ELEC0431

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ULiège - Institut Montefiore - ACE

July 17, 2023

Examination

Instructions

- June session : Wednesday June 14, 13:30, B37, auditoires 01-02
- August session : Friday August 18, 14:00, B31 (Fac. Droit) auditoire Domat
- You are allowed to have a hand-written formula sheet (your handwriting, no text, diagrams are ok) of 2 pages maximum (one recto, one verso)
- Also bring with you: pen, colour pencil (except red), plastic square (équerre), protractor (rapporteur), calculator
- Duration 150 minutes
- The lab interrogations count for 15% of the final mark

What should I study ?

- Lecture slides (6 chapters) and the corresponding additional notes, all available on the course webpage :
  https://people.montefiore.uliege.be/geuzaine/ELEC0431/
- Overview of Electrical Machines (slides presented Friday 03/03)
- All exercises solved during the exercise sessions
- No need to practice with exercises of past years
- There will be **no** questions specifically on the lab manuals, nor on the technical aspects of the lab experiments.

What is important to know ?

- Chapter 1: The concepts of e.m.f. and m.m.f., and magnetic circuits
- Chapter 2: Detailed derivation of the equivalent circuit of the transformer, exterior characteristic
- Overview of electrical machines: analogy DC machine-magnetic dipole, rotating field
- Chapter 3: Potier and Behn-Eschenburg, torque and stability, Mordey
- Chapter 4: Power diagram, mechanical characteristic and stability, speed control, circle diagram
- Chapter 5: Analogy with a magnetic dipole, armature reaction, Picou construction, auto-excitation of the shunt generator, series motor
- Chapter 6: How one can control voltage amplitude without using resistances, duty cycle, buck and boost converters

What skills should I have ?

- Be able to derive the equivalent circuits and phasor diagrams from first principles (Maxwell's equations, Lorentz and laplace forces, . . .)
- Be able to identify the lumped elements of the equivalent circuits by means of no-load and/or short-circuit experiments (which simplifications of the circuit are assumed, when do I use the current, when do I use the voltage, caring for the factors 3 and $\sqrt{3}$ in the three-phase case, . . .)
- Be informed about the technical importantce of non-idealities like losses, saturation, leakage, . . .
- Be able to orient the currents in a machine (excitation, armature) knowing the field orientation and the direction of the rotation (auto-evaluation of Lecture 9)
- Master phasor algebra and **systematically** identify phasor quantities with an upper bar
- Be accurate in the explanations. Never write "the current", but write e.g., "the excitation current of the generator", never write "in series" but write "in series with the armature of the motor", etc. . .
- . . .

Organisational info of the course

Labs

- 4 labs by groups of 4 students
- "Les séances de laboratoire sont obligatoires. En cas d'absence non justifiée, une note d'absence sera donnée pour le cours dans son ensemble."
- **Schedule** and **instruction manuals** (one for each lab) available on https://people.montefiore.uliege.be/geuzaine/ELEC0431
- Bring with you: the theoretical course, paper, pen, (colour) pencil, plastic square (équerre), protractor (rapporteur), calculator
- General instructions during each lab session:
  - Prepare the laboratory beforehand by reading the corresponding instruction manual
  - At the beginning of the session, rewrite lisibly the **nameplate info** of the studied machines on a sheet of paper. Draw also on that sheet the **equivalent circuits** of the studied machines and a **typical phasor diagram** (the equations of the machine in case of the DC machines) with the names of all the important quantities. This sheet remains visible on the labo table during the whole session.
  - Locate the various components of the experimental set-up. Check and understand how they are linked together.
  - Before each manipulation, sketch on a sheet of paper the relevant **equivalent circuit** and **phasor diagrams**. Check them with an assistant before connecting apparatus and measuring
  - Be accurate with **bars on phasor quantities** and **primed quantities**, (R_2', $\bar{I}_2'$, ...)
  - Call an assistant if any question.
- There will be a short **individual interrogation** at the end of each session (counting in total for 15% of the final note). The idea of these interrogations is to check that each student has been active and participative during the lab. The evaluation focuses exclusively on the concepts seen during the lab (measurements done, phasor diagrams used, ...)

Lectures

- Prof Geuzaine's slides + overview "EM machines" before starting labos sessions
- Reference material for all the theoretical part
- They are complete but maybe somewhat demanding
- Presented slowly, questions welcome at any time

- Hint: Insert pages with extra informations/explanations given during the lectures
- Expand mathematical developments and explain them with your own words
- Onelab models to illustrate important and useful concepts
- Further reading (Wildi), videos... not needed

Exercises

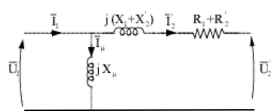
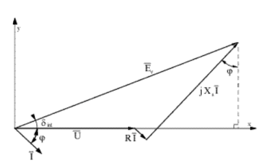
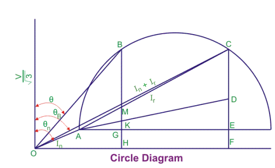
- Exercise_Manual.pdf on-line
- Complete reference material for all the exercise part
- Theory sections in Chapters 1-3 in the manual have been revised

Websites

- https://www.programmes.uliege.be/cocoon/20222023/cours/ELEC0431-2.html
- https://people.montefiore.uliege.be/geuzaine/ELEC0431
- https://gmsh.info
- https://getdp.info
- https://onelab.info

Lecture 1 (10/2/2023)

- Context : EM conversion is important in an engineer formation, Data, Electrical power production, (electric) cars...
- Goal : we go in this course all the way from Maxwell's eqts to the mental pictures electrical engineers use to understand the physical behaviour of the main types of electrical machines

- "1_Introduction.pdf" slides 1-14
- Simulation life "transfo.pro": field lines, flux, field uniformity, leakage flux
- Slides 14-15

Stokes theorem

$$\int_V \operatorname{div} \mathbf{F} \, \mathrm{d}V = \oint_{\partial V} \mathbf{F} \cdot \mathbf{n} \, \mathrm{d}S$$
$$\int_S \operatorname{curl} \mathbf{F} \cdot \mathbf{n} \, \mathrm{d}S = \oint_{\partial S} \mathbf{F} \cdot \mathbf{dL}$$

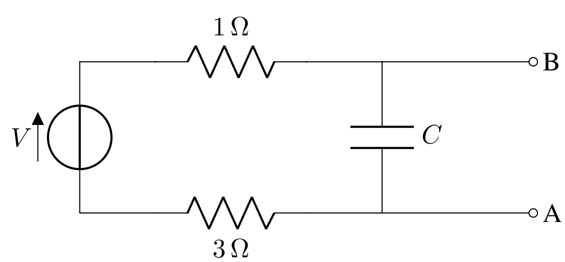
where V is a volume, S a smooth surface and ∂ the boundary operator.

Homework:

- Read theory on magnetic circuits (“Exercise_Manual.pdf”, Chapter 3, p 22-23)
- Install onelab (from https://onelab.info) and run the “transfo.pro” model
- Complete Exercise 3

Auto-evaluation

What is the current delivered by the DC voltage source $V = 5\mathrm{V}$? What is the voltage at the AB terminals ? What if the DC source is replaced by a 50 Hertz AC source ?

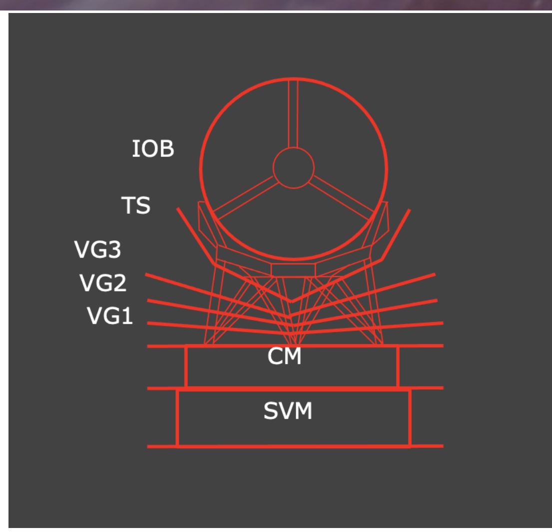


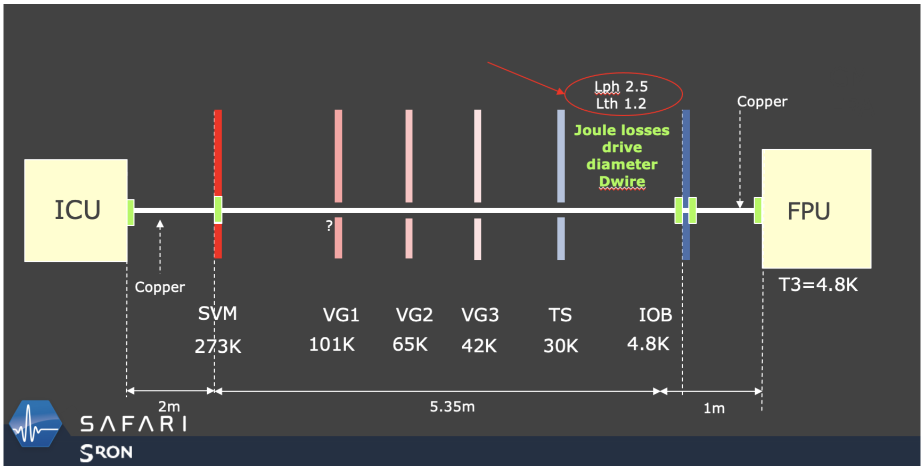
If you cannot solve this swiftly, you should refresh your background in electric circuit theory.

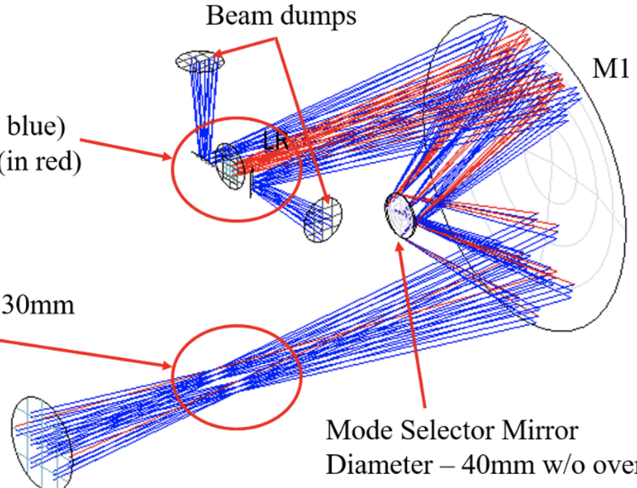
Lecture 2 (17/2/2023)

- Magnetic circuit theory : “Exercise_Manual.pdf” p 22-23
- Application: MSM CSL-ESA-SAFARI project Bi-stable actuator for the mirror of a spectrometer functioning at 5K, called Mode Selector Mechanism (MSM).


Mode Selector Mechanism (MSM)
November 6th, 2019
Liege
Martin Eggens


IOB
TS
VG3
VG2
VG1
CM
SVM





- Working principle of the MSM :
  - Bi-stable actuator with locking force
  - Force in air gap crossed by a magnetic flux ϕ

$$F = \frac{\phi^2}{2S\mu_0}$$

    where S is the cross-section of the air gap.
  - Permanent magnet (PM) in the central leg $\rightarrow$ locking force (must be large enough to withstand take off, 25g*security factor)
  - Spring pivot tends to bring back anchor in horizontal position

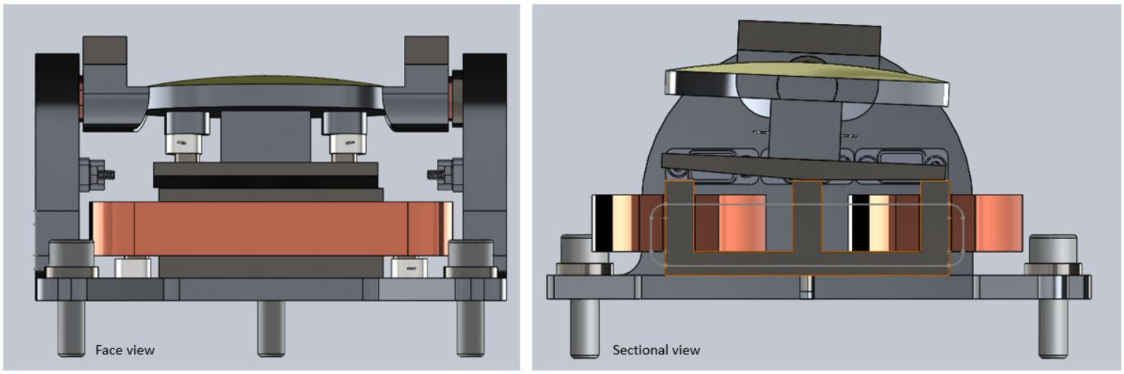


Figure 1: Front and side view of the MSM device

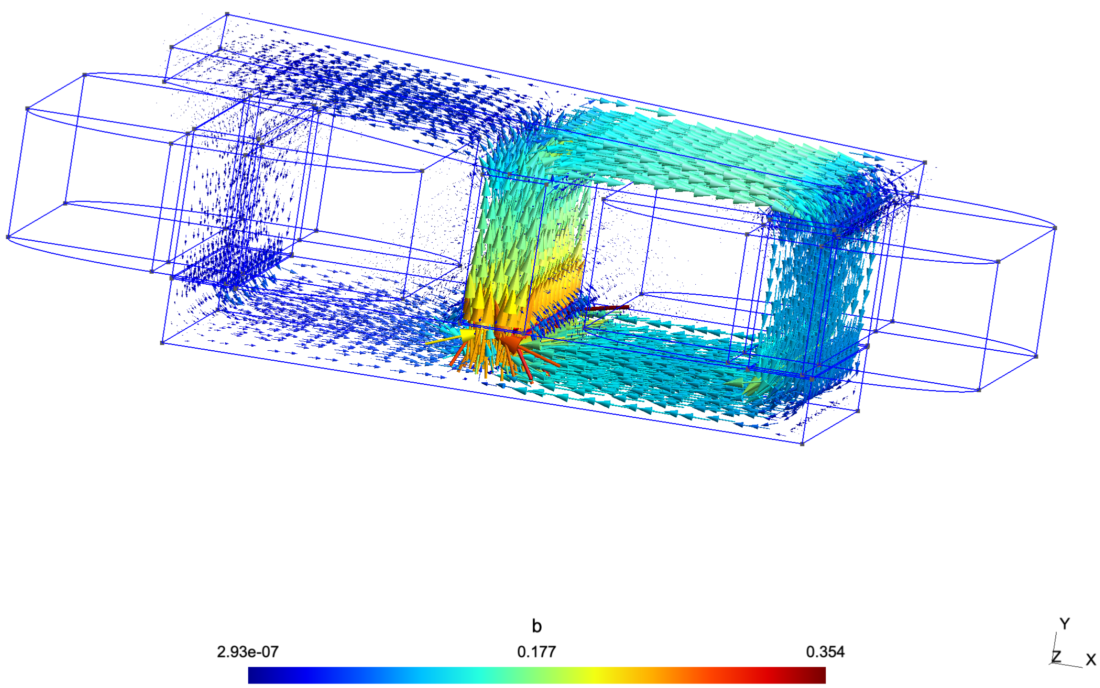


Figure 2: 3D model

– To switch the actuator (from right to left position), a current is injected in the right coil to compensate the flux produced by the PM. When the flux crossing the air gap is small enough, the spring force dominates the locking force and the anchor rotates towards the left stable position

– This actuation must be done with a very little current (a few mA) in order

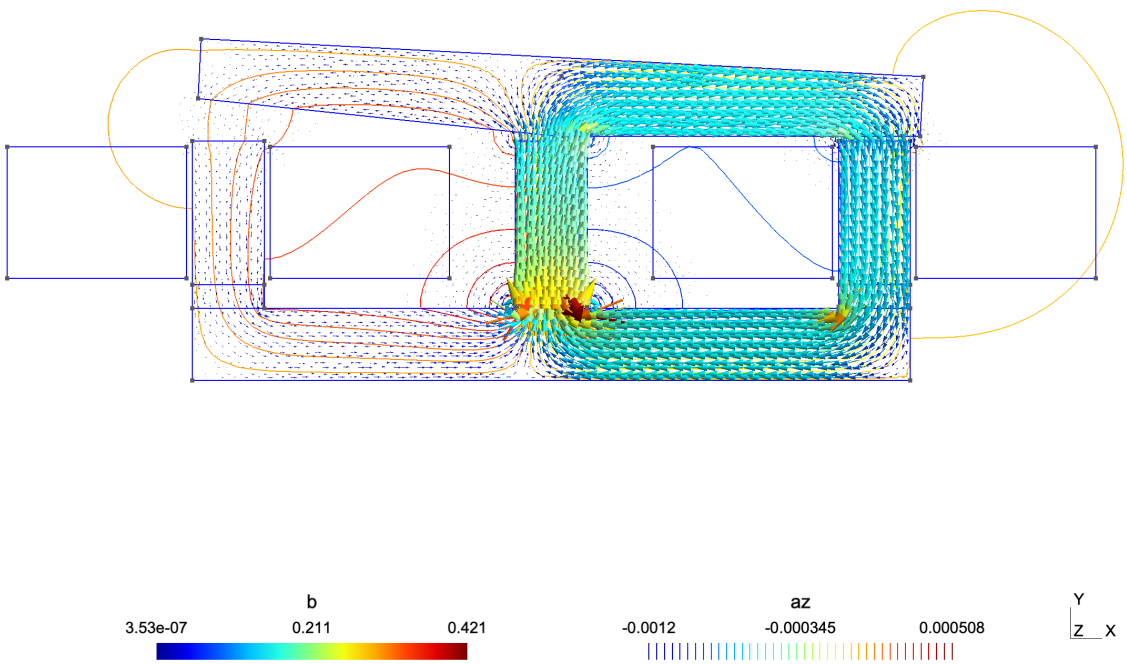


Figure 3: 2D model

to maintain the temperature of the spectrometer below 5K.

- Simulation life "safari.pro": filed lines, Reluctance of air gaps, effect of parameters (PM thickness, currents, core relative permeability), dimensions, safari.geo, safari.pro, ...
- Reluctance

$$R = \frac{L}{\mu_0 \mu_r S}$$

- L(iron, $\mu_r = 1000$) < 100 mm, L(air gaps, $\mu_r = 1$) > 0.4+0.4+0.14 $\approx$ 1mm. The reluctance of iron pieces represents less that 10% of the total reluctance of the loops, $R_{air} > 10R_{iron}$. The air gaps define the flux.
- "safari.py" : analytic magnetic circuit model considering only the air gaps, the magnet and the coils.
- Importance of the analytic model :
  - Faster than Finite element models, but less accurate
  - The analytic model helps understanding the physical aspects of the working device, and tells what is important (what field lines do not).

– Analytic models are essential to validate the more costly and more accute finite element (2D or 3D) simulations

- "2_Transformer.pdf" : Slides 1-6
- Definitions missing on slide 2:

$$\lambda_1 = \frac{n_1^2}{R_{f1}} \quad , \quad \lambda_\mu = \frac{n_1^2}{R} \quad , \quad \lambda_2 = \frac{n_2^2}{R_{f2}} \quad , \quad \lambda_2' = \frac{n_1^2}{R_{f2}}$$

Homework:

- Understand the implementation of the magnetic circuit equations in the "safari.py" file.
- Install Onelab (from https://onelab.info) and run the "safari.pro" model

Auto-evaluation

"2_Transformer.pdf", slide 5. Establish

$$\bar{U}_2' = \frac{jX_\mu}{R_1 + jX_1 + jX_\mu}\bar{U}_1$$

for the **no-load** case, and

$$\bar{I}_1 = \frac{R_2' + jX_2' + jX_\mu}{jX_\mu}\bar{I}_2'$$

for the **short-circuit** case.

Lecture 3 (24/2/2023)

- Summary of previous lectures
- "2_Transformer.pdf" : Slides 5-6
- Exterior characteristic of the transformer (on black board, notes available on the website)
- Onelab simulation "transfo.pro"
  - Compute the exterior characteristic with resistive load
  - Show it has the elliptic shape predicted by the phasor approach
  - Compare field lines in CC and No-Load,
  - Show that $I_\mu <<$ in CC , i.e., nearly no flux from primary reaches the secondary
- "1_Introduction.pdf" : Slides 4, 6 and 11 (losses)

- “2_Transformer.pdf” : Slides 7-10
- The T-shaped equivalent circuit has 2 applications.
  - As a compact transformer model in a **circuit solver**. All 6 parameters of the circuit represented at slide 7 are then determined individually. This model can be solved in frequency domain (with phasors), but it can also be solved in time-domain, and in that case it can take non-linearity (saturation of X_μ) into account.
  - Further simplified (as depicted in slide 6), the primary loop becomes trivial and the whole behaviour of the transformer can be described by the secondary loop only, as a **phasor diagram**.

Lecture 4 (3/3/2023)

- Summary of previous lectures
- “OverviewEM.pdf”
- Simulation “wfsm_4p.pro”. Show pole pairs, symmetries in machine models, distributed stator winding, stator leakage flux, ...
- “3_Synchronous.pdf” : Slides 1-5

Auto-evaluation

In “OverviewEM.pdf”, on slide 3/27, the orientation of the currents is indicated in the figure for all stator and rotor conductors. Determine from that the orientation of the torque exerted by the DC machine.

If the circular arrow shown on the shaft indicates the sense of rotation of the rotor, determine whether the machine operates as a motor or a generator.

Lecture 5 (10/3/2023)

- Summary of previous lectures
- “3_Synchronous.pdf” : Slides 1-5, revision
- “3_Synchronous.pdf” : Slides 6-16

Auto-evaluation

The Permanent Magnet Synchronous Machine depicted in Fig. 4 has 4 pole pairs ($p = 4$). Indicate on the figure a configuration of N and S poles for the permanent magnets at the rotor, and the currents to be injected in the 24 slots of the stator to comply with a 4 pole pairs machine. Use A, A', B, B', C, C' to indicate the phase currents, and use a distributed winding, as explained in “OverviewEM.pdf”, slide 11/27.

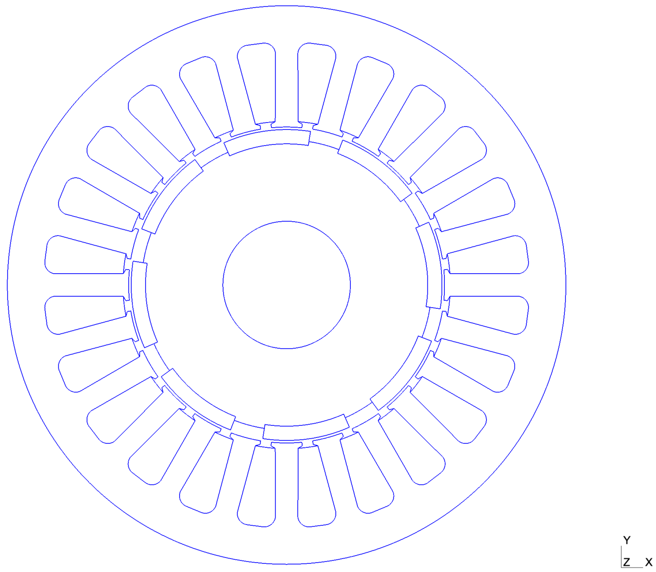


Figure 4: PMSM machine

Lecture 6 (17/3/2023)

- Summary of previous lectures
- "4_Asynchronous.pdf" : Slides 1
- Relationship between poles and field lines
- Simulation "im_3kW.pro". Show rotating field, poles, synchronous speed, ...
- "4_Asynchronous.pdf" : Slides 2-8

Lecture 7 (24/3/2023)

- Summary of previous lectures
- "4_Asynchronous.pdf" : Slides 9-13

Lecture 8 (31/3/2023)

- Communications

- Simulation “im_3kW.pro” and “im.pro”. Compare currents density distribution in deep sloots vs normal slots. Show the effect of increasing the electric conductivity of the rotor bars.
- “OverviewEM.pdf”: basic principle of the DC machine
- “5_DC.pdf” : Slides 1-9

Lecture 9 (21/4/2023)

- Communications
- Review of the fundamental equations of the DC machine
- “5_DC.pdf” : Slides 10-28 (slides 12, 14, 24, 25 are skipped)
- Didactical video to explain visually the functioning of the DC motor (in French): https://www.youtube.com/watch?v=A3b3Km5KVXs

Auto-evaluation

The slide 16 in “5_DC.pdf” shows side by side a DC machine operated as a motor and as a generator. Assuming that, as in the figure, the field lines with the direction of field $\mathbf{B}$ are indicated, and that the sense of rotation of the rotor is also given, you are able to orient the currents (using the conventional signs $\odot$ and $\otimes$) in all depicted excitation (stator) and rotor conductors.

For rotor conductors, remember that in a motor the torque drives the rotation (torque vector and rotation vector are thus parallel). Knowing the direction of the torque vector, you know the direction of the force vector $\mathbf{F}_k$ acting on individual rotor conductors, and using $\mathbf{F}_k = \mathbf{I}_k \times \mathbf{B}$, the orientation of the current $\mathbf{I}_k$ can be determined for each rotor conductor. In a generator, the torque is resisting, and therefore opposes the rotation of the rotor (torque vector and rotation vector are thus antiparallel). Besides this difference, same analysis as above.

Lecture 10 (28/4/2023)

- “6_Electronics.pdf ” : Slides 1-24 (all)
- MOS transistor operated as an amplifier or as a switch.

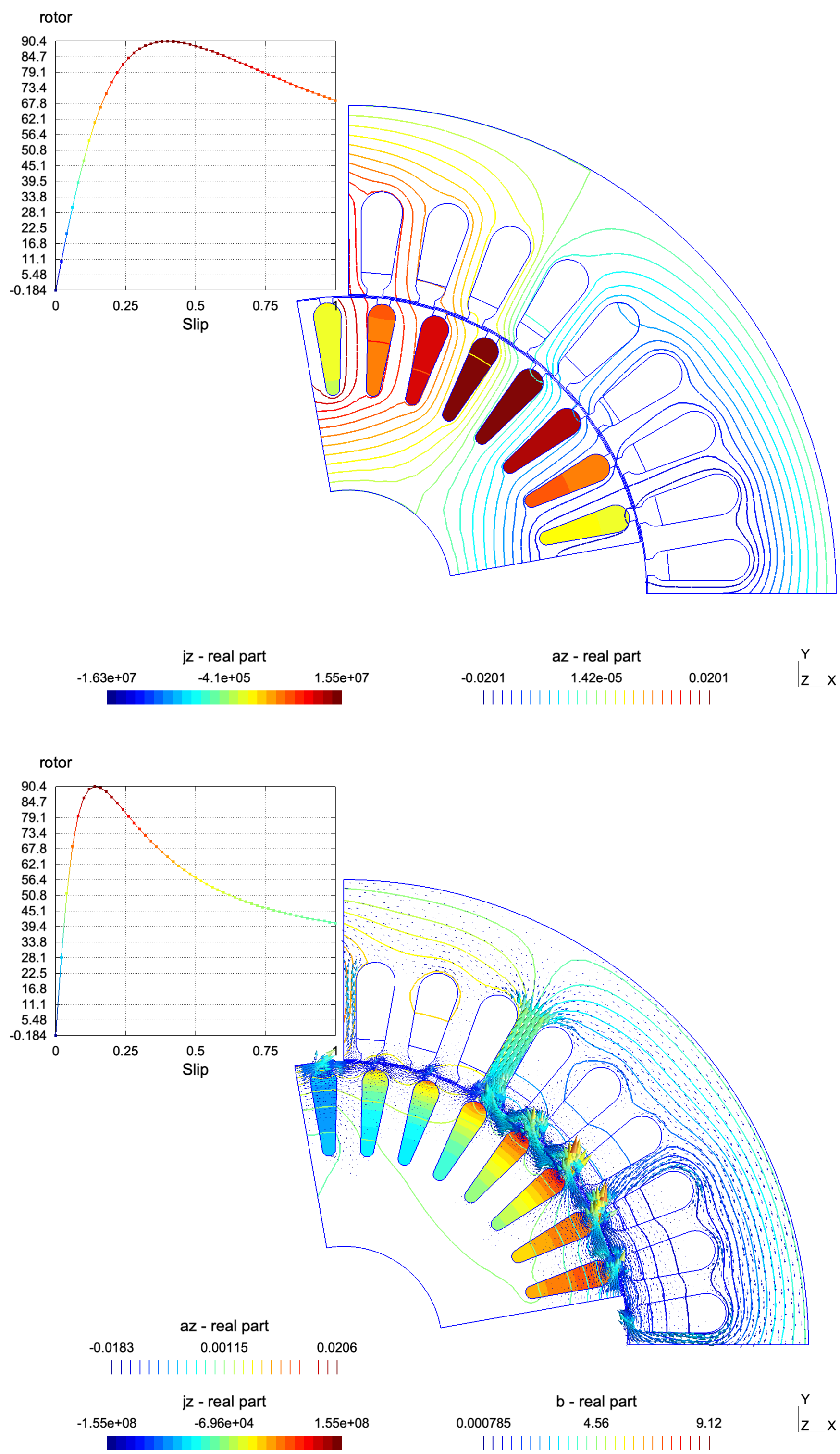


Figure 5: Simulation of the mechanical characteristic of the "im_3kW.pro' machine with the reference electric conductivity of the rotor bars σ_{bar} (top), and with $3\sigma_{bar}$, i.e., R_2' three times smaller (bottom). The effect on the $C(g)$ characteristic is conform to the one predicted by the analytical model.

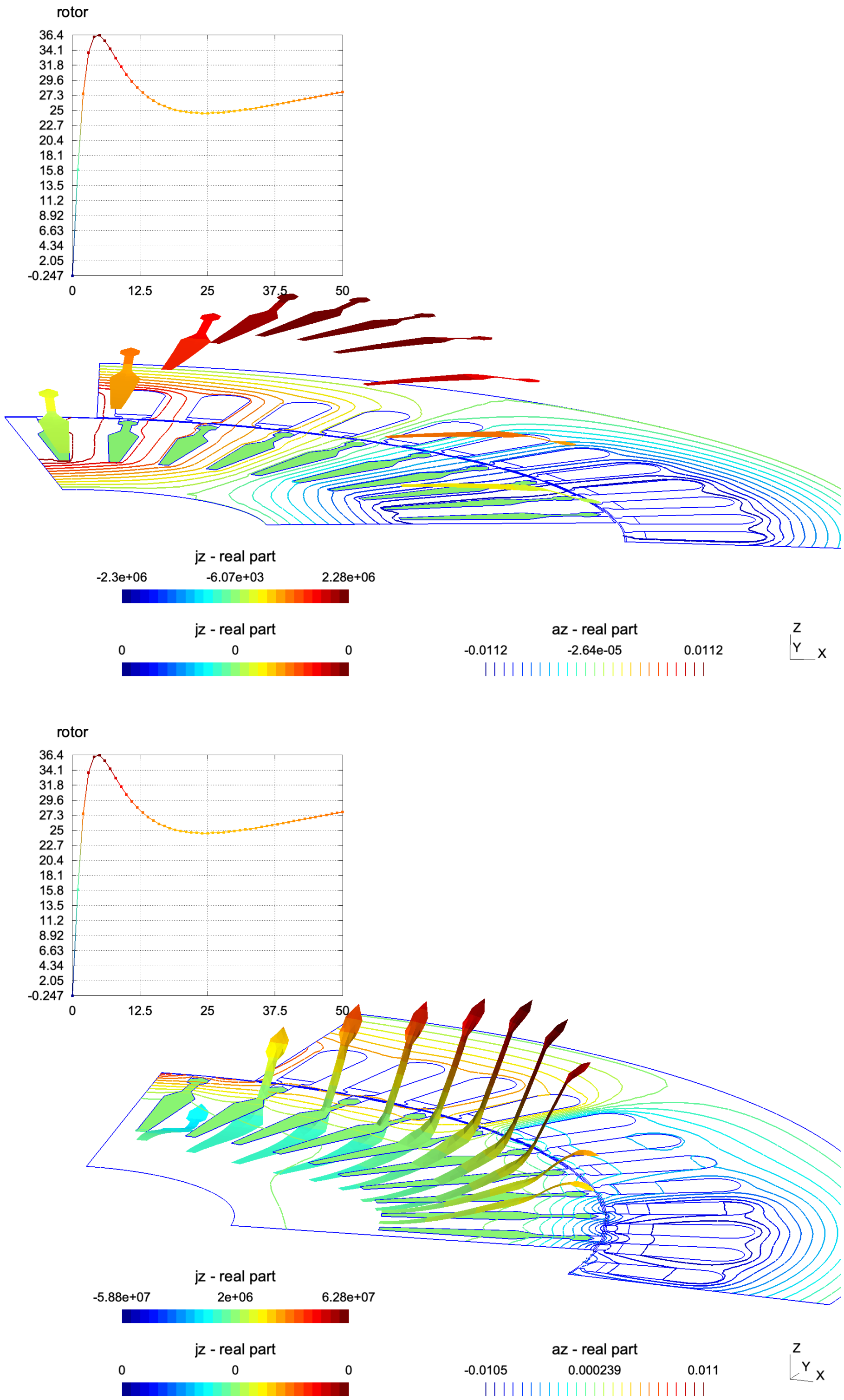


Figure 6: Difference of the current density distribution in a deep slot induction motor "im.pro" at low slip with $g <<$ (top), and start-up with $g = 1$ (bottom).