Lab session 4 – H9x34A
Electromagnetic and thermal analysis of a high voltage underground cable

Ruth V. Sabariego
KU Leuven, Dept. of Electrical Engineering ESAT/EnergyVille
ruth.sabariego@kuleuven.be

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The objective of this lab session is to model the high-voltage three-phase underground cable described in [1]. This type of cable plays a key role in the power distribution network. Numerical simulations help studyng the cables and their performance from an electromagnetic, thermal or mechanical point of view, including possible coupled analysis. Ageing, degradation and fails may be prevented.

You are going to perform an electromagnetic and thermal study of the cable in Fig. 1. All dimensions are compiled in Table 1.

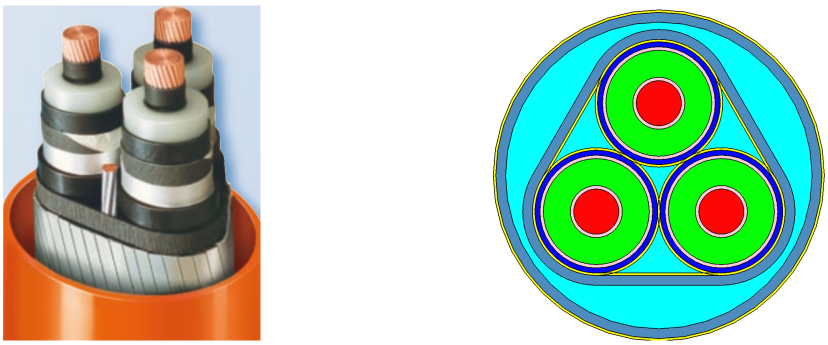

Figure 1: Left: Picture of a high voltage three-phase underground cable from NKTcables. Right: Geometrical model, the HV cable comprises: three copper stranded conductors (red), XLPE (green), semiconductors (pink and yellow), APL-sheath (dark blue), steel armour and pipe (grey), air (light blue).

The three phase conductors are made of stranded copper; the insulating material is cross linked polyethylene (XLPE). 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 cables 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. Geometrical data of the cable are given in Table 2.

Parameter	**dimensions [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-sheat thickness	1.0
Steel-armour thickness	2.0
Steel-pipe thickness	4.0
Polyethylene-covering thickness	1.0
Outer diameter	135.0

Table 1: Geometrical data.

The cable is placed at a depth of 1.2 m. The three-phase voltages and currents are balanced at frequency $f = 50\,\mathrm{Hz}$.

Material	ϵ_r	μ_r	σ [S/m]	κ [W/(m·K)]
copper	1	1	5.99e7	400
steel	1	4	4.7e6	50.2
aluminum	1	1	3.77e7	237
polyethylene	2.25	1	1.0e-18	0.46
semiconductor	2.25	1	2	10
XLPE	2.5	1	1.0e-18	0.46
soil (dry)	1	1	28	0.4

Table 2: Electromagnetic and thermal material properties.

1 Electrodynamic analysis

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

$$\begin{aligned} \mathrm{curl}\,\underline{e} &= 0 && (1)\\ \mathrm{curl}\,\underline{h} &= \underline{j} + \imath\omega\underline{d} \Rightarrow \mathrm{div}\,(\underline{j} + \imath\omega\underline{d}) = 0 && (2)\\ \underline{j} &= \sigma\,\underline{e} && (3)\\ \underline{d} &= \epsilon\,\underline{e}\,. && (4) \end{aligned}$$

with ve the electric field, $\underline{h}$ the magnetic field, j the electric current density, $\underline{d}$ the electric flux, σ the conductivity and ϵ the permittivity. You may use an electric scalar potential v formulation:

$$-\,\mathrm{div}\,(\sigma\,\mathrm{grad}\,v + \imath\omega\epsilon\,\mathrm{grad}\,v) = 0\,, \quad \underline{e} = -\mathrm{grad}\,v\,. \tag{5}$$

The weak formulation is analogous to the one in `03discretisation.pdf` (slides 5-9). The problem is completed with Dirichlet conditions: at the boundary for the computational domain and at the conductors (120° phase shift between the phases). The RMS value of the line voltage is 132 kV. According to the cable technical data, the maximum field strength at the conductor and core screens is 10.3 kV/mm and 4.9 kV/mm, respectively.

Defects (voids, bubbles) in the XLPE insulation may cause stronger electric fields. Insert a circular defect (diameter 2 mm) in phase 2 at a distance from the conductor of $d = 5\,\mathrm{mm}$ and 2 mm.

Answer the following questions:

- Define your computational domain, where do you truncate the domain?
- Perform the simulation with and without defect and check that the electric field respects the above limits.
- How do the result vary with the mesh?
- Compute the per-unit-legth capacitance (μF/km) and compare with an analytical value (indicate assumptions if any).
- Can you simplify the geometry withouth degrading the precision?

2 Electro-magnetodynamic analysis

Let us add now the magnetic part. We may solve the quasi-static steady-state electromagnetic problem (frequency f, angular frequency $\omega = 2\pi f$) via a magnetic-vector-potential formulation, it reads

$$\mathrm{curl}\,(\nu\mathrm{curl}\,\underline{a}) + \imath\omega\sigma\underline{a} - \omega^2\epsilon\underline{a} = \underline{j}_s \tag{6}$$

with $\underline{a}$ the magnetic vector potential defined such that $\underline{b} = \operatorname{curl} \underline{a}$, $\underline{j}_s$ the imposed current density. The weak formulation is analogous to the one in `03discretisation.pdf` (slides 17-20). The problem is fully defined by imposing $\hat{n} \times \underline{a} = 0$ at the boundary of the computational domain and the current density $\underline{j}_s$. The maximum value of the current is $I_0 = 406\,\mathrm{A}$ and we have a 120° phase shift between the phases. For stranded conductors, the current density is given by:

$$\underline{j}_s = \frac{I_s}{\mathcal{A}_c}\,, \tag{7}$$

with Is the source current and $\mathcal{A}_c$ the cross-section of the conductors.

The joule losses, that generate heat, are directly computed from the induced current $\underline{j} = \sigma \underline{e} = -\imath\omega\sigma\underline{a}$:

$$p = \frac{|\underline{j}|^2}{2\sigma} = \frac{\omega^2\sigma|\underline{a}|^2}{2}\,. \tag{8}$$

Provide the following results:

1. Define your computational domain, where do you truncate the domain?
2. Get the magnetic flux density (or induction) in the cable.
3. Get the current density in the aluminum shealth, the steel armour and the steel pipe.
4. Get the joule losses (kW/km) in the aluminum shealth, the steel armour and the steel pipe.
5. Get the per-unit AC-resistance (Ω/km).
6. Get the per-unit inductance (mH/km).
7. How do the results vary with the mesh?
8. Can you simplify the geometry withouth degrading the precision?

3 Coupled electromagnetic-thermal analysis

The steady-state heat conduction equation to consider is:

$$-\operatorname{div}(\kappa \operatorname{grad} T) = Q\,, \tag{9}$$

with T the temperature distribution (K), κ the thermal conductivity W/(m·K), and Q the heat source (W/m^3). The heat source Q is given by the joule losses (8)[1].

The ambient temperature is $T_{\mathrm{amb}} = 15°\mathrm{C}$ (technical data of the cable). The operating temperature of the cable varies between 70°C and 90°C Solve the coupled problem and determined the temperature distribution in the cable and surroundings. Concretely, answer the following questions:

1. Define your computational domain, where do you truncate the domain?
2. Get the temperature distribution in the cable. Is it in the operating temperature limits?
3. Get the temperature distribution around the cable. What is the maximum temperature at the interface ground/air?
4. How do the results vary with the mesh?

[1] The thermal source is computed from the complex MVP `{a}`, without `Dof`. Notation: `<a>[ my_function ]` must appear in front of any function applied to `a` in the thermal formulation to indicated that the result of the operation is a real quantity.

You can find the theory about thermal formulation in and coupled problems in `03discretisation.pdf` (slides 5-9). and `07Circuits_Movement_CoupledProblems.pdf` (slides 37-40), respectively.

Till this point, we have consider that the conductivity σ does not depend on the temperature T. Let us account for an electrical conductivity that varies with the temperature:

$$\sigma(T) = \frac{\sigma_0}{1 + \alpha(T - T_{\text{ref}})}, \tag{10}$$

with σ_0 the conductivity at $T_{\text{ref}} = 20°\text{C}$, given in Table 2, and α equal to 0.00386K^{-1} for the copper and 0.00390K^{-1} for the aluminum.

Solve the coupled nonlinear problem, iterating between the electromagnetic and the thermal problems. Obtain the following quantities, field distributions and compare with the linear case (σ invariant):

1. How many nonlinear iterations do you need for achieving convergence (stop criterion $1e-6$)? Is this convergence influenced by the mesh density?
2. Get the magnetic flux density (or induction) in the cable.
3. Get the current density in the aluminum shealth, the steel armour and the steel pipe.
4. Get the joule losses (kW/km) in the aluminum shealth, the steel armour and the steel pipe.
5. Get the AC-resistance-per-unit length (Ω/km).
6. Get the inductance-per-unit length (mH/km).
7. Get the temperature distribution in the cable. Is it in the operating temperature limits?
8. Get the temperature distribution around the cable. What is the maximum temperature at the interface ground/air?

4 To include in the report

The `geo` and `pro` files you have created and/or modified.

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 phase 2 (cut in the radial direction) without and with defect of different distances.
- Per-unit-capacitance (μF/km), comparison with analytical capacitance.

Electro-magnetodynamic analysis:

- Post-processing map of the magnetic flux density norm in the cable area.
- Post-processing map of the current density norm in the in the aluminum shealth, the steel armour and the steel pipe.
- Joule losses (kW/km) in the aluminum shealth, the steel armour and the steel pipe.
- Per-unit AC-resistance (Ω/km).
- Per-unit inductance (mH/km).

Coupled electromagnetic-thermal problem

- Post-processing map of the temperature in the cable.
- Post-processing map of the temperature outside the cable.

For the nonlinear coupled case with $\sigma(T)$, the new maps and values asked in previous section.

References

[1] S. Conti, E. Dilettoso, S.A. Rizzo, "Electromagnetic and thermal analysis of high voltage three-phase underground cables using finite element method", *In IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Palermo, Italy, June 12-15, 2018. https://ieeexplore.ieee.org/document/8525354.