In The Name of God The Most Compassionate, The Most Merciful

Brushless PM Machines

Design, Optimization and Analysis

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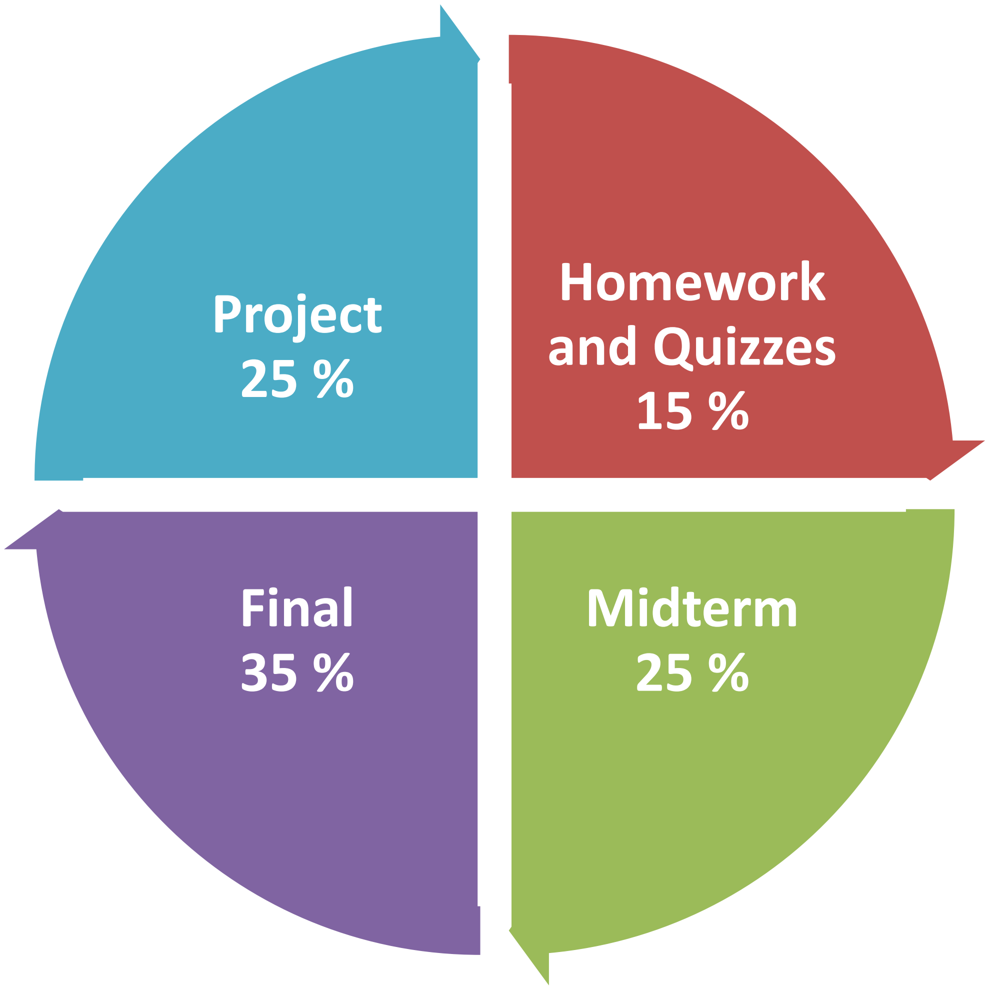
Evaluation



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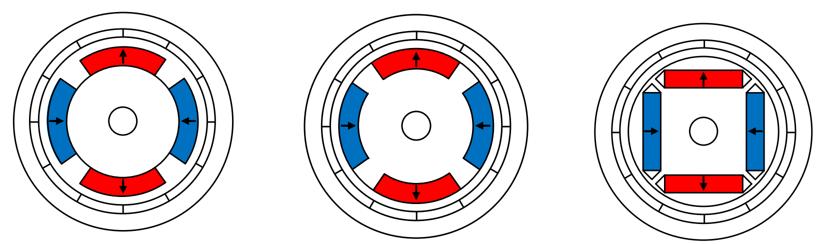
BLPM Machine Optimal Design Procedure

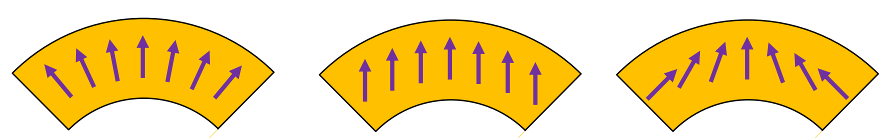
1. Specify the machine **requirements** (listed in the following slides)

2. Select the proper **machine type** (linear or rotary motion), (radial flux, axial flux or transverse flux), (slotless or stotted stator) and (inner or outer rotor)

3. Select suitable **magnet structure** (surface mounted, surface inset, interior, spoke, …)



4. Select the **magnetization pattern** if applicable (radial, parallel, Halbach magnetization)



BLDC Machine Optimal Design Procedure

5. Select **materials** such as magnet grade, ferromagnetic sheets type

6. Define the **optimization variables** and initialize the constant parameters

Machine Dimensions

7. Express the **objectives and constraints**

8. **Relate** the objectives and constraints to the optimization parameters

9. **Solve** the optimization to obtain the optimal machine structure.

List of Requirements

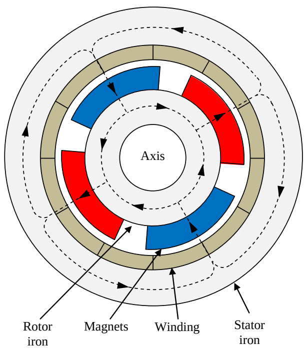
- Continuous **torque** (or power) and maximum torque
- Nominal and maximum **speed**
- Supply **voltage** (supply frequency if AC source)
- **Forward/reverse** operation
- **Motoring/braking** operation
- Type of **control** required (torque, velocity or position)
- **Precision** and bandwidth required in closed-loop control
- **Soft-starting** requirement
- Dynamic requirement: **torque/inertia** ratio, acceleration/ deceleration capability

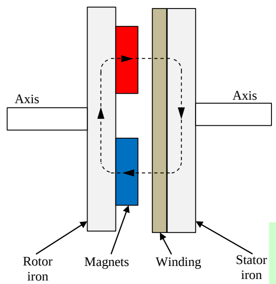
List of Requirements

- **Gearbox** or **direct drive**
- Inlet & outlet **temperature** of available coolant: air/oil/water flow-rate
- **Environmental factors**: dust, hazardous chemicals, explosive gases
- **Compatibility** with insulation, magnets and other motor materials
- Maximum level of acoustic **noise**
- Compliance with regulations on **EMC** and harmonics
- **Vibration** withstand levels
- **Fault** protection: overcurrent, overvoltage, under-voltage, over-temperature, winding fault, vibration sensors

Electric Machines

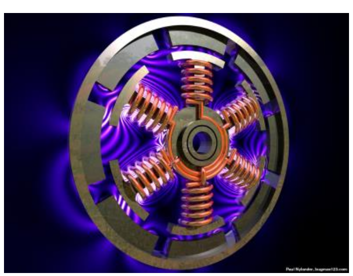
Classification in terms of motion and flux direction

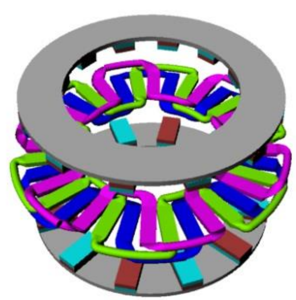


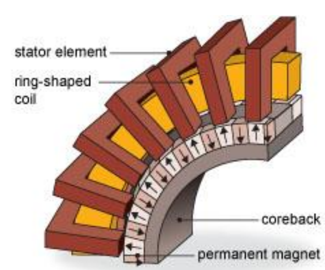


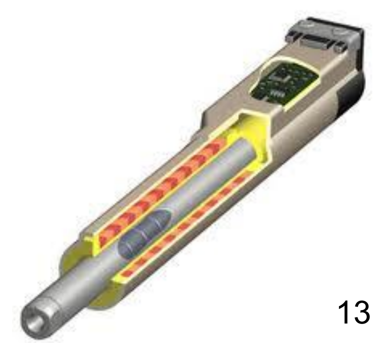
Electric machines

- **Rotary motion**
  - Radial flux
    - Inner rotor
      - Slotted stator
      - Slotless stator
    - Outer rotor
      - Slotted stator
      - Slotless stator
  - Axial flux
    - Single sided
      - Slotted stator
      - Slotless stator
      - Salient-pole stator
    - Double sided
      - Internal stator
      - Internal rotor
    - Multi-stage
  - Transverse flux
    - Surface mounted
    - Flux focusing
- **Linear motion**
  - Transverse flux
  - Longitudinal flux
    - Flat (planar)
      - Single sided
      - Double sided
    - Tubular







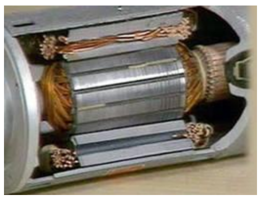


A Comparison Between Radial and Axial Flux Configurations

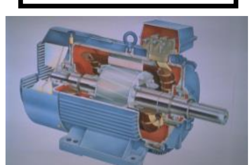
	Radial flux	Axial flux
Power density	Lower	Higher
Stator manufacturing cost	Lower	Higher
Maximum allowable number of poles	Lower	Higher
Ventilation	Worse	Better
Size characteristics	Larger length to diameter	Larger diameter to length
High power motor	Commonly used	Cannot be used

Electric Machines

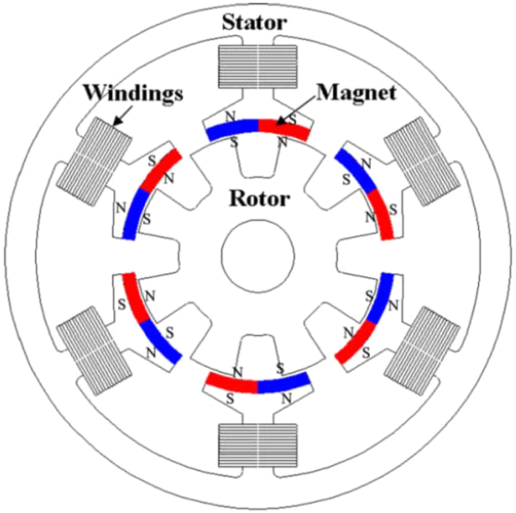
Classification in terms of brush and input sources



- Electric Motors
  - Brushed
    - Self excited DC
      - Series
      - Shunt
      - Compound
    - Separately excited DC
      - Wound
      - PM
  - Brushless
    - Sinusoidal fed
      - Induction
        - Squirrel cage
        - Wound rotor
      - Synchronous
        - Wound rotor
        - PM rotor
        - Reluctance
    - Square fed
      - **BLDC**
      - SRM
      - PM on stator
        - Flux-switching DSPM
        - Flux-reversal DSPM
        - DSPM



Magnet on Stator Concept



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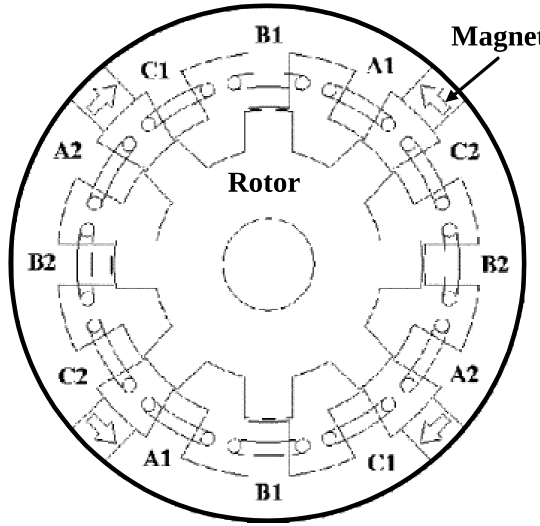


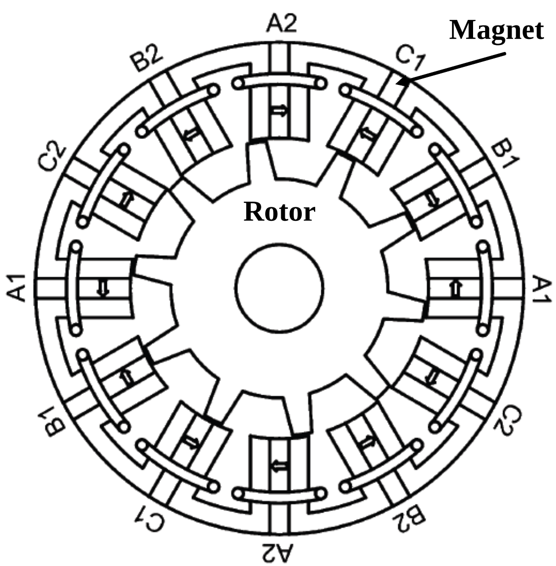
(a)

(a) Doubly-salient permanent magnet (DSPM)

(b) Flux-reversal DSPM with surface mounted

(c) Flux-reversal DSPM with surface inset

(d) Flux-switching DSPM



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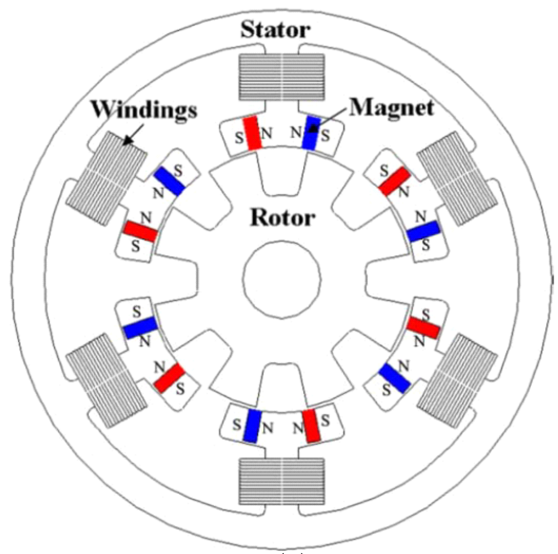


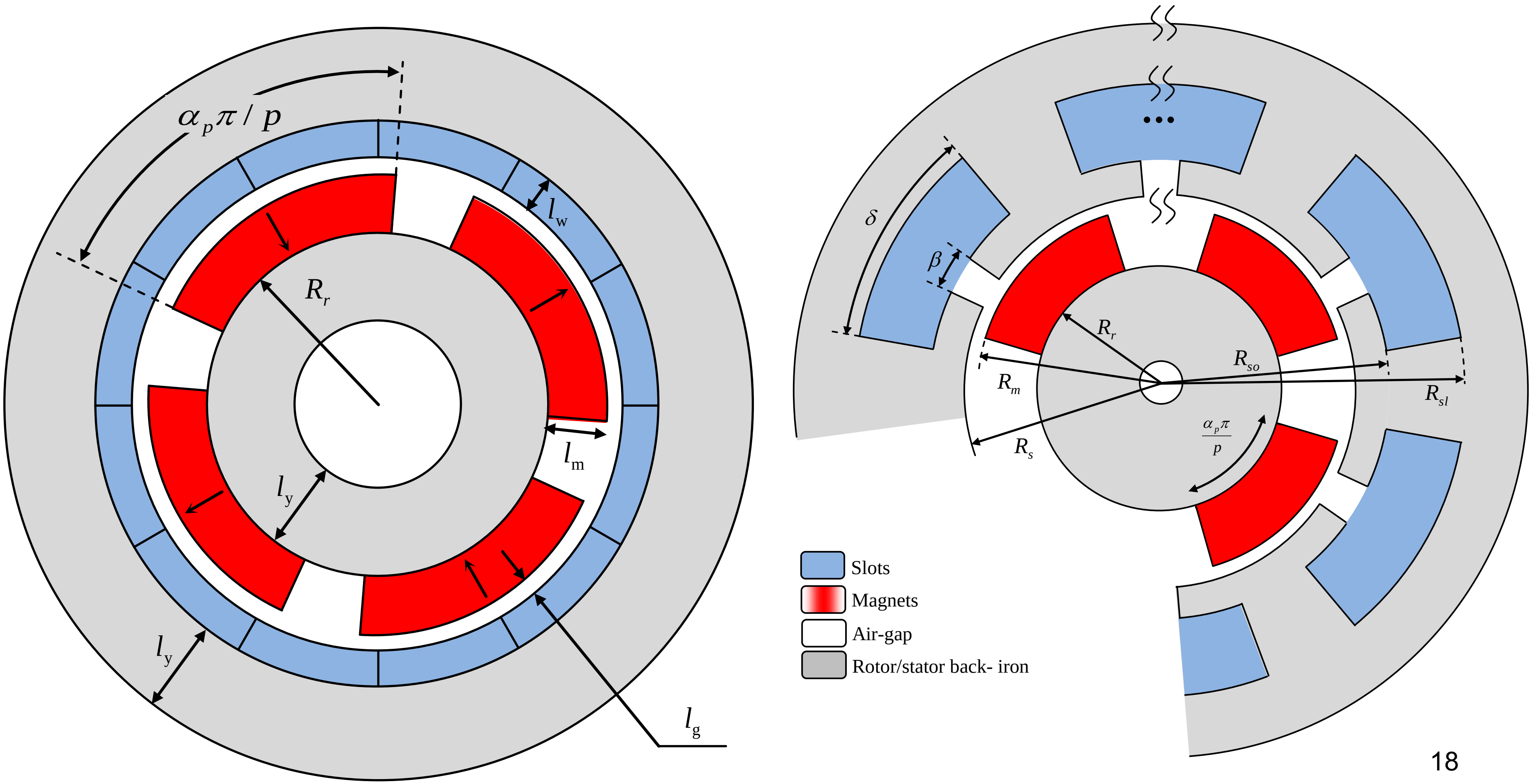
(c)

Differences Between BLDC and BLAC drives

	BLDC	BLAC
Desired back-emf shape	Trapezoidal	Sinusoidal
Applied current shape	Rectangular	Sinusoidal
Position sensing	Discrete (e.g. Hall effect)	Continuous (e.g. resolver or shaft encoder)
Torque ripple	Higher	Lower
Motor constant (for the same back-emf amplitude)	Higher	Lower
Cost	Lower	Higher

Brushless PM Machines

Slotless vs. Slotted Stator

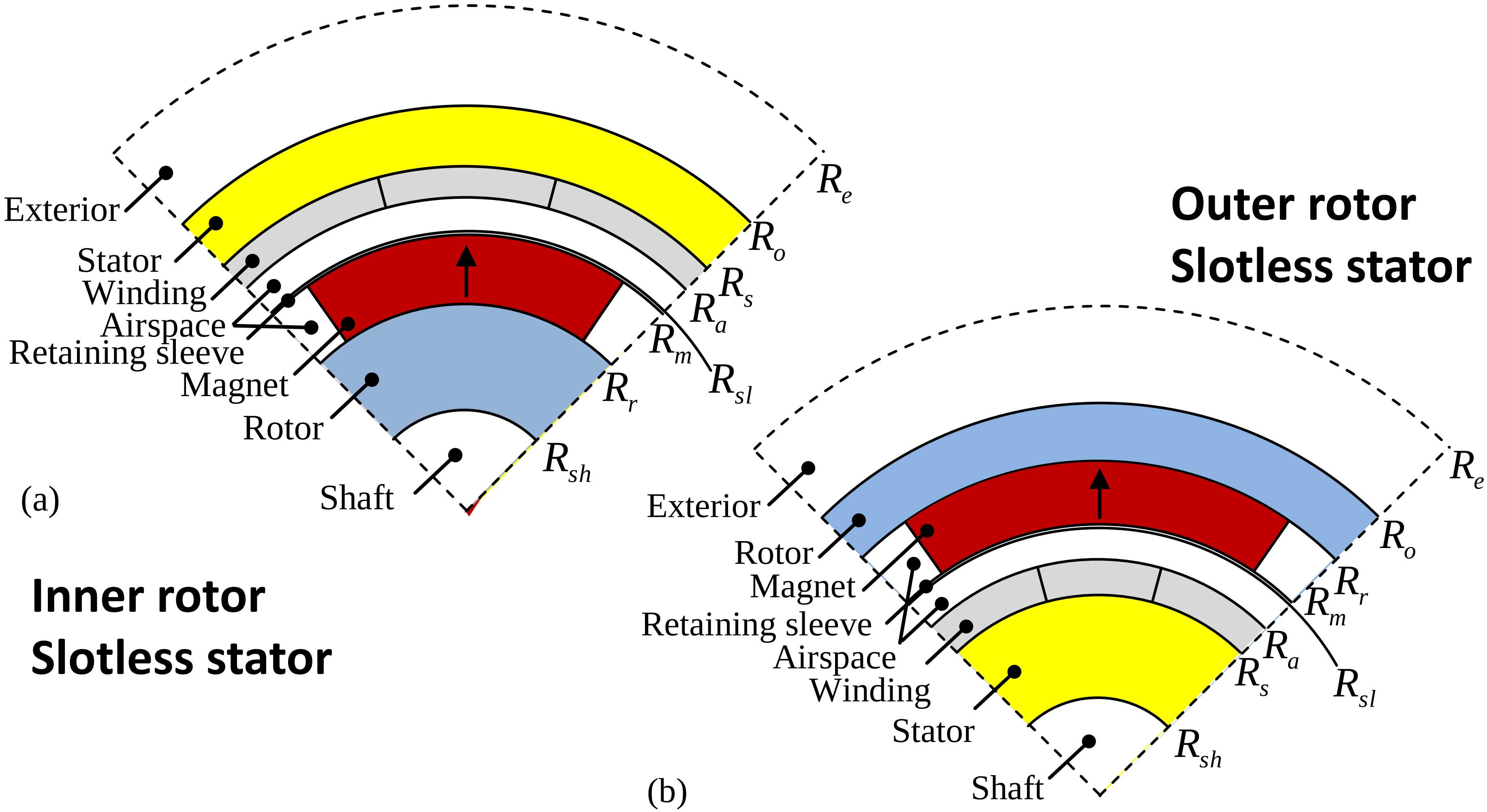


A Comparison Between Slotless and Slotted Stator Structures

	Slotted	Slotless
Cogging torque	Exists	Almost nothing
Cost of winding	Higher	Lower
Magnetic air gap length	Smaller	Larger
Air gap flux density	Higher	Lower
Inductance	Higher	Lower
Heat removal	Better	worse
Winding space	Lower	Higher
Electric per magnetic loadings	Lower	Higher

Brushless PM Machines

Inner vs. Outer rotor

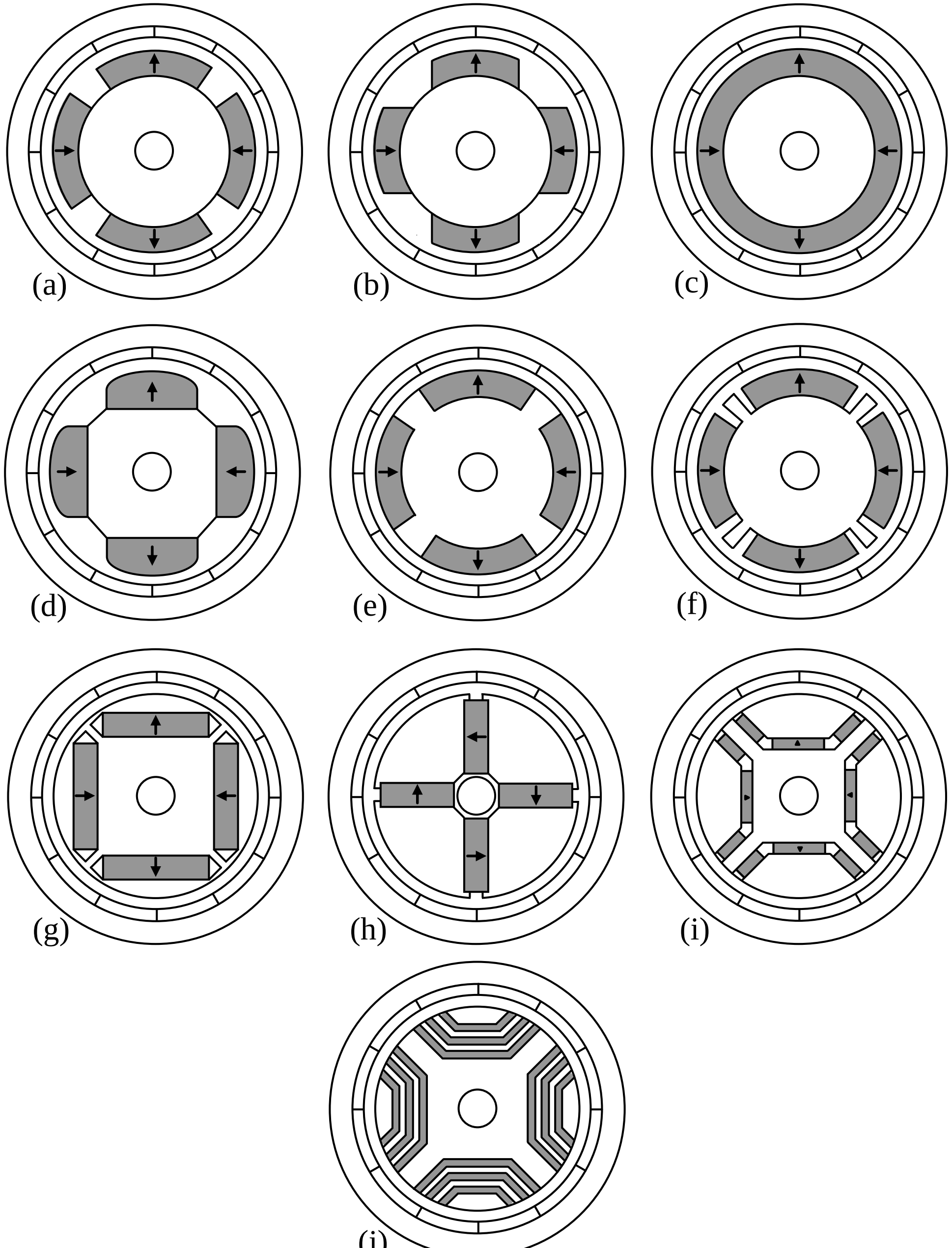


Inner rotor
Slotless stator

Outer rotor
Slotless stator

A Comparison Between Inner and Outer Rotor Configurations

	Inner rotor	Outer rotor
Heat removal	Better	Worse
Air gap radius	Lower	Higher
Developed torque	Lower	Higher
Torque/inertial ratio	Higher	Lower
Winding	More difficult	Easier
Robustness for surface mounted PM	Lower	Higher
Applications	Rapid acceleration and deceleration (Servo systems)	Constant speed (fans and blowers)



Brushless PM machines

Classification in terms of Magnet structures

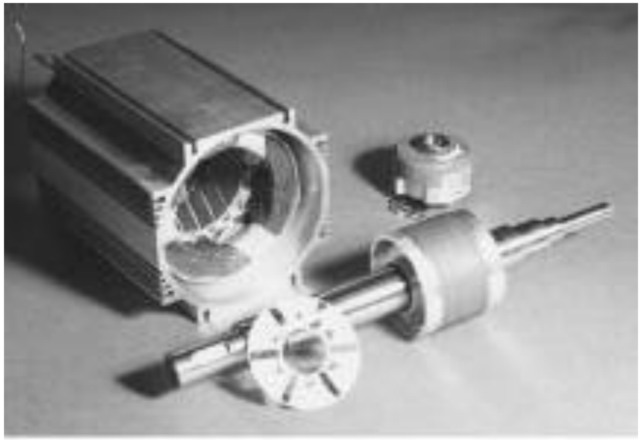
Different structures of PM in radial flux slotless internal rotor brushless PM motors:

(a) surface mounted magnet
(b) surface mounted with parallel edges
(c) ring magnet
(d) bread-loaf magnet
(e) surface inset magnet
(f) surface inset magnet with airspace between magnets and iron inter-poles
(g) buried or interior magnet
(h) spoke magnet
(i) multi-segment interior magnet
(j) multilayer interior magnet

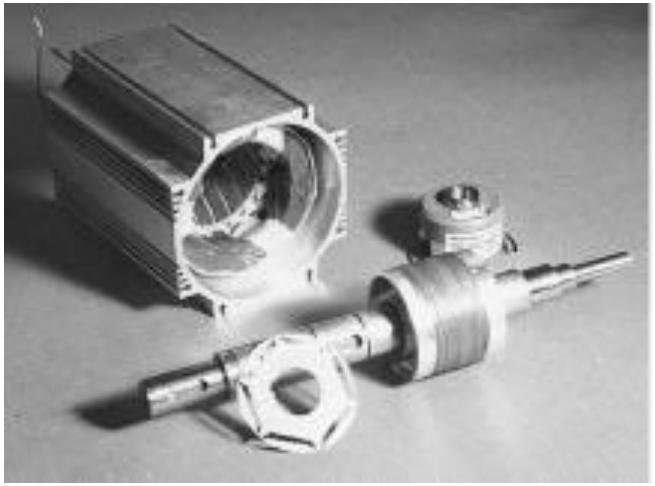
Four different magnet structures

(a) Surface mounted PM

(b) Surface inset PM



(c) Radial interior PM (Spoke)



(d) Circumferential interior PM (Buried)

Different Magnet Structures

	Surface mounted PM (a), (b), (c), (d)	Surface inset PM (e), (f)	Buried PM (g), (i), (j)	Spoke PM (h)
Cost	Low	Low	High	Medium
Robustness	Low	Medium	Very high	High
Maximum speed	Low	Medium	High	High
D/Q axis reluctance	≈ 1	>1	>1	<1
Magnet Eddy current losses	High	Medium	Low	Low
Harmonics in PM due to stator MMF	High	Medium	Low	Low
Power extension capability	Low	High	Very high	Very high

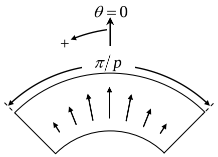
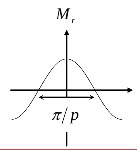
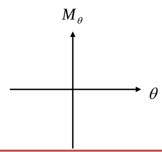
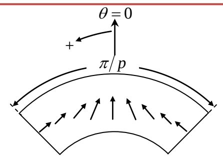
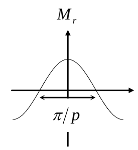
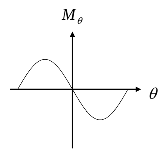
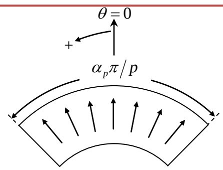
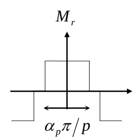
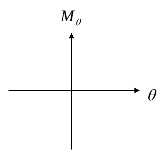
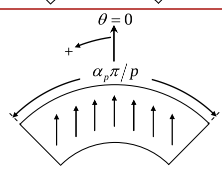
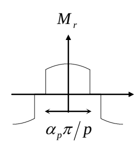
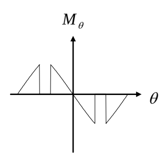
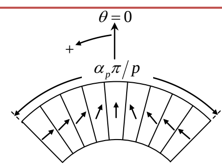
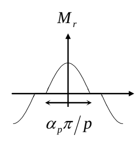
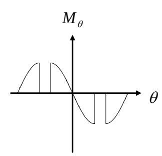
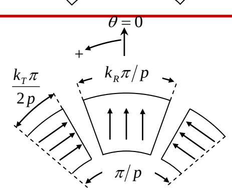
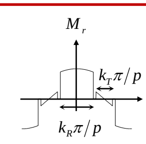
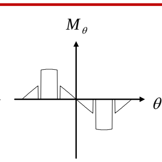
Brushless PM Machines

Classification in terms of magnetization patterns for SM or SI

$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mu_0 \mathbf{M}$

2-D polar coordinates

$\mathbf{M} = M_r \mathbf{r} + M_\theta \boldsymbol{\theta},$

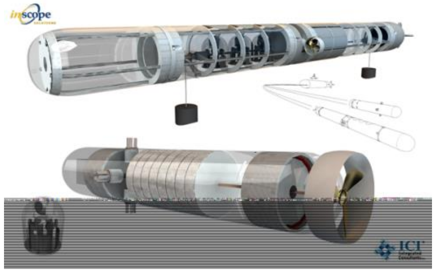
Magnetization patterns	Illustrative representation	Radial component waveform	Tangential component waveform	Radial components,	Tangential components,
Radial sinusoidal amplitude magnetization				$M_r = \frac{B_{rem}}{\mu_0}\cos(p\theta)$	$M_\theta = 0$
Ideal Halbach or sinusoidal angle magnetization				$M_r = \frac{B_{rem}}{\mu_0}\cos(p\theta)$	$M_\theta = \mp\frac{B_{rem}}{\mu_0}\sin(p\theta)$
Radial magnetization				$M_r = \begin{cases} \frac{B_{rem}}{\mu_0} & \lvert\theta\rvert \le \frac{\pi}{2p}\alpha_p \\ 0 & \frac{\pi}{2p}\alpha_p \le \lvert\theta\rvert \le \frac{\pi}{2p}(2-\alpha_p) \\ -\frac{B_{rem}}{\mu_0} & \frac{\pi}{2p}(2-\alpha_p) \le \lvert\theta\rvert \le \frac{\pi}{p} \end{cases}$	$M_\theta = 0$
Parallel magnetization				$M_r = \begin{cases} \frac{B_{rem}}{\mu_0}\cos\theta & \lvert\theta\rvert \le \frac{\pi}{2p}\alpha_p \\ 0 & \frac{\pi}{2p}\alpha_p \le \lvert\theta\rvert \le \frac{\pi}{2p}(2-\alpha_p) \\ -\frac{B_{rem}}{\mu_0}\cos\left(1-\frac{\pi/\lvert\theta\rvert}{p}\right)\theta & \frac{\pi}{2p}(2-\alpha_p) \le \lvert\theta\rvert \le \frac{\pi}{p} \end{cases}$	$M_\theta = \begin{cases} -\frac{B_{rem}}{\mu_0}\sin\theta & \lvert\theta\rvert \le \frac{\pi}{2p}\alpha_p \\ 0 & \frac{\pi}{2p}\alpha_p \le \lvert\theta\rvert \le \frac{\pi}{2p}(2-\alpha_p) \\ \frac{B_{rem}}{\mu_0}\sin\left(1-\frac{\pi/\lvert\theta\rvert}{p}\right)\theta & \frac{\pi}{2p}(2-\alpha_p) \le \lvert\theta\rvert \le \frac{\pi}{p} \end{cases}$
Bar magnets in shifting directions [9]				$M_r = \begin{cases} \frac{B_{rem}}{\mu_0}\cos\left(\frac{p\theta}{\alpha_p}\right) & \lvert\theta\rvert \le \frac{\pi}{2p}\alpha_p \\ 0 & \frac{\pi}{2p}\alpha_p \le \lvert\theta\rvert \le \frac{\pi}{2p}(2-\alpha_p) \\ -\frac{B_{rem}}{\mu_0}\cos\left(\frac{p-\pi/\lvert\theta\rvert}{\alpha_p}\right)\theta & \frac{\pi}{2p}(2-\alpha_p) \le \lvert\theta\rvert \le \frac{\pi}{p} \end{cases}$	$M_\theta = \mp\begin{cases} \frac{B_{rem}}{\mu_0}\sin\left(\frac{p\theta}{\alpha_p}\right) & \lvert\theta\rvert \le \frac{\pi}{2p}\alpha_p \\ 0 & \frac{\pi}{2p}\alpha_p \le \lvert\theta\rvert \le \frac{\pi}{2p}(2-\alpha_p) \\ -\frac{B_{rem}}{\mu_0}\sin\left(\frac{p-\pi/\lvert\theta\rvert}{\alpha_p}\right)\theta & \frac{\pi}{2p}(2-\alpha_p) \le \lvert\theta\rvert \le \frac{\pi}{p} \end{cases}$
Two-segment Halbach				$M_r = \begin{cases} \frac{B_{rem}}{\mu_0}\cos\theta & 0 \le \theta \le \frac{\pi}{2p}k_R \\ 0 & \frac{\pi}{2p}k_R \le \theta \le \frac{\pi}{2p}(1-k_T) \\ -\frac{B_{rem}}{\mu_0}\sin\left(\theta-\frac{\pi}{2p}\right) & \frac{\pi}{2p}(1-k_T) \le \theta \le \frac{\pi}{2p} \end{cases}$	$M_\theta = \pm\begin{cases} -\frac{B_{rem}}{\mu_0}\sin\theta & 0 \le \theta \le \frac{\pi}{2p}k_R \\ 0 & \frac{\pi}{2p}k_R \le \theta \le \frac{\pi}{2p}(1-k_T) \\ -\frac{B_{rem}}{\mu_0}\cos\left(\theta-\frac{\pi}{2p}\right) & \frac{\pi}{2p}(1-k_T) \le \theta \le \frac{\pi}{2p} \end{cases}$

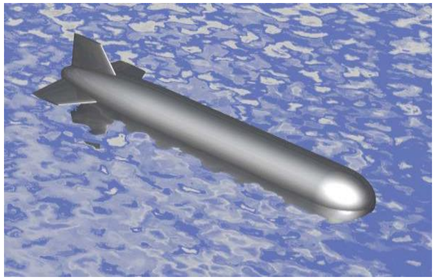
PM Machines Applications

- **Automobiles with combustion engines:**
- **Transportation:**
  - elevators and escalators
  - people movers
  - light railways and streetcars (trams)
  - electric road vehicles
  - aircraft flight control surface actuation
  - electric ships
  - boats
- **Defence forces:**
  - tanks
  - missiles
  - radar systems
  - submarines
  - torpedoes
  - rockets
  - space shuttles
  - satellites



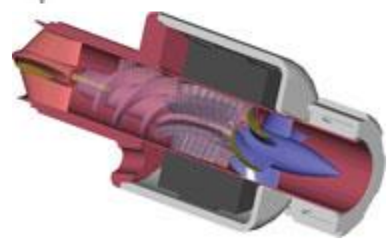



PM Machines Applications

- **Medical and healthcare equipment:**
  - dentist's drills
  - electric wheelchairs
  - air compressors
  - rehabilitation equipment
  - artificial heart motors

- **Power tools:**
  - drills
  - hammers
  - screwdrivers
  - grinders
  - polishers
  - saws
  - sanders
  - sheep shearing hand-pieces





- **Renewable energy systems**
- **Research and exploration equipment**

PM Machines Applications

- **Industry**:
  - industrial drives, e.g., pumps, fans, blowers, compressors, centrifuges, mills, hoists, handling systems, etc.
  - machine tools
  - servo drives
  - automation processes
  - internal transportation systems
  - robots
- **Public life:**
  - air conditioning systems
  - catering equipment
  - coin laundry machines
  - autobank machines
  - automatic vending machines
  - money changing machines
  - ticketing machines
  - bar-code readers at supermarkets
  - environmental control systems
  - amusement park equipment

PM Machines Applications

- **Domestic life:**
  - clocks
  - kitchen equipment (refrigerators, microwave ovens, mixers, dishwashers, etc.)
  - bathroom equipment (shavers, hair dryers, tooth brushes)
  - washing machines and clothes dryers
  - heating and air conditioning systems
  - vacuum cleaners
  - lawn mowers
  - swimming pool pumps
  - toys
  - vision and sound equipment
  - security systems (automatic garage doors, automatic gates)

- **Information and office equipment:**
  - computers
  - printers
  - plotters
  - scanners
  - facsimile machines
  - photocopiers

How to model electric machines?

Static vs. dynamic models

- Normally **static** models are used for **design** purposes
- **Dynamic** models are employed to **dynamically analyse** designed electric machines
- **Dynamic** models are also used for **control design** purposes

Therefore we focus on static models hereafter

Analytical approaches:

- **Zero dimension (0-D)**
- **One-dimension (1-D)**
- **Two-dimension (2-D)**
- **Three-dimension (3-D)**

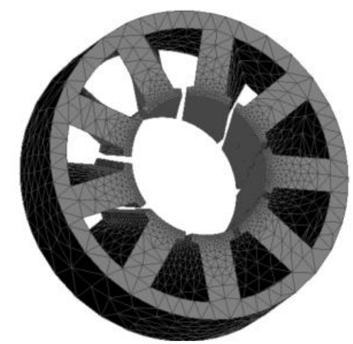
Numerical approaches: such as FEM

- **Two-dimension (2-D)**
- **Three-dimension (3-D)**

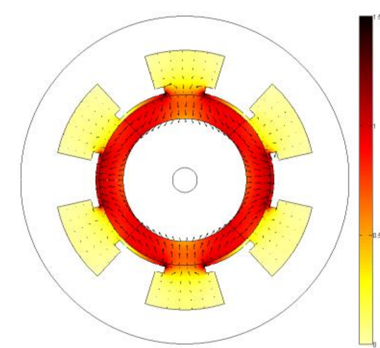
Modelling of Brushless PM machines

Having known the **inputs** (voltage/current, …), machine **geometry** (length, radius, …) and **material** specifications of the machine, the rest of electrical, magnetic and mechanical **quantities** may be calculated.

1. In the most complete case, all **3 spatial dimensions** (e.g. x,y,z in Cartesian coordinates or r,θ,z in cylindrical coordinates) and time are considered; however in static cases, the temporal variable is excluded.

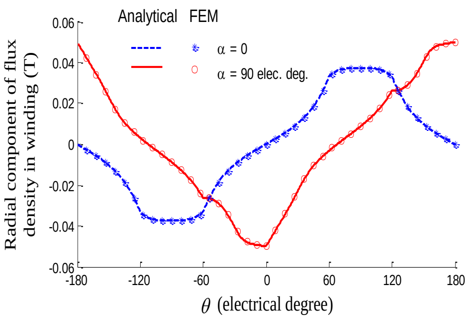


2. In rotary machines with axial symmetry (e.g. without any skew) the machine can be presented by **2 dimensions** (i.e. r and θ).



Modelling of Brushless PM machines

3. If we are interested in the air-gap quantities such as air-gap flux density and the effective air-gap length is small, the flux travels mostly in radial direction and the tangential component is negligible; in those cases only radial component is considered as a function of angular position (**one dimension**). It is noted that in surface mounted magnet brushless machines, the effective air-gap is large and 1-D analysis leads to losing accuracy.

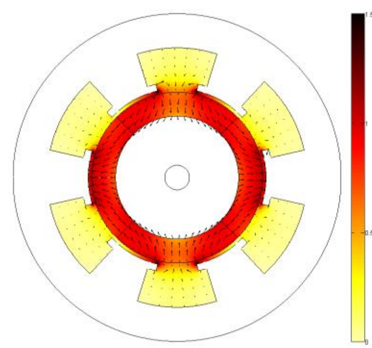


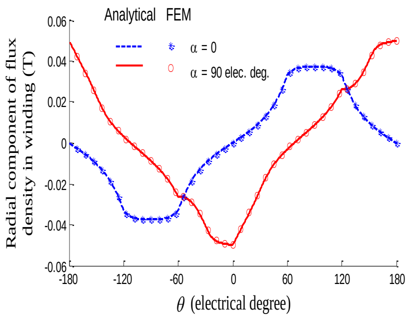
4. In some simple cases, only the maximum or average of quantities is required (**zero dimension**) and both spatial and temporal components are excluded.

Just a value

Different Modelling in terms of number of dimensions

	3-D	2-D	1-D	0-D
Coordinates	$(r\,,\ \theta\ ,\ z)$	$(r\,,\ \theta\,)$	θ	-
Flux density	$\mathbf{B} = B_r\,\vec{r} + B_\theta\,\vec{\theta} + B_z\,\vec{z}$	$\mathbf{B} = B_r\,\vec{r} + B_\theta\,\vec{\theta}$	$B = B_r\,\vec{r}$	$B_{\max}$

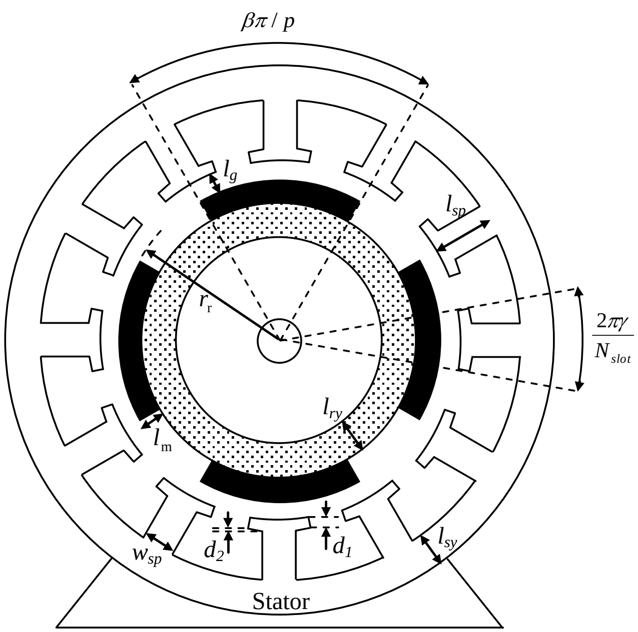


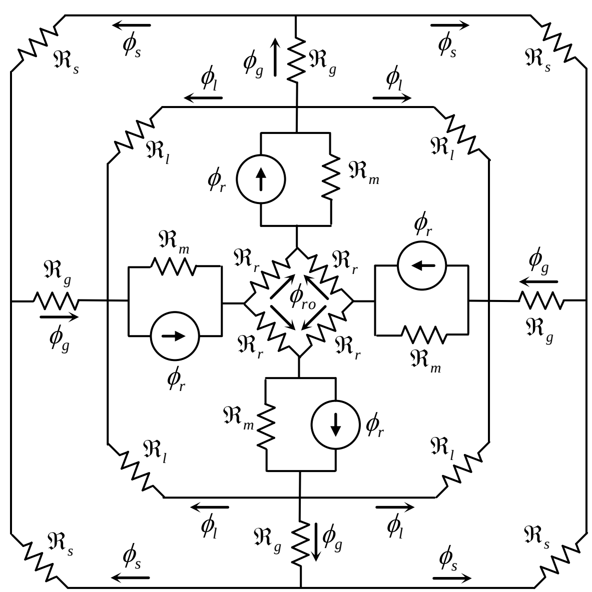


Modelling of Brushless PM machines

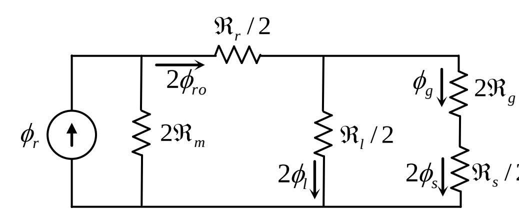
0-D cases (Analytic)

- **Magnetic equivalent networks** or **lump parameter networks** are used to find the maximum or average value of magnetic flux.





Open-circuit magnetic equivalent circuit of the two-pole-pair BLDC motor



Open-circuit magnetic equivalent circuit of a *p*-pole-pair BLDC motor

0-D optimal design procedure of BLPM motors

The design procedure of a BLPM motor can be summarized as follows,

1. The **design parameters** of the motor (i.e. the parameters to be optimized) are introduced and their upper and lower **limits** are set.
2. The **constant parameters** and the motor **requirements** are initialized.
3. A general **equivalent circuit** of open-circuit BLPM motors is drawn.
4. The rotor, stator, air-gap and permanent magnet **reluctances** are expressed in terms of the motor geometries.
5. The **open-circuit magnetic flux** is expressed in terms of the reluctances.
6. The **fringing effect** and **Carter's** coefficients are considered.
7. The **flux leakage** is expressed and considered.
8. **Air-gap flux density** and electromagnetic **torque** are expressed in terms of motor geometries.

0-D optimal design procedure of BLDC motors

9. The electromotive force (**EMF**) and the **terminal voltage** of the motor are written as functions of motor geometries.
10. The **inductances** of the motor are also expressed in terms of motor geometries.
11. The **maximum rotational speed** of the motor is related to the motor resistance and inductance.
12. The electrical, mechanical and magnetic power **losses** are expressed.
13. The **objective functions** (e.g. motor cost, power loss and volume) are defined and related to the motor geometries.
14. The necessary **constraints** are expressed and imposed to the optimization problem.
15. Select an **optimization technique** (e.g. genetic algorithms) to solve the optimization problem.

Modelling of Brushless PM machines

2-D or 3-D cases (Analytic or Numeric)

- In a brushless PM motor, having the armature current waveform (as input), the magnet characteristics, the motor geometry and the material specifications, the quantities such as the **open circuit flux density** and the **armature reaction flux density** can be found.
- Based on the **open circuit flux density**, **flux linked** with each coil, induced **back-emf** in the armature winding, **stator eddy current losses**, **winding eddy current losses**, **local traction** and **cogging torque** can be obtained. $\phi = \int \mathbf{B} \cdot d\mathbf{S}$, $E = -N \frac{d\phi}{dt}$
- Using the **armature reaction flux density**, **the self- and mutual-inductances**, rotor (PM, retaining sleeve and rotor back-iron) **eddy current losses** and **reluctance torque** are calculated.
- Employing **both flux densities**, the **electromagnetic torque** and **unbalanced magnetic forces** are computed.

$$T(t) = T_{cog}(t) + T_{em}(t) + T_{rel}(t)$$

$$T(t) = L \int_{-\pi}^{\pi} \frac{1}{\mu_0} \left(B_{r,PM} + B_{r,AR}\right)\left(B_{\theta,PM} + B_{\theta,AR}\right) r^2 \, d\theta$$

2-D Analytical Model of Brushless PM Machines

The following steps are performed to analytically calculate the magnetic field distribution

- A set of **assumptions** is normally made.
- The **problem domain is divided** into a number of sub-regions based on the assumptions, the geometry of the machine and the electrical and magnetic properties of each part of the machine.
- Based on Maxwell's equations and the assumptions made, the governing **PDEs** are derived for each sub-region.
- A set of **boundary and interface conditions** are defined based on the sub-regions and their geometry.
- Depending upon the number of phases, the current waveform in each phase and the winding distribution, the **armature current density distribution** is represented as a function of time and spatial position.
- The **magnetization vector** of the magnets is also expressed using the Fourier series expansion. It is normally represented as a function of spatial position.
- For each sub-region a **general solution** is found to satisfy the governing PDEs and also has the potential to satisfy the boundary conditions.
- The boundary conditions are imposed to determine the **integration constants** of the general solutions.
- **Validate** the analytical model.

BLPM Machine Design based on 2-D Analytical Model

1. Magnetic **flux density** distribution due to **PM** (open circuit flux density)
2. Armature **current** waveforms (depends on control technique)
3. **Winding configuration** and factors
4. Magnetic **flux density** distribution due to the **armature current** (from 2 and 3)
5. **Back-emf** calculation (from 1 and 3)
6. **Electromagnetic torque** (from 1 and 4) or (from 2 and 5)
7. **Ripple** and **average** electromagnetic torques (from 6)
8. **Cogging torque** (from 1)
9. **Reluctance torque**, just for salient rotor motors (from 4)
10. **Stator iron losses**: hysteresis, eddy current and excess eddy current (from 1)
11. Eddy current **losses in permanent magnets** (from 4)

BLPM Machine Design based on 2D Analytical Model

12. **Rotor iron losses**: hysteresis, eddy current and excess eddy current (from 4)
13. **Copper losses** (from 2 and winding characteristics)
14. Leakage, self and mutual **inductances** (from 2, 3 and 4)
15. **Mechanical losses**: windage, ventilation and bearing friction
16. The **objective functions** (e.g. motor cost, power loss and volume) are defined and related to the motor geometries.
17. The necessary **constraints** are expressed and imposed to the optimization problem.
18. Select an **optimization technique** (e.g. genetic algorithms) to solve the optimization problem.

E.g., Optimization formulation of slotless stator BLDC Motors

Optimization variables

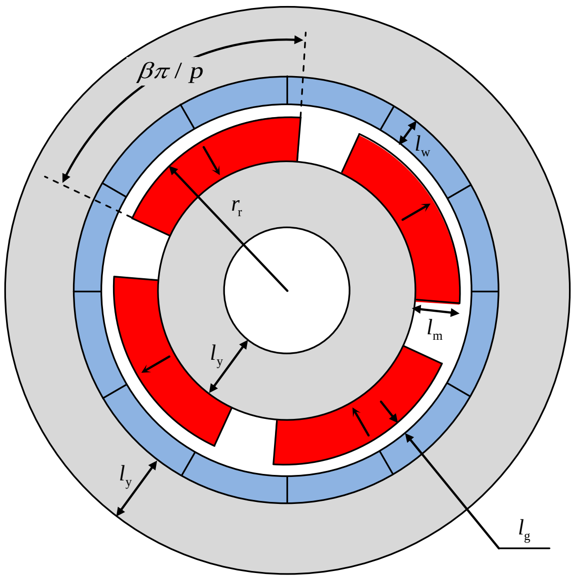
- Number of pole-pairs (p)
- Pole-arc per pole-pitch ratio (β)
- Magnet radial thickness (l_m)
- Stator/rotor back-iron thickness (l_y)
- Winding space radial thickness (l_w)
- Mechanical air-gap length (l_g)
- Rotor radius (r_r)
- Winding current density (J_{cu})
- Wire gauge
- Stator/rotor axial length (l_s)

Constraints

- Upper and lower limits of the optimization variables
- Maximum heat allowance of winding

Optimization objectives

- Power loss minimization
- Motor volume minimization
- Cost minimization
- Required torque generation
- Required speed achievement
- Keep flux below saturation limit



Optimization formulation

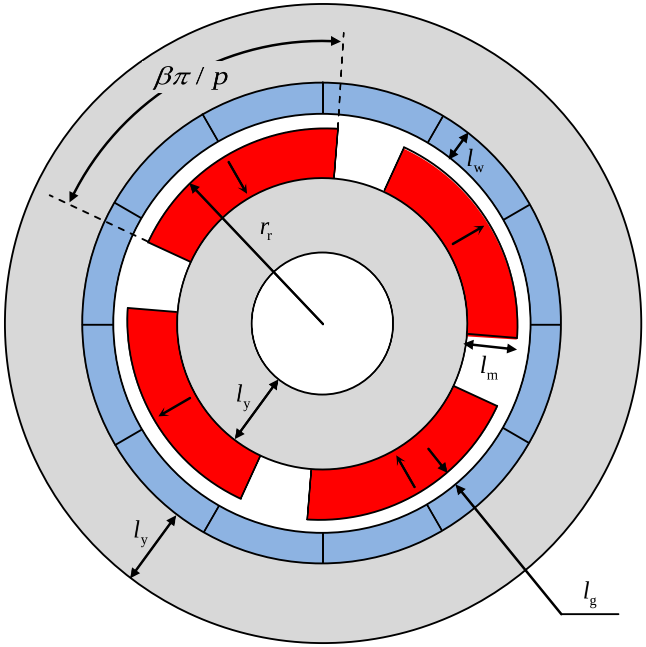
The following quantities should be expressed as functions of motor geometry

- **Electromagnetic torque**
- **Power losses (Copper, eddy current, hysteresis and mechanical losses)**
- **Inductance and resistance of the winding**
- **Back-EMF**
- **Motor active part volume**
- **Motor cost**

$$f_{\mathrm{o}}(\mathbf{x}) = w_{\mathrm{P}} P_{\mathrm{l}}(\mathbf{x}) + w_{\mathrm{V}} V_{\mathrm{a}}(\mathbf{x}) + w_{\mathrm{C}} C(\mathbf{x}) +$$

$$\frac{1}{\varepsilon}\left[f_{\mathrm{u}}\left(1 - T_{\mathrm{em}} / T_{\mathrm{em}}^{*}\right) + f_{\mathrm{u}}\left(1 - \omega_{\mathrm{r}}^{\max} / \omega_{\mathrm{r}}^{*}\right) + f_{\mathrm{u}}\left(B_{\mathrm{sy}} / B_{\mathrm{sy}}^{\mathrm{knee}} - 1\right)\right]$$

$$f_{\mathrm{u}}(x) = \frac{1}{1 + e^{-\sigma x}}$$



Materials

Materials used to construct an electric machine are categorized in three groups:

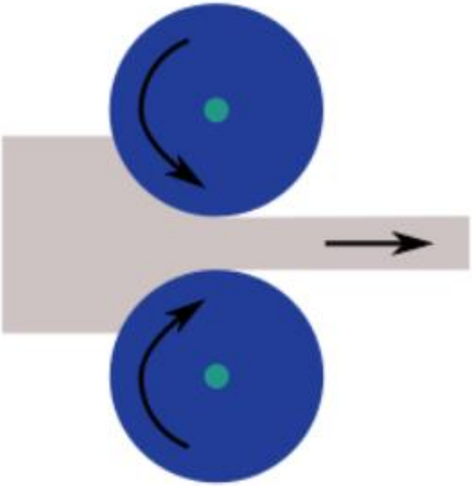
1. **Active** materials (electric conductors, superconductors, electrotechnical steels, sintered powders and PMs)

2. **Insulating** materials

3. **Construction** materials

Electrotechnical Steel Sheets

Typical magnetic circuits of electrical machines are laminated and are mainly made of **cold-rolled** electrotechnical steel sheets:



1. **Oriented** (anisotropic) textured

2. **Nonoriented** with silicon

3. **Nonoriented** without silicon

Nowadays, **hot-rolled** electrotechnical steel sheets are never used.

Electrotechnical Steel Sheets

- **Oriented steel sheets** are used for the ferromagnetic cores of transformers, transducers and large synchronous generators.
- **Nonoriented steel sheets** are used for construction of large, medium, and low power rotary electrical machines, micro-machines, small transformers and reactors, electromagnets, and magnetic amplifiers.
- **Silicon content** increases the maximum magnetic permeability corresponding to critical magnetic field intensity, reduces the area of the hysteresis loop, increases the resistivity, and practically excludes the ageing (ageing means an increase in the steel losses with time).

High-Saturation Ferromagnetic Alloys

- **Cobalt-iron alloys** have the highest known saturation magnetic flux density.

- They are the natural choice for applications where **mass and space saving** are of prime importance.

- The nominal composition is up to
  - **50% Co** (cobalt)
  - **2% V** (vanadium)
  - **the rest is Fe** (iron)

Permalloys

- Small electrical machines and micro-machines working in **humid or chemical active** atmospheres must have stainless ferromagnetic cores.
- The best corrosion-resistant ferromagnetic material is **permalloy** (Ni-Fe-Mn).
- But its **saturation magnetic flux density** is **lower** than that of electrotechnical steel sheets.

Amorphous Materials

- Core losses can be substantially reduced by replacing standard electrotechnical steels with **amorphous magnetic alloys**.
- Amorphous ferromagnetic sheets, in comparison with electrotechnical sheets with crystal structure, do not have arranged in order, regular inner crystal structure (lattice).
- Owing to very low specific core losses, amorphous alloys are ideal for power and distribution transformers, transducers, and high frequency apparatus.

Solid Ferromagnetic Materials

- **Solid ferromagnetic materials** as cast steel and cast iron are used for:
  - salient poles,
  - pole shoes,
  - solid rotors of special induction motors and
  - reaction rails (platens) of linear motors.

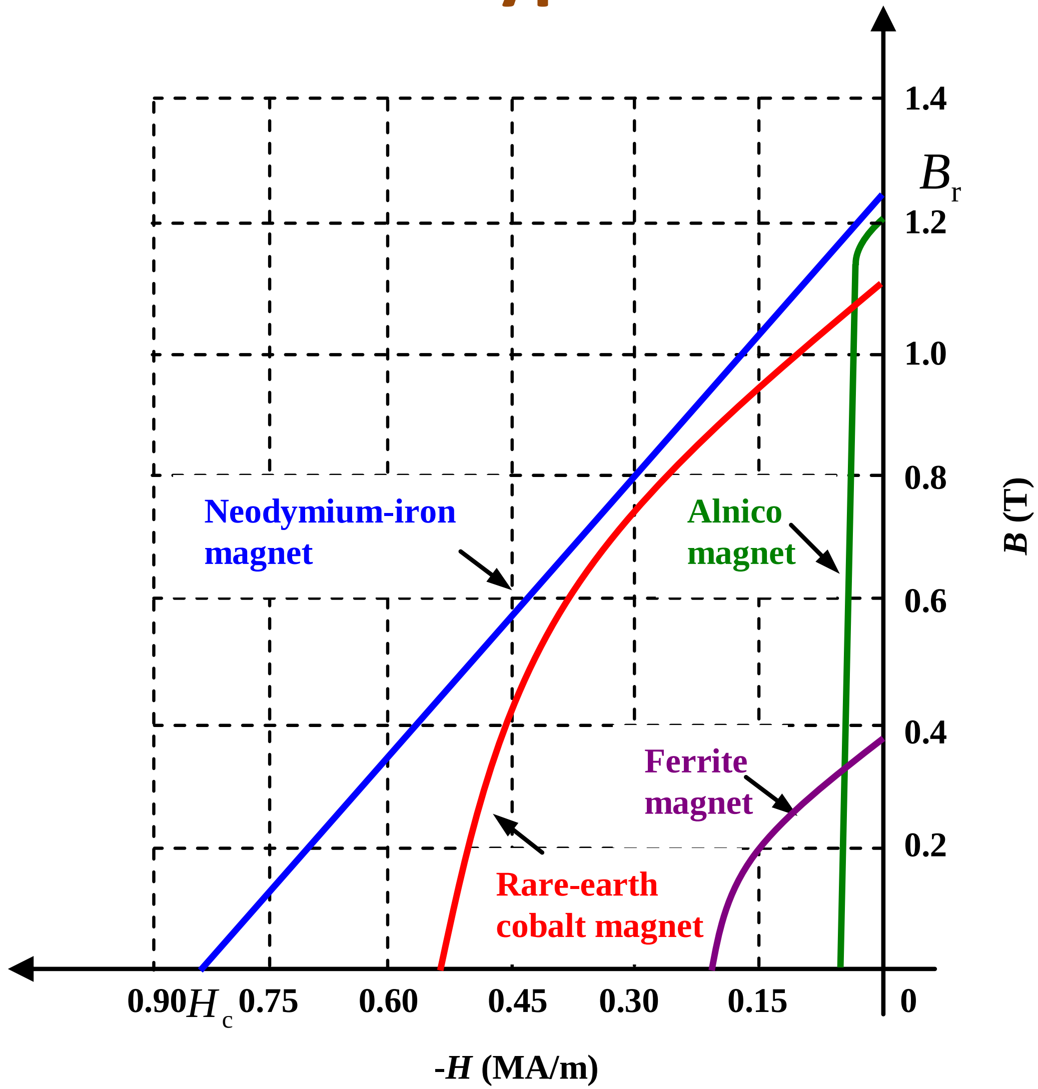
Soft Magnetic Powder Composites

- Powder metallurgy is used in production of ferromagnetic cores of **small** electrical machines or ferromagnetic cores with **complicated shapes**.

- The components of *soft magnetic powder composites* are **iron powder**, **dielectric** (epoxy resin) and **filler** (glass or carbon fibers) for mechanical strengthening.

- Powder composites can be divided into:
  - dielectromagnetics and magnetodielectrics,
  - magnetic sinters.

Common types of PM



Demagnetization curve of four types of permanent magnets

Common types of PM

	Typical at 20 °C				Relative material cost	Resistance to corrosion	Temperature performance	Shape complexity
	B_r (T)	H_c (kA/m)	H_{ci} (kA/m)	$(BH)_{max}$ (kJ/m^3)				
NdFeB [1]	1.18	840	1040	**256**	High	Poor (coating is vital)	Poor	Very simple
NdFeB [2]	0.56	400	800	**60**				Complex
NdFeB [3]	0.70	480	840	**84**				Simple
Sm_2Co_{17} [1]	1.00	480	558	**192**	Very high	Good	Very good	Very simple
$SmCo_5$ [1]	0.83	600	1440	**128**				Very simple
$SmCo_5$ [2]	0.65	460	620	**80**				Complex
Sm_2Co_{17} [3]	0.86	497	800	**130**				Simple
Alnico-5 [1]	1.05	48	50	**24**	Low	Good	Excellent	Very simple
Alnico-5 [4]	1.24	51	51	**44**				Complex
Ferrite [1]	0.41	223	231	**32**	Very low	Excellent	Good	Very simple
Ferrite [2]	0.30	191	223	**16**				Complex

[1] Sintering [2] Injection moulding [3] Compression bonding [4] Casting

Conductors

- Armature windings of electric motors are made of solid **copper** conductor wires with round or rectangular cross sections.
- When the price or mass of the motor are paramount, **aluminum** conductor wires can be better.
- After coils are wound, they must be secured in place to avoid movement. Two methods are used to **secure the conductors** in place:
  - **Dipping** the whole component into a varnish-like material, and then baking off its solvent.
  - **Trickle impregnation** method, which uses heat to cure a catalyzed resin which is dripped onto the component.

Conductors

- Following **impregnating materials** for treatment of stator or rotor windings are used:
  - **Polyester resin**
  - **epoxy resin**
  - **silicon resin**

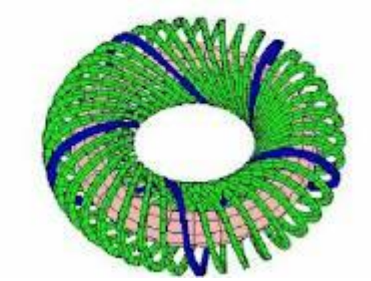
- A new method of conductor securing without the need of any additional material, which uses very low energy input, has emerged.

- The solid conductor wire (usually copper) is coated with a **heat and/or solvent activated adhesive**.

Principles of Superconductivity

Applications of superconductivity:

- Large turbo alternators
- DC machines
- Linear synchronous machines
- Energy storages
- Magnetic levitation trains
- Transmission cables
- Fault-current limiters
- High temperature superconductor (HTS) filters



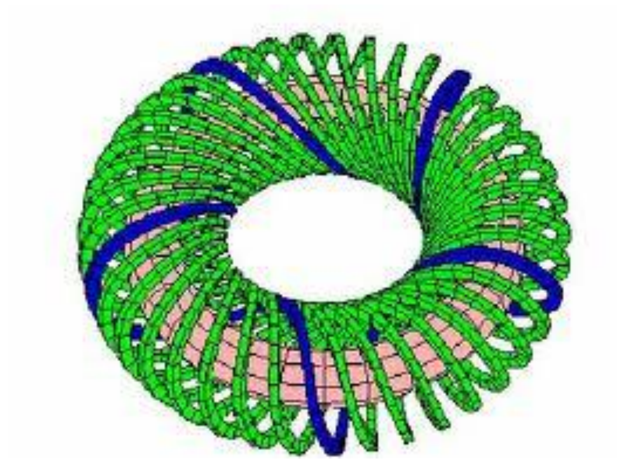
Principles of Superconductivity

The use of superconductivity in electrical machines

- Reduces the excitation **losses**
- Increases the magnetic **flux density**
- Eliminates ferromagnetic **cores**
- Reduces the synchronous **reactance** (in synchronous machines)

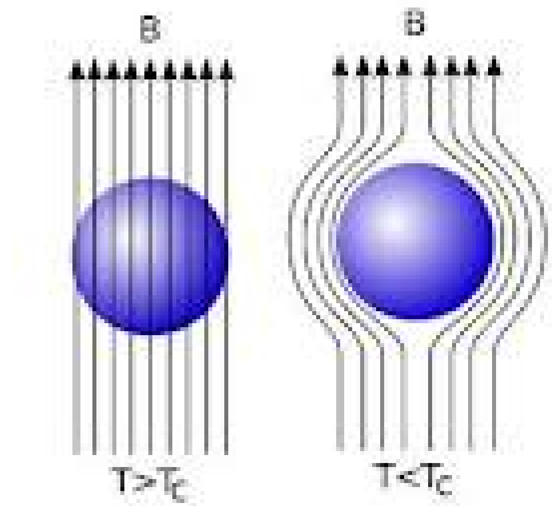
Principles of Superconductivity

- Superconductors can **carry** a large direct **current** without **any resistance**.



- They can also **exclude** a static magnetic **flux** from its **interior**.

- The second property is known as *Meissner effect*, that distinguishes a superconductor from merely being a perfect conductor.



Principles of Superconductivity

- Superconductivity happens only when the temperature goes below the critical temperature which ranges from **1 to 130K**.

- Two other critical quantities are: the critical magnetic flux density and the critical current density.

- These critical values, which are dependent on one another, **must not be exceeded** at any case otherwise the material loses its superconductivity and generates the electrical resistance (*quench effect*).

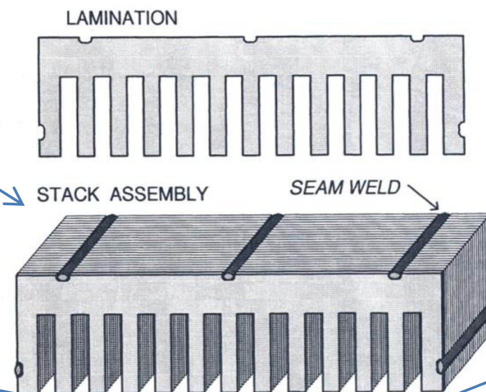
Laminated Stacks

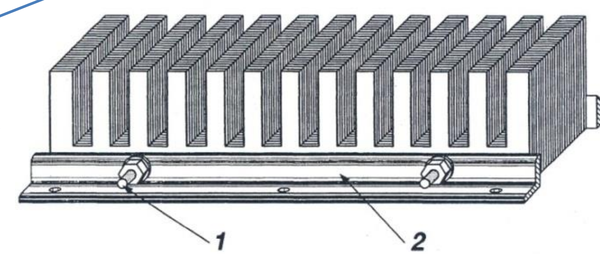
- Most electric machines use **laminated** armature stacks with semi-open or open slots.
- In low-speed industrial application the frequency of the armature current is well **below** the power frequency 50 or 60 Hz.
- So from electromagnetic point of view, laminations can be thicker than **0.5 or 0.6 mm**.
- The laminations are cut to dimensions using
  - **stamping presses** in mass production or
  - **laser cutting** machines when making prototypes.

Laminated Stacks

The **laminations are kept** together with the aid of

- Seam welding
- Spot welding
- bolts and bars
- Bonding with epoxy or Loctite
- Riveting
- Self-cleating
- Slot liners





Armature Windings of Slotted Cores

- Armature windings are usually made of **insulated (enamelled) copper** conductors.
- The cross section of conductors can be **circular** or **rectangular**.
- Sometimes, to obtain a **high power density**, a **direct water cooling** system has to be used and consequently **hollow** conductors are used.
- It is **difficult** to make and shape armature coil if the round conductor is **thicker that 1.5 mm**.
- If the current density is too high, **parallel conductor** wires of smaller diameter are rather recommended than one thicker wire.
- Armature windings can also have **parallel current paths**.

Note on High Speed Machines

- The **power** of an electric machine can be expressed as:

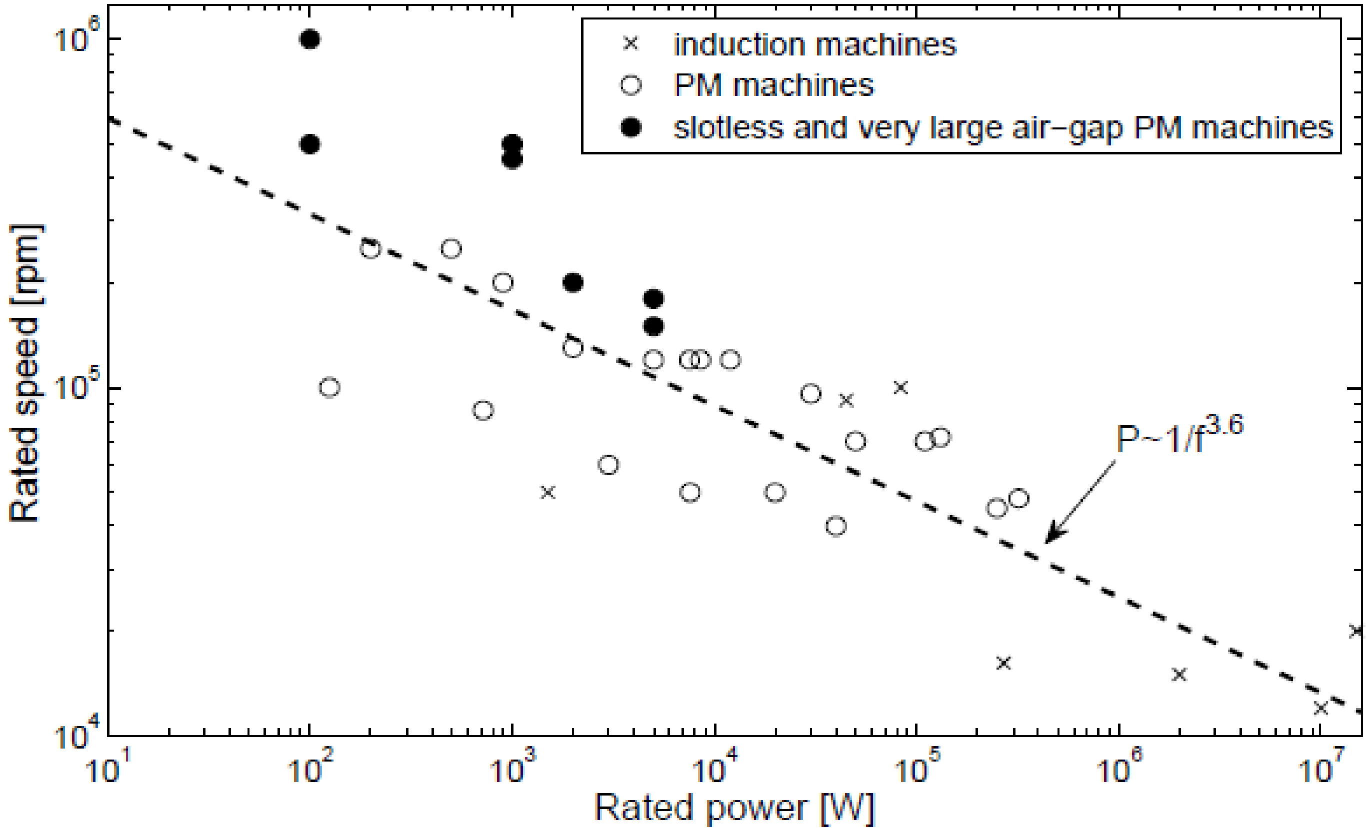
$$P = CD^2LN$$

where D is the **rotor diameter**, L is the **active axial length**, N is the **rotational speed** of the machine and C is **Esson's utilization factor**, which depends on the **machine type** and other various variables such as the **cooling system**.

- As evident from the above expression, at high, very-high and ultra-high speed machines, the machine volume/power is reduced more and more.

Note on High Speed Machines

Rated speed vs. rated power for high speed machines



Note on High Speed Machines

Some of the applications of ultrahigh speed machines include:

1. **drilling micron-sized holes**,

2. a single hand held **drilling tool for dentists**,

3. electric-assisted **turbochargers** for car engines,

4. portable power generation units based on **gas turbines**, and

5. flywheel **energy storage** systems

Note on High Speed Machines

1. Machining Spindles for Grinding, Milling, and Drilling

- The recent trend in **mechanical systems** has been toward **smaller sizes** (miniaturization),
- which, in turn, requires **high-precision** manufacturing.
- To accomplish this high precision requires the use of **smaller size and higher speed drilling, milling, and grinding tools**.
- For example, **notch grinding of silicon wafers** requires motor speeds of up to **150 000 rpm**.

Note on High Speed Machines

1. Machining Spindles for Grinding, Milling, and Drilling

- In the **electronics industry**, **smaller and more compact** printed circuit boards (**PCBs**) are required.
- Therefore **smaller holes** (microvias) have to be drilled.
- For example, **fine-pitch ball grid arrays** (BGAs) now have over 1700 pins.
- Presently, microvias with diameters of **75 μm** can be produced economically with mechanical PCB drills that operate with speeds of up to **250 000 rpm** and with a motor power of **200 W**.
- For **10 μm** hole diameters, the drilling speed must be increased to over **1 million rpm**.

Note on High Speed Machines

2. Spindles for Dental Drills and Medical Surgery Tools

- Majority of today's dental drill hand pieces are powered by an **air turbine** from a compressed air supply.

- Therefore, each hand piece is designed to operate at a single speed, and accurate speed control is **not** possible.

- High-speed operation allows for **higher performance** in terms of **cutting speed** and the use of **smaller diameter drills**.

Note on High Speed Machines

2. Spindles for Dental Drills and Medical Surgery Tools

- In the high-speed range, air turbine hand pieces operate up to **400 000 rpm**, with power levels between **10 and 20 W**.
- The currently available electrical powered hand pieces operate their electric motors up to a maximum of **40 000 rpm**,
- and then a **triple-gear system** steps the speed up to a maximum of **200 000 rpm**.
- Compared to the air powered hand piece, a direct drive electrical machine requires a speed increase of a **factor of 10**.
- The increased speed would allow a **smaller machine design**.

Note on High Speed Machines

3. Compressors and Turbochargers

- Recent **environmental concerns** have caused the improvement of **automotive fuel efficiency**.
- A major thrust has been in the development of hydrogen based **fuel cells** for propulsion systems.
- These fuel cells require a constant supply of **pressurized air** that is provided by an air compressor system.
- To achieve a compact size, the compressor speed has been increased to **120 000 rpm** at a power level of up to **12 kW**.

Note on High Speed Machines

*3. Compressors and **Turbochargers***

- To increase the fuel economy and reduce the CO_2 of cars, **smaller capacity internal combustion engines** have to be developed.
- To provide a higher performance and improved efficiency, a **turbocharger** is employed.
- Turbochargers do **not** perform well at **low engine speeds**.
- **Electrically assisted turbochargers** provide the pressure boost at low speeds.
- An **electrical machine** is mounted on the same shaft between the turbine and the compressor.

Note on High Speed Machines

3. Compressors and Turbochargers

- The electrical machine has to operate at the same speeds of the turbocharger (**up to 200 000 rpm**) and provide at least **1.5 kW** to influence the acceleration performance of the vehicle.
- The major drawback of the electrically assisted turbocharger is that the electrical machine must operate at **extremely high temperatures**,
- since there is a direct connection to the **exhaust gas** turbine.
- Therefore, there have been developments of a **separate air compressor** that operates together with the turbocharger to provide additional boost at low engine speeds.
- The speed is **86 000 rpm** with a system input power of **720W**.

Note on High Speed Machines

4. Portable Power Generation—Gas Turbine Generators

- There are emerging applications for portable, **low-power gas-turbine** based power generation systems.
- One application is for the **modern soldier**, who now carries electrical equipment with a power consumption of up to **100 W**.
- At these power levels, the gas turbine system occupies a very small volume if the rotational speeds are increased to over **500 000 rpm**.
- For power levels of less than **10 W**, the trend is for speeds over **1 million rpm** where the construction uses micro-electrical-mechanical system (**MEMS**) techniques.

Note on High Speed Machines

5. Energy Storage (Flywheels)

- Two types of flywheel energy storage systems exist:
  - those with **large mass** and **low rotational speeds** (<10 000 rpm)
  - those with **low mass** and **high rotational speeds** (>10 000 rpm).
- Special applications exist in the **aerospace industry** for low-mass, high-speed flywheel systems.
- In particular, NASA is investigating their use for both **attitude control and energy storage** in satellites and the international space station.
- As part of a research project, a **3-kW**, **40 000-rpm** flywheel energy storage system has been tested that also provides attitude control.

Note on High Speed Machines

6. Optical Scanning Systems

- In the field of **optical scanning systems** a transparent cube needs to be rotated at very high speeds.
- It is to facilitate the depth scanning of human retinas through reflectometry measurement from coherent light sources.
- In this application, an air spindle operating at **580 000 rpm** is used.
- Therefore, good opportunities exist to replace the air spindle with an **electrical drive system** with speed control.

Note on High Speed Machines

7. Ultracentrifuges

- Another application of high-speed electric machines is in the field of **megagravity science**.
- This is the study of solids and liquids under **high acceleration** (and temperatures).
- An ultracentrifuge produces an acceleration of **1 million times gravity** through the use of a **220 000-rpm** air turbine.
- It describes that electrical drive centrifuges exist with maximum speeds up to **120 000 rpm**, although there is no reason why this cannot be increased with the correct design.