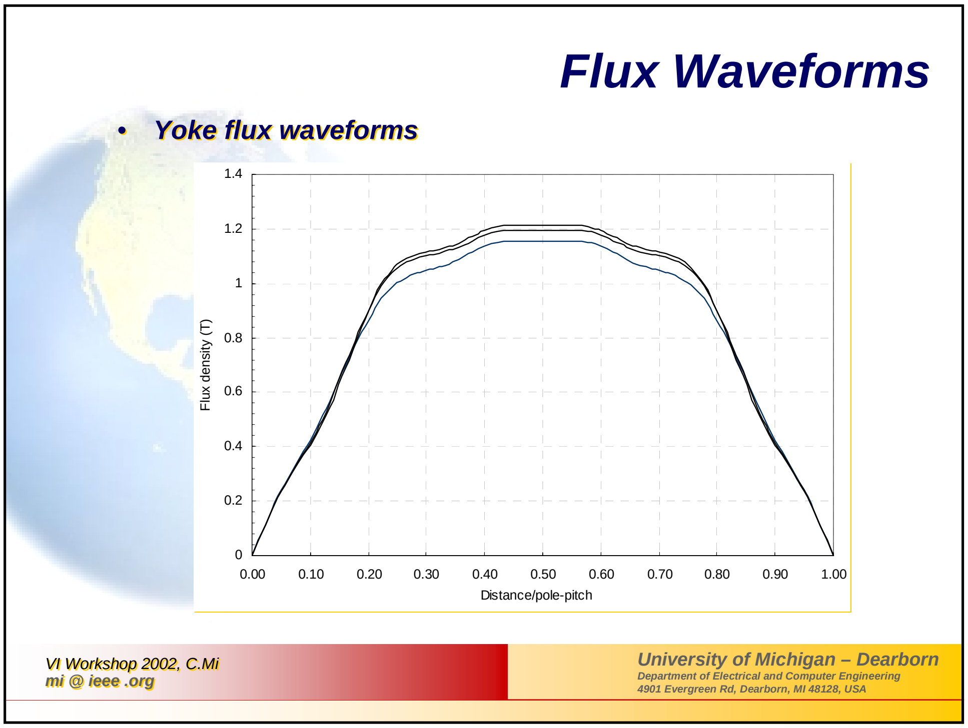




Flux Waveforms

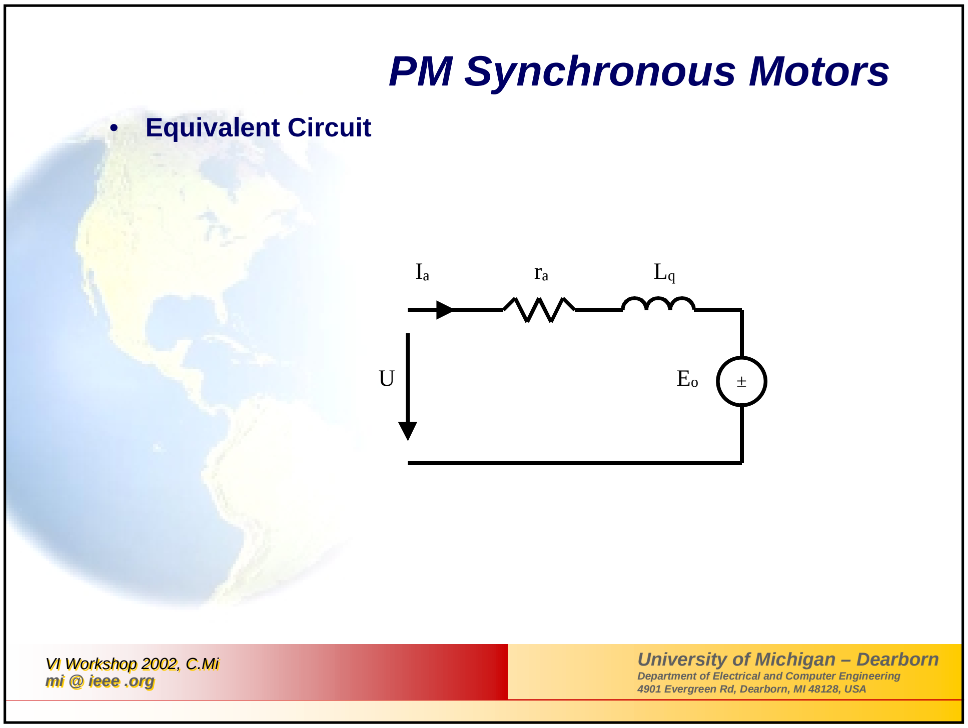
- ***Tooth flux waveforms***





Flux Waveforms

- *Yoke flux waveforms*

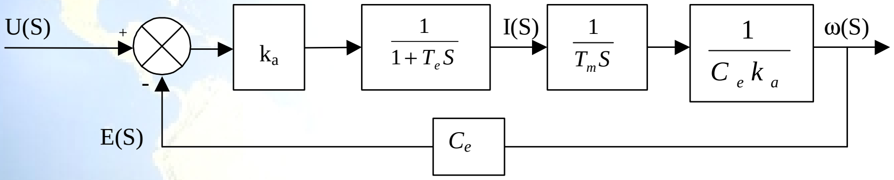


PM Synchronous Motors

- **Equivalent Circuit**

PM Synchronous Motors

- **Transfer function**



PM Synchronous Motors

- **Speed-torque curve (DC)**

$$E_a = K_a \omega_m$$

$$T = K_a I_a$$

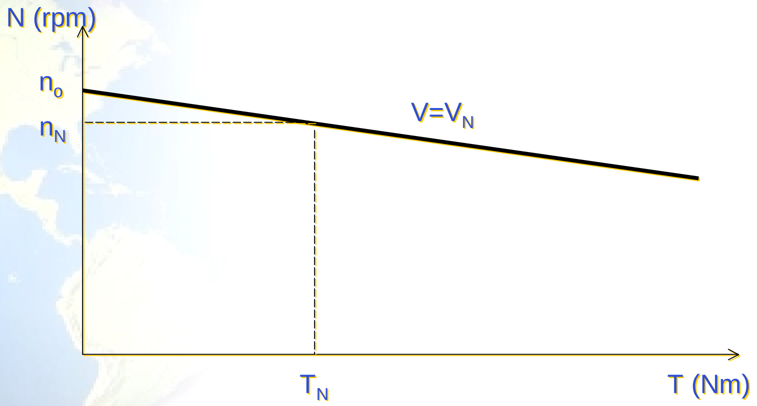
$$V_d = E_a + I_a R_a$$

$$\omega_m = \frac{V_d}{K_a} - \frac{R_a}{K_a^2} T \quad or$$

$$n = n_o - kT$$

PM Synchronous Motors

- **Speed-torque curve (DC)**



PM Synchronous Motors

- **Speed-Torque curve**

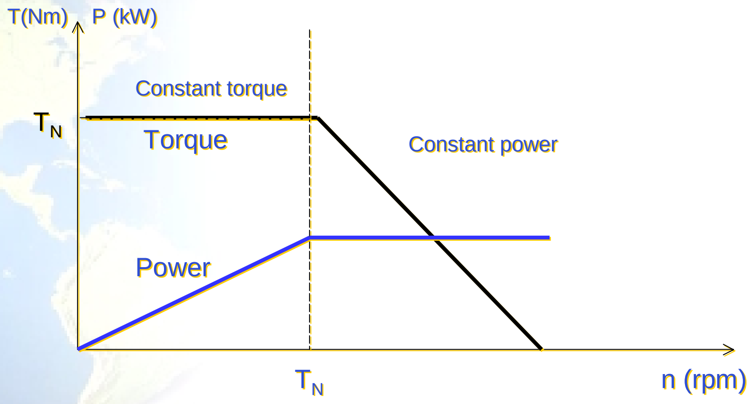
$$T = \frac{K_a}{R_a} V_d - \frac{K_a^2}{R_a} \omega_m \qquad or$$

$$\omega_{\max} = \frac{V_{d,\max}}{K_a} \quad if \;\; R_a \; is \, negligible$$

- **To keep constant torque, Vd needs to be variable**
  - Once Vd reaches maximum, no more constant torque can be maintained
  - Beyond the constant torque region, speed can be further increased by maintaining a constant power

PM Synchronous Motors

- **Speed-Torque curve**

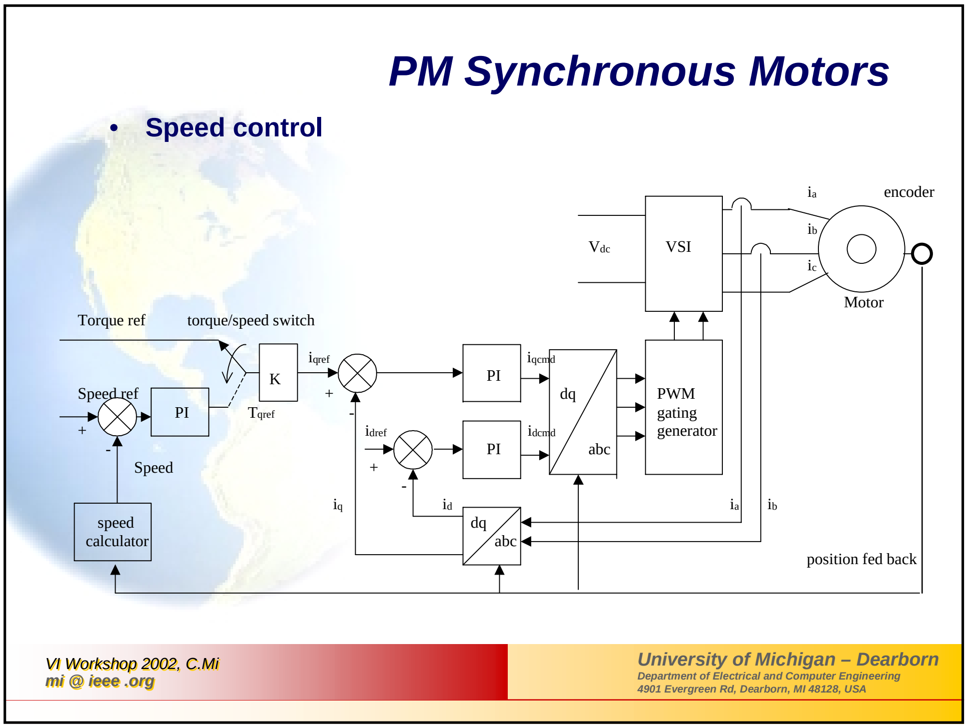


PM Synchronous Motors

- **Torque compensation**
  - Actual torque at rated current will fluctuate due to the decrease of total flux due to temperature and armature reaction

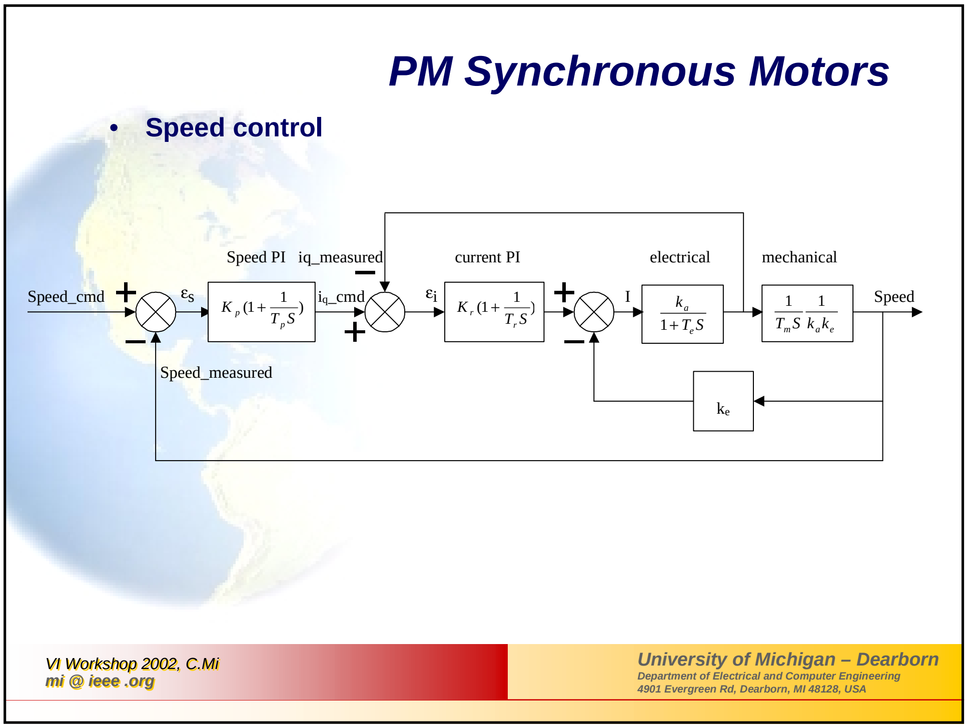
$$T = K_a{}' \Phi I_a$$

  - In order to maintain a constant torque, current must be compensated



PM Synchronous Motors

- **Speed control**

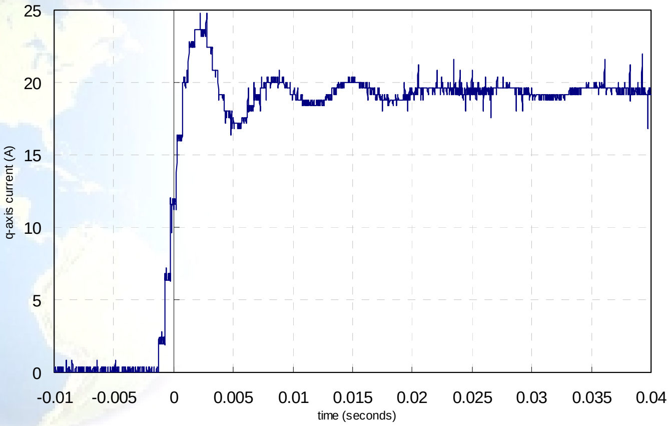


PM Synchronous Motors

- **Speed control**

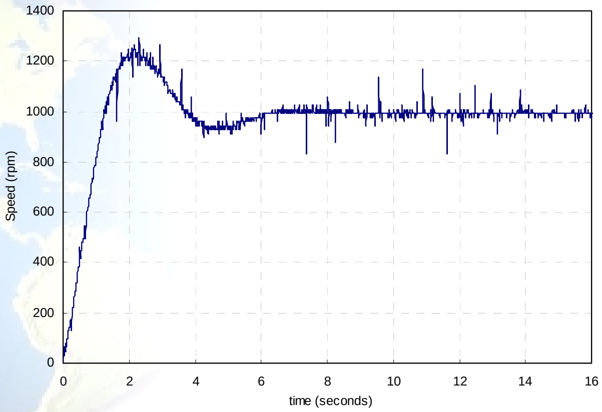
PM Synchronous Motors

- **Current response**



PM Synchronous Motors

- **Speed response**

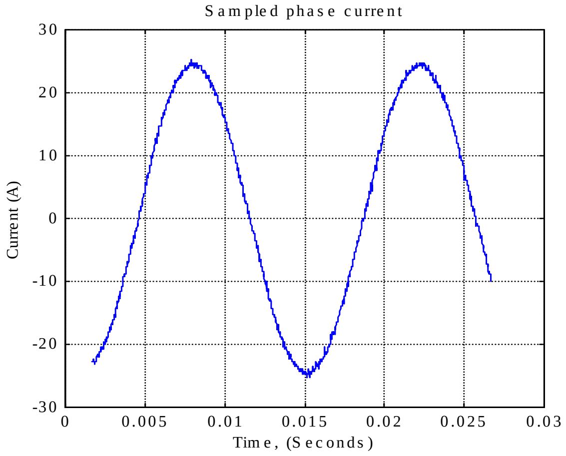


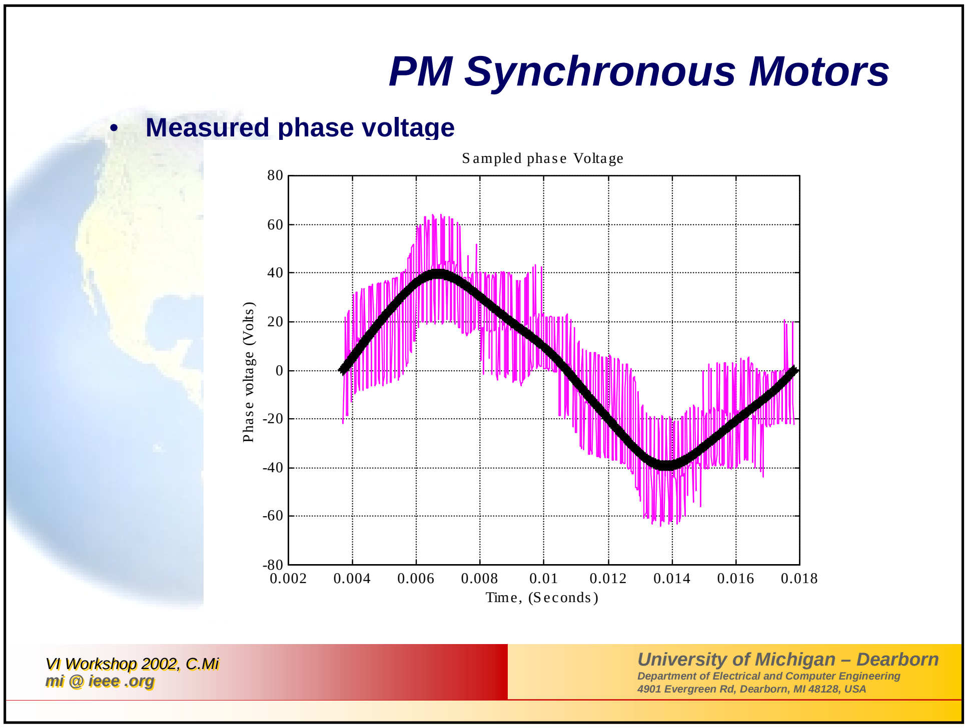
PM Motors - Losses

- **Loss components**
  - Copper loss
  - Windage and friction loss
  - Iron loss
  - No rotor loss in general
- **Loss measurement**
  - Mechanical loss and iron loss are always present, it's usually difficult to separate them
  - Use the rotor of an identical induction machine to measure windage and friction loss
  - Use a replica of rotor with non-magnetic stator
  - Measuring before magnets assembled, preferably with non-magnetized magnets assembled on the rotor (A dummy rotor)
- **Measurement of power**
  - Voltage are PWM waves
  - Validate measurement using phasor analysis for fundamental quantities
  - Computerized data acquisition
  - Matalb implementation of power and loss calculation

PM Synchronous Motors

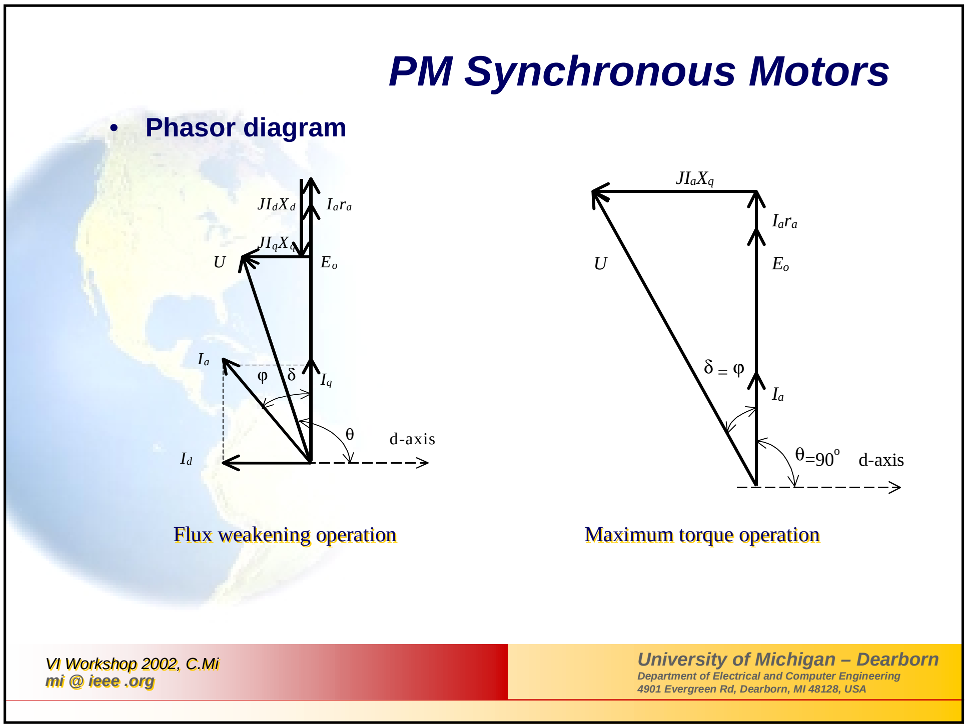
- **Phase current at steady state operation**





PM Synchronous Motors

- **Measured phase voltage**



PM Synchronous Motors

- **Phasor diagram**

Flux weakening operation

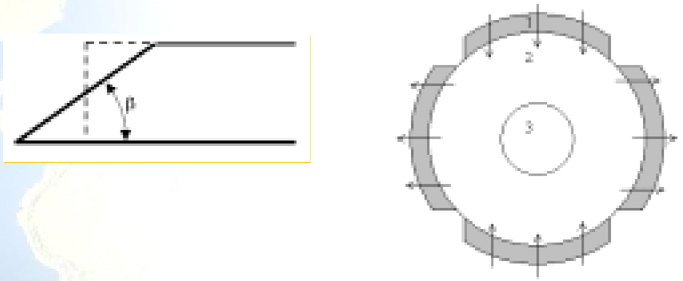
Maximum torque operation

PM Motors - Optimization

- **Criteria**
  - Balance between manufacturing cost, efficiency, power factor, and torque capability
  - Using better material
  - Optimized design and control algorithm
- **Rotor**
  - Beveled magnet edge
  - Appropriate magnet coverage
- **Stator**
  - Skewed stator slots
  - Partly closed slots
  - Sinusoidal winding distribution but less possible slots
- **Number of poles**
  - Free choice of number of poles, not constrained by speed
  - Better torque by using more poles due to reduction of stator yoke size
  - Efficiency has optimal value when poles are 4, 6, or 8

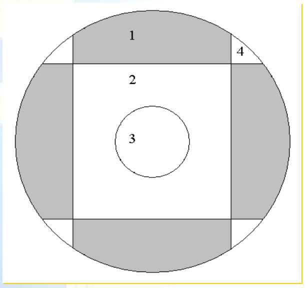
Alternative Configurations

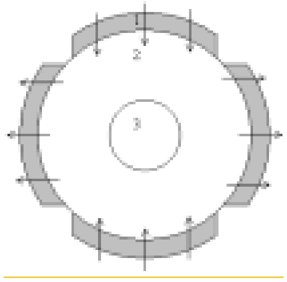
- ***Beveled magnet edge can significantly reduce iron losses***



Alternative Configurations

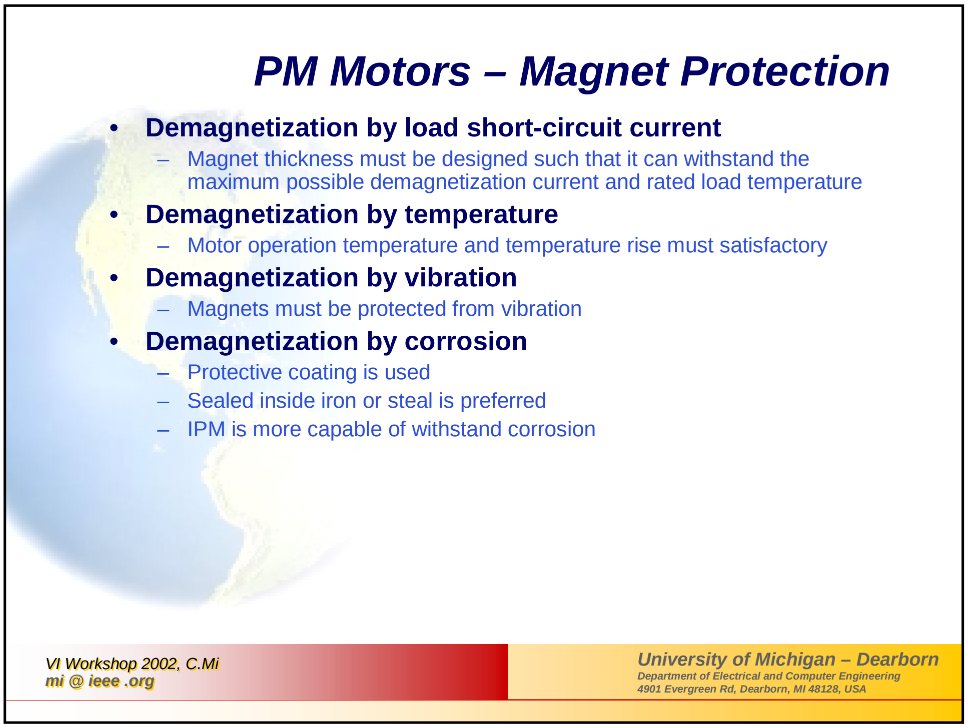
- *Curved magnets and optimized magnet coverage to reduce iron losses*





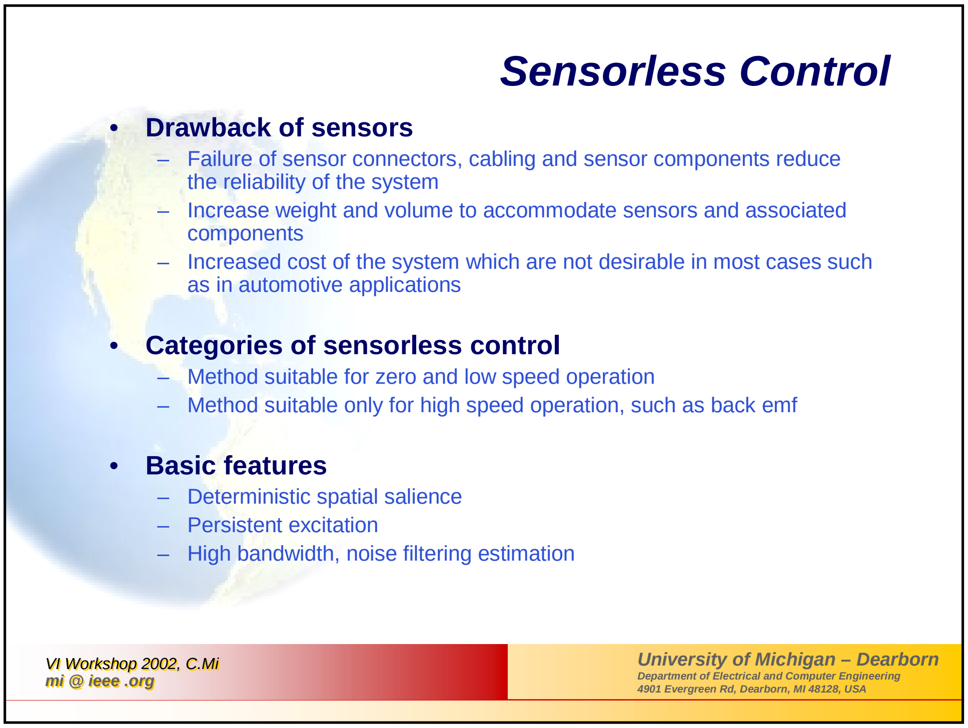
PM Motors – Cogging Torque

- **Cogging torque – Not a desired feature for any application**
  - Noise
  - Non-smooth low speed operation
  - Damage of load unit
- **Causes**
  - Stator slots
  - PWM waves and its harmonics
  - Rotor salience
- **Cogging torque reduction**
  - Improved control algorithm
  - Skewed stator slots
  - Curved magnets
  - Pole width and spacing
  - Tooth/slot ratio
  - Increased resolution of rotor position feedback



PM Motors – Magnet Protection

- **Demagnetization by load short-circuit current**
  - Magnet thickness must be designed such that it can withstand the maximum possible demagnetization current and rated load temperature
- **Demagnetization by temperature**
  - Motor operation temperature and temperature rise must satisfactory
- **Demagnetization by vibration**
  - Magnets must be protected from vibration
- **Demagnetization by corrosion**
  - Protective coating is used
  - Sealed inside iron or steal is preferred
  - IPM is more capable of withstand corrosion



Sensorless Control

- **Drawback of sensors**
  - Failure of sensor connectors, cabling and sensor components reduce the reliability of the system
  - Increase weight and volume to accommodate sensors and associated components
  - Increased cost of the system which are not desirable in most cases such as in automotive applications
- **Categories of sensorless control**
  - Method suitable for zero and low speed operation
  - Method suitable only for high speed operation, such as back emf
- **Basic features**
  - Deterministic spatial salience
  - Persistent excitation
  - High bandwidth, noise filtering estimation

Sensorless Control

- **Deterministic salience of PM machines**
  - Create or identify salience of the machine
  - Inset PM (IPM) synchronous machine have inherently large salience
  - Design modification to introduce salience, such as skew stator slots, add magnetic shoes to surface mounted magnets
  - Use saturation induced salience
- **Persistent excitation**
  - Excitation must present in order to see the salience
  - Excitation must not interfere the power conversion or generate noise
- **High bandwidth, noise filtering estimation**
  - Extract the salience information
  - Low carrier frequency is desirable
  - Many algorithm can be used for this purpose

Sensorless Control

- **Main issues**
  - Salience must strong enough for desired accuracy
  - Optimal salience without interference machine characteristics
  - Eliminate interference of saturation
  - Eliminate interference of load current
- **Elimination of current sensor**
  - Embedded into power devices

PM Motors-Direct Drive

- **Reduce parts count**
  - For automotive and many applications, eliminate gear box, ball screw, belts/pulleys, couplings, or chain drives
  - Reduce total space usage and weight
  - Simplify installation process
- **Reduced maintenance and better performance**
  - Reduce maintenance for lubrication of gears, seal leakage and replacement
  - Less noise, cleaner, last longer
  - Increase system efficiency: higher efficiency motor and eliminate loss of mechanical units
- **Better control accuracy**
  - High feedback resolution
  - Better repeatability of position feedback
  - True position of the load unit

PM Motors-Direct Drive

- **Inside out design made possible**
  - Flexible out rotor design
  - Easier manufacturing process
- **Increase reliability**
  - Reduce premature failure of mechanical transmission
  - Increase reliability due to reduce parts count
- **Integrate brake function**
  - Generative brake or electromagnetic brake
  - Reduce wear and maintenance of brake unit

Reluctant Motors

- **Simple and economical**
- **Need absolute position sensor**
- **Pulsating torque and acoustic noise**
- **Not able to compete with PM machines**

Time Line

- **Electrical machines**
  - James Watts: Steam engine in 1785
  - Michael Faraday: a true DC machine - a PM machine, 1833
  - Thomas Edison: DC generator and power distribution, 1870
  - James Maxwell publishes Maxwell's equations, 1873
  - Nickola Tesla: commercial electrical machine, 1888
  - Harrison: first brushless motor using transistor, 1955
- **Materials**
  - Iodestone: first use of magnets in 800BC
  - William Gilbert publishes *de Magnete,* 1600
  - Cobalt Chrome Steel, 1921
  - Alnico, 1935
  - Ferrite, 1951
  - Samarium-cobalt magnets, 1969
  - Neodymium-Iron-Boron(NdFeB),1983

Wrap-up

- **Questions from last seminar**
  - What are the differences between Brushless PM DC and PM synchronous?
  - What are the advantages using PM machines instead of induction motors?
  - What are the main applications of PM motors in automotives?
  - What is cost of a typical PM synchronous motor for a passenger car?
  - What is cost of a typical drive unit for a PM synchronous motor of a passenger car?
  - How to determine the torque and power rating for a vehicle?
  - What's the relationship of motor volume/weight and motor speed
  - How to start a design? What parameters have to be assumed first?
  - What is more reliable: mechanical transmission vs. electrical transmission?
  - What is more reliable: mechanical components vs. and operation –by-the-wire?
  - What is the typical range of an pure battery operated electrical vehicle?
  - How much torque can a PM machine supply at standstill?
  - What is the most appropriate voltage rating for an electrical vehicle from the motor and drive point of view?

Wrap-up

- **Questions from this seminar seminar**
  - ??

To Probe Further

- B. K. Bose, *Power Electronics and Variable Frequency Drives*
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  - John Wiley & Sons, 1995
- Duane C*. Hansclman, Brushless Permanent-Magnet Motor Design*
  - McGraw-Hill, 1994
- Kenjo, T. & Nagamori, S., *Permanent-Magnet and Brushless DC Motors*
  - Clarendon Press-Oxford Univ., 1985
- James R. Hendershot T. J. Miller, *Design of Brushless Permanent-Magnet Motors*
  - Oxford University Press, 1994

Questions, Comments?

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Thank You !