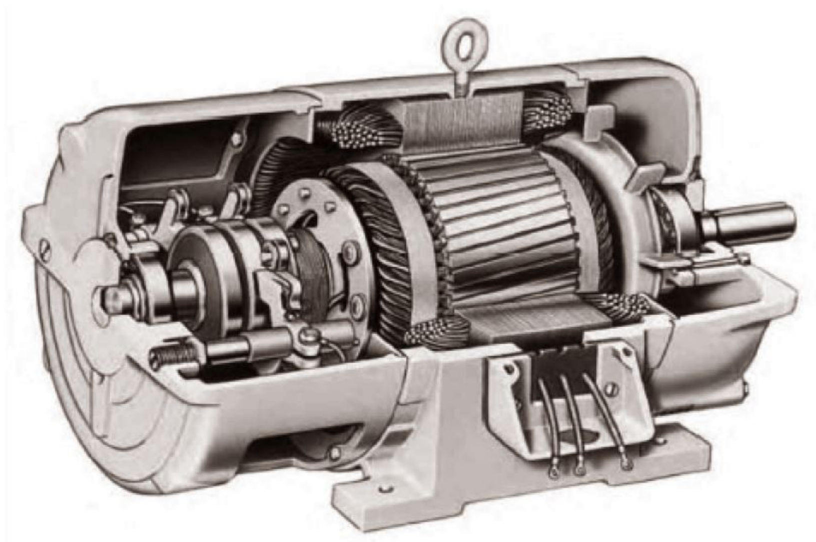
ELEC0431 - Electromagnetic energy conversion:

Laboratory manual (V2.0)



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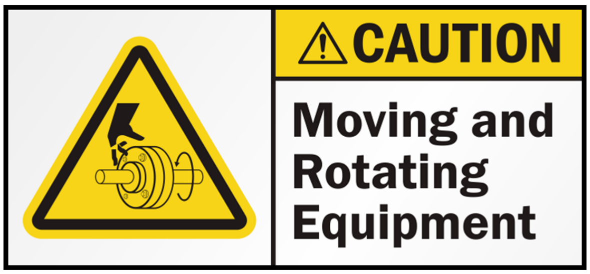
Electrical engineering
Academic year 2021/2022

Université de Liège - Faculté des Sciences Appliquées

WARNING

Switch-off before acting on the installation!



Keep your hands away from the rotating shafts and tie long hairs!

Contents

Chapter 1

Transformers

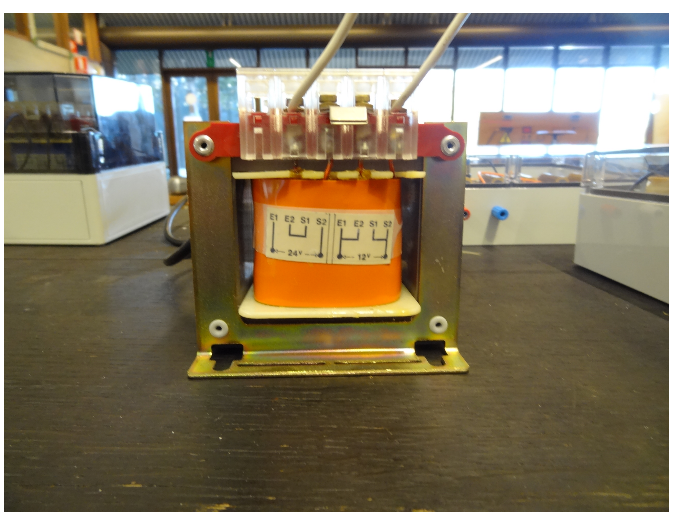
1.1 Single phase transformer

This laboratory involves high currents and voltages, think before acting!

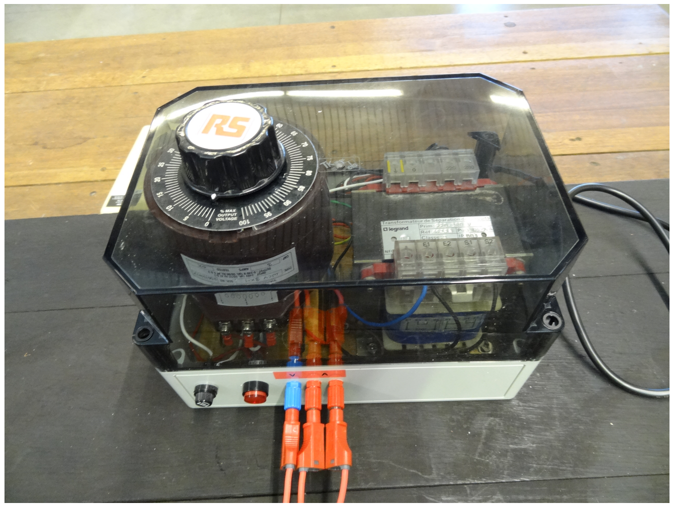
- **When switching off the transformer, always bring back the auto-transformer voltage to "0".**
- **For the short circuit measurements, keep the autotransformer voltage as low as possible. In this case, it should not exceed 10%.**
- **Never exceed rated current or voltage.**

1.1.1 Components

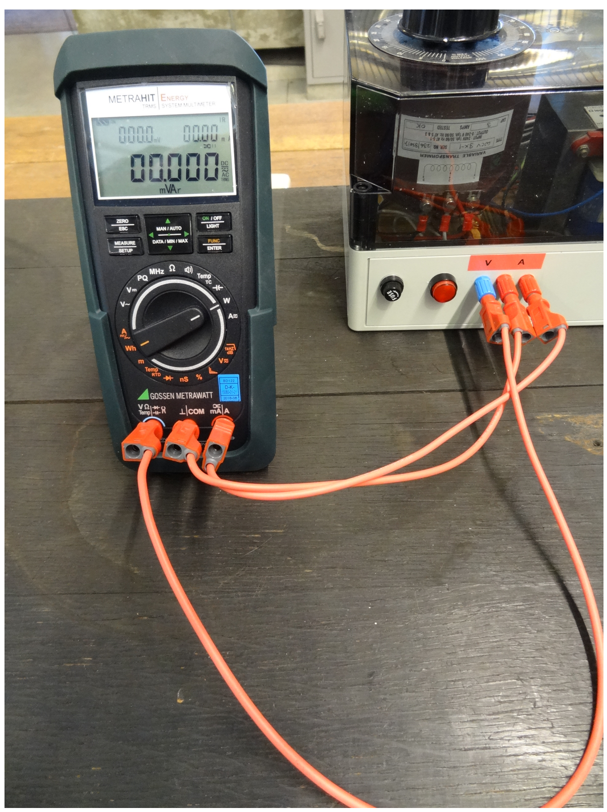
The following transformer will be studied:



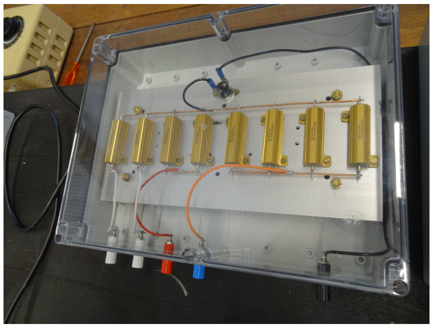
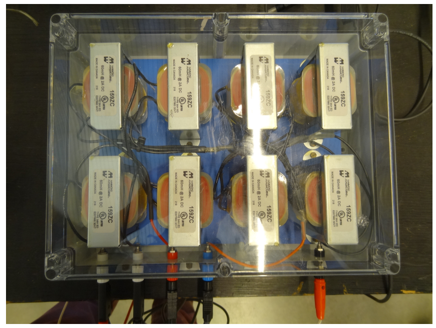
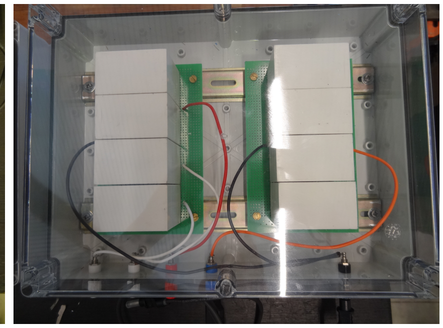
This transformer is powered with the combination of an auto-transformer and an isolation transformer. The auto-transformer allows varying the studied transformer input voltage while the isolation transformer is introduced for increased safety. On the next figure, the auto-transformer appears on the left and the isolation transformer on the right:



A wattmeter has to be connected to the transformer primary. This is equivalent to connect it to the isolation transformer output:



Three different loads will be used: Resistive, inductive and capacitive loads:

1.1.2 Start-up

1. Ensure that the autotransformer is set to "0" ⇒ The transformer input tension is "0".
2. Increase the voltage up to 230 V

1.1.3 Questions

Question 1

Locate all components that will be used in the lab and understand how they are connected. What are the current, voltage and power ratings of the transformer? **You should not exceed those ratings for the rest of the lab.** *Hint: You will find all the information written on the nameplate on top of the transformer.*

Question 2

Perform 2 measurements to deduce the impedances of the transformer's electric model. On which side of the transformer are the measurements performed? Do your approximations make sense? Explain the electric model, the two tests and the underlying approximations/assumptions to your supervisor before measuring. **Do not forget to start the short-circuit test with 0 % at the autotransformer and to remain under 10 %.**

Question 3

Measure the U-I output characteristic for the resistive load. What would be the theoretical curve? Are we close to it? Why don't we have the theoretical curve? Be prepared to explain it to your supervisor.

Question 4

Measure the U-I output characteristic for the inductive and capacitive loads. What would be the theoretical curve? Are we close to it? Why don't we have the theoretical curve? Be prepared to explain it to your supervisor.

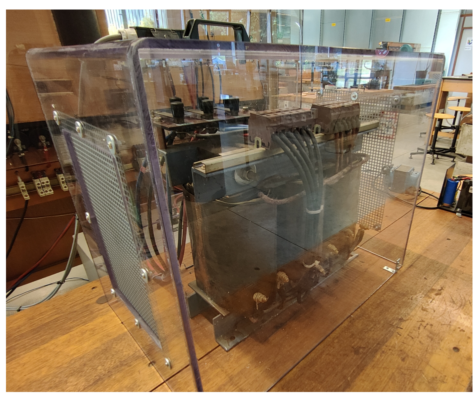
1.2 Three-phase transformer

This laboratory involves high currents and voltages, think before acting!

- **When switching off the transformer, always bring back the autotransformer voltage to "0".**
- **For the short circuit measurements, keep the autotransformer voltage as low as possible. In this case, it should not exceed 10%. Do not short the terminals by yourself, call the teaching assistant!**
- **Never exceed rated current or voltage.**

1.2.1 Components

A three-phase transformer will be studied. This transformer stands behind the lab table:



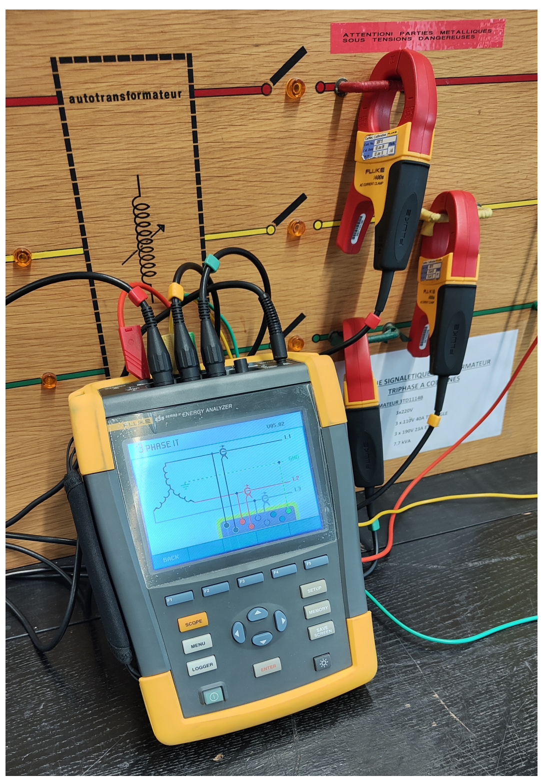
Just as for the one-phase transformer, the voltage is supplied through an autotransformer:

This autotransformer allows to deliver an output voltage whose value depends on the angular position of the black indicator on top. This output voltage is the input voltage of the primary winding of the studied transformer.

On the right side of the table, there is a resistive load that will be connected to the transformer's secondary winding. The value of this load can be easily changed by turning a button on it:

When on "0" the secondary winding is an open circuit. When on "1" it is 27Ω, "2" is $\frac{27}{2}\Omega$, "3" is $\frac{27}{3}\Omega$,... The secondary winding can not be shorted using this technique. A manual short-circuit on the back side of the table is thus required.

All the power measurement will be performed using a power quality analyzer (Fluke 434 or equivalent):

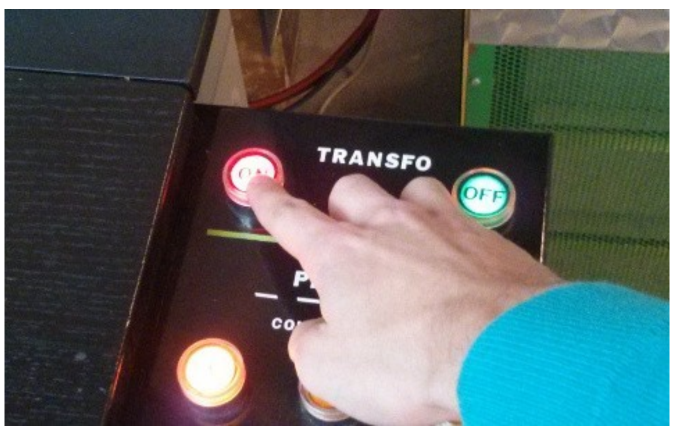


Do not forget to choose the phase coupling mode: "Y" or "Delta" configuration. Also, pay attention to the power flow direction when installing the clamps.

1.2.2 Start-up

First, turn on the table by pressing the red buttons next to the table right leg:

Then, switch on the transformer by pressing the "ON" button:



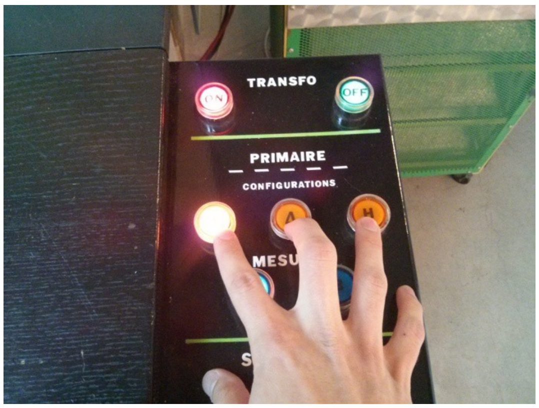
1.2.3 Questions

Question 1

Locate all components that will be used in the lab and understand how they are connected. What are the current, voltage and power ratings of the transformer? Why are there 2 U-I ratings but only 1 power rating? **You should not exceed those ratings for the rest of the lab.**
Hint: You will find all info written on the nameplate on top of the transformer. You may have difficulties to read this information. For ease, it is thus written again on the table panel. All ratings as well as the voltage measurements shown on the board are indicated for the line voltage.

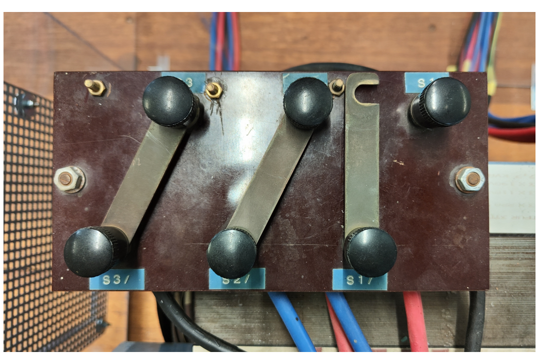
Question 2

What is the transformer ratio? How does it change when the primary or secondary winding is in a Y or Delta configuration? Use graphics to detail your explanations.
Hint: Switching configuration is easily done by pressing on the corresponding buttons ("H" is not used here) when the transformer is off. The picture shows the selection for the primary winding. All voltages shown on the board are line voltages.



Question 3

Perform 2 measurements to deduce the impedances of the transformer electric model. Do your approximations make sense? Explain the electric model, the two tests and the underlying approximations/assumptions to your supervisor before measuring.
Hint: When the output load is on "0", you have an open circuit. The short-circuit has to be done manually on the back side of the table, as shown on the picture. ***Ask the teaching assistant to short the transformer output for you.*** *When short-circuited the board will stop showing the measurements on the secondary side but you can still measure P and Q on the primary side.*



Do not forget to start the short-circuit test with 0 % at the autotransformer and do not forget to take into account the Y and delta voltage ratio to guarantee to keep I_{out} lower than the rating.

Question 4

Measure the U-I output characteristic for the connected resistive load. What would be the optimal curve? Are we close to it? Why don't we have the optimal curve? Link the voltage drop to the measured impedances in the electrical model. What would you get for a capacitive and inductive load? Why? Be prepared to explain it to your supervisor.

Hint: Put the autotransformer to 100 % and choose the right configuration (Y or Δ) for primary and secondary to maximize the output voltage. You do not have to perform the short circuit test, just interpolate graphically your results.

Question 5

What are two different ways to measure the efficiency of the transformer? Put the transformer in the question 4 configuration that you set to maximize the output voltage. Evaluate then the transformer efficiency by the output over input power ratio. Is it good?
Hint: Measure the efficiency at the nominal power and with the configuration (Y or Δ) that maximises the output voltage.
What does a high efficiency mean for the size of a transformer (or any electromagnetic energy conversion system)?

Chapter 2

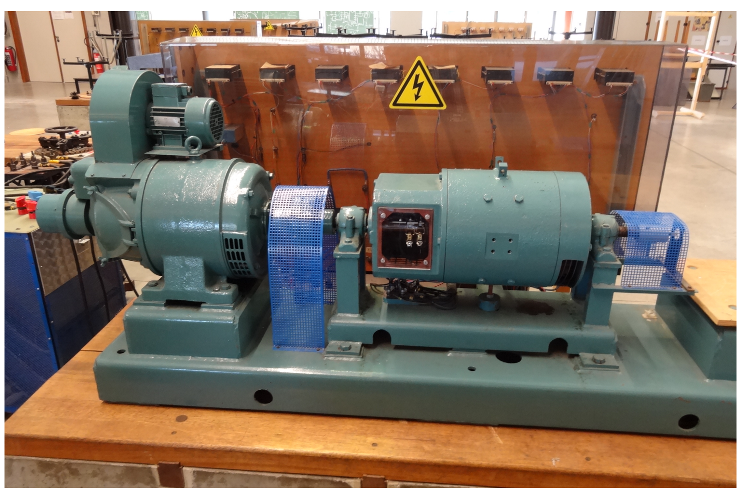
Synchronous machines

This laboratory involves high currents and voltages, think before acting!

- **Never exceed rated current or voltage.**

2.1 Components

Synchronous machine on the left, separately excited DC motor on the right.



A voltage, phase & frequency comparator (between grid and generator) is used to bring the generator output smoothly to the power network so that the generator can be connected to the network. V line has an arrow on the outer side of the circle which indicates the network voltage (divided by 2 via a transformer). It has also an inner arrow which shows the generator's output voltage. The two boxes below compare the phase difference as well as the network frequency with the generator frequency. To connect the generator to the network, the middle box should optimally have its arrow pointing to the top without moving : this means a frequency match, as well as a phase match. This in turn guarantees a smooth connection to the network without vibration or voltage spikes.

A load is connected to the synchronous generator's output, consisting of resistor in series with a variable inductor. The three loads for the three phases are balanced and connected in a delta configuration. For the resistor : when on "0" the resistance is infinity. When on "1" it is $36\,\Omega$, "2" is $\frac{36}{2}\,\Omega$, "3" is $\frac{36}{3}\,\Omega$,... To vary the inductance, turn the wheel from the bottom picture. Only one every two contacts is connected to the inductive load so that as you turn the wheel you will go through an open circuit connection before being again connected to an inductive load with a different value than before. To connect a "purely" inductive load to the generator's output, the resistors should be short-circuited, pay attention: **The current in the cables should stay below $10\,A$.**

2.2 Start-up

First, press the 2 “marche” buttons

Then, start the DC motor. It will start in 3 audible steps by progressively increasing the motor’s input voltage. Please set the excitation current I_e to the maximum before starting to limit the in-rush current.

Finally, press on “charge”, this will connect the load to the synchronous generator’s output, then press “on”. **DO NOT press “reseau” as the generator’s output is not close to the networks voltage and frequency yet.**

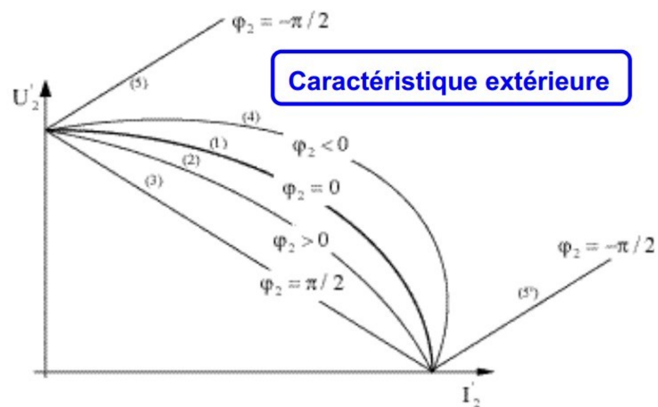
2.3 Questions

Question 1

Make sure you are aware of the current and voltage ratings so you know what you should not exceed.
Hint: You will find all information written on the nameplate of the machines.

Question 2

Measure the U-I output curve of the synchronous generator for a purely inductive charge as well as for a resistive charge. "U unloaded" should be chosen to $70\,V$ (measuring "I short-circuit" is not required). Do your measurements follow the theoretical curve, as displayed below? Explain to your supervisor why for a purely inductive charge U decreases faster than for a resistive charge and why the decrease is linear. What is the U-I curve for a resistive load with a perfect generator? Make a link to the U-I curves of the transformer.



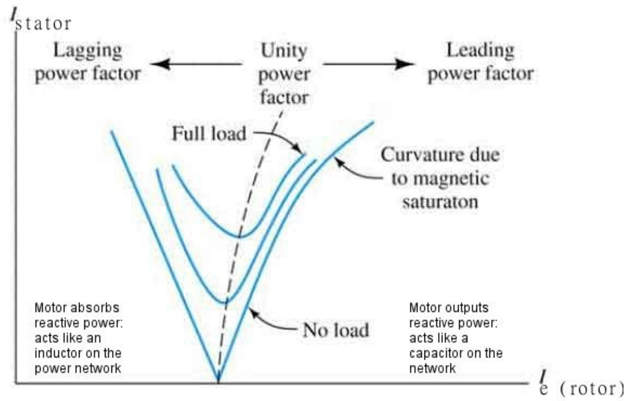
For a purely inductive charge, how many watts are transferred to the load? Explain in your case how reactive power transfer leads to power losses. *Hint: This test requires a constant rotor speed. You can adjust the rotor speed by changing the excitation current of the DC motor as explained in the DC machines lab.*

Question 3

Cite the 4 requirements needed to safely and smoothly connect the synchronous generator to the electrical grid. **To turn on the comparator, press the "reseau" button**. Once, the 4 required conditions are fulfilled, press the "on" button to connect the generator to the electrical grid (**ask your supervisor to check all parameters before connecting the generator to the network**). Now that the generator is connected, see what happens when you change the DC motor's and the generator's excitation current. Explain why. What would happen if the generator's output voltage was lower than the network voltage? Explain it. Increase the DC motor's "I_e" until the synchronous generator's output power gets negative. Why is it negative? How does the synchronous machine now act like? How about the DC motor? What would happen if the generator's output frequency was lower than the network frequency?

Question 4

Make sure you understand the meaning of the "V" curves. Explain to your supervisor what it represents, in which conditions it is to be measured, why it looks like a "V". Since all points in a same "V" curve have the same active power transfer under the same network voltage, why does the stator current still change? What consequence does this have on the efficiency? Deduce where the efficiency is maximized. Based on the "V" curves, explain how one could stabilize the network using an unloaded synchronous motor. Why do we want the synchronous motor to be unloaded?



V curves for a synchronous motor with variable excitation.

Measure the "V curve" at no-load. Do you get the theoretic curve ?
Hint: couple back the generator to the network if you powered off the machine in the meantime

Chapter 3

Asynchronous machines

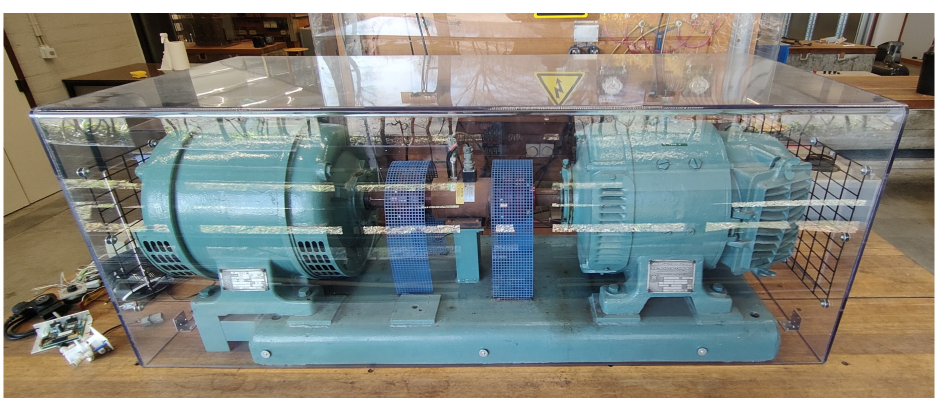
3.1 Old asynchronous machine

This laboratory involves high currents and voltages, think before acting!

- **Always maintain the current transformer short-circuited.**
- **Never unplug the ammeter from the current transformer when a current is flowing, this would cause electric arcs possibly damaging the current transformer or causing injuries.**
- **Never exceed rated current or voltage.**

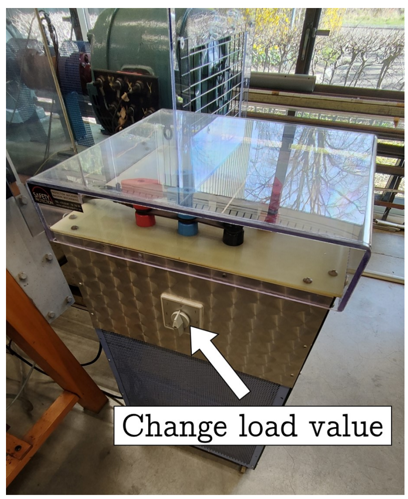
3.1.1 Components

On the right, a DC generator is used as a variable mechanical load and, on the left, the three-phase asynchronous motor that will be studied.



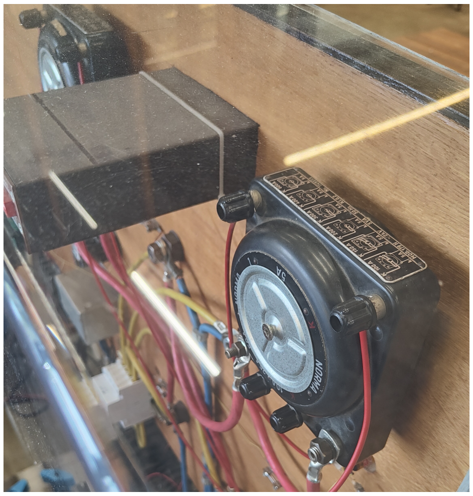
The voltage is supplied through an autotransformer:

This allows to deliver an output voltage whose value depends on the angular position of the black indicator on top. This output voltage is used to power up the asynchronous motor. The load is connected to the DC generator's output. It allows to electrically change the asynchronous motor's load torque:

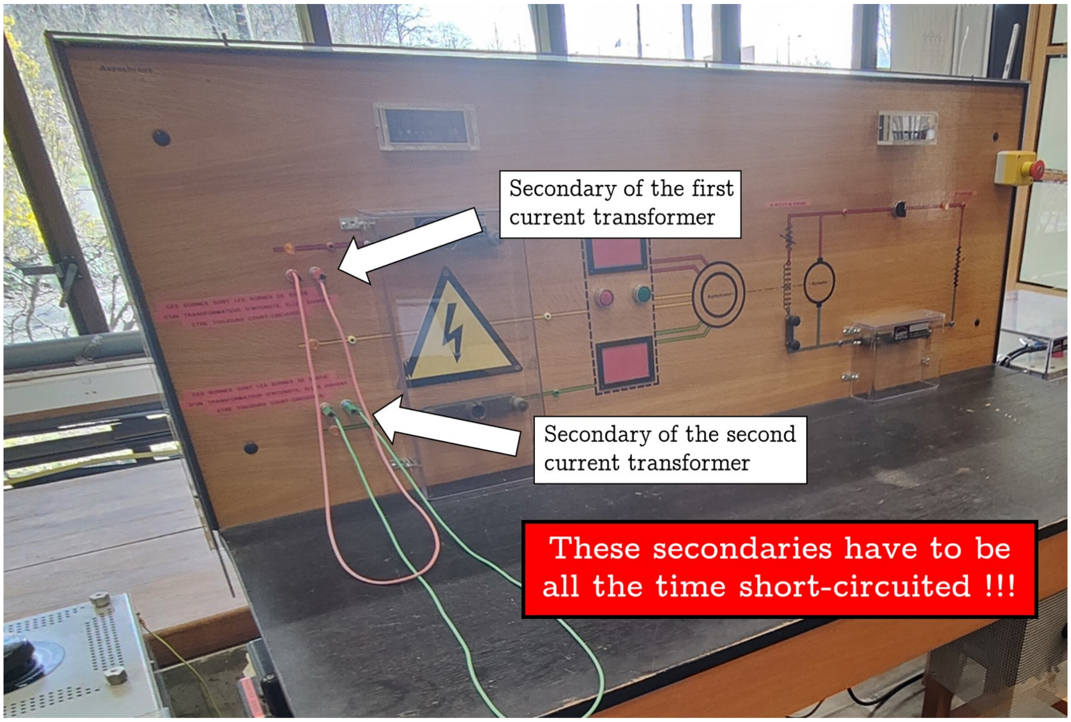


When on "0" the DC motor output is an open circuit. When on "1" it is $36\,\Omega$, "2" is $\frac{36}{2}\,\Omega$, "3" is $\frac{36}{3}\,\Omega$,... When the load decreases the DC generator generates more electric power and thus the torque applied on the asynchronous motor by the DC generator increases. Changing the excitation current of the DC generator's stator is another way to change the torque applied to the asynchronous motor (moving the wheel clockwise increases the excitation current):

Two current transformers are used to convert the currents to measure from the 50 A range to a 5 A range. They are visible at the back of the table:



It is particularly important to always maintain the secondaries of these current transformers constantly short-circuited. In case they are not in short-circuit, a really high voltage can rise at the secondary, create electric arcs and possibly lead to the destruction of the component. The secondaries appear at the front of the table:



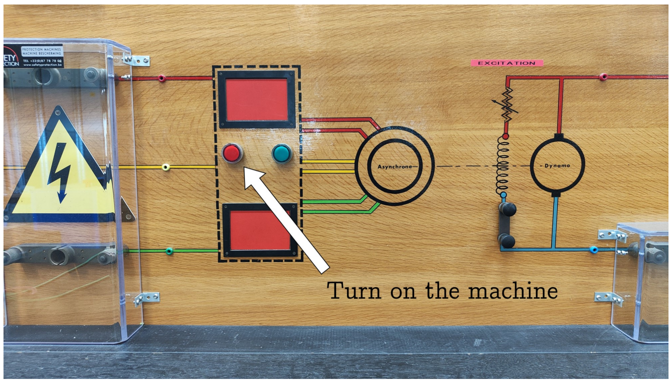
Three-phase power will be measured using the two wattmeter method. The current is measured through the current transformers. In such a situation, the short-circuits are mainted through the ammeters. Do not forget to take into account the transformer ratios during your calculations (currents are divided by 10 and so are the measured powers).

3.1.2 Start-up

Make double sure the current transformer secondaries are short-circuited. Check also that the two following switches are up:


Then, press the red buttons to turn on the table (press green ones to turn it off):

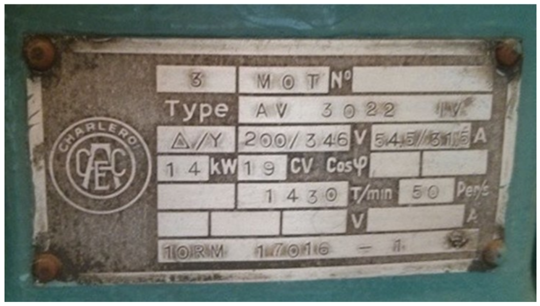
Finally, start the asynchronous motor:



3.1.3 Questions

Question 1

Why does the asynchronous motor have 2 current ratings but only one power rating?



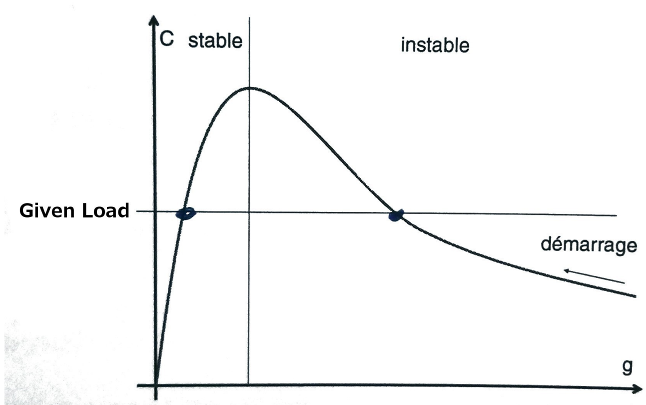
Proof that the considered motor is an asynchronous motor. What is the motor's synchronous speed ? What is the slip value at the rated speed? What about the torque? Why is the motor input connected in a "Y" configuration when starting?
Hint: You will find all information written on the nameplate of the asynchronous motor. The motor is a motor with 2 pole pairs.

Question 2

Explain the asynchronous motor's electric model and the link to the transformer model. Measure its impedances. Which two tests do you need to perform? Explain it to your supervisor. Why is the magnetic coupling worse than for the transformer?
Hint: Short circuit test on asynchronous machine is usually performed by blocking the rotor so to force it to be motionless. The slip value is then 1. Here, it is impossible to proceed this way due to plastic protection around the machine. The test is thus performed by slowly increasing the input voltage until the point the shaft starts rotating. Place yourself at the limit (a slight increased in the input voltage would make it rotate) and make your measurements.

Question 3

Measure the torque C with respect to the slip g to capture the stable zone of the theoretic graph from the picture. Based on the motor power factor, explain why the torque increases as the rotor starts to spin. What is the effect of putting a series resistor on the rotor at $g = 1$ and $g = 0$? Explain it to your supervisor.



Show that the asynchronous motor's efficiency increases when g gets closer to 0. In our case what is the best efficiency you can measure? What is the effect of increasing the autotransformer output voltage?
Hint: You can easily measure the efficiency of the asynchronous motor by dividing the mechanical power by the input electric power. To change g you just have to play around with the DC motor load, with its excitation current.

3.2 New asynchronous machine

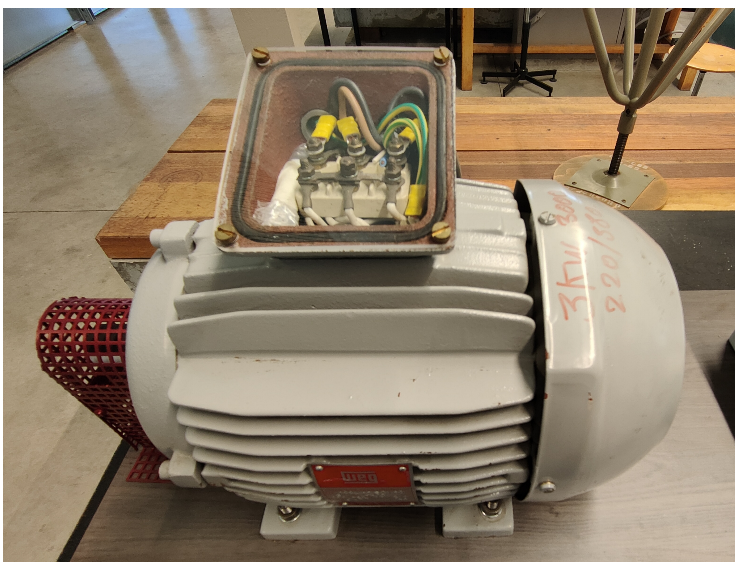
This laboratory involves high currents and voltages, think before acting!

- **Never exceed rated speed.**

3.2.1 Components

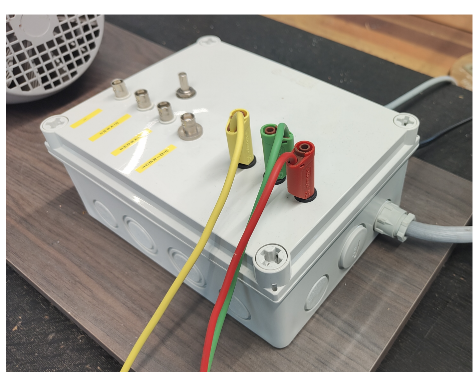
In this lab, the studied asynchronous machine is not directly connected to the three-phase power supply. Instead, it is powered by the `UMV 4301` speed controller. This controller takes the one-phase power supply as input and turns it into a three-phase power to supply the asynchronous machine. On the table, you can find:

The studied asynchronous machine:



The `UMV 4301` speed controller:

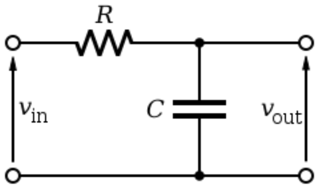
Do not modify the speed using the speed controller. The speed can be easily modified by turning the switch on a small electrical box placed next to the asynchronous machine:



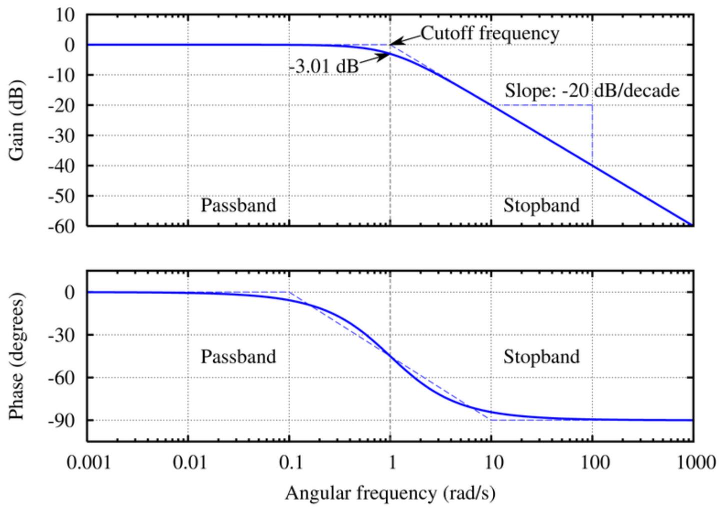
This electrical box also holds, among other things, three banana connectors. The yellow, green and red cables hold the three-phase voltages generated by the speed controller. **These three voltages are high, do not unplug them if the table is ON!**. There also are four coaxial connectors allowing to measure the following signals:

- I: The current flowing through one of the phases.
- U_{direct}: The phase voltage measured on the same phase as for the current.
- U_{48Hz}: The signal U_{direct} after a low pass filter of cutoff frequency $f_c = 48\,HZ$.
- U_{480Hz}: The signal U_{direct} after a low pass filter of cutoff frequency $f_c = 480\,HZ$.

The basic low pass filter is a RC circuit used to filter all frequencies higher than the specified cutoff frequency:



The cutoff frequency is then given by $f_c = \frac{1}{2\pi RC}$. Note that the low pass filter also introduces a phase shift. The following graph summarizes it:



To visualize the signals, the following oscilloscope is used:

3.2.2 Start-up

The table is turned on by pressing the red buttons above the table:

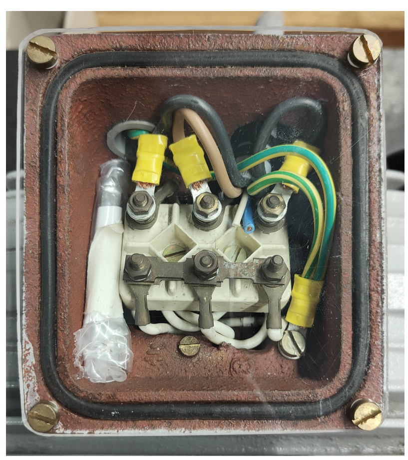
The machine will starts as soon as the buttons are pressed. To turn the table off, press the green buttons.

3.2.3 Questions

Question 1

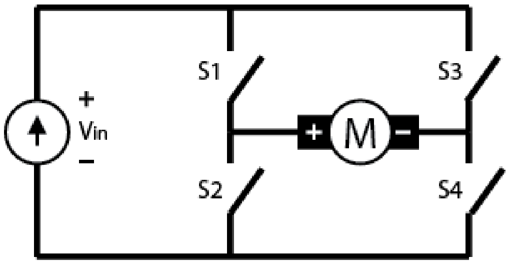
- Take note of the maximum ratings. Always make sure you do not exceed them. You will find this information on the nameplate of the machine.
- The nameplate provides two values for the maximum voltages and currents but only one for the power. Explain why and the the different values.
- The motor can be connected according to two different configurations. Can you tell what is the configuration that is used here ?

Hint: The machine configuration can be easily checked by looking at how cables are connected:



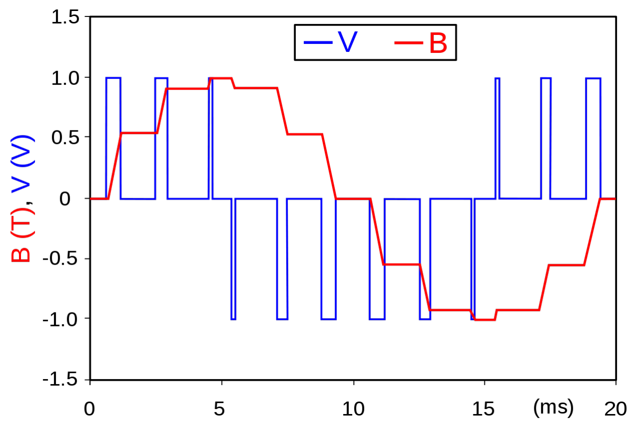
Question 2

The basic operating principle of the speed controller can be understood by considering H-bridges which are basic electrical circuits used to drive motors. The figure below introduces their functioning:



Switch configuration				voltage at M
S_1	S_2	S_3	S_4	
closed	open	open	closed	$V_M > 0$
open	close	close	open	$V_M < 0$
open	open	open	open	$V_M = 0$

Switches are controlled to drive a positive, negative or no voltage through the motor. It allows to create pulsed signals which are smoothed directly by the motor. For instance, The following graph is obtained by considering a perfect inductor. In this condition, the magnetic field is directly proportional to the integral of the voltage over time. By playing with the voltage sign and with the width of the pulses, the magnetic field evolution can take the shape of a sinusoidal curve. This technique is called "pulse width modulation" or PWM in the abbreviated form.



- Show on the oscilloscope the signals U_{direct} and I. Can you interpret the results ?
- Measure the switching frequency.

Hint: The oscilloscope has functionalities to help you measuring time intervals. In particular, the button "cursor" allows to place two cursors and to measure the time interval between them. The "run/stop" button can also be useful here since it allows to take a screen-shot of the screen. Finally, do not forget to play with the trigger to stabilize the signal.

Question 3

- Make the machine rotate at its nominal speed and measure the phase angle between U and I. To do this, can you use the signal U_{480Hz}? Can you also use the signal U_{48Hz}? Compare the two signals and explain what are the differences between the two. Where do these differences come from ?
- Compare the value of φ you measured with the one displayed on the machine nameplate. Are you close from it ?

Question 4

- Measure the peak-to-peak voltage you obtained on U_{48Hz} for a speed of 500 RPM, 1000 RPM, 2000 RPM and for the nominal speed. Does the tension evolves linearly with respect to the rotation speed ? If not, why is this ?

Hint: Measuring a peak to peak voltage is easily performed on the oscilloscope when pushing the "measure" button.

Question 5

- Measure the power density of the two asynchronous machine. What can you say from them ?

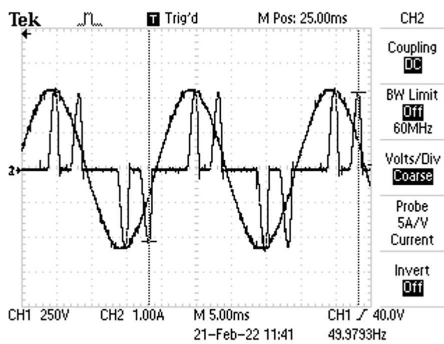
Hint: The power density of a machine is simply defined as its nominal active power over its volume.

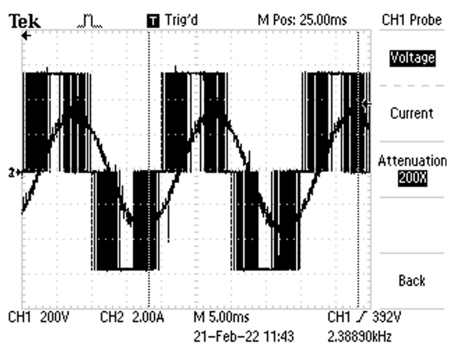
Question 6

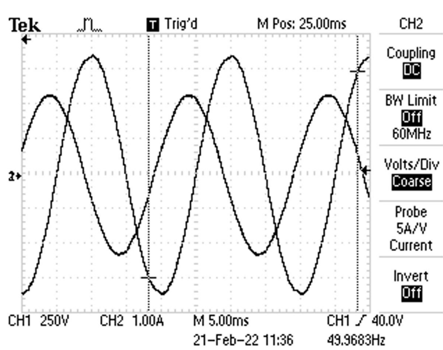
- How would you proceed to reverse the sense of rotation of the machine. Present your solution to the teaching assistant before experimenting it.

Question 7

Three graphs have been plotted from the oscilloscope. The first one shows the voltage and current at the input of the speed controller. The second one shows the voltage and current at its output. Finally, the last one plots the voltage and current at the input of the asynchronous machine in case it is powered directly by the three-phase power supply:







- For each of these graphs, which curve is the current, which one is the voltage ?
- In case the asynchronous machine was connected directly by the three-phase power lines, would it make more or less noise ? Would it be hotter, colder ? Would it vibrate more ?

Chapter 4

DC machines

This laboratory involves high currents and voltages, think before acting!

- **Never exceed rated current or voltage.**

4.1 Components

DC motor on the left, DC generator on the right.

The DC generator output is connected to a resistor:

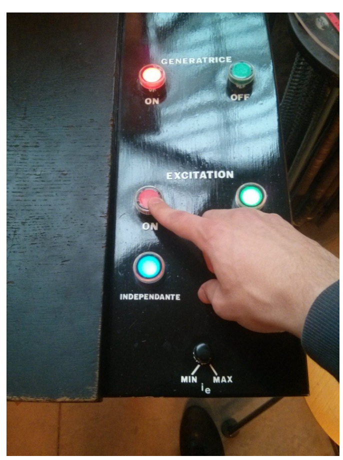
As shown on the above pictures, the resistor can be adjusted from a short-circuit to an open circuit when rotating the wheel.

4.2 Start-up

First, turn on the table by pressing the red buttons:

Second, turn on the motor by pressing the ON button:

Once the motor is started, start the generator by pressing the "generator ON" button and connect the excitation circuit by pressing the button on the picture.



4.3 Questions

Question 1

Make sure you are aware of the current and voltage ratings for both the DC motor and generator. You will find this information on the nameplate of the machines.

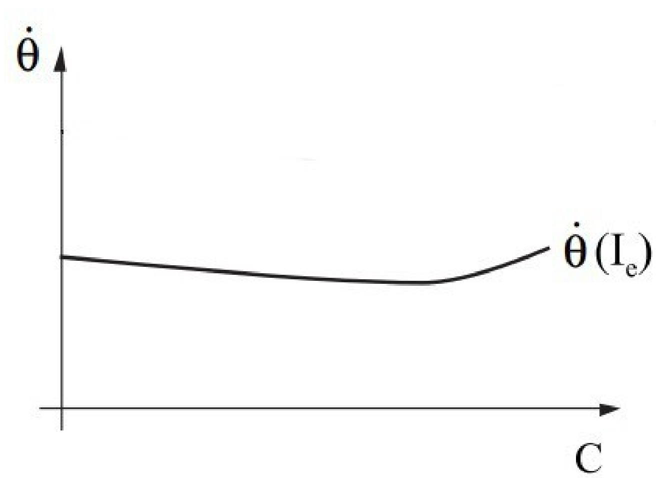
Why does the motor start in 3 audible steps? How is the motor started? In which fixed configuration is the motor wired (have a look at the board drawings)? What is the only difference in the construction of the DC generator in front of you and the DC motor? Why?
Hint: Think about the position of the brushes.

Question 2

What is the effect of decreasing the generator's load? How does it change the rotating speed? What is the effect of increasing and decreasing the shunt motor's excitation current? Why?
Hint: You can easily increase the excitation currents by rotating the little buttons called "Ie" clockwise.

Question 3

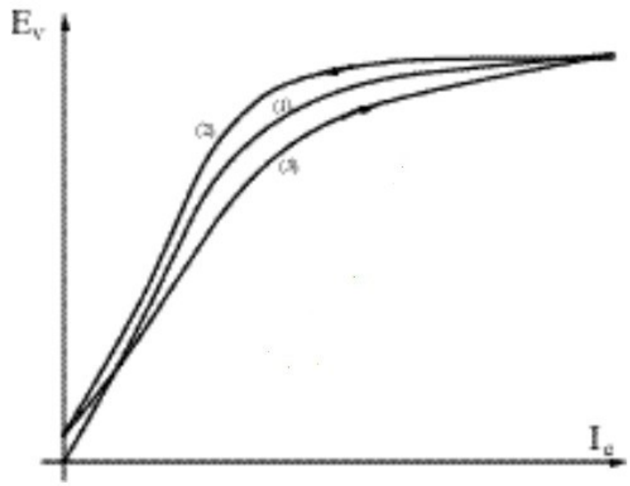
Measure the speed with respect to the torque delivered by DC shunt wound motor. Compare your results with the theoretical curve below and justify that behavior.



Hint: You do not have a torquemeter but there is however a simple way to increase the torque applied to the motor by using the generator. Do not forget to keep all currents and voltages below the values found in question 1.

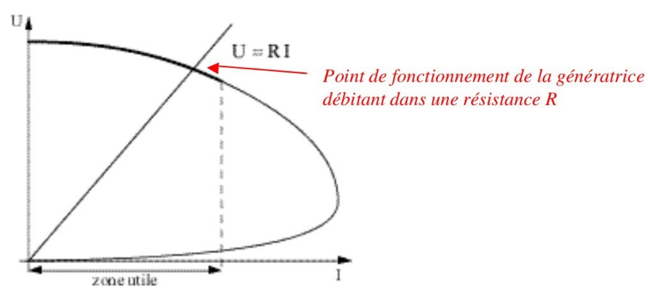
Question 4

Measure the unloaded E_v-I_e excitation graph for the separately excited DC generator. You should get something similar to the figure below. Increase I_e of the generator and then decrease it again. What do you observe? Why?



Question 5

Measure the U-I graph of the shunt wound DC generator at 1500 RPM. For this test to provide good results, set the generator's excitation current at a value that leads to $100\,V$ of RMS output voltage when unloaded at 1500 RPM. Explain the physical reasons for this curve to your supervisor.



Hint: This test is to be done at constant speed. Use the motor side to keep the rotating speed constant.