Study of HVDC Grounding Systems Using Finite Element Methods

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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)
• Typical designs: (a) monopolar, (b) bipolar (Kimbark, 1971)
  
  - Bipolar lines can operate in monopolar mode, in case of contingency
• “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 known method is the Schlumberger, basically another arrangement for the electrodes,
- For deep measurements, magnetotelluric methods could be employed, among others.

\[
\rho_e = \frac{4 \pi a R_w}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \approx 2 \pi a R_w
\]
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 \( \sim 2000 \, \Omega \text{m} @ -10^\circ\text{C} \) to \( \sim 60 \, \Omega \text{m} @ 25^\circ\text{C} \) (ABNT, 2012)
- Other relevant quantities are permittivity, thermal conductivity and heat capacity;
Soil resistivity measurement

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

Table from Loke (2001)

<table>
<thead>
<tr>
<th>Resistivity in ohm m</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^8</td>
</tr>
<tr>
<td>10^7</td>
</tr>
<tr>
<td>10^6</td>
</tr>
<tr>
<td>10^5</td>
</tr>
<tr>
<td>10^4</td>
</tr>
<tr>
<td>10^3</td>
</tr>
<tr>
<td>10^2</td>
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<tr>
<td>10^1</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>10.0</td>
</tr>
<tr>
<td>100.0</td>
</tr>
<tr>
<td>1000.0</td>
</tr>
<tr>
<td>10000.0</td>
</tr>
<tr>
<td>100000.0</td>
</tr>
<tr>
<td>1000000.0</td>
</tr>
</tbody>
</table>

Materials:
- Granite
- Diorite
- Andesite
- Basalt
- Gabbro
- Hornfels
- Schists
- Marble
- Quartzite
- Slate
- Conglomerates
- Sandstone
- Shale
- Limestone
- Dolomite
- Marls
- Clay
- Alluvium
- Oil Sands
- Fresh Groundwater
- Sea Water
- 95% Pyrrhotite
- 95% Massive Galena
- 95% Pyrite
- Hematite ore
- Magnetite ore
- Graphitic slate
- Anthracite
- Lignite
- 0.01 Molar KCl
- 0.01 Molar NaCl
- 0.01 Acetic acid
- Iron

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 $\Omega$ m, lower layer 1000 $\Omega$ m, depth 10 m
Case 1: Validation of Wenner Method

Upper layer 1000 $\Omega$ m, lower layer 100 $\Omega$ m, depth 10 m
Case 1: Validation of Wenner Method
Effect of an irregular soil

Streamline: Current density  Surface: Electric potential (V)
Case 1: Validation of Wenner Method
Effect of an irregular soil

Soil $100 \, \Omega\text{m}$, rock $1e6 \, \Omega\text{m}$
Case 1: Validation of Wenner Method
Effect of an irregular soil

Soil 1000 $\Omega$ m, rock 1e6 $\Omega$ m
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity</td>
<td>50 Ωm</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.3 W/°C m</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>1 MJ/m³ °C</td>
</tr>
<tr>
<td>Maximum natural soil temperature</td>
<td>28°C</td>
</tr>
<tr>
<td>Maximum electrode temperature</td>
<td>96°C</td>
</tr>
<tr>
<td>Current distributor (electrode core)</td>
<td>Metallic rod</td>
</tr>
<tr>
<td>Electrode body</td>
<td>Coke</td>
</tr>
<tr>
<td>Coke resistivity</td>
<td>0.2 Ωm</td>
</tr>
</tbody>
</table>

  From CIGRÉ(1998) – Foz do Iguaçu Station

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

- Metallic core
- Coke
- Fillet (represent practical aspect from construction & avoid singularities)
- Metallic core
Case 2: Comparison of Electrode Designs

Theoretical temperature rise in electrode core in a time span of 3 weeks
Case 2: Comparison of Electrode Designs
Case 2: Comparison of Electrode Designs
Case 2: Comparison of Electrode Designs

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
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.
Case 2: Comparison of Electrode Designs

Line Graph: Current density, r component (A/m²)

- Current density, r component (A/m²)
- depth (m)

Graph shows the variation of current density with depth, with a notable increase near depth 70 m.
Case 2: Comparison of Electrode Designs

Investigation of the “hot spot”

- $J_{\text{core}} \gg J_{\text{coke}} \rightarrow$ manual color range;
- Sometimes, singularity caused by bad meshing $\rightarrow$ 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).
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: \(0.5822 \, \Omega\)
- Induced current in AC system: \(25.4149 \, \text{A}\)
- Results change with:
  - Distance from the electrode,
  - Distance between AC stations,
  - Orientation (worst condition is aligned with the field),
  - Transformers connection.
- Results don’t change with:
  - Electrode topology,
Case 3: induced current in AC systems

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;
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).
References

• EPRI, HVDC Ground Electrode Design, Project 1467-1, report EL-2020, August 1981.
Thank you.

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