Centro de Pesquisas de Energia Elétrica – CEPEL

Departamento de Linhas e Estações

Eletrobras
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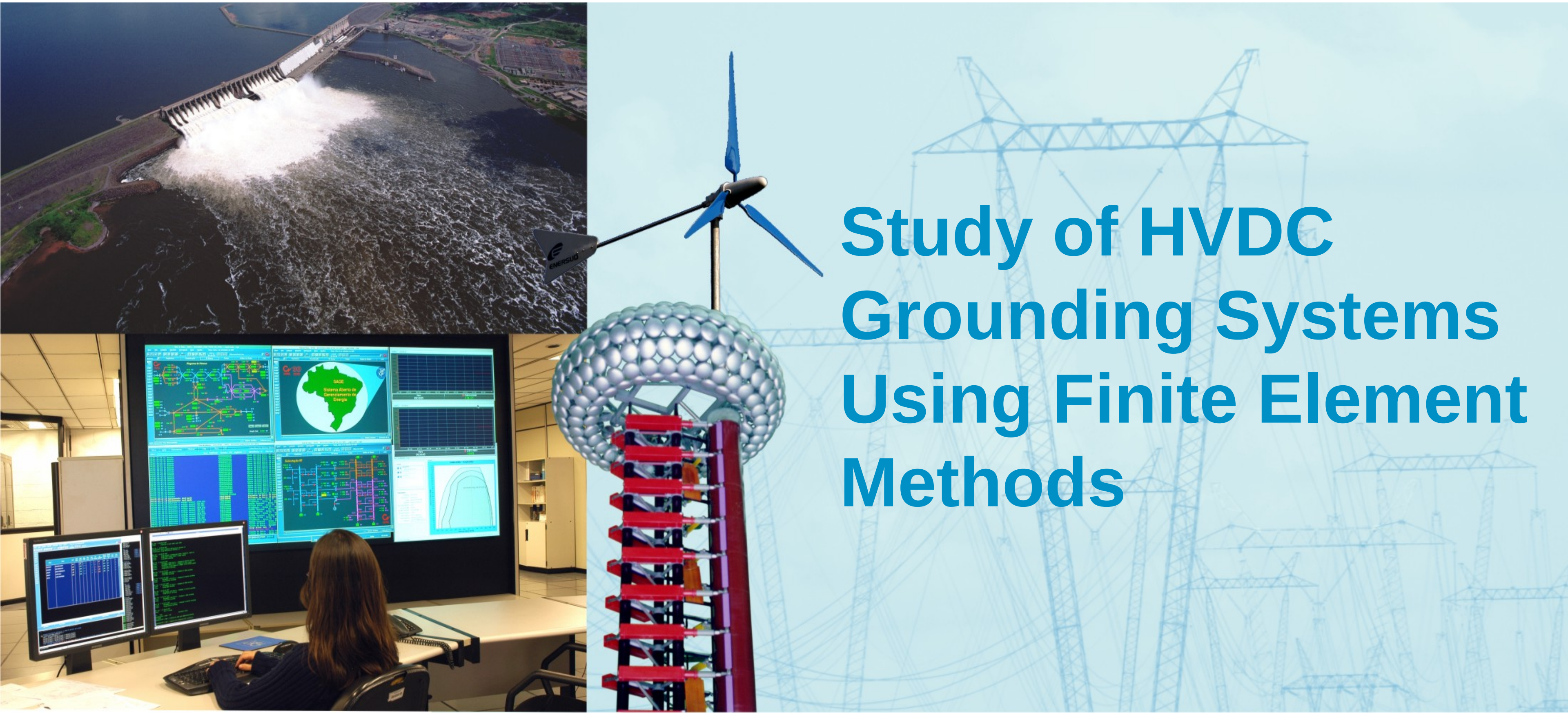

Study of HVDC Grounding Systems Using Finite Element Methods

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COMSOL
CONFERENCE
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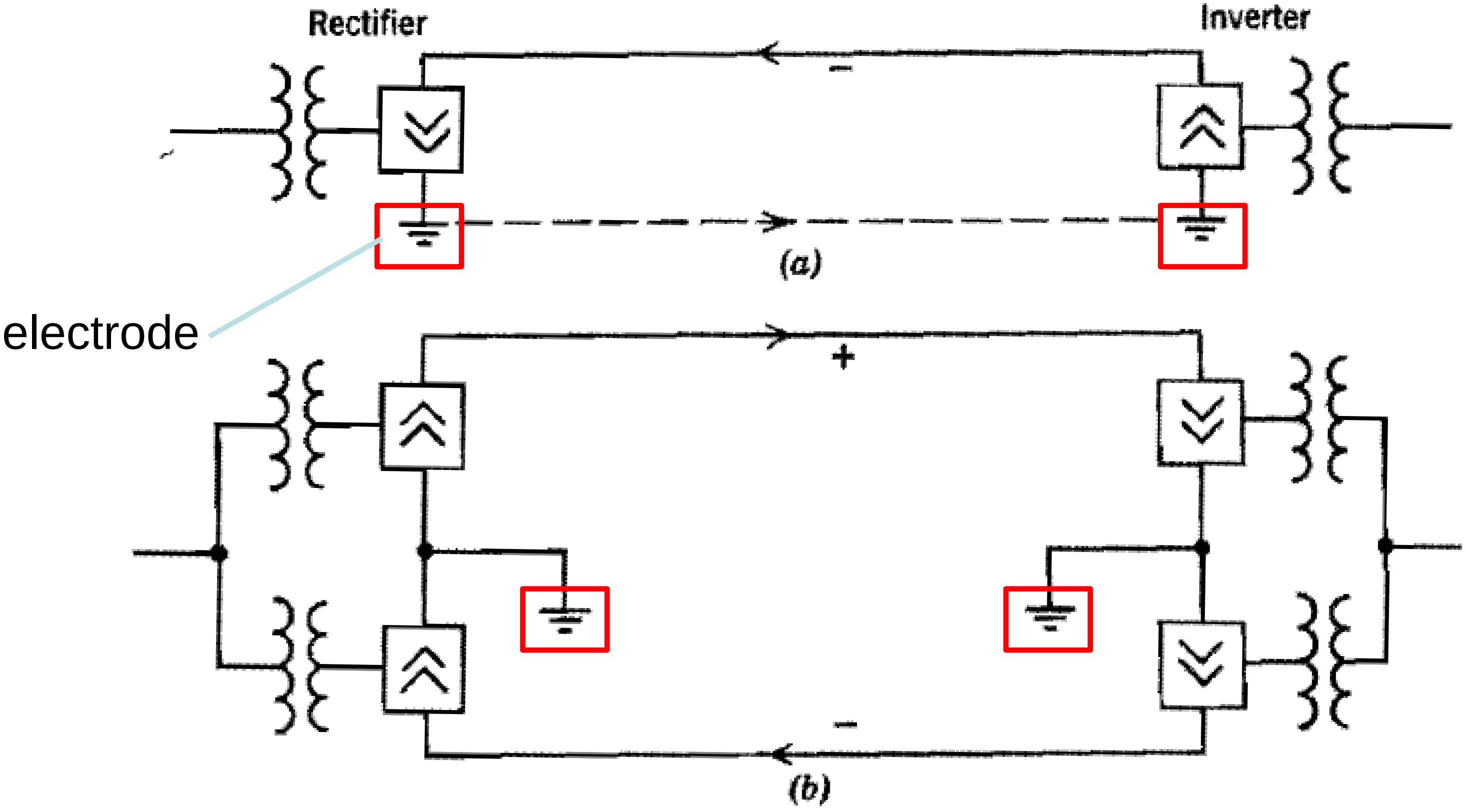
Different aspects, according to the function

- AC: “system reference”, low usage (balanced system)
- Transient (e.g. lightning, short circuit, surge arrester): high power, short time (ms to s)
- DC (monopolar): high power and long time
  - High energy → high current density → electroosmosis and soil drying → lost of conductivity/ contact
  - Self corrosion or in nearby structures
  - Transformer core saturation through neutral current
- DC (bipolar): contingency only (hours to days/ year)

Introduction
HVDC Link Design

- Typical designs: (a) monopolar, (b) bipolar (Kimbark, 1971)
  - Bipolar lines can operate in monopolar mode, in case of contingency



Introduction

Project considerations

- “A return path via ground electrodes will normally have a considerably smaller resistance than any reasonable metallic conductor return” (Cigré WG, 1998)
- Distances between converter stations to electrodes range from 8 to 85 km, because:
  - Cost/ permission of the site,
  - Distance to metallic objects (the converter station, pipelines, cables, grounding networks, other AC stations, distribution transformers)
  - Proper geology (resistivity, moisture, thermal conductivity, water depth etc)
- Two groups of problems with different aspects:
  - **Distant problems**, far from the electrode: conducted current in metallic structures → deep soil layers;
  - **Local problems**: current density, touch and step potentials, contact resistance, heating and drying → electrode material, geometry, shallow layer;

Objectives

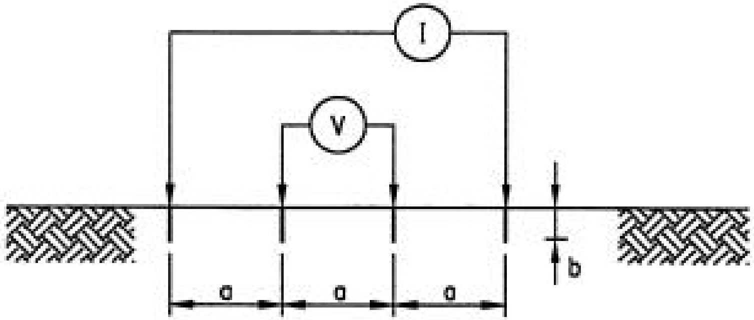
Apply the Finite Element Method in some aspects of HVDC electrode design:

- Ground resistivity estimation
  - Simulation of the Wenner Method in irregular layers
- Electrode performance
  - Multiphysics simulation (electrical + thermal) of some electrode designs
    - Horizontal (Ring)
    - Vertical (Rods)
  - Effects in metallic structures
- Considerations for future research

Soil resistivity measurement

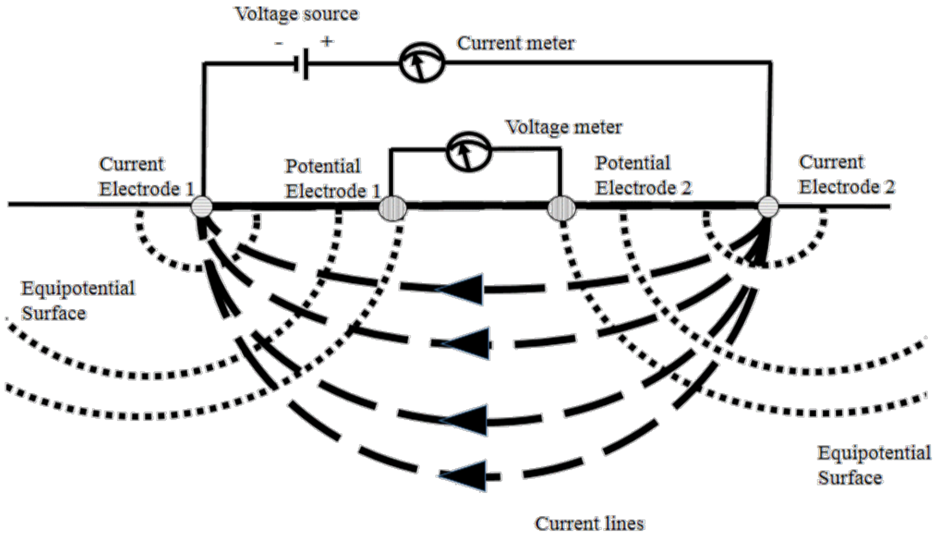
- The Wenner Method (1915) is very usual and reliable for shallow measurements (equal to distance a);
- Other know method is the Schlumberger, basically another arrangement for the electrodes,
- For deep measurements, magnetotelluric methods could be employed, among others.

$$\rho_e = \frac{4\,\pi\,a\,R_w}{1+\frac{2a}{\sqrt{a^2+4b^2}}-\frac{a}{\sqrt{a^2+}}} \cong 2\,\pi\,a\,R_w$$



Soil resistivity measurement

- The soil are assumed to be stratified, composed by layers of distinctive materials;
- The Wenner measures the relation V/I, giving resistance (for a certain frequency);
- The resistivity is an approximate relation by volume traversed by the electric current → depth approx. to distance a;
- The resistivity are greatly influenced by moisture, salinity and temperature, e.g. from ~2000 Ωm @ -10°C to ~60 Ωm @ 25°C (ABNT, 2012)
- Other relevant quantities are permittivity, thermal conductivity and heat capacity;



Soil resistivity measurement

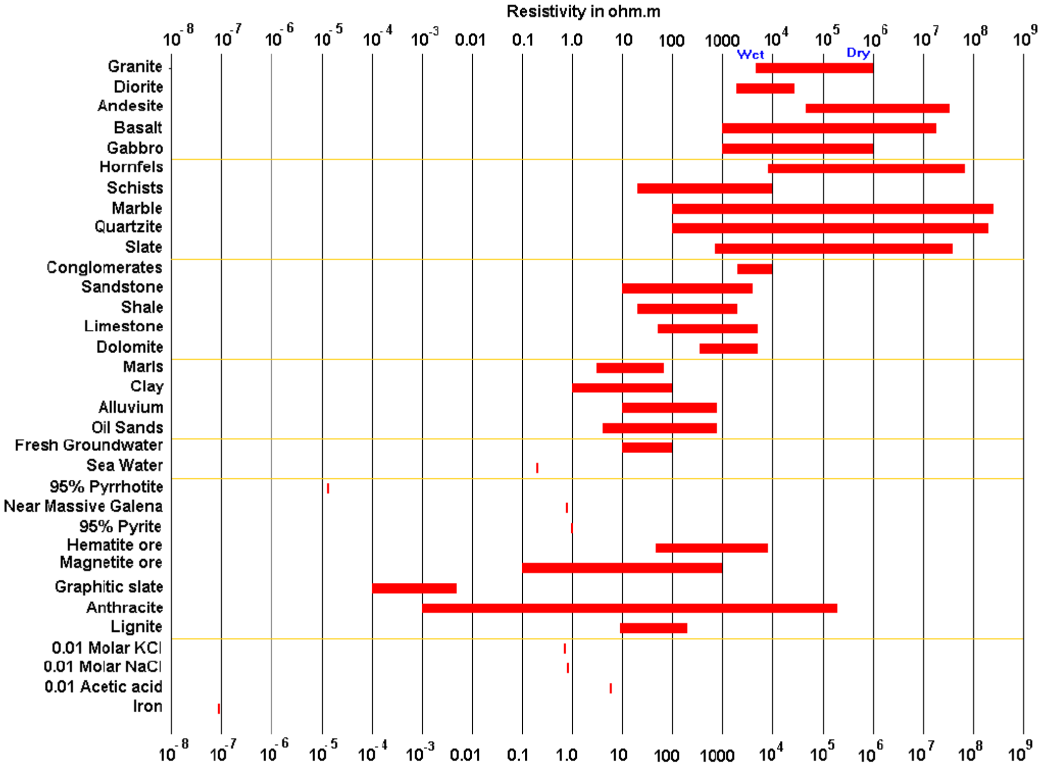
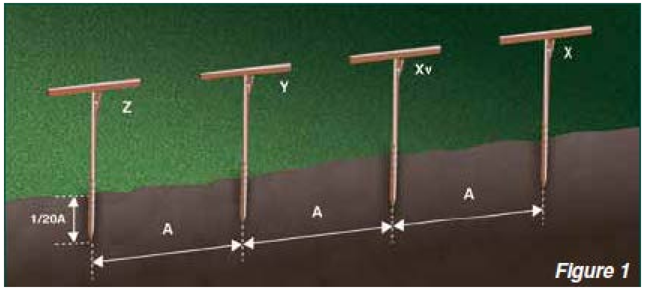
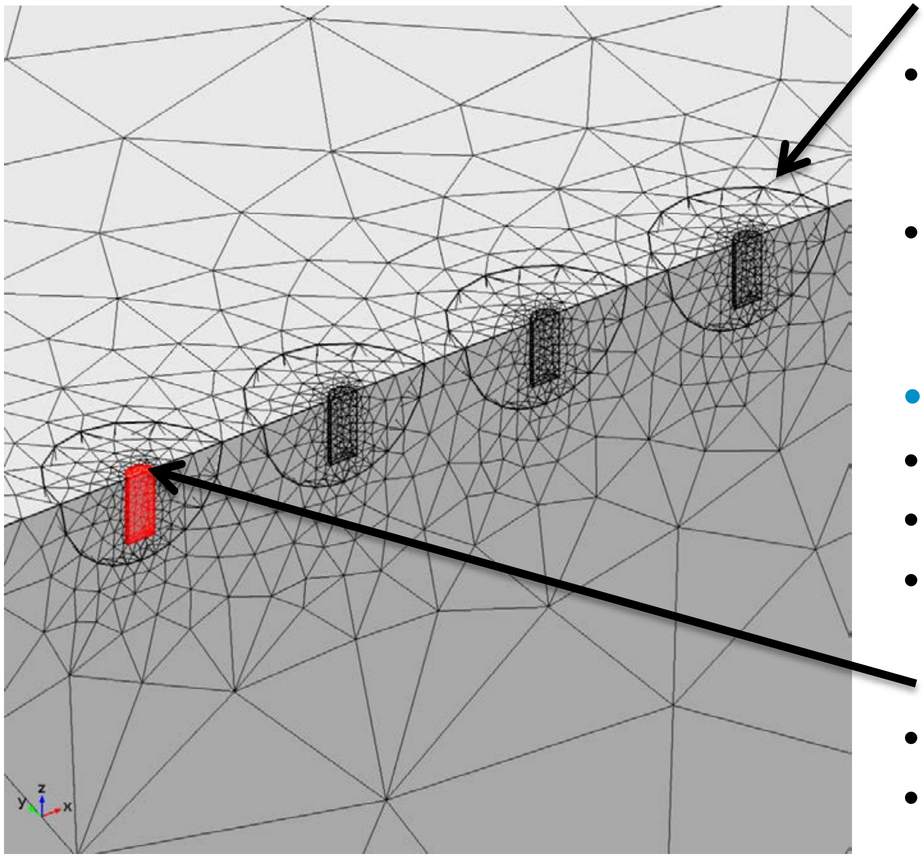


Table from Loke (2001)



Images from http://www.shopaemc.com/content/aemc-understanding-soil-resistivity-testing.html

Case 1: Validation of Wenner Method



•Meshing

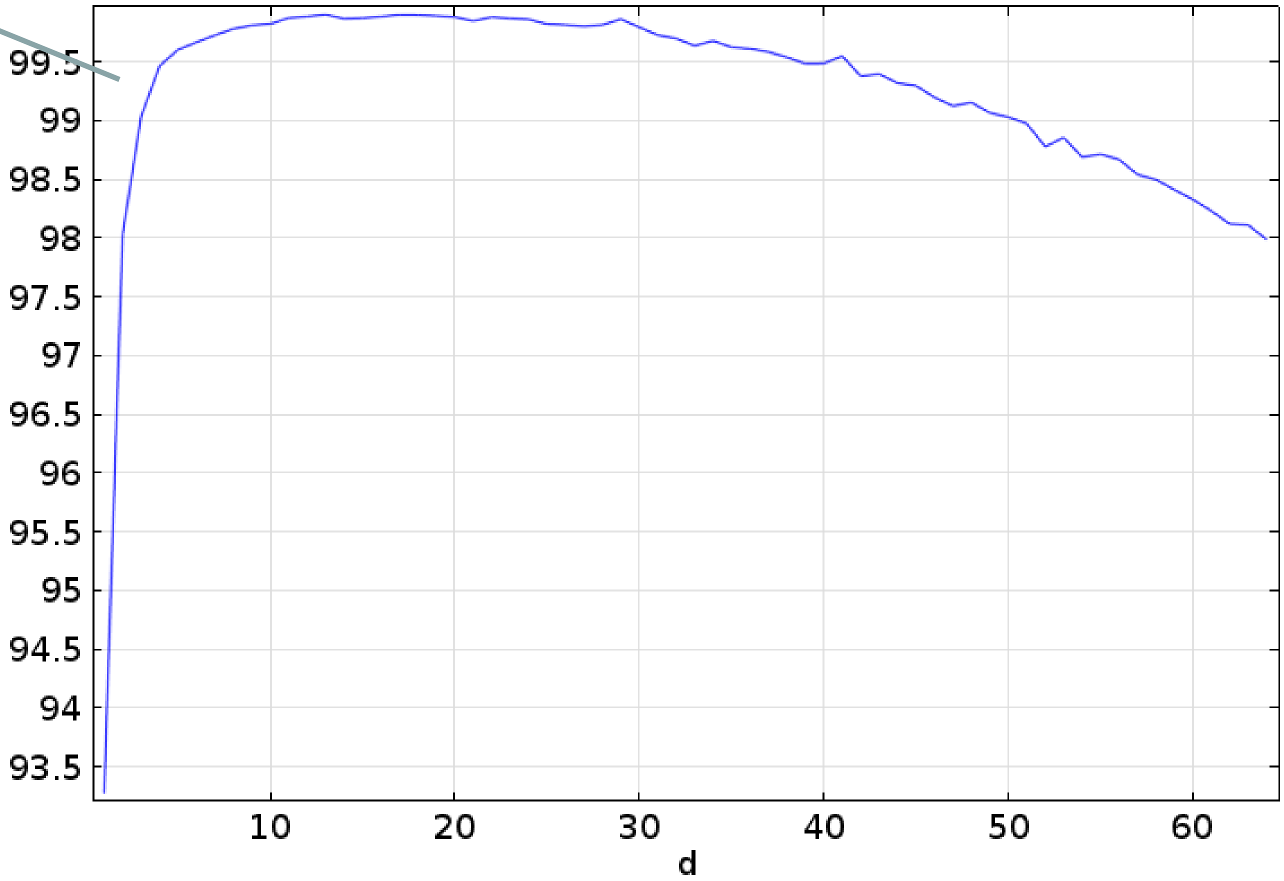
- Subdomains near the electrodes, for proper meshing;
- Initially used ”copy domain” in the wenner probes, but default “free tetrahedral” works fine;
- Infinite domain (hemispherical domain 250 m radius with boundary layer 20 m thick)

•Study configuration

- Probe depth 30 cm;
- Parametric sweep of distance a;
- Electrical circuit physics emulates the earth meter (current source + resistor as the voltmeter);
- Terminals at the top of each rod;
- “ideal ground” at the infinite domain;

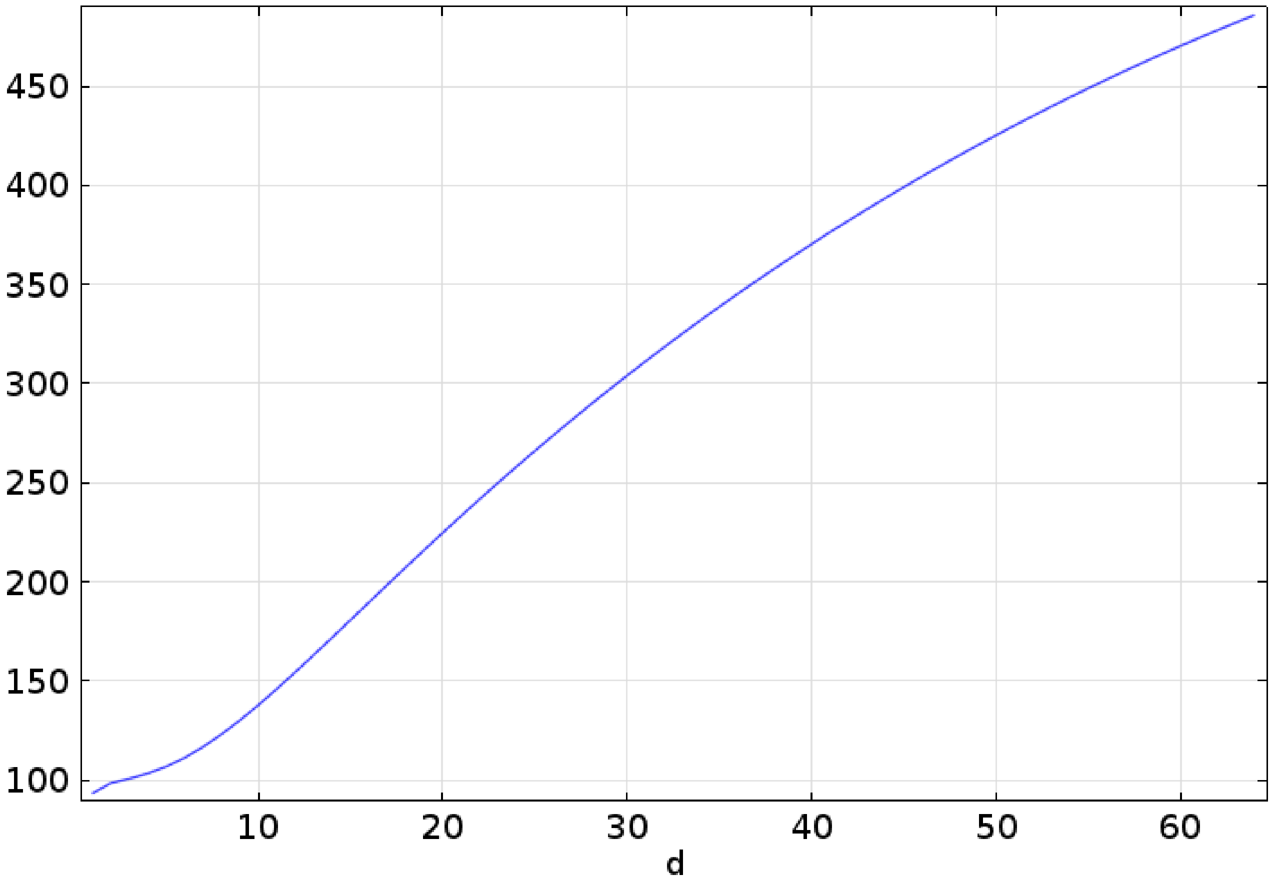
Case 1: Validation of Wenner Method

Proximity between electrodes (recommended by ABNT 2012 as probe depth < a/10)



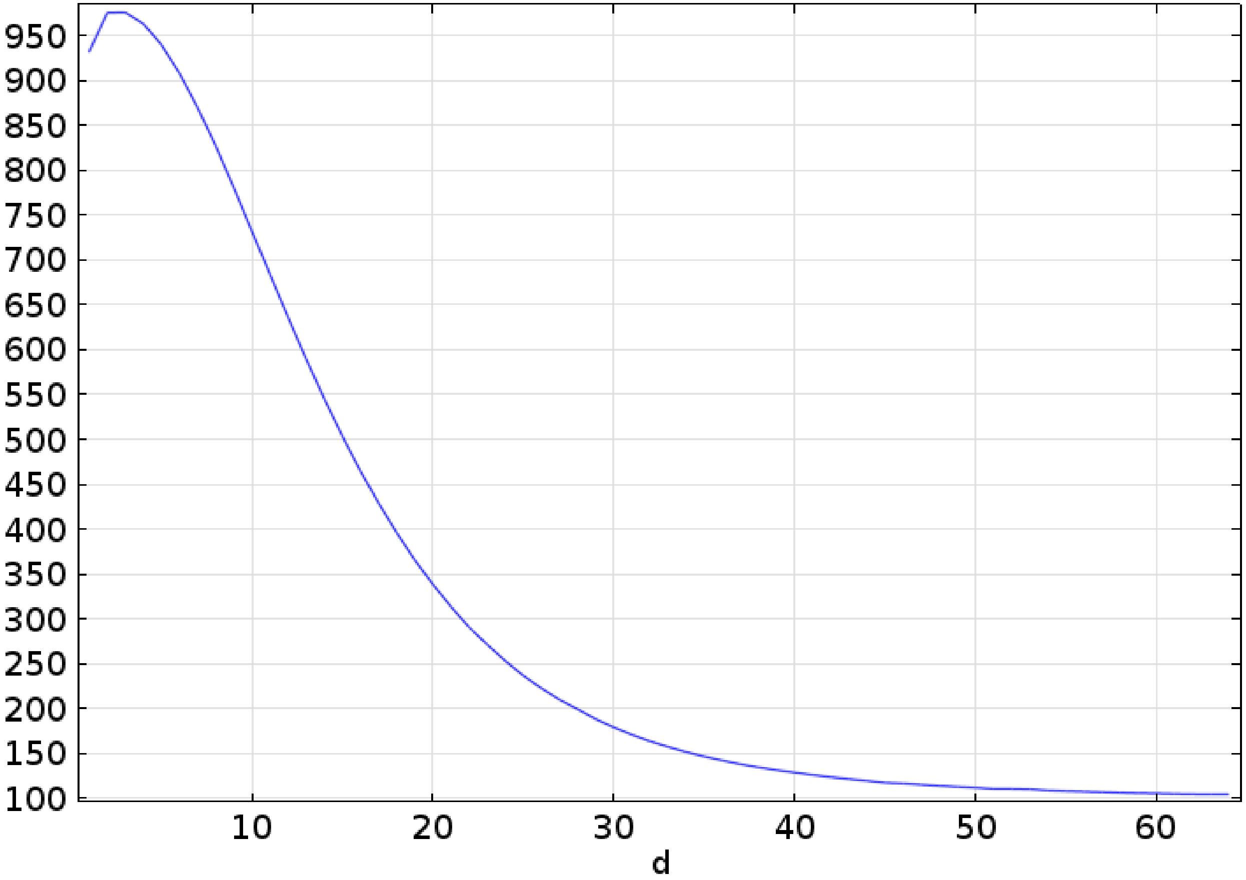
Constant soil, 100 Ωm

Case 1: Validation of Wenner Method



Upper layer 100 Ωm, lower layer 1000 Ωm, depth 10 m

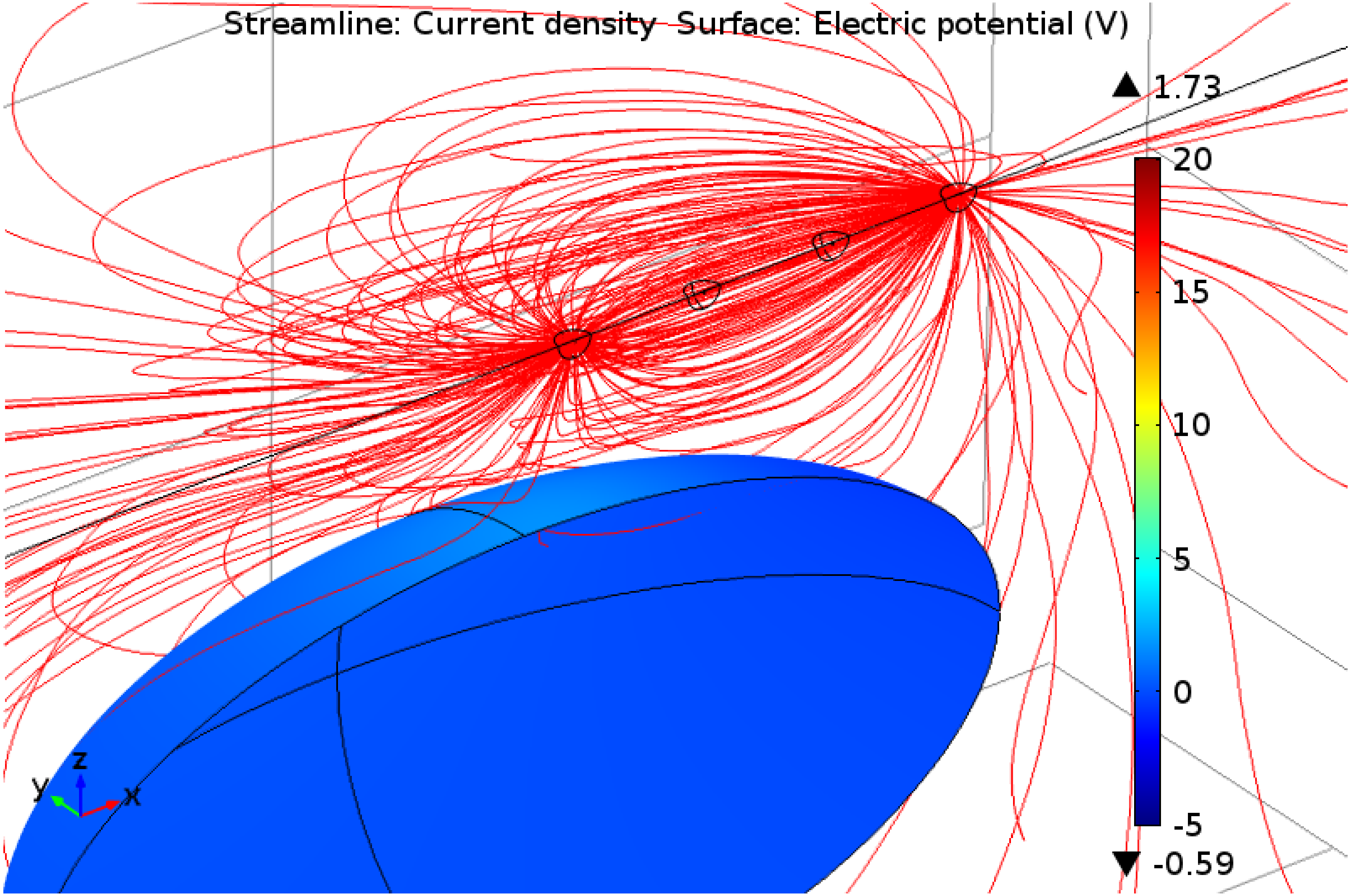
Case 1: Validation of Wenner Method



Upper layer 1000 Ωm, lower layer 100 Ωm, depth 10 m

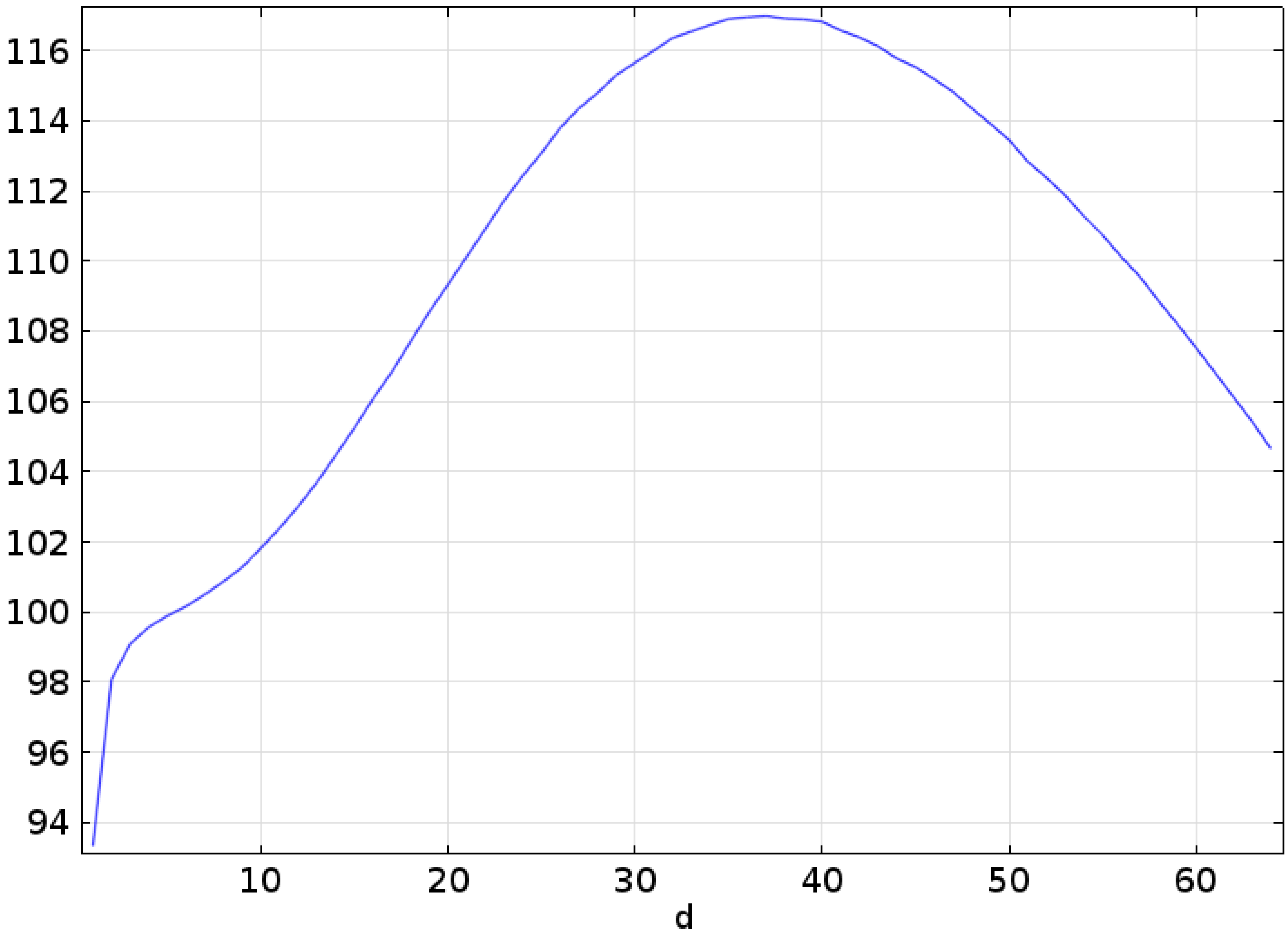
Case 1: Validation of Wenner Method

Effect of an irregular soil



Case 1: Validation of Wenner Method

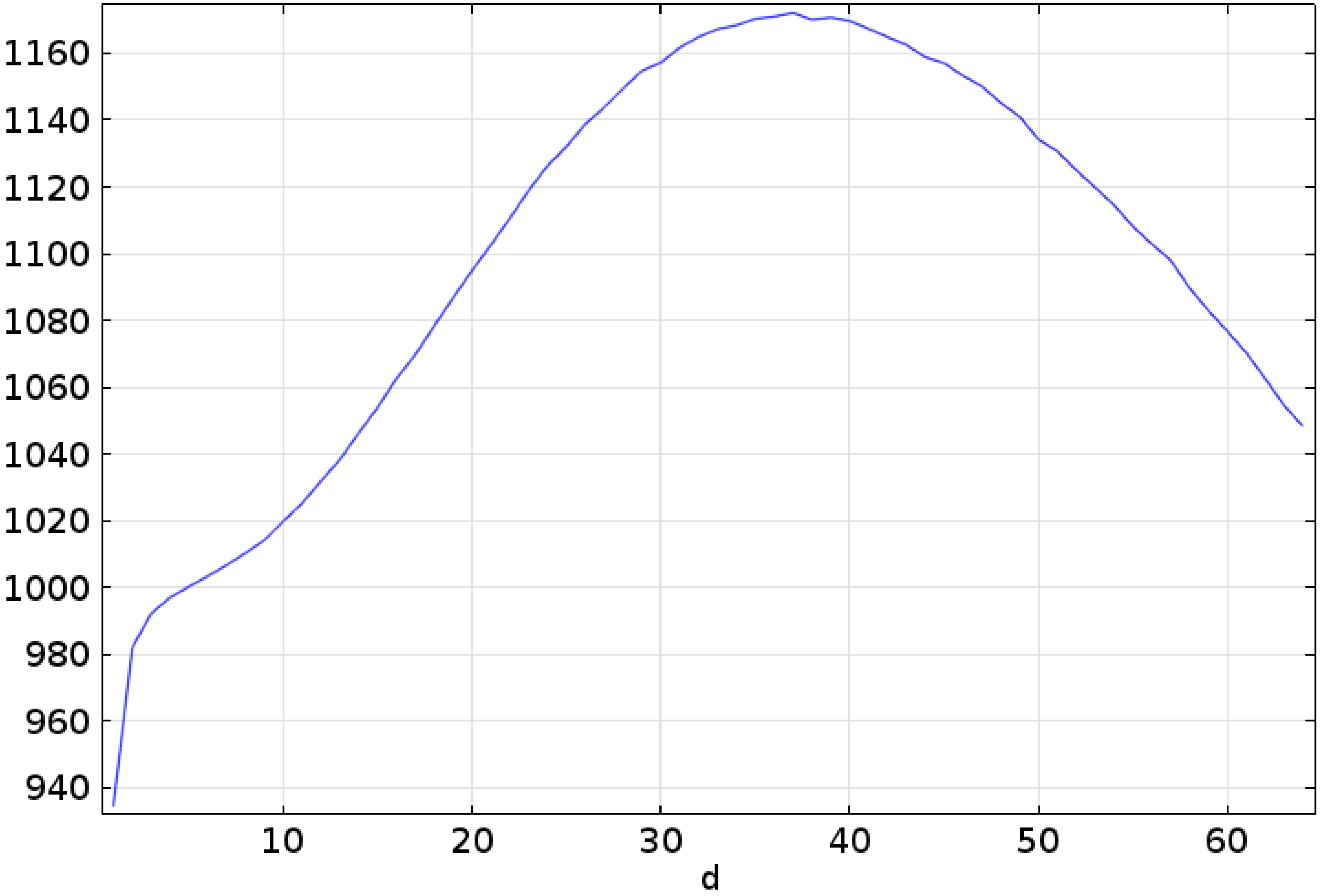
Effect of an irregular soil



Soil 100 Ωm, rock 1e6 Ωm

Case 1: Validation of Wenner Method

Effect of an irregular soil



Soil 1000 Ωm, rock 1e6 Ωm

Case 2: Comparison of Electrode Designs

- Some theoretical configurations are presented:
  - Land electrode
    - Horizontal (ring, toroidal)
    - Vertical (rod)
- Considerations are made with typical values, for a real case study consider:
  - Measure on site,
  - Statistical variations,
  - Dependency/ correlation between parameters.
- Expected results:
  - Current density;
  - Ground potential rise;
  - Maximum ground electric field;
  - Temperature profile;

Case 2: Comparison of Electrode Designs

- Parameters considered in the case:

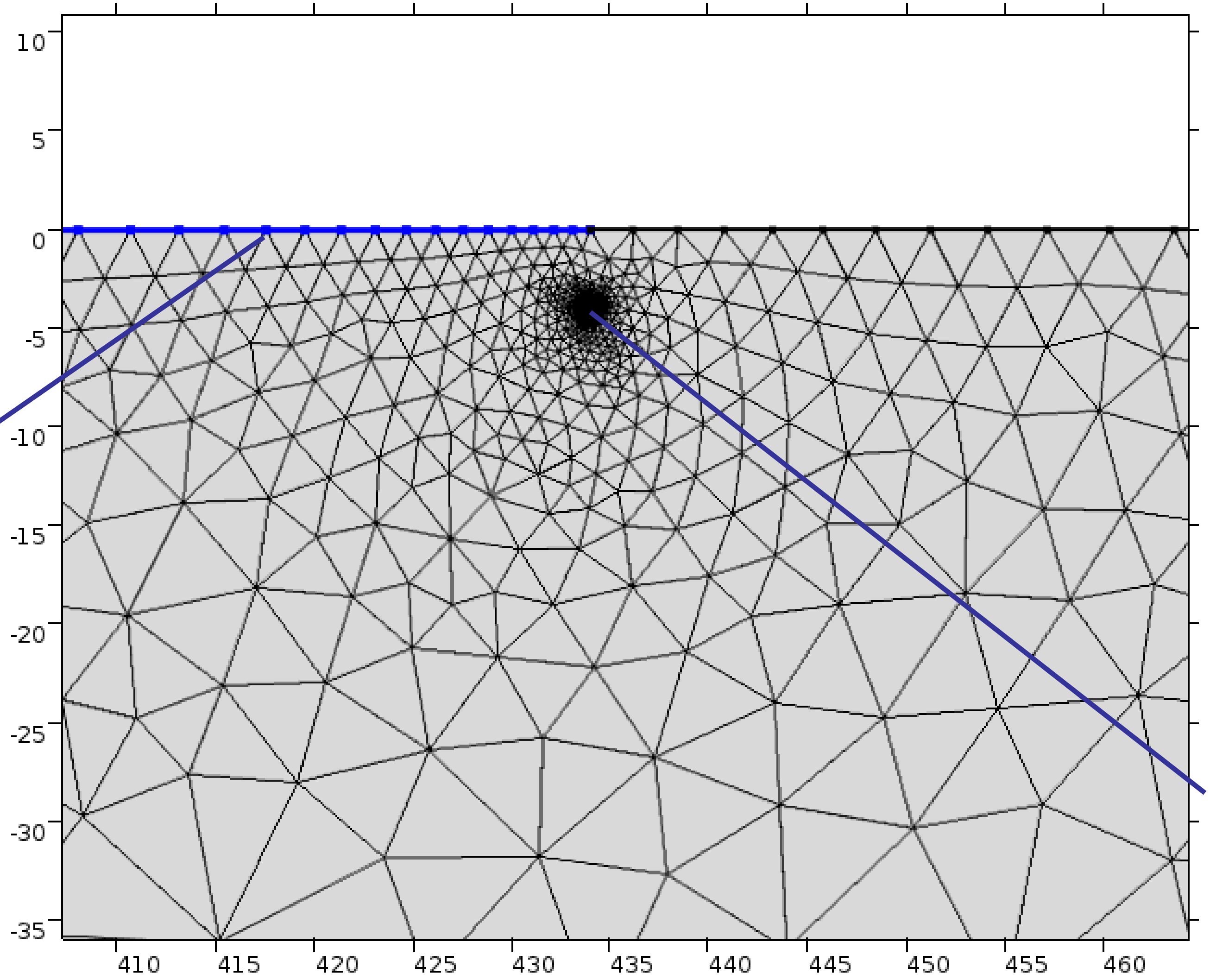
From EPRI (1981) – sample case

Soil resistivity	50 Ωm
Thermal conductivity	1.3 W/°C m
Heat capacity	1 MJ/m^3 °C
Maximum natural soil temperature	28°C
Maximum electrode temperature	96°C
Current distributor (electrode core)	Metallic rod
Electrode body	Coke
Coke resistivity	0.2 Ωm

From CIGRÉ(1998) – Foz do Iguaçu Station

Design current @ maximum time	2625 A @ 8-10 d/ yr
Equivalente resistance	0.267 Ω
Maximum gradient	26.2 V/m
Electrode diameter	868 m
Electrode depth	3.86 m
Core diameter	45 mm
Coke cross section	Square 0.53 x 0.53 m
Soil profile	
•First layer	400 Ωm
•Second layer	50 Ωm @ 400 m
•Third layer	14000 Ωm @ 15 km
•Fourth layer	800 Ωm @ 30 km

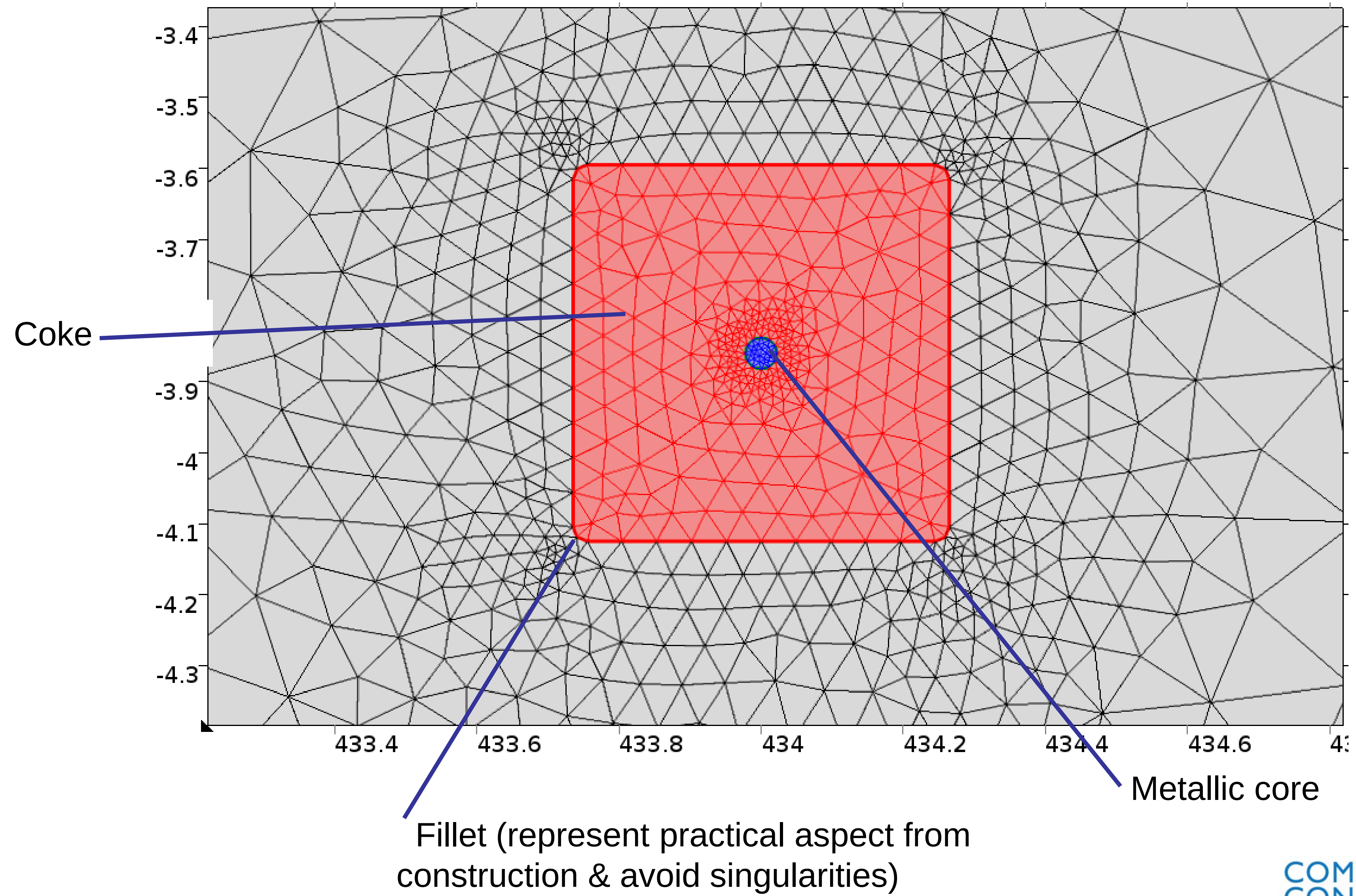
Case 2: Comparison of Electrode Designs



Proper meshing at surface (predefined distribution type, element ratio > 50)

Extreme dimensional differences

Case 2: Comparison of Electrode Designs



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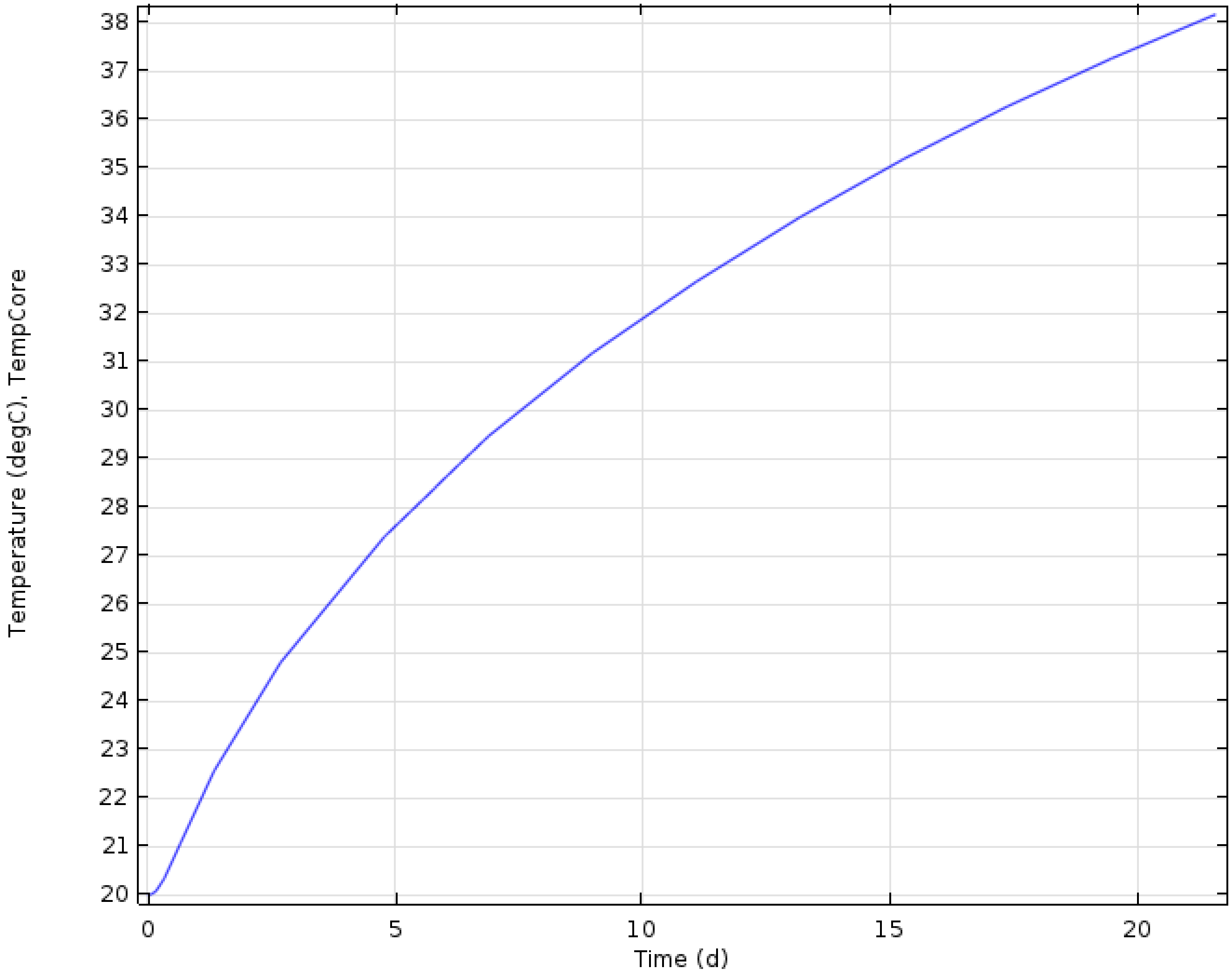
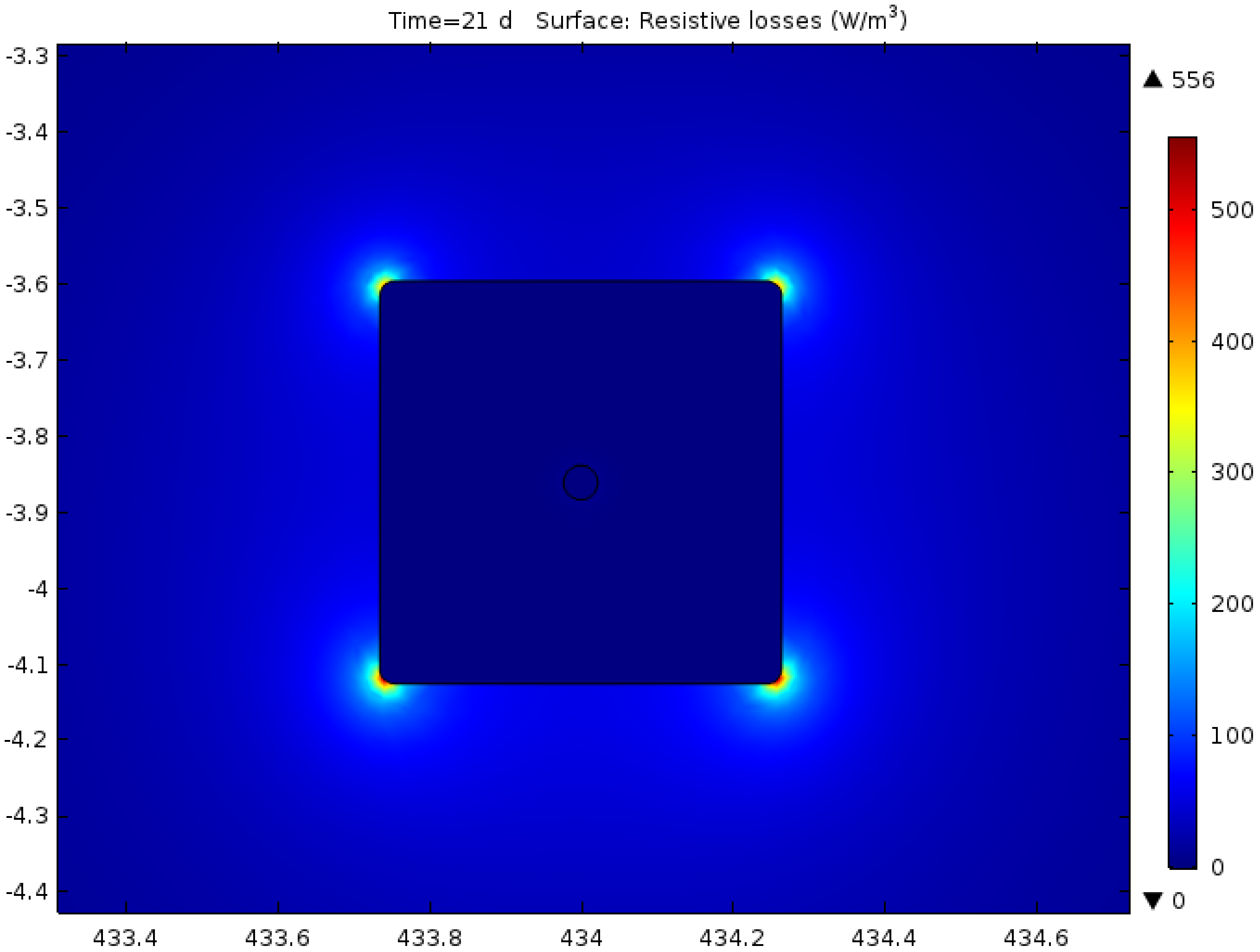


Theoretical temperature rise in electrode core in a time span of 3 weeks

Case 2: Comparison of Electrode Designs



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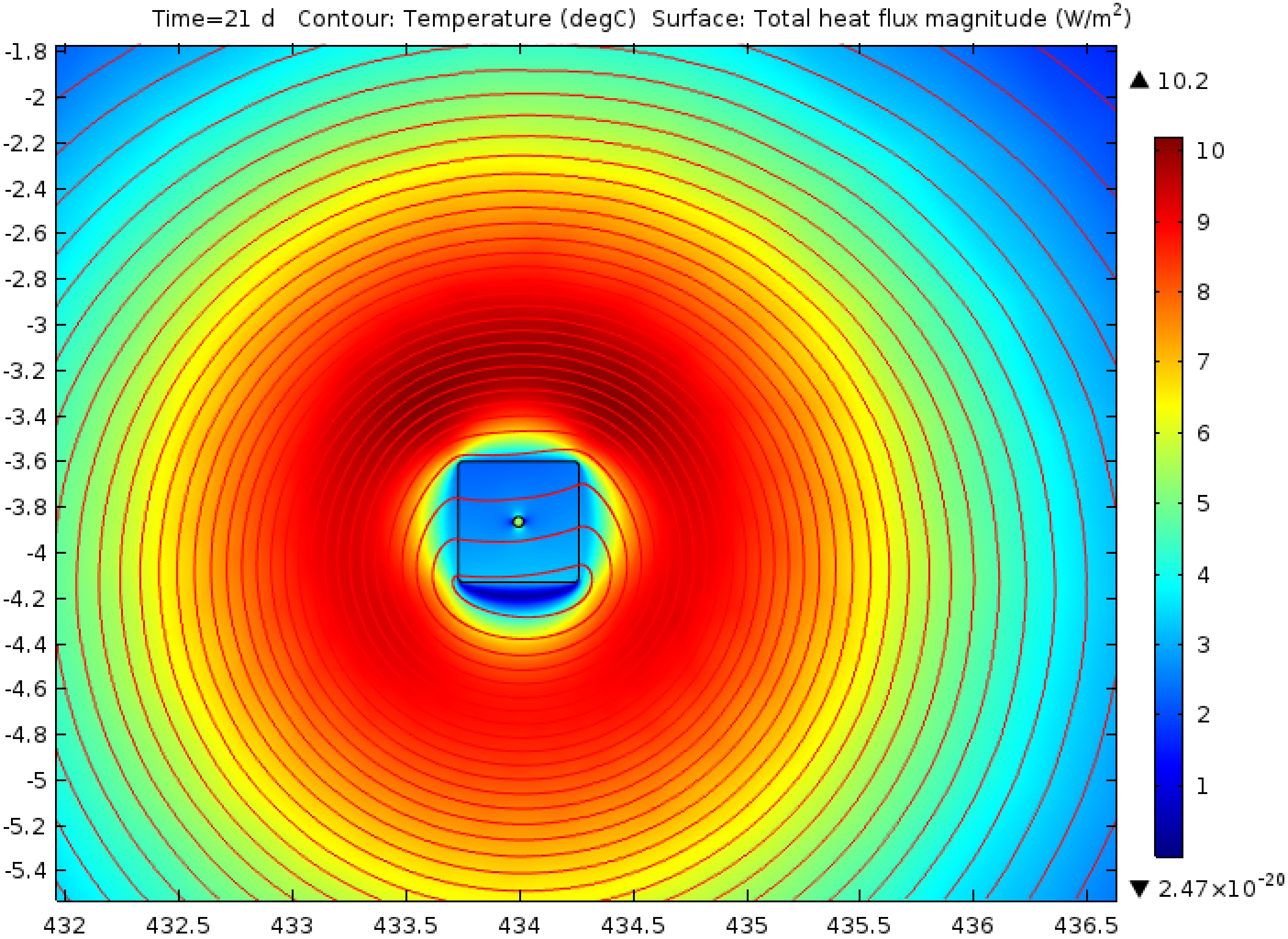

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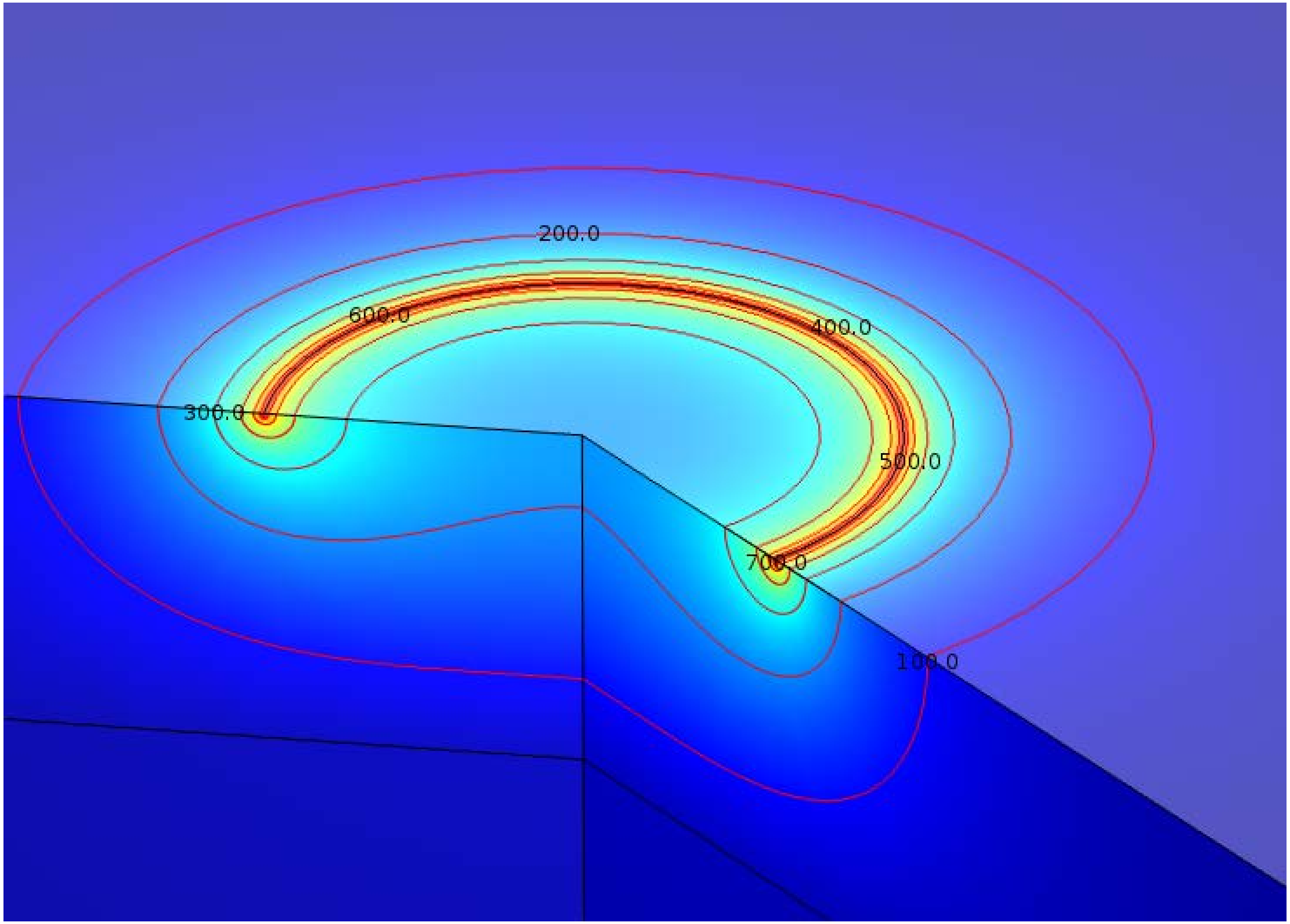
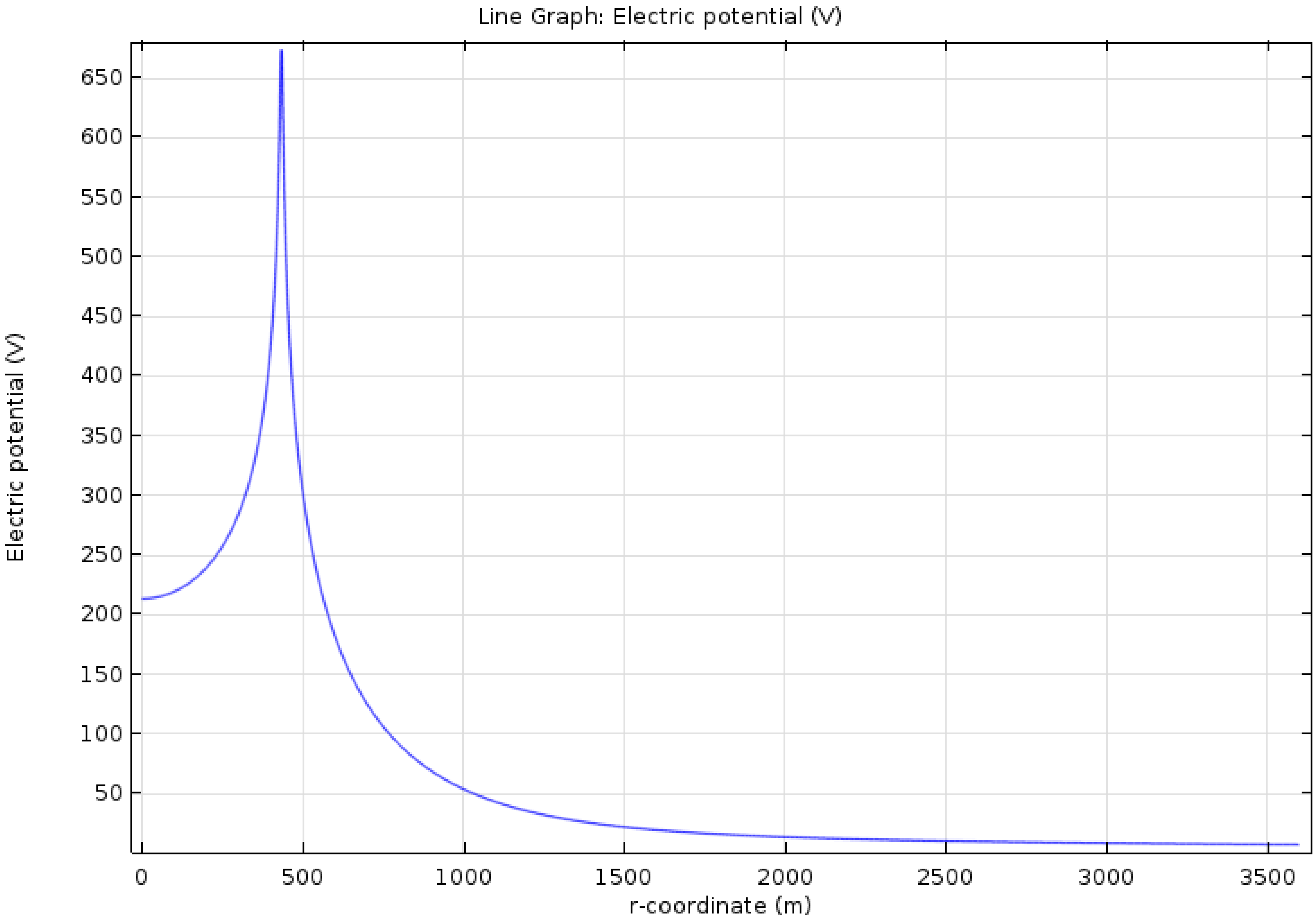


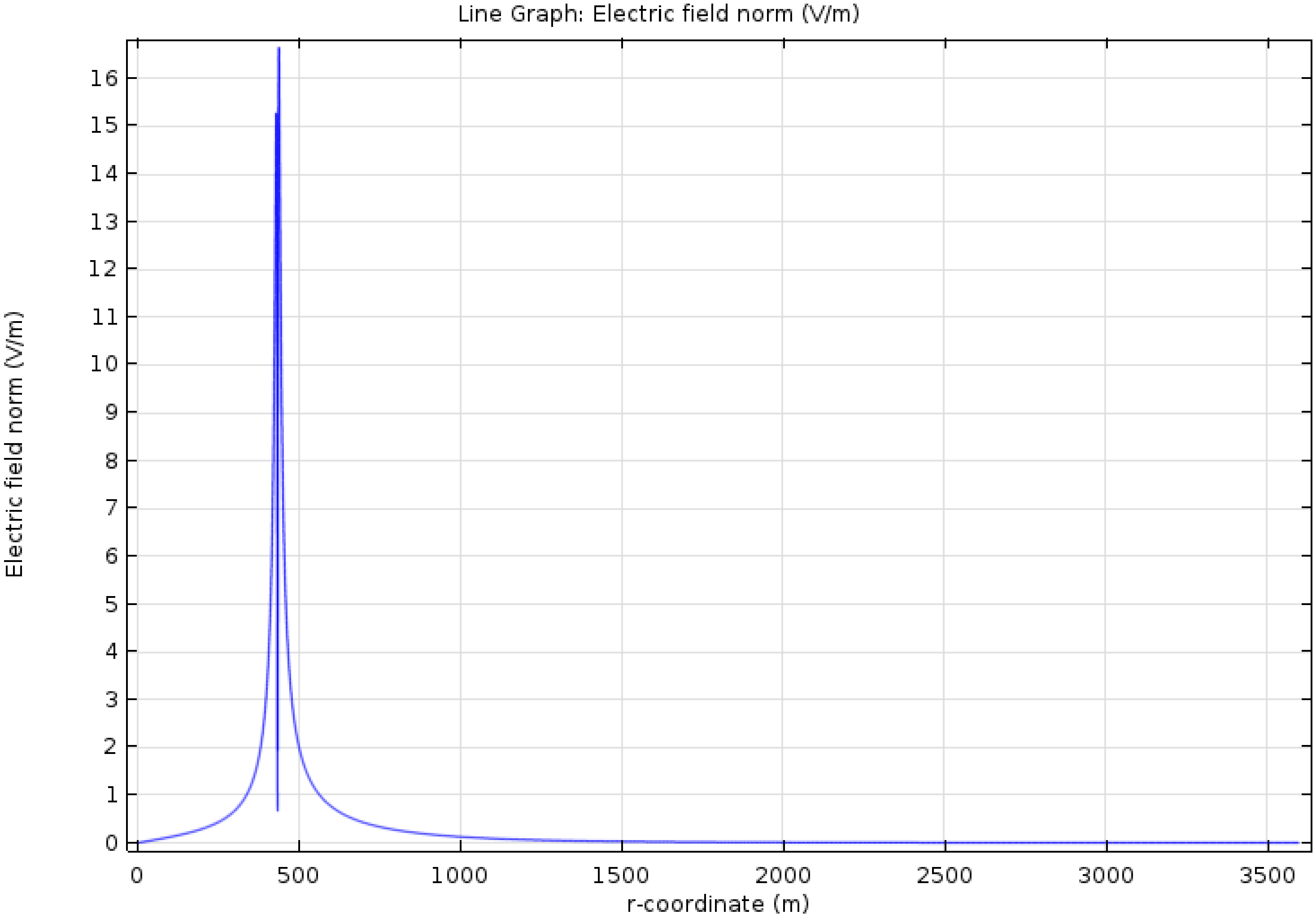
Surface plot, revolved, potentials

Case 2: Comparison of Electrode Designs



Profile at ground level

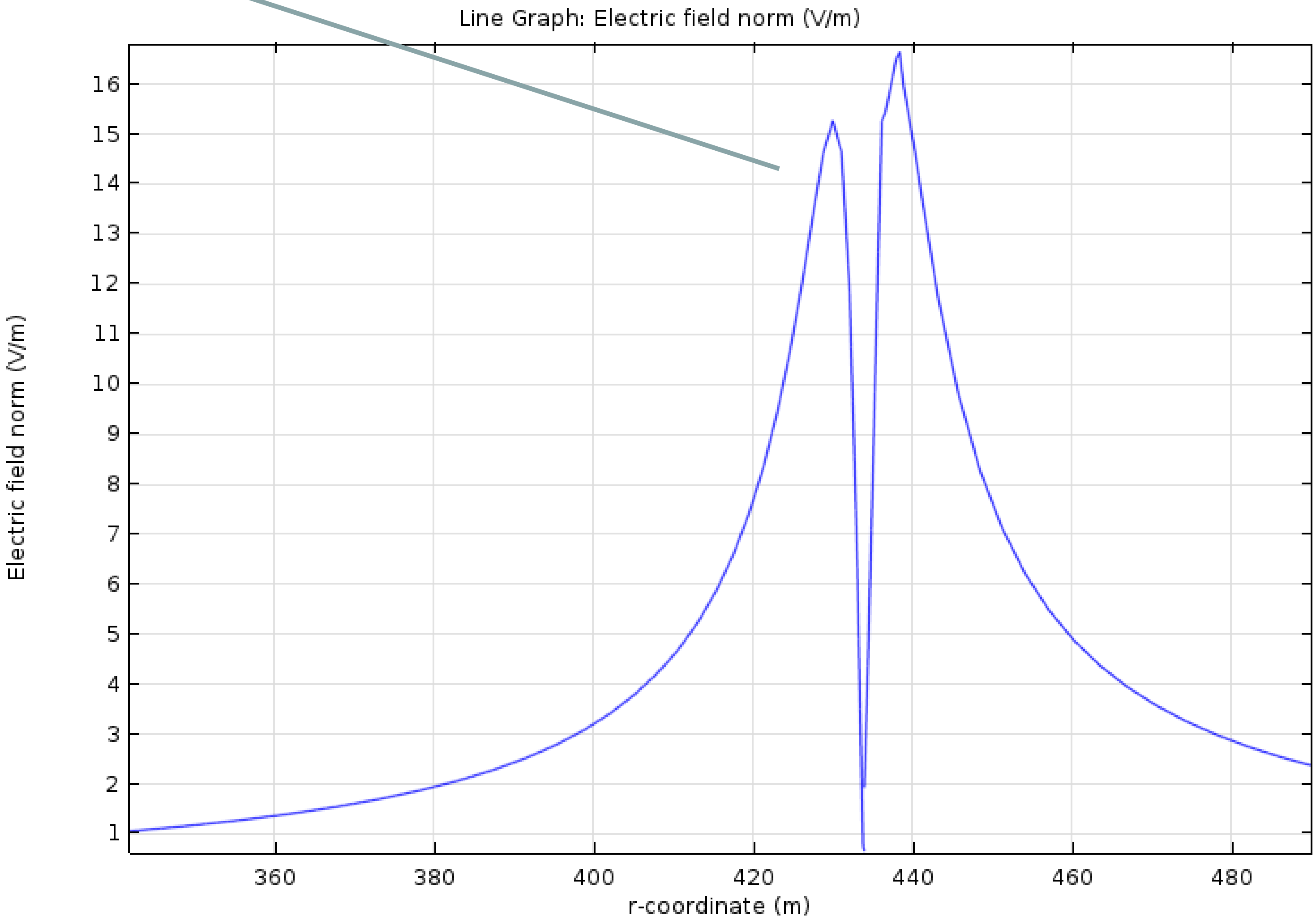
Case 2: Comparison of Electrode Designs



Profile at ground level

Case 2: Comparison of Electrode Designs

More precaution are needed in the ground surface meshing

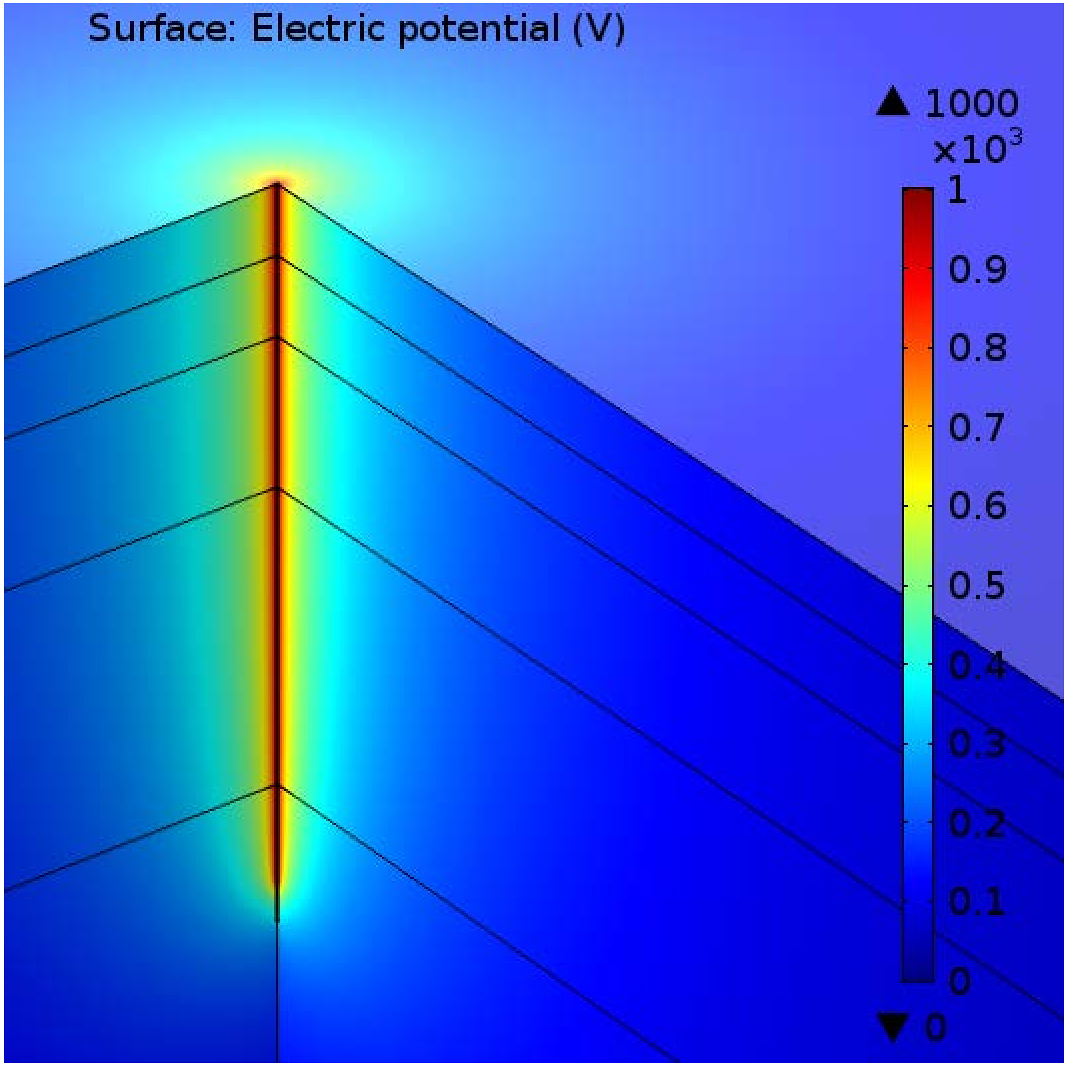


Profile at ground level – detail near the electrode

Case 2: Comparison of Electrode Designs

What about vertical electrodes?

- Good solution when the land cost is very high AND the deep layers are favorable (in thermal and electrical aspects);
- A continuous electrode causes a bad current distribution → segment the electrode core;
- Array of vertical electrodes → 3D simulation if distance between them are similar with the length.



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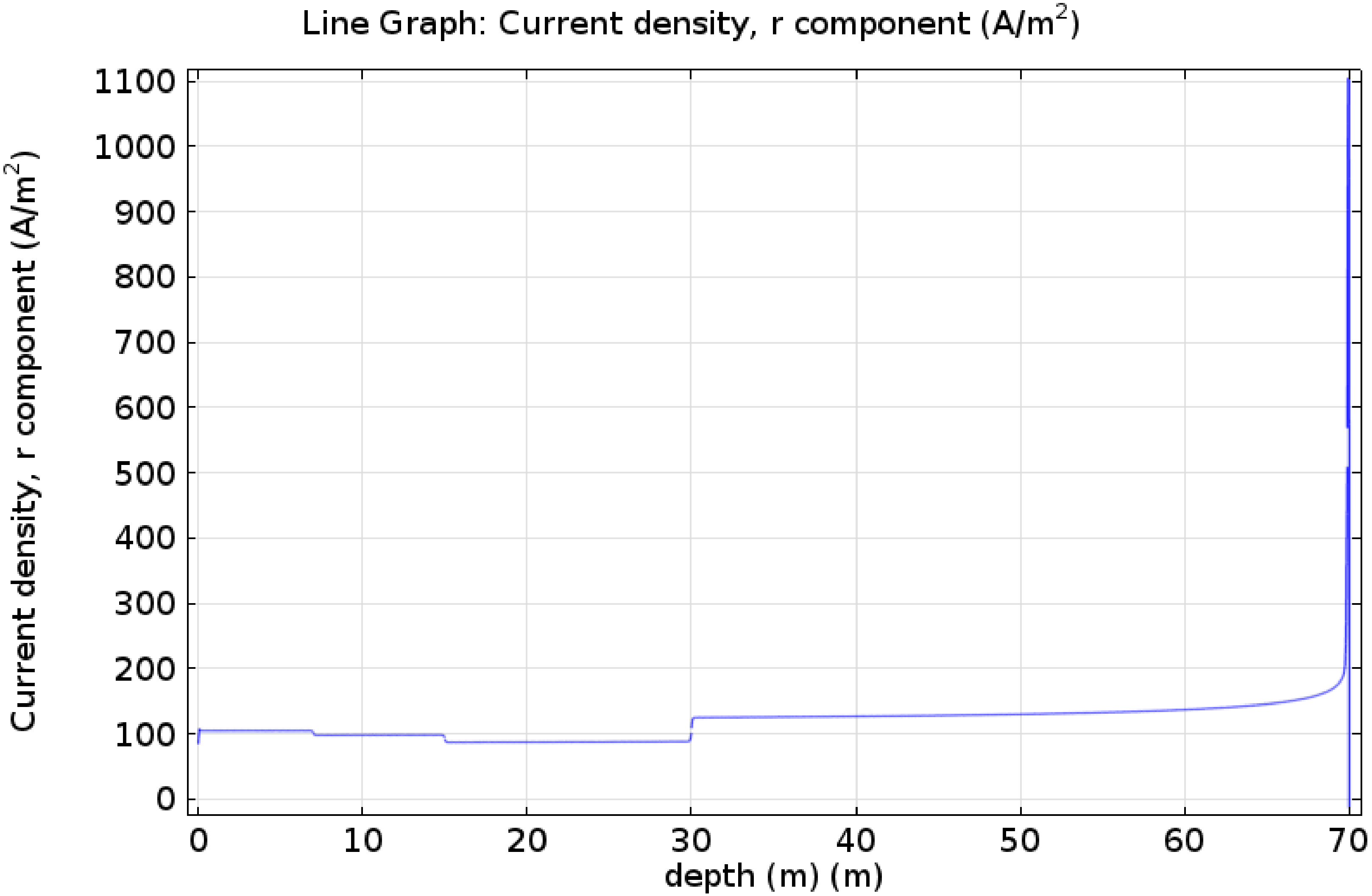
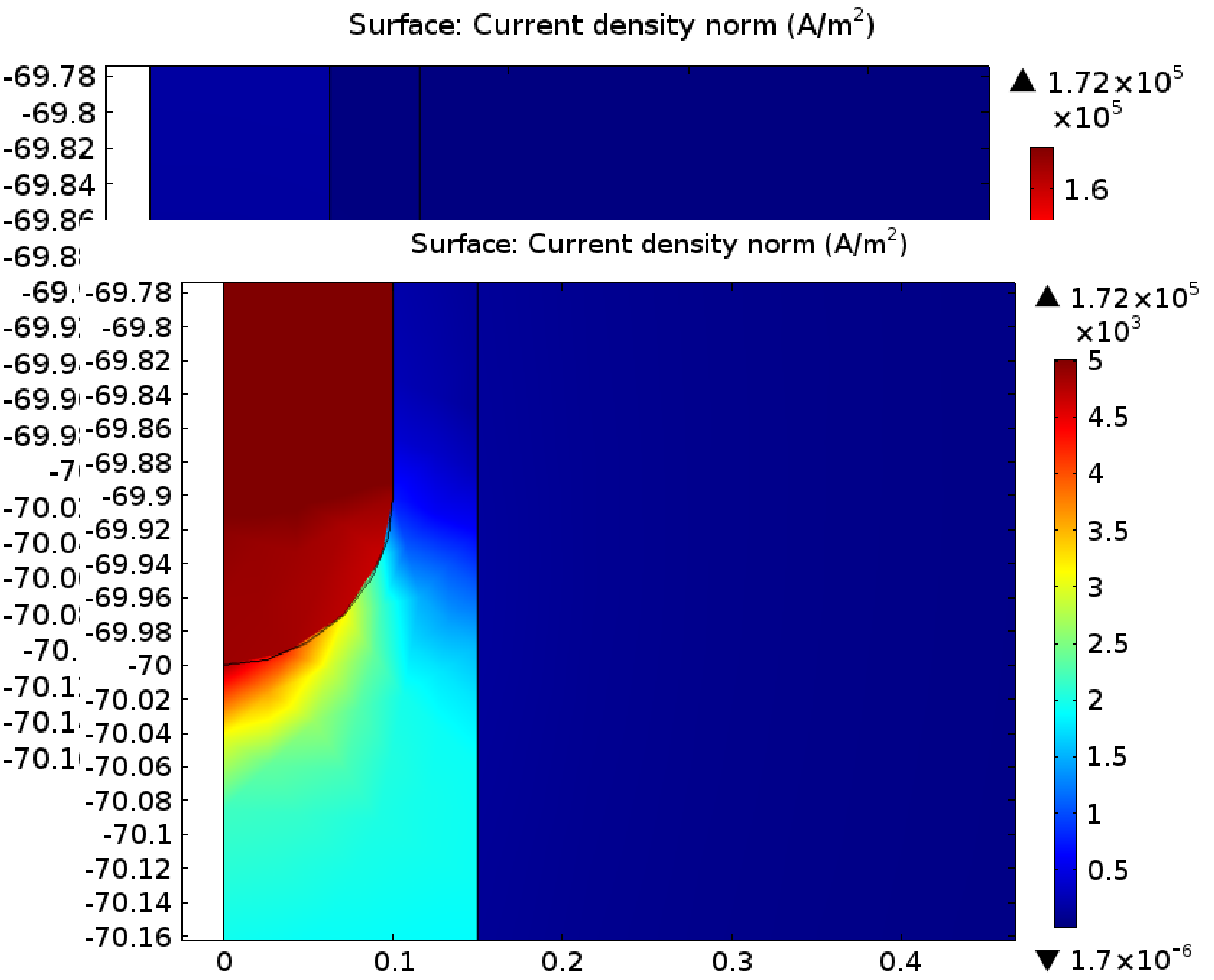


Case 2: Comparison of Electrode Designs

Investigation of the "hot spot"

- $J_{core} >> J_{coke}$ → manual color range;
- Sometimes, singularity caused by bad meshing → fillet it;
- Check parameters consistency.



Case 3: induced current in AC systems

- Buried metallic structure (insulated or in direct contact)
  - Minimum practical distance of 8-10 km (CIGRÉ WG, 1998);
  - Worse condition is when the HVDC electrode operates as a cathode (for an anode, the impact is reduced by ~5 times);
- Using FEM is possible to model a practical installation
  - The connected grounding systems modify the ground potentials;
  - The result is as good as the involved parameters (e.g. do not matter in duct details if the resistivity are roughly estimated).

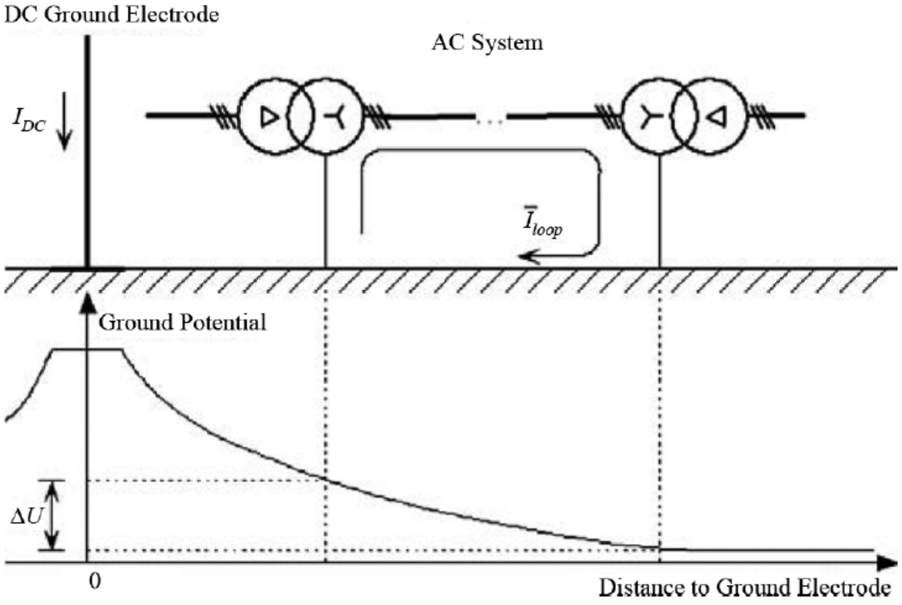
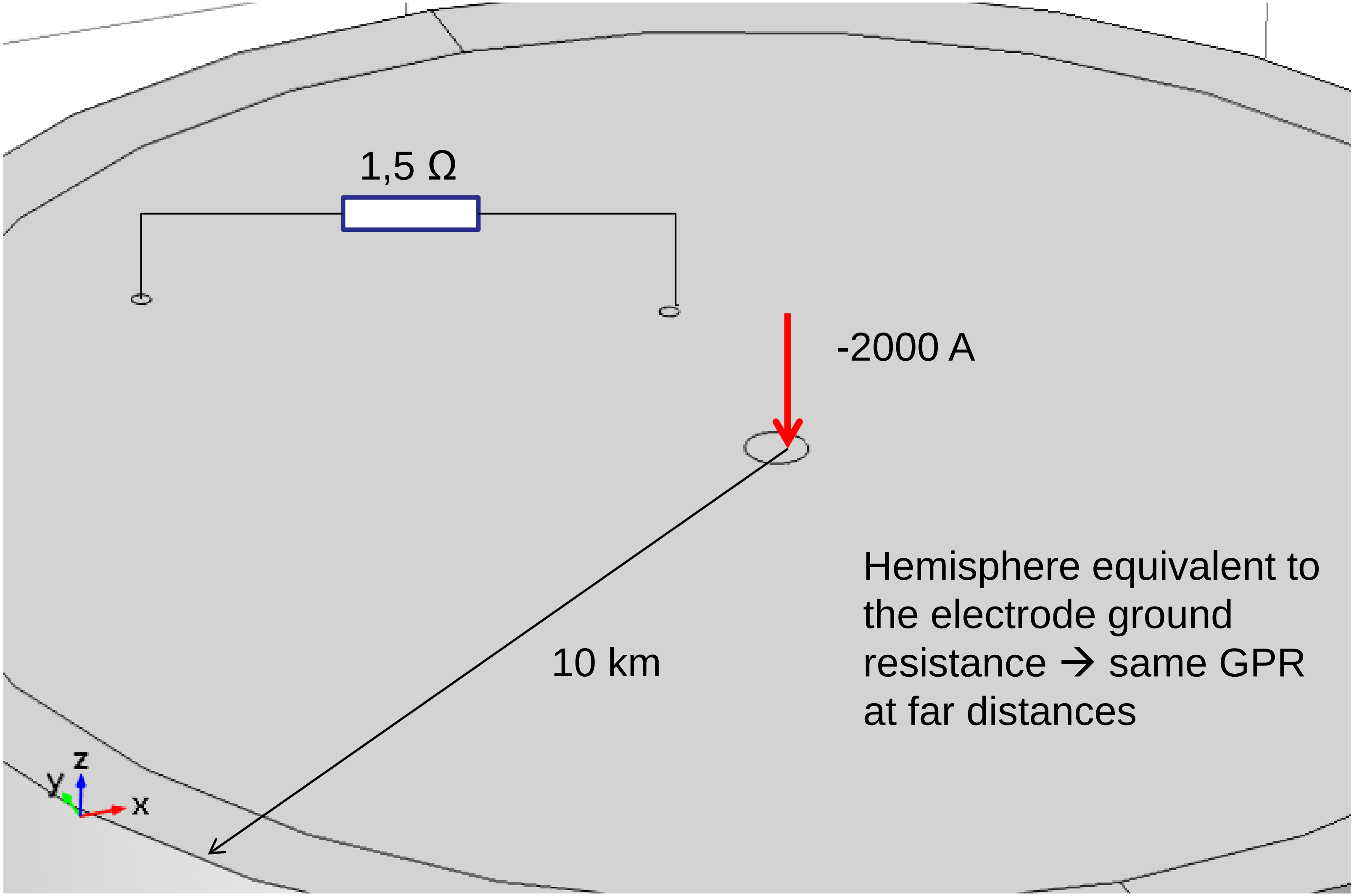


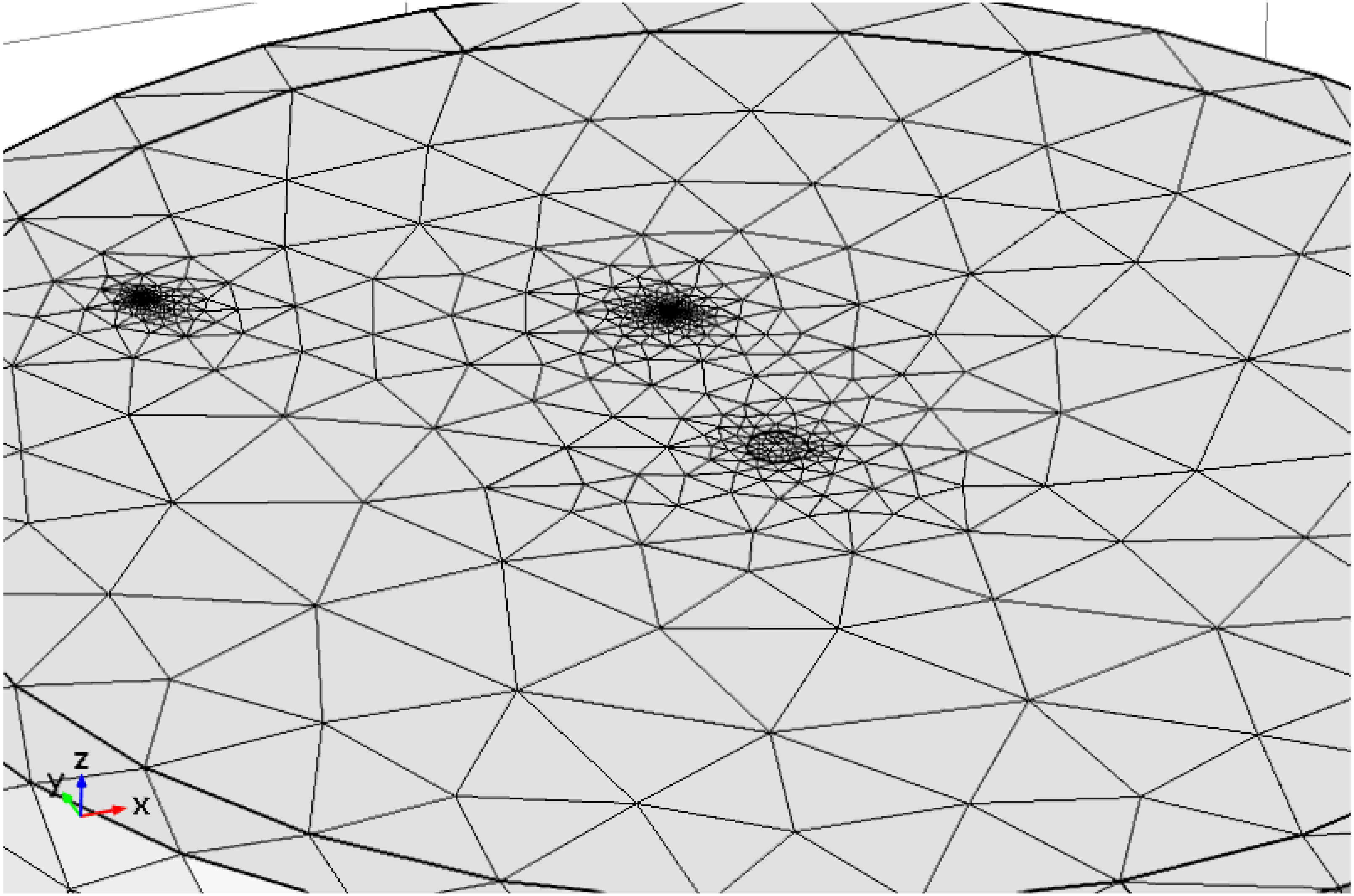
Figure from Zeng (2011)

Case 3: induced current in AC systems



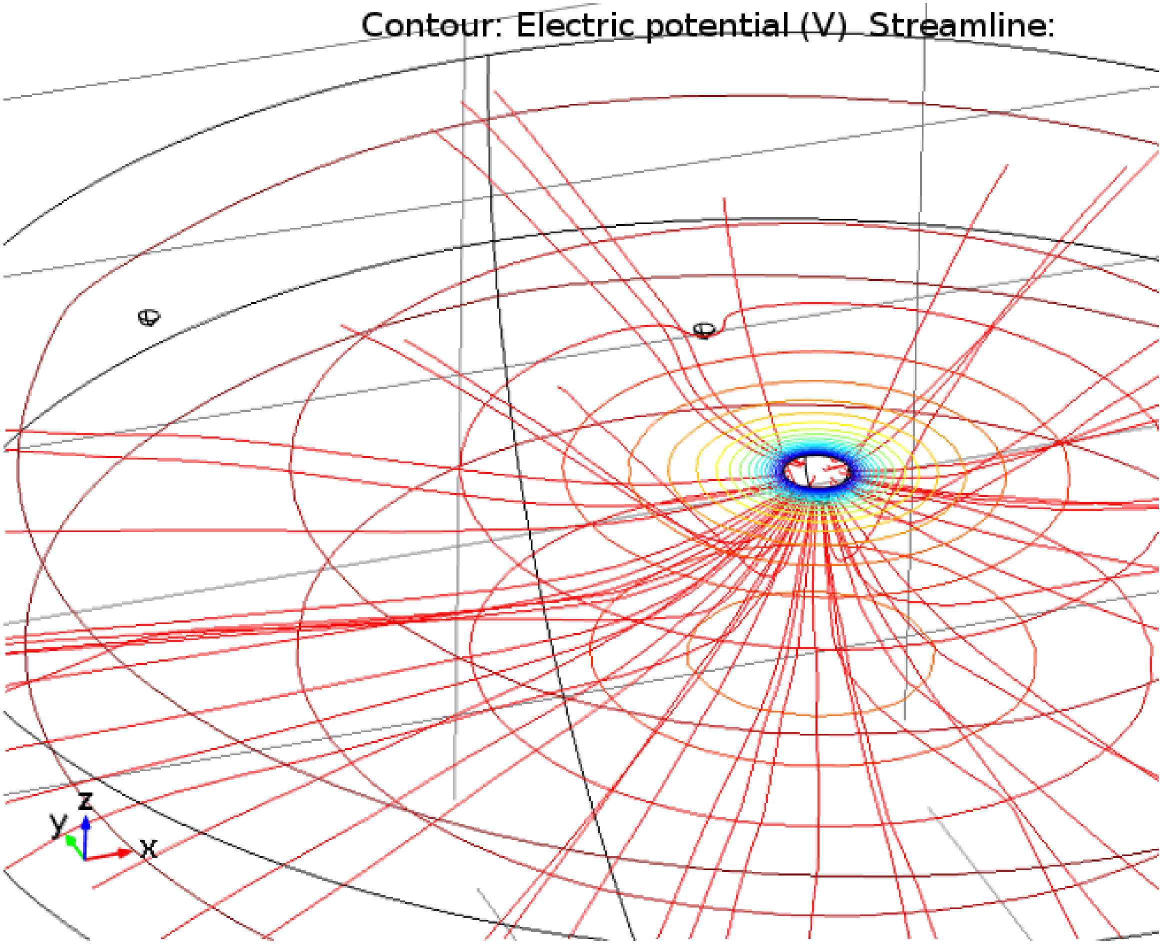
Hemisphere equivalent to the electrode ground resistance → same GPR at far distances

Case 3: induced current in AC systems



Case 3: induced current in AC systems

- Electrode resistance: 0.5822 Ω
- Induced current in AC system: 25.4149 A
- Results changes with:
  - Distance from the electrode,
  - Distance between AC stations,
  - Orientation (worst condition is aligned with the field),
  - Transformers connection.
- Results don't changes with:
  - Electrode topology,



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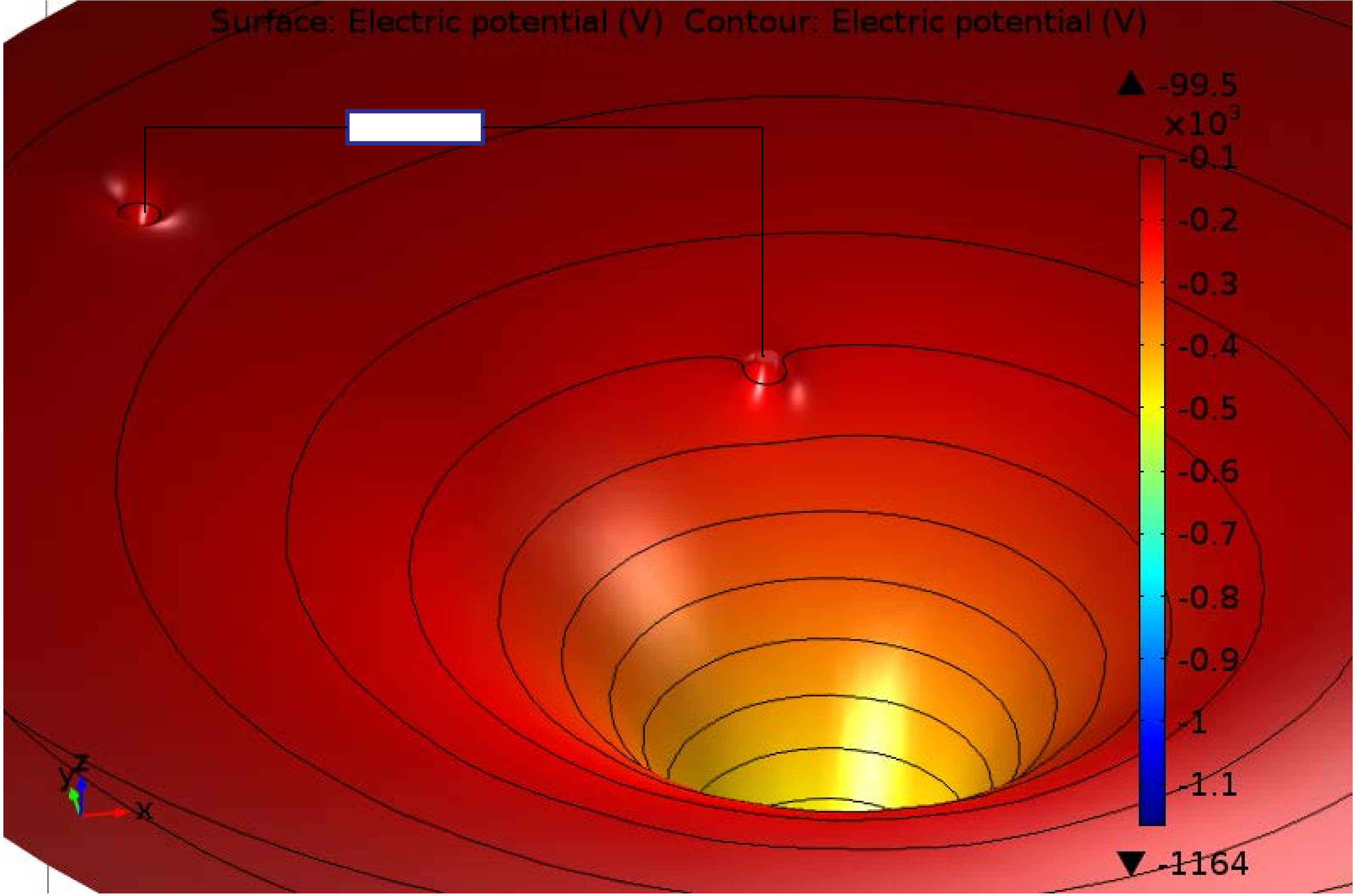

Height expression in surface + contour plot, ground potentials, electrode touch potential -1164 V

Conclusions

- FEM can represent several aspects in HVDC electrode design,
- COMSOL provides great resources, but caution are recommended:
  - Saturation in transformer core by DC current → Magnetic simulation are tricky (e.g. investigate sharp corners with high magnetic field & nonlinear materials)
  - Don’t try simulate all aspects at once:
    - Begin simple, add complexity gradually;
    - Divide to conquer (using equivalent electrode to far field effects);
    - Mesh size → good enough for your problem, nothing more;
  - Avoid corners → fillet, layered sphere for open domains;
  - Caution when filtering the results:
    - Have a look with “no refinement” resolution,
  - Secure if parameters are good:
    - Infinite domains (are enough space?) → huge domains + coarse mesh;
    - Mesh discretization (like magnetic simulation);
    - Solver, time step;
  - Ideal ground (zero voltage reference) × real ground:
    - Look for the ΔV, not V;

Future research

Some possibilities for further research regarding HVDC electrodes:

- Study of other measurement techniques (magnetotelluric, ground penetrating radar – GPR) in inhomogeneous soil, frequency model (RF module);
- Interaction between electroosmosis and corrosion (Batteries & Fuels Cells module, Corrosion module);
- Influence of other geological aspects (Subsurface Flow module);
- Hydrodynamics in sea or shore electrodes (CFD Module, Electrochemistry module, Flow in porous media).

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Thank you.

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