METE 3100U
Actuators and Power Electronics

Lecture 18

Synchronous Machines

Outline of Lecture 18

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

- Model an synchronous machine
- Find an equivalent transformer model
- Estimate the torque of an synchronous machine

Applications

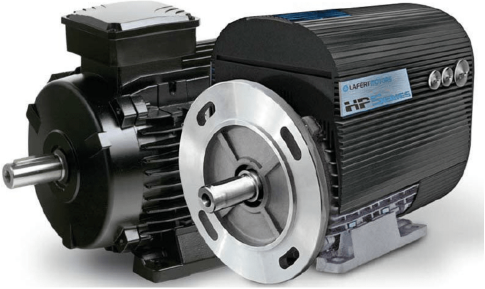
Synchronous machines are used primarily as generators of electrical power.
What is the difference between an induction and a synchronous machine?

Applications

In a synchronous motor, the rotor is excited by a DC current and the stator is connected to an AC power. Why?

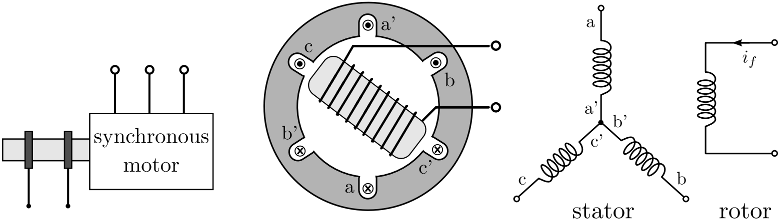
Applications

Because of the higher efficiency compared to induction motors, synchronous motors can be employed for loads which require a constant speed.



Operating principle

In a synchronous motor, both the rotor and the stator are exited by an external power supply.



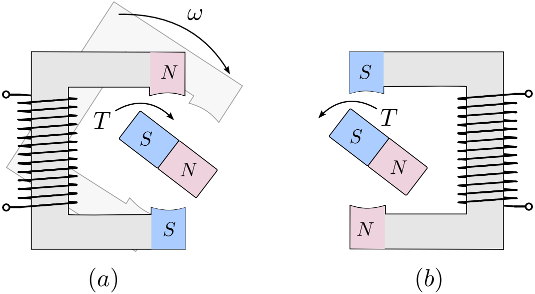
→ The stator is connected to a 3-phase AC supply

→ The rotor has a coil connected to a DC supply

→ The motor does not self-start

Motor start

The the stator and rotor are connected to a AC and a DC supply, the rotor vibrates.



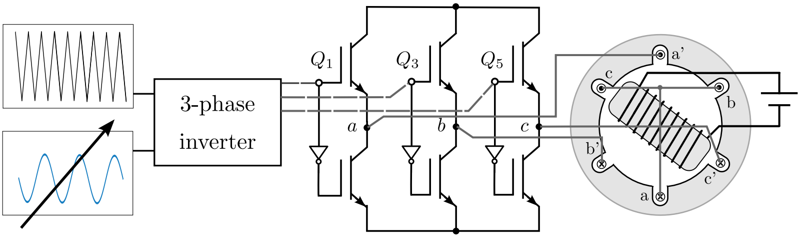
→ In (a) the torque is clockwise

→ In (b), the field is rotated by 180° w.r.t (a)

→ In (b), the torque is counterclockwise

Start with variable frequency supply

Option 1 - Start the motor at a low frequency and gradually increase it



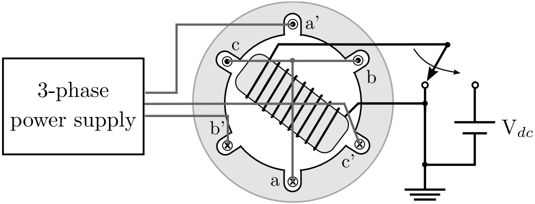
→ Requires a variable frequency voltage inverter

→ Expensive to implement

→ **Propose an alternative solution**

Start as an induction motor

Option 2 - Start the motor as an induction machine



→ At start, short-circuit the rotor winding

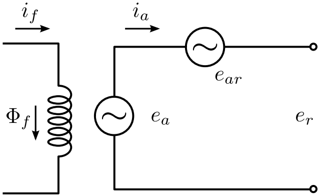
→ The motor starts and approaches the synchronous speed

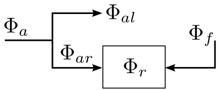
→ Then, apply a DC voltage to the rotor

→ Requires only a single frequency 3-phase supply

Equivalent circuit

The equivalent circuit will be derived for a motor in **steady-state**





→ i_f in the field winding produces a flux Φ_f is the air gap

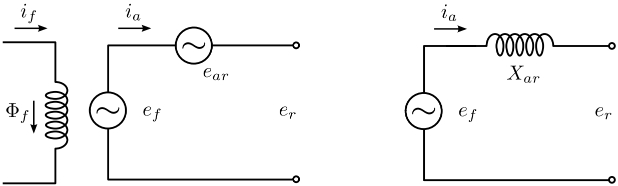
→ i_a in the stator winding produces a flux Φ_a is the air gap

→ $\Phi_a = \Phi_{al} + \Phi_{ar}$ where Φ_{al} is the leakage flux

The result air gap flux Φ_r is

$$\Phi_r = \Phi_{ar} + \Phi_f \tag{1}$$

Equivalent circuit



The armature reaction voltage is a function of Φ_{ar}

$$E_r = E_{ar} + E_f \tag{2}$$

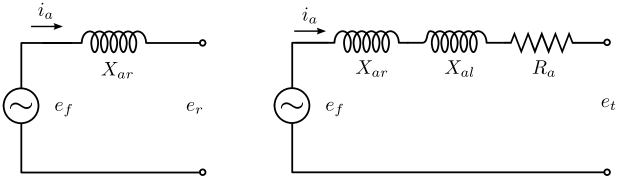
The equivalent circuit can also be represented as

$$E_f = i_a X_{ar} + e_r \tag{3}$$

$\rightarrow$ X_{ar} is the armature reactance

Equivalent circuit

The total reactance X_s includes the armature X_{ar} and leakage reactance X_{al}



The armature reaction voltage is a function of Φ_{ar}

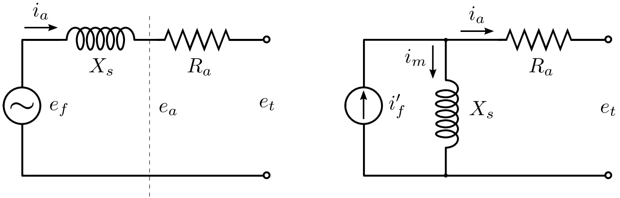
$$X_s = X_{ar} + X_{al} \tag{4}$$

The total or synchronous impedance is

$$Z_s = R_a + jX_s \tag{5}$$

Equivalent circuit

An equivalent form can be expressed using the Norton circuit



The armature reaction voltage is a function of Φ_{ar}

$$i'_f = \frac{e_f}{X_s} = \qquad (6)$$

It can be shown that[1]

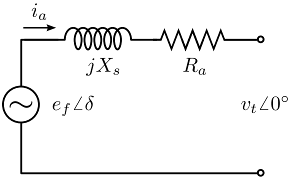
$$|i'_f| = \frac{X_{ar}}{X_s} i_f \frac{\sqrt{2}}{3} \frac{N_{re}}{N_{se}} \qquad (7)$$

$\rightarrow$ N_{re} and N_{se} are the field and stator winding turns

[1] G. Slemon and A. Straughen, Electric Machines, Wesley, 1980

Torque and power characteristics

The per-phase equivalent circuit



$$
\begin{aligned}
v_t &= |v_t|\angle 0^\circ \\
e_f &= |e_f|\angle\delta \\
Z_s &= R_a + jX_s = |Z_s|\angle\theta
\end{aligned}
$$

The current is

$$
i_a = \left|\frac{e_f - v_t}{Z_s}\right| = \frac{e_f}{Z_s} - \frac{v_t}{Z_s} = \frac{|e_f|\angle-\delta}{|Z_s|\angle-\theta} - \frac{|v_t|}{|Z_s|}\angle\theta = \left(\frac{|e_f|}{|Z_s|}\angle(\theta-\delta) - \frac{|v_t|}{|Z_s|}\angle\theta\right) \tag{8}
$$

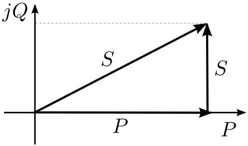
Power characteristics

The per-phase complex power at the terminal is

$$S = v_t i_a \tag{9}$$

from the previous equations:

$$S = \frac{|v_t||e_f|}{|Z_s|}\angle(\theta - \delta) - \frac{|v_t|^2}{|Z_s|}\angle\theta \tag{10}$$

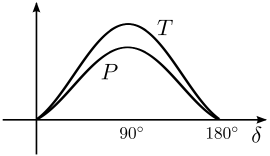


The real power P and the reactive power Q per phase are

$$P = \frac{|v_t||e_f|}{|Z_s|}\cos(\theta - \delta) - \frac{|v_t|^2}{|Z_s|}\cos\theta \tag{11}$$

$$Q = \frac{|v_t||e_f|}{|Z_s|}\sin(\theta - \delta) - \frac{|v_t|^2}{|Z_s|}\sin\theta \tag{12}$$

Torque characteristics



If $R_a \to 0$, then $Z_s = X_s$ and $\theta = 90^\circ$

For a 3-phase machine the power becomes

$$P_{3\phi} = 3\frac{|v_t||e_f|}{|X_s|}\sin\delta \tag{13}$$

$$Q_{3\phi} = 3\frac{|v_t||e_f|}{|Z_s|}\cos(\delta) - 3\frac{|v_t|^2}{|X_s|} \tag{14}$$

The developed torque is

$$T = \frac{P_{3\phi}}{\omega_{syn}} = \frac{3}{\omega_{syn}}\frac{|v_t||e_f|}{X_s}\sin\delta \tag{15}$$

where ω is the synchronous speed.

Open-loop speed control

To maintain the torque and avoid saturation, the voltage must be controlled

$$P = T\omega = 3\frac{v_t e_f}{X_s}\sin\delta \tag{16}$$

where

$$\omega = \frac{4\pi f}{p} \tag{17}$$

let

$$X_s = 2\pi f L_s \tag{18}$$

If $i_f = cte$, e_f is proportional to the speed, thus

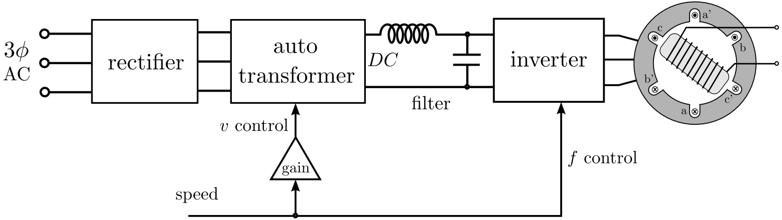
$$e_f = k_1 f \tag{19}$$

thus

$$T = K v_t \sin\delta \tag{20}$$

Open-loop speed control

Speed can be controlled by changing the frequency of the power supply.

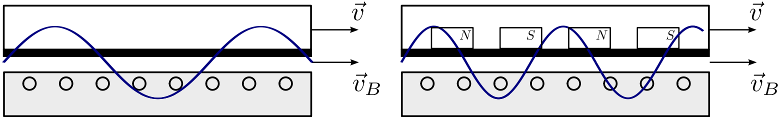


Simultaneous voltage and frequency control

→ f controls the speed

→ v controls the torque

Linear synchronous motors



asynchronous/induction synchronous

The synchronous linear speed v is

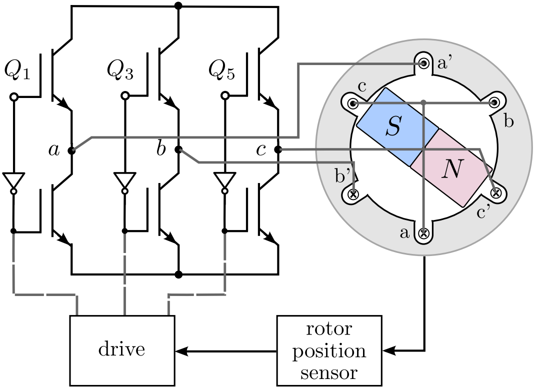
$$v = 2T_pf \text{ m/s} \tag{21}$$

where T_p is the pole pitch

In the induction motor, the slip is

$$s = \frac{v - v_B}{v} \tag{22}$$

Brushless DC motors



Exercise 83

A 3-phase, 4-pole, synchronous machine is operated at 208V (phase to phase) at 60 Hz. The field excitation is adjusted so that the power factor is unit when the machine draws 3 kW from the source. The synchronous reactance per phase is 8 Ω.

Determine:

(a) The excitation voltage of the rotor e_f

(b) The power angle δ

(c) If the field excitation is increased, determine the maximum torque that the motor can deliver.

Exercise 83 - continued

3-phase, 208 V phase-to-phase, 60 Hz, 3 kW.

(a) The excitation voltage of the rotor e_f

Exercise 83 - continued

4-pole, 208 V phase-to-phase, 60 Hz, 3 kW, $e_f = 137.35$ V.

(c) The maximum torque the motor can deliver.

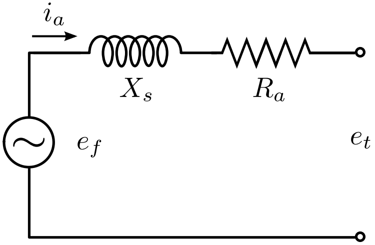
Exercise 83 - continued

3-phase, 208 V phase-to-phase, 60 Hz, 3 kW.

(c) The power angle δ

Exercise 84

A 3-phase, 2300 V, 60 Hz synchronous motor has a synchronous reactance of $X_s = 11\ \Omega$ per phase. When it draws 165.8 kW from the source, the power angle is $\delta = 15^\circ$. Neglect resistive losses.

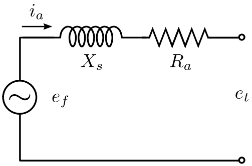


(a) Determine the excitation voltage per phase e_f

(b) Determine the supply line current i_a

(c) Determine the line current when the load is removed (in this case $\delta = 0$).

Exercise 80 - continued

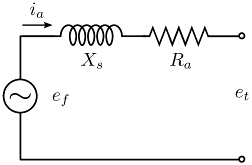


(a) The excitation voltage per phase e_f

(b) Determine the supply line current i_a

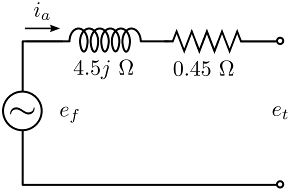
Exercise 84 - continued

(c) The no-load line current ($\delta = 0$).



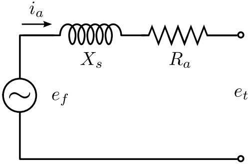
Exercise 85

A 3-phase, 11 kV, 60 Hz, 25 MVA synchronous motor has the equivalent model parameters shown.



If the power factor is 0.85, determine the rotor excitation voltage e_f required for this operating condition.

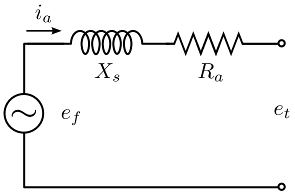
Exercise 85 - continued



3-phase, 11 kV, 60 Hz, 25 MVA, power factor 0.85

Exercise 86

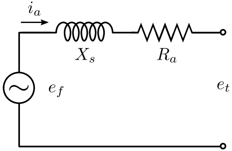
A 208 V, four-pole synchronous motor has a synchronous reactance of 1.5Ω per phase and a negligible stator resistance.



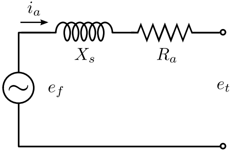
(a) The field current and the mechanical input power are adjusted so that the the motor delivers 10 kW at 0.8 power factor. Determine the excitation voltage e_f and the power angle δ.

(b) The field current is adjusted to make the power factor unit, determine the field current change with respect to **(a)**.

Exercise 86 - continued

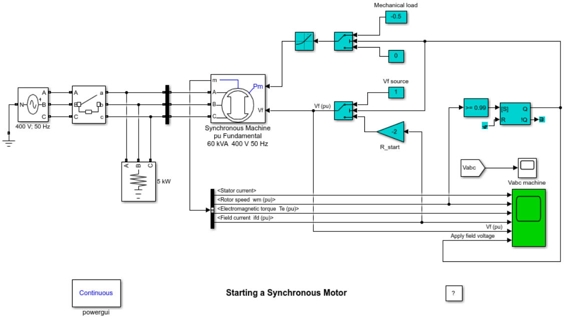


Exercise 86 - continued



Exercise 87 - Matlab

Type the following command on Matlab to open the simulation model of a synchronous motor: power_smstarting.



Study and describe the function of the "R_start" constant.

Quiz

Q1 - At which speed does a synchronous machine having 4 poles and supplied with 60 Hz supply rotate ?

(a) 3600 rpm

(b) 1500 rpm

(c) 1800 rpm

(d) 900 rpm

(e) $2 \times 4 \times \pi \times 60$ rpm

Quiz

Q2 - What is the effect of motor load on the motor speed?

(a) The speed is independent of the load

(b) The speed increases with high loads

(c) The speed decreases at high loads

(d) The slip of rotor increases

(e) The motor cannot run with a load

Quiz

Q3 - In synchronous machine, 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?

(a) Induction motors are self-starting, synchronous motors are not

(b) Induction motors are not self-starting, synchronous motors are

(c) Induction and synchronous motors are not self-starting

(d) Induction and synchronous motors are both self-starting

(e) Induction and synchronous motors run at the synchronous speed

Quiz

Q5 - Open-loop speed control of synchronous machine is done by changing

(a) The excitation voltage

(b) The supply current

(c) The supply frequency

(d) The supply voltage

(e) None of the above

Quiz

Q6 - What is the slip factor in a synchronous motor?

(a) $s = 0$

(b) $s = 1$

(c) $0 < s < 1$

(d) $-1 < s < 1$

(e) $-1 \leq s \leq 1$

Student course feedback survey

https://cci-survey.ca/uoit/ca

Next class...

- Single phase motors

Additional supporting materials for Lecture 18:

Linear synchronous motors: `https://youtu.be/0_QBl6-_jJU`

Synchronous motors for kids: `https://youtu.be/Vk2jDXxZIhs`

Brushless DC motor `https://youtu.be/bCEiOnuODac`