

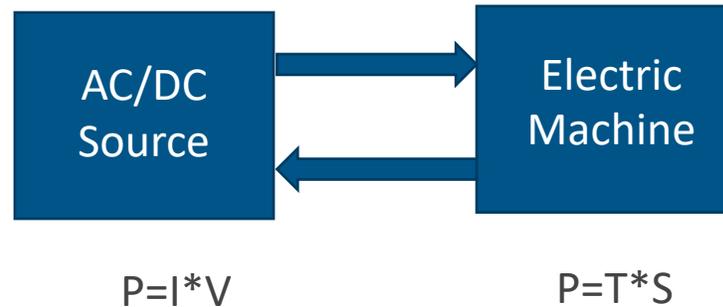


# Motor Design: Basic Tutorial



# Electric Machine

- Electric machine - transducer for converting electrical energy to mechanical energy or mechanical energy to electrical energy.



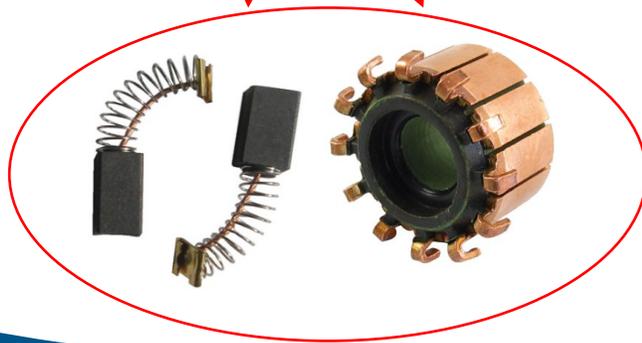
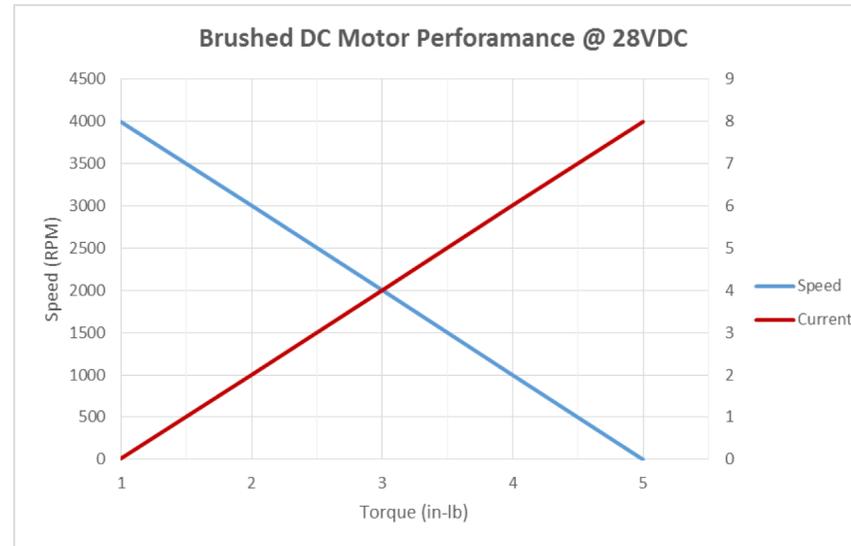
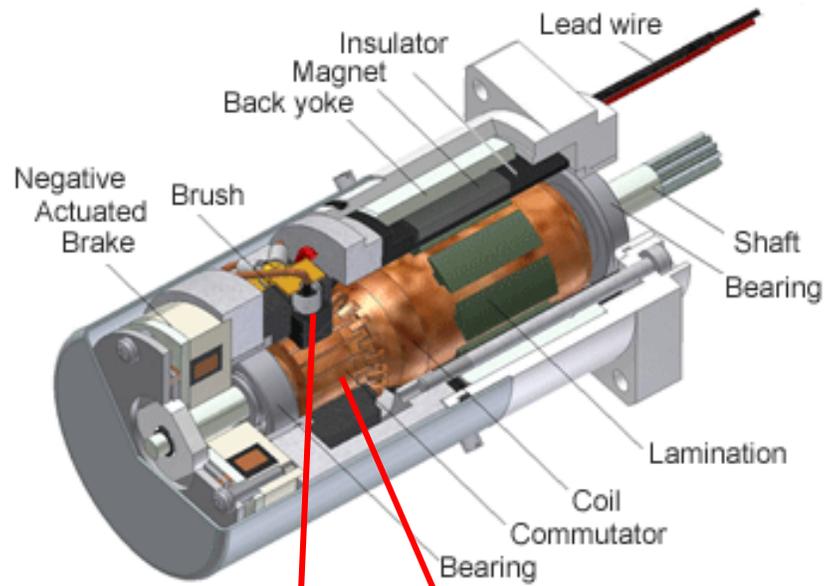
- Type of Electric machine
  - Motors
  - Generators
  - Sensors
  - Electromagnets
  - Electromagnetic amplifiers, etc.

# Types of Motors (Commonly used in our industry)

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- AC Induction
  - Squirrel Cage
  - Wound Field
- Brushed DC
- AC Synchronous
  - Permanent magnets
  - Wound field
- Brushless AC/DC
- Switched reluctance
- Linear
  - Flat
  - Tubular
- Stepper
  - Permanent Magnet (PM)
  - Variable Reluctance (VR)
  - Hybrid Stepper
  - Linear

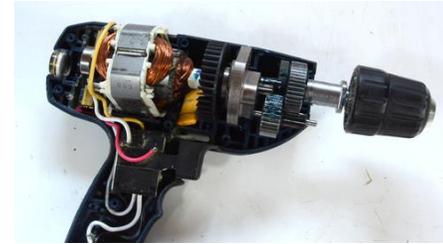
# Typical Brushed DC Motor Construction and Performance



- Easy to predict motor performance
- Difficult to design brush system
- Availability of the brush system components
- Very difficult to predict brush life
- Not a motor of choice for new applications, replacement or redesign
- Manufacturing cost very low for mass production, when fully tooled

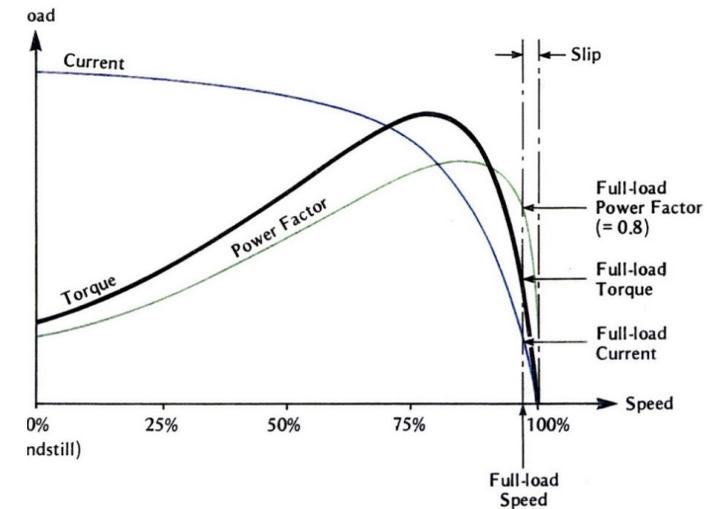
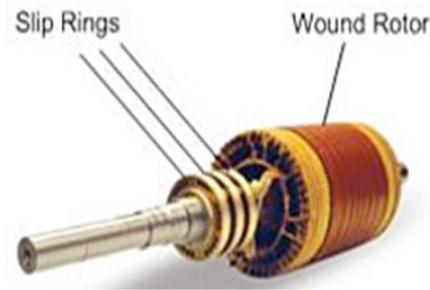
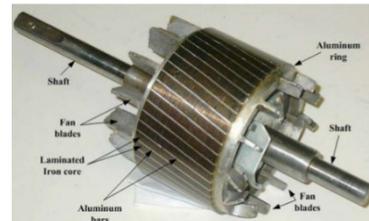
# Applications for Brushed DC Motor

- Appliances
- Hand tool
- Automotive
- Military and aerospace
- Autopilot/Auto-throttle Applications
- Fin Controls
- Gimbal Applications
- Optics & Radars
- Down-hole oil and gas exploration



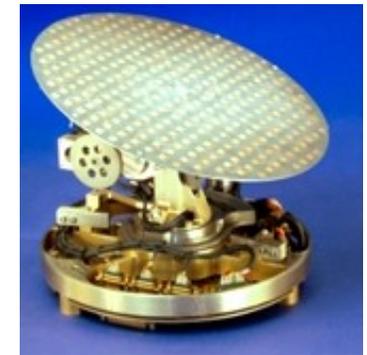
# Typical Induction Motor Construction and Performance

- Easy to predict motor performance for a three phase design, notoriously difficult for a single phase design
- Limited availability for copper fabricated rotors
- Still a motor of choice for a new 400 Hz aerospace applications
- Manufacturing cost low for mass production, when fully tooled



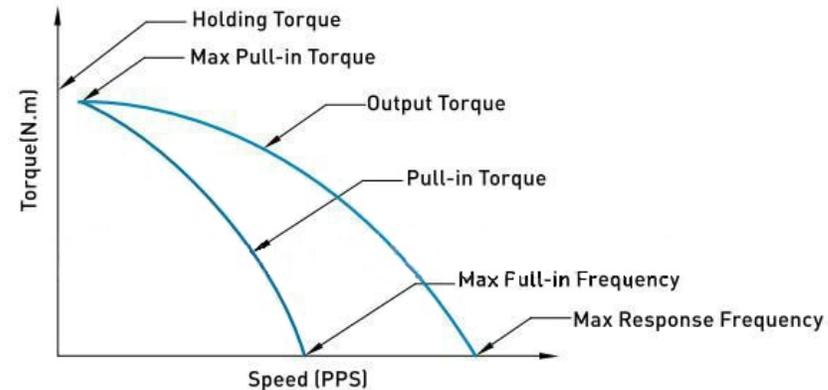
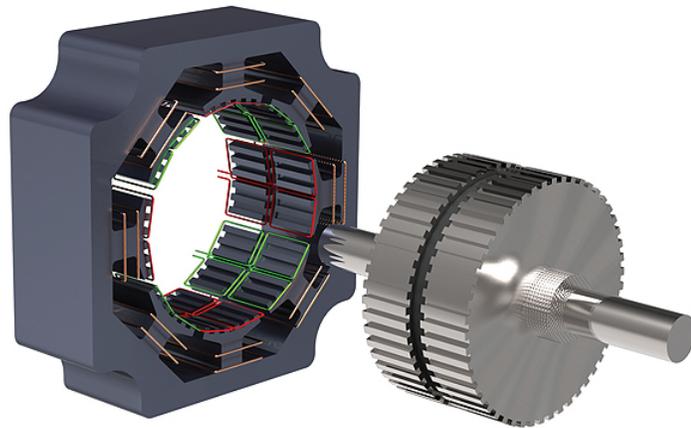
# Applications for AC Induction Motor

- Fans, Blowers & Pumps
- Aerospace
- Industrial
- Flight Controls
- Radar Drives
- Environmental Control Systems
- Throttle/Pilot Interface Devices
- Down Hole Applications
- Valves



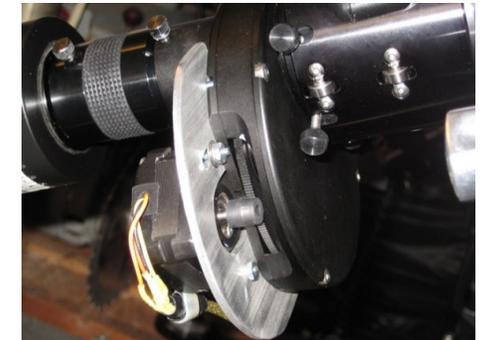
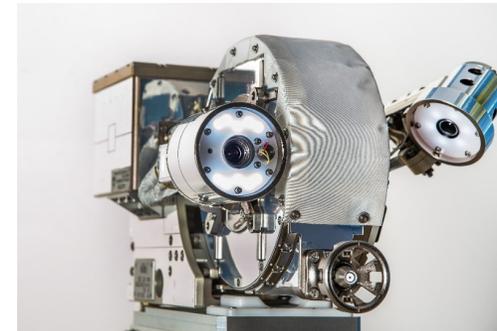
# Typical Hybrid Stepper Motor Construction and Performance

- Difficult to predict motor performance, based on design experience
- Not a motor of choice for new applications, however is still attractive for some space applications when feedback device not used, replacement or redesign
- Sometimes require precision lamination stamping
- Manufacturing cost very low for mass production, when fully tooled, for example, NEMA 17 hybrid stepper motor cost less than \$10.



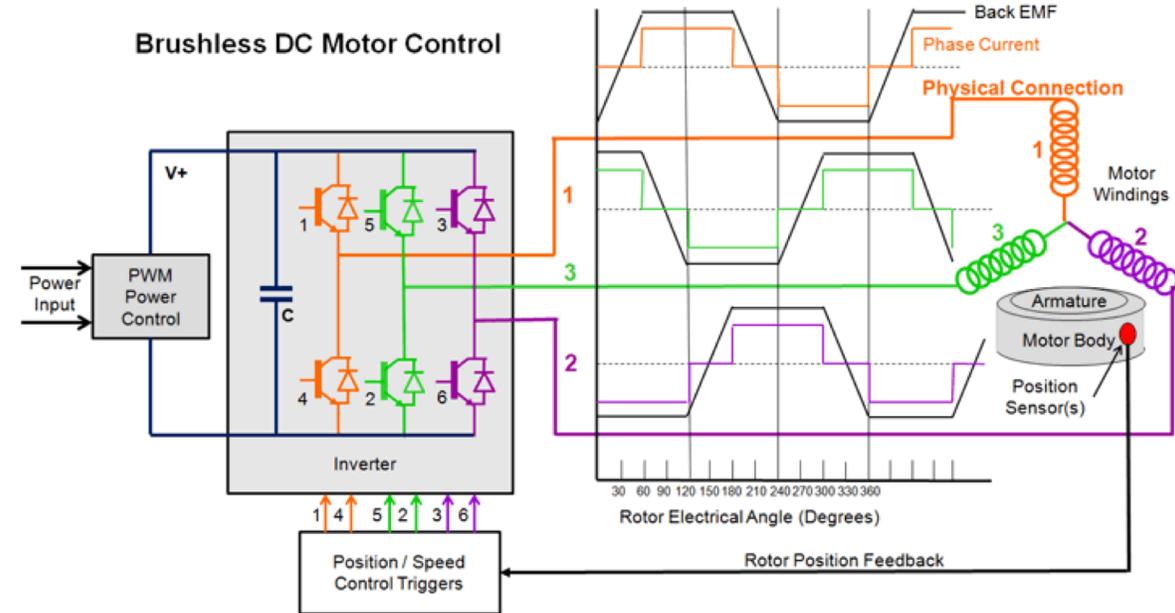
# Applications for Stepper Motor

- Incremental Positioning Applications with *no feedback device*
- Optics – Use for Positioning Filters or Lenses in Optics
- Robotic Joint Positioning
- Pan & Tilt Assemblies
- Low Power, Low Speed Scanners
- Radar Drives (limited rotation, low inertia or power).
- 3D Printers
- Proportional Valves – Hydraulic, Fuel Control etc.

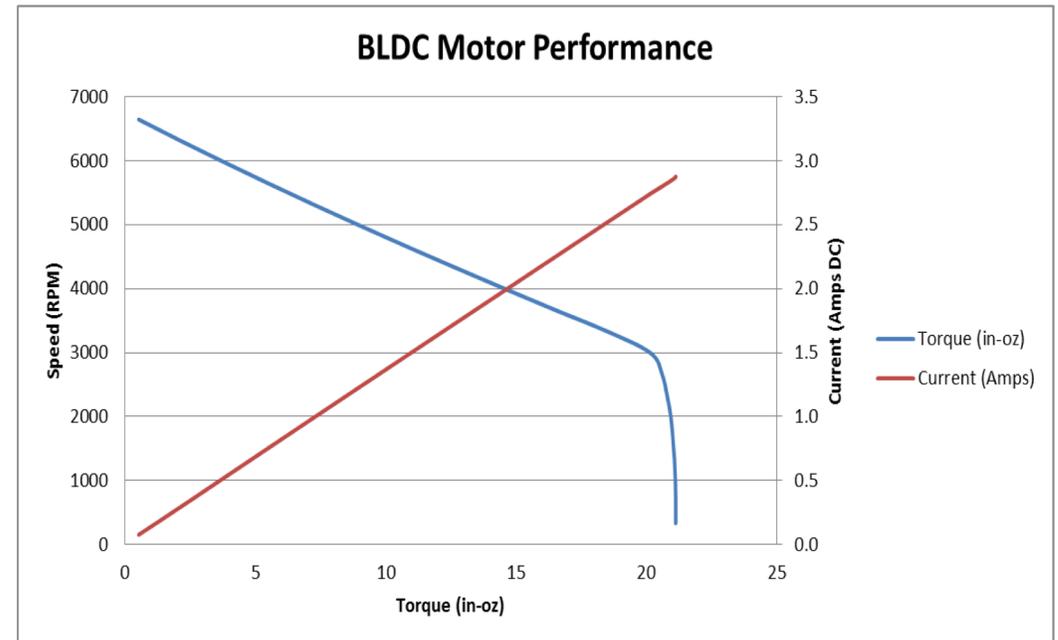
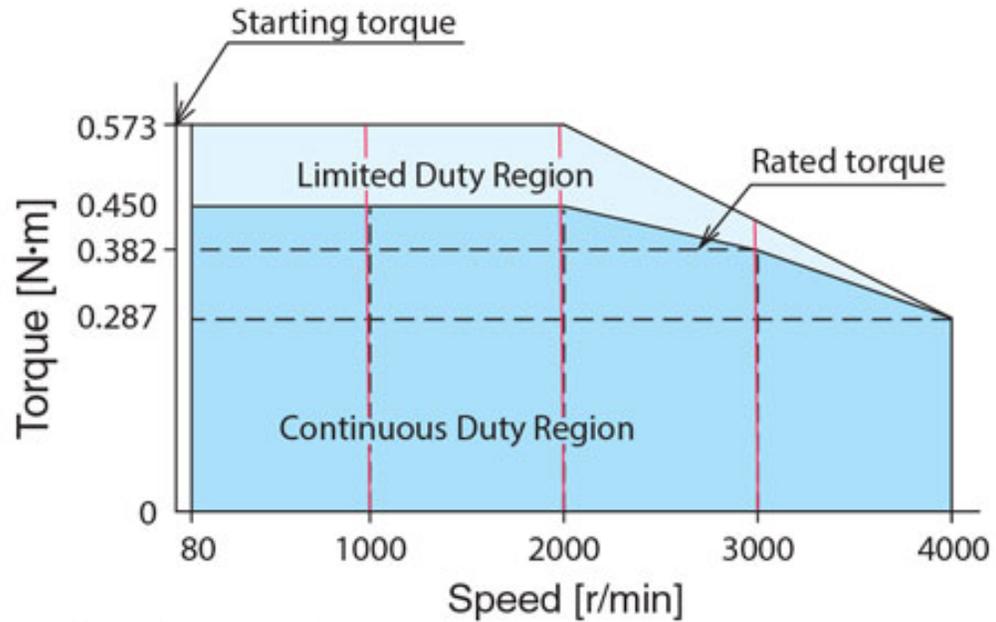


# Brushless DC Motor Construction and Performance

- Easy to predict motor performance, however motor performance drive/controller dependent.
- Motor of choice for new applications.

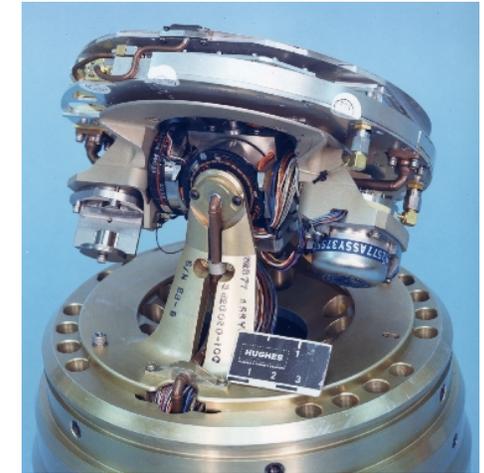
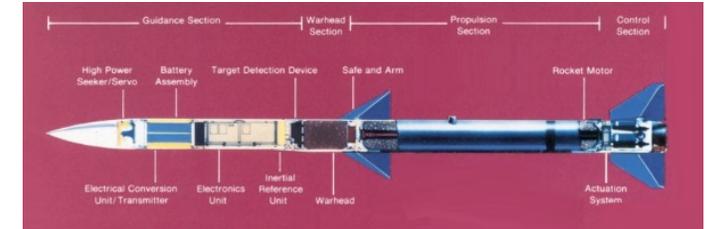


# Brushless DC Motor Construction and Performance



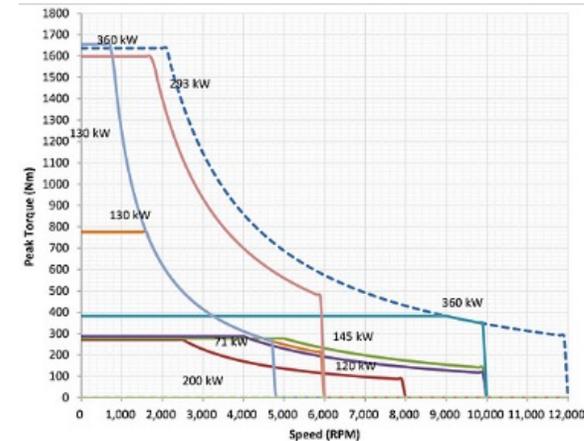
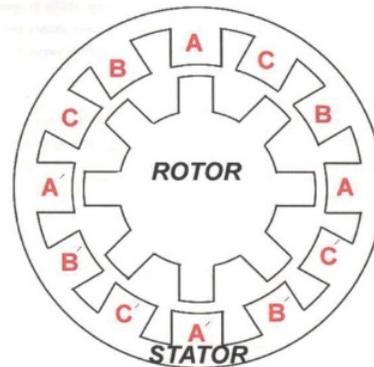
# Applications for Brushless Motor

- Highest Performance Applications
  - Fin Controls
  - TVC Controls
  - Multi-Mode Radar/Gimbal Drives
  - Weapons Gimbals
  - Turret Drives
  - Primary & Secondary Flight Controls
  - High speed / High Power Pumps & Fans
  - Vehicle Traction Drives
- High Reliability and Storage Life.



# Switched Reluctance Motor Construction and Performance

- Electronically Commutated
- No Permanent Magnets!!
- High Torque Ripple
- Difficult to predict motor performance
- Once was a major alternative to induction and brushless DC
- Manufacturing cost low for mass production, when fully tooled



# Applications for Switched Reluctance Motor

- Appliances
- Hand tool
- Automotive
- Locomotive traction

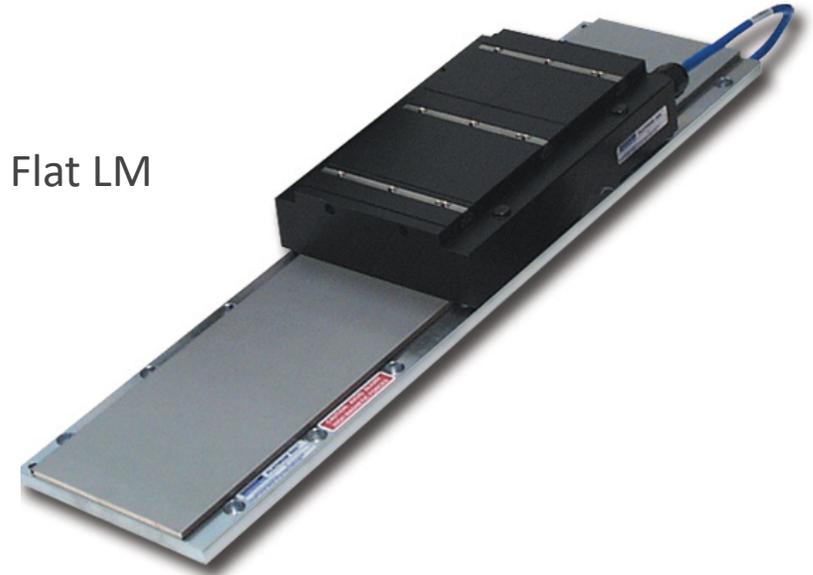


# Linear Motor Construction and Performance

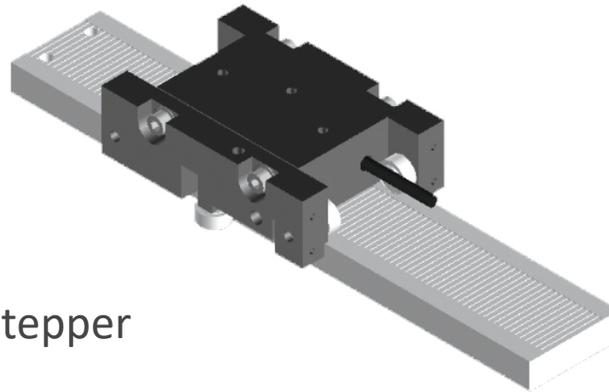
Tubular LM



Flat LM



Stepper

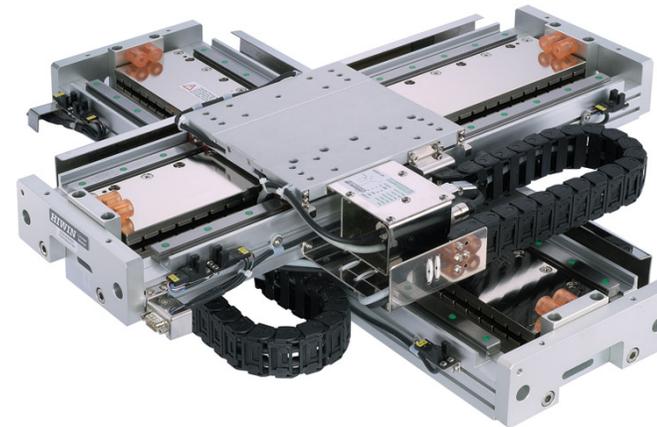


# Motor Construction and Performance

- Easy to predict motor performance
- Motor of choice for new applications.
- Manufacturing cost high

## APPLICATION OF LIM

- Small Linear Motors:
  - a. Conveyor systems
  - b. Airport baggage handling
  - c. Accelerators and launchers
  - d. Pumping of Liquid metal
- Large Linear Motors:
  - a. Transportation(Low & Medium Speed trains)
  - b. Sliding Doors Closure(Malls, Metros)
  - c. People movers
  - d. Material handling and storage



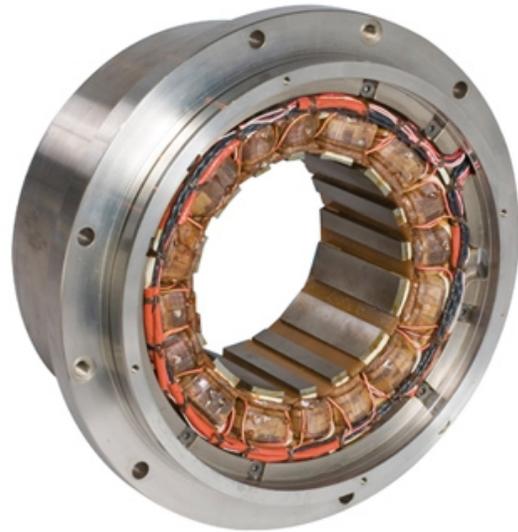
# Commonly Used Sensors

- Resolvers
- Synchro's
- Industrial Servo motors
- Aerospace and Military
- Down hole oil and gas exploration
- Applications with high temperature and mechanical vibration requirements
- Difficult to predict performance
- Difficult to achieve high accuracy due to manufacturing variances
- Manufacturing cost can be low in mass production, when fully tooled
- No new development, mainly second source by matching resolver performance



# Electromagnets/Solenoids

- Industrial
- Magnetic mechanical support
- Automotive



Electromagnetic bearing



# Commonly Used Materials

## Magnetic Materials

- Carbon steels
- Stainless steel
- Silicon steels
- High saturation alloys
- Amorphous ferromagnetic alloys
- Soft magnetic powder composites
- Nanostructured materials
- Ceramic
- Alnico
- Rear Earth

## Dielectric Materials

- Paper
- Epoxy
- Plastic

## Magnet Wire

- Copper
- Aluminum
- Litz

# Commonly Used Materials in Our History

Carbon steels/Stainless steels /Silicon steels/High saturation alloys

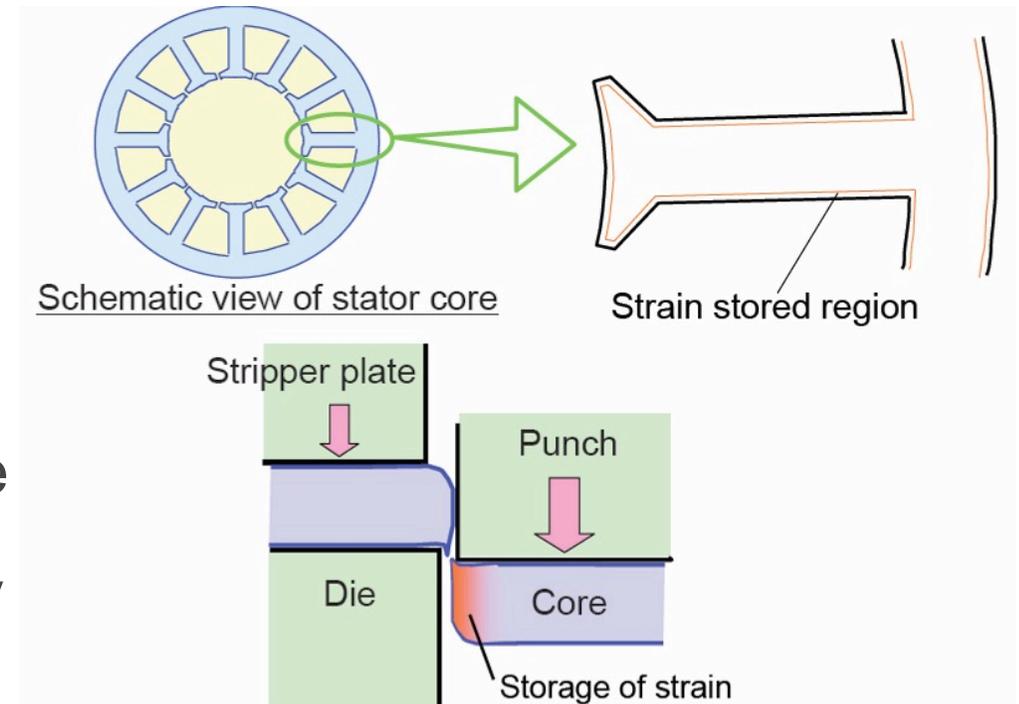
Material	Basic material property and cost data								Energy density force per area		Cost per unit		Energy per unit cost $E_j/CD_2$ , J/\$
	Flux density $B_{int}$ ( $H=100$ Oe), T	Relative perm. $\mu_r$ ( $B = B_{int}/2$ )	Coercive force $H_c$ ( $B = 10$ kG), Oe	Electrical conduct. $\xi$ 1/ $\Omega$ m	Curie temp. $T_c$ , °C	Density		Cost C, \$/lb*	$B_{int}^2/2\mu_0$		Volume $CD_2$ , \$/in <sup>3</sup>	Energy $CD_2/E_2$ , \$/J	
						$D_1$ , g/cc	$D_2$ , lb/in <sup>3</sup>		$E_2$ , kN/m <sup>2</sup>	$E_2$ , lb/in <sup>2</sup>			
Carbon steels													
1008/1010	1.84	3.29E+3	1.20	5.00E+6	760	7.84	0.283	0.35	1347	195	0.10	0.004	222.87
1018	1.78	2.54E+3	1.30	5.00E+6	760	7.84	0.283	0.44	1261	183	0.12	0.006	165.91
1020	1.78	2.54E+3	1.30	5.00E+6	760	7.84	0.283	—	1261	183	—	—	—
1030	1.74	1.16E+3	2.40	5.00E+6	760	7.84	0.283	—	1205	175	—	—	—
CH135 (0.005% C)	1.78	4.45E+3	0.61	5.00E+6	760	7.84	0.283	—	1261	183	—	—	—
Silicon steels													
M-15, 2.7% Si	1.76	8.00E+3	0.35	1.96E+6	800	7.70	0.278	—	1232	179	—	—	—
M-19, 2.7% Si	1.72	8.19E+3	0.36	2.00E+6	800	7.70	0.278	—	1177	171	—	—	—
M-22, 2.0% Si	1.72	7.82E+3	0.39	2.00E+6	800	7.75	0.280	0.66	1177	171	0.18	0.010	104.39
USS M-27, 2.0% Si	1.71	5.03E+3	0.48	2.27E+6	800	7.75	0.280	0.59	1163	169	0.17	0.009	115.42
M-36, 2.0% Si	1.75	7.81E+3	0.50	2.27E+6	800	7.75	0.280	—	1219	177	—	—	—
M-43, 1.6% Si	1.76	7.40E+3	0.55	1.60E+6	800	7.80	0.282	0.45	1232	179	0.13	0.006	159.28
M-45, 1.6% Si	1.77	7.08E+3	0.81	2.94E+6	800	7.80	0.282	—	1247	181	—	—	—
High saturation alloys													
430F stainless	1.42	1.8E+3	2.00	1.67E+6	671	7.75	0.280	—	802	116	—	—	—
Core iron 0.06% C	1.70	2.7E+3	1.40	10.0E+6	760	7.86	0.284	—	1150	167	—	—	—
1.0% Si core iron A	1.80	4.5E+3	0.90	4.00E+6	810	7.75	0.280	—	1289	187	—	—	—
2.5% Si core iron B	1.80	5.0E+3	0.70	2.50E+6	799	7.65	0.276	—	1289	187	—	—	—
4.0% Si core iron C	1.65	4.0E+3	0.60	1.72E+6	788	7.60	0.275	—	1083	157	—	—	—
High perm 49	1.50	50.0E+3	0.07	2.08E+6	475	8.25	0.298	8.25	895	130	2.46	0.168	5.97
HyMu 80	0.73	200.E+3	0.02	1.72E+6	460	8.75	0.316	13.99	212	31	4.42	1.272	0.79
Hyperco-50	2.28	8.00E+3	0.60	2.50E+6	940	8.11	0.293	47.09	2068	300	13.80	0.407	2.46

# Examples

Material Type	Core Loss	Saturation Flux Density	Permeability	Ease of Processing	Raw Material Relative Cost
CRML Steel	Fair	Good	Good	Best	0.5
Non-Oriented Silicon Steel	Good	Good	Fair	Good	1.0
Grain-Oriented Silicon Steel	Better	Good	Better	Fair	1.25
Amorphous Alloy–Iron based	Better	Fair	High	Much Care Required	1.25
Thin-Gauge Silicon Steel	Better	Good	Good	Fair	10
6½% Silicon Steels	Better	Good	Good	Care Required	12
49% Nickel-Iron Alloy	Better	Fair	High	Care Required	12
80% Nickel-Iron Alloy	Best	Low	High	Care Required	15
Cobalt-Iron Alloy	Good	Best	Better	Care Required	45
Powdered Alloys–SMC	The ultimate properties and cost of SMC materials are determined in large measure by the design of the machine and thus are not referenced in this table				

# Examples

- Deterioration of Magnetic Properties due to Punching
- Fully processed material is simply material which has been annealed to optimum properties at the steel mill. Even though annealed at the mill, fully processed material may require further stress relief anneal after stamping. The stresses introduced during punching degrade the material properties around the edges of the lamination, and must be removed to obtain maximum performance. This is particularly true for parts with narrow sections, or where very high flux density is required.



# Commonly Used Magnet Materials

<i>Material</i>	<i>Magnetic Properties</i>	<i>Magnetic Characteristics</i>	<i>Curie Temperature</i>	<i>Temperature Coefficient of Induction</i>	<i>Cost \$ / lb.</i>
<i>Cast Alnico</i>	Br - 5,500 - 13,500 Hc - 475 - 1,900 MGOe 1.4 - 10.5	Cast to Shape, Hard, Crystal Structure - Grind or EDM	840°C	0.02% / °C	\$40
<i>Sintered Alnico</i>	Br - 6,000 - 10,800 Hc - 550 - 1,900 MGOe 1.4 - 5.0	Powder Pressed to Shape, Hard Structure - Grind or EDM	840°C	0.02% / °C	\$23
<i>Ceramic (Hard Ferrite)</i>	Br - 3,450 - 4,100 Hci - 3,000 - 4,800 MGOe 2.7 - 4.0	Simple Shapes: Arcs, Rect., Plugs, Rings - Hard-Grind	450°C	0.2% / °C	\$2
<i>Samarium Cobalt</i>	Br - 8,800 - 11,000 Hci - 11,000 - 21,000 MGOe - 18 - 32	Very Brittle - Grind or EDM	750°C / 825°C	0.035% / °C	\$125
<i>Neodymium Iron Boron</i>	Br - 10,500 - 14,000 Hci - - 14,000 MGOe 27 - 50	Requires Coating to Prevent Oxidization Grind or EDM	310°C	0.13% / °C	\$95
<i>Iron-Chrome Cobalt</i>	Br - 9,000 - 13,500 Hc - 50 - 600 MGOe - 4.25 - 5.25	Can be Formed, Stamped, Thin Rolled Mat'l 0.050" - .0005"	600°C	0.02% / °C	\$30
<i>Bonded Flexible (Callenared or Extruded)</i>	Br - 2,500 - 5,600 Hci - 3,500 - 16,000 MGOe 1.4 - 6.2	Flexible, Thermal Shock Resistant, Low-to-no Tooling Charge, Available In Wide Range of Sizes	Ferrite 450°C Neo 310°C	0.18% / °C 0.07 to 0.13% / °C	\$3 \$30 - \$50
<i>Bonded Plastic (Molded)</i>	Br - 2,500 - 6,900 Hci - 3,000 - 16,000 MGOe - 1.5 - 10.5	Complex Shapes, Thin Walls, Tight Dimensions without Machining, Good Strength	Ferrite 450°C Neo 310°C	0.18% / °C 0.07 to 0.13% / °C	\$3 \$60
<i>Compression Bonded Neo (Epoxy)</i>	Br - 6,200 - 8,200 Hci - 4,300 - 18,000 MGOe - 7.5 - 15.0	Simple Geometry, Close Tolerancing W.O Machining Higher BhMax Than Inj. Molded With Lower Tooling Cost	Neo 310°C	0.07 to 0.13% / °C	\$60

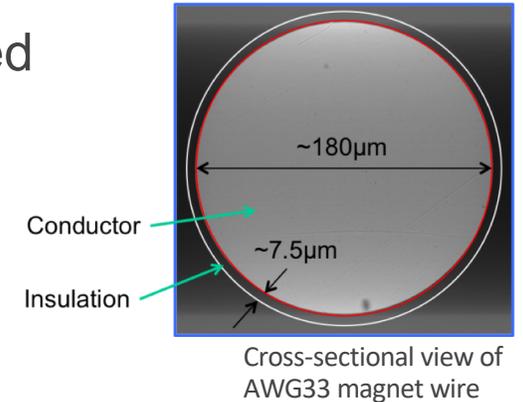
# Commonly Used Epoxy

Temp class	Product no.	Description	Specific gravity	Cut-through resistance	Edge coverage	Impact resistance	Gel time @ 193°C (380°F) hot plate	Dielectric strength	Volume resistivity	Color
B	260 260CG	Spray and fluid bed dip application	1.43	215°C (410°F)	35–45	100 (11.3)	12–16 s	1000 (12–15-mil coating)	10 <sup>15</sup>	Green
B	262	Spray and fluid bed dip applications	1.34	130°C (266°F)	38–48	100 (11.3)	12–16 s	1000 (10-mil coating)	10 <sup>13</sup>	Red
B	263	Spray and fluid bed dip applications in high-temperature cut-through resistance	1.47	290°C (554°F)	40–50	100 (11.3)	8–14 s	1000 (12–15-mil coating)	10 <sup>15</sup>	Green
B	270	Spray and fluid bed dip applications for higher-temperature cut-through and bridging gaps	1.48	250°C (482°F)	35–40	120 (13.8)	12–16 s	1000 (10-mil coating)	10 <sup>13</sup>	Green
B	5555	Cold electrostatic fluid bed, hot venturi spray, or hot fluid bed dip for fractional horsepower motor stators and armatures	1.7	>340°C (644°F)		160 (18.1)	8–12 s	1300 (V/mil)		Green
B	5388	Electrostatic fluid bed process, superior cut-through resistance and well heat, chemical and moisture resistance	1.57	>340°C (644°F)	35 (11.3)	100	25–35 s	1100 (V/mil)		Blue
B	5133	Electrostatic coating for cold as well as heated parts	1.45	160°C (320°F)	15 (13.8)	120		500 (V/mil)	5 × 10 <sup>14</sup>	Light blue

# Commonly Used Magnet Wire

## ■ Conductor

- The most suitable materials for magnet wire applications are unalloyed pure metals, particularly copper.
- High-purity oxygen-free copper grades are used for high-temperature applications
- Aluminum magnet wire is sometimes used as an alternative for transformers and motors. Because of its lower electrical conductivity, aluminum wire requires a 1.6-times larger cross sectional area than a copper wire to achieve comparable DC resistance.

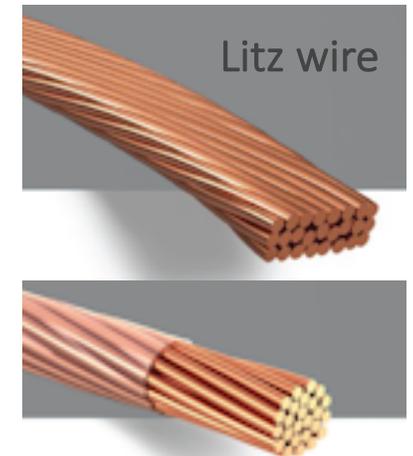


## ■ Insulation

- Modern magnet wire typically uses one to four layers of polymer film insulation, often of two different compositions, to provide a tough, continuous insulating layer.

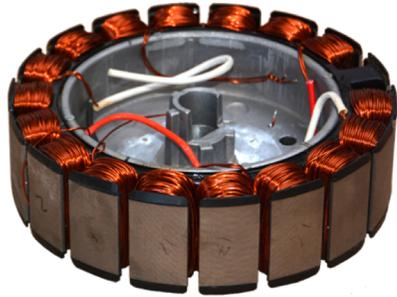
## ■ Classification

- Magnet wire is classified by diameter (AWG /SWG or millimeters) or area (square millimeters), temperature class, and insulation class

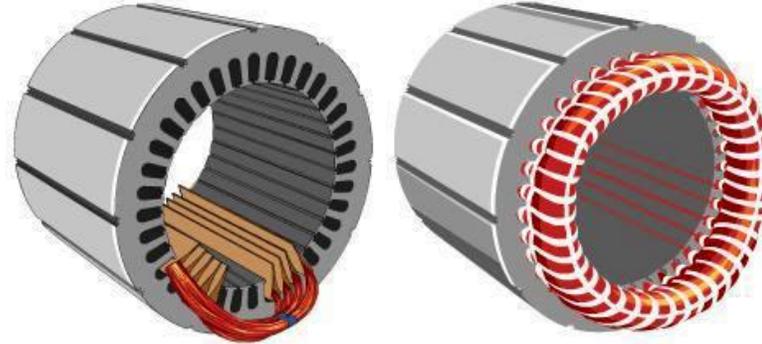


# Stator's Most Common Constructions

Concentrated Winding



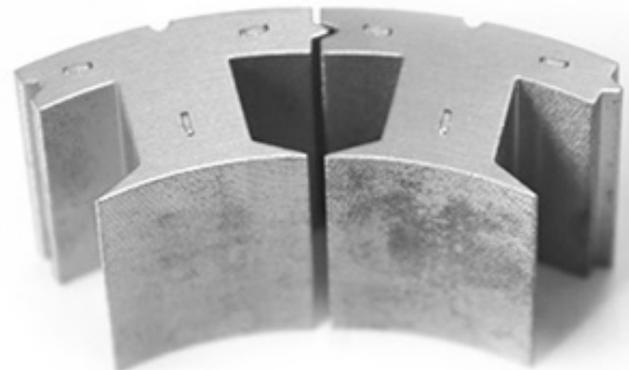
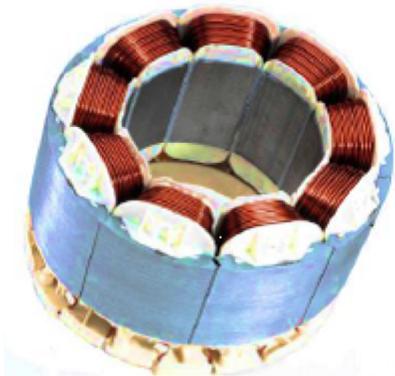
Distributed Winding



Two Pole Winding



Concentrated Winding with segmented stator construction

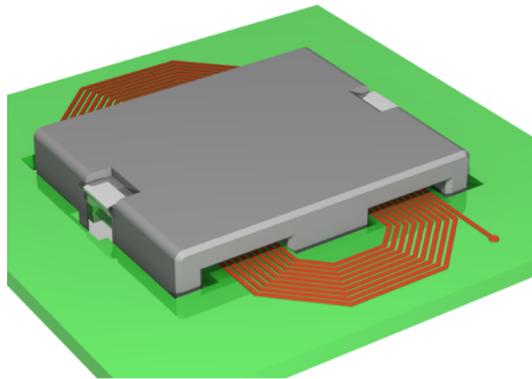


Slotless Winding



# Stator's Most Common Constructions

PCB winding

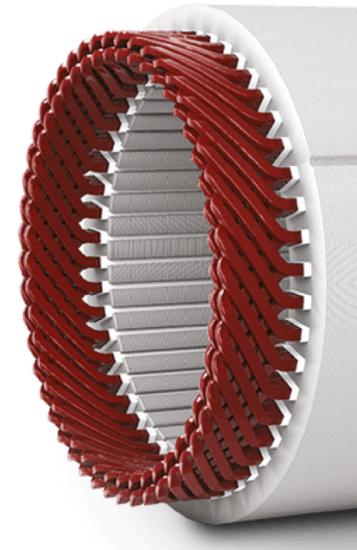


Planar transformer



Inductive resolver

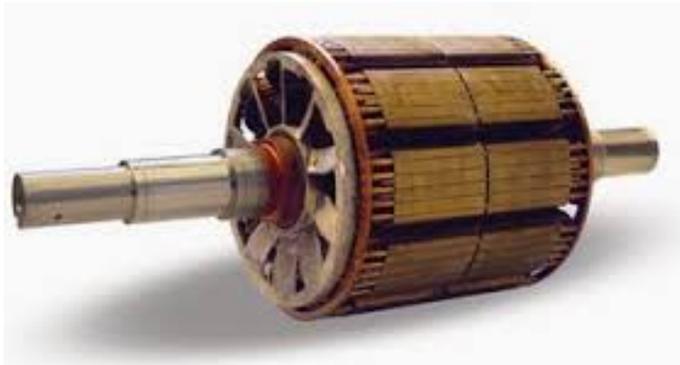
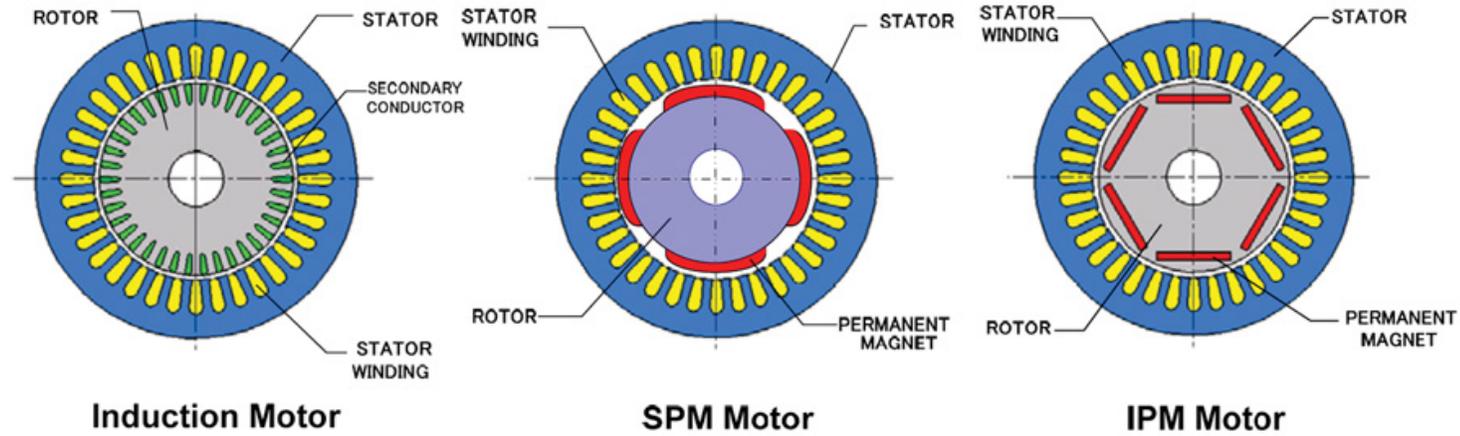
Copper bar winding



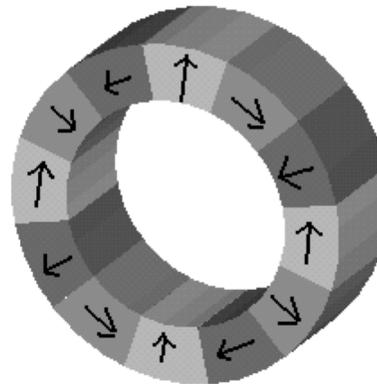
Slotless axial air gap winding



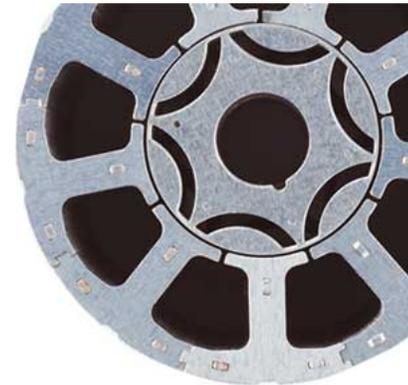
# Rotor's Constructions



Synchronous generator wound field rotor



Halbach array



# Electric Machine Parameter and Testing

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- Mechanical Dimensions
  - Geometric Dimensioning and Tolerancing (GD&T) is a system for defining and communicating engineering tolerances. It uses a symbolic language on engineering drawings and computer-generated three-dimensional solid models that explicitly describes nominal geometry and its allowable variation. It tells the manufacturing staff and machines what degree of accuracy and precision is needed on each controlled feature of the part.
- GD&T is used to define the nominal (theoretically perfect) geometry of parts and assemblies, to define the allowable variation in form and possible size of individual features, and to define the allowable variation between features.
- ASME standards ASME Y14.5 – Dimensioning and Tolerancing
- ISO TC 10 Technical product documentation
- ISO/TC 213 Dimensional and geometrical product specifications and verification

# Electric Machine Parameter and Testing

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- Electrical parameters

- Example:

- Measure and record A-B, B-C, C-A line-line resistances and inductances.
    - Hipot and surge test the stator after varnish at 1800VAC, max current leakage 5mA  
Before and after varnish, perform corona test(partial discharge) with pulse up to but not exceeding 3000V.

- Resistance

- The electrical resistance of an electrical conductor is the opposition to the passage of an electric current through that conductor. Electrical resistance shares some conceptual parallels with the mechanical notion of friction. The SI unit of electrical resistance is the ohm ( $\Omega$ )

- Inductance

- Inductance is a property of an electrical conductor which opposes a change in current. The Henry (symbol: H) is the SI derived unit of electrical inductance

# Electric Machine Parameter and Testing

## Different Methods of Tests in the Stator Insulation of Electric Machine

S.No.	Method	Standards	Insulation Tested and Diagnostic Value
1.	Insulation Resistance	IEEE 43. NEMA MG 1	Find contaminations and defects in phase-to-ground insulation
2.	Polarization Index	IEEE 43	Find contaminations and defects in phase-to-ground insulation
3.	DC High Potential Test ( <i>Dielectric Withstand Test</i> )	IEEE 95, IEC 34.1, NEMA MG 1	Find contaminations and defects in phase-to-ground insulation
4.	AC High Potential Test ( <i>Dielectric Withstand Test</i> )	IEC 60034 NEMA MG 1	Find contaminations and defects in phase-to-ground insulation
5.	Surge Test	IEEE 522 NEMA MG 1	Detects deterioration of the turn-to-turn insulation
6.	Partial Discharge Test	IEEE 1434	Detects deterioration of the phase-to-ground and turn-to turn insulation
7.	Dissipation-Factor	IEEE 286 IEC 60894	Detects deterioration of the phase-to-ground and phase-to phase insulation

# Electric Machine Parameter and Testing

## ■ High Potential Test

- Three types of High Potential Test tests are commonly used. These three tests differ in the amount of voltage applied and the amount (or nature) of acceptable current flow:
- Insulation Resistance test measures the resistance of the electrical insulation between the copper conductors and the core of the stator. Ideally, this resistance should be infinite. In practice, is not infinitely high. Usually, lower the insulation resistance, it is more likely that there is a problem with the insulation.  
Dielectric Breakdown Test. The test voltage is increased until the dielectric fails, or breaks down, allowing too much current to flow. The dielectric is often destroyed by this test so this test is used on a random sample basis. This test allows designers to estimate the breakdown voltage of a product's design and to see where the breakdown occurred.
- Dielectric Withstand Test. A standard test voltage is applied (below the established Breakdown Voltage) and the resulting leakage current is monitored. The leakage current must be below a preset limit or the test is considered to have failed. This test is non-destructive providing that it does not fail and is usually required by safety agencies to be performed as a 100% production line test on all products before they leave the factory.

IEEE Std 43-2000

IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery

# Electric Machine Parameter and Testing

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- Surge Test

- If the turn insulation fails in a form-wound stator winding, the motor will likely fail in a few minutes. Thus the turn insulation is critical to the life of a motor. Low voltage tests on form-wound stators, such as inductance or inductive impedance tests, can detect if the turn insulation is shorted, but not if it is weakened. Only the surge voltage test is able to directly find stator windings with deteriorated turn insulation. By applying a high voltage surge between the turns, this test is an overvoltage test for the turn insulation, and may fail the insulation, requiring bypassing of the failed coil, replacement or rewind.

# Electric Machine Parameter and Testing

- Partial Discharge Test

- IEC TS 60034-27

For many years, the measurement of partial discharges (PD) has been employed as a sensitive means of assessing the quality of new insulation as well as a means of detecting localized sources of PD in used electrical winding insulation arising from operational stresses in service. Compared with other dielectric tests (i.e. the measurement of dissipation factor or insulation resistance) the differentiating character of partial discharge measurements allows localized weak points of the insulation system to be identified. The PD testing of rotating machines is also used when inspecting the quality of new assembled and finished stator windings, new winding components and fully impregnated stators.

The measurement of partial discharges can also provide information on:

- points of weakness in the insulation system;
- ageing processes;
- further measures and intervals between overhauls.

Although the PD testing of rotating machines has gained widespread acceptance, it has emerged from several studies that not only are there many different methods of measurement in existence but also the criteria and methods of analyzing and finally assessing the measured data are often very different and not really comparable. Consequently, there is an urgent need to give some guidance to those users who are considering the use of PD measurements to assess the condition of their insulation systems.

# Organization/Standards/Directives

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- **NEMA** National Electrical Manufacturers Association
  - NEMA sets standards for many electrical products, including motors. For, example, "size 11" mean the mounting face of the motor is 1.1 inches square
  - **Standards Publication ICS 16** standard covers the components used in a motion/position control system providing precise positioning, speed control, torque control, or any combination thereof. Examples of these components are control motors (servo and stepping motors), feedback devices (encoders and resolvers), and controls.
- **IEC** International Electro technical Commission
  - IEC 60034 is an international standard for rotating electrical machinery.
  - IEC 60034-1 Rating and Performance
- **ISO** International Organization for Standardization
- **ANSI** American National Standards Institute
- **ASTM** American Section of the International Association for Testing Materials

# Organization/Standards/Directives

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- **REACH** Registration, Evaluation, Authorization and Restriction of Chemicals
- **RoHS** Restriction of Hazardous Substances Directive
- **DO-160** Environmental Conditions and Test Procedures for Airborne Equipment is a standard for the environmental testing of avionics hardware. It is published by the Radio Technical Commission for Aeronautics (RTCA, Inc.)
- **MIL-STD-810**, Environmental Engineering Considerations and Laboratory Tests, Published by the United States Department of Defense
- **ITAR** The International Traffic in Arms Regulations and the Export Administration Regulations (EAR) are two important United States export control laws that affect the manufacturing, sales and distribution of technology.

# Organization/Standards/Directives

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- **AS9001** Quality Management Systems - Requirements for Aviation, Space and Defense Organizations
- **AS9002** Aerospace First Article Inspection Requirement
- **ISO/TS 16949** common automotive quality system requirement based on ISO 9001 and customer specific requirements from the automotive sector.



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