Basic Concepts of A Machine
Basic Concepts of A Machine (1)

- Stator: stationary portion of the machine
- Rotor: rotating portion of the machine
- Shaft: the stiff rod that the rotor is mounted on
- Air gap (Gap): between stator and rotor
Basic Concepts of A Machine (2)

- Load current: the current that varies with load
- Magnetizing current: provide magnetic field and independent of load
- Armature: the winding that carries only load current
- Field: the winding that carries only magnetizing current

- dc machine: the input/output current is dc
- ac machine: the input/output current is ac;
  - two categories: synchronous machine
    - induction machine (no field winding, similar to transformer)
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Basic Concepts of A Machine (4)

round rotor

salient pole rotor
At steady state

\[ f_e = \frac{P}{2} f_m \]

mechanical speed \( n_m \) revolution/minute (rpm)

\[ f_m = n_m \frac{1}{60} = \frac{n_m}{60} \text{ rev/second} \]
Slots and Coils (1)

Double Layer Lap Winding
Slots and Coils (2)

$N_c$ turns, $2N_c$ conductors
Slots and Coils (3)

On armature

- Each slot has 2 positions: top and bottom (double layer winding)
- Each coil needs to occupy 2 positions: top position of one slot and bottom position of another slot

Number of armature coils = Number of armature slots ($S$)

$m$ phase machine:

Number of coils per phase: $S_{ph} = \frac{S}{m}$

Number of turns per phase: $N_{ph} = \frac{S \times N_c}{m}$

Number of conductors per phase: $C_{ph} = \frac{S \times N_c \times 2}{m}$

Note: The above three equations are independent of the number of poles ($P$). For balanced $m$-phase design, $S_{ph}$ should be an integer.
3 phase, 24 slots

8 coils, $8N_c$ turns, $16N_c$ conductors per phase

$N_{ph} = 8N_c$ turns

$\frac{N_{ph}}{P/2} = 4N_c$ turns

2 pole, Phase A, full-pitch

4 pole, Phase A, full-pitch
Slot Pitch

Slot pitch in electrical angle is defined by \[ \gamma = \frac{P}{2} \gamma_m \]

where \( \gamma_m \) is the mechanical angle between two adjacent slots:

\[ \gamma_m = \frac{2\pi}{S} \quad \Rightarrow \gamma = \frac{\pi P}{S} \]

The slot pitch is also defined as the arc length between two slots on stator inner circle (with diameter D):

\[ \tau_s = \frac{\pi D}{S} \]

3 phase, 24 slots, 2 pole
Phase A, full-pitch
Pole Pitch

Pole Pitch: angular distance between two adjacent poles on a machine.

\[ \rho_p = \frac{360^\circ}{P} = \frac{2\pi}{P} \]  \hspace{1cm} \text{(in mechanical degree)}

Regardless of the number of poles on the machine, a pole pitch is always 180° or \( \pi \) in electrical degrees.

The pole pitch is also defined as the arc length between two adjacent poles on stator inner circle (with diameter D):

\[ \tau_p = \frac{\pi D}{P} \]  \hspace{1cm} \text{(in meter or inch)}

Number of Slots per Pole:

\[ S_p = \frac{S}{P} \]

Note: \( S_p \) may not be an integer.
Coil Pitch

Full-Pitch Coil: If the armature coil stretches across the same angle as the pole pitch, it is called a full-pitch coil. The coil spans across $S_p$ slots, if $S_p$ is an integer.

Fractional-Pitch Coil: If the armature coil stretches across an angle smaller than a pole pitch, it is called a fractional-pitch coil (or short-pitched coil, chorded coil). The coil spans less than $S_p$ slots.

Let $S_c$ be the number of slots that the coil spans.
Let $\rho_m$ be the mechanical angle that the coil spans or $\rho_m = S_c \gamma_m$.

Coil pitch in electrical angle is defined by $\rho = \frac{P}{2} \rho_m$

$$\Rightarrow \frac{\rho}{\pi} = \frac{\rho_m}{\rho_p} = \frac{S_c}{S_p}$$
Fractional Pitch Coil (1)

24 slots, 2 pole, 3 phase

\[ \rho_p = \frac{2\pi}{2} = \pi \]
\[ \gamma_m = \frac{2\pi}{24} = \frac{\pi}{12} \]
\[ \gamma = \gamma_m = \frac{\pi}{12} \]

Phase A, full-pitch
\[ \rho = \rho_m = \pi = 180^\circ \]

Phase A, (11/12)-pitch
\[ \rho = \rho_m = \frac{11}{12} \pi = 165^\circ \]
Fractional Pitch Coil (2)

24 slots, 4 pole, 3 phase

\[ \rho_p = \frac{2\pi}{4} = \frac{\pi}{2} \]
\[ \gamma_m = \frac{2\pi}{24} = \frac{\pi}{12} \]

\[ \gamma = \frac{4}{2} \gamma_m = \frac{\pi}{6} \]

Phase A, full-pitch
\[ \rho_m = \frac{\pi}{2} = 90^\circ \]
\[ \rho = \pi = 180^\circ \]

Phase A, (5/6)-pitch
\[ \rho_m = \frac{5\pi}{6} \]
\[ \rho = \frac{5\pi}{6} = 75^\circ \]
\[ \rho = \frac{5}{6}\pi = 150^\circ \]
Group (1)

4 pole, 3 phase, 24 slot machine
Phase A, (5/6)-pitch

This group consists of 2 coils.

Number of coils per group:

$$q = \frac{\text{Number of Stator Slots (S)}}{\text{Number of phases (m)} \times \text{Number of poles (P)}}$$

$$q = \frac{S}{3P} \quad \text{for 3 phase machine}$$

Number of coils = Number of slots \quad \text{for double layer winding}

Number of groups = Number of poles (P) \quad \text{for double layer winding}
Group (2)

$q$ can take fractional number

\[
q = \frac{18}{3 \times 4} = 1.5
\]

4 pole, 3 phase, 18 slot

\[
q = \frac{9}{3 \times 2} = 1.5
\]

2 pole, 3 phase, 9 slot
Torque

\[ T = R \times F \]

How to understand torque:
Put the thumb in the direction of torque.
The other four fingers point to the direction of rotation.
Torque from a Current Loop

\[ \mathbf{dF}_1 = Idx \mathbf{a}_x \times \mathbf{B} = Idx(B_y \mathbf{a}_z - B_z \mathbf{a}_y) \]

\[ \mathbf{R}_1 = -\frac{1}{2} dy \mathbf{a}_y \]

\[ \mathbf{dT}_1 = \mathbf{R}_1 \times \mathbf{dF}_1 = -\frac{1}{2} dy \mathbf{a}_y \times Idx(B_y \mathbf{a}_z - B_z \mathbf{a}_y) \]

\[ = -\frac{1}{2} dxdyIB_y \mathbf{a}_x \]

\[ \mathbf{dT}_3 = \mathbf{R}_3 \times \mathbf{dF}_3 = \frac{1}{2} dy \mathbf{a}_y \times (-Idx)(B_y \mathbf{a}_z - B_z \mathbf{a}_y) \]

\[ = -\frac{1}{2} dxdyIB_y \mathbf{a}_x = \mathbf{dT}_1 \]

\[ \mathbf{dT}_1 + \mathbf{dT}_3 = -dxdyIB_y \mathbf{a}_x \]

Likewise \( \mathbf{dT}_2 + \mathbf{dT}_4 = -dxdyIB_x \mathbf{a}_y \)

\[ \mathbf{dT} = \mathbf{dT}_1 + \mathbf{dT}_2 + \mathbf{dT}_3 + \mathbf{dT}_4 \]

\[ = Idx dy (\mathbf{a}_z \times \mathbf{B}) = IdS \times \mathbf{B} \]

Define \( \mathbf{dm} = IdS \Rightarrow \mathbf{dT} = \mathbf{dm} \times \mathbf{B} \)

Note: \( \mathbf{dm} \) is in the same direction of \( \mathbf{B}_{\text{loop}} \) and \( \mathbf{dm} = k \mathbf{B}_{\text{loop}} \)

\[ \mathbf{dT} = k \mathbf{B}_{\text{loop}} \times \mathbf{B} \]
Torque Property of a Machine (1)

\[ T = k B_R \times B_S \]

\[ T = k B_R B_S \sin \alpha \]

Since \[ B_{net} = B_R + B_S \]

\[ T = k B_R \times (B_{net} - B_R) \]

\[ = k B_R \times B_{net} \]

\[ T = k B_R B_{net} \sin \delta \]
Torque Property of a Machine (2)

6 pole synchronous machine
Torque Property of a Machine (3)

\[ \mathbf{T} = k \mathbf{B}_R \times \mathbf{B}_S \]

Motor

Generator