METE 3100U
Actuators and Power Electronics

Lecture 19

Single Phase Motors

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Outline of Lecture 19

By the end of today's lecture, you should be able to

- Understand the working principle of single phase motors
- Model a single phase motor
- Understand the different architectures of single phase motors

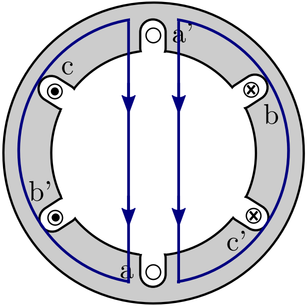
Applications

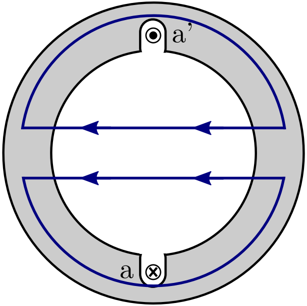
Single phase motors are very widely used in home, offices, workshops etc. as power delivered to most of the houses and offices is single phase.

Applications

Single phase induction motor mainly used in small capacity, ceiling fans, water pumps, high speed vacuum cleaner, compressor, electric shavers and drilling machines.

3-phase *vs* single phase motors





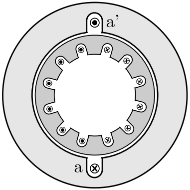
Single phase induction motors

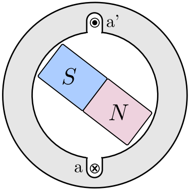
Single-phase induction motors are of three types

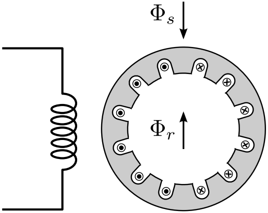
→ Single-phase induction motors

→ Single-phase synchronous motors

→ Single-phase series or universal motors

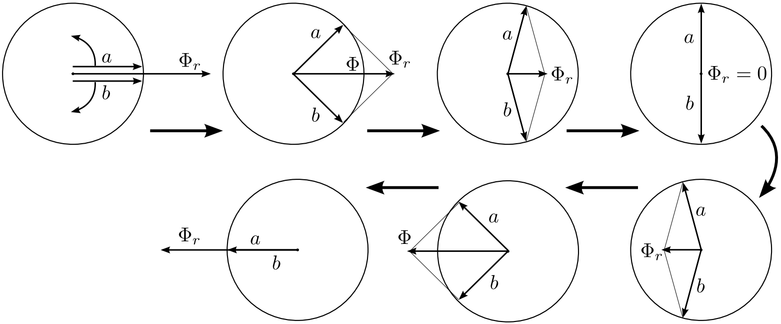






Double revolving field theory

An alternating flux can be resolved into two fluxes rotating in opposite directions.



→ Vectors a and b rotate at the same speed and $\Phi = a + b$

→ The magnitude of the resultant vector is $0 \leq |\Phi_r| \leq (a + b)$

Double revolving field theory

The mmf along a position θ is

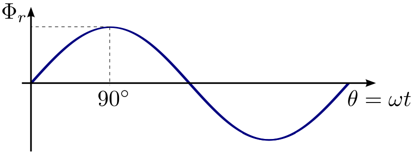
$$F(\theta) = Ni\cos(\theta) \quad (1)$$

where N is the number of stator winding turns. Let the applied current be

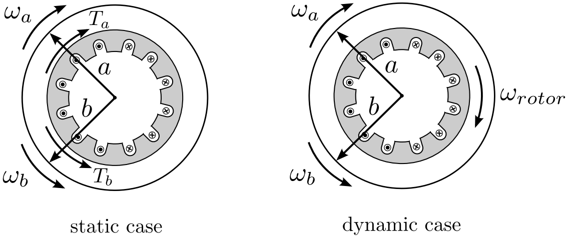
$$i(t) = I_{max}\cos(\omega t) \quad (2)$$

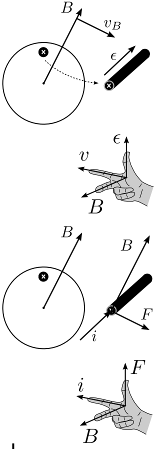
the mmf is

$$\begin{aligned} F(\theta, t) &= NI_m max \cos(\theta)\cos(\omega t) \\ &= \frac{NI_{max}}{2}\cos(\omega t - \theta) + \frac{NI_{max}}{2}\cos(\omega t + \theta) \\ &= a + b \end{aligned}$$



Double revolving field theory





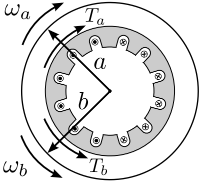
→ Note that $\omega_a = -\omega_b$ is the synchronous speed (ω_s)

→ Torques due to the revolving mmfs a and b can be superimposed

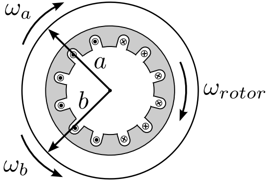
→ When $\omega_{rotor} = 0$, $T_a = -T_b \therefore \sum T = 0$

→ The motor is not self-starting ☹

Slip and dynamic torque



static case



dynamic case

Assuming that the rotor rotates clockwise

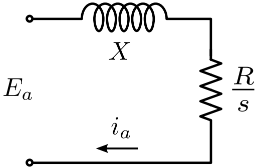
→ Mmf a rotates in the direction of the rotor ($n_a = n$)

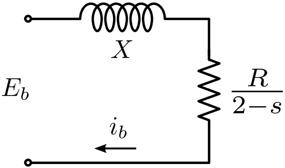
$$s_a = \frac{n_s - n_a}{n_s} = \frac{n_s - n}{n_s} = s \tag{3}$$

→ Mmf b rotates in the opposite direction of the rotor ($n_b = -n$)

$$s_b = \frac{n_s - n_b}{n_s} = \frac{n_s - (-n)}{n_s} = \frac{2n_s - n_s + n}{n_s} = 2 - s \tag{4}$$

Resultant torque





→ Since $0 < s < 1$, then $i_b > i_a$

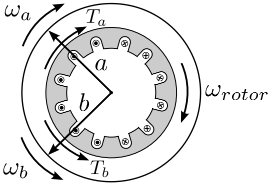
→ The emmfs of a and b oppose the stator mmf

→ The net flux around a is higher that at b.

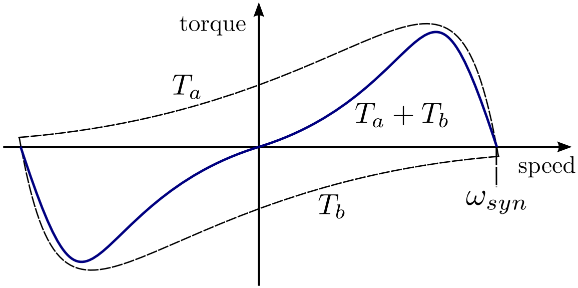
Thus:

$$T_a > T_b \therefore ☺$$

How to start the motor?

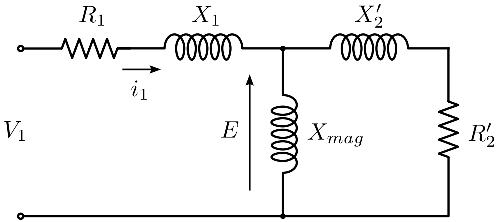


Resultant torque



Equivalent circuit model

At standstill: Equivalent to a transformer with a shorted secondary

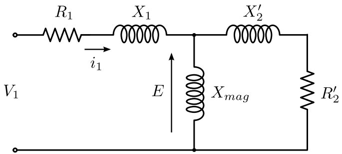


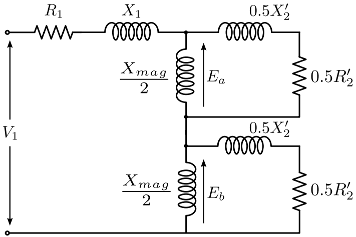
R_1	stator winding resistance
X_1	stator winding leakage reactance
X_{mag}	magnetization reactance
R_2'	rotor resistance referred to the stator
X_2'	rotor leakage reactance referred to the stator
V_1	supply voltage
E	induced voltage in the stator winding

$$E = 4.44 f N \Phi \tag{5}$$

Equivalent circuit model

At standstill: Equivalent to a transformer with a shorted secondary



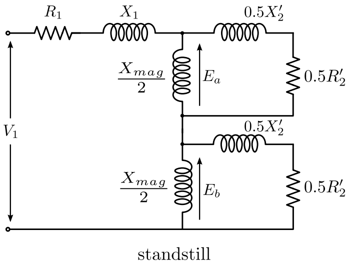


$$E_a = 4.44fN\Phi_a \quad (6)$$

$$E_b = 4.44fN\Phi_b \quad (7)$$

Equivalent circuit model

Running condition: The impedance of the secondary changes



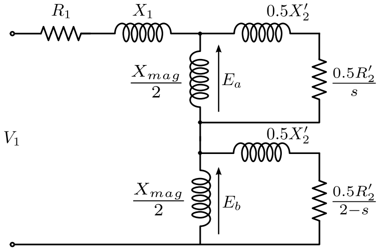
Backward field induces a current in the rotor with frequency

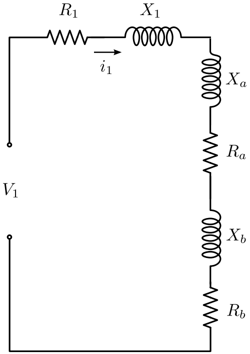
$$(2 - s)f \approx 2f \tag{8}$$

Forward field induces a current in the rotor with frequency

$$sf \tag{9}$$

Simplified circuit model





$$Z_a = R_a + jX_a = \frac{j0.5X_{mag}\left(j0.5X_2' + 0.5\frac{R_2'}{s}\right)}{\left(0.5\frac{R_2'}{s}\right) + j0.5(X_{mag} + X_2')} \tag{10}$$

$$Z_b = R_b + jX_b = \frac{j0.5X_{mag}\left(j0.5X_2' + 0.5\frac{R_2'}{2-s}\right)}{0.5\left(\frac{R_2'}{2-s}\right) + j0.5(X_{mag} + X_2')} \tag{11}$$

Simplified circuit model

The power developed in the air gap is

$$P_a = i_1^2 R_a, \qquad P_b = i_1^2 R_b \tag{12}$$

The corresponding torque is

$$T_a = \frac{P_a}{\omega_{syn}}, \qquad T_b = \frac{P_b}{\omega_{syn}} \tag{13}$$

The resultant torque is

$$T = T_a - T_b = \frac{i_1^2}{\omega_{syn}}(R_a - R_b) \tag{14}$$

The developed mechanical power is

$$\begin{aligned} P_m &= T\omega_m \\ &= T\omega_{syn}(1-s) \\ &= i_1^2(R_a - R_b)(1-s) \\ &= (P_a - P_b)(1-s) \end{aligned}$$

Simplified circuit model

The power output is

$$T_{out} = P_{mech} - P_{loss} \tag{15}$$

Forward field copper loss

$$P_{ca} = sP_a \tag{16}$$

Backward field copper loss

$$P_{cb} = (2 - s)P_b \tag{17}$$

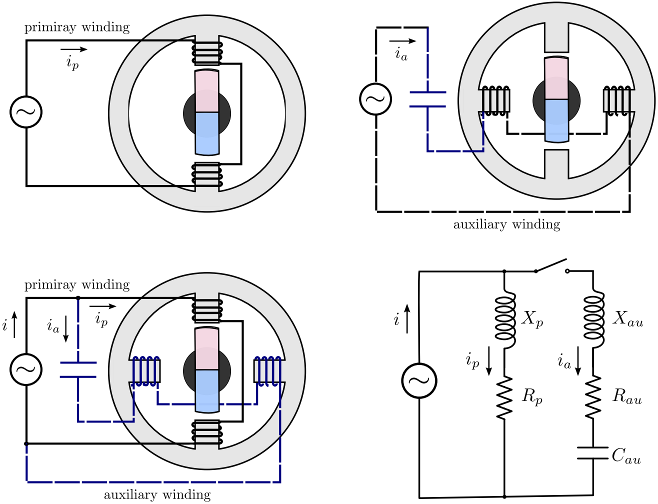
The total rotor copper loss

$$P_c = sP_a + (2 - s)P_b \tag{18}$$

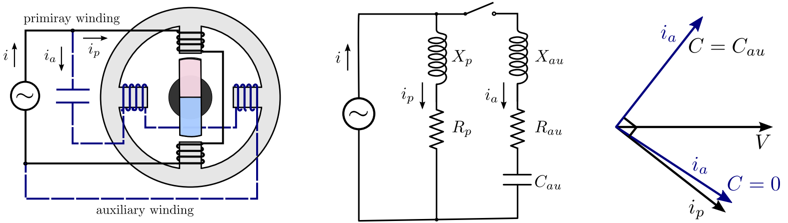
The total air gap power is

$$P = P_a + P_b \tag{19}$$

Starting of single phase motors



Starting of single phase motors

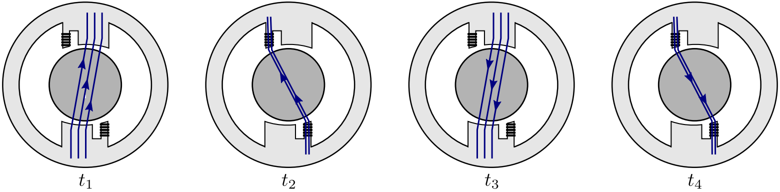


→ An auxiliary winding is displaced 90° from the primary winding

→ The capacitor is connected in series to shift the current

→ C_{au} is chosen such that i_a and i_p are 90° out of phase

Shaded pole motors



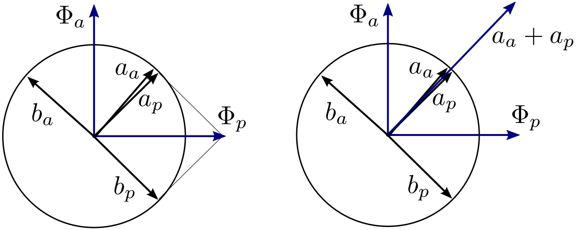
→ The auxiliary winding (shading coil) is short-circuited

→ The auxiliary coil develops a current due to the changing field

→ The auxiliary current leads to the magnetic flux

→ The auxiliary flux is delayed from the the main flux

Revolving field with an auxiliary coil



The backward rotating fields cancel out

$$b_a + b_p = 0 \tag{20}$$

The forward rotating fields add up

$$\mathcal{F} = a_a + a_p \tag{21}$$

Exercise 88

A one-phase, 120 V, 60 Hz, 4-pole induction motor is rotating in the clockwise direction at a speed of 1728 rpm. Calculate per unit slip of the motor for the following cases:

(a) In the direction of rotation

(b) In the backward direction

Exercise 88

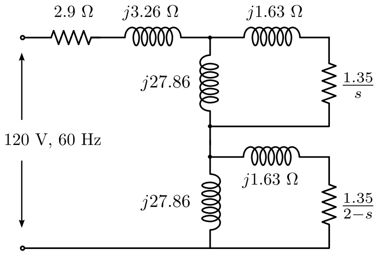
One-phase, 120 V, 60 Hz, 4-pole, 1728 rpm.

(a) Slip in the direction of rotation

(b) Slip in the backward direction

Exercise 89

A 120 V, 4-pole, 60 Hz, 1730 rpm single phase motor has the stator and rotor parameters shown. Friction and windage loss dissipate 73 W of the useful power.



Determine

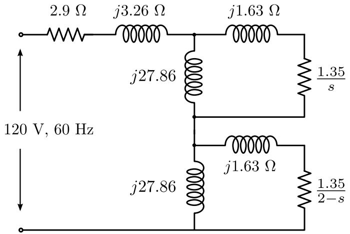
(a) Input current, power, and power factor.

(b) Developed torque, output power, and efficiency.

(c) Rotor copper loss.

Exercise 89 - continued

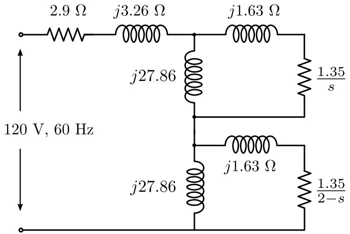
(a) Input current, power, and power factor.



Exercise 89 - continued

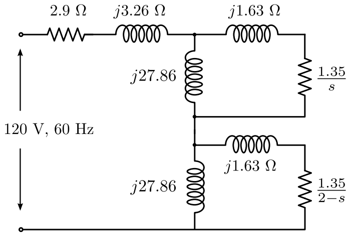
$$Z_{input} = 16.51 + j21.60$$

$$V = 120\ \text{V}$$



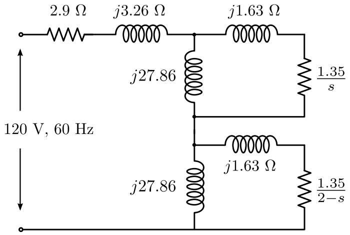
Exercise 89 - continued

(b) Torque, output power, and efficiency.



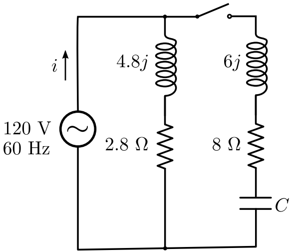
Exercise 89 - continued

(c) Rotor copper loss.



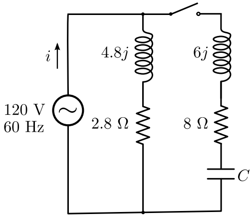
Exercise 90

A 1-phase, 120 V, 60 Hz, induction motor has the following impedance parameters at standstill.



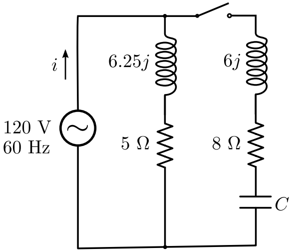
Determine the value of the capacitor C to be connected in series to the auxiliary winding to produce a pure forward mmf wave.

Exercise 90 - continued



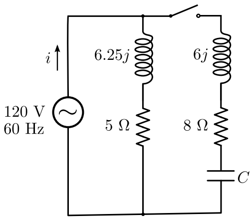
Exercise 91

A 1-phase, 120 V, 60 Hz, induction motor has the following impedance parameters at standstill.

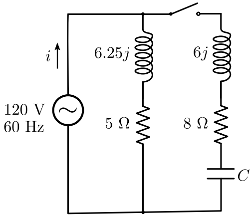


Determine the value of the capacitor C to be connected in series to the auxiliary winding to obtain maximum starting torque. Compare the auxiliary current with and without the capacitor.

Exercise 91 - continued



Exercise 91 - continued



Quiz

Q1 - Which of the following motors is mostly used for position control?

(a) Servo motor

(b) 3-phase induction motor

(c) single phase induction motor

(d) Synchronous motors

(e) DC motors

Quiz

Q2 - Out of the following motors, which will give the highest starting torque?

(a) Induction motor

(b) Single-phase motor

(c) DC motor

(d) 3-phase motors

(e) Synchronous motors

Quiz

Q3 - In single-phase induction machines, rotor windings are supplied with

(a) AC, 3-phase power

(b) AC, single phase power

(c) no power (rotor windings are short-circuited)

(d) DC and AC power

(e) DC power

Quiz

Q4 - Which of the following statements is true regarding a single-phase inductance motor?

(a) Shaded pole motors have four coils

(b) Capacitors are used to filter PWM-controlled voltages

(c) Single-phase motors are synchronous

(d) Single-phase motors are self-starting

(e) Single-phase motors run at the synchronous speed

Quiz

Q5 - In shaded pole induction motors, shaded coils are used to:

(a) Reduce copper losses

(b) Protect against sparking

(c) Concentrate the magnetic flux

(d) Reverse the magnetic flux

(e) Cancel out the backward revolving field

Quiz

Q6 - Which of the following motors can operate at high speeds?

(a) Servo motors

(b) Unipolar stepper motors

(c) Reluctance motor

(d) DC motors

(e) Bipolar stepper motors

Quiz

Q7 - A capacitor start single phase motor works similarly to a:

(a) 3-phase induction motor

(b) 2-phase induction motor

(c) 3-phase synchronous motor

(d) DC motor

(e) stepper motor

Next class...

- Transients and dynamics

Additional supporting materials for Lecture 19:

Single phase induction motor: `https://youtu.be/awrUxv7B-a8`

Single-phase motor in Matlab/Simulink `https://bit.ly/2Y4PVVS`