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H04C0a - Finite Elements for Electromagnetic Fields:
Exercises

Electrodynamic analysis

Group 30

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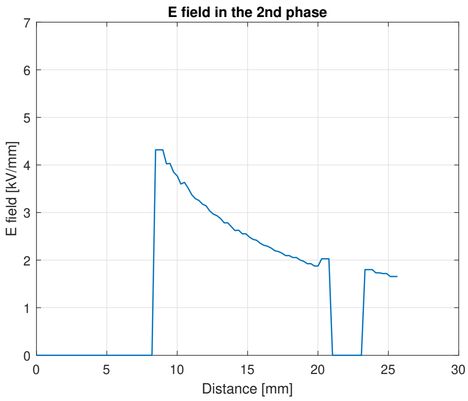
1 Electrodynamic analysis

1.1 Computational domain

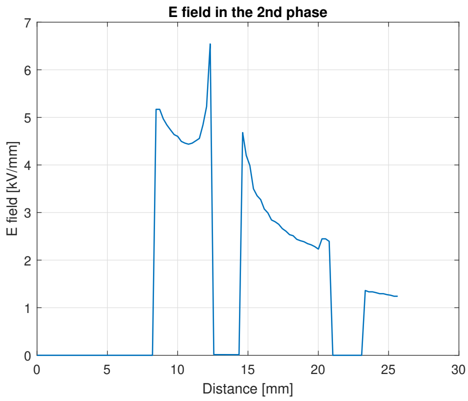
For this analysis, our computational domain is a circle of five times the diameter of our cable. As we cannot do a FEM analysis on an unbounded domain, we do a truncation of the outer boundary. On this outer boundary, we will set a Dirichlet boundary condition and impose the electric scalar potential to be zero. We have thus to place the boundary far enough from our domain of interest such that its effect on the solution is minimal and do not lead to exaggerated computational cost by having a too big domain. A rule of thumb is to pick the the distance between the outer boundary and the centre of the domain as five times the distance between the centre of our problem and the end of the domain of interest. This is what we have implemented for our study.

1.2 Electric stress limits

The conductors and the core screens can withstand an electric field strength of $10.3\,\mathrm{kV/mm}$ and $4.9\,\mathrm{kV/mm}$. From Figure 1, we see that the first threshold in respected in any case, while the presence of a defect (air bubble of 2 mm diameter) increases the electric field above the limit in the insulation.



(a) Without defect



(b) With defect

Figure 1: Electric field in a radial cut in phase 2

1.3 Variation of the result with the mesh

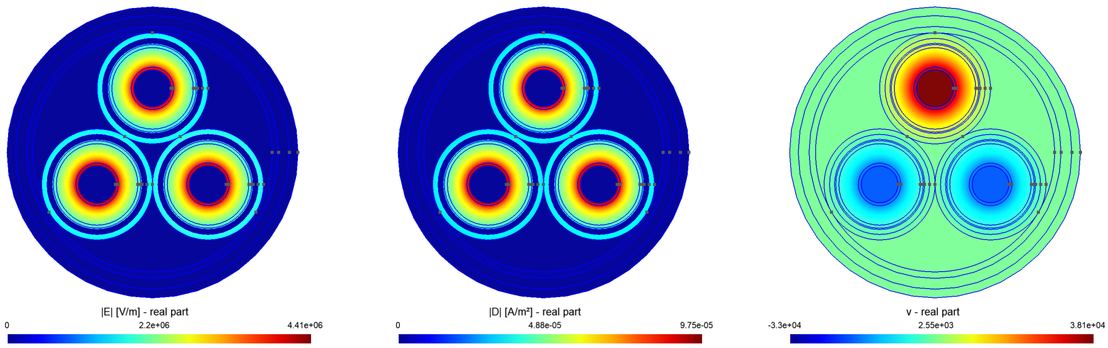
The results of the simulation are displayed in Figure 2 and 3. The size of the mesh for this result is $D_{tot}/5$ ($D_{tot} = 134.5$ mm), the mesh being refined by a factor 16 at the outer layers and then 32 in the cable.

When we refine the mesh to $D_{tot}/10$, the maximal values observed in the cable increase for the electric field and the displacement current. The mesh element being smaller, we can have a better approximation at the interface with the wire as the value displayed is the mean over the element. If we focus of the electric field the maximal value observed $4.82\,10^6$ V/m and is in generally a bit higher in the cable non conducting materials for the finer mesh of about $0.1\,10^6$. The opposite occur for a mesh of size $D_{tot}/2.5$ with a maximal value for the electric field of $4.35\,10^6$ V/m. However the boundary value for the voltage do not change as the maximum and minimal one occur in the wire and are homogeneous.

Adding the defect, we refined the mesh even more, in particular around the defect. Indeed, if we do not do that the mesh in the neighbouring of the defect is too big. The mesh have to be sized accordingly with the characteristic length of the geometry close to it. We want to avoid to have averaged results on too big areas with respect to the different part of the cable geometry and have a smooth enough evolution of the fields. The defect seems to have a bigger influence on the electric field and displacement current than on the voltage.

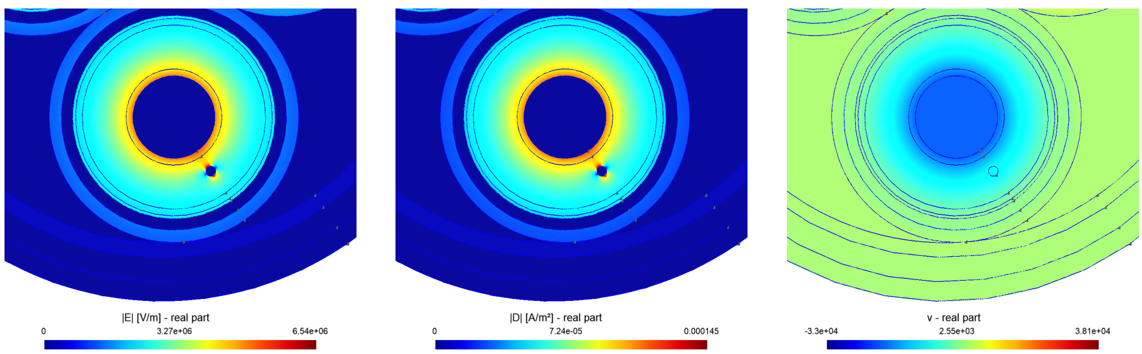
We conclude that the finer the mesh the higher the resolution. When the mesh is refined enough the changes become small enough to be neglected. The mesh should be sized and refined according to the characteristic size of the neighbouring geometry.

A last thing is that it is important to have a critical regard on the legend. Although a big part of the cable is dark blue for the electric field and the displacement current, the value is not especially zero! Indeed the smaller variation are "inhibited" on the colormap by the fact that the maximum value on the legend is far bigger.



(a) Electric field (b) Displacement current (c) Voltage

Figure 2: Different fields in the cable without defect



(a) Electric field (b) Displacement current (c) Voltage

Figure 3: Different fields in the cable with defect

1.4 Per-unit-length capacitance computation

It is a well-known fact that the conductors in a cable are separated by dielectric and there is the insulation between the core and metallic sheath. When there is a potential difference applied between the conductor, combination of six capacitance can be modelled as in right side of Figure 4. The left side model represents that three C_c (core-to-core capacitances) are connected in delta, while C_s (core-to-sheath capacitances) are star-connected due to the metallic sheath forming a single point N. Thus, the total capacitance of $C_s + 3C_c$ will be evaluated for one branch core as in Figure 5.

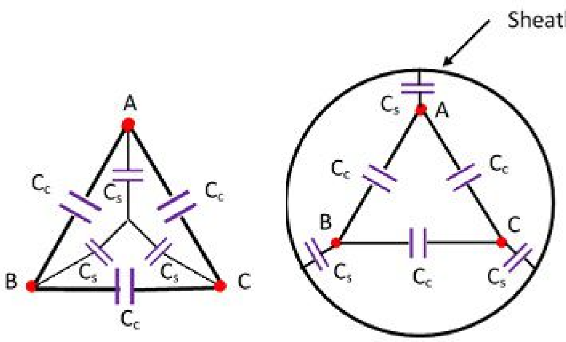


Figure 4: Capacitance in three-core conductor.

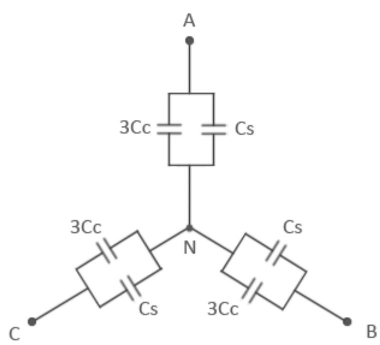


Figure 5: Simplified model of the submarine cable.

In terms of the geometrical distance, we can define two parameters: core-to-core distance (D_{cc}) and core-to-sheath distance (D_{cs}). Their values can be formulated and found to be: D_{cc} = 57.3 mm and D_{cs} = 20.85 mm.

As we aim at finding the capacitance-per-phase value, we did not take into consideration the electric filed effect towards nearby phase cables. In turn, it gives an opportunity to neglect the armouring and serving layers. Finally, we come up with the model circuit that represents the interaction between the core and sheath layers as in Figure 5.

Any capacitance value between point 1 and 2 can be given in the following order:

$$V_{1-2} = \int_{x1}^{x2} \frac{E_p}{x}\, dx = \int_{x1}^{x2} \frac{q}{2\pi\epsilon_0\epsilon_r}\frac{1}{x}\, dx = \frac{q}{2\pi\epsilon_0} \ln \frac{x2}{x1}(V) \tag{1}$$

$$C_{1-2} = \frac{q}{V_{1-2}} = \frac{2\pi\epsilon_0\epsilon_r}{\ln \frac{x2}{x1}}(F/m) \tag{2}$$

For C_c, if we substitute D_{cs} and D_{cc} in (2), we will have:

$$C_c = \frac{2\pi\epsilon_0\epsilon_{water}}{\ln \frac{D_{cc}}{r}} = \frac{2\pi * 8.85 * 10^{-12} * 81}{\ln \frac{57.3}{8.45}} = 2.3531 \times 10^{-9}\,\mathrm{F/m} \tag{3}$$

It should be noted, as far as the selected cable is submarine type, we concern of water as the medium between cores. As for C_s, the same procedure can be repeated except for the permittivity of XLPE insulation:

$$C_s = \frac{2\pi\epsilon_0\epsilon_{XLPE}}{\ln \frac{D_{cs}}{r}} = \frac{2\pi * 8.85 * 10^{-12} * 2.5}{\ln \frac{20.85}{8.45}} = 1.5392 \times 10^{-10}\,\mathrm{F/m} \tag{4}$$

Thus, the total capacitance for one branch can be calculated using (3) and (4),

$$C = 1.5392 * 10^{-10} + 3 \times 2.3531 \times 10^{-9} = 7.213\,\mathrm{nF/m} \tag{5}$$

To recapitulate, as a result of the simulation we had the capacitance C of $0.4215\,\mu\mathrm{F/km}$, which is differed from the analytical solution by only one order of magnitude. This inconsistency might have been caused by the fact that we have applied approximated model in order to compute the capacitance per phase. The neglected medium layers might have affected the effective value of the permittivity.

1.5 Simplification of the geometry

In terms of the electrodynamics nature of the cable, Figure 4 represents the approximated model of the capacitances between different elements of the cable. Without degrading the precision, we have considered only the model of conductor-insulation-sheath-bedding-armouring by overlooking the thin layers as in Figure 6.

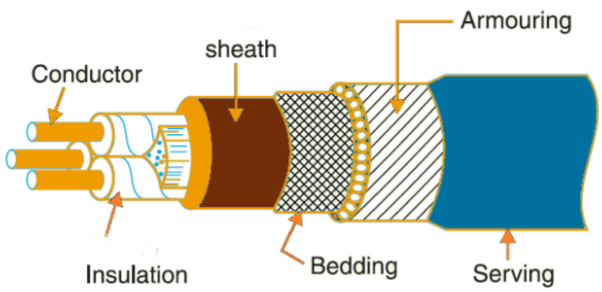


Figure 6: Simplified model of the submarine cable.

We can assume that there will be a global insulation layer instead of set of insulation layers. Since the geometrical thickness of those neglected layers are small enough, it will have insignificant impact on the final result.

To simplify our FEM geometry we could merge the three XLPE layers and the PE one that have nearly the same relative permittivity to have less layer in the model. We also could do an averaged layer for the tree last layers as the relative permittivity is 2.2, 1, 2.2 respectively. The resulting geometry will be much simpler and the difference in the results will be negligible.