31-AC Machine Construction
text: 7.1 to 7.7

ECEGR 450
Electromechanical Energy Conversion

Overview

- Introduction
- Physical Construction
- Armature Windings
- Pitch Factor
- Distribution Factor
- Winding Connections
- Rotor

Introduction

- Recall that
  - DC machines: armature windings in rotor
  - AC machines: armature windings in the stator
- AC machines (generators, motors) have similar stators
- Rotors are different
  - Induction
  - Synchronous
- Analyze physical construction of AC machines

Introduction

Advantages of armature windings in the stator:

- Larger coils can be used since they are located in the stator
- High power rated slip rings can be avoid
- Easier to cool stator than rotor
- Easier to construct the armature winding if it is in the stator
- Easier to electrically insulate the stator

Stator

- Houses armature windings
- Contains large gauge coils (low R)
- Conductors are symmetrically arranged to form a balanced poly-phase winding
- Induced emf can be in kV range
- Power ratings can be in MVA range

Armature Windings

- Common for the armature (stator) windings to be three-phase
- Windings are identical, but displaced by 120° electrical
- Can be delta or wye connected (generators)
  - wye is common if higher voltage is needed
    - neutral point is grounded
- Windings are commonly double layer
  - Equal number of slots and windings

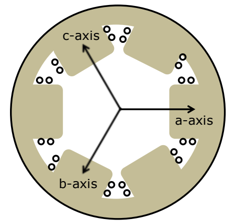
Salient vs Cylindrical

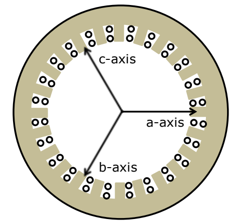
- Early machines used salient pole stators
  - Salient poles still used in rotors
- Modern machines use cylindrical stators

salient pole

cylindrical

Salient-Pole vs Cylindrical





Armature Windings

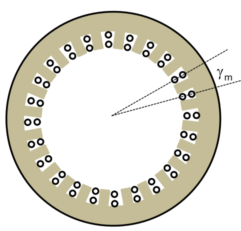
- Mechanical slot span:

$$\gamma_m = \frac{360^\circ}{\#\ \text{of slots}}$$

- Electrical slot span:

$$\gamma = \frac{360^\circ}{\#\ \text{of slots}} \times \frac{P}{2} = \gamma_m \times \frac{P}{2}$$

- Example: 24 slot, 4 pole machine
  - $\gamma_m = 15^\circ$
  - $\gamma = 30^\circ$



Armature Windings

- Balanced three phase:
  - Number of coils connected in series and in parallel in each phase must be equal
    - Total number of coils must be an integer multiple of the number of phases
- Coils are distributed equally among the poles
  - Number of coils (slots) per pole must be an integer
- Number of coils per phase must be an integer

Armature Windings

- Mathematically

$$n = \frac{S}{Pq}$$

  - S: number of armature slots
  - P: number of poles
  - q: number of phases
  - n: number of coils per pole per phase (integer)
- P x q = is the number of <u>phase groups</u> (phase coils under the same pole)
  - n is also equal to the number of coils per phase group

Armature Windings

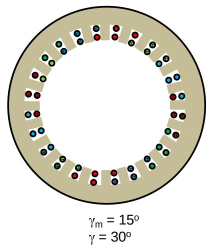
- Example: a three-phase, 4-pole synchronous generator has 24 slots.
  - P = 4 (poles)
  - S = 24 (slots)
  - q = 3 (phases)
- therefore

$$n = \frac{S}{Pq} = \frac{24}{4 \times 3} = 2$$

  - 24/4 = 6 coils per pole
  - 24/3 = 8 coils per phase
  - 6/3 = 2 coils per pole per phase
  - 4 x 3 = 12 phase groups (4 phase groups per phase)

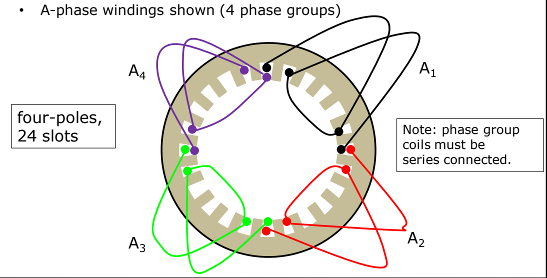
Armature Windings

- 24 total coils (24 slots)
- A-phase:
  - 8 coils total
  - 4 phase groups
  - 2 coils per phase group
- B-phase:
  - 8 coils total
  - 4 phase groups
  - 2 coils per phase group
- C-phase:
  - 8 coils total
  - 4 phase groups
  - 2 coils per phase group



Armature Windings

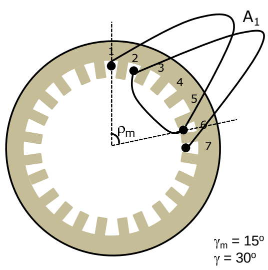
- Coils in each phase group are connected in series
- A-phase windings shown (4 phase groups)



Coil Span

- Each coil spans 5 slots
  - 75 degrees (mechanical)
  - 150 degrees (electrical)
- Coil span: angular span of each coil
  - ρ_m: coil span (mechanical)
  - ρ : coil span (electrical)

$$\rho = \rho_m \times \frac{P}{2}$$



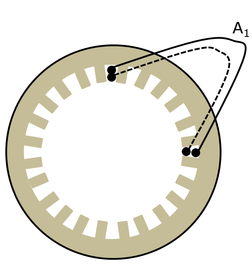
Coil Span

- If ρ = 180°, then known as "full pitch" coils
- If ρ < 180, then known as "fractional pitch" or "partial pitch" coils
- Typical coil span strategy:

  $\rho = 180 - \gamma \times$ (# of coils in each phase group-1)

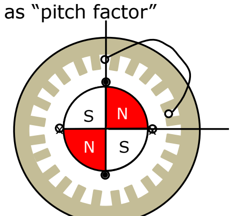
Pitch Factor

- Example of "full pitch" coils
- Fractional pitch is used:
  - Reduces harmonics (have a sinusoidal voltage output)
  - Shortens length of end connections (less copper, less resistance)
  - Reduces leakage and magnetizing losses
  - Reduces the induced emf (disadvantage)



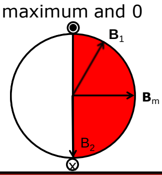
Pitch Factor

- Consequence of partial pitch is reduction of flux through each coil
- Must account for partial pitch coils by a de-rating factor known as "pitch factor"



Pitch Factor

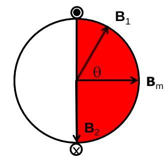
- Flux density is not uniform over face of rotor pole
- Flux density is maximum (B_m) at the face of the pole
  - $|\mathbf{B}_m|$: maximum flux density
  - $|\mathbf{B}_2|$: minimum flux density
  - $|\mathbf{B}_1|$: between maximum and 0

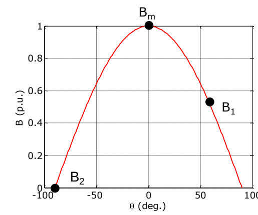


Pitch Factor

Flux density of a cylindrical rotor can be approximated as
$B = B_m \cos\theta$

- B_m: maximum flux density per pole (T)

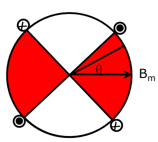




Pitch Factor

For multi-pole rotors: $\theta_m = \frac{2}{P}\theta$

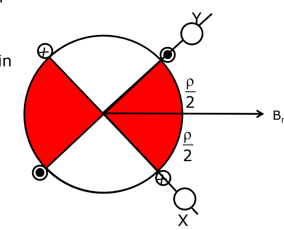
- θ_m: mechanical angle
- θ: electrical angle



Pitch Factor

- Consider a full-pitch coil with coil conductors X, Y in the stator
  - ρ = 180°
- Orientation shown results in maximum flux
- Flux through the coil:

  $\phi_P = \int_S \mathbf{B} \bullet d\mathbf{s}$



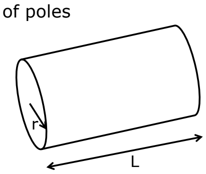
air gap exaggerated

Pitch Factor

- From the geometry of the rotor (see Figure 7.5):

  $d\mathbf{s} = Lrd\theta_m = Lrd\theta_m \frac{2}{P}$

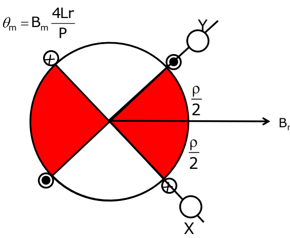
  - L: axial length of the rotor (m)
  - r: radius of the rotor (m)
  - P: number of poles



Pitch Factor

- Maximum flux through a full pitch coil:

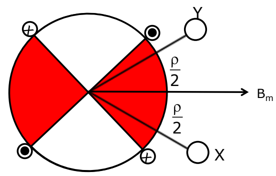
$$\phi_P = \int_S \mathbf{B} \bullet d\mathbf{s} = \int_{-\pi/2}^{\pi/2} B_m \cos(\theta_m) \frac{2Lr}{P} d\theta_m = B_m \frac{4Lr}{P}$$



air gap exaggerated

Pitch Factor

- Now consider a fractional-pitch coil
  - $\rho < 180^o$



air gap exaggerated

Pitch Factor

- For a fractional pitch coil:

$$\phi_{cm} = \int_s \mathbf{B} \bullet d\mathbf{s} = \int_{-\rho/2}^{\rho/2} B_m \cos(\theta_m) \frac{2Lr}{P} d\theta_m = \frac{4LrB_m}{P} \sin(\rho/2)$$

$$= \phi_p \sin(\rho/2) = \phi_p k_p$$

$$k_p = \sin(\rho/2)$$

  - ϕ_{cm}: maximal flux per coil (Wb)
  - ρ: span of the coil (rad)
  - k_p: pitch factor (less than or equal to 1)

Example

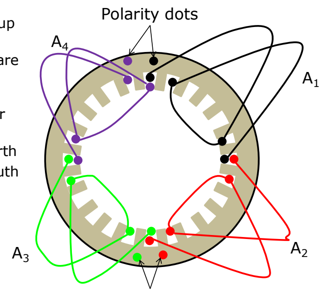
Calculate the pitch factor of a 48-slot, 4-pole three phase AC machine.

Example

- Calculate the pitch factor of a 48-slot, 4 pole three phase winding
  - 12 slots per pole, so each slot spans $180^o/12 = 15^o$ (electrical)
  - $n = 48/(4 \times 3) = 4$ coils per phase group
    - Coil 1: slot 1, slot 10
    - Coil 2: slot 2, slot 11
    - Coil 3: slot 3, slot 12
    - Coil 4: slot 4, slot 13
  - Each coil spans $9 \times 15^o = 135^o$ (electrical)
  - $k_p = \sin(135^o/2) = 0.924$

Winding Connection

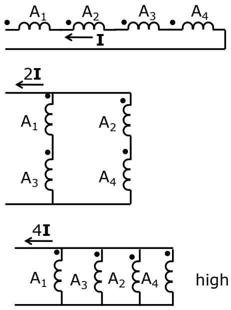
- Coils in each phase group are series-connected
- Series-connected coils are "windings"
- Note the orientation of the coils under the rotor poles
  - A_1, A_3 are under North
  - A_2, A_4 are under South



Winding Connection

- Several possible ways to connect each winding in a phase
  - Series
  - Parallel
  - Series/parallel

Winding Connections

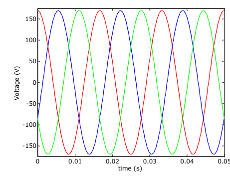


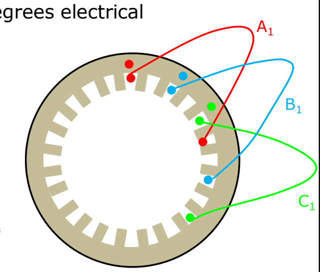
low current, high voltage

high current, low voltage

Winding Connections

To achieve 3 phase, A, B, C phases must be displaced by 120 degrees electrical





Distributed Windings

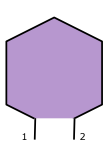
- Cylindrical stators use “distributed windings”
- Advantages (motors)
  - Greater starting torque
  - Quieter operation
- Advantages (generators)
  - Less harmonic distortion in induced voltage

Distributed Windings

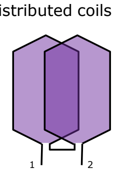
- To create a sinusoidal voltage, there are more than one coil in each phase group
- Coils within a phase group are connected in series and are in distributed across the pole
- Each coil in a phase group therefore has a different induced voltage at a given point in time

Distributed Windings

single full-pitch coil

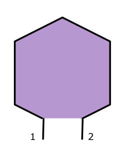


two series-connected distributed coils

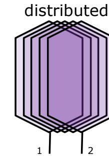


Distributed Windings

single full-pitch coil



five series-connected distributed coils



end connection detail not shown

Distribution Factor (text 7.5)

- Distribution factor: k_d
- Accounts for the different phasing of the coils
- De-rates induced voltage
  - $k_d = 1$ only if the coils in a phase group are in the same slots
- We can show that: $k_d = \dfrac{\sin(n\gamma/2)}{n\sin(\gamma/2)}$
  - γ: slot pitch (electrical degrees) (see Figure 7.7)

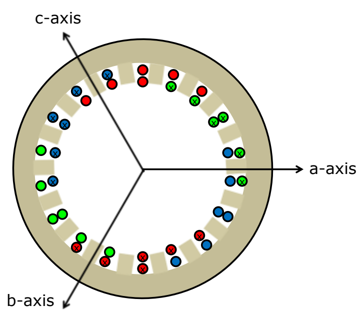
Distribution Factor

- Distribution factor k_d and pitch factor k_p are combined into the winding factor
  - $k_w = k_d k_p$
- Winding factor accounts for the physical characteristics of the stator windings
  - Typically: $0.8 < k_w < 0.95$

Stator Winding Example

2-pole
18 slot machine

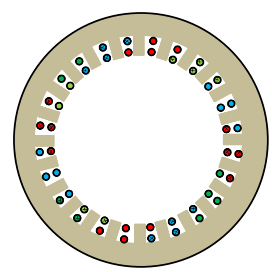
n = 3
Pole pitch ρ: 140°
Pitch factor: 0.939
Slot pitch γ: 20°
Dist. factor: 0.959
Winding factor: 0.901



Stator Winding Example

4-pole
24 slot machine

n = 2
Pole pitch ρ: 150°
Pitch factor: 0.966
Slot pitch γ: 30° (electrical)
Dist. factor: 0.911
Winding factor: 0.879

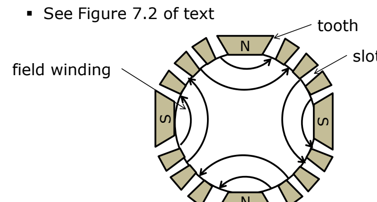


Rotor (Synchronous)

- DC current or PM used to establish flux
- Usually: number of poles in stator = number of poles in rotor
- DC current is provided by DC generator
  - can be coupled to the same prime mover as the ac generator
- Two common types:
  - Cylindrical
  - Salient-pole

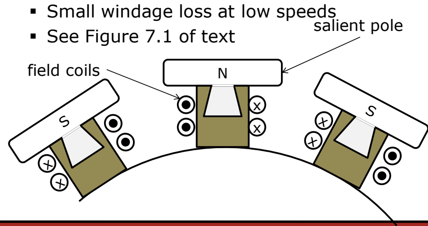
Rotor

- Cylindrical rotor
  - Quiet operation at high speeds
  - Better balance
  - Low windage loss at high speeds
  - See Figure 7.2 of text



Rotor

- Salient Pole
  - Used in low or medium speed application
  - Better ventilation (cooling) of rotor
  - Small windage loss at low speeds
  - See Figure 7.1 of text



Summary

- Modern AC machines use cylindrical stators with partial pitch and distributed windings
- Distributed windings reduce harmonics, and increase torque
- Induced voltage de-rated by distributed windings and partial pitch coils
- Rotors of synchronous machines may be cylindrical or salient
  - Induction machine rotors are often squirrel cage