HVDC electrodes with ground or water return current impact assessment with COMSOL5.4 AC/DC module

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The article describes the analysis of the electric and thermal impact of HVDC electrode installations, which use the earth and/or sea as the conductive medium for the HVDC transmission system.
The analysis requires the modeling of both local and remote impacts, using multiple coupled 2D/3D models in the AC/DC module, each describing the physics of the HVDC link at different scales: 2D electric current coupled to lumped parameter circuits physics for evaluation of corrosion on metal structures such as pipes or railways in the large scale models, 3D models with electric currents, joule heating and convective heating physics for evaluation of voltages and temperature in the models of the electrodes.
The results of the analysis can be used highlight potential health hazards (or lack thereof), and to define mitigation measures, test specifications and maintenance intervals.

Introduction

HVDC electrodes are installed on HVDC transmission systems to provide a low resistance current return path for currents, using the earth and/or sea as the conductive medium. HVDC electrodes with ground return current are in general less costly and have lower losses than dedicated metallic return conductors.

Numerous HVDC electrodes have been installed now for close to 40 years without arising concerns for public health and or for the environmental impact. Well known examples are found in Massangä (Gotland), Skagerrak (Lövens Breddning), Kontek (Bjäverskov), Changcuicun (Heyuan, China), Puer-Qiaoxiang (China), Nelson River BP1 (Radisson). In recent years though the growing number of installations and a general increase in public awareness of the potential impacts have caused a tightening of the requirements for environmental approval, pushing new installations to further reduce the impact by selecting more suitable electrode materials, design and location, based upon the results of the geophysical survey and modeling, and by performing more advanced analyses of the thermo and electrical distributions around the electrode and along the HVDVC link.

There are large variations in geographical, geophysical and technical properties of electrode sites and HVDC system requirements differ from one system to another. Therefore, a variety of electrode shapes, and configurations have been developed for each of the different types of electrodes such as shallow land electrodes, vertical land electrodes, deep well land electrodes, sea electrodes and shore electrodes (beach and pond).

Shallow land electrodes have the advantage that the electrode can be located close to the converter station, to reduce the line power losses, but in general may cause high temperature rise, high potentials and electro-osmosis. Sea electrodes have low resistance toremote earth and therefore low power losses, no temperature rise and no risk of electro-osmosis, but could cause chlorine development should high current densities occur.

For the description of the guidelines for the site selection process and best practices, including geophysical, geological, social and environmental condition investigations we refer to CIGRE, WG B4.61 'General guidelines for HVDC electrode design' and references therein.

The following sections focus on the analysis of the electric and thermal effects of HVDC electrodes with ground return current.

Local and large-scale electric effects

Feasibility studies for HVDC projects often involve the consideration of both local and large-scale effects, since most of the HVDC links extend over several hundreds of kilometers
The electrodes must be located in such a way that the electric potential gradients are at acceptable levels, for all sensitive infrastructures along the link. The electric field gradient at points some distance from the electrode (the far field) depends on the magnitude of

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the current, the distance from the electrode and the resistivity distribution or the soil structure.

The performance of an electrode is influenced both by the local soil immediately adjacent to the electrode as well as soil materials that are further away. An electrode placed in a thin layer of low-resistivity soil cover underlain by high-resistivity rock will have high resistance to remote earth.

The shape and local arrangement of the electrode does not have a measurable impact at a distance that is large in comparison to the physical size of the electrode, but will rather have an effect of the local distribution [1].

Large-scale electric effects

The effective resistivity of the earth may vary three or four orders of magnitude between areas of different geological conditions and the resistivity distribution is therefore a critical parameter in the selection of an electrode site. Problems with stray currents due to electric potential gradients may occur at tens of kilometers away from an electrode. The resistivity earth's crust and the upper part of the mantle of an area extending to perhaps 100 km or more from the electrode site must be considered in such cases [1].

The electric potential distributions along the entire length of the link can be used to evaluate the stray currents in and out of conductive structures in the area, such as pipelines, railways and powerlines to determine the risk of corrosion.

Figure 1 - **Figure 2** show the example of a 2D model of the 740km x 400km area around an HVDC link, describing the sea depth and how this affects the voltage distribution. The rectangles highlight higher resolution zones around the electrodes.

In this case a model based upon two horizontal layers with different resistance is appropriate:

$$\frac{\mathbf{1}}{\boldsymbol{R_{eq}}} = \frac{\mathbf{1}}{\boldsymbol{R_{water}}} + \frac{1}{\boldsymbol{R_{bedrock}}}$$

Given the difference in conductivity between the sea water and the bedrock, the conductivity is mainly determined by the sea depth.

More detailed models can be used around the electrodes, where the voltage gradients are expected to be more sizable.

Figure 3 shows a higher resolution model of the 20kmx40km area around a submerged electrode and the pipelines located in proximity of the electrode.

Figure 3 shows an example of the resulting voltage isopotential lines (for a different location) and how these would correlate with the sea depth. Finally **Figure 5** shows the expected depletion rates along the pipelines.

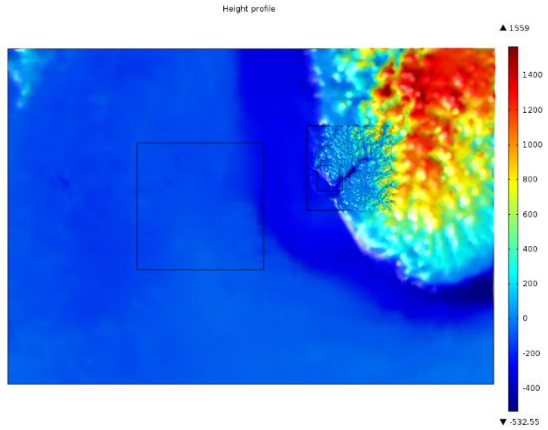

Figure 1 – Model of the 740kmx400km area around the HVDC link. The rectangles highlight higher resolution zones around the electrodes.

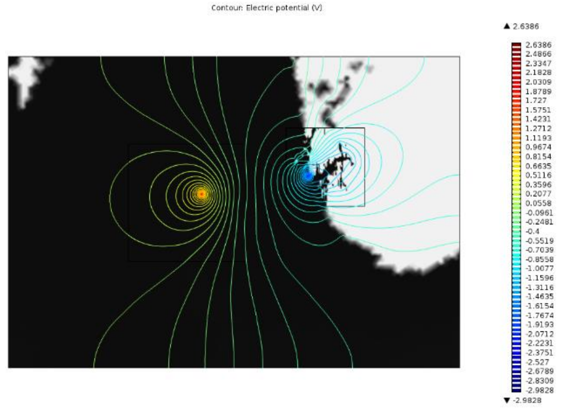

Figure 2 – Voltage distributions in a model of the 740kmx400km area around the HVDC link.

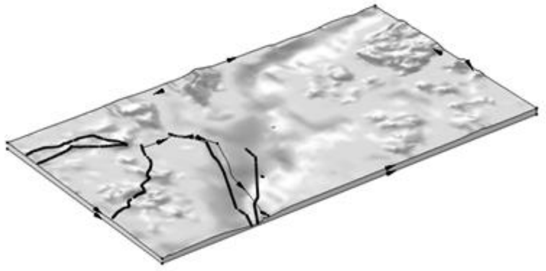

Figure 3 – Model of the seabed of the 20km x 40km area around a submerged sea electrode. The lines indicate pipelines.

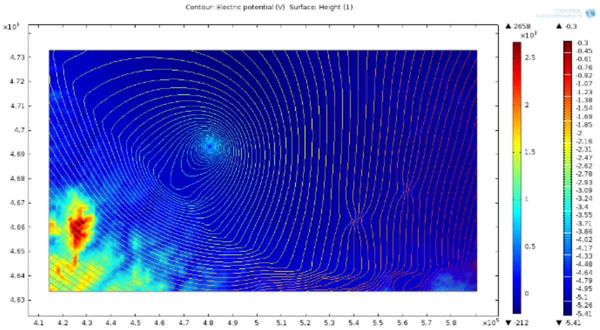

Figure 4 – The voltage distribution in the area surrounding a submerged electrode.

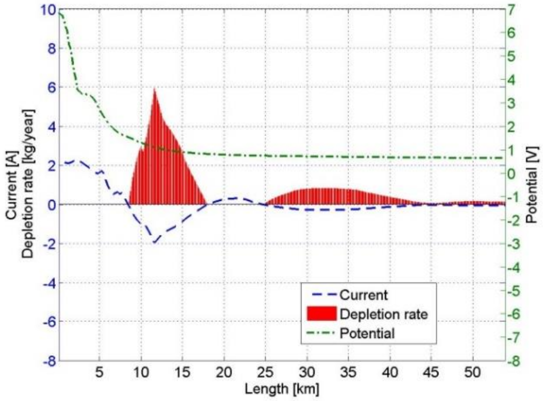

Figure 5 – Depletion rates along a pipeline length, based upon the assessment of the stray currents.

Local electric effects

For sea electrodes, it is important to keep electric fields low to avoid effects on swimmers accidentally entering the area and sea animals. The current density must also be kept low to avoid unacceptably high chlorine emissions.

The low resistivity of salty or brackish water will usually keep electric fields at low levels around sea and shore electrodes but significant electric fields can occur if a sea electrode is located in a shallow water environment underlain by high-resistivity solid, crystalline rock. The seawater will almost act as one single large electrode volume in such cases and high electric gradients can be created perpendicular to the shoreline at quite large distances from the electrode. It is therefore important to select sites with rapid transition to deep water and direct access to the open sea.

Figure 6 shows a 3D model of the voltage distribution in a 1kmx1km area around three sea electrodes which was used to determine touch voltages.

Similar models can be used for land electrodes to determine touch and step voltages, to determine transferred potentials along long metallic fences and radial irrigation systems, to determine the voltage across the insulation of cables (for instance power cables) or the design criteria for the earth leads of HV and MV cable shields.

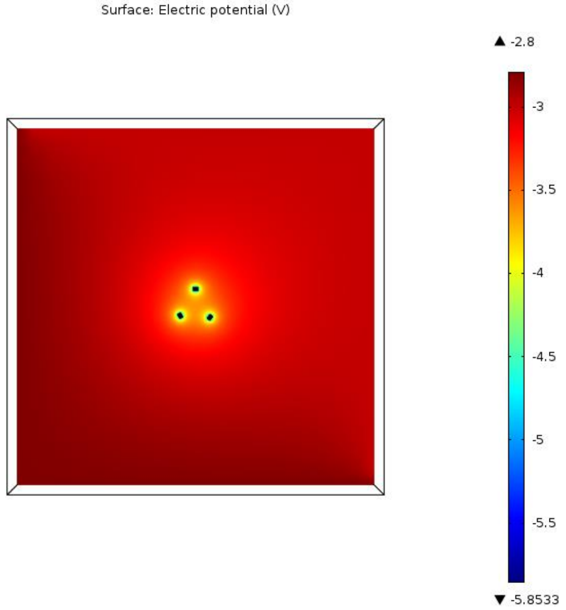

Figure 6 – Evaluation of voltage gradients in the immediate vicinity of the electrode for the assessment of step and touch voltages.

Electrode resistance to remote earth, thermal heating effects and electro-osmotic effects are dependent on the design of the electrode. A large electrode with large contact surface to the host material is less likely to have problems but will also be more expensive.

A proper selection of electrode site might therefore be cost saving.

The evaluation of the electric field strength around submerged coastal electrodes, and the current density at the electrode are used, among other things, to determine the impact in terms of electrolysis products from the anode, such as hypochlorite, hypobromite, bromide, chloroform and bromoform.

Further concerns are economical, to determine material selection (typically titanium mesh), electrode testing and commissioning.

Other applications are temperature rise evaluations (for land electrodes).

The temperature at any point of the soil can be determined by solving the Laplace differential equation of heat conduction

$$\nabla(k_T \cdot \nabla T) + g = d_s \cdot \gamma \cdot \partial T_{i,j,l.}$$

With $g = \rho \cdot J^2$, and where

k_T is the soil thermal conductivity (W/°C·m), g is the heat dissipated by Joule Effect (W/m3), d_s is the soil density(kg/m^3), γ is the specific heat capacity of the soil (J/(°C*kg)), $T_{i,j,l}$is the temperature(°C), t is the time (Seconds), ρ is the soil resistivity (Ω·m) and J is the current density (A/m^2).

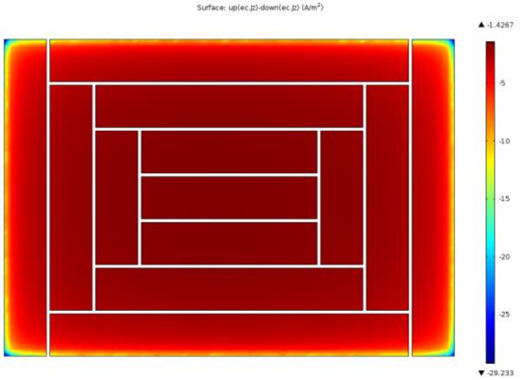

Figure 7 – Electrode design prior to optimization. High current density at the corners of the electrode may cause release of chlorine gas.

Coupling large scale models to local models

The electric voltage, current and temperature distributions for the HVDC link can be evaluated using multiple coupled 2D/3D models in the AC/DC module of COMSOL5.4, each describing the physics of the HVDC link at different scales.

For the evaluation of the voltage distributions along the entire length of the HVDC link one may use a 2D models of the area surrounding the installation such as the one shown in **Figure 1**, describing the topography (bathimetry) of the region and resistivity of the soil/water (in the case of subsea electrodes), in which the anode and cathode are represented by electric current point sources, and pipes and metal structures can be represented by external lumped parameter circuits, coupled to physical points in the model via voltage coupling.

The sea depth function z(x,y) and the corresponding resistivity function sigma(x,y) are imported as simple interpolation functions and applied as material properties.

In order to have a better resolution around the sources, the large scale 2D model (model 1) is then coupled to smaller scale 2D models (model 2) of the area surrounding the electrodes, using the general extrusion feature to map the voltage distributions found in the larger models to the boundaries of the smaller model.

Figure 8 shows areas in the model 1 with higher depth and resistivity resolution. The edges of the higher resolution areas are defined are identity mapping (in mod1>Definitions, apply idmap1 to the boundaries). Then the voltages are mapped, by applying the mod1.idmap1(mod1.V) in model 2, in the physics node, electric currents, electric potential.

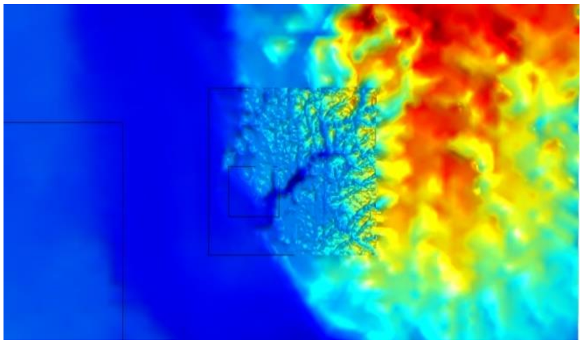

Figure 8 – The identity map feature is used to map voltage distributions along the edges of the square area in model 1 to the outer boundaries of the more detailed model 2

A similar feature can be exploited to couple 2D models of the area with more detailed 3D models of the electrode arrangements.

Figure 9 shows an area in the 2D model 1 with higher depth and resistivity resolution. The edges of the higher resolution areas are defined are generally extruded (in mod1>Definitions, apply genext1 to the boundaries). Then the voltages are mapped, by applying the mod1.genext1(V) in the 3D model 2, in the physics node, electric currents, electric potential.

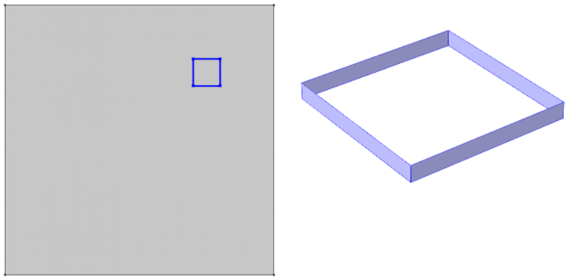

Figure 9 – The general extrusion feature is used to map voltage distributions along the highlighted edges of the 2D model to the corresponding boundaries in the 3D model.

Coupling electric currents and lumped circuits

Pipelines, metal fences and transmission lines can be represented as lumped parameter circuits, with a given resistance along the pipe and resistance to soil (or water), which exchange voltage and current with the 2D FEM model.

Long lines of point-like terminals in the 2D FEM model, represent the pipe segmented into fixed length sections. Each terminal exchanges current with the corresponding lumped parameter circuit section External I Vs. U 1.

This approach was used to determine the impact on surrounding structures, when the trains move along the tracks.

Figure 10 shows the lumped parameter circuit representing a train moving along its tracks. While **Figure 11** shows the voltages induced in the surroundings as the train move in opposite directions.

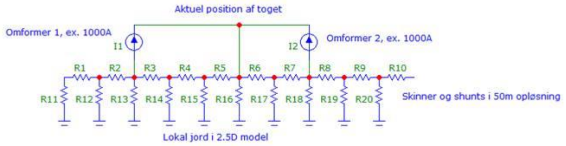

Figure 10 – Lumped parameter circuit representing a train moving along its tracks.

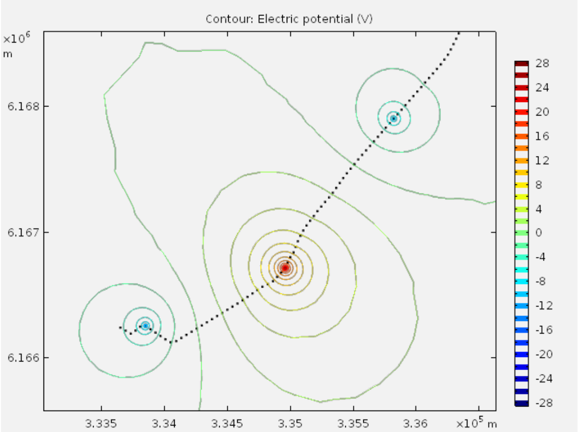

Figure 11 –Potential in the 2D FEM model when two trains move in along the tracks.

The lumped parameter circuit and the coupling is generated in Matlab, exploiting Livelink.

Conclusions

The complexity of the evaluations involved for the feasibility studies for HVDC links discussed above, requires the use of finite element models.

Ground potential rise, potential gradient and maximum step/touch voltage, and DC resistance to remote earth can be mathematically estimated for various types and shapes of electrodes for the soil resistivity of uniform, 2-layer or 3-layer distribution.

However, such methods are not sufficient if the soil in the immediate area of the electrode is not of uniform resistivity or when operation is required with outages of a portion of the electrode.

Similarly, estimates of the average current density from an electrode would fail to capture the high current density from sharp corners or to provide mush input into the electrode design optimization.

For these evaluations FEM simulations are required. Furthermore, the evaluations, though generally based on straightforward electric current, static simulations, require the coupling of the different types of physics which are relevant at the different scales.

As the results of these analyses can be used highlight potential health hazards (or lack thereof), and to define mitigation measures, test specifications, reliability, maintenance intervals, life cycle their use is highly recommended.

References

1.CIGRE, WG B4.61 '*General guidelines for HVDC electrode design*' (2017)