

Project assignment: Electromagnetic and thermal analysis of high-voltage cables

ELEC0041: Modeling and design of electromagnetic systems

Spring 2026

Context

The objective of this project is to study a three-phase power cable system using electrodynamic, magnetoquasistatic, and coupled magneto-thermal finite element models.

You will need to choose a power cable (high or medium voltage, single- or three-core) from, e.g., scientific papers or manufacturers datasheets:

- NKT cables: 33 kV single core cable XLPE-AL
- NKT cables: Medium Voltage Cables with XLPE Insulation
- ABB cable systems

In any case you should model a **three-phase system**.

From the literature or datasheets, you will extract geometrical dimensions, electromagnetic and thermal properties, similar to data provided in Table 1 and Table 2.

The cable must be placed in an environment (air, soil, water, ...) with appropriate material properties. The problem must be bounded, and simplifying assumptions should be made to reduce the complexity of the problem. Please discuss the feasibility of your model with the teaching team.

As a starting point, a simple cable model is provided (`simple_cable.geo`, `simple_cable.pro`) for linking the geometry, which you need to implement and adapt to your problem, with the FE formulations also included in the `simple_cable.pro` file. Note that the electrodynamic and magnetoquasistatic formulations are already implemented, while the coupling with thermal physics needs to be added. The file `simple_cable.pro` also contains the Jacobian transformation and numerical integration settings (number of Gauss points) common to all formulations.

Your work will be evaluated regularly during in-class sessions, with dedicated feedback from the teaching team at each of the three milestones. The milestones won't affect the final grading, but they are meant to help you to structure your work and receive feedback on time. You are expected to have a regular progress and to be able to present intermediate results during the in-class sessions. Please use the dedicated Gitlab repository for submitting your work and sharing it with the teaching team.

Example Cable Model

Figure 1 shows an example of a three-phase high-voltage underground cable inspired from NKT cables.

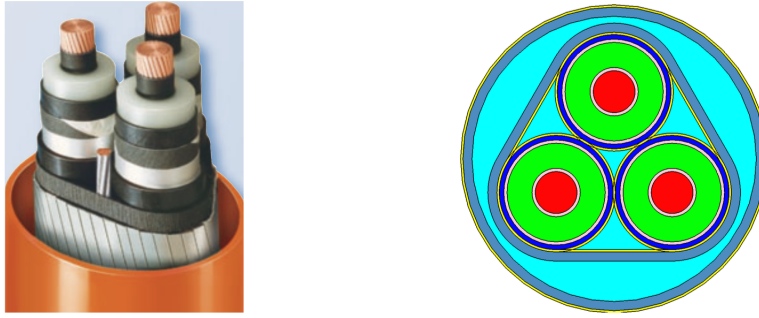


Figure 1: Left: picture of a high-voltage three-phase underground cable. Right: geometrical model.

The cable is a three-core cable with stranded copper conductors and cross linked polyethylene (XLPE) as insulating material. A semi-conductor layer surrounds the copper and the XLPE insulation. Each single core is surrounded by aluminum polyethylene laminated (APL) sheath. The group of the three cores is sheathed by polyethylene. Both wire armor and external pipe are made of steel. Finally, the external covering of the pipe is a polyethylene layer. In this example, the cable is buried at a depth of 1.2m. The three-phase voltages and currents are balanced at frequency $f = 50$ Hz.

Parameter	Dimension [mm]
Conductor diameter	18.4
Inner semiconductor thickness	1.4
XLPE insulation thickness	11.0
Outer semiconductor thickness	1.4
APL sheath thickness	2.0
Polyethylene sheath thickness	1.0
Steel armour thickness	2.0
Steel pipe thickness	4.0
Polyethylene covering thickness	1.0
Outer diameter	135.0

Table 1: Example geometrical parameters.

Material	ϵ_r	μ_r	σ [S/m]	κ [W/(m·K)]
Copper	1	1	5.99×10^7	400
Steel	1	4	4.7×10^6	50.2
Aluminum	1	1	3.77×10^7	237
Polyethylene	2.25	1	10^{-18}	0.46
Semiconductor	2.25	1	2	10
XLPE	2.5	1	10^{-18}	0.46
Soil (dry)	1	1	28	0.4

Table 2: Example electromagnetic and thermal material properties.

1 Electrodynamic Analysis Proposed milestone: March 17, 2026

The goal of this analysis is to determine the electric stress within the cable. Excessive electric fields may cause dielectric damage or early ageing. The problem can be solved by using an electrodynamic model accounting for the resistive and capacitive effects. Assume a time-harmonic steady-state problem (frequency f , angular frequency $\omega = 2\pi f$).

1. Clearly discuss your cable geometry and material properties.
2. Define the computational domain (e.g., where do you truncate the domain?), equations to be solved and boundary conditions.
3. Discuss possible geometry simplifications. Is it possible to simplify parts of the geometry without losing accuracy?
4. Study the influence of mesh refinement.
5. Add an insulation defect and compare results with and without defect. Does the cable withstand the defect? Is the electric field within the prescribed limit to be defined based on the cable specifications?
6. Compute the resistive and displacement current densities in the cable area. Is current conservation satisfied?
7. Compute the per-unit-length capacitance ($\mu\text{F km}^{-1}$) and compare with an analytical value. Discuss the assumptions of the analytical approximation. Does the capacitance vary with frequency?
8. Propose improvements to the cable design. Provide quantitative arguments.

2 Magnetoquasistatic Analysis Proposed milestone: April 14, 2026

Solve the magnetoquasistatic problem using a magnetic vector potential formulation (frequency f , angular frequency $\omega = 2\pi f$).

1. Define the computational domain, equations to be solved and boundary conditions.
2. Discuss possible geometry simplifications. Is it possible to simplify parts of the geometry without losing accuracy?
3. Check mesh quality and refine the mesh where needed.
4. Compute the magnetic flux density inside and around your cable.
5. Compute the current density in conducting regions.
6. Compute Joule losses (kW/km) in conducting regions.
7. Determine the per-unit AC resistance (Ω/km). How does it compare to the DC resistance?
8. Determine the per-unit inductance (mH/km). How is it defined? Does it vary with frequency?
9. Study the influence of mesh refinement.
10. Propose improvements to the cable design in order to reduce losses. Provide quantitative arguments.

3 Coupled Magneto-Thermal Analysis Proposed milestone: May 5, 2026

The losses computed via the magnetoquasistatic model are the source for a simple steady-state heat conduction problem. The steady-state heat conduction problem is governed by:

$$-\nabla \cdot (\kappa \nabla T) = Q,$$

with T the temperature (K), κ the thermal conductivity (W/(m·K)), and Q the heat source (W/m³).

1. Define the equations to be solved. In particular, how are the losses computed in the magnetoquasistatic model used as heat source in the thermal model?
2. Define the computational domain and boundary conditions. In particular, how is the cable cooled (buried in soil, air convection, . . .)? What is the ambient temperature? It should be consistent with the specifications of the cable datasheet.
3. Study mesh refinement effects.
4. Compute the temperature distribution in the cable. Identify the hottest spot. Is the cable operating within the prescribed temperature limits?
5. Compute the temperature distribution in the surroundings. What is the temperature at the soil/water surface (depending on your study case)?

Now consider a temperature-dependent electric conductivity:

$$\sigma(T) = \frac{\sigma_0}{1 + \alpha(T - T_{\text{ref}})},$$

with $T_{\text{ref}} = 20^\circ\text{C}$, and α equal to 0.00386 K^{-1} for the copper and 0.00390 K^{-1} for the aluminum. Solve the coupled nonlinear problem, iterating between the magnetoquasistatic and the thermal problems. Obtain the previously-introduced magnetoquasistatic and thermal quantities, field distributions and compare with the linear case (constant conductivity).¹

6. Discuss convergence and number of iterations. What convergence criterion is used? Is this convergence influenced by the mesh density?
7. Discuss the impact of temperature-dependent conductivity on the magnetoquasistatic and thermal results. Provide corresponding field maps to support your discussion.

4 Oral Examination May 12, 2026

At the end of the project, you will present your work in a **30-minute presentation** followed by a 15-minute Q&A session with the teaching team. The presentation should summarize your modeling approach, main results and conclusions. In particular, **at least one slide must be dedicated to the discussion of each item listed in the previous sections**. You are expected to be able to answer questions related to your work, and to discuss the assumptions and limitations of your model. Each student will be assigned a time slot for the presentation, and will be assessed based on the quality of the presentation, the answers to questions, as well as the originality of the work.

¹The thermal source is computed from the complex MVP \mathbf{a} , without Dof. Notation: $\langle \mathbf{a} \rangle [\text{my function}]$ must appear in front of any function applied to \mathbf{a} in the thermal formulation to indicated that the result of the operation is a real quantity.

To Include with the Submission of Slides

Submitted files All .geo and .pro files that have been created and/or modified during the project must be submitted with the slides. The code must run without errors and reproduce the results presented in the slides.

As mentioned, the slides must answer all items mentioned in the previous sections. Among other results, the slides should contain the following field maps and results:

Electrodynamic analysis

- Post-processing map of the electric potential in the cable area.
- Post-processing map of the electric field in the cable area (with and without defect).
- Post-processing map of the displacement current in the cable area (with and without defect).
- Electric field stress of the cable in a phase (cut in the radial direction) when adding a defect in the insulation. Comparison with the case without.
- Per-unit-capacitance ($\mu\text{F}/\text{km}$), comparison with analytical capacitance.

Magnetoquasistatic analysis

- Post-processing map of the magnetic flux density norm in the cable region.
- Post-processing map of the current density norm in the conducting parts of the cable.
- Joule losses in the conducting parts of the cable (kW/km).
- Per-unit-length AC resistance ($\Omega \text{ km}^{-1}$).
- Per-unit-length inductance (mH/km).

Coupled magneto-thermal analysis

- Post-processing map of the temperature distribution inside the cable.
- Post-processing map of the temperature distribution in the surrounding environment.

For the nonlinear coupled case with temperature-dependent conductivity $\sigma(T)$, the same field maps and quantities as listed above must be provided and compared with the linear case.

Additional Investigation (Optional)

Depending on the chosen cable system, you may investigate:

- different environments (soil, air, water),
- burial depth or cooling conditions,
- convection at the air–oil interface,
- cable arrangements or multiple cables,
- further model simplifications using symmetry and/or periodicity,
- monolithic (numerical) coupling between the magnetoquasistatic and thermal problems,
- any relevant design or physical effect.

After the first milestone, the teaching team will indicate the precise additional investigation to perform.