Electromagnetic Energy Conversion ELEC0431

Exercise session 8: Asynchronous machines

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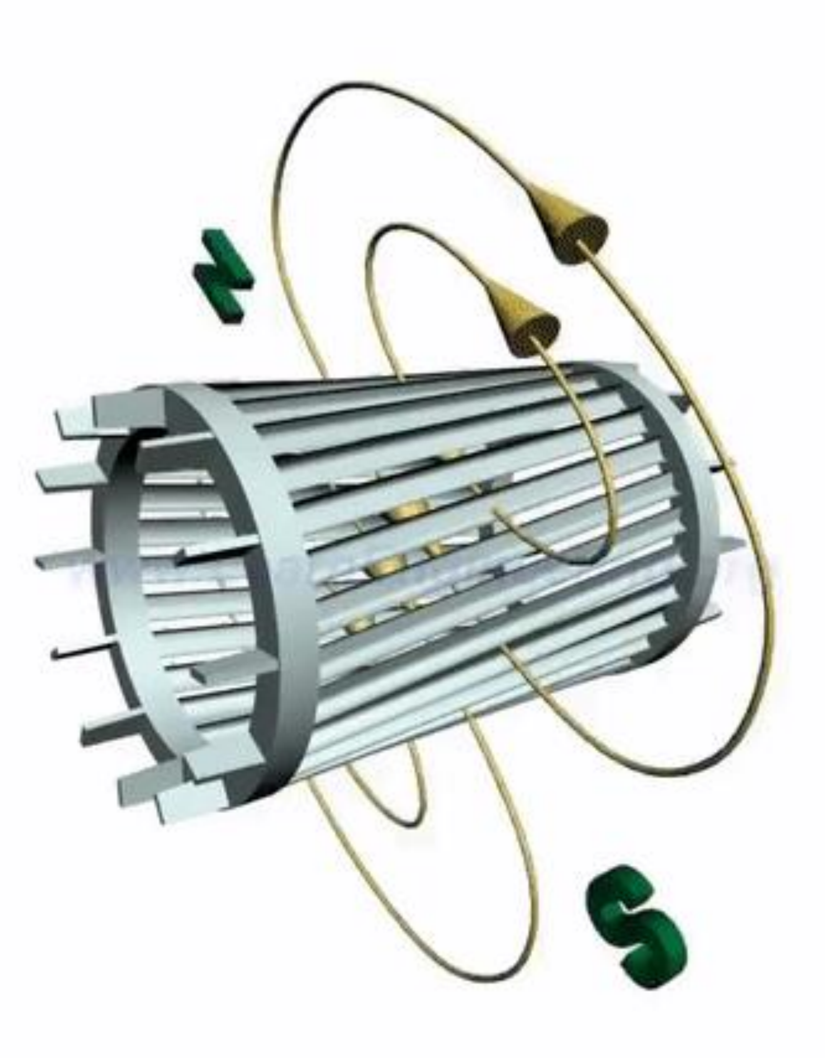
Reminders

The asynchronous machine

The asynchronous machine – working principle



start-up:

3-phase currents in stator windings ➔ rotating magnetic field ➔ variational magnetic field through rotor closed loop windings ➔ e.m.f. ➔ currents in closed loop rotor windings (eddy currents) ➔ torque due to Laplace: $\bar{F} = q\bar{v} \wedge \bar{B}$

➔ the rotor starts moving.

Rotation speed:

- $\dot{\theta}$ ➔ Speed of rotation of the rotor
- $\dot{\theta}_s$ ➔ Speed of rotation of the magnetic field
- $g = \frac{\dot{\theta}_s - \dot{\theta}}{\dot{\theta}_s}$ = the slip (**g**lissement in French)

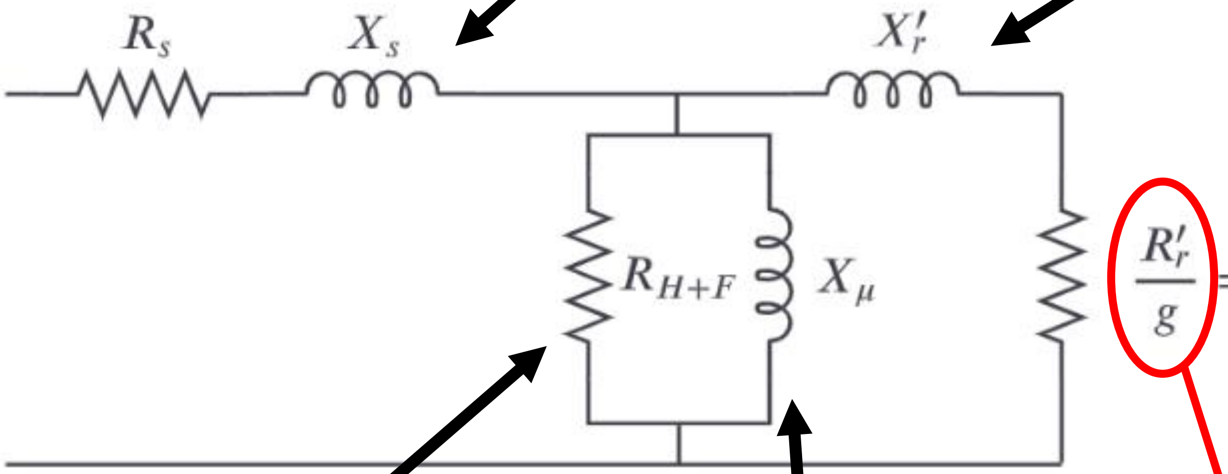
➔ $\dot{\theta} \leq \dot{\theta}_s$ ➔ $g \in [0; 1]$

The asynchronous machine – equivalent model

Joule losses in the stator winding

Leakage flux of the stator

Leakage flux in the rotor winding (seen from the stator)



$$\frac{R'_r}{g} = R'_r + \frac{1-g}{g} R'_r$$

Power transmitted to the shaft

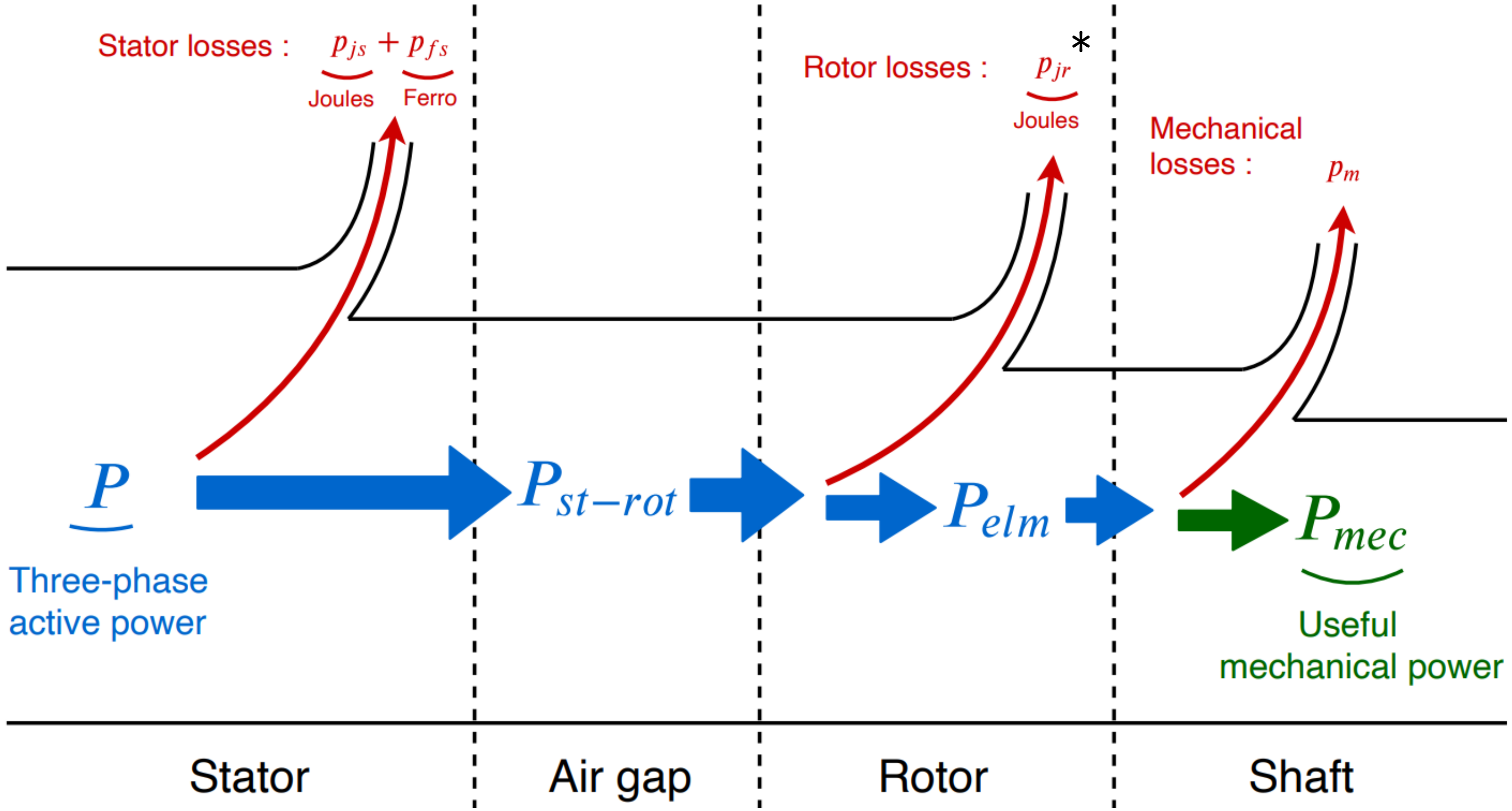
Magnetic losses in the core

Magnetizing reactance

Joule losses in the rotor winding (seen from the stator)

Both joule losses and useful power

The asynchronous machine – Power balance



* Ferromagnetic losses in the rotor can be neglected since the rotoric current frequency is much smaller than the grid frequency

Exercises

Exercise 19: Asynchronous motor for washer cleaner

Exercise 20: Asynchronous motor of a fan

Exercise 19: Asynchronous motor for washer cleaner

A star-shaped asynchronous motor of a high-pressure washer cleaner has the following nominal characteristics:

- $P_n = 5.5\ kW$
- RMS composed voltage value $U_{sn} = 400\ V$
- Frequency $f_n = 50\ Hz$
- RMS line current intensities $I_{sn} = 11\ A$
- Speed of rotation $\dot{\theta}_n = 1460\ RPM$

Assume that the stator reactance X_s is equal to the stator resistance R_s Use a single-phase equivalent model of the asynchronous motor when needed.

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

1. Calculate the synchronous speed of rotation $\dot{\theta}_s$, the number of pair of poles of the motor and the nominal slip g_n.
2. Determine the value of the stator resistance R_s given that a current of RMS value $I_0 = 10\ A$ flows when a voltage of RMS value $U_0 = 20.6\ V$ is applied.
3. At the nominal operating point, without mechanical load, the motor draws a current of RMS value $I_{so} = 3.07\ A$ for an active power $P_{so} = 245\ W$. Calculate the overall losses and calculate the resistance modelling ferromagnetic losses R_{H+F} and the magnetizing inductance L_μ, assuming that mechanical losses equal ferromagnetic losses;

Consider that the machine operates at nominal speed and produces the nominal mechanical power P_n to the mechanical load. The nominal mechanical power can also be denoted P_{mec}.

4. At the nominal operating point, calculate the transmitted power from the stator to the rotor and the Joules losses in the stator P_{js} and deduce the total consumed power P.
5. Calculate the rotoric resistance R'_r and the leak inductance L'_r seen from the stator.
6. At the nominal operating point, calculate the mechanical torque Γ_{un} and the electromagnetic torque Γ_n, the power factor $\cos\varphi_n$ and the efficiency η_n.
7. Compute the RMS value I_s of the line currents, and the power factor $\cos\phi$ at a rotation speed of 0 RPM.

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

1. Calculate the synchronous speed of rotation $\dot{\theta}_s$, the number of pair of poles of the motor and the nominal slip g_n.

$$f_n = 50\ Hz$$
$$= 50\,.\,60 = 3000\ RPM$$
$$= p\ *\ \dot{\theta}_s$$

⇒

p	$\dot{\theta}_s = 3000/p$
1	3000
2	1500
3	1000
4	750

$\dot{\theta}_s$ closed from $\dot{\theta}_n$ and higher

⇒ Two pairs of poles and synchronous speed of $\dot{\theta}_s = 1500\ RPM$.

$$g_n = \frac{\dot{\theta}_s - \dot{\theta}_n}{\dot{\theta}_s} = \frac{1500 - 1460}{1500} = 0.0267$$

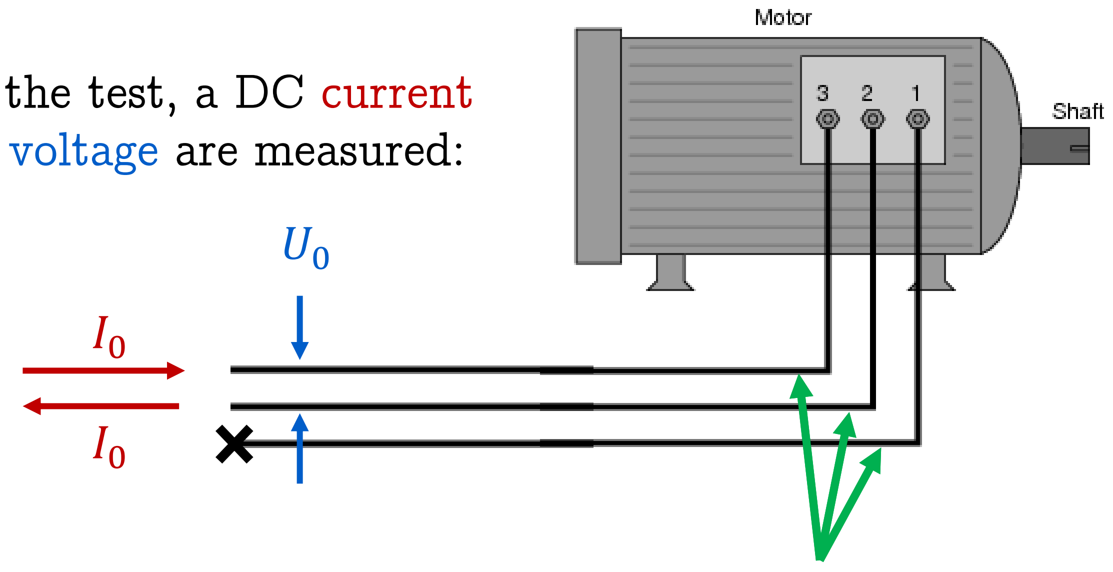
Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

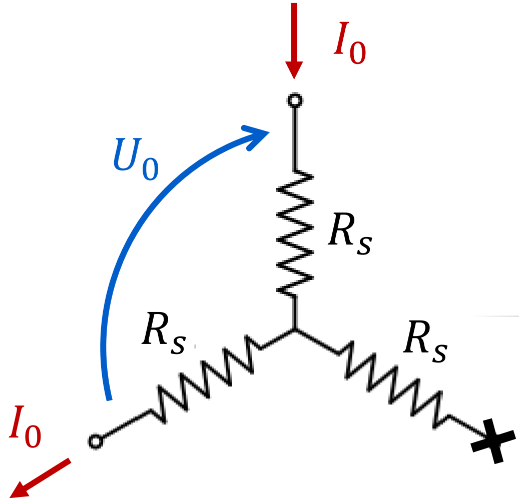
$\dot{\theta}_s = 1500\ RPM$

2. Determine the value of the stator resistance R_s given that a current of RMS value $I_0 = 10\ A$ flows when a voltage of RMS value $U_0 = 20.6\ V$ is applied.

For the test, a DC current and voltage are measured:



The voltage drop is due only to the resistance of the stator windings R_s



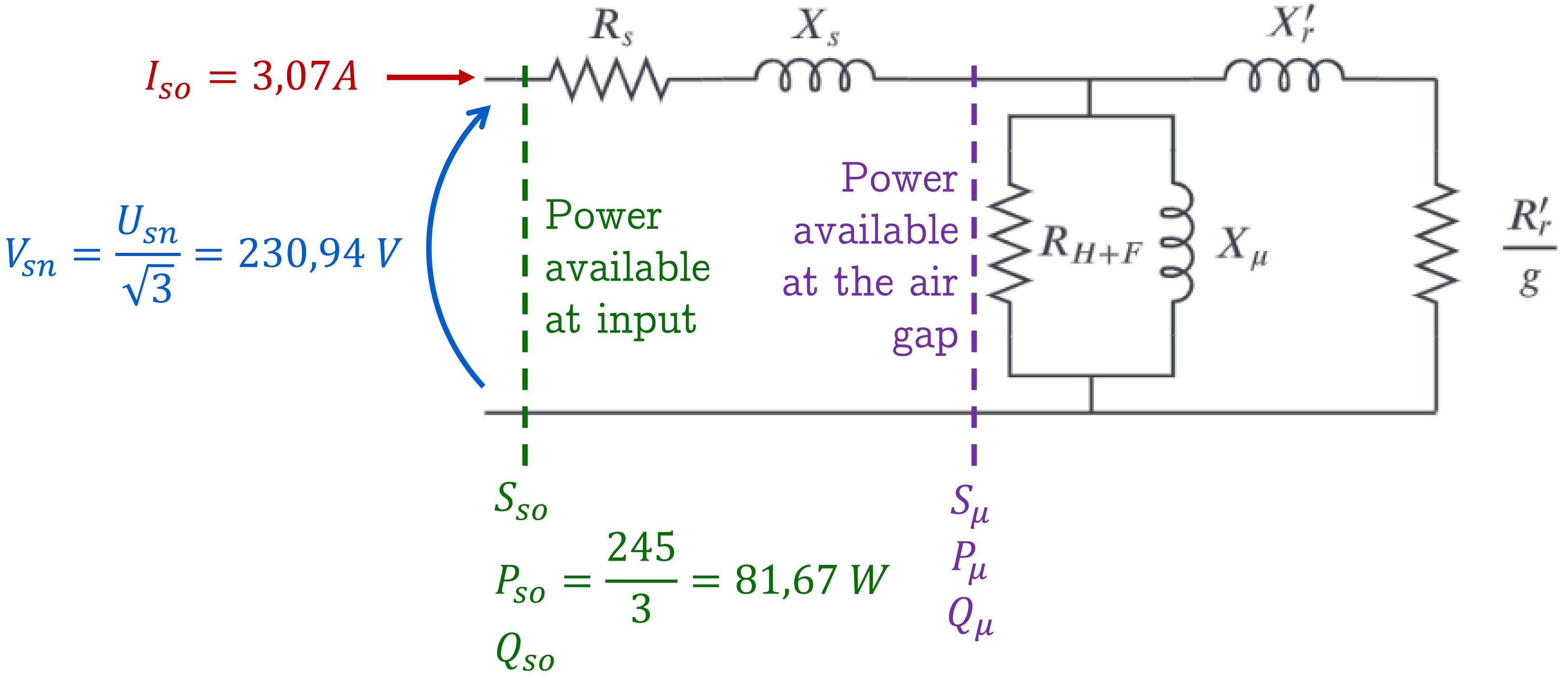
$$U_0 = (2\,.\,R_s)\,.\,I_0 \Leftrightarrow R_s = \frac{U_0}{2\,I_0} = 1{,}03\ \Omega$$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

$\dot{\theta}_s = 1500\ RPM$ - $R_s = 1{,}03\Omega$

3. At the nominal operating point, without mechanical load, the motor draws a current of RMS value $I_{so} = 3.07\ A$ for an active power $P_{so} = 245\ W$. Calculate the overall losses and calculate the resistance modelling ferromagnetic losses R_{H+F} and the magnetizing inductance L_μ, assuming that mechanical losses equal ferromagnetic losses



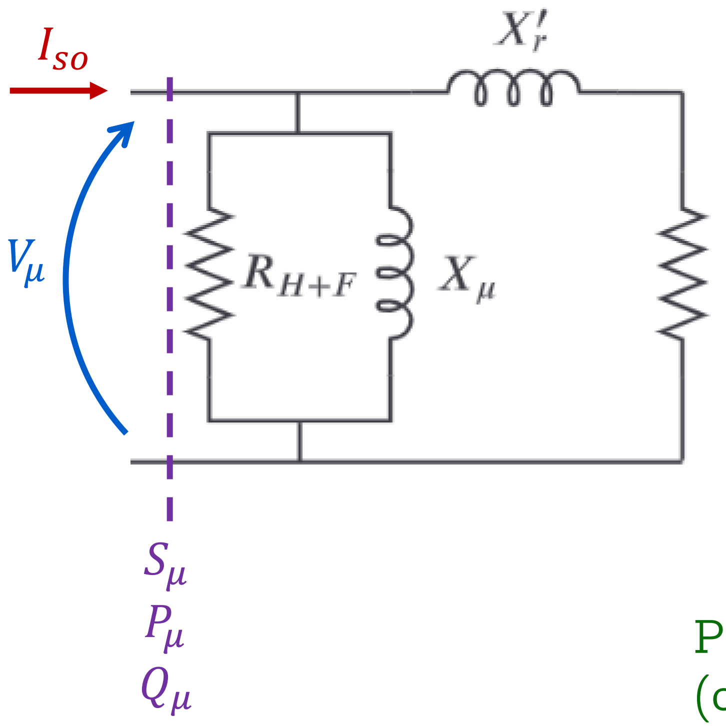
1. $S_{so} = V_{sn}\, I_{so}$
2. $Q_{so} = \sqrt{S_{s0}^2 - P_{so}^2}$
3. $P_\mu = P_{so} - R_s\, I_{so}^2$
4. $Q_\mu = Q_{so} - X_s\, I_{so}^2$
5. $S_\mu = \sqrt{P_{so}^2 + Q_{so}^2}$
6. $V_\mu = \frac{S_\mu}{I_{so}}$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

$\dot{\theta}_s = 1500\ RPM$ - $R_s = 1{,}03\Omega$

3. At the nominal operating point, without mechanical load, the motor draws a current of RMS value $I_{so} = 3.07\ A$ for an active power $P_{so} = 245\ W$. Calculate the overall losses and calculate the resistance modelling ferromagnetic losses R_{H+F} and the magnetizing inductance L_μ, assuming that mechanical losses equal ferromagnetic losses



losses due to the resistance in the rotor windings

$$\frac{R_r'}{g} = R_r + \frac{1-g}{g} R_r'$$

Negligeable for $g \ll$

Power delivered to the shaft (only mechanical losses here)

All the active power available at the air gap is lost either with R_{H+F} (ferromagnetic losses) or with $\frac{1-g}{g} R_r'$ (mechanical losses)

$$\Rightarrow \quad P_\mu = P_f + P_m$$

$$= 2\ P_{ferro}$$

$$= 2\frac{V_\mu^2}{R_{H+F}}$$

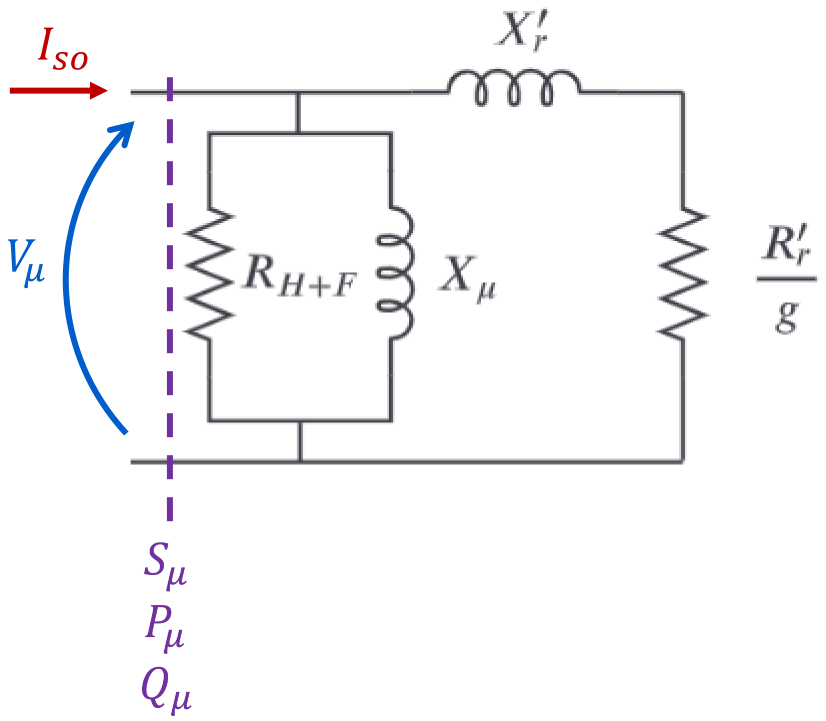
$$\Rightarrow \quad R_{H+F} = \frac{2\ V_\mu^2}{P_\mu} = 1437{,}88\ \Omega$$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

$\dot{\theta}_s = 1500\ RPM$ - $R_s = 1{,}03\Omega$ - $R_{H+F} = 1437{,}88\ \Omega$

3. At the nominal operating point, without mechanical load, the motor draws a current of RMS value $I_{so} = 3.07\ A$ for an active power $P_{so} = 245\ W$. Calculate the overall losses and calculate the resistance modelling ferromagnetic losses R_{H+F} and the magnetizing inductance L_μ, assuming that mechanical losses equal ferromagnetic losses



By considering $X'_r \ll X_\mu$, all the reactive power available at the air gap can be considered to be lost in X_μ:

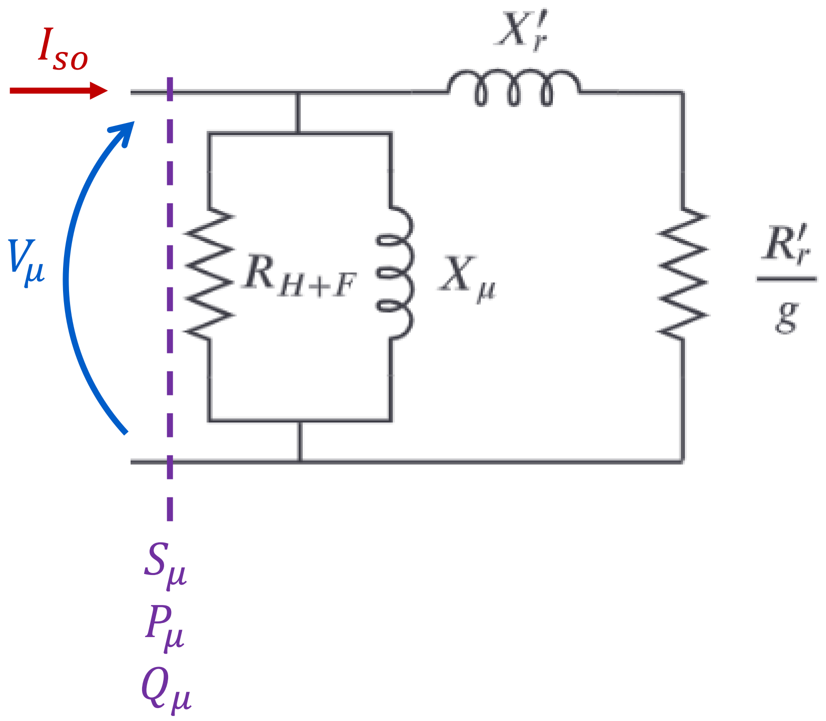
$$Q_\mu = \frac{V_\mu^2}{X_\mu} \Leftrightarrow X_\mu = \frac{V_\mu^2}{Q_\mu} = 74{,}84\ \Omega$$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

$\dot{\theta}_s = 1500\ RPM$ - $R_s = 1{,}03\Omega$ - $R_{H+F} = 1437{,}88\ \Omega$ - $X_\mu = 74{,}84\ \Omega$

3. At the nominal operating point, without mechanical load, the motor draws a current of RMS value $I_{so} = 3.07\ A$ for an active power $P_{so} = 245\ W$. Calculate the overall losses and calculate the resistance modelling ferromagnetic losses R_{H+F} and the magnetizing inductance L_μ, assuming that mechanical losses equal ferromagnetic losses



Half P_μ is for the mechanical losses, the other half is for the ferromagnetic losses ➔ Considering three phases:

$$P_m = 3\,\frac{P_\mu}{2} = 107{,}94\ W$$

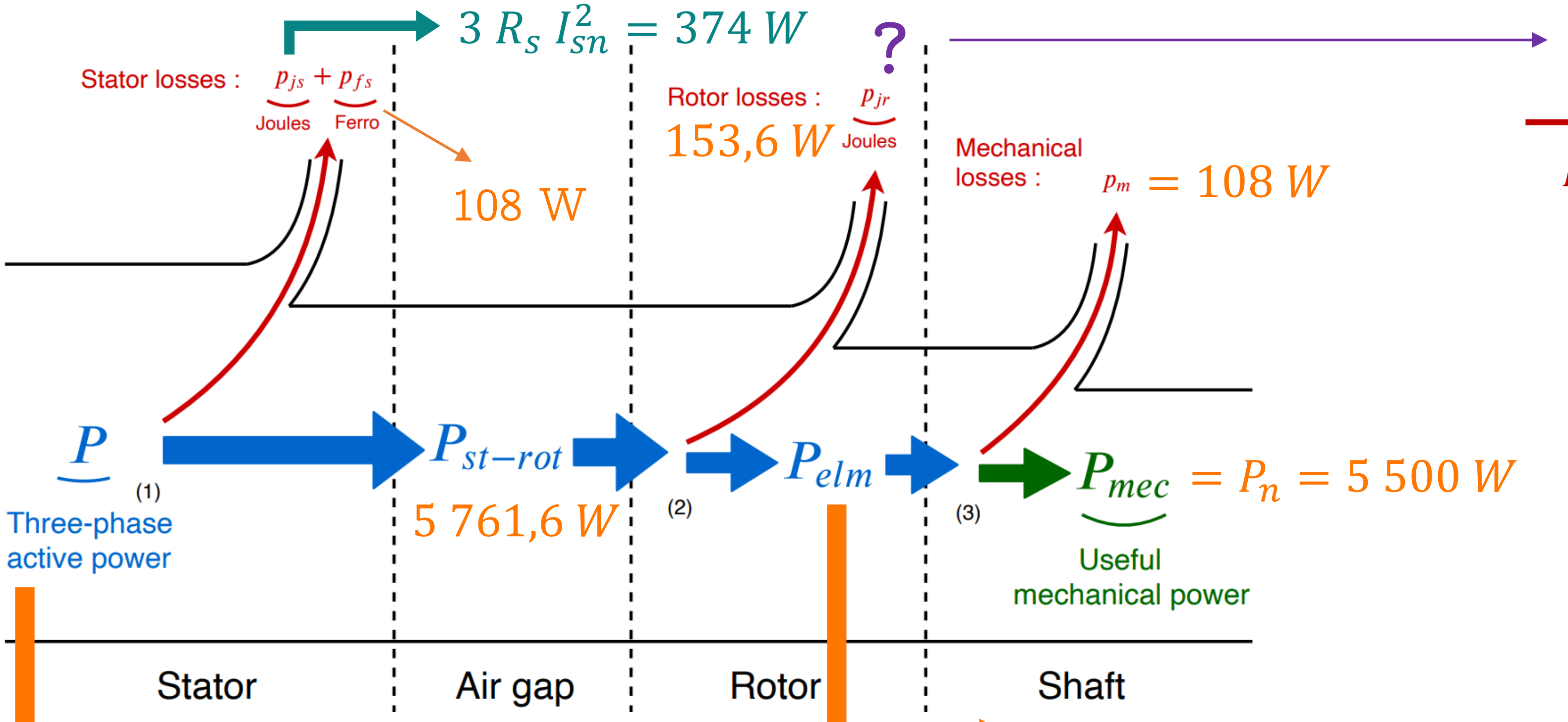
$$P_f = 3\,\frac{P_\mu}{2} = 107{,}94\ W$$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$

$\dot{\theta}_s = 1500\ RPM$ - $R_s = 1{,}03\Omega$ - $R_{H+F} = 1437{,}88\ \Omega$ - $X_\mu = 74{,}84\ \Omega$ - $P_m = P_f = 107{,}94\ W$

4. At the nominal operating point, calculate the transmitted power from the stator to the rotor and the Joules losses in the stator P_{js} and deduce the total consumed power P.



$P = P_{st-rot} + p_{js} + p_{fs}$
$= 6\ 243{,}6\ W$

$P_{elm} = P_n + P_m$
$= 5\ 500 + 108$
$= 5608\ W$

p_{jr} is the joules losses at the rotor:

$$p_{jr} + P_{elm} = P_{st-rot}$$

I_r

$$R'_r + \frac{1-g}{g} R'_r$$

$$P_{st-rot} = I_r^2\ R'_r \left(1 + \frac{1-g}{g}\right)$$

$$= \frac{1-g}{g} R'_r\ I_r^2 \left(\frac{g}{1-g} + 1\right)$$

$$= \frac{P_{elm}}{1-g} = 5761{,}6\ W$$

And $p_{jr} = P_{st-rot} - P_{elm} = 153{,}6\ W$

Exercise 19: Asynchronous motor for washer cleaner

Star configuration - $P_n = 5{,}5\ kW$ - $U_{sn} = 400\ V$ - $f_n = 50\ Hz$ - $I_{sn} = 11\ A$ - $\dot{\theta}_n = 1460\ RPM$ - $X_s = R_s$
$\dot{\theta}_s = 1500\ RPM$ - $R_s = 1{,}03\Omega$ - $R_{H+F} = 1437{,}88\ \Omega$ - $X_\mu = 74{,}84\ \Omega$ - $P_m = P_f = 107{,}94\ W$ - $P = 6\ 244\ W$

5. Calculate the rotoric resistance R_r' and the leak inductance L_r' seen from the stator.
6. At the nominal operating point, calculate the mechanical torque Γ_{un} and the electromagnetic torque Γ_n, the power factor $\cos\varphi_n$ and the efficiency η_n.
7. Compute the RMS value I_s of the line currents, and the power factor $\cos\phi$ at a rotation speed of 0 RPM.

Exercise 20: Asynchronous motor of a fan

On the nameplate of an asynchronous motor of a fan used in an air handling unit, the following characteristics are read:

4.4 kW; 230/400 V; 15.5/9 A; 50 Hz; 4 poles

Using a single-phase equivalent model of the asynchronous motor:

1. Explain the meaning of each element on the nameplate;
2. The motor is used on a 230 V network, explain which winding coupling should be used for the stator;
3. Calculate the synchronous speed of rotation $\dot{\theta}_s$;
4. Given that the (DC) resistance value measured between two stator terminals is $R_a = 0.654\,\Omega$, compute the value of the statoric resistance R_s of the equivalent single-phase model;
5. A calibrated motor is used to rotate the shaft of the unpowered considered motor, upto reaching the synchronous speed, at which the calibrated motor consumes 86 W. Calculate the mechanical losses of the motor and explain why assuming that these mechanical losses remain constant is a good approximation;
6. At the nominal operating point, without mechanical load, the motor draws a current of RMS value $I_{so} = 3.82$ A for an active power $P_{so} = 300$ W. Calculate the resistance modelling ferromagnetic losses R_{H+F} and the statoric inductance L_μ;

Exercise 20: Asynchronous motor of a fan

7. The rotor shaft of the motor is stalled while a voltage of RMS value $U_{sc} = 57.5\,\text{V}$ is applied for a consumed three-phase active power $P_{sc,3\phi} = 374\,\text{W}$ and three-phase reactive power $Q_{sc,3\phi} = 1.09\,\text{kvar}$. Calculate the rotoric resistance R_r' and the leak inductance X_r' seen from the stator.

A direct voltage of value V_s and frequency f is applied on each phase of the motor.

8. Using single-phase equivalent model of the asynchronous motor, express the RMS current value I_s in terms of V_s, R_s R_r', g et X_r';
9. Calculate the transmitted power from the stator to the rotor;
10. Calculate the electromagnetic torque C_{elm} and give the maximal reachable torque $\Gamma_{\max}$ after showing that C_{elm} is maximal for a slip value g_{max};
11. Plot C with respect to g for an applied voltage V_s equal to V_n, $\frac{V_n}{\sqrt{2}}$ and $\frac{V_n}{2}$;
12. Explain why a control on the rotor voltages is not suitable for speed variation for load having constant resistive torque;
13. To limit the peak current when starting the motor, a star/delta starter is frequently used. Assuming that this transient mode is much more longer compared to period corresponding to the frequency f of the applied voltages, calculate the RMS current values of the line currents compared to those drawn by using a star/delta starter.