Electromagnetic Energy Conversion
ELEC0431

Exercise session 9: DC machines

22 April 2022

Florent Purnode (florent.purnode@uliege.be) – Nicolas Davister (ndavister@uliege.be)

Montefiore Institute, Department of Electrical Engineering and Computer Science,
University of Liège, Belgium

Exercise 20: Asynchronous motor of a fan (continued)

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:

$$\boxed{4.4\,\text{kW}; 230/400\,\text{V}; 15.5/9\,\text{A}; 50\,\text{Hz}; 4\,\text{poles}}$$

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 $I_{so} = 3.82\,\text{A}$ for an active power $P_{so} = 300\,\text{W}$. 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.

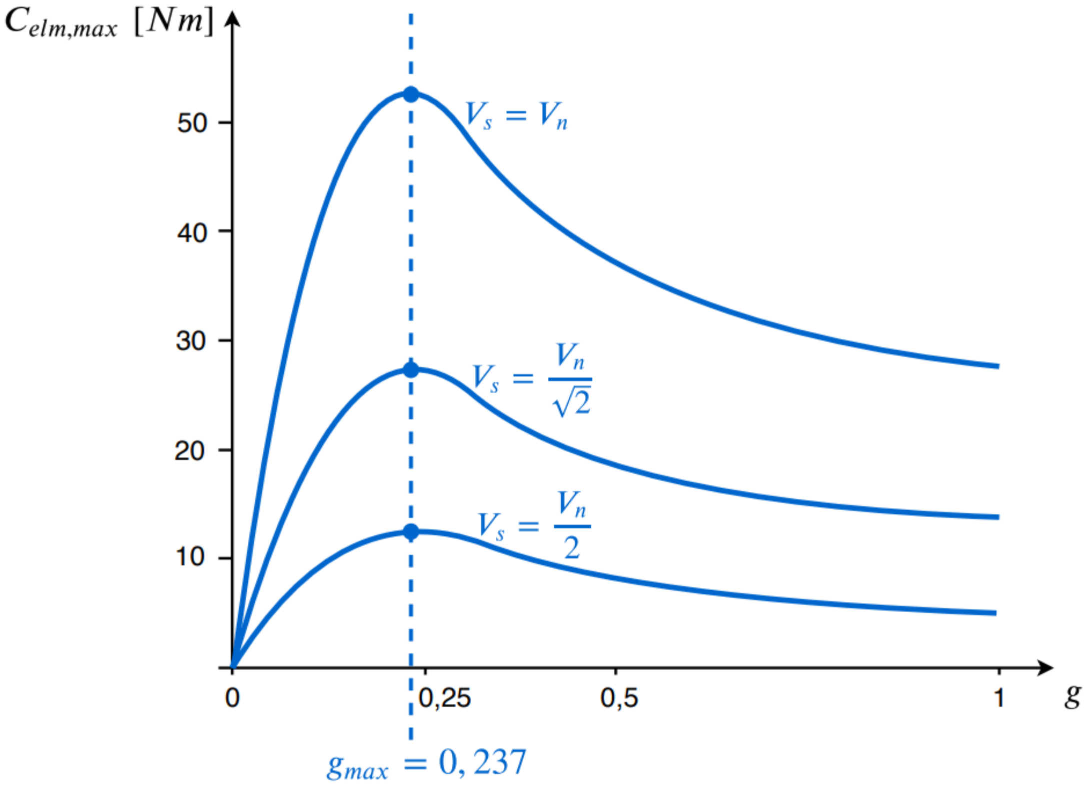
A direct voltage of value V_s and frequency f is applied on each phase of the motor.

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.

Exercise 20: Asynchronous motor of a fan

11. Plot C with respect to g for an applied voltage V_s equal to V_n, $\frac{V_n}{\sqrt{2}}$ and $\frac{V_n}{2}$;

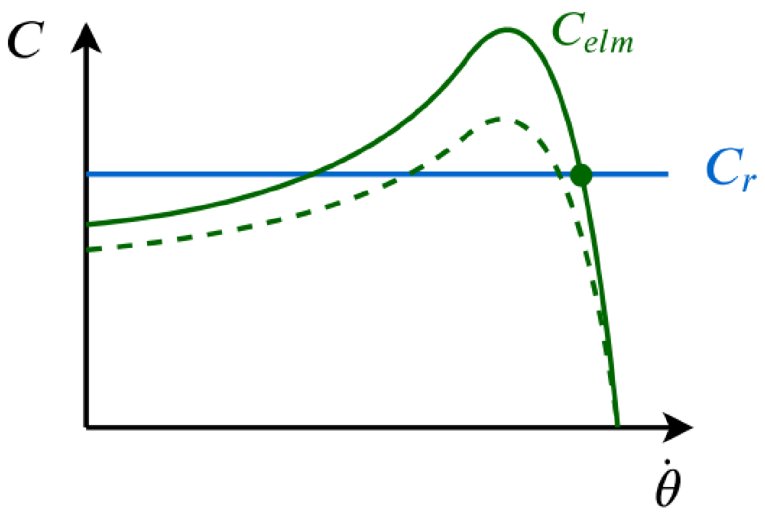
$$C_{elm} = \frac{3\,R_r'}{g\,\dot{\theta}_s} \frac{V_s^2}{\sqrt{\left(R_s+\frac{R_r'}{g}\right)^2+X_r'^2}} \qquad C_{elm,max} = \frac{3\,V_s^2}{2\,\dot{\theta}_s} \frac{1}{R_s+\sqrt{R_s^2+X_r'^2}} \quad \text{for} \quad g_{max} = \frac{R_r'}{\sqrt{R_s^2+X_r'^2}} \text{ (same whatever } V_s\text{)}$$



Exercise 20: Asynchronous motor of a fan

12. Explain why a control on the rotor voltages is not suitable for speed variation for load having constant resistive torque;

$$C_{elm} = \frac{3\,R'_r}{g\,\dot{\theta}_s} \frac{V_s^2}{\sqrt{\left(R_s+\frac{R'_r}{g}\right)^2 + {X'_r}^2}} \quad \& \quad g = \frac{\dot{\theta}_s - \dot{\theta}}{\dot{\theta}_s}$$



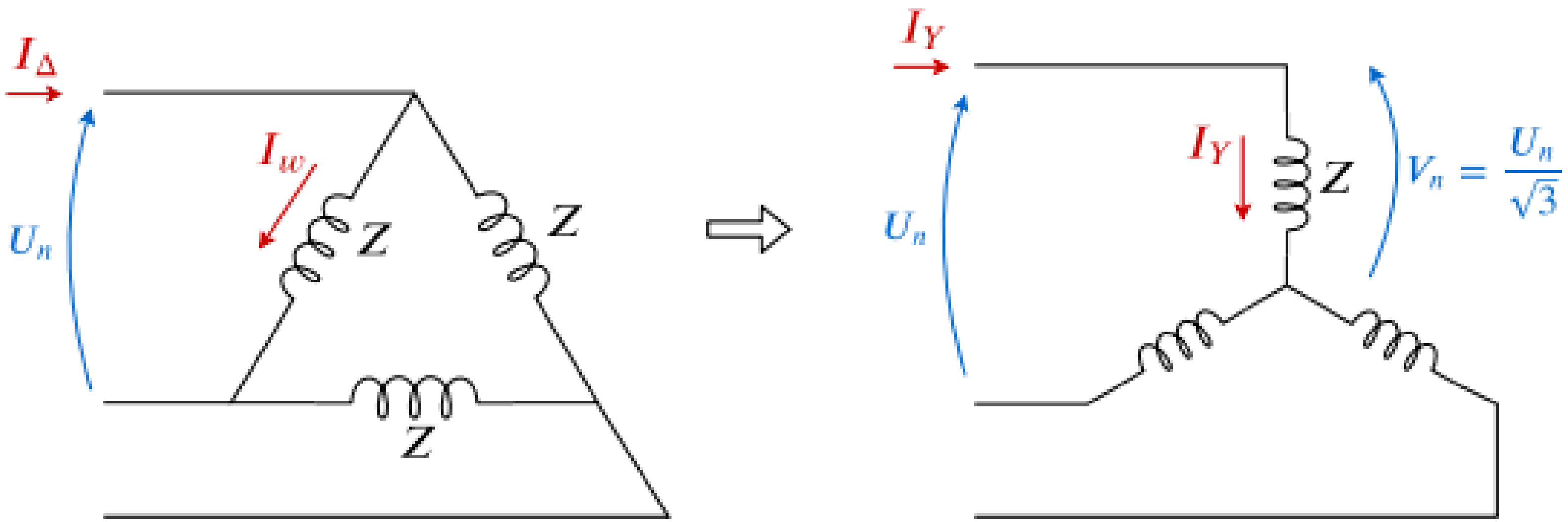
➔ Modifying the voltage has a very small impact on the rotation speed.

➔ the machine must remain in the stable region which is narrow.

Exercise 20: Asynchronous motor of a fan

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.

The use of the star/delta connection allows to reduce the inrush current by a factor of 3.



Winding current : $I_w = \frac{I_\Delta}{\sqrt{3}} = \frac{U_n}{Z}$

Winding current : $I_Y = \frac{V_n}{Z} = \frac{U_n}{\sqrt{3}\,Z} = \frac{I_\Delta}{\sqrt{3}}\frac{1}{\sqrt{3}} = \frac{I_\Delta}{3}$

Reminders

The DC machine

The DC machine – working principle

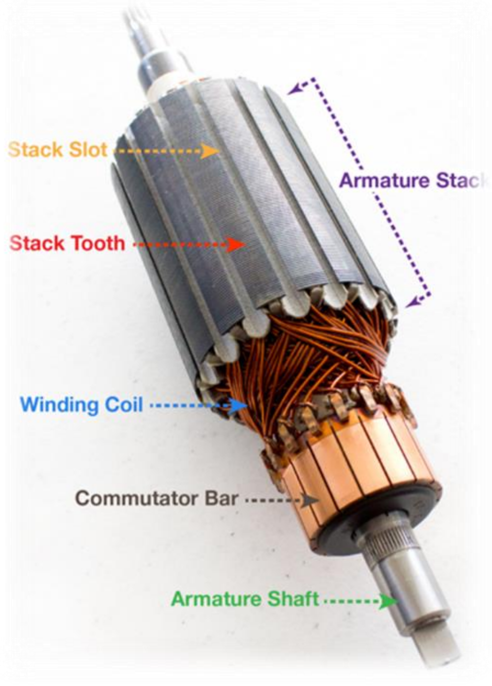
The stator generates a constant magnetic field.

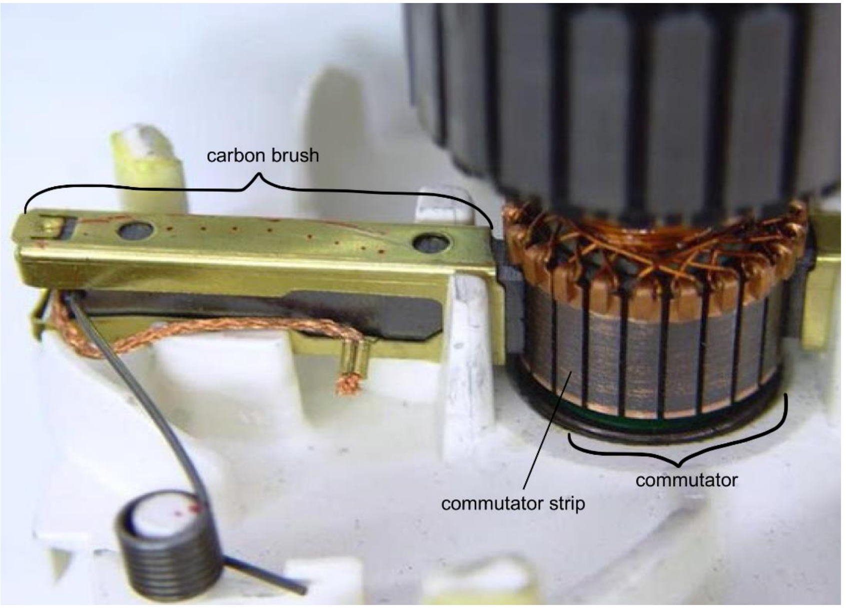
For a motor: DC current in the rotor leads to Lorentz force ➔ The rotor spins.

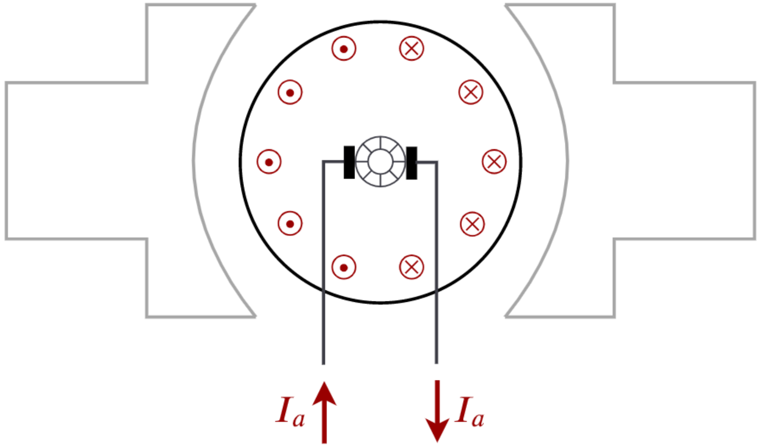
For a generator: Varying magnetic field in closed loop winding ➔ e.m.f.

The DC machine – rotor composition

A current flows in the rotor. This current arrives to the rotor thanks to brushes.

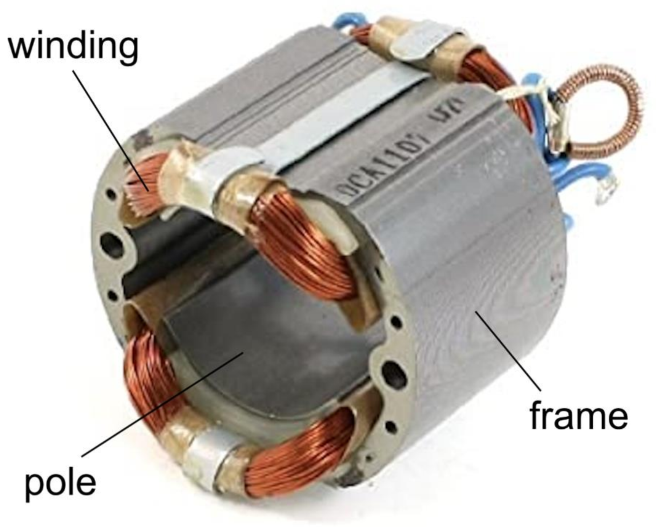




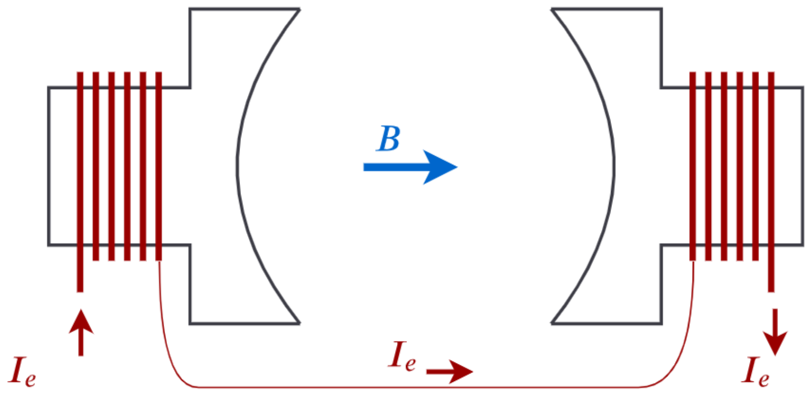


The DC machine – stator composition

The constant magnetic field is obtained with a permanent magnet or with an electromagnet.



For an electromagnet,
an excitation current I_e is required:

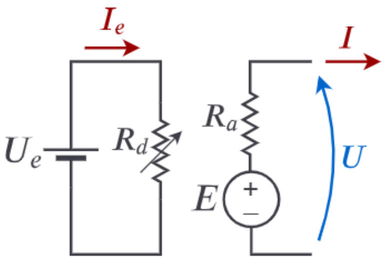


The DC machine – types of excitation

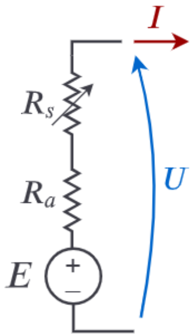
When using electromagnets, different winding connections are possible:

	Independent	Series	Shunt	Compound

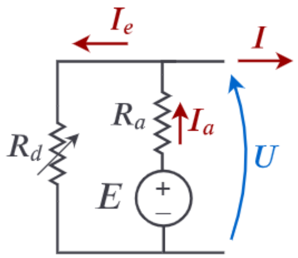
DC machine as a generator:



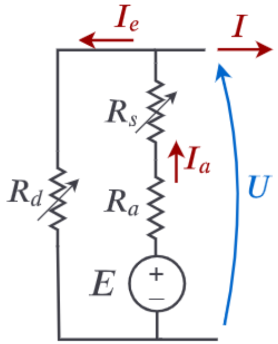
$I = I_a$



$I = I_a = I_e$

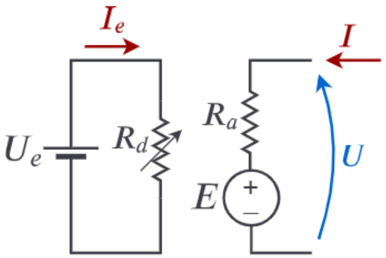


$I_a = I_e + I$

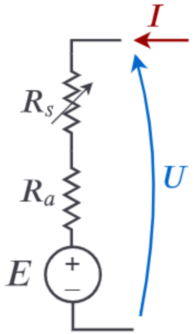


$I_a = I_e + I$

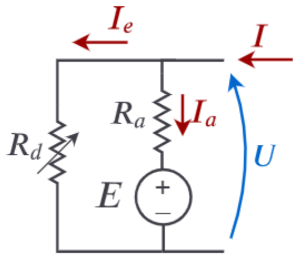
DC machine as a motor:



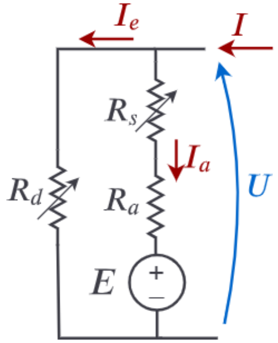
$I = I_a$



$I = I_a = I_e$



$I = I_e + I_a$



$I = I_e + I_a$

Take care at the current directions !!!

Exercises

Exercise 22: Brushed DC motor

Exercise 23: Brushed DC motor with series excitation

Exercise 22: Brushed DC motor

The motor of a hammer drill has the following characteristics:

- independant excitation DC machine,
- 2 poles (1 pair),
- Nominal power $P_n = 800\,\mathrm{W}$,
- Nominal speed of rotation $\dot{\theta}_n = 1500\,\mathrm{RPM}$,
- Nominal power voltage $U_n = 220\,\mathrm{V}$,
- Nominal rotor current intensity $I_n = 4.6\,\mathrm{A}$,
- Nominal stator current intensity $I_{en} = 0.35\,\mathrm{A}$.

Using two different excitation currents I_e, the electromotive force has been determined for different rotation speeds

$I_e = 0{,}35\ A$

n [RPM]	E [V]
1670	240
1510	220
1380	200
1040	150
820	120
510	75
110	20
0	0

$I_e = 0{,}2\ A$

n [RPM]	E [V]
1800	186
1450	150
1150	120
850	90
560	60
260	30
0	0

Exercise 22: Brushed DC motor

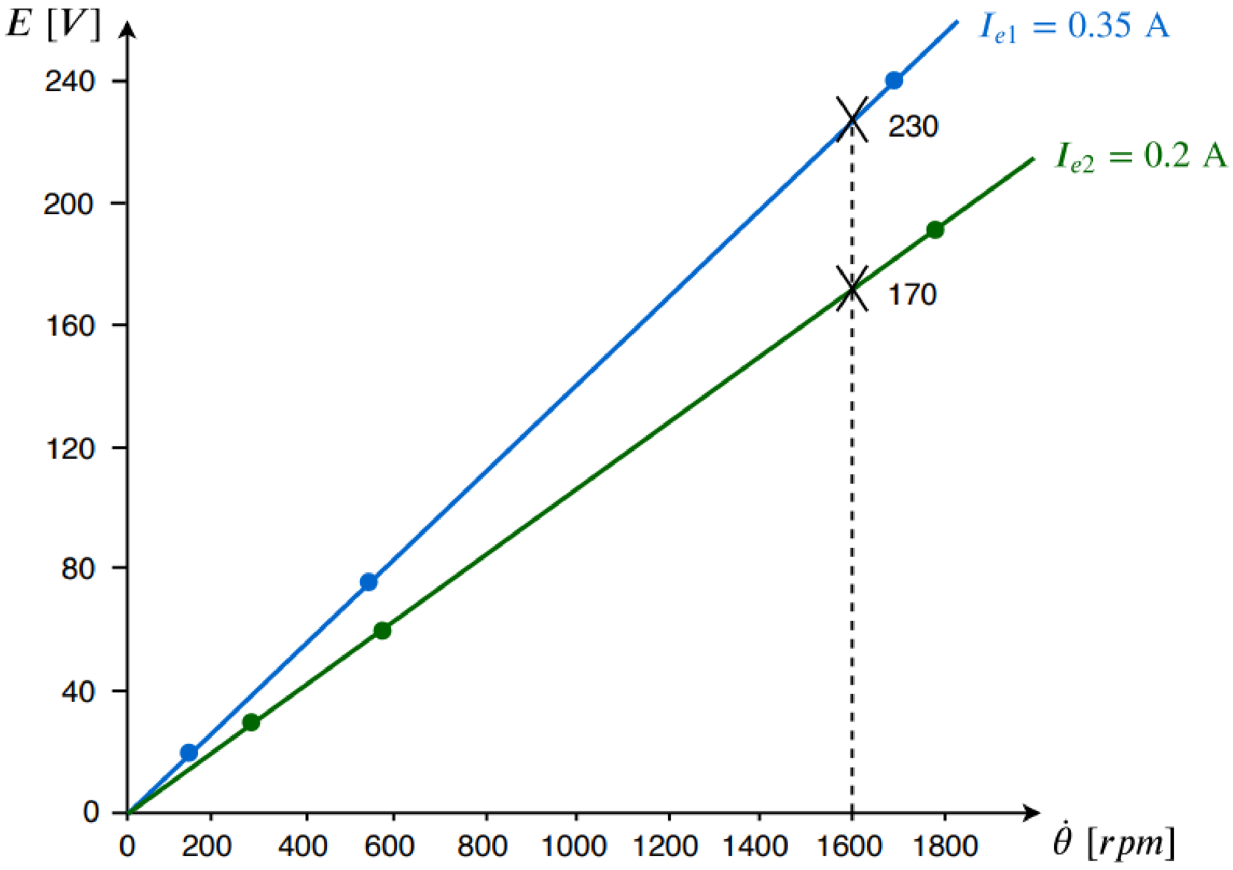
1. Plot E with respect to $\dot{\theta}$ for I_{e1} and I_{e2} and justify the shape of the curves;

$I_e = 0{,}35\ A$

n [RPM]	E [V]
1670	240
1510	220
1380	200
1040	150
820	120
510	75
110	20
0	0

$I_e = 0{,}2\ A$

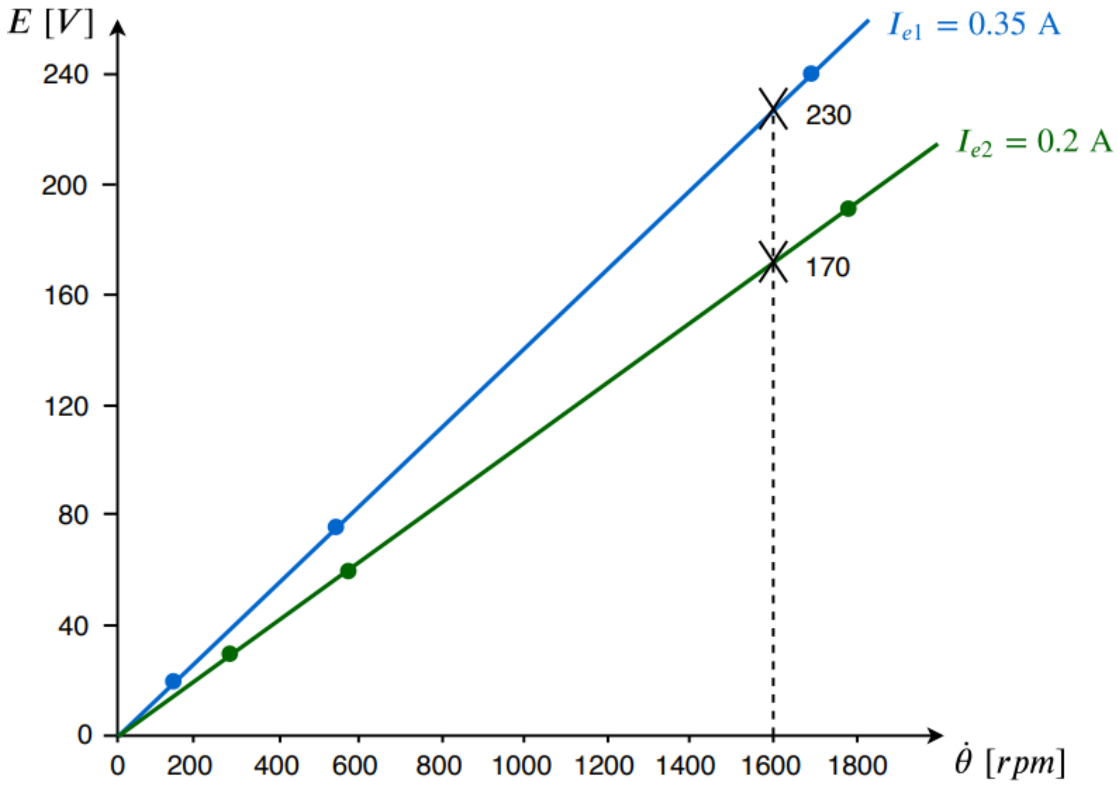
n [RPM]	E [V]
1800	186
1450	150
1150	120
850	90
560	60
260	30
0	0



$E = k\,\dot{\theta}\,\phi(I_e)$ ➔ Linear evolution with respect to $\dot{\theta}$.

Exercise 22: Brushed DC motor

2. Show that the flux Φ is not proportional to the excitation current intensity I_e.



The excitation current I_{e1} is $\frac{I_{e1}}{I_{e2}} = \frac{0,35}{0,2} = 1,75$ times the excitation current I_{e2}.

On the other hand, at $\dot{\theta} = 1600\ RPM$, the voltage E is increased by a factor $\frac{230}{170} = 1,35$.

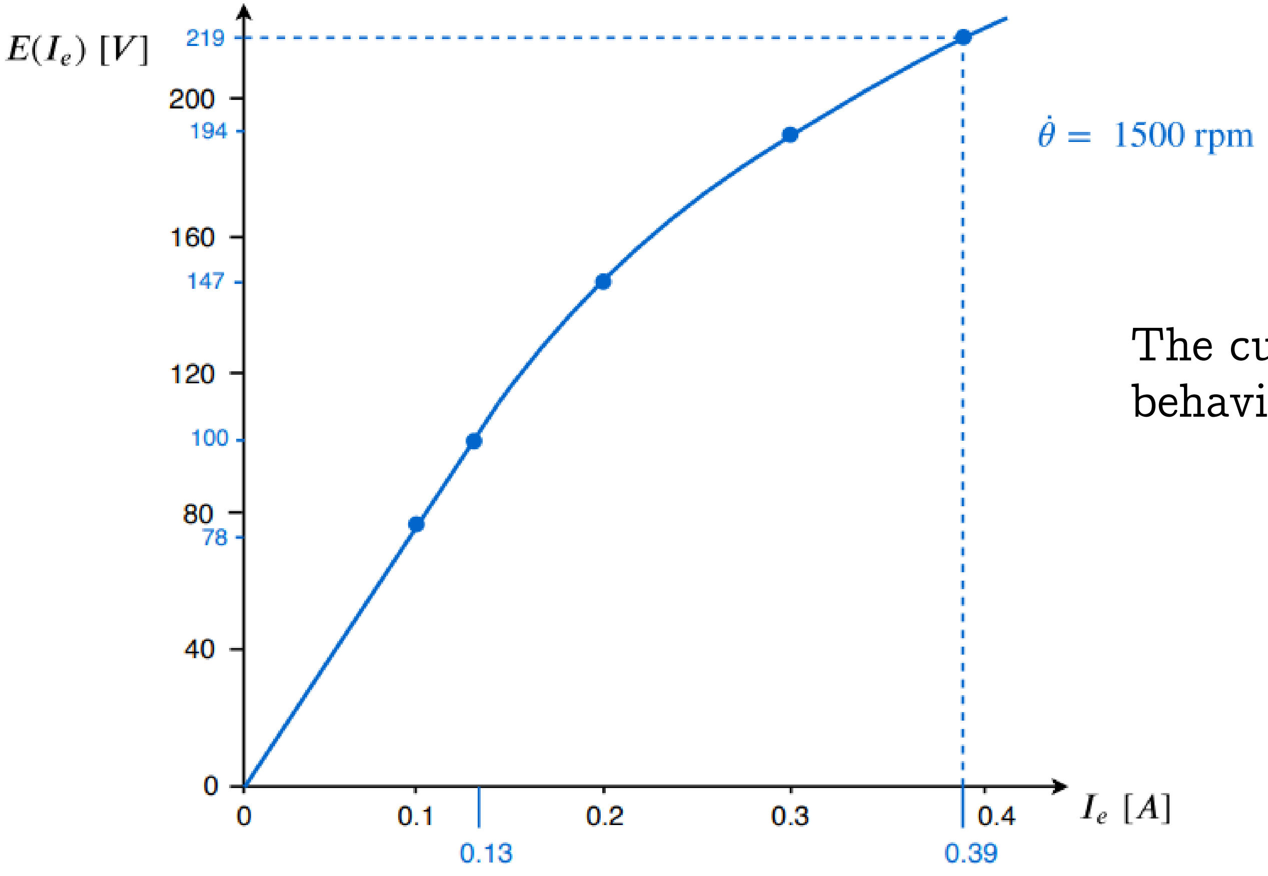
The relation linking I_e to E is $E = k\ \dot{\theta}\ \phi(I_e)$.

➔ The flux is not proportional to the excitation current. This is because of the saturation.

Exercise 22: Brushed DC motor

3. Maintaining the nominal speed of rotation, the electromotive force is measured for different excitation currents I_e. Plot E with respect to I_e and justify the shape of the curves.

I_e [A]	E [V]
0.39	219
0.35	210
0.33	204
0.31	198
0.3	194
0.28	188
0.26	179
0.24	168
0.22	158
0.2	147
0.18	137
0.17	130
0.14	107
0.13	100
0.11	87
0.1	78
0.08	65
0.07	56



The curve behaves as the $B(H)$ behaviour. There is saturation.

Exercise 22: Brushed DC motor

Some measurements have allowed to quantify the stator resistance value, which is $Re = 512.1\,\Omega$ and the rotor resistance value is $R = 4.6\,\Omega$.

4. Draw the equivalent model of the motor.

A test at constant nominal speed has been performed to measure the voltage across the rotor U and the current drawn in the rotor I for different excitation currents value I_e.

I_e [A]	U [V]	I [A]
0.4	222	0.43
0.35	213	0.44
0.3	198	0.45
0.25	176	0.48
0.2	151	0.56
0.15	120	0.66
0.1	85	0.92

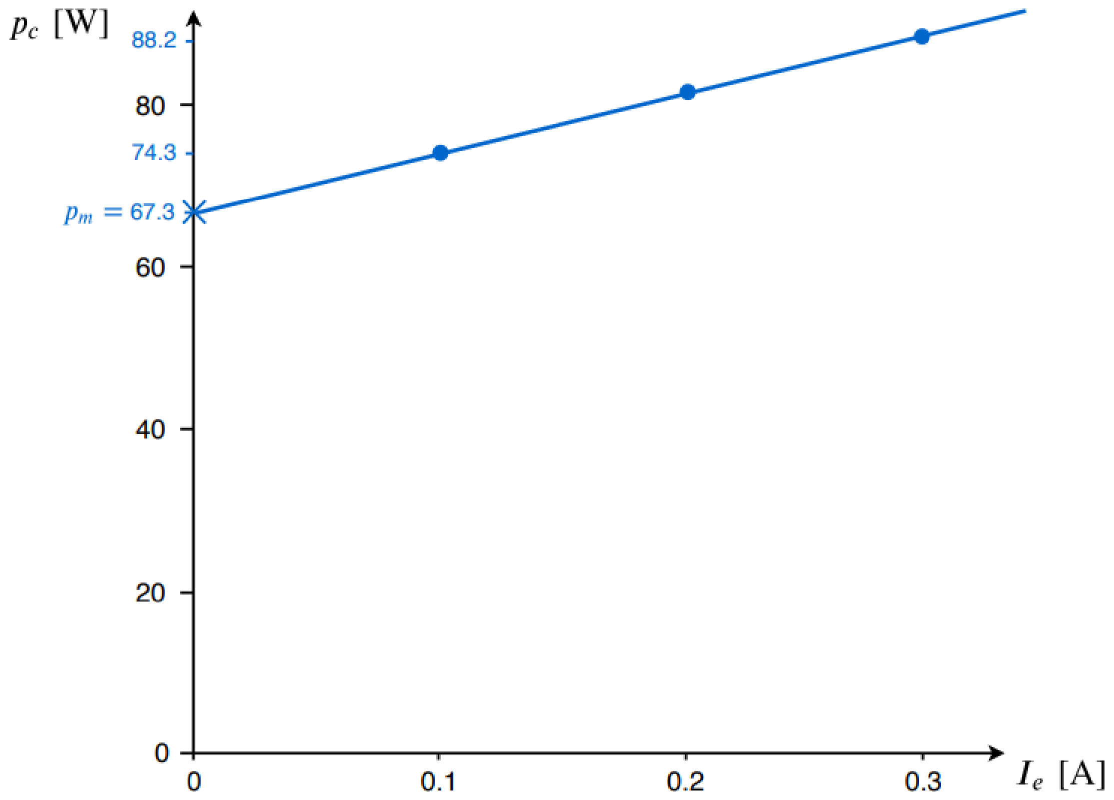
5. Plot the collective (i.e. ferromagnetic plus mechanical) losses p_c with respect to I_e

Exercise 22: Brushed DC motor

Developments on board

$$p_c = UI - R\,I^2$$

I_e [A]	U [V]	I [A]	p_c [W]
0.1	85	0.92	74.3
0.2	151	0.56	83.1
0.3	198	0.45	88.2



6. For the linear part of the curve, determine the mechanical losses p_m at the nominal speed of rotation.

Exercise 22: Brushed DC motor

A hole is drilled using the drill. The nominal speed of rotation remains constant while the rotor draws a current of $I_0 = 3A$ when a voltage $U_0 = 212\,V$ is measured on the rotor terminals.

7. Calculate the electromotive force and deduce the value of the excitation current I_{e0}.

8. Compute the shaft output power P_u.

9. Deduce the resistive torque C_r induced by the drilling process.

Exercise 23: Brushed DC motor with series excitation

Consider a brushed DC motor with its excitation in series. This motor is fed by a constant voltage source $U = 220$ V. In order to simplify the study, the resistances of the armature and the inductor as well as the collective losses will be neglected.

1. Show that the electromagnetic torque is proportionnal to the square of the consumed current.
2. Show that the electromagnetic torque is inversely proportionnal to the speed of rotation of the motor.
3. Deduce that there is a runaway of the motor at no load.
4. According to the second sub-question, one can write that :

$$\boxed{C_u = \frac{a}{\dot{\theta}^2}} \tag{335}$$

   where C_u corresponds to the useful torque of the motor in Nm, $\dot{\theta}$ is the speed of rotation in rpm and a is the constant to be determined. The nameplate of the machine indicates a nominal voltage of 220 V, a nominal speed of rotation of 1 200 rpm and a nominal current of 7.8 A. Deduce the value of the constant a.

In the following, we will take the value of $a = 20 \cdot 10^6 \quad [Nm \cdot rpm^2]$

5. Draw the mechanical characteristics of C_u.
6. The motor drives a hoist whose resistive torque is constant : $C_r = 10$ Nm. Deduce the rotation speed of the whole set.