28-Principles of AC Machines
Text 3.5

ECEGR 450
Electromechanical Energy Conversion

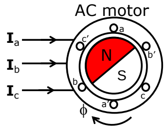
Overview

- Introduction
- Rotating Magnetic Field
- Magnetic Field Rotational Speed
- Synchronous Speed

Introduction

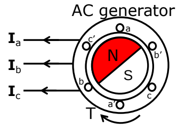
- AC machines rely on a rotating magnetic field
- Stator houses current-carrying conductors
  - Stator is the armature

AC motor



revolving magnetic
field provided by stator

AC generator

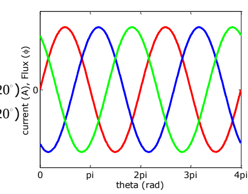


revolving magnetic
field provided by rotor

Rotating Magnetic Field

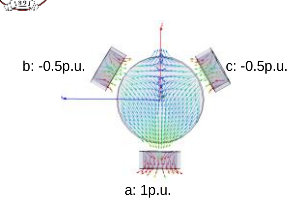
- Three-phase motors are very common
- Requires a three phase source
- Under linear conditions, flux and current will have similar waveforms

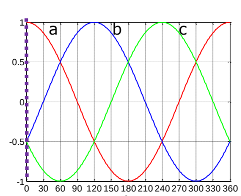
$\mathbf{I}_a = i_{max}\sin(\omega t)$
$\mathbf{I}_b = i_{max}\sin(\omega t - 120^\circ)$
$\mathbf{I}_c = i_{max}\sin(\omega t + 120^\circ)$

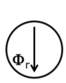


$\boldsymbol{\Phi}_a = \phi_{max}\sin(\omega t)$
$\boldsymbol{\Phi}_b = \phi_{max}\sin(\omega t - 120^\circ)$
$\boldsymbol{\Phi}_c = \phi_{max}\sin(\omega t + 120^\circ)$

Conceptual Illustration $\theta_e = 0^o$

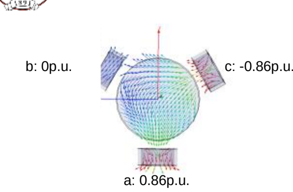


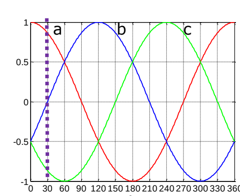


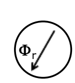


direction of flux through rotor

Conceptual Illustration $\theta_e = 30^o$



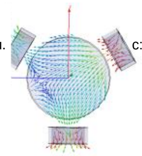




direction of flux through rotor

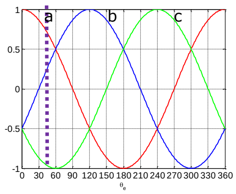
Conceptual Illustration θ_e = 45°

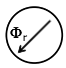
b: 0.255p.u.



c: -0.97p.u.

a: 0.707p.u.

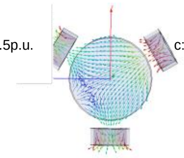




direction of flux through rotor

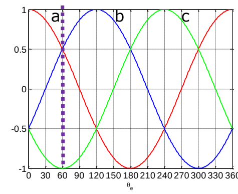
Conceptual Illustration θ_e = 60°

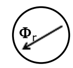
b: 0.5p.u.



c: -1p.u.

a: 0.5p.u.

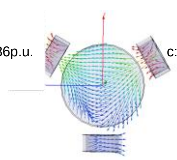




direction of flux through rotor

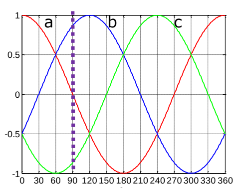
Conceptual Illustration θ_e = 90°

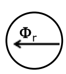
b: 0.86p.u.



c: -0.86p.u.

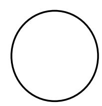
a: 0p.u.



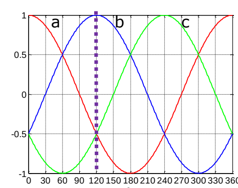


direction of flux through rotor

Conceptual Illustration θ_e = 120°

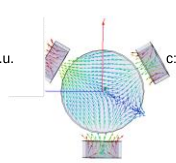


What direction will the flux through the rotor be when θ_e = 120°?



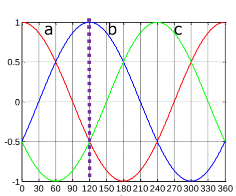
Conceptual Illustration θ_e = 120°

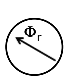
b: 1p.u.



c: -0.5p.u.

a: -0.5p.u.

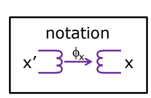


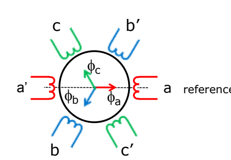


direction of flux through rotor

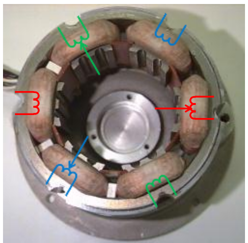
Two-Pole Three-Phase Revolving Field

- Coils are spatially separated by 60°
  - Do not confuse the spatial direction with the phase of the flux
- We will analyze how the flux varies with time
- Note: if flux is negative, the direction is opposite as shown

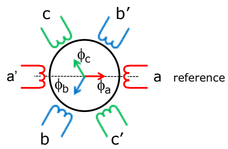




Three-Phase AC Motor



Note: salient windings are shown.
Large motors use cylindrical windings.

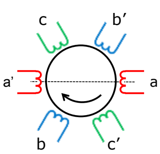


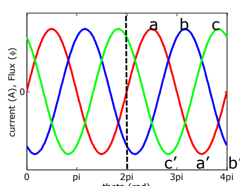
Rotating Magnetic Field

- Want to analyze the net flux as seen by the rotor
- General approach:
  - Consider the flux at 0, 60 and 120 degrees in time
  - Compute the a, b, c phase flux magnitudes
  - Determine resulting flux by adding a, b, c phase flux
  - Generalize results

Rotating Magnetic Field

- Maximum flux occurs in the following sequence
  - a, c′, b, a′, c, b′ and so on
  - same relative ordering of coils around stator





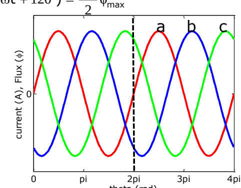
Rotating Magnetic Field

Let $\omega t = 0$. The magnitudes are:

$$|\Phi_a| = \phi_{max}\sin(\omega t) = 0$$

$$|\Phi_b| = \phi_{max}\sin(\omega t - 120^\circ) = \left|-\frac{\sqrt{3}}{2}\phi_{max}\right|$$

$$|\Phi_c| = \phi_{max}\sin(\omega t + 120^\circ) = \frac{\sqrt{3}}{2}\phi_{max}$$

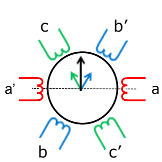


Rotating Magnetic Field

- At $\omega t = 0$ the flux is as shown
- The resulting flux, Φ_r, is found through vector addition

$$\Phi_r = \Phi_a + \Phi_b + \Phi_c$$

$$= 0 + \frac{-\sqrt{3}}{2}\phi_m\angle 240^\circ + \frac{\sqrt{3}}{2}\phi_m\angle 120^\circ = 1.5\phi_m\angle 90^\circ$$



$$\Phi_a = 0\angle 0^\circ$$

$$\Phi_b = -\frac{\sqrt{3}}{2}\phi_{max}\angle 240^\circ$$

$$\Phi_c = \frac{\sqrt{3}}{2}\phi_{max}\angle 120^\circ$$

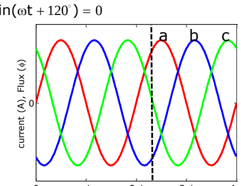
Rotating Magnetic Field

At $\omega t = 60°$:

$$|\Phi_a| = \phi_{max}\sin(\omega t) = \frac{\sqrt{3}}{2}\phi_{max}$$

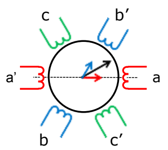
$$|\Phi_b| = \phi_{max}\sin(\omega t - 120^\circ) = \left|-\frac{\sqrt{3}}{2}\phi_{max}\right|$$

$$|\Phi_c| = \phi_{max}\sin(\omega t + 120^\circ) = 0$$



Rotating Magnetic Field

$$\mathbf{\Phi}_r = \mathbf{\Phi}_a + \mathbf{\Phi}_b + \mathbf{\Phi}_c$$
$$= \frac{\sqrt{3}}{2}\phi_m\angle 0^\circ + \frac{-\sqrt{3}}{2}\phi_m\angle 240^\circ + 0 = 1.5\phi_m\angle 30^\circ$$

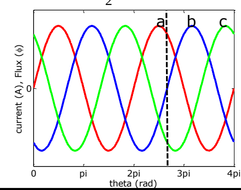


$$\mathbf{\Phi}_a = \frac{\sqrt{3}}{2}\phi_{max}\angle 0^\circ$$
$$\mathbf{\Phi}_b = -\frac{\sqrt{3}}{2}\phi_{max}\angle 240^\circ$$
$$\mathbf{\Phi}_c = 0\angle 120^\circ$$

Rotating Magnetic Field

- Let $\omega t = 120^\circ$

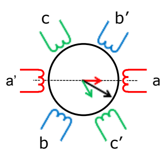
$$|\mathbf{\Phi}_a| = \phi_{max}\sin(\omega t) = \frac{\sqrt{3}}{2}\phi_{max}$$
$$|\mathbf{\Phi}_b| = \phi_{max}\sin(\omega t - 120^\circ) = 0$$
$$|\mathbf{\Phi}_c| = \phi_{max}\sin(\omega t + 120^\circ) = |-\frac{\sqrt{3}}{2}\phi_{max}|$$



Rotating Magnetic Field

- At $\omega t = 60^\circ$ the flux is as shown
- The resulting flux is found through vector addition

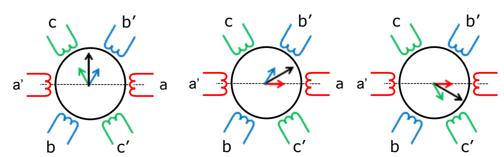
$$\mathbf{\Phi}_r = \mathbf{\Phi}_a + \mathbf{\Phi}_b + \mathbf{\Phi}_c$$
$$= \frac{\sqrt{3}}{2}\phi_m\angle 0^\circ + 0 + -\frac{\sqrt{3}}{2}\phi_m\angle 120^\circ = 1.5\phi_m\angle -30^\circ$$



$$\mathbf{\Phi}_a = \frac{\sqrt{3}}{2}\phi_{max}\angle 0^\circ$$
$$\mathbf{\Phi}_b = 0\angle 240^\circ$$
$$\mathbf{\Phi}_c = -\frac{\sqrt{3}}{2}\phi_{max}\angle 120^\circ$$

Rotating Magnetic Field

$\omega t = 0^\circ$ $\omega t = 60^\circ$ $\omega t = 120^\circ$



resulting flux vector rotates CW in time

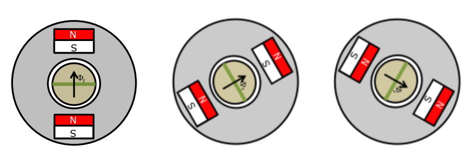
Rotating Magnetic Field

Observations:

- Resulting flux magnitude is constant
- Direction of the resulting flux rotates with time
- 120° phase shift in the time domain has shifted the spatial orientation of the flux 120°
- To make the field rotate in the opposite direction (counter clockwise) switch any two phases (e.g. b and c phases)

Rotating Magnetic Field

Conceptually like rotating magnets around the periphery



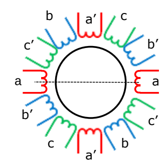
$\omega t = 0^\circ$ $\omega t = 60^\circ$ $\omega t = 120^\circ$

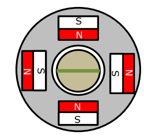
Magnetic Field Rotational Speed

- For a two pole motor one full rotation of the magnetic field occurs after one complete electrical cycle
- How does a 4-pole motor affect the rotational speed of the magnetic field?

Magnetic Field Rotational Speed

- Coils separated by 30 degrees
  - a, c′, b, a′, c, b′ ordering is preserved
- Four poles, examine one pole-pair

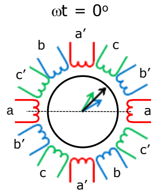




Magnetic Field Rotational Speed

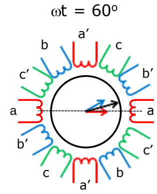
60 degrees time shift resulted in spatial rotation of 30 degrees

ωt = 0°



θ_m = 45°

ωt = 60°



θ_m = 15°

Magnetic Field Rotational Speed

- For a 4 pole-motor one full rotation of the magnetic field requires two complete electrical cycles
- To generalize: $T_s = \frac{P}{2}T$
  - T_s: period of the flux rotation (s)
  - T: period of the AC waveform (s)
  - P: number of poles

Note: do not confuse "T" for period, with "T" for torque.

Magnetic Field Rotational Speed

- Also $n_s = \frac{1}{T_s} = \frac{2f}{P}$
  - n_s: speed of the revolving field (revolutions/s)
  - f: frequency of the AC waveform (Hz)
- n_s is known as the synchronous speed

Note: this and previous equations relate frequency of applied source with rotation of magnetic field, not the actual rotation of the rotor.

Example

Write N_s, the synchronous speed in revolutions per minute (RPM) and radians per second (ω_s) as a function of the number of poles and frequency f

Example

An 6-pole AC motor is connected to 50 Hz source. What is the synchronous speed of the motor in rpm?

Summary

- Magnetic field rotates with constant magnitude
- The resulting flux is 0.5n times the single phase flux, where n is the number of phases
- The synchronous speed is inversely proportional to the number of poles and proportional to the frequency of the applied source