The Basics of Permanent Magnet Motor Operations

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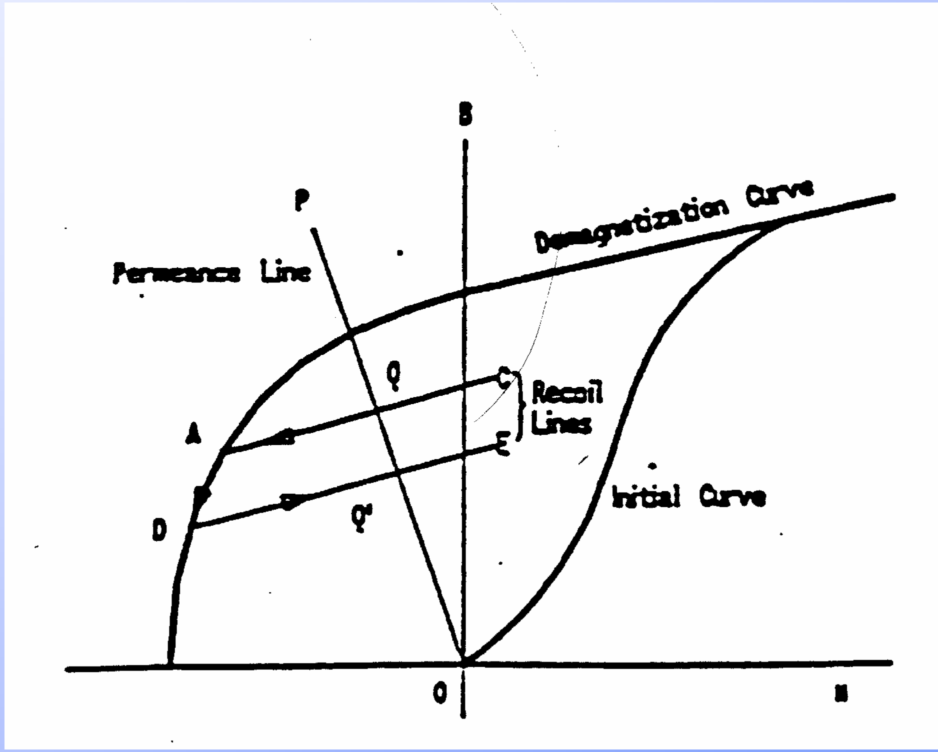
Introduction

- Introduction
- The physics of permanent magnets
- Basic PM motor operating principles
- Basic motor parameters
- Motor construction

The Physics of Permament Magnets

The Physics of Permament Magnets

- a typical magnetization curve for a PM magnet is shown here



The Physics of Permament Magnets

- the outmost outline of the magnetization curve is for a single cycle of a fully magnetized magnet
- as the operating point of the magnetic circuit's permeance **P** line intersects with the demagnetization curve the magnet "weakens"
- the magnetization is not a single curve, but a family of curves

The Physics of Permament Magnets

- the permeance *P* of the magnetic circuit determines the operating point of the permanent magnet

$$P = \frac{F \cdot m}{\Re \cdot g}$$

F : magnetic flux leakage

m : magnet thickness parallel the direction of flux in inches

$\Re$: magnetic reluctance factor - typically 1.1 - 1.5

g : air gap thickness parallel the direction of flux in inches

The Physics of Permament Magnets

- plotting the permeance into the magnetization curve yields the operating point of the magnetic circuit

  – idealistic assumption
    - no saturated steel
    - $\mu_r >> 1$

  – ignores the effects of demagnatization
    - internal field from windings
    - demagnetization curve
    - magnet temperature

  – ignores the effect of the magnet's temperature

The Physics of Permament Magnets

- the magnet’s flux changes with temperature
  - reversible
  - irreversible

The Physics of Permament Magnets

- the magnet's linear, reversible flux change as a function of temperature is:

$$B(T) = B(T_0)[1 - \beta(T - T_0)]$$

$B(T)$: air gap flux density at temperature T

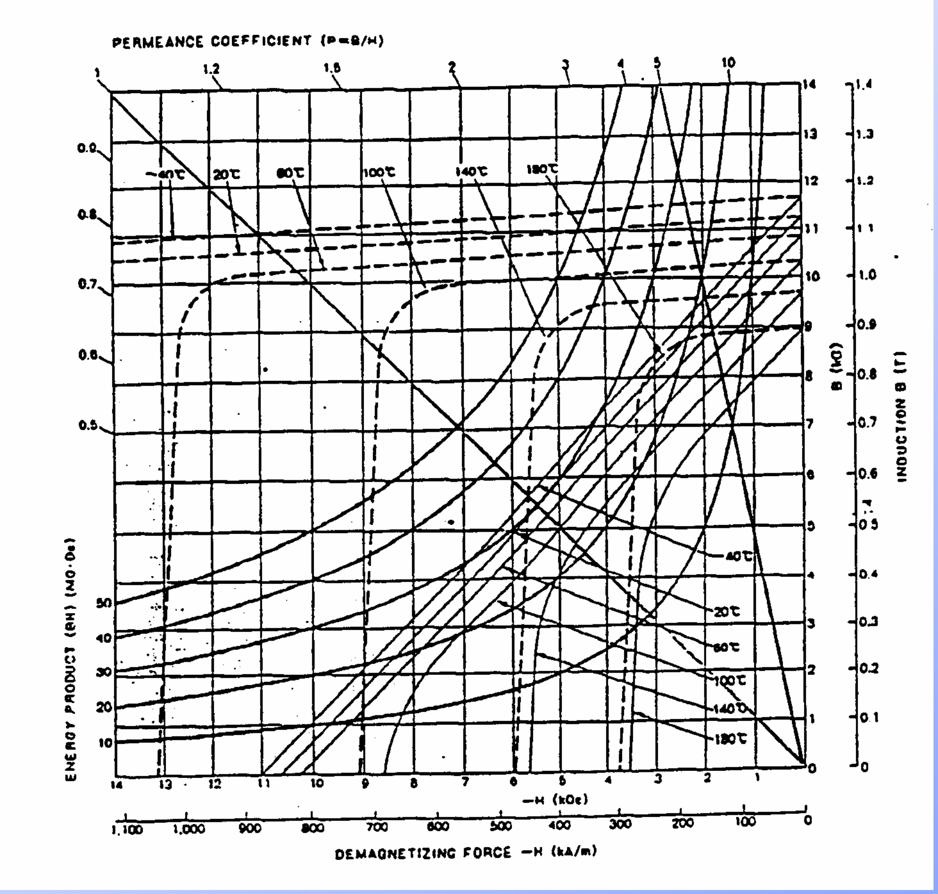
$B(T_0)$: air gap flux density at temperature T_0

β : linear coefficient of demagnetization

T : magnet temperature (°C)

The Physics of Permament Magnets

- irreversible changes can occur in the magnet well below its Curie temperature



The Physics of Permament Magnets

- the motor's conductors can cause irreversible damage to its magnet
- the flux generated by an inductor in the magnet is:

$$H = \frac{Z \cdot i}{3 \cdot P \cdot (m + g)}$$

Z : total number of conductors

i : the winding current

P : the permeance of the magnetic circuit

m : magnet thickness parallel the direction of flux in inches

g : air gap thickness parallel the direction of flux in inches

The Physics of Permament Magnets

- each PM motor therefore has
  - a thermal current rating due to wire constraints
  - an absolute peak current rating due to magnet constraints

The Physics of Permament Magnets

- most PM motors use one of the following PM magnet materials
  - Alnico: Aluminum Nickel Cobalt
  - Fe_3O_4: Ceramic/Ferrite
  - SmCo: Samarium Cobalt
  - NeFeBo: Neodymium Iron Boron
- none is generally “better” or “worse”

The Physics of Permament Magnets

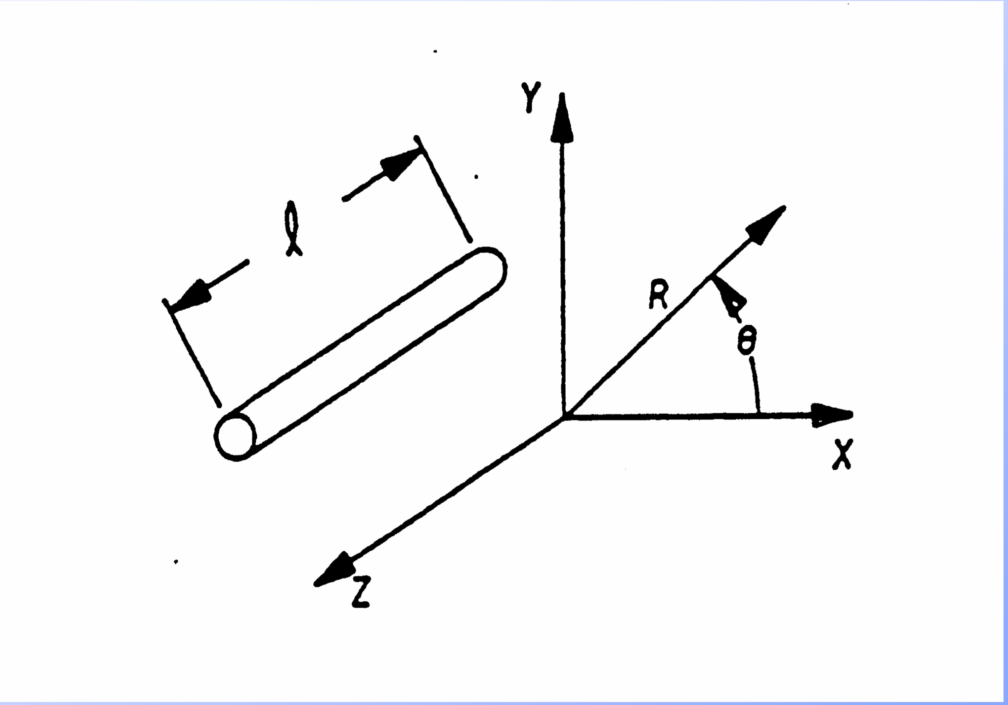
- a comparison of different magnet materials

Magnet Material	Price $ per lb.	B_r - Max (gauss)	Coercivity (oersted)	Typical P	Curie Temp (°C)	β (1/°C)
Alnico 5-7	$40	12,500	650	50-75	850	0.0001
Ferrite	$7	4,000	3,600	10-20	450	0.002
NdFeB	$100	11,000	10,000	2-5	320	0.001
SmCo	$180	8,000	7,500	4-8	800	0.00045

Basic PM motor operating principles

Basic PM motor operating principles

- PM motors operate on the principle that a force is generated when current flows in an inductor that is placed in a magnetic field



Basic PM motor operating principles

- force generated in a conductor in a magnetic field

$$\overline{F_m} = i \cdot \bar{l} \otimes \overline{B}$$

$\overline{F_m}$: mechanical force vector

i : current flowing in the conductor

$\bar{l}$: length of the conductor (perpendicular to magnetic flux)

$\overline{B}$: magnetic flux vector

Basic PM motor operating principles

- this force generates torque in a rotary motor

$$T = B \cdot r \cdot l \cdot Z \cdot i$$

T : rotor torque

B : magnetic flux

r : average winding radius

l : effective conductor length (stack length)

Z : number of conductors

i : current flowing in the conductor

Basic PM motor operating principles

- a conductor that moves in a magnetic field generates a voltage

$$V = \int_0^l \overline{v_y} \otimes \overline{B_x} \cdot \overline{dz} = -B \cdot l \cdot v$$

V : induced voltage

$\overline{v_y}$: velocity of inductor perpendicular to the magnetic field

$\overline{B_x}$: magnetic flux vector

Basic PM motor operating principles

- a rotary motor produces the back-EMF (Lenz's Law)

$$V = -B \cdot r \cdot l \cdot Z \cdot \omega$$

V : induced voltage

B : magnetic flux vector

r : radius

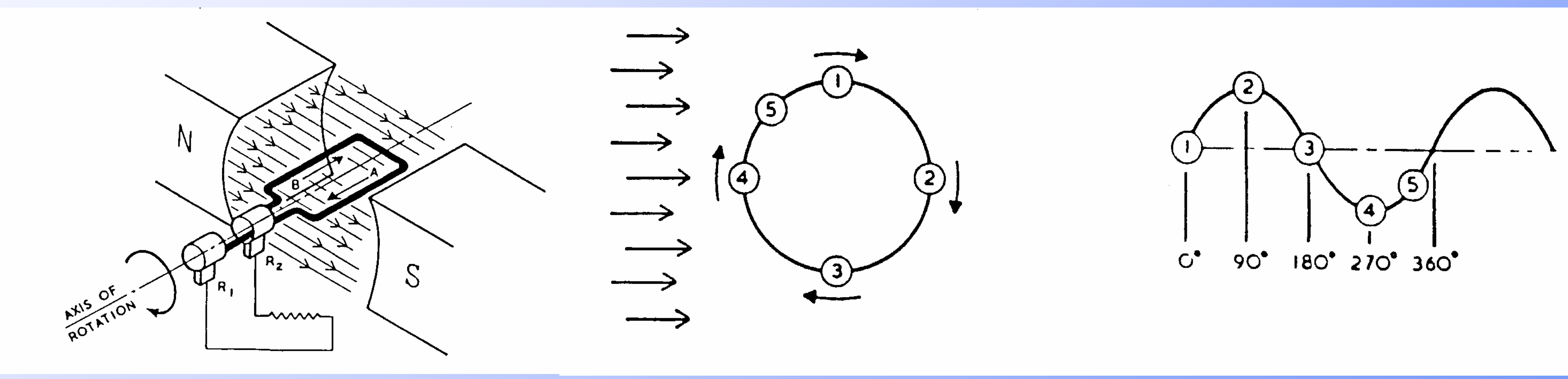
l : effective conductor length (stack length)

Z : number of condutors

ω : angular velocity

Basic PM motor operating principles

- inductor loop in a magnetic field



Basic PM motor operating principles

- adding a mechanical commutator yields a brush PMDC motor
- adding two or more mechanically offset windings yields a PM DLDC or PM BLAC motor

Basic motor parameters

Basic motor parameters

- the torque constant K_t

$$T = K_t \cdot \omega \qquad (\mathrm{N \cdot m})$$

$$K_t = B \cdot r \cdot l \cdot Z \qquad (\mathrm{N \cdot m / A})$$

Basic motor parameters

- the back-EMF (voltage) constant K_e

$$V = K_E \cdot \omega \quad \text{(volt)}$$

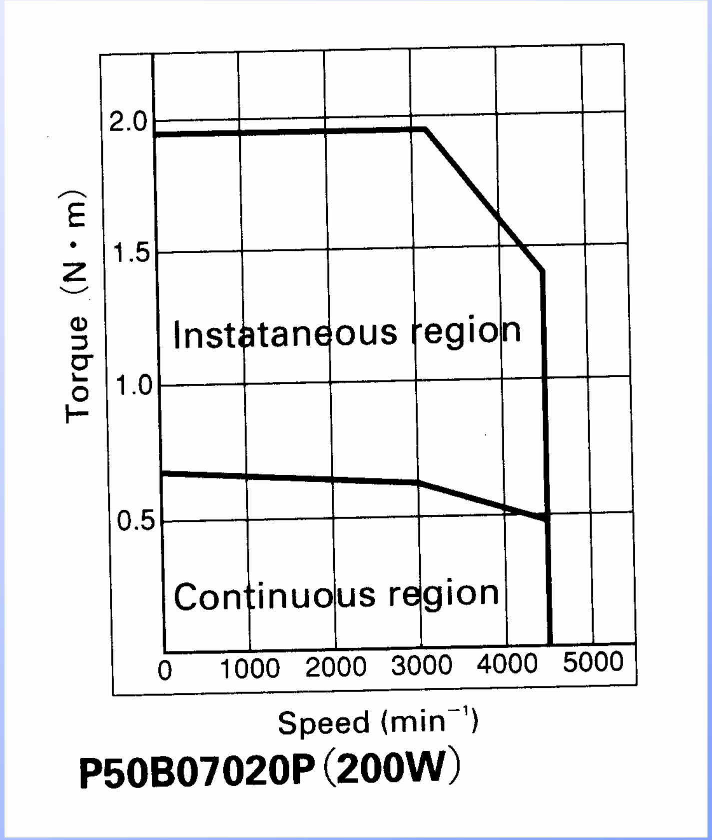
$$K_E = B \cdot r \cdot l \cdot Z \quad \text{(volt/rad/sec)}$$

Basic motor parameters

- armature resistance R_a (Ohm)
- armature inductance L_a (Henry)
- electrical time constant τ_e (sec)
- rotor inertia J_r (Kg · m^2)
- damping constant D_m (N · m / rad / sec)
- mechanical time constant τ_m (sec)
- thermal resistance R_Θ (°C / Watt)
- thermal capacitance C_Θ (Joules / °C)
- thermal time constant τ_{therm} (sec)

Basic motor parameters

- example of a typical speed/torque curve of a PM motor



Basic motor parameters

- the “Safe Continuous Operating Area” SCOA
  - the motor can safely be operated continuously anywhere in this region
- the “Safe Intermittent Operating Area” SIOA
  - the motor may be operated in this region for short periods of time (typically < 1 min)

Basic motor parameters

- the electrical equation for the PM DC machine is:

$$V = L_a \cdot \frac{dI}{dt} + R_a \cdot I + K_E \cdot \omega$$

Basic motor parameters

- the electrical equation for a single phase of the PM BLDC/BLAC machine with sinusoidal phase current is:

$$V(\vartheta) = L_a \cdot \frac{2\cdot\pi}{360} \cdot \cos(\frac{2\cdot\pi\cdot\vartheta}{360}) + R_a \cdot I \cdot \sin(\frac{2\cdot\pi\cdot\vartheta}{360}) + K_E \cdot \frac{2\cdot\pi}{360} \cdot \sin(\frac{2\cdot\pi\cdot\vartheta}{360}) \cdot \frac{d}{d}$$

Basic motor parameters

- the power balance for the PM DC machine is:

$$P = \frac{d}{dt}\left(\frac{L \cdot I^2}{2}\right) + R \cdot I^2 + K_E \cdot \omega \cdot I$$

$$P = \frac{d}{dt}\left(\frac{L \cdot I^2}{2}\right) + R \cdot I^2 + \frac{d}{dt}\left(\frac{J \cdot \omega^2}{2}\right) + (D_M + D_L) \cdot \omega^2 + (T_m + T_L) \cdot \omega$$

Basic motor parameters

- the power analysis reveals that:

$$\frac{d}{dt}\left(\frac{L \cdot I^2}{2}\right) \ : \ \text{magnetization energy}$$

$$R \cdot I^2 \ : \ \text{electrical copper losses in the windings -> heat}$$

$$\frac{d}{dt}\left(\frac{J \cdot \omega^2}{2}\right) \ : \ \text{mechanical energy}$$

$$(D_M + D_L) \cdot \omega^2 \ : \ \text{damping losses}$$

$$(T_m + T_L) \cdot \omega \ : \ \text{friction losses}$$

Basic motor parameters

- the power supplied to the load is:

$$P_{mech} = K_E \cdot \omega \cdot I - D_M \cdot \omega^2 - T_m \cdot \omega$$

Basic motor parameters

- the maximum continuous current allowed is:

$$I_{\max_{\text{cont}}} = \sqrt{\frac{T_{rise} - T_{25^\circ C}}{R(T_{rise}) \cdot R_{\Theta}}} \quad (\text{A})$$

- the maximum continuous torque allowed is:

$$T_{\max_{\text{cont}}} = K_t(T_{rise}) \cdot \sqrt{\frac{T_{rise} - T_{25^\circ C}}{R(T_{rise}) \cdot R_{\Theta}}} \quad (\text{N} \cdot \text{m})$$

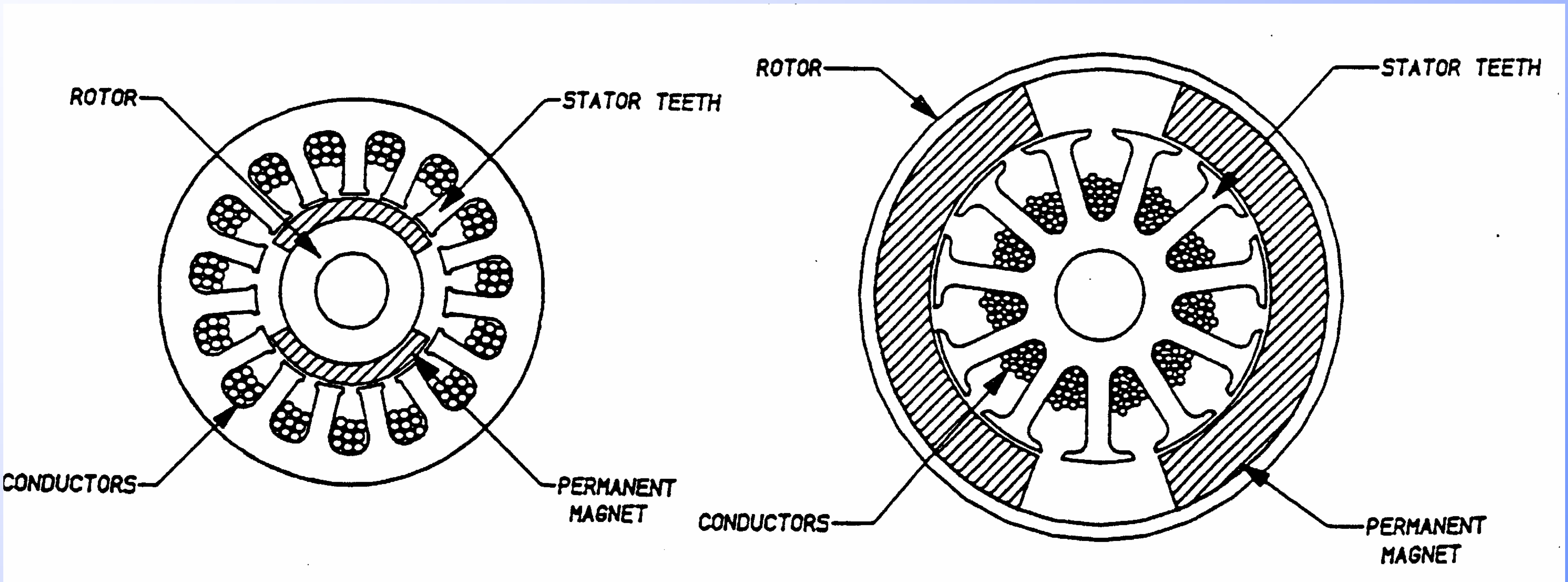
Motor construction

Motor construction

- the field in the stator poles changes continuously, thus we must use laminated steel to reduce eddy current losses

- the backiron to support the PM flux is relatively constant and solid steel can be used

Motor construction



Motor construction

- the eddy current losses are:

$$P_{\text{eddy}} = \frac{\pi^2 f^2 \tau^2 B_P^2 V}{6\rho}$$

f : electrical frequency of the motor (Hz)

τ : thickness of the lamonations (m)

B_P : peak AC flux density (T)

V : lamination volume

ρ : volume electrical resistivity (ohm / m^3)

Motor construction

- motor steel choices

AISI Designation	Allegheny Ludlum Designation	General Use
M-6	Silectron 66	Lowest core loss at high induction for use in power & distribution transformers and large turbogenerators.
M-14	Transformer AA	Low core loss transformer steel for high efficiency rotating machines and transformers
M-15	Transformer A	Higher core loss than M-14 Used for distribution transformers & rotary machines
M-17	Transformer B	Used occasionally for power transformers
M-19	Transformer C	Most suitable for high performance servo motors
M-22	Dynamo Special	Most suitable for high performance induction motors
M-27	Dynamo	Popular grade for servo motors
M-36	Electrical	Used especially for rotary machines. Popular grade for permanent magnet motors.
M-43	Armature	Used for fractional horsepower motors and relays
M-50	Field	Used for pole pieces and intermittent electric devices

Motor construction

- motor windings are generally copper wire with insulation (magnet wire)

- magnet wire comes in different grades
  - temperature
    - B, F, H, C
  - insulation
    - double, triple
    - voltage rating

Motor construction

- the resistance of the magnet wire changes with (the wire's) temperature

$$R(T) = R(T_0) \cdot [1 + \alpha \cdot (T - T_0)]$$

$R(T_0)$: resistance at reference temperature, typically 25°C (ohm)

T : winding temperature (°C)

α : thermal coefficient for copper wire the value is 0.0039/°C