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KAR

INVESTIGATE OF SYNCHRONOUS MACHINE

Measurement practice III.

FOR VEHICLE ENGINEER STUDENTS

Version: 1.0

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1. Introduction

The aim of the laboratory exercise is to learn how to use the electric motor test bench and the operation of the synchronous machines (SM).

1.1 Objectives

- Structure of SM, working principle;
- Investigate of the motor nameplate;
- Investigate of electric motor test bench construction and control;
- Studying simpler control mechanism;
- Plot characteristics.

2. Literature review

2.1 Introduction

Synchronous machines (SM) are often used in the electric power generation sector and the permanent magnet version is used to drive many electric cars (Permanent Magnet Synchronous Motor – PMSM). SM are mostly designed with three phases winding. For the sake of completeness, the grouping of synchronous machines is shown in the first figure. Reluctance machines are not discussed in detail in this document.

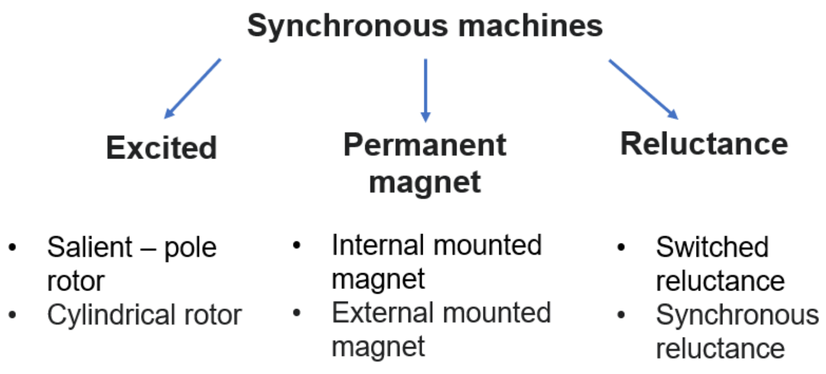

Fig.1. Grouping of synchronous machines (main types)

2.2 Structural design of synchronous machines

SM is structurally divided into two main parts: the stator and the rotor (the stator of an SM is structurally identical to the stator of an asynchronous machine (ASM), see later).

2.2.1 Stator

As can be seen in the first figure, several additional elements are part of the stator:

- Frame (motor housing);
- Bearing;

- Endshield;
- Fan and fan cover;
- Terminal box;
- Nameplate
- Eyebolt etc.;

The stator is made of sheet metal construction, not solid (cast) construction. This is to reduce eddy current losses in the iron core (like in a transformer). The iron plates are electrically isolated from each other (laminated). This is why they are called laminated iron cores.

Fig.2. Core lamination

The stator carries the winding (which in most cases is three-phase). The winding is formed during manufacture. The coil is covered with a thin layer of lacquer which acts as an insulator. To further increase insulation, insulating paper is used in the stator grooves. At the end of production, the coil is taped and varnished for better insulation and mechanical strength.

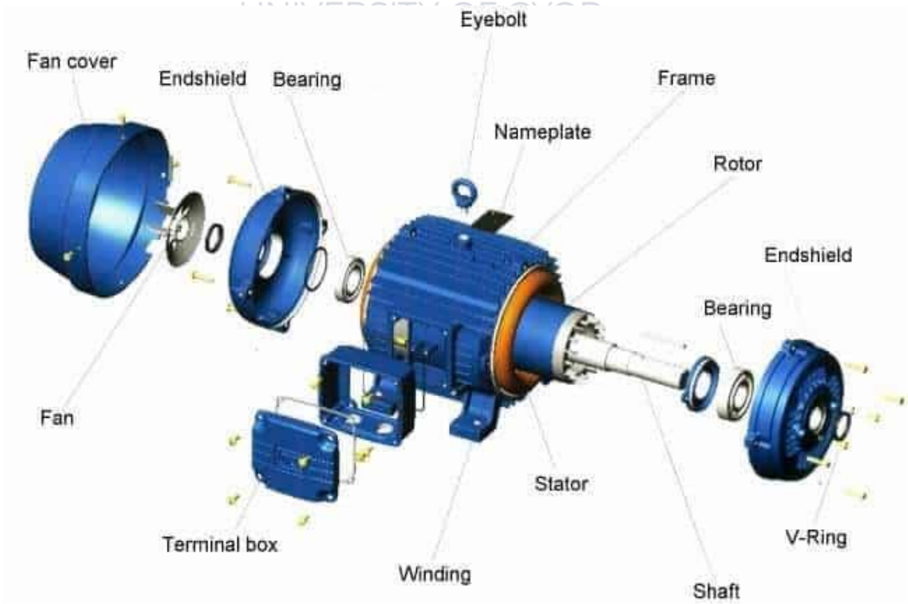

Fig.3. Structure electric rotating machine (SM and ASM machines)

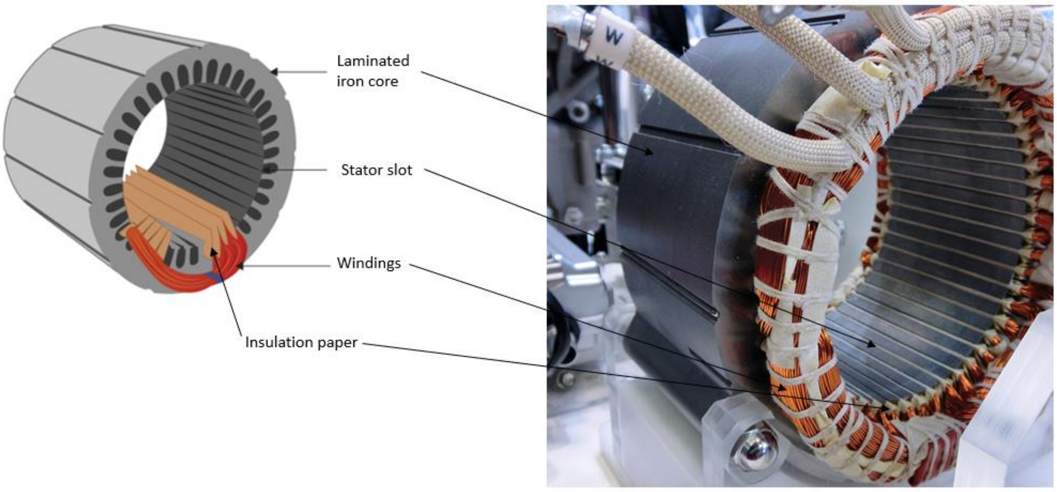

Fig.4. Structure of the stator (round copper wire)

Besides the "classic" (round) wire winding, the so-called hairpin winding is increasingly used (see Fig. 5.). Hairpin winding is a type of coil winding technique commonly used in electric motor and transformer manufacturing. Instead of using round wires, hairpin winding utilizes preformed copper or aluminum conductors that resemble hairpins (Fig 5, left). These conductors are inserted into the stator slots, creating a compact and efficient winding configuration. This technology is very new and is becoming widespread in the manufacture of electrical machinery.

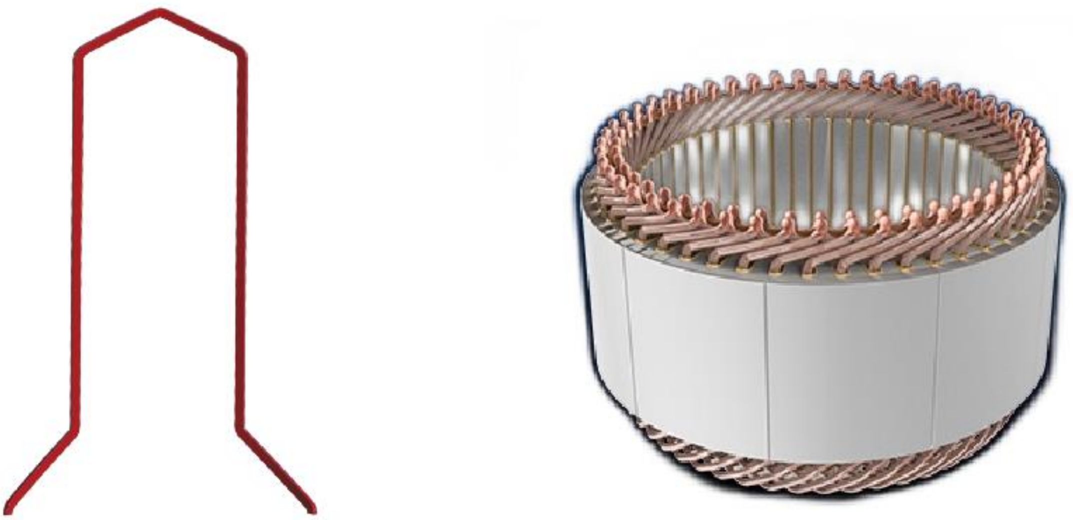

Fig.5. Copper wire in typical hairpin geometry and hairpin winding structure

2.2.2 Rotor

Two basic types of rotors are distinguished from excited machines: round (cylindrical) and the salient pole (Fig. 6.).

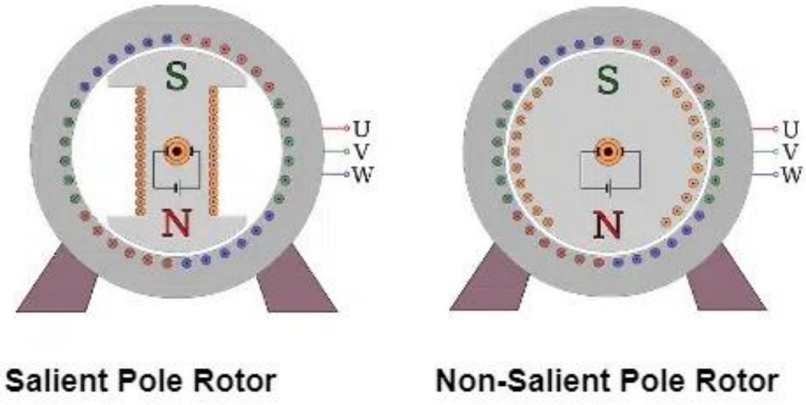

Fig. 6. Rotor design for synchronous machines

Properties:

- Single pole machines are generally round pole, and multi-pole machines are of the salient pole type.
- In the round rotor design, the excitation coils are placed in grooves, while in the case of the cantilevered rotor, they are placed on the cantilevered poles.
- Machines with salient poles are generally used for lower speeds, while round rotor machines are used for higher speeds;
- The number of poles of the excitation coil (rotor) is the same as the number of poles of the stator.
- In the case of a round rotor, the magnetic resistance (reluctance) is the same in all directions (since the air gap is constant around the circumference), whereas it is not in the case of a pole projecting.

The rotor is energized by (DC) direct current (like an electromagnet). The associated auxiliary energy is supplied to the motor rotor by carbon or bronze brushes and slip rings. Its design is shown in Fig. 7.

Due to the slip-ring design, this type of electric rotary machine requires some mechanical maintenance from time to time, due to the wear of the brushes.

Fig. 7. Slip-rings of synchronous machine

2.2 Working principle (3ph)

The stator's electrical function is to create a rotating magnetic field. It was mentioned earlier that in electric drive systems, 3-phase motors are used. The simplest implementation of this is that each phase is associated with a so-called pole pair (e.g. in Fig. 8. A1-A2 is a pole pair).

Let's look at how it works!

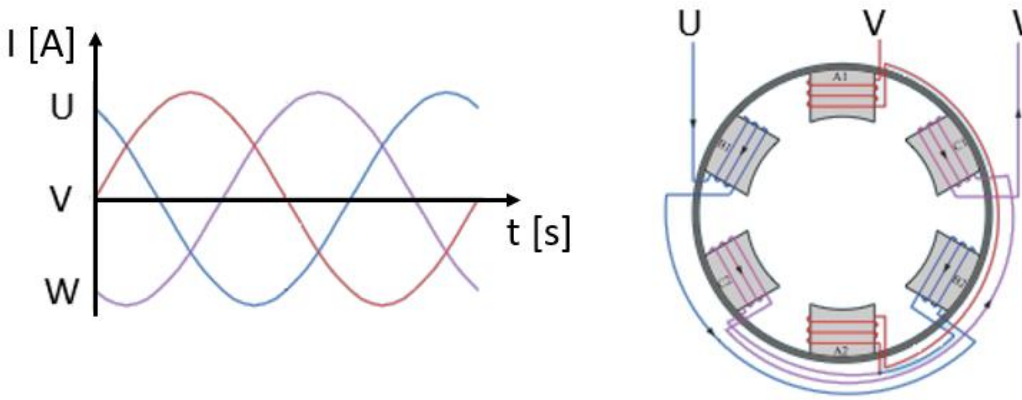

Fig. 8. Illustration of the rotating magnetic field and pole pair

A sinusoidal alternating voltage (AC power) is connected to the phases (e.g. a power line), i.e. U, V and W. These terminals are located in a terminal box on the side of a real machine. The three-phase signals are 120° offset from each other (electrical angle). The alternating currents in the coils result in an alternating magnetic field. In Fig. 3, a phase is associated with a pair of poles. In practice, a phase has several parallel branches so that a larger magnetic field can be created.

In case of excited type machines, the rotor coil is excited with DC current, so the armature (rotating part) will behave as an electromagnet. When the rotor is set in rotation, magnetic lines of force will intersect the stator conductors and induce a voltage in them. This is the generator mode.

If a rotating magnetic field is created in the stator by connecting the three-phase winding to the mains and placing the DC excited rotor in it (and accelerating it to synchronous speed), the field will cause the rotor to rotate at synchronous speed. This is the motor mode.

Why can't the synchronous motor start on its own?

When a three-phase AC voltage is applied to the stator of the motor, it creates a magnetic field rotating at synchronous speed. This can be understood as the stator field being a synchronous rotating magnet. If the DC excitation of the rotor is switched on, the magnetic field of the stator will attract and repel the still stationary rotor 50 times per second. The rotor of the machine cannot follow this rapid change due to its high inertia, so the synchronous motor can only rotate by bringing the rotor to synchronous or near synchronous speed before the stator is connected to the mains.

The synchronous speed (1/min) of the stator (n_s) depends on the excitation frequency (f_s) and the number of pole-pair (p):

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$$n_s = \frac{60 \cdot f_s}{p}. \quad (1)$$

A short example: our machine has 2 pole-pairs, and the motor is operated from the mains (50Hz). Calculate the synchronous (nominal) speed!

$$n_s = \frac{60 \cdot f_s}{p} = \frac{60 \cdot 50}{2} = 1500 rpm. \quad (2)$$

In modern driving systems, starting is done by means of a frequency converter, i.e. the frequency of the voltage applied to the motor is varied. After starting, the frequency is freely variable, so that the speed can be controlled as desired (see later laboratory exercise). In addition, the frequency converter allows the motor to run above rated speed (field weakening mode).

2.3 Permanent magnet synchronous machines

Permanent magnet synchronous motors are electrical machines that cannot function at all without electronics. Commutation is achieved electronically. Accordingly, the main difference compared to synchronous motors is that the motor does not contain a mechanical commutator, carbon or bronze brushes. The winding in the motor does not move, instead the permanent magnets rotate, and the armature remains stationary. To start the rotation, it needs to know the exact position. In the simplest case, this is determined by Hall sensors. See Fig. 9.

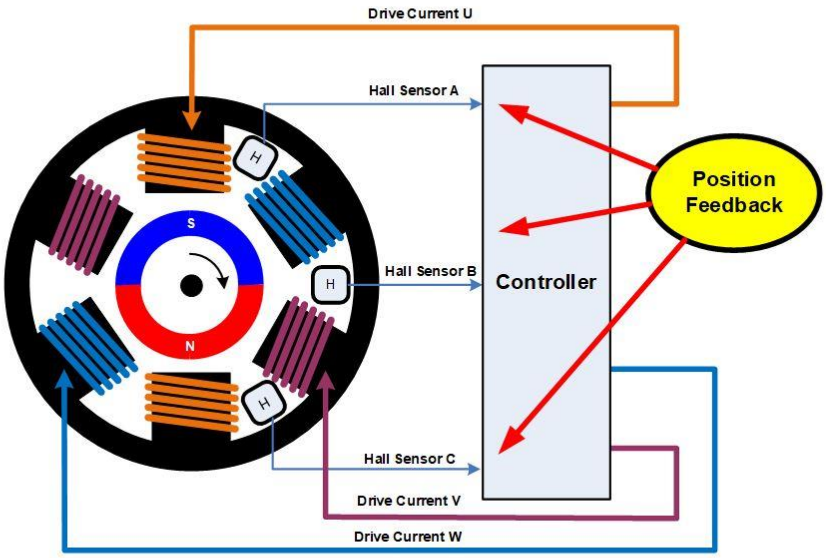

Fig. 9. Brushless motor with controller -example- [2]

Brushless motors are usually grouped according to the magnetic field (induced voltage or back electromotive force or back EMF) generated in the air gap. Two main types can be distinguished in this respect:

- If the air gap field has a sinusoidal shape similar to classic AC motors, then brushless AC - with the English abbreviation BLAC, or Brushless AC motor - is the usual name. The more common name in the literature is PMSM.
- If the air-gap field is trapezoidal, as in classical DC motors, then the common name is brushless DC, abbreviated BLDC (Brushless DC motor);

The back EMF (electromotive force) characteristics for both motors are shown in Fig. 10.

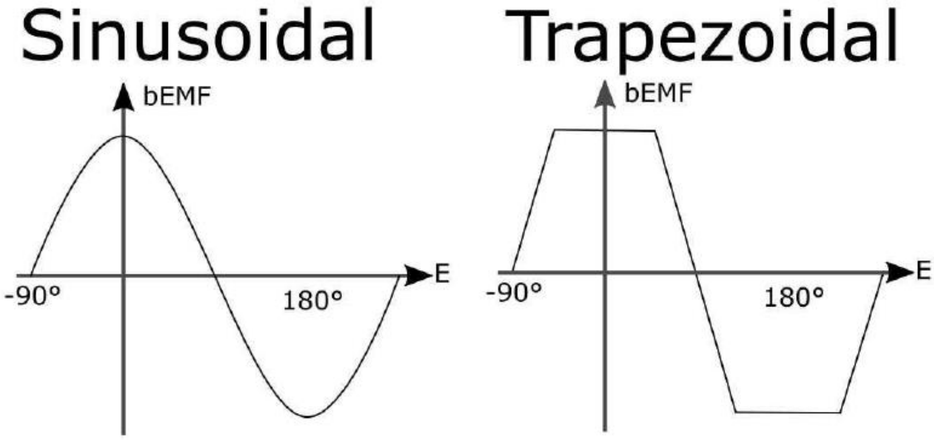

Fig. 10. Diagram of sinusoidal and trapezoidal Back EMF signals

But what is the back EMF?
The back emf is represented as a variable emf that opposes the one driving the motor. Back emf is zero when the motor is not turning, and it increases proportionally to the motor's angular velocity. Back emf is the generator output of a motor, and so it is proportional to the motor's angular velocity ω.

2.3.1 Structural design of synchronous machines

Permanent magnet synchronous motors are constructed from an electromagnetically excited stator and a permanent magnet rotor. Some literature also includes control of electronics, without which the motor is inoperable.
In terms of rotor positioning, the classic design where the rotor is positioned in the wound stator. There is also the external rotor design. This design is often used in e-scooters and electric vehicles (see. Fig. 11.).

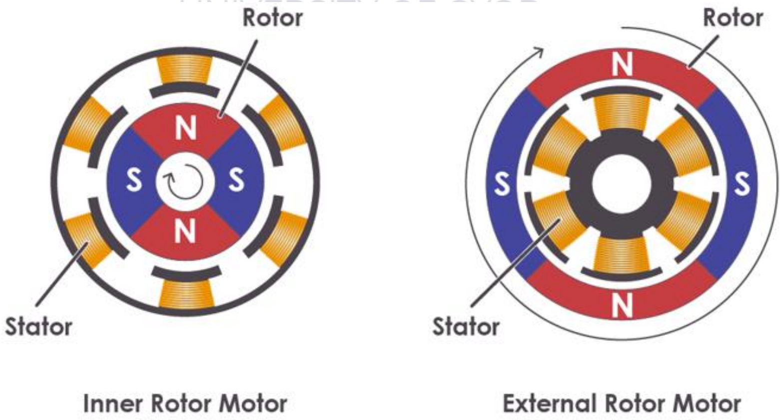

Fig. 11. Inner and external rotor motor construction

Based on the positioning of the magnets in internal rotor motors, a basic distinction is made between surface-mounted and internal magnet versions (see Fig. 12).

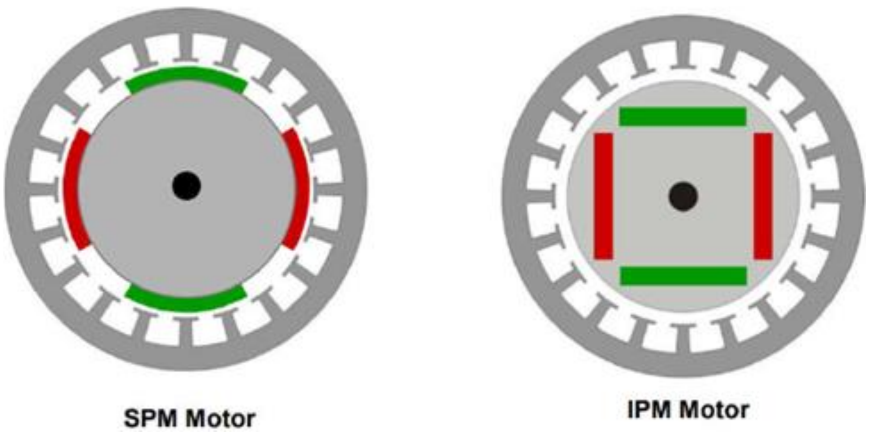

Fig. 12. Scheme of the magnet on the surface and in the rotor

The different versions influence the characteristics of the engine, but it can be stated that the type of surface PM is basically operated at a lower speed.

The BLDC motor has a simple design, with concentric windings, i.e. the windings are arranged in a circle around the teeth and form a pole pair with the windings at 180 electrical degrees. In all cases, the magnets are concentrically wound on the surface of the rotor. In the case of simple bonded rectangular magnets, the internal induced voltage of the motor is back EMF trapezoidal shape, which is well suited for simple six-step control.

The most characteristic feature of the PMSM motor, resulting from its design, is the different internal induced voltage shape. The so-called sinusoidal field design results from a more complex implementation of armature winding. Different designs of the stator are shown in Fig. 13.

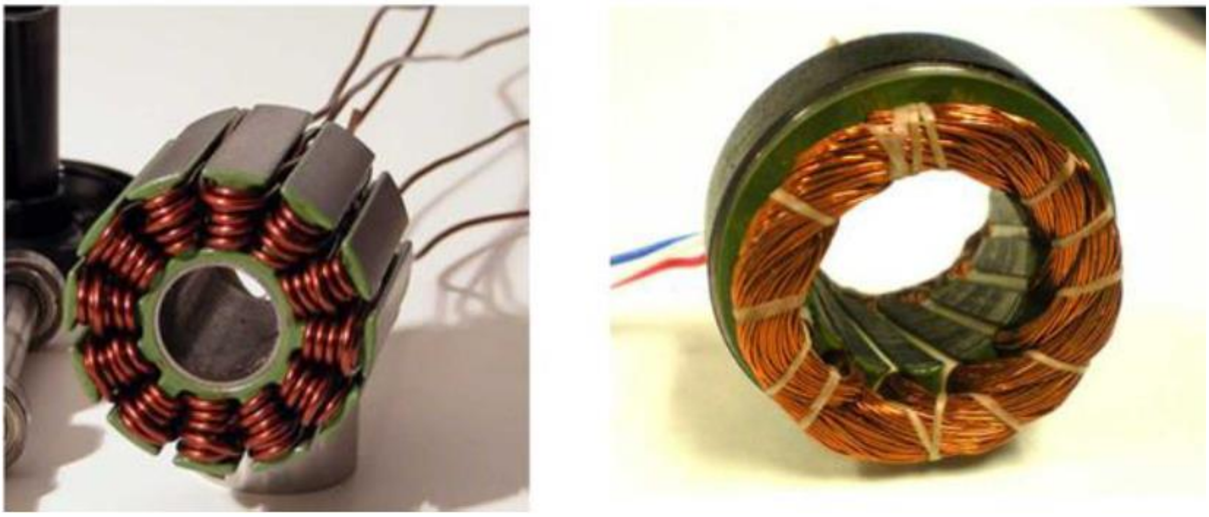

Fig. 13. Stator with concentrated and distributed winding, external and internal rotor design

3. Experiments

3.1 Test bench start-up

1. Turn the main switch to energise the inverters of the machines.
2. Select the language (English / Hungarian) via the HMI and click on the next button to get the control panel for the machines.
3. Turning a key safety switch without the permission of the instructor or the person supervising the measurement is forbidden!
4. It is IMPORTANT to reset the torque meter and clear any error codes before measuring!
5. Switch on the DC system rail, the test (BENCH - asynchronous servo motor - black machine) and the tested (UUT - SM with cylindrical rotor - blue machine) machine according to the operating instructions. It is important that both machines are started before starting the measurement!

Note: Take into account the HMI response time before saving the measured data! The software manual will help you to analyze the data structure.

3.2 First measurement: investigate the operation of the synchronous machine!

Steps of the measurement:

1. Determine the number of the motor pole pair (the necessary correlation is given in this syllabus).
2. Select any 7 measuring points over the full speed range (100 – n_0 RPM reference!
3. Set the motor excitation current to 1A!
4. Measure the frequency of the inverter at the selected speeds!

Type of motor:
Excitation current:
Pole pair of motor (calculated):

Speed (set) [rpm]	**Frequency (calculated) [Hz]**	**Frequency (measured) [Hz]**

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3.3 Second measurement: Plot the speed-voltage-frequency curve of the synchronous machine

Make the same measurements as the first measurement, but also record the voltage to be measured on the synchronous machine.

Steps of the measurement:

1. Select any of the 7 measurement points in the full speed range (100 - n0 speed reference)!
2. Set the excitation current of the motor to 1A!
3. Measure and write down the inverter frequency and voltage at the selected speeds!

Speed (set) [rpm]	Frequency (measured) [Hz]	Voltage [V]

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5. Conclusions

What is the relationship between speed-frequency-voltage?
How does the speed of the motor depend on the number of poles?

6. Homework

Create a report using the template provided, with the required content and criteria.

7. References

[1] L. Tokos, *Permanens mágneses DC és AC motorok és korszerű szabályozásuk* (In Hungarian), Thesis, 2021.

[2] https://www.monolithicpower.com/en/learning/resources/brushless-vs-brushed-dc-motors