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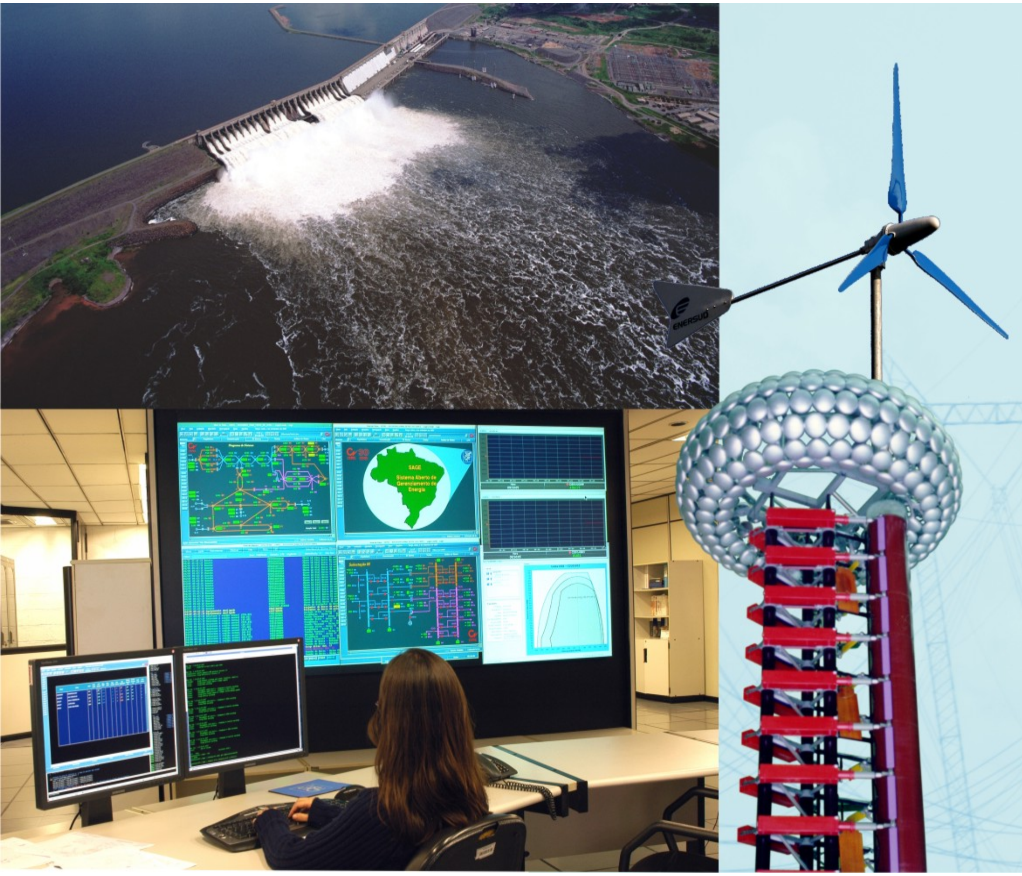

Comparison of Power Transmission Line Models with Finite Elements

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COMSOL
CONFERENCE
2014 CURITIBA

Introduction

- Extra-high voltage transmission lines (TLs)
- Ultra-high voltage TLs (> 765 kV AC or > 600 kV DC)
  - Unknown issues
  - Experimental lines - costly
- Unconventional TLs
  - Project optimization for existing voltage levels
  - Recapacitation/ uprating
  - High Surge Impedance Line - HSIL (a.k.a. *Linha de potência natural elevada – LPNE*)

Introduction

Some project criteria

- Electric field at conductor surface – Corona effect
- Current density – Skin effect
- Electromagnetic field at ground level – Environmental restrictions
- Impedance and admittance (balanced and unbalanced) – circuit model: load flow, fault calculations etc.

Analytical models

Introduction

HSIL test line - FURNAS

Objectives

Compare some aspects regarding TL design using analytical models and Finite Elements (COMSOL)

- Advantagens and limitations shall be discussed for both methods

Governing equations

- Basic circuit relations

$$\begin{bmatrix}\Delta v_1\\ \Delta v_2\\ \Delta v_3\end{bmatrix} = \begin{bmatrix}z_{11} & z_{12} & z_{13}\\ z_{21} & z_{22} & z_{23}\\ z_{31} & z_{32} & z_{33}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\\ i_3\end{bmatrix} \qquad \begin{bmatrix}v_1\\ v_2\\ v_3\end{bmatrix} = \begin{bmatrix}p_{11} & p_{12} & p_{13}\\ p_{21} & p_{22} & p_{23}\\ p_{31} & p_{32} & p_{33}\end{bmatrix}\begin{bmatrix}q_1\\ q_2\\ q_3\end{bmatrix}$$

$$\frac{d\boldsymbol{v}}{dx} = \boldsymbol{Z}\cdot\boldsymbol{i} = (\boldsymbol{R} + j\omega\boldsymbol{L})\boldsymbol{i} \qquad \frac{d\boldsymbol{i}}{dx} = j\omega\boldsymbol{C}\cdot\boldsymbol{v} \qquad \mathrm{q} = \mathrm{P}^{-1}\cdot\mathrm{v} = \mathbf{C}\cdot\mathbf{v}$$

- Skin effect

$$\mathrm{Z_i} = \frac{j\omega\mu}{2\pi r_0}\,\frac{\mathrm{K}_1(\rho_0)\mathrm{I}_0(\rho_1) + \mathrm{K}_0(\rho_1)\mathrm{I}_1(\rho_0)}{\mathrm{I}_1(\rho_1)\mathrm{K}_1(\rho_0) - \mathrm{I}_1(\rho_0)\mathrm{K}_1(\rho_1)}$$

- Electric field

$$\mathrm{E_{kx}} = \frac{q_{rx} + jq_{ix}}{2\pi\varepsilon}\left[\frac{x_m}{x_m^2 + (h_k - h_m)^2} - \frac{x_m}{x_m^2 + (h_k + h_m)^2}\right]$$

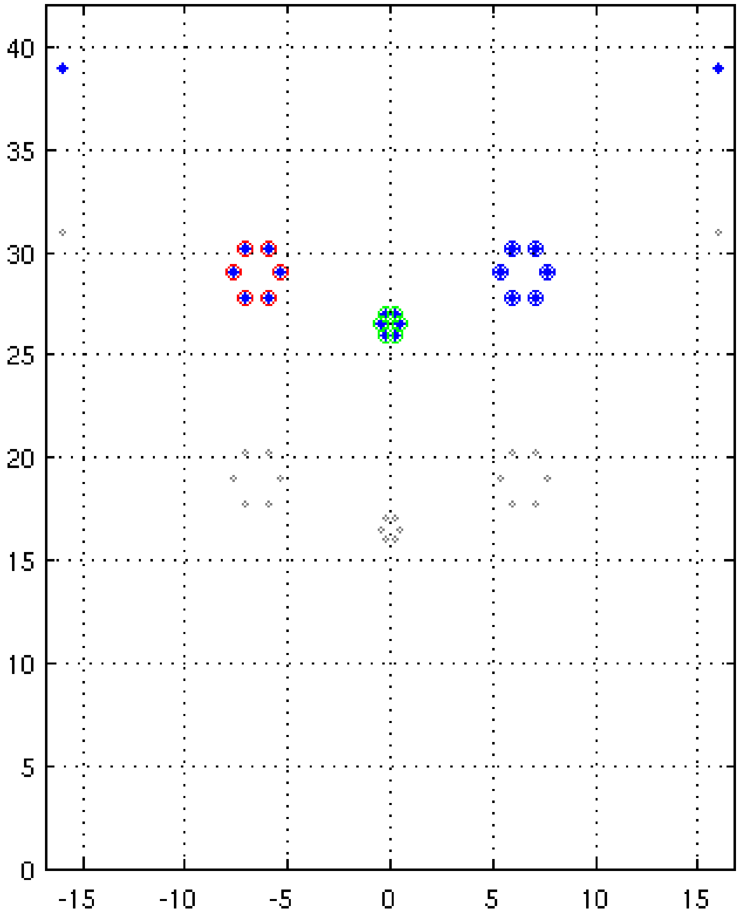
$$\mathrm{E_{ky}} = \frac{q_{rx} + jq_{ix}}{2\pi\varepsilon}\left[\frac{h_m - h_k}{x_m^2 + (h_k - h_m)^2} - \frac{h_m + h_k}{x_m^2 + (h_k + h_m)^2}\right]$$

$$\mathrm{E_x} = \sum_k \mathrm{E_{kx}} = \mathrm{E_{rx}} + j\mathrm{E_{ix}}$$

$$\mathrm{E_y} = \sum_k \mathrm{E_{ky}} = \mathrm{E_{ry}} + j\mathrm{E_{iy}}$$

Proposed test case

Nominal voltage level	500 kV, phase-phase RMS
Current per phase	1000 A
Conductor	Phase: ACSR Tern Ground wire: EHS 3/8"
Number of conductors	6 per phase, 2 ground wires
Bundle radius (ellipsis major/ minor axis)	Outer phases: 1.4/ 1.12 m Center phase: 0.6/ 0.48 m
Bundle asymmetry (relation between axis)	0.8
Height at tower	Outer phases: 29 m Center phase: 26.5 m Ground wires: 39 m
Sag at nominal conditions	Phases: 12.58 m Ground wire: 7.64 m
Distance between phases (bundle centers)	6.5 m



Test case profile, conductor positions at tower (color) and mid-span (gray)

Modeling

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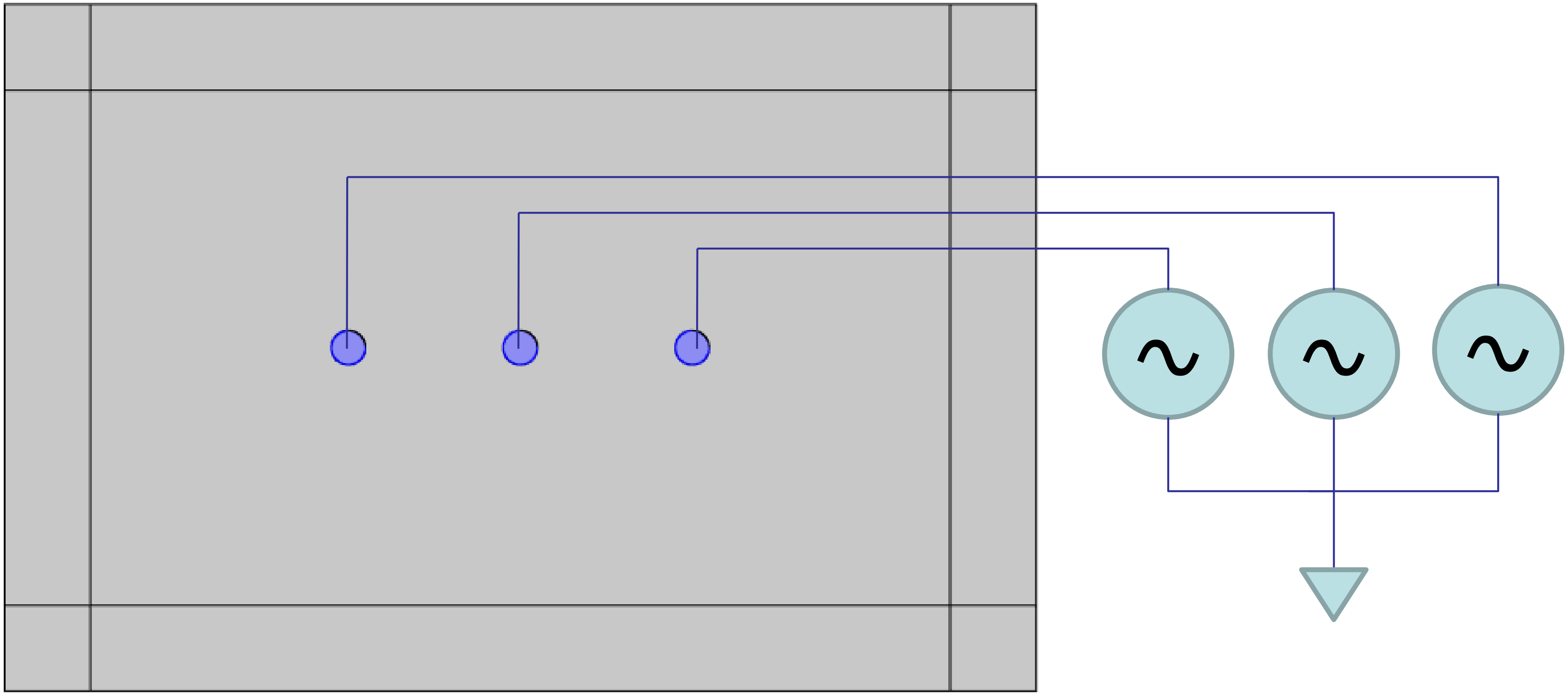
Some peculiarities:

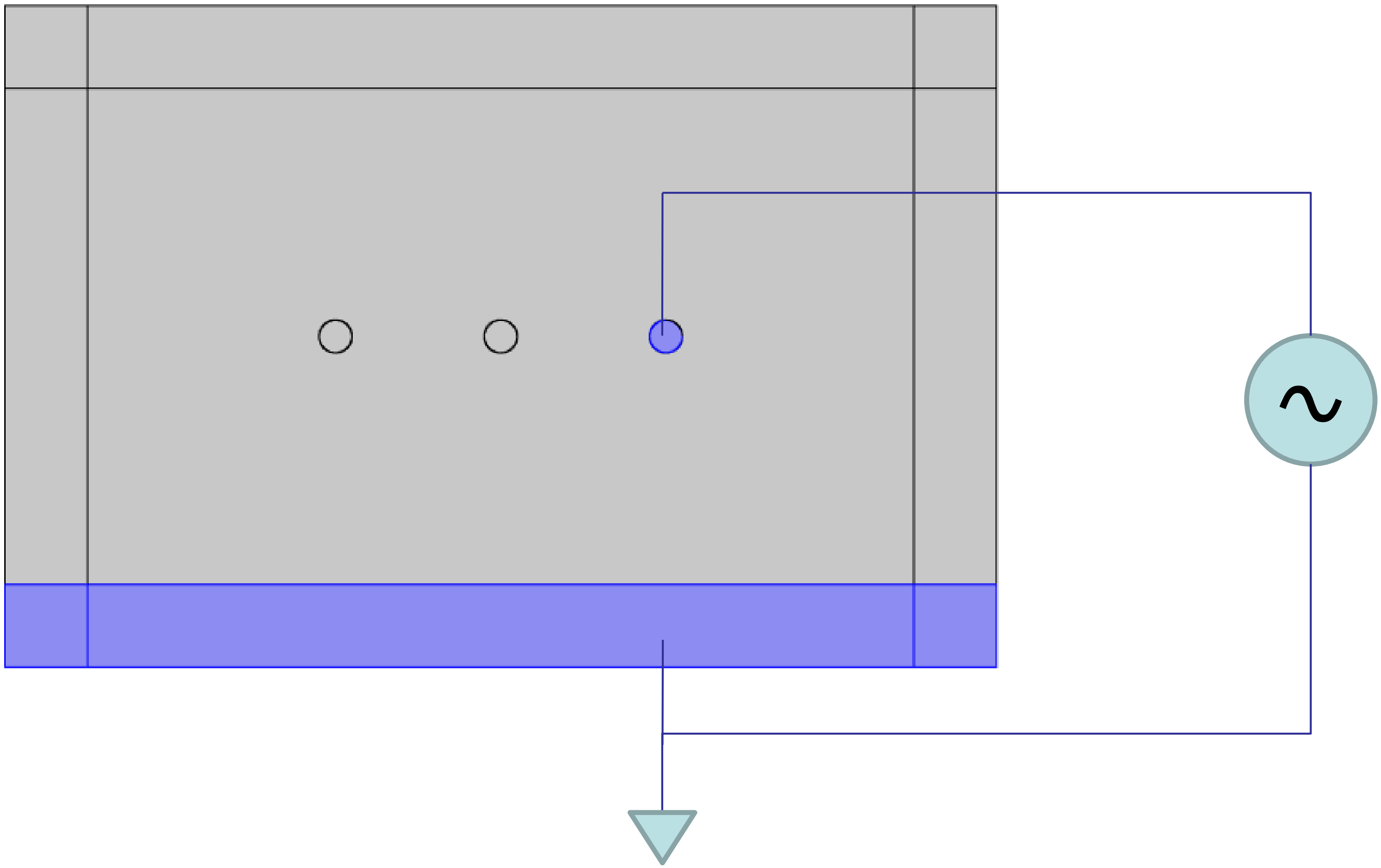
- 2D approximation
  - Valid for studies at midspan → higher electric fields at conductors and ground level
- Three phase system
  - Simultaneous interaction
  - “Three leg” coil in magnetic field model?
  - Unbalanced system → return to ground
- ACSR cables (aluminum wires with steel core)
  - Magnetic interaction, relevant for Joule losses
- Domain dimensions
  - From 1 cm (cable diameter) up to 100 m (cable height or right-of-way width) or 100 km (line length)
  - Infinite domain consideration
- Ground resistivity
  - Infinite domain with current return?

Modeling considerations
Three-phase balanced line



Modeling considerations

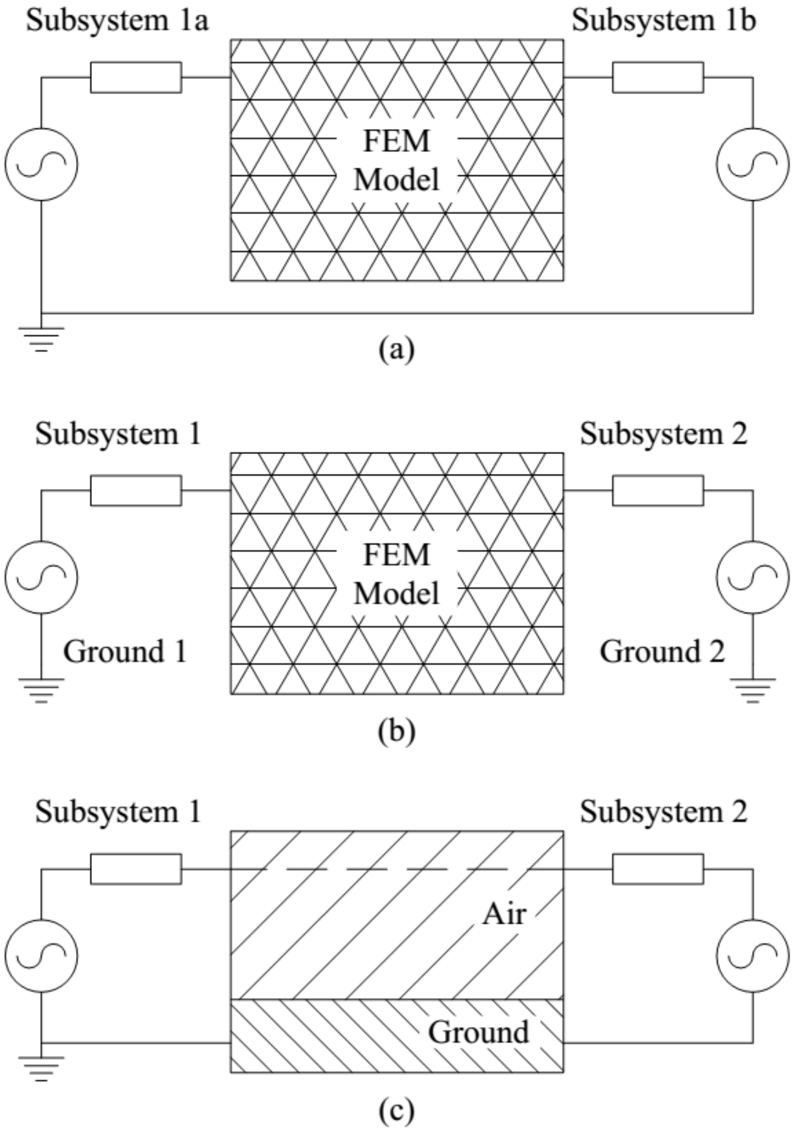
Three-phase unbalanced line / single phase



Modeling considerations
Domain-circuit interaction

A TL, by definition, connects two systems

- The “ground node” is not in the same potential, like case (b) – numerical methods demands exactly one reference node
- Case (a) is acceptable for short lines or balanced system (single phase reduction)
- Proposed case (c) should consider correctly the earth return (good for fault simulations) – not supported in Comsol



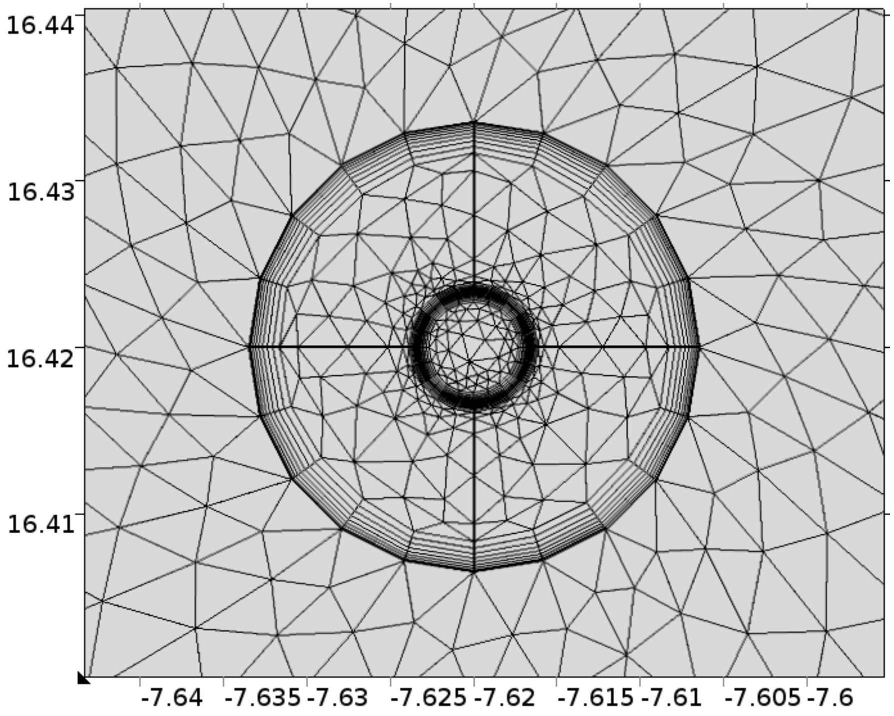
Modeling
COMSOL Configuration

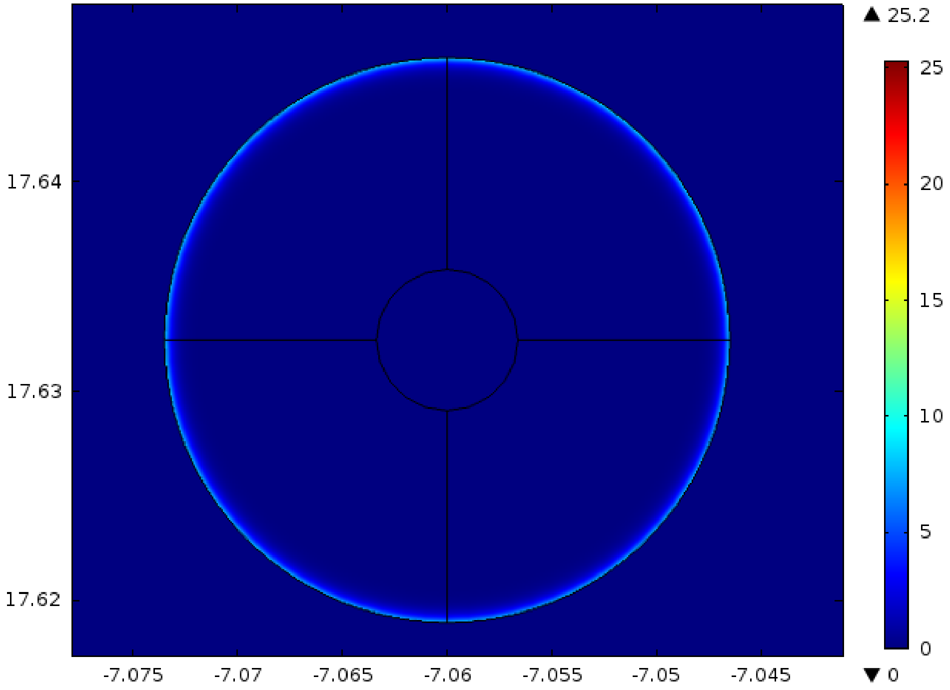
- Infinite elements (open domain)
- Single coil representing each current injection, grouped by bundles,
- A return coil for ground, for unbalanced loads,
- Separation of real ground bounded by a ideal ground underneath a infinite element layer,
- Representation of steel core of ACSR cables for proper skin effect observation,
- Meshing of cables and ground surface, layer refinement in one conductor.
- Using the same geometry, it's possible to build a number of meshes, specific for each study

Study outputs

- Admittance matrix (“electrostatics”, frequency domain)
- Electric field at conductor (“electrostatics”, frequency domain)
- Impedance (magnetic fields, frequency domain)
- EM fields at ground level (magnetic fields and electrostatics, time dependent and frequency domain)

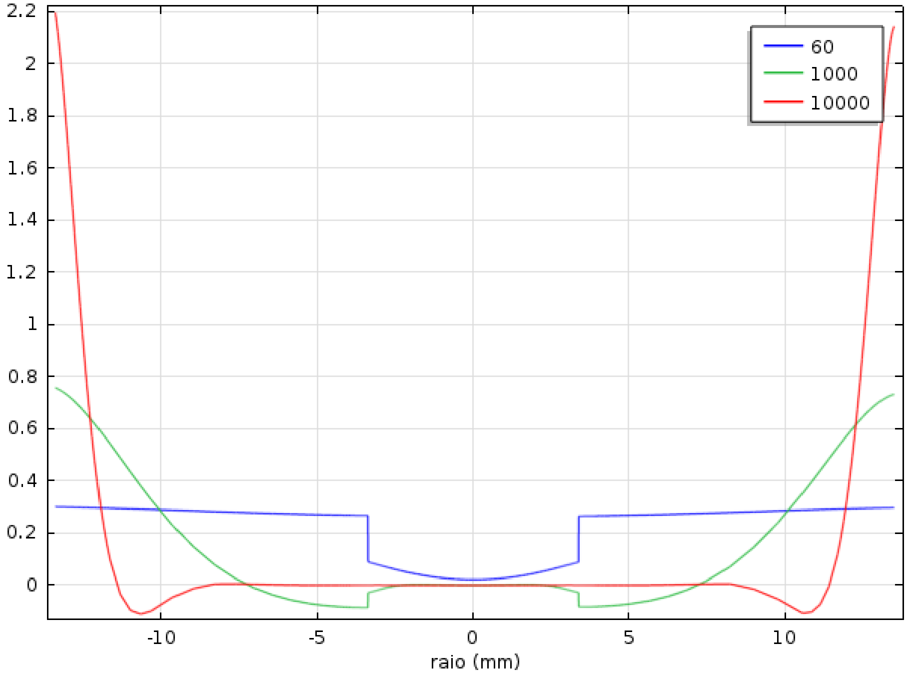
Meshing



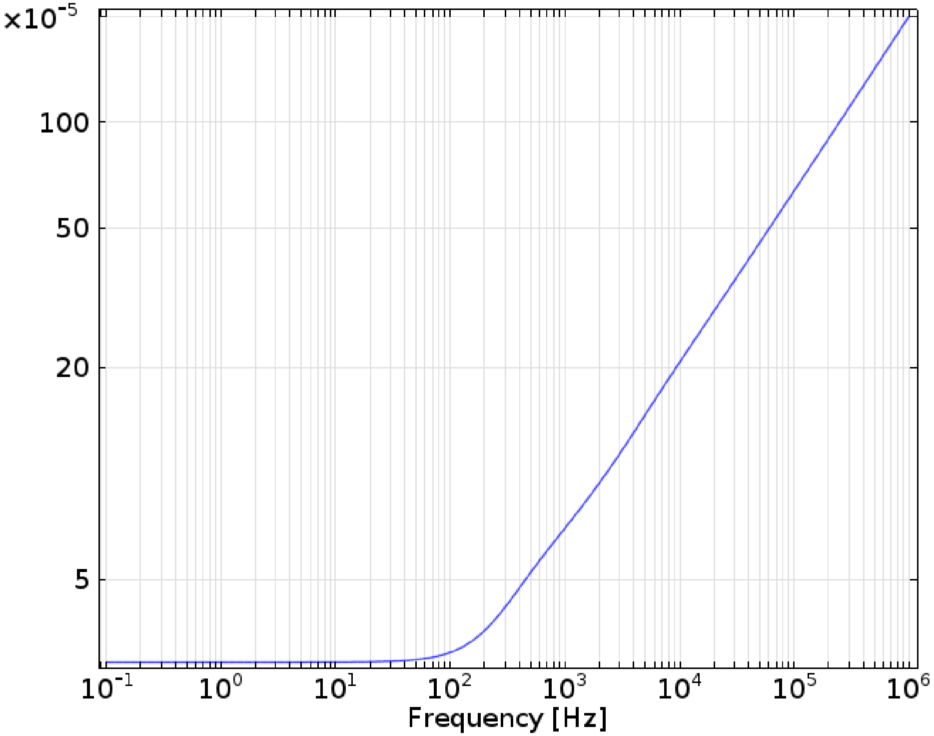


2D plot of skin effect in ACSR cable (current density, A/mm²), 100 kHz

Results
Skin effect



Current density profile at phase conductor for selected frequencies [A/mm²]



Equivalent resistance for an ACSR cable – frequency sweep [Ω/m]

Results
Capacitance Matrix

17.5816	-5.6852	-2.8138
-5.6852	16.4572	-5.6852
-2.8138	-5.6852	17.5816

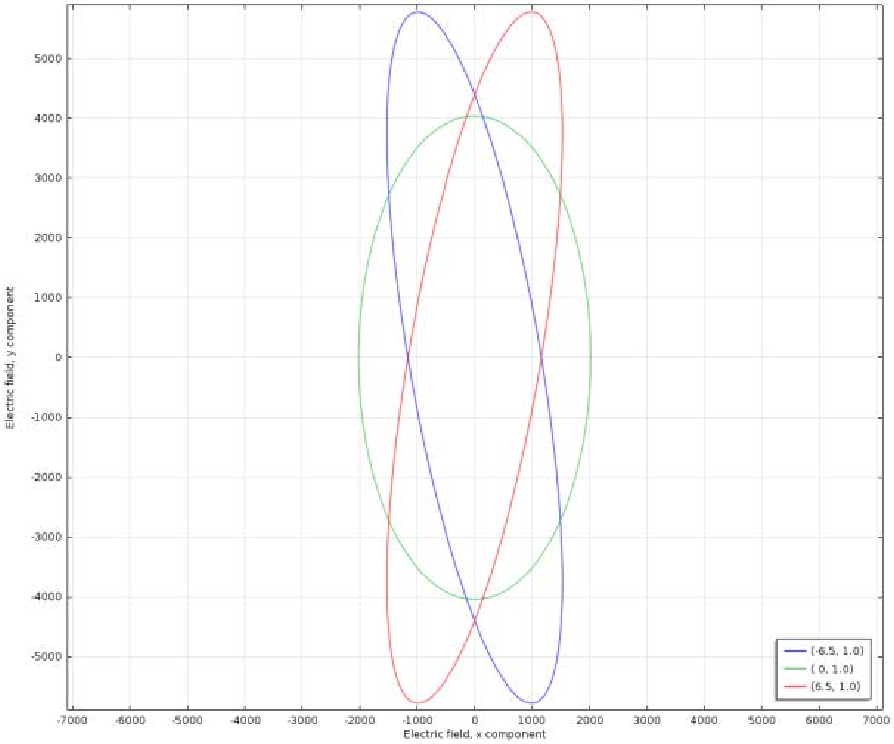
Capacitance Matrix, analytic [nF/km]

17.33746	-5.79948	-3.18350
-5.79948	16.48686	-5.79950
-3.18350	-5.79950	17.33751

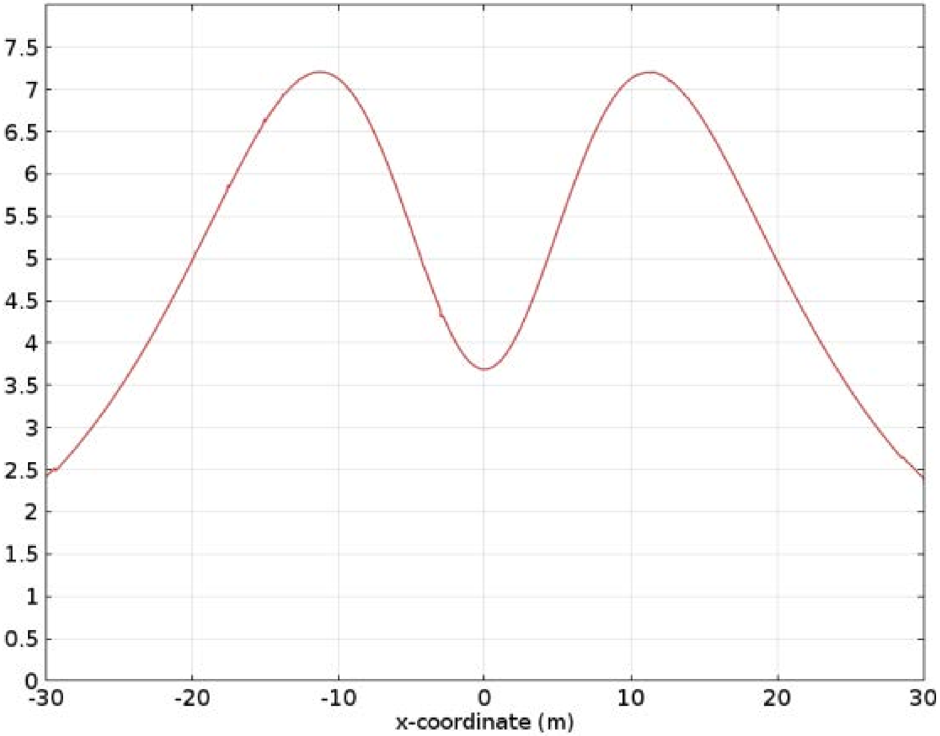
Capacitance Matrix, FEM [nF/km]

Results

Electric field at Ground Level

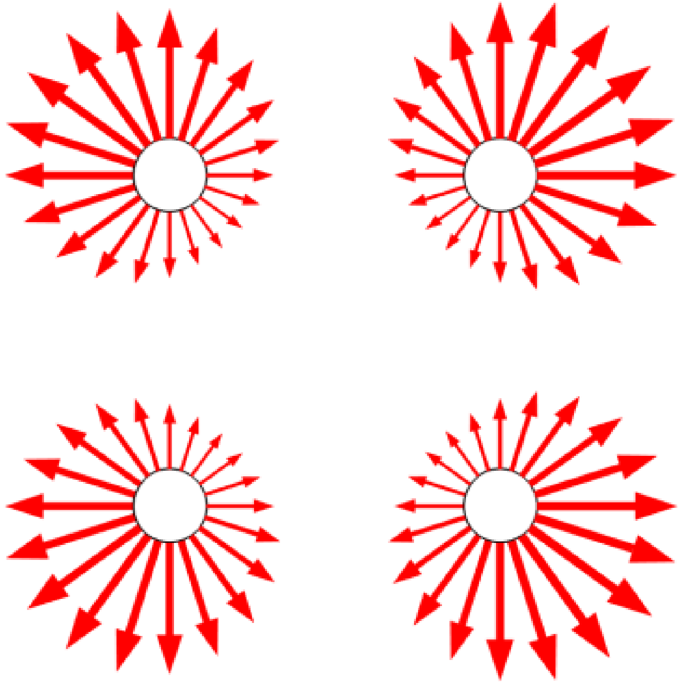


Parametric plot of electric field near ground level [kV/m], at points below each phase

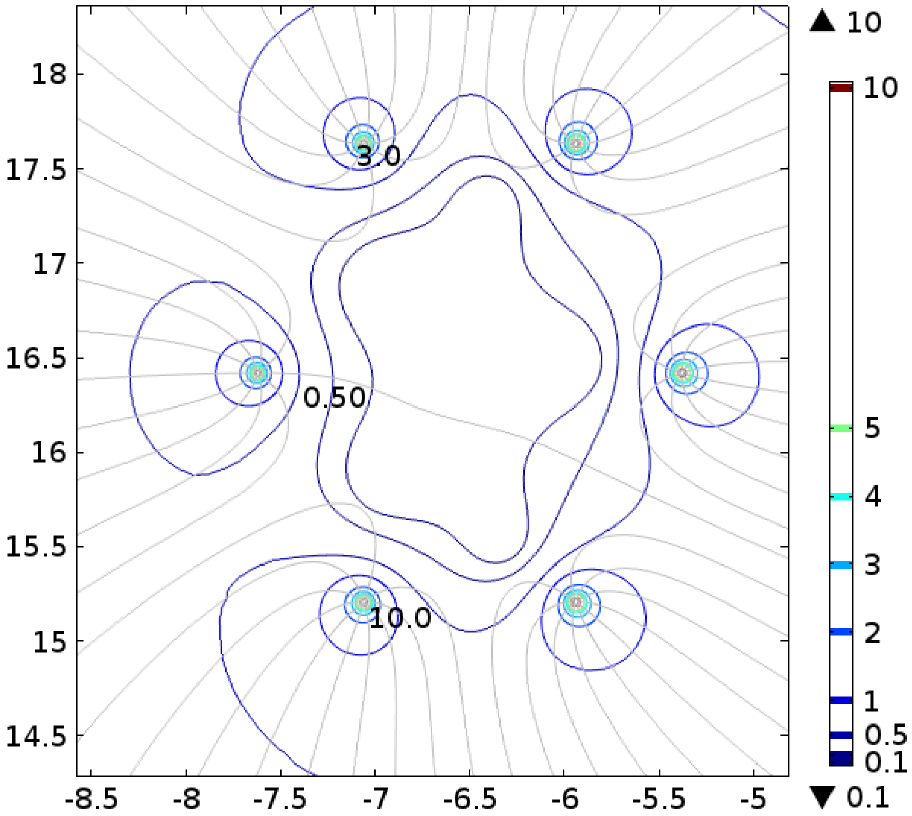


Electric field profile near ground [kV/m]

Results
EM Field near conductors

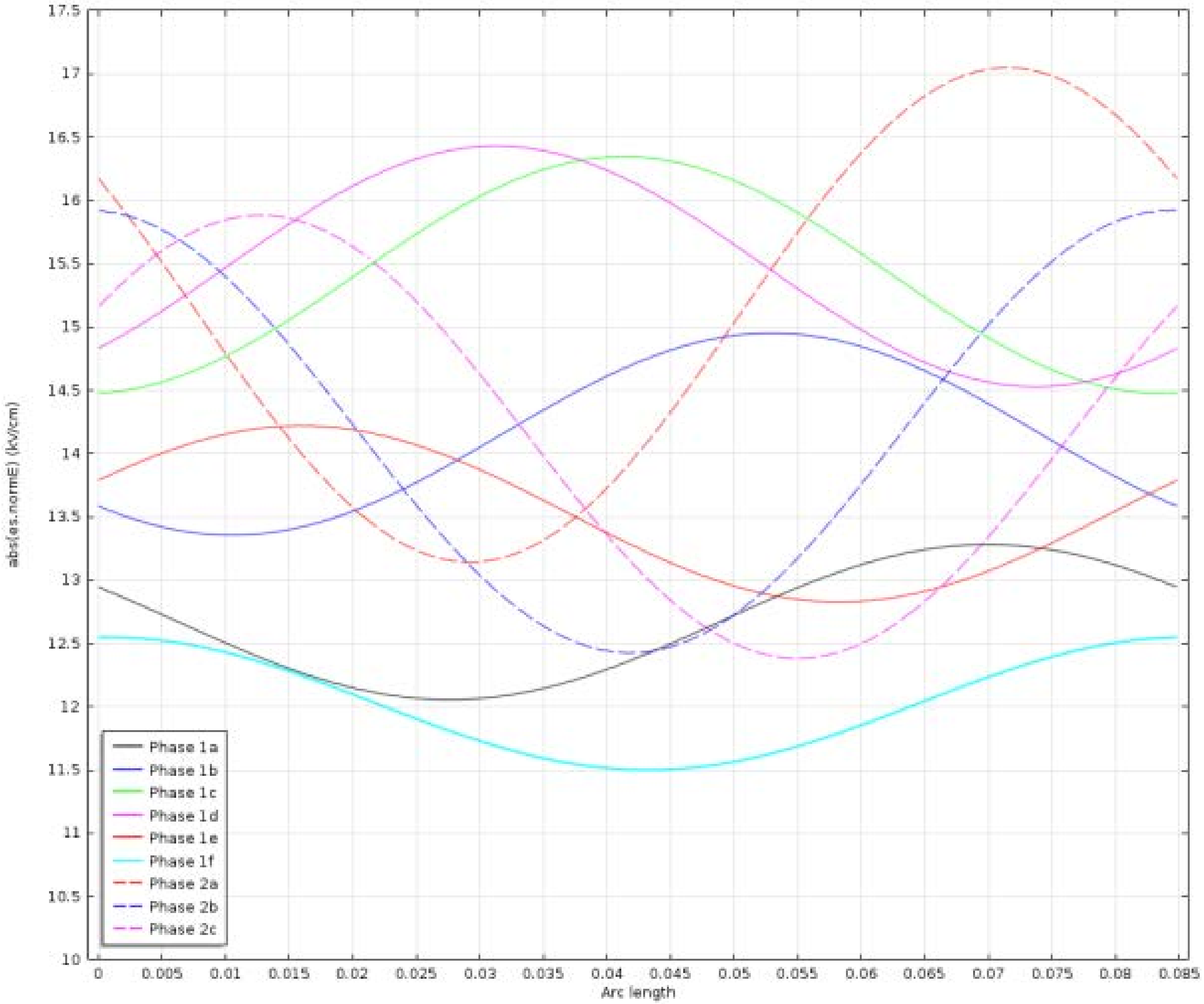


Electric field distribution for a commercial 18” bundle (45.7 cm)



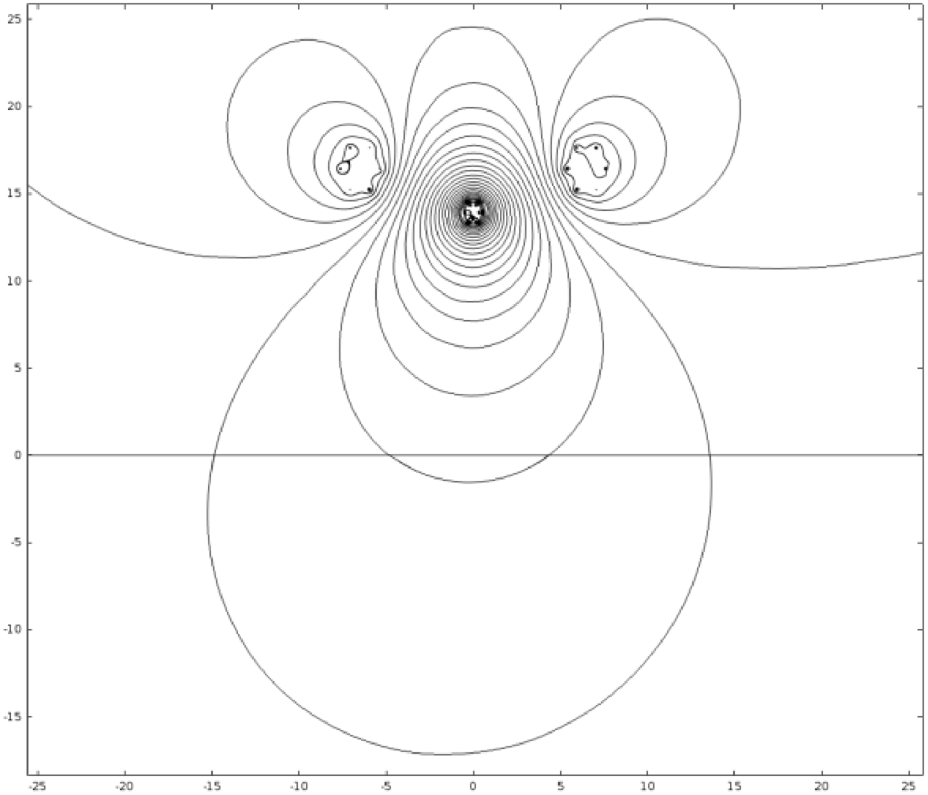
Electric field intensity at outer phase [kV/cm]

Results
EM Field near conductors

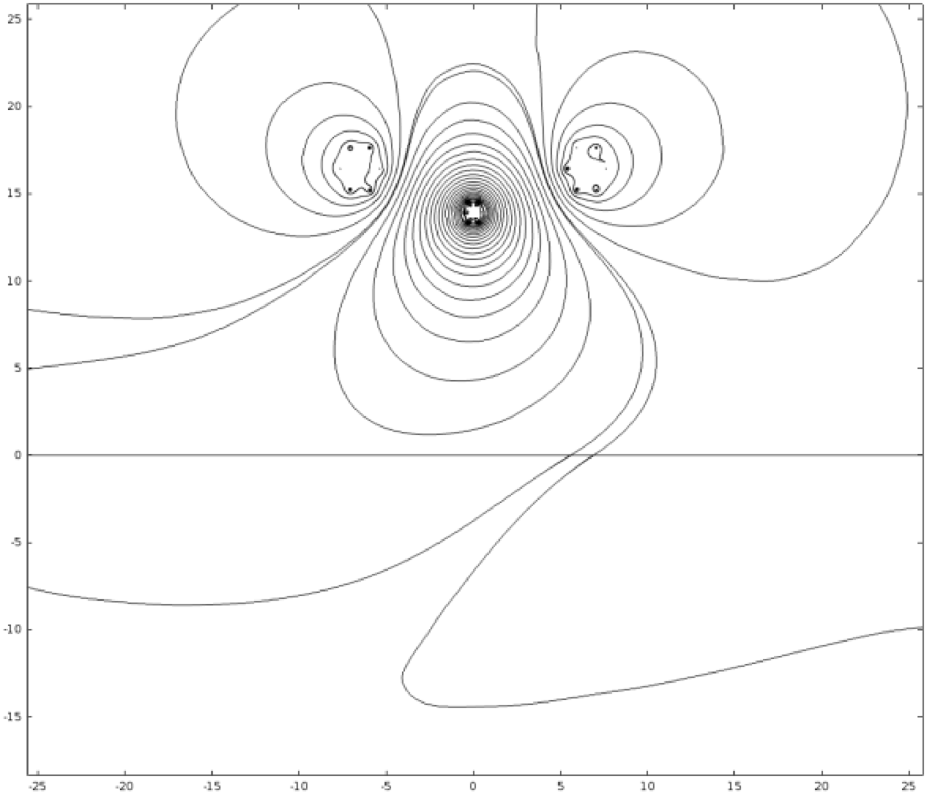


Electric field around outer phase conductors (filled line) and center phase (dashed line)

Results
Magnetic Field



Magnetic lines for 60 Hz current with 10 Ω/m soil, maximum at center phase



Magnetic lines for 100 kHz current, same conditions

Conclusions

- Meshing is a relevant aspect, which must be made with caution. The “boundary layers” option is of great value for observe the skin effect.
- The work arises some questions regarding established premises in both sides, FEM and analytical, such the homogeneous ground in unbalanced systems and the inductance calculation.
- The authors suggests further development in the circuit models inside COMSOL:
  - Two uncoupled circuits (no common ground/ zero port) connected through a 3d model with ports
  - 2d model, but with distinguishable in/ out port

Future research

- Precise modeling of ACSR conductor, including each wire, in 2D and 3D, using helicoidal objects, to investigate the “transformer effect”,
- Interaction with two independent circuit models and a FEM domain, including considerations about “remote ground” reference,
- Extrusion of 2D solution for a 3D model, as an analogy of “3D revolve”,
- 2D magnetic model with assumptions of “in” and “out” terminals for a same domain.

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Thank you.

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