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HVDC- Projects based on a mutual understanding between involved parties with respect to corrosion protection

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ABSTRACT

High Voltage Direct Current (HVDC) transmission systems may cause interaction on long metallic pipelines. It is however possible to avoid conflicts, when taking this into consideration during planning of new energy transport systems.

This approach showed its benefits to all parties as preliminary investigations for the planned North Sea HVDC links were made. 3-D modelling of the electric conductive earth strata was used to describe possible effects on corrosion protection and necessary mitigation efforts.

1. Introduction

Energy transportation is an important issue in the technological developed world. It is equally important whether it is in the one or the other form. The focus in this paper is however only on a transport relation between High Voltage Direct Current (HVDC) and steel pipelines.

The subject is consideration and respect, and I take the liberty to claim, that it is a wise decission to construct and operate energy transport systems with a mutual technical understanding and respect, and even more detailed – with respect to corrosion protection.

Transport of energy products is often confined to transport corridors. These corridors are relatively narrow, and the proximity between systems may cause interaction. Influence on pipelines from electric railways and high voltage alternating current lines are well recognised factors, that are dealt with when planning new installations or extensions of existing installations. There are however situations, where alternative routes are used, and this is particularly the case, when it comes to HVDC links. Handling the important questions, related to possible effects on corrosion protection from HVDC links, is not every day work. HVDC links in Europe are mainly utilised to connect islands with the main land and as an interconnection between the Western European synchronous ac system (UCPTE) and the Scandinavian synchronous ac system (NORDEL).

Influence from (monopolar operated) HVDC links was hardly recognised by European HVDC operators nor pipeline owners/operators until stray current density levels exceeding cathodic protection current densities were registered. This was particularly the case as well coated pipelines approached the large HVDC links between Norway and Denmark and Sweden and Denmark in the eighties. Since that time, the involved parties have gathered a comprehensive understanding of the nature of the rather complex problems, and this has resulted in a fruitful dialog in advance of new HVDC projects – for example the extension of the Skagerrak link, Kontek link, Baltic Cable, Viking Cable, EuroKabel and NorNed Kabel. The three latter, the North Sea HVDC projects performed an extensive study on possible impacts of stray currents produced by the operation of the three HVDC links. The approach and the results of this study are referred to in this paper.

2. HVDC principle

The basic set up is a monopolar HVDC links, i.e. high voltage direct current is transported in a cable between two stations and returned by utilising the ground as return conductor, see the principal diagram in Figure 2-1. The ground path has a very low resistance and correspondingly low power loss in comparison with a metallic line conductor of economical size and equal length, but it is of course possible to use an insulated return cable.

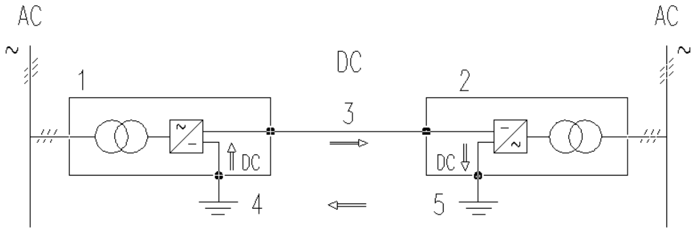

Figure 2-1 Monopolar HVDC system with ground as return conductor

1 and 2 : Converter station.
3 : HVDC transmission line.
4 : Earth electrode (cathode).
5 : Earth electrode (anode).
=> : Current direction.

The electric power is converted from alternating current (ac) to direct current (dc) at the converter station transmitting power. The reverse conversion takes place at the receiving end. The direct current direction remains the same whether energy is transmitted in the one or the other direction by changing the voltage polarity.
Ground return is utilised by monopolar HVDC links and by so called bipolar and multipolar links when current in the one direction is different to current in the opposite direction.

3. Geology and the electrical field

With a monopolar HVDC system, the return is through conductive sea/earth layers, i.e. through the top soil or water and the conductive strata below.
As the current runs through the sea/ground the potential difference between the two electrodes - anode and cathode sets up an electric potential distribution between the electrodes.
The potential difference between the electrodes, is determined by the resistance and the current between the electrodes, Ohms law.
For the North Sea HVDC projects, we looked specifically at the conductive section which would carry the return current between the South tip of Norway and the Dutch/German North Sea coast. See Figure 3-1.

The conductive section comprises the geological layers above the bed-rock plus the top soil or sea on top. The top soil and the sea is generally some few metres to some few hundred metres thick. The thickness of the conductive geological layers in the areas we have been collecting data on is varying from virtually zero in land in central and north Scandinavia up to 8 kilometres in the middle of the North Sea. It is again rather thin in the east-west directed mountains south of the Netherlands.

The potentials will reach numerical maximum values at the electrode locations. Between the two electrodes there will be a zero zone where the potentials shifts from negative to positive as they pass through zero. The maximum numerical potentials are ranging from more than 100V on land electrodes to less than 5V on off-shore electrodes. The potential vanishes by increasing distance from the electrodes, but it can not be neglected. An estimated potential on a sea electrode off the Norwegian coast was –2,1V. Approximately 75 kilometres South of the electrode the potential was reduced to -0,3V. On the opposite electrode off the German coast, the potential was calculated to 0,9V. Approximately 150 kilometres South of the electrode, in land the potential was reduced to 0,15V. See Figure 3-2.

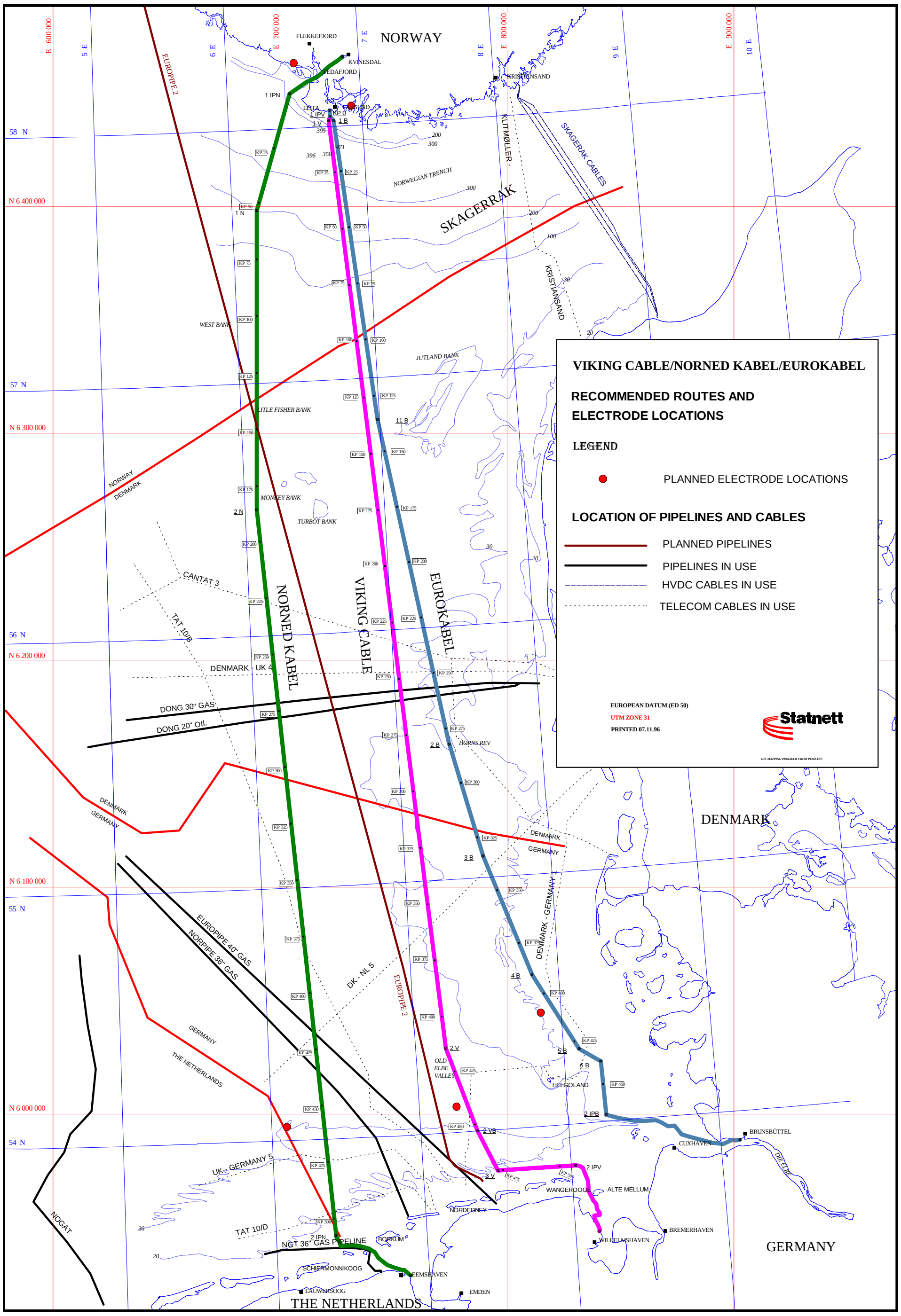

Figure 3-1 North Sea HVDC project.

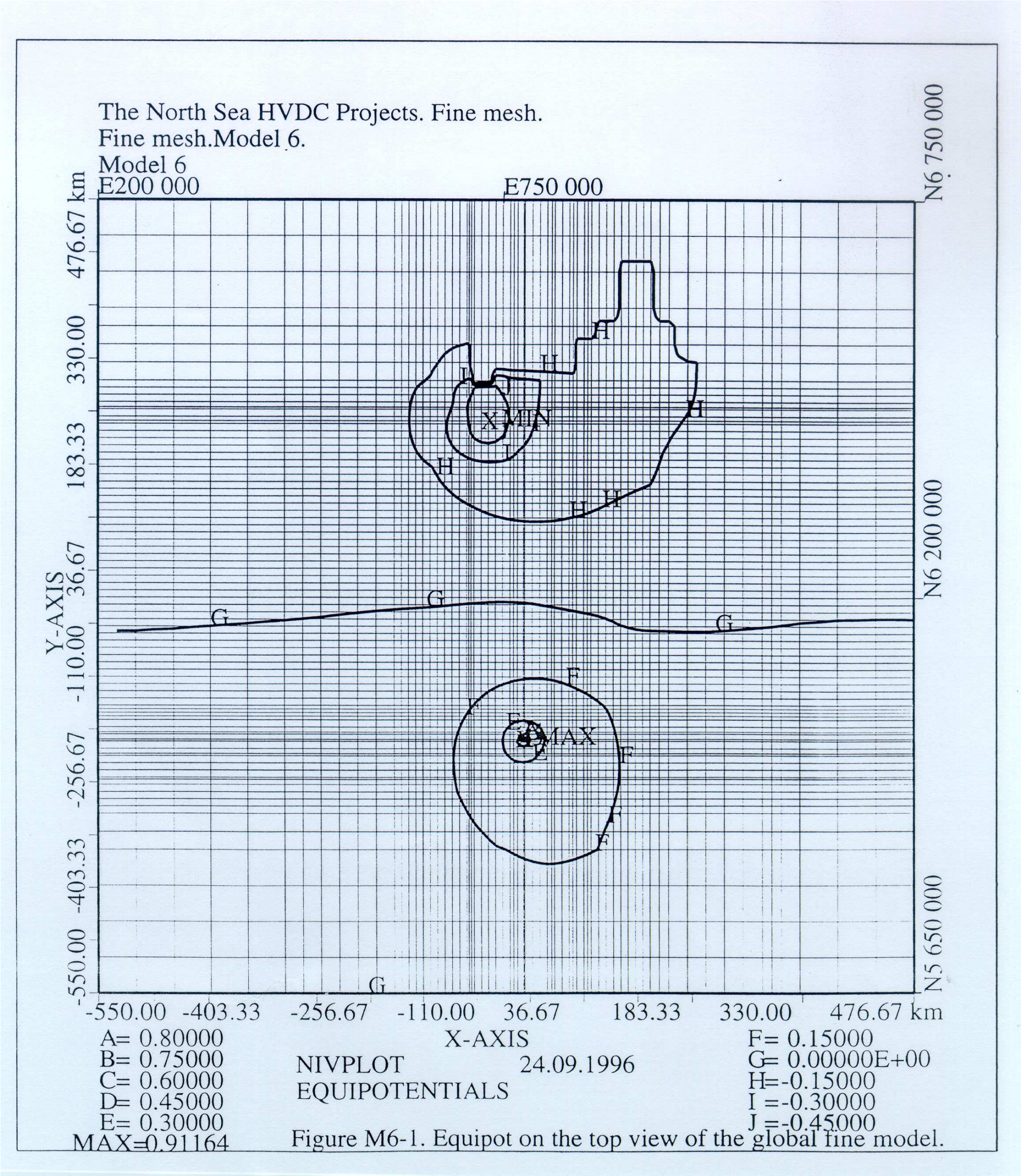

Figure 3-2 Equipotential lines around two off-shore HVDC electrodes in the North Sea by 1600A through the ground loop.

It is visible in Figure 3-2, that the distance between the electric equipotential lines is influenced by the conductivity in the ground. The equipotential lines are squeeze together above the top electrode and follows the Norwegian shore line, as the Norwegian land part represents a poor conducting mass. This again causes an increased current density to the south-west.

4 Stray current influence

The electric field set up by the HVDC return current will make stray current enter and leave the pipelines. The following influence levels were anticipated to arise from the North Sea HVDC links.

4.1 Land pipelines (State 1997)

Longitudinal potential differences were calculated up to approximately 250 mV in Germany and the Netherlands for the most influenced pipelines.

The longitudinal potential differences would be < 100 mV on pipelines in Denmark.

There were no reports of large steel pipelines within the 100 mV equipotential line in Norway.

It is necessary to convert the longitudinal soil potentials along the pipelines to pipe/soil potentials, in order to evaluate the interaction levels. The actual pipe/soil potential is dependant on the electric contact between the pipeline and the soil. A homogeneous and very high coating resistance can be obtained with polyethylene (PE) coated pipelines. Bitumen coated pipelines can also have a relatively homogeneous resistance, though not as high as for PE-coated pipelines. However, electrical connections to cathodic protection stations, drainage installations etc. disturbs the homogeneity. Therefore, only measurements can show the actual potential distribution.

The following conversion is a practical attempt to assess the influence.

A simple conversion from the longitudinal potential differences to pipe/soil potentials can be derived, assuming that the insulation on the pipeline is homogenous. The method is to “balance” the potential along the pipeline route around a “zero axis”, see Figure 4-1. The area A above the “zero axis” is equivalent to the area B below the “zero axis”.

The potential influence on the land pipelines was estimated to be limited.

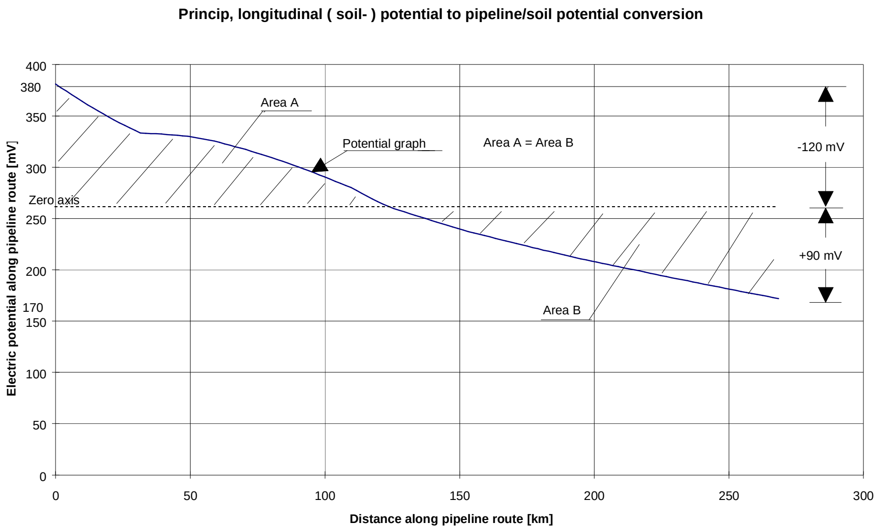

Figure 4-1 Conversion of longitudinal (soil) potential to pipe/soil potential.

4.2 Submarine structures (State 1997)

It has been established with the foreseen current densities on the pipelines, that all stray current leaving the pipelines will do so via the anodes, due to the galvanic effect of the anodes versus the steel.

The most likely corrosive interaction effect will therefore be an increased depletion rate of anodes, where current leaves the pipe, i.e. no premature corrosion on the pipes was expected.

The plot in Figure 4-2 concerns Europipe 2, and is showing a maximum stray current density, app. 40 micro A/m^2 at kilometre 0 (zero). The pipeline outside diameter is app. 1 m, the pipeline surface between two anodes, 72 m apart is hence app. 225 m^2 which gives a current of app. 10 mA per anode. This current will cause an anode consumption of app. 0.03 kg/year and anode.
This value is equivalent to 3.5 kg/year “Worst Case Point Anode Depletion” at “Location” km 0, when dividing by 100 (anodes). Asuming that all current leaves via one anode.

It is in Figure 4-2 indicated that the stray current density is decreasing from 40 micro A/m^2 to 0 (zero) within approximately 20 kilometres. The adjacent negative values are indicating that stray current is entering the pipeline over an approximately 30 kilometre long section, again followed by a section where current leaves the pipeline up to approximately kilometre 100. Between kilometre 100 and 420 nothing happens. From kilometre 420 to the right end of the diagram, there are two entry areas and one exit area.

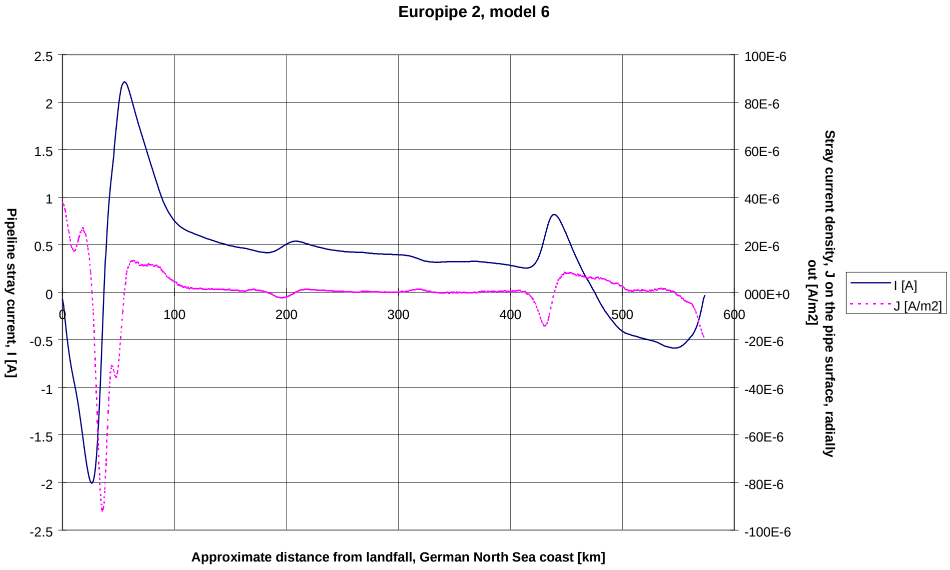

Figure 4-2 Stray current density.

Based on the above and similar analyses for a large number of submarine pipelines, it was concluded that the influence on submarine pipelines is most likely limited to a slightly increased anode consumption. The increased anode depletion rates are in the range 0.1-0.9%. It was hence not likely that any protective actions would be needed on the submarine pipelines.

5. Approach

I have in the previous sections briefly described the mechanism and the anticipated influence from the North Sea HVDC links at the planning state in 1997. The following is a description of the steps that were taken.

5.1 Scope of work

The planned owners/operators of the three planned HVDC links between the Netherlands, Germany and Norway were/are:

NorNed Kabel : (NN)	Sep (N.V.Samenwerkende electriciteitsproduktiebedrijven), the Netherlands Statnett SF in Norway
EuroKabel : (EK)	EST EuroStrom Trading GmbH, Germany Statnett SF, Norway
Viking Cable : (VC)	PreussenElektra AG, Germany Statnett SF, Norway

Balslev A/S was commissioned by the three projects to carry out a study of possible stray current corrosion on secondary structures (i.e. metallic conductive structures as pipelines, cables, platforms, risers and well-casings) induced by earth return current in the three HVDC links.

The scope of work included the following items :

- To calculate the electric potential distribution on the land surface and the sea bed produced by the HVDC earth return current between the earth electrodes for the North Sea HVDC Projects.

- To optimise electrode locations and current directions based on the least influence on specific submarine pipelines.

- The electric potential distribution calculations were to be carried out on a 3-D model of the conducting layers covering relevant parts of the North Sea as well as land areas in Norway, Germany, the Netherlands and Denmark.

- To evaluate potential stray current interaction on (metallic constructions) off-shore and on land on the basis of the output from the 3-D model. The structures of concern were submarine and land pipelines, submarine cables as well as platforms, risers and well-casings in the vicinity of the HVDC electrodes.

- To discuss the mitigation of potential corrosive effects and to provide recommendations.

The structures included in the study was submarine pipelines and cables situated in the North Sea, East of Longitude 2°E and South of Latitude 61°N, and buried oil/gas pipelines on land in the Netherlands, Germany and Denmark.

Structures outside this area would virtually not be influenced by the HVDC links, as the electric potential distribution between the HVDC sea/ground electrodes vanishes by increasing distance from the electrodes.

5.2. Methodology

HVDC and geological data were collected and processed for use in a computer model where HVDC earth return current in the North Sea and the geological layers conducting the current was simulated.

The purpose of the model was to determine the electric potential distribution caused by the earth return current, as this is the driving force causing stray current to enter and leave conductive structures traversing the electric field.

The geological data for the model was collected from :

- Geological Survey of Denmark and Greenland (GEUS) - Copenhagen.
- Bundesanstalt für Geowissenschaft und Rohstoffe (BGR) - Hannover.

Data on the HVDC links was provided by the HVDC Projects.

The parameters in the model were:

- Location of the different geological layers and their specific resistivities.
- Location of HVDC-sea/ground-electrodes.
- HVDC earth/sea return current direction.

The variables in the model were:

- HVDC earth return currents (0 or 1600A) in each of the three HVDC-links and any combination hereof, i.e. three cases with one, three cases with two and one case with all three monopolar links simultaneously.

Data for pipelines and cables of concern was collected from owners and operators.

Potential stray current influence was evaluated on the basis of the electric potential distribution from the above described computer model.

The output from the model was potentials on the top surface of the model, from which the electric potentials along the studied structures were determined.

Based on these potentials, stray currents entering and leaving the influenced submarine structures were calculated in order to estimate corrosive interaction. The approach was to evaluate the “worst case” conditions for each pipeline. Where this analysis indicated a significant or marginal effect, the affected section was evaluated more closely, and possible mitigation methods considered.

The approach on land pipelines was different from submarine pipelines.

On land pipelines it is the change of soil/structure potential which is important. In general, the potential change may not exceed +0.1V in Germany and the Netherlands. In Denmark there is also a negative level not to be exceeded, as the off-potential on cathodic protected pipelines must be within -0.85V to -1.1V versus a Cu/$CuSO_4$-reference electrode.

A potential difference in the soil along the pipeline can change the soil/structure potential. Where stray current enters the pipeline the potential is shifted in negative direction and where the current leaves the pipeline the potential is shifted in positive direction.

Pipe/soil potentials were estimated and potential remedial actions were proposed.

Marine cables were divided into “good” and “poor” coated types. The cable armour on “poor” coated cables was modelled in the same way as submarine pipelines. On “good” coated cables the coating must be damaged at the most “inconvenient” locations before significant stray current can enter and leave the cable armour. Coating damages were therefore simulated at “worst case” locations.

5.3. Field calculations

We utilised expertise on 3-D Finite Element Modelling of the conductive layers between the HVDC sea/ground electrodes by IVO International Ltd, Helsinki.

Parallel to the 3-D Finite Element Modelling we made a 2-D model. The purpose of the 2-D modelling was to make a simulation equivalent to the 3-D model, but using a totally different approach. It was in this way possible to compare the outcome of independent calculations and hence make a quality check of the modelling.

5.3.1. 2-D model

The 2-D calculations were made by means of a field calculation programme where a current was impressed between to points in a two dimensional resistivity pattern. It was hence necessary to convert the resistivity of the spatial geological layers to a number of bricks (1m x 1m), where each brick represented the conductivity of the layers underneath it. See Figure 5-1 / 1 &2 , Figure 5-2 / 3 and Figure 5-3 / 4 & 5.

Fig. 1. Geological section with current flow at the earth surface caused by an HVDC link between A and C

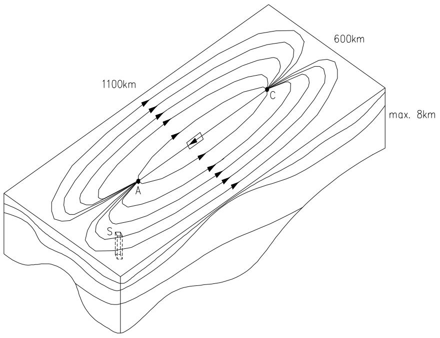

Fig. 2. Small geological section at S (see fig. 1) with parallel connection of the small geological layers.

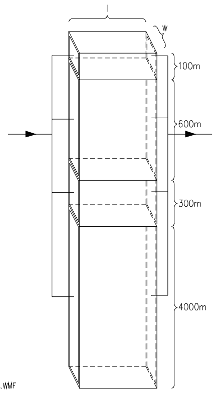

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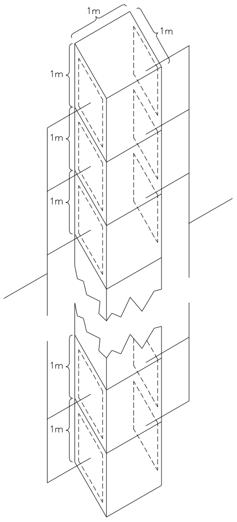
Figure 5-1 / 1 & 2   3-Dimensional geological sections

Fig. 3. A geological layer is considered as a parallel connection of small elements, e.g. 1 m^3 each.



00PROJEK\VIKING_C\CORR_STD\FL\FIG3.WMF

Figure 5-2 / 3 Parallel connection of small elements

Fig. 4. A surface element with a surface resistivity represents the parallel connection of the different geological layers in volume element S (see fig 1. and 2.).

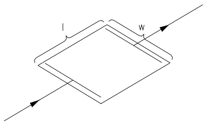
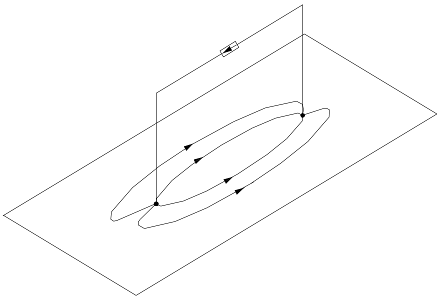


Fig. 5. A 2-dimensional current flow situation represents the 3D problem shown in fig. 1



I:\AFD24HER\CORR_STD\FIG4-5.dwg

Figure 5-3/ 4 & 5 A surface element (brick) and a 2-D current situation

6. Electrode Locations

A preinvestigation was made in order to determine which combination of electrodes would be most suitable for further investigations. 74 combinations of electrode locations and different current directions for the three HVDC links were analysed.

The selected electrode locations (and there utilization) are listed by model numbers in Table 6-1 and described in detail below.

The model numbers listed in Table 6-1 are covering the 7 combinations which can be set up with the 3 independent HVDC links. Each individual link can be in operation mode, i.e. 1600 A is running in the link(-s) or out of operation mode - no current is running in the link(-s).

As an example, model 37:

- NN-link out of operation.
- VC-link 1600 A in the earth from “Tiefwasser” to “Farsund”.
- EK-link 1600 A in the earth from “Farsund” to “EK-1”.

Model No.	HVDC links		
	NN : Breidvika(+)/ Loc.3(-)	VC : Farsund(-)/ Tiefwasser(+)	EK : Farsund(+)/ EK-1(-)
61 E_{3B}	•	•	•
3 E_{3B}	•		
6		•	
9			•
24 E_{3B}	•	•	
27 E_{3B}	•		•
37		•	•

Table 6-1 Description of model 61 E_{3b} with its submodels.

(+): Anode

(-): Cathode

• : Link in operation

After the necessary decision was taken concerning electrodes (location and operation mode), the study was concentrated on producing information on detailed potential distribution along the influenced structures.

7. Expected influence

We combined the results of the electric field calculations with expertise on submarine structures provided by Det Norske Veritas A/S, Oslo. The result was a detailed evaluation of worst case anode depletion on pipelines and submarine cables in the North Sea. The figures concerning the most influenced submarine pipelines are presented in Table 7-1.

Pipeline	Model Number	Worst Case Point Anode Depletion (kg/year)	Location (km points)	Distributed Worst Case Anode Depletion (%)
Europipe 1	61, E_{3b}	2.0	65	0.1
Europipe 2		3.8	431	0.2
Norpipe		7.4	103	0.9
NGT		1.5	51	0.1
NOGAT)		1.9	74	0.2
Europipe 1	3, E_{3b}	1.6	65	0.1
Europipe 2		3.8	431	0.2
Norpipe		7.2	103	0.9
NGT		1.5	51	0.1
NOGAT		2.1	74	0.2
Europipe 1	6	3.3	0	0.2
Europipe 2		3.5	0	0.2
Norpipe		4.2	0	0.5
NGT		1.8	5	0.2
NOGAT		0.7	245	0.1
Europipe 1	9	0.4	2	0.0
Europipe 2		2.6	431	0.2
Norpipe		1.6	76	0.2
NGT		2.8	11	0.3
NOGAT		0.8	74	0.1
Europipe 1	24, E_{3b}	2.4	65	0.2
Europipe 2		2.5	0	0.2
Norpipe		7.6	103	0.9
NGT		2.7	5	0.3
NOGAT		1.1	74	0.1
Europipe 1	27, E_{3b}	1.2	65	0.0
Europipe 2		6.4	431	0.4
Norpipe		7.1	103	0.9
NGT		2.8	11	0.3
NOGAT		2.9	74	0.2
Europipe 1	37	3.1	0	0.2
Europipe 2		3.1	0	0.2
Norpipe		2.1	0	0.3
NGT		0.9	0	0.1
NOGAT		0.2	245	0.0

Table 7-1 Calculated anode depletion for pipelines in The North Sea

Land pipelines, witch would be exposed to a potential difference of more than 0,1V, were looked at in detail. Potential shifts on these land pipelines were estimated by using the conversion principple discussed in section 4.1. The result are summarised in Table 7-2.

Land pipelines Longitudinal ΔU>100mV	Estimated pipe/soil potential shifts increase ΔU (+) / decrease ΔU (-) [mV]						
	Model No.						
	3 E_{3b}	6	9	24 E_{3b}	27 E_{3b}	37	61 E_{3b}
Ruhrgas							
Emden - Werne	-	-70/+60	-	-	+90/-105	-	-
Etzel - Werne	-	-70/+55	+55/-60	-	+90/-90	-	-
BEB Gas							
Achim - Bünder Tief - Rheine	-	-	-	-	+50/-50	-	-
NWO Oil							
Wilhelmshaven - Köln	-	-75/+95	+80/-75	-	+95/-160	-	-
Gasunie							
Spijk - Beverwijk - Rijswijk	-	-85/+45	-	-	+105/-85	-	-
Spijk - Nijkerk - Rijswijk	-	-85/+45	-	-	+115/-75	-	-
Spijk - Zweekhorst - Abbenbr.	-	-85/+45	-	-	+130/-65	-	-
Spijk - Zweekh. - Z. Kraayert.	+70/-50	-95/+45	+75/-30	-	+140/-95	-	-
Spijk - Zweekh. - Gravenvoer.	+70/-45	-90/+50	+65/-40	-	+135/-90	-	+45/-65

Tabel 7-2 Estimated pipe/soil potential shift for pipelines influenced with more than 100mV longitudinal potential difference.

Adjustment of the potentials by means of existing or new cathodic protection installations was expected to be a sufficient remedy on the German and Dutch pipelines. It was hence not regarded necessary to section the influenced pipelines by use of additional isolating joints.

(Similar concern has been paid to submarine cables. This matter will however not be discussed in this paper.)

8. The North Sea HVDC projects, development

The North Sea HVDC projects have been changed since the study on possible effects on corrosion protection was completed. It has been announced that the EuroKabel link will not be constructed as the parties behind project have terminated their agreement. It has further been announced that the Viking Cable and the NorNed Kabel will both be operated without an earth return loop. There will hence be no need for HVDC earth electrodes and there will be no influence on secondary structures from these two HVDC links.

9. Conclusion

Balslev A/S has over the last 15 years been involved in a number of projects with relation to HVDC. We have noticed how a good understanding of the importance of reliable data has eased the unavoidable process where an information flow between the involved parties leads to a consensus.

The North Sea HVDC projects will not be constructed as monopolar HVDC links as originally planned. The reason here fore is not that it would have been complicated to mitigate stray current effects. I find that a quotation from the North Sea HVDC projects study is an appropriate end to this paper:

“The study of possible effects on corrosion protection has shown that it is likely that the planned North Sea HVDC links can be operated without jeopardising the integrity of other installations in the North Sea as well as on land in the Netherlands, Germany and Denmark, provided relatively simple actions are taken. The planned off-shore electrodes are located with respect to submarine telecommunication cables and submarine pipelines, in order to minimise influence. The study result shows that this aim is fulfilled.”