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Compilation and evaluation of earth current measurements in the Forsmark area

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Abstract

Earth currents from the high-voltage direct current (HVDC) earth return electrode at Fågelsundet may, directly or indirectly, be a cause to corrosion at Forsmark. The electrode is located around 25 km from Forsmark and it injects or collects current to/from ground during monopolar or unbalanced bipolar operation of the Fenno-Skan HVDC link.

A regional resistivity model of the Fågelsundet-Forsmark area has been constructed from available information. An electric current source in the model at a position corresponding to Fågelsundet results in an electric potential as calculated numerically using a finite-difference approximation (DCIP3D from UBC-GIF). The modelling predicts an electric potential at Forsmark at around 5 V relative a remote reference when 1 000 A current is injected at the electrode. The electric field is estimated to be around 700 mV/km horizontally. The vertical component of the electric field is estimated to around 2 000 mV/km at SFR. The reason behind the stronger vertical component compared to the horizontal is that the conductive sea water tend to act as an extended part of the electrode that transmit current down into the electrically much more resistive bedrock.

Measurements of electrical fields related to earth currents have been carried out with a number of different methods and configurations at Forsmark. Measurements include time series monitoring between boreholes, borehole logging, surface profiling and measurements of DC current in power supply grounding grids. The results of different types of measurements have been compiled and summarized results are presented. The measured electric fields show a strong correlation with the current magnitude through the Fågelsundet electrode. The direction and magnitude of the measured field is however not consistent with the expected and modelled primary electric field from the Fågelsundet electrode, especially for measurements in the vicinity of the Forsmark power plants and the high-voltage AC sub-station.

A conceptual model is presented that would explain the measurement results. The AC power-lines, the sub-station and the power plant are grounded at Forsmark. The groundings are either in direct galvanic contact or through short routes via ground in contact with remote groundings of the AC power grid through power-line top and ground conductors. The grounding system at Forsmark is also expected to have good current supply from ground due to the short distance to sea water. An elevated electric potential at Forsmark due to anodic operation of the Fågelsundet electrode will drive a current through the grounding system, via the top and ground conductors to remote groundings (and the opposite for cathodic operation of the electrode). The grounding system will thus act as a secondary cathode if the Fågelsundet electrode is operated as an anode. Such a process will create an electric field around Forsmark that is of larger magnitude than the primary electric field due to the electrode operation. The concept predicts a strong vertical component of the electric field by such a secondary cathode, especially in the vicinity of the power plant and the high voltage AC sub-station. Such a vertical component is in opposite direction compared to the primary vertical component due to current injection at Fågelsundet.

The different drill sites with monitored boreholes at Forsmark have power supply with a mutual grounding grid. The grid nodes (drill sites) are expected to be at different electric potential by the secondary effects described above. A DC current flows in the grid from drill sites at high potential to the ones at low potential. Drill site grounds thus act as tertiary anodes or cathodes due to electrode operation at Fågelsundet. Current magnitudes are rather weak but they might create significant electric fields locally at the drill sites.

Sammanfattning

Jordströmmar från returelektroden för högspänd likström (HVDC) belägen vid Fågelsundet kan, direkt eller indirekt, orsaka korrosion vid Forsmark. Elektroden är belägen ca 25 km från Forsmark och den skickar ut eller tar emot ström från jord under perioder av monopolär eller obalanserad bipolär drift av Fenno-Skanlänken.

En regional resistivitetsmodell för Fågelsundet-Forsmarkområdet har tagits fram utifrån tillgänglig information. En elektrisk strömkälla i en position i modellen motsvarande Fågelsundet resulterar i en elektrisk potential som beräknats numeriskt med hjälp av en finita-differens approximation (DCIPF3D from UBC-GIF). Modelleringen predikterar en elektrisk potential på ca 5 V relativt en avlägsen referens för en injekterad ström av 1 000 A. Den horisontella komponenten av det elektriska fältet uppskattas till ca 700 mV/km medan den vertikala komponenten uppskattas till ca 2 000 mV/km vid SFR. Anledningen till att den vertikala komponenten dominerar vid SFR är att havsvattnet tenderar att fungera som en utvidgad del av elektroden som skickar ned ström i den underliggande högresistiva berggrunden.

Mätningar av elektriska fält relaterade till jordströmmar har utförts med ett antal olika metoder och konfigurationer vid Forsmark. Metoderna inkluderar tidsseriemätningar mellan borrhål, borrhålsloggning, profilmätning på marken samt mätning av likström i jordningskablar. Resultat från olika typer av mätningar har sammanställts och en sammanfattning av den sammanställningen presenteras. Uppmätta elektriska fält uppvisar en klar korrelation med utsänd strömstyrka vid elektroden i Fågelsundet. Riktningen och styrkan på fältet avviker emellertid från det förväntade fältet från elektroden, speciellt för mätningar utförda i närheten av kraftverket och ställverket.

En konceptuell modell presenteras som förklarar uppmätta resultat. Kraftledningarna, ställverket och kraftverket är jordade vid Forsmark. Jordningarna är antingen i direkt galvanisk kontakt eller via korta strömbanor i marken i kontakt med avlägsna jordningar i kraftnätet via topp- och jordledningar i kraftledningarna. Jordningssystemet vid Forsmark kan också antas ha tillgång till god strömförsörjning från jord på grund av närheten till havsvatten. En förhöjd elektrisk potential vid Forsmark på grund av användning av Fågelsundet-elektroden som anod driver alltså en ström genom jordningssystemet, via topp- och jordledningar till avlägsna jordningar (det motsatta gäller om elektroden är katod). Enligt antagandet ovan kommer jordningssystemet att fungera som en sekundär katod om elektroden vid Fågelsundet används som anod. En sådan process ger upphov till ett elektriskt fält kring Forsmark som är starkare än det primära fältet orsakat av Fågelsundet-elektroden. En kraftig vertikal komponent av det elektriska fältet skapas av en sådan sekundär katod, speciellt i närheten av kraftverket och ställverket. En sådan vertikalkomponent är i motsatt riktning jämfört med den primära vertikala komponenten orsakad av ströminjektion vid Fågelsundet.

De olika borrplatserna vid Forsmark har strömförsörjning med ett gemensamt jordningsnät. Jordningspunkterna (borrplatserna) hamnar på varierande elektrisk potential av den sekundära effekt som beskrivs ovan. I ett sådant fall drivs en likström genom jordningsnätet från borrplatser med hög potential till borrplatser med låg potential. Jordningarna verkar då som tertiära anoder eller katoder på grund av användningen av elektroden vid Fågelsundet. Strömstyrkan i jordningsnätet är relativt svag, men signifikanta elektriska fält kan uppstå lokalt vid borrplatserna på grund av detta fenomen.

Contents

1 Introduction

1.1 Background

The Swedish and Finnish power grids are interconnected with the Fenno-Skan high-voltage direct current (HVDC) link. Power may be traded between Sweden and Finland via this link. Fenno-Skan consists of two poles with separate sub-sea cables that transmit current in opposite directions. Unbalanced current is returned through ground with the help of sea electrodes close to the Swedish and Finnish shore respectively. The link can be used in monopolar mode if one of the poles is out of operation due to maintenance or repair. The return current will then be through ground only. The Swedish electrode is located at Fågelsundet, around 25 km north-west of Forsmark nuclear power plant (Figure 1-1).

SKB have carried out site investigations for a deep repository for spent nuclear waste at Forsmark and Oskarhamn. Based on the investigations, Forsmark was subsequently chosen as the preferred location for the repository. The planned repository will be constructed at around 500 metres depth in the bedrock, where the spent fuel will be stored in copper canisters. Deep boreholes from the site investigation program have been equipped with monitoring sensors and are presently used for long-term investigations of hydrogeological and hydrochemical conditions in the bedrock.

A repository for short-lived radio-active waste (SFR) is also located around 50 m underground at Forsmark (Figure 1-2). SFR was commissioned in 1988 and handles various types of waste like protective clothing and filters. Waste like scrap metal and construction material from future dismantling of Swedish nuclear power plants will also be stored at Forsmark in an extension of the present SFR.

Earth currents can be a cause to corrosion in metallic structures that are buried in the ground or in galvanic contact with the ground. Of special concern are elongated and/or insulated objects. Minor damages in the insulation may set different exposed parts of the object at different electric potential if earth currents are present. An electric current will then be channelled through the object and corrosion may arise where the current leaves the object and returns back to the ground. Another possible consequence of earth currents is induced movement of ionic radionuclides.

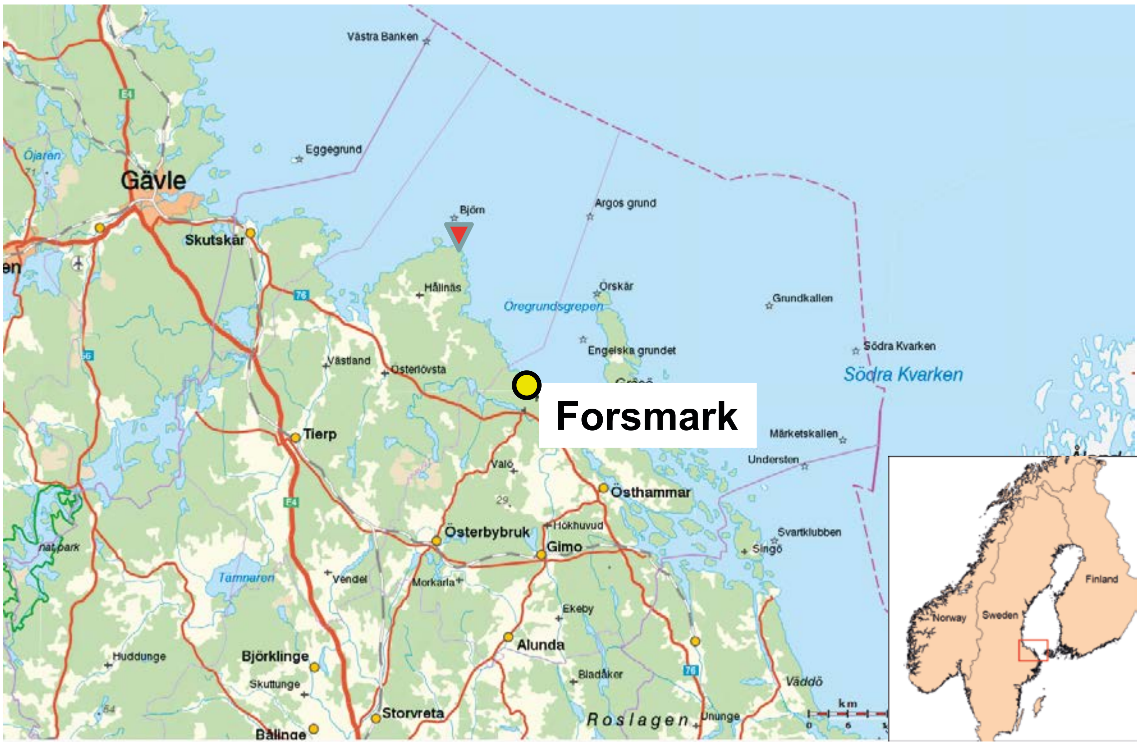

Figure 1-1. Map showing the location of the power plant at Forsmark and the electrode at Fågelsundet (red symbol).

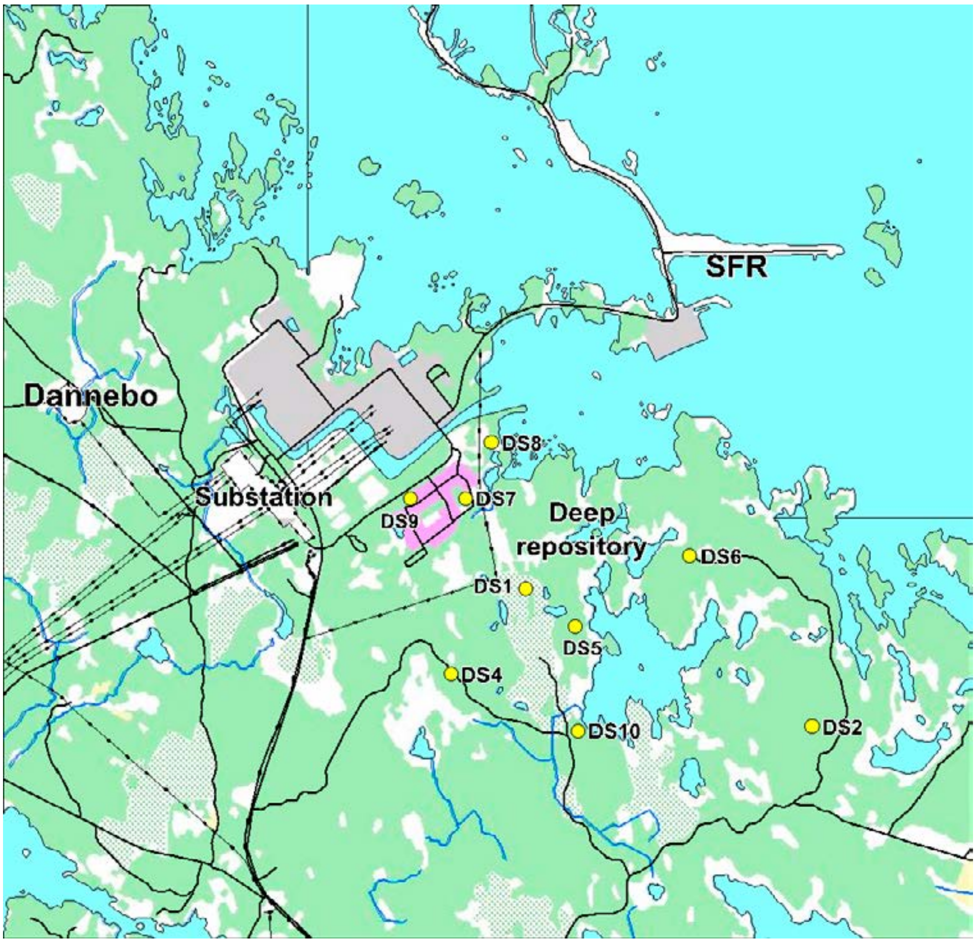

Figure 1-2. *Map of the Forsmark power plant area showing the location of the Dannebo HVDC converter station, SFR, the planned deep repository, the AC substation and the drill sites (DS) with monitoring boreholes.*

1.2 Earth currents and corrosion at Forsmark

Earth currents from the Fågelsundet electrode create an electric potential field that can be detected at Forsmark. Corrosion has damaged monitoring equipment in several deep boreholes at Forsmark. The details of the corrosion process in not fully understood, but earth currents from the Fågelsundet electrode is suspected as one primary driving force.

Some of the waste at SFR will be metallic, like e.g. dismantled reactor tanks. It is of course important to predict to what extent metallic objects in the repositories might be subjected to corrosion at Forsmark due to earth currents. Most waste at SFR is deposited in such a way that corrosion is not an issue in the safety analysis. However, corrosion of deposited reactor tanks from future dismantled reactors might possibly lead to release of radionuclides. Corrosion caused by earth currents from monopolar operation of the Fenno-Skan link is however estimated to be negligible compared to normal corrosion rates (SKB 2014). Monopolar operation of the Fenno-Skan link is also estimated to cause negligible corrosion on copper canisters in the future deep repository for spent nuclear fuel (Taxén et al. 2014).

A rather large number of investigations have been carried out at Forsmark that relates to earth currents and corrosion problems. Some of these are presented in Chapter 6 of this report.

1.3 Aim and scope

The aim of this report is to provide a general background about issues related to DC earth currents in the Forsmark area. The report includes a compilation of previous work and may serve as a starting point for future investigations. The report includes:

- A brief description of naturally occurring earth currents.
- A brief description of high-voltage DC power transmission systems and earth electrodes used for transmitting return currents.
- Predictions of electric fields due to the electrode at Fågelsundet, based on the present knowledge of the resistivity structure of the ground at Forsmark and on numerical modelling. The Fågelsundet electrode is expected to be the single most important primary driving force for earth currents. It is therefore important to estimate the magnitude and the direction of the electric field due to the electrode so that other sources, that do not fit such a pattern, may be identified.
- A description of other DC current sources at Forsmark, both primary and secondary sources.
- A compilation of different measurements of electric fields caused by earth currents.
- A conceptual description of how current sources interact with each other and with grounding systems and how that may explain the results from different measurements.
- Conclusions and recommendations for future work.

2 Spontaneous electrical potentials

Earth currents may be created by electro-chemical processes in the ground. The electric potential fields related to such currents are usually referred to as spontaneous potentials or self-potentials (SP). Measurements of SP have been used in applied geophysics as a method to detect metallic mineralization, ground water flow, redox processes etc. Logging of SP along boreholes is also a common method for discrimination of clayey units in sedimentary environments.

2.1 Different causes to spontaneous electrical potentials

There are a number of electro-chemical processes that can cause charge separation in the ground (e.g. Dukhin and Derjaguin 1974, Friborg 1997). Such charge separation is the cause to natural earth currents and corresponding spontaneous potentials. The earth currents will preferably take paths with low resistance, not necessarily coinciding with the gradient of the causative charge separation. The different processes are:

- *Streaming potential*. An electric double layer is formed at the interface between mineral grains and the surrounding electrolyte. The solid surface becomes electrically charged and ions of opposite polarity are attracted. The outer part of this ion layer may be dragged along by moving fluid in the pore space. This will introduce a charge separation between the upstream side and the downstream side. An accumulation of positive ions can usually be seen on the downstream side and the return conduction current will in such cases be directed towards the upstream side of the hydraulic pressure field. The properties of the electric double layer are dependent on a number of factors like mineral type, temperature, pH and salinity. Streaming potentials are expected to be weak in saline environments. Streaming potentials with a magnitude of several hundred mV have been recorded in areas of steep topography causing high flow rates and across embankment dams.
- *Diffusion potential*. Differences in salinity may be equalized by diffusion of ions towards volumes of lower salinity. The diffusion rate may differ between different ions, especially across clayey units or other materials with strong ion exchange capacity thus causing a charge separation. There is significant practical experience of recording diffusion potentials from wireline logging in sedimentary rock (e.g. Ellis and Singer 2008). Diffusion potentials can be fairly strong, but are usually limited to a few tens of mV in magnitude.
- *Redox potential*. Chemical gradients in the ground can cause electrical fields, analogous with galvanic cells. The possible potential difference between a volume with cathodic reactions and a volume with anodic reactions is limited by the standard potentials of the active reactions. The potential difference also depends on the concentrations of the reaction products and the reactants. Recorded redox potentials are usually rather weak except for special cases like e.g. at heaps of weathered mine waste.
- *Electrode potentials*. Electrode potentials are not truly SP as they occur when a man-made metallic object is brought into contact with ground. They are however introduced here as they in practice are indistinguishable from true SP variations during measurements. A potential difference will be set up at the contact between the metal and the surrounding earth electrolyte. The potential difference is dependent on temperature, electrolyte salinity etc. It is rarely possible to measure true SP variations with metallic electrodes because the above effect will most likely not be the same at the two electrodes. If they were the same, then the potential differences would cancel out. SP measurements are therefore carried out with non-polarizable[1] electrodes where the metal is surrounded by a saturated solution of its own salt e.g. Cu-$CuSO_4$. The solution is then in contact with the ground through a porous material like wood or porcelain. The electrode (corrosion) potential of a metallic object can be measured by connecting it to a reference non-polarizable electrode.

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[1] So called non-polarizable electrodes are not truly non-polarizable. They will to some extent be affected by e.g. temperature variations.

- *Mineral potentials*. Strong negative SP anomalies are often seen at electrically conductive bodies in the ground like ore bodies of sulphide or oxide minerals. The exact mechanism behind such potentials is debated. The magnitude of mineral potentials may be several hundred mV or even more. SP measurements have therefore been used in mineral exploration.

The above listed potentials are usually treated as DC sources. Alternating earth currents are created by induction, e.g. due to the radiation of charged particles from the sun. The earth's rotation around its axis will create 24 h variations in induced earth currents. The electric potential fields related to low frequency earth currents are however of rather weak magnitude, except during magnetic storms caused by increased solar activity. This has been shown by measurements at Forsmark (Pedersen et al. 2008).

2.2 Spontaneous potentials at Forsmark

Spontaneous potentials have been measured through borehole loggings at Forsmark during the site investigation programme. Examples are shown in Chapter 6 of this report.

Streaming potentials are not expected to be of any major significance at Forsmark. Flow rates in the ground are low, especially towards depth. The rather saline environment towards depth will also inhibit the build-up of streaming potentials.

Diffusion potentials are likely to occur at Forsmark due to the salinity gradient towards depth. The difference in diffusion rates between different ions is however expected to be too small for the build-up of strong SP. Redox potentials are also likely to occur at Forsmark.

The combined magnitude of diffusion and redox potentials may be evaluated from SP loggings in deep boreholes. Such loggings were carried out during the site investigation programme. It is however suspected that the loggings at Forsmark were strongly affected by earth currents from the HVDC electrode at Fågelsundet (Section 6.1). Correlation of SP variations can be made with geological features like deformation zones. Such SP variations in the borehole logs are of a magnitude of a few tens of mV at Forsmark (cf. Figures 7-1 and 7-2). Comparisons may also be made with logging results from the site investigation programme in Oskarshamn. Salinity gradients are seen at large depths in the Laxemar area. The recorded SP variations in deep boreholes at Laxemar are however only a few tens of mV. A HVDC link transmits power between the mainland and Gotland with an electrode not far from Laxemar. The Gotland HVDC link however operates in bipolar mode and rarely with any strong unbalanced currents that are returned through ground via the electrodes.

The magnitude of natural SP variations at Forsmark are not fully known since measurements are complicated by the presence of electric infrastructure, especially the HVDC electrode at Fågelsundet. Based on the available data and comparisons with data from Oskarshamn it is however reasonable to assume that SP variations are of the order of a few tens of mV. Such variations may be seen over short distances in the ground, e.g. around deformation zones. The natural SP variations will be overprinted on potential fields caused by electric infrastructure.

3 HVDC electrodes

3.1 Use of HVDC links

High voltage direct current (HVDC) power transmission is used to either transfer electric power from major production centres to load centres or to interconnect different power grids and thereby enable trade of power (e.g. Arrillaga 1998, EPRI 1981). Presently, power ratings for operational HVDC links are up to 8 000 MW with a voltage of up to 800kV. HVDC technology has some advantages over AC technology like e.g:

- Power losses are smaller for a HVDC system when power is transmitted over large distances.
- Smaller line towers can be used and line corridors can therefore be narrower.
- Long sub-sea or buried cables may be used. HVDC is the only realistic choice for power transmission across water for more than a few tens of km.
- Non-synchronous grids may be connected.
- Mixed 50/60 Hz grids may be connected.

The main disadvantage with HVDC technology is the extra cost involved for converter stations.

HVDC links may be operated in different modes. The three most common modes are illustrated in Figure 3-1.

- *Monopolar mode* means that a single cable or line is used for power transmission. The current will always be in the same direction. The return current is injected/collected to/from ground with the help of electrodes that are located not far from the respective converter stations. One electrode will always be used as cathode and the other electrode will always be used as an anode. The Fenno-Skan link was initially a monopolar system, before Fenno-Skan 2 came into operation.
- *Bipolar mode* means that two poles transmit current in opposite directions and the currents will closely balance each other. Unbalanced current will be returned through ground with the help of electrodes. Injected currents at the electrodes will usually be small. However, bipolar systems may be operated in monopolar mode during periods of maintenance or repair of one pole. The electrodes must be designed in such a manner that both can be used as an anode or cathode. The Fenno-Skan link became a bipolar system with the introduction of Fenno-Skan 2, although with an unusual design since the two poles have different power ratings.
- *Monopolar mode with metallic return* means that the return current runs in a low-voltage cable/line and no current will be through electrodes. The cost for the extra conductor may however be considerably larger compared to electrodes, and power losses will usually also be larger with metallic return compared to electrodes. The environmental impact from earth currents is avoided with metallic return since no current is injected into ground. Metallic return can, in principle, also be used for bipolar systems during contingent monopolar operation, if the return current can be transferred through the temporary unused high-voltage cable. The SwePol link between Sweden and Poland is an example of a HVDC link with metallic return.

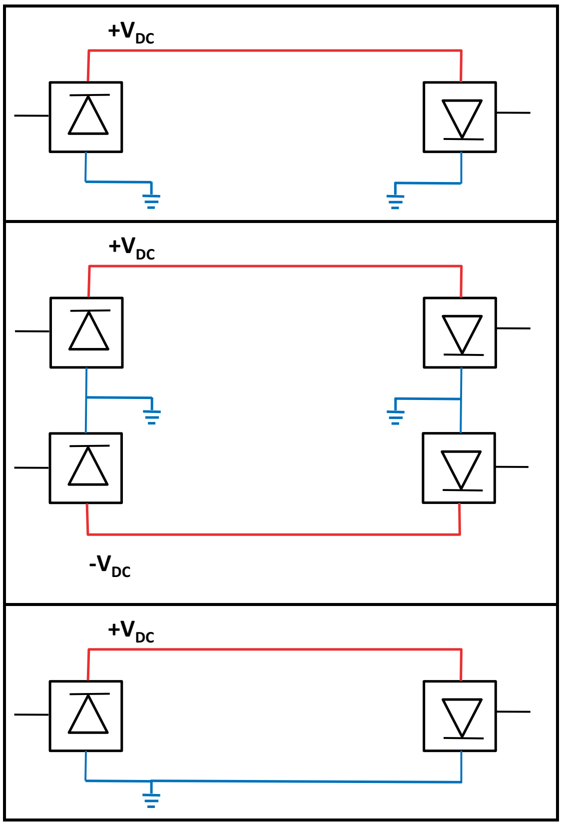

Figure 3-1. *Simplified circuit drawings illustrating different modes of operation for HVDC systems. Red connections shows high-voltage, power carrying cables/lines, whereas blue connections show low-voltage return-current cables/lines. Top: Monopolar operation with ground return. Middle: Bipolar operation. Bottom: Monopolar operation with metallic return.*

3.2 Description of the design and use of electrodes

There are many factors to consider for locating and designing HVDC electrodes. First of all it has to be decided if the electrode should be placed on land, at the shore or on the sea floor. A location on the sea floor is usually the obvious choice if the converter station is located close to the sea since the sea water is electrically conductive. Most electrode installations in Europe are on the sea floor or by the shore, whereas land electrodes are common in Asia, Africa, North and South America.

For sea electrodes the following factors will have to be considered:

- Earth currents may enter grounded star points of transformers and can thereby cause saturation of the core and thus the creation of harmonics. HVDC electrodes should therefore not be located in such a manner that earth potentials at the converter station or at other transformer stations are too high. The electrode must be placed at some distance away from such stations. The distance in question is a function of the peak injected current, the depth and resistivity of the sea water and the resistivity of the underlying soil and rock. Rock properties down to a depth of many km may have to be considered if the sea water is shallow and the bedrock is of high resistivity.
- Earth currents may be channelled through metallic structures that are in galvanic contact with ground. This may cause corrosion where the current leaves the structure. The amount of corrosion will depend upon the primary electric potential difference across the object and the ability of the ground to supply current. The operational mode of the HVDC electrode is also important. Bipolar HVDC systems are of less concern since the electrode usually will be in use only during short periods. Objects that may be affected include pipe-lines, grounded low-voltage AC nets, power-line towers, water pumps, fences etc. Corrosion problems can usually be mitigated, but the electrode should preferably be located so far away from sensitive objects that problems are avoided.

- The design criteria for an electrode usually include a maximum allowable resistance. A sea electrode should therefore be located some distance away from the shore and not in shallow water. The location should also preferably be close to deep sea areas. The resistivity of the underlying soil and rock will be of great importance if deep sea areas not are to be found within an acceptable distance from the converter station. The physical size of the electrode will also affect the resistance. Low resistance will keep losses down and reduce heating. It should however be pointed out that electrode losses usually are insignificant in comparison with other transmission losses and that thermal effects at a sea electrode is of minor concern because of convection heat transfer.
- A suitable material must be chosen for the electrode. An electrode that only will be used as a cathode may be constructed from e.g. stranded copper wire. Material that is not consumed by the electrode reactions must be chosen for an anode. Coated titanium nets are frequently used, although e.g. silica-iron-alloys and coke also are possible choices.
- The electrode reactions at the anode will, at least to some extent, involve emission of chlorine. Chlorine emission will depend on e.g. water salinity, electrode material and current density. Emissions will therefore be kept low if the electrode is made large. Sea fauna may be affected by strong electrical gradients close to the surface of the electrode. Such gradients will also be kept low by making the electrode sufficiently large.
- The expected life-time, operational mode and the dissipation of electrode material will impose a lower limit on the size of the electrode.
- Large distance to the shore, deep water and rough sea-bottom topography will complicate the construction, monitoring, maintenance and repair of an electrode.
- Environmental factors like sea currents, erosion, sedimentation and ice must be considered.
- Apart from the above factors that are more or less directly related to the design, construction and operation of an electrode, a number of factors that not are directly related to the electrode itself will have a large influence on the location of the electrode. Many areas will be excluded as possible locations. Reasons for this will include land access, cost and environmental impact of the electrode line, possible interference with fishing, tourism, waterways and boating. Natural reserves and cultural heritages will also be excluded.

3.3 Electric fields from electrodes

The electric field due to current injected into, or collected from, the ground by a HVDC electrode is strongly dependent on the resistivity structure of the ground, including soil cover and sea water. Numerical modelling with a full three-dimensional resistivity model is therefore necessary for realistic predictions of the electric field. The field at a distance that is large compared to the physical size of the electrode may be modelled by a point source, whereas the field closer to the electrode must take the actual size and shape of the electrode into account.

We can consider the simple example of a homogeneous and isotropic half-space. The electric potential for a point source on the surface of such a half-space will be:

$$V = \frac{\rho \cdot I}{2\pi \cdot r}$$

where ρ is electric resistivity of the half-space, I is the current magnitude and r is the distance. The electric field is found by differentiation to be:

$$E = -\frac{\partial V}{\partial r} = -\frac{\rho \cdot I}{2\pi \cdot r^2}$$

The electric potential (relative infinity) and electric field as a function of distance is plotted in Figure 3-2 for a half-space of resistivity 2 000 Ωm and a current of 1 000 A (black curve). The electric potential at a distance of 25 km will be 12.7 V and the magnitude of the electric field will be 0.5 V/km. The value for the electric field is of the same order as measured data at Forsmark due to current injection at the Fågelsundet electrode (cf. Chapter 6).

We can now examine the effect of the resistivity at large depth. The electric potentials for two-layered earth models are shown in Figure 3-2. We start by adding a resistive substratum (20 000 Ωm) at 4 km depth below the 2 000 Ωm medium (blue curves in Figure 3-2). The potential at 25 km distance from the source will then be 83 V and the electric field will be 2.1 V/km for a 1 000 A source, i.e. the potential is 6.5 times larger and the electric field is 4.2 times larger compared to the homogeneous half-space case. The effect of a low-resistive substratum (200 Ωm) at 4 km depth is shown with green curves in Figure 3-2. The electric potential for such a model at 25 km distance is 1.3 V and the electric field is 0.062 V/km, i.e. the potential is 9.8 times smaller and the electric field is 8.1 times smaller compared to the half-space case. We can thus conclude that for distances that are relevant for transformer stations and other infrastructure, the electric potentials and electric fields due to a HVDC electrode will be strongly dependant on the resistivity of rock at depths that are beyond the investigation depth of both normal drilling and most geophysical methods. The only available methods to investigate the electric properties at depths of many km are magnetotellurics or to measure the electric field due to the electrode itself. Good magnetotelluric data can however be difficult to acquire close to power-lines or transformer stations due to the electromagnetic noise level.

The effect of a thin, very conductive near-surface layer is also shown in Figure 3-2. A 10 m thick layer with a resistivity of 1.0 Ωm has been added on top of the 2 000 Ωm half-space (red curves in Figure 3-2). Such numbers for the near-surface layer would approximately correspond to the near-shore, shallow brackish sea water outside Forsmark. Not surprisingly, the electric potential and the electric field are much reduced close to the electrode compared to the half-space. The electric potential at 25 km distance from the electrode will however be 10.3 V and the electric field will be 0.32 V/km. This corresponds to 81% and 64% respectively of the values for the 2 000 Ωm half-space case. We can thus conclude that the electric potential and the electric field can be quite strong at some distance away from a HVDC electrode, if the electrode is placed in shallow brackish sea water underlain by e.g. granitoid rock.

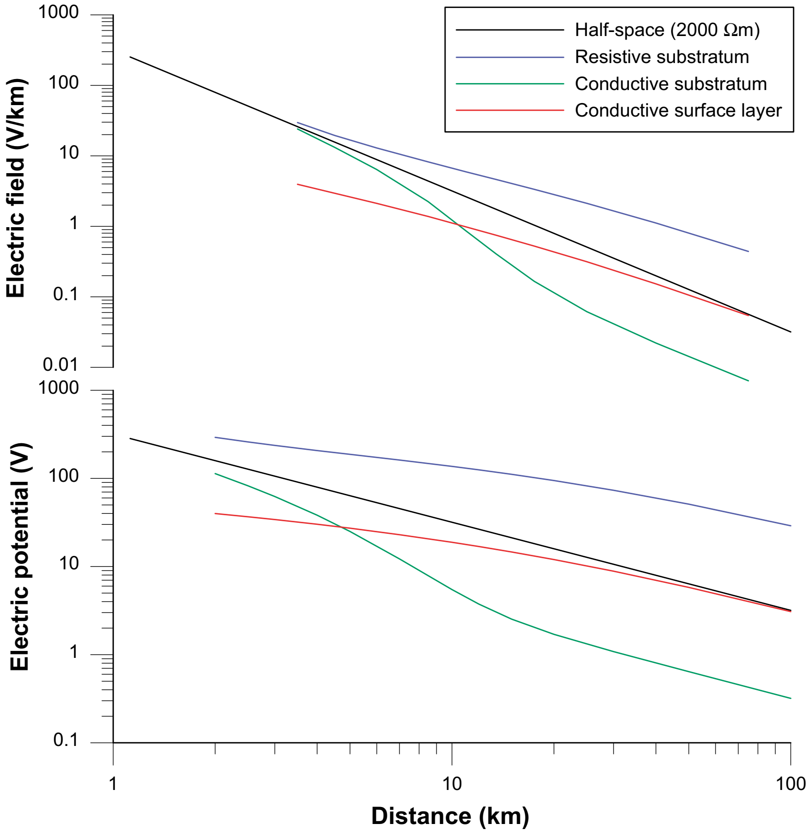

Figure 3-2. *Calculated electric field and electric potential due to a 1 000 A point source on the surface. Black: 2 000 Ωm homogeneous half-space, Blue: 2 000 Ωm with 20 000 Ωm substratum at 4 km depth, Green: 2 000 Ωm with 200 Ωm substratum at 4 km depth, Red: 10m/1Ωm surface layer and 2 000 Ωm below.*

3.4 Examples of different electrode installations

Hatch Ltd (2008) has compiled technical information on electrode installations that existed at the time of writing their report. In total 31 HVDC projects are listed where electrodes are used. The report is a few years old and some new projects have become operational afterwards. However, if corrosion is the main concern, electrodes that have been in operation for some time are the most relevant ones. Some installations operate in bipolar mode where only minor amounts of unbalanced current are passed into the ground. Environmental permits put restrictions on the use of electrodes for some installations. For a number of installations the average operational time of the electrodes exceed 500 hours per year (Table 3-1). The list in Table 3-1 also includes the Cahora Bassa, Gotland and Konti-Skan links since they have been in use for a substantial time and during periods have been operated in monopolar mode with ground return or with strong unbalanced currents in bipolar mode. Only seven HVDC links were operational 2008 with ground return for more than 500 hours per year on an average.

O'Brien et al. (2006) describe the environmental impacts around the electrodes for HVDC transmission between the North Island and South Island, New Zealand. The only corrosion problem that was noted was with a metal fence constructed by a local land owner not far from one of the electrodes. The problem could be remedied by the installation of insulators.

Nyman et al. (1988) report corrosion damage around the mainland electrode for the Gotland HVDC link. Corrosion occurred in groundings of low-voltage network in the vicinity of the electrode. The screen of a telecommunications cable and reinforcement to a power cable were also affected. All corrosion damage occurred within about 4 km distance from the electrode.

Rosenberg and Sandberg (1992) report corrosion problems around the Risö electrode of the Konti-Skan link. Significant corrosion was observed on telecommunication cables in the Gothenburg area. A gas pipeline that was built between Falkenberg and Gothenburg in the late 1980's was also affected by stray currents as far as 45 km from the electrode. The commissioning of Konti-Skan 2 reduced the problems, but Konti-Skan has been operated in monopolar mode during periods after 2010 and corrosion problems on pipelines have been reported (Sandberg B 2015, personal communication).

Table 3-1. HVDC-links where the average operational time of the electrodes exceed 500 h per year (Hatch Ltd 2008) and links where the electrodes historically have been use in monopolar mode or bipolar mode with strong unbalanced currents.

HVDC-link	Connected countries or areas	Operational mode	Type of electrode	Average yearly operation hours	In service from
Baltic Cable	Sweden Germany	Monopole	Sea Sea	8652	1994
Fenno-Skan	Sweden Finland	Monopole*	Sea Sea	8700	1989
Grita	Italy Greece	Monopole	Sea Sea	8700	2002
Kontek	Denmark Germany	Monopole	Sea Sea	8700	1996
New Zealand	North Island South Island	Monopole*	Shore Land	2500	1965/92
Skagerrak	Denmark Norway	Three-polar**	Land Sea	1000	1975/76/93
Sacoi	Italy (mainland) Corsica Sardinia	Monopole	Sea Land Shore	8700	1967/92
Cahora Bassa	Mocambique South Africa	Bipole	Land Land	168	1976
Gotland	Gotland Mainland Sweden	Bipole***	Shore Shore	300	1954/83/87
Konti-Skan	Sweden Denmark	Bipole****	Sea Shore	160	1965/88/2006

* Upgraded to bipole.
** The currents of poles 1 and 2 are balanced by the current in pole 3 under normal operation.
*** The first commissioned link was run in monopolar mode and the two first links were run in homopolar mode (same current direction) for some time.
**** The link was first a monopole. Since the commissioning of the second pole the current is usually, but not always, balanced by the two poles.

The operational modes and geological conditions for the different electrodes in Table 3-1 can be compared with the corresponding mode and conditions for the Fågelsundet electrode. Some comments follow below.

HVDC links Grita and Sacoi have electrodes that are located near deep sea areas. The bedrock at these locations consists of formations that are expected to have rather low resistivity. The electric fields are therefore weak around these electrodes and corrosion problems are not anticipated.

The Songo electrode in Mozambique (Cahora Bassa Link) is installed in a geological position that has some similarities with Fågelsundet. On one side of the electrode are exposed granitic basement rocks and on the other side a low resistivity setting with sedimentary rocks underlain by presumably granitoid basement. The sedimentary rocks are likely to have a similar effect on current distribution as the sea has at Fågelsundet. No corrosion problems have been noted around the Songo electrode (Magg T 2014, personal communication). The distance between the electrode and the Cahora Bassa power station and Songo town is about 15 km. The Apollo electrode of the Cahora Bassa Link in South Africa is located in a gently dipping graphite bearing formation that is known to have a large lateral extent.

Tykeson et al. (1996) shows results from electric potential measurements around several HVDC electrodes in northern Europe. The electric potential is very low around the Danish electrode of Konti-Skan (Sweden-Denmark link), and both electrodes of the Baltic Cable (Sweden-Germany). These three electrodes are all located in areas with thick piles of sedimentary rocks that are expected to have low resistivity. Similar geological conditions are also seen around the Gotland electrode and both Kontek (Denmark-Germany link) electrodes. Electrodes causing stronger electric potentials according Tykeson et al. (1996) include the mainland Gotland linkelectrode, the Swedish Konti-Skan electrode and the Swedish Fenno-Skan (Fågelsundet) electrode. The two former have however been in operation only 300 and 160 hours/year respectively on an average according to Hatch Ltd (2008).

The Norwegian electrode of the Skagerrak Link is located close to shore in an area of gneissic basement rocks. The distance to deep sea water (> 200 m, ~ 0.2 Ωm) is around 10 km. Any corrosion problems around the Norwegian Skagerrak electrode is therefore expected within rather close range.

The most obvious choice for comparisons with the Fågelsundet electrode is of course the electrode on the Finnish side of the Fenno-Skan link. That electrode is located in the sea outside the village Ketteli, some 23 km from Rauma. The location is in an area where the bedrock to a considerable extent consists of Häme migmatites. Several electrically conductive bodies, presumably graphite bearing, can be seen in airborne electromagnetic maps of the area. The distance to the electrically strongly conductive Vammala migmatite belt is some 60 km. It is therefore likely that earth currents from the Fenno-Skan electrode outside Rauma to a considerable extent are channeled through the earth's crust by graphitic units in these migmatite belts.

Considering the above, there is hardly any HVDC electrode in the world where operational modes and geological conditions are similar to the Fågelsundet electrode and direct comparisons of corrosion problems with other electrodes are not straightforward. Electrodes with some similarity to Fågelsundet include the Finnish Fenno-Skan electrode, the Swedish Konti-Skan electrode, the mainland Gotland link electrode, the Norwegian Skagerrak link electrode and the Songo electrode of the Cahora Bassa link.

4 The Fågelsundet electrode

The Fågelsundet HVDC electrode is located on the seabed in shallow water not far from the shore around 25 km north-west of the Forsmark power plant area (Figure 4-1). The water depth in the sea outside the electrode is locally up to 60 m but on an average only around 25 m. The water depth in Öregrundsgrepen outside Forsmark is in general less than 20 m. The bedrock is dominated by meta-granites with some inclusions of gneiss, felsic meta-volcanics, meta-arenites and mafic intrusive rocks. All rock types in the area are expected to be of high electric resistivity.

Jonsson et al. (1992) and Tykeson et al. (1996) present electric potential measurements along a profile in the sea water radially away from the Fågelsundet electrode (Figure 4-2). The measurements were made with full power load on Fenno-Skan 1. The potential was estimated to around 9 V at a distance of 20 km. Those data can be re-calculated to a homogeneous half-space apparent resistivity to get an idea about the effective bulk resistivity of the subsurface in the Fågelsundet area (Figure 4-2 right graph). The short distance measurements are affected by the shallow sea water, but the apparent resistivity tends to asymptotically reach a value of around 1 100 Ωm for large distances where the effect of the water on the measurements is small. The measurements for the largest separations in Figure 4-2 are influenced by the electric properties of the ground down to a depth of around 10 km. It thus seems as the bulk resistivity of the rock down to such a depth is around 1 100 Ωm. It is of course likely that both lateral and vertical resistivity variations exist that are not reflected by the data in Figure 4-2.

Unpublished data similar to those in Figure 4-2 along a profile running from Skutskär towards Uppsala indicate a bulk resistivity on land of around 3 000 to 7 000 Ωm. The closest measurement point was around 30 km from the electrode and the measurements therefore only yield information about the lower crust and upper mantle in the area.

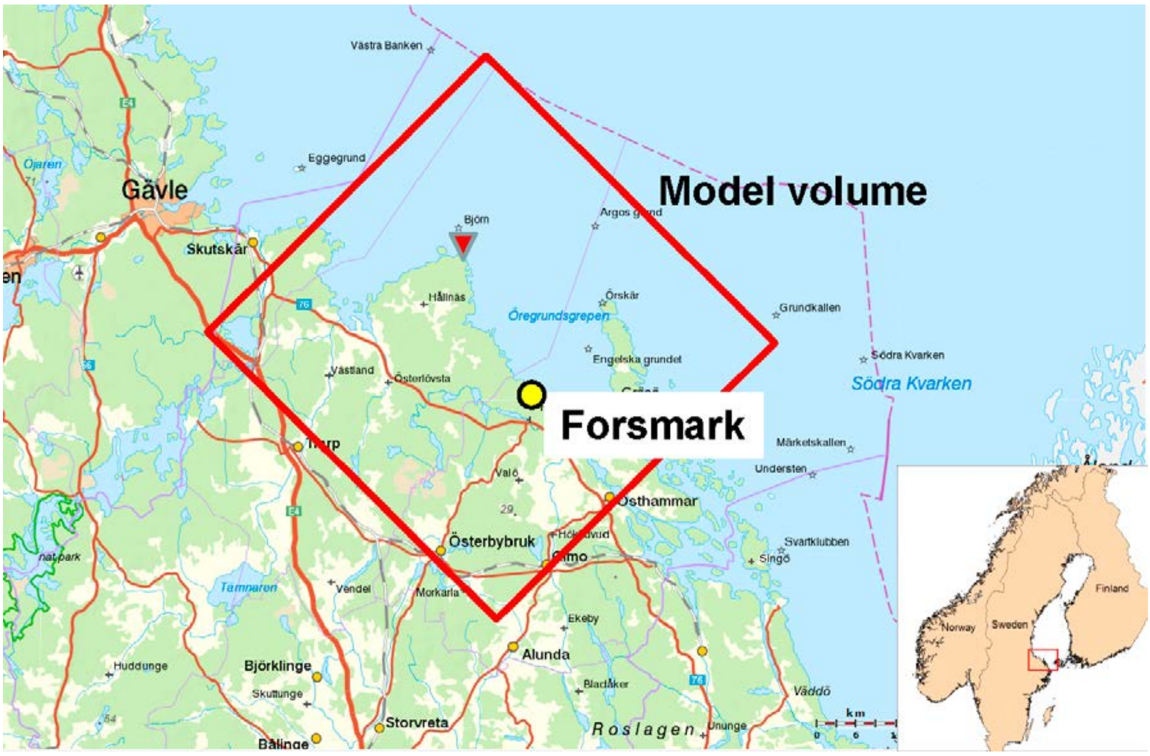

Figure 4-1. Map showing the location of Forsmark, the Fågelsundet electrode (red symbol) and the model volume for a 3D resistivity model (red rectangle).

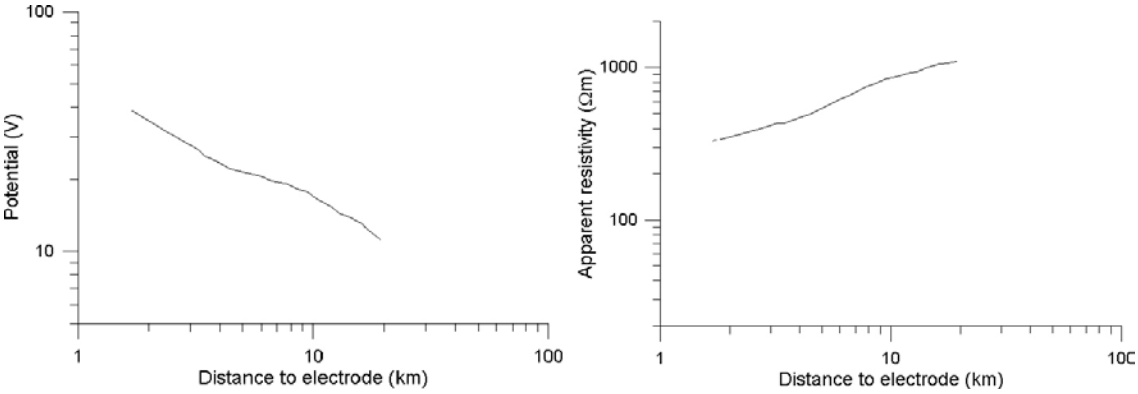

Figure 4-2. *Left: Measured electric potential along a profile in the sea due to injection of 1 280 A at the Fågelsundet electrode (redrawn from Jonsson et al. 1992). Right: The same data expressed as homogeneous half-space apparent resistivity.*

4.1 Regional resistivity model for the Forsmark area

A resistivity model has been created with the aim of estimating the electric potential due to the Fågelsundet electrode. The resistivity structure of the sub-surface in the area is not known in detail, so the model should be treated with some care. The model has been constructed from:

1. Measurements of the electric potential in the sea outside the electrode (Jonsson et al. 1992, Tykeson et al. 1996).
2. TEM (transient electromagnetic) soundings at Forsmark and surroundings (Thunehed and Pitkänen 2007).
3. Electric soundings at Forsmark (Thunehed and Pitkänen 2003).
4. Petrophysical measurements on rock samples (e.g. Isaksson et al. 2004, Thunehed 2007).
5. Geophysical borehole logging (e.g. Nielsen et al. 2005, 2006, Nielsen and Ringgaard 2007a, b, c).
6. Measurements of electric fields between boreholes (Pedersen et al. 2008, 2013).
7. Sea charts were used for the construction of a sea water layer with variable thickness.

An illustration of the resistivity model can be seen in Figure 4-3. The model consists of rectangular cells with a horizontal dimension of 250 by 250 m in the central part that includes both the electrode site and the Forsmark area. The uppermost layer has a vertical thickness of 2 m. Cell dimensions increase gradually outwards and towards depth[2]. A flat upper surface has been imposed, thereby disregarding the effect of topography on land.

The resistivity model consists of four domains. It is assumed that different rock types will not have significantly different electric properties. Deformation zones with low resistivity are known to exist in the area, but the widths of such zones are fairly small in comparison with the size of the model so the effect of deformation zones is included in the bulk resistivity values for different domains. Deformation zones will perturb the electric potential pattern, but on a regional scale only to a minor degree. However, since the current density in the ground is inversely proportional to the resistivity (and proportional to the potential gradient), a low-resistivity deformation zone can serve as a pathway for electric current even if it does not affect the electric potential distribution very much. The lowermost domain in the model (light blue, Figure 4-3) correspond to rock saturated with saline water. The bulk resistivity and the depth to such a domain away from the coast have been estimated by TEM-soundings (Thunehed and Pitkänen 2007). A resistivity of 1 250 Ωm for the domain is compatible with the TEM-soundings, the potential measurements away from the electrode (Jonsson et al. 1992, Tykesson et al. 1996), measurements between boreholes (Pedersen et al. 2013) and petrophysical

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[2] The cell size increases by around 30% for each row and column in the mesh outside the core of the mesh. The thickness of mesh layers increase by around 50% for each layer from the surface.

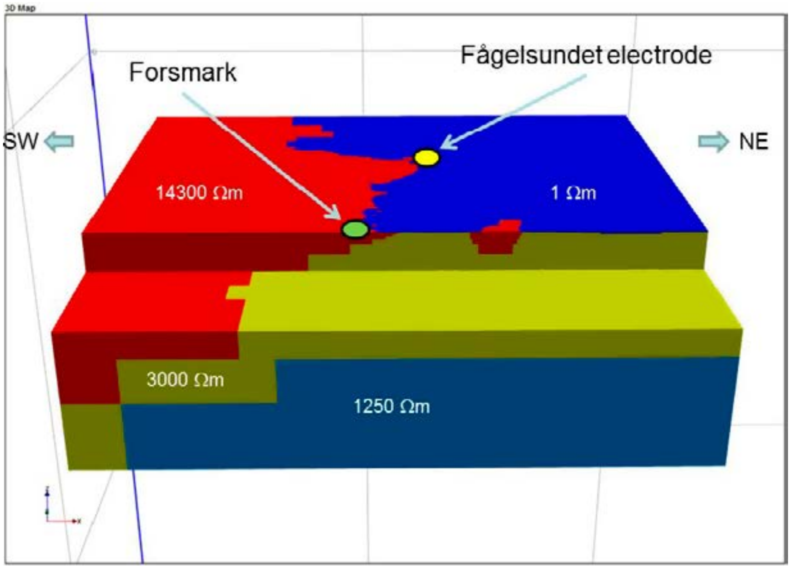

Figure 4-3. *Resistivity model for the Fågelsundet-Forsmark area. The model covers the area indicated by a red rectangle in Figure 4-1. The vertical scale is exaggerated by a factor 8. Only the top 3.5 km of the model are shown. The complete model extends to 41 km depth.*

data (Isaksson et al. 2004, Thunehed 2007). The gently dipping interface seen in Figure 4-3 is also compatible with the hydrogeochemistry model for the Forsmark area (Laaksoharju et al. 2008). The next layer corresponds to rock saturated by brackish water (yellow in Figure 4-3). The resistivity of this layer has been set to 3 000 Ωm, which is mainly taken from the TEM soundings. The thickness of the layer is defined from TEM-soundings and the hydrogeochemical model (Laaksoharju et al. 2008). The red unit in Figure 4-3 corresponds to rock saturated by fresh water. The resistivity of this unit (14 300 Ωm) is defined from petrophysical data, borehole resistivity logging, electric soundings and TEM soundings. The thickness of the layer is defined by the TEM-soundings and the hydrogeochemical model. A thin layer corresponding to sea water is the top layer. The thickness of this layer varies in accordance with sea charts (difficult to see in Figure 4-3). The water layer is quite thin (average 26.8 m) especially close to land, including around the location of the electrode, but it has a significant impact on the electric potential due to the low resistivity of 1.0 Ωm. The resistivity of the different rock units is lower compared to average resistivity values seen in the borehole loggings. The values for the model are however bulk values that also include the effect of fractures and deformation zones.

4.2 Modelled electric field

The electric potential due to a point source located at Fågelsundet and the resistivity model of Figure 4-3 was calculated with the finite-difference program DCIPF3D (Li and Oldenburg 2000). The results for a unit current (1 A) can be seen in Figure 4-4. On the surface, the potential is higher at sea areas compared with areas at corresponding distance from the electrode on land. The reason for this is that the sea water almost will act as an extension of the electrode due to the low resistivity of the water. This also has the consequence that the potential gradient will have a vertical component close to the surface by the shore also at large distance from the electrode since current will be transmitted from the sea water down into the rock.

According to the model, the electric potential at Forsmark is estimated to around 0.005 V/A (5V/kA). The potential is a bit higher at SFR. The potential gradient is estimated to 700 mV/km/kA horizontally and 2 000 mV/km/kA vertically at SFR. The potential decreases with depth, which does not agree with the SP loggings in deep boreholes at Forsmark (cf. Chapters 6 and 7). Electric infrastructure is not included in the model and it is explained in Chapter 7 how such infrastructure may explain the disagreement between modelling results and measured data. The direction of the horizontal gradient is roughly NS at Forsmark which also is in disagreement with measurements (cf. Chapter 6).

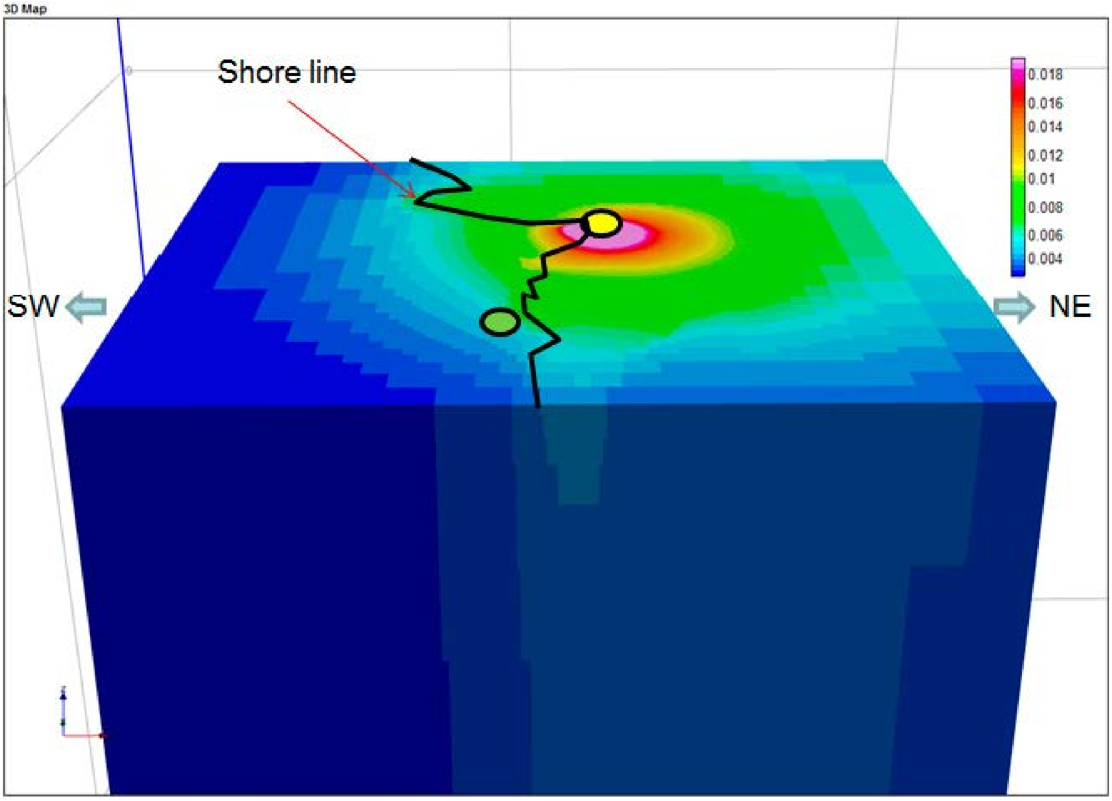

***Figure 4-4.** Calculated electric potential (V/A) due to a point source at Fågelsundet for the resistivity model in Figure 4-3.*

5 Other sources of DC electric fields

5.1 Grounding lines

Functional and protective grounding of electric equipment may serve as secondary sources to earth currents through so called transferred potentials. A grounding that is at a high electric potential will transfer current through the circuitry to a connected grounding that is at a lower electric potential. The former will thus act as a local cathode whereas the latter will act as a local anode. The amount of current that is transferred is dependent on the grounding resistances, the primary potential difference and the ability of the ground to supply current. The resistance in the connecting cable can in many cases be neglected and the electric potentials at different inter-connected groundings will therefore be more or less the same.

Groundings may end up in locations with different potentials for different reasons. The potential levels may temporally change due to telluric currents caused by solar activity. Spontaneous potentials from electrochemical reactions in the ground may be another cause but anthropogenic sources are often dominating. HVDC electrodes, active corrosion protection and other DC sources will set the ground at varying electric potential.

The current flow in a grounded circuit depends on the ability of the ground to supply current. The current flow is therefore likely to be larger for a grounding that is in galvanic contact with a low-resistive structure like a water-bearing deformation zone in the ground or with sea water. Groundings at Forsmark may potentially have good current supply due to the proximity to the sea.

The power supply to the drill sites at Forsmark is grounded at each drill site. The groundings are then inter-connected to a common circuit. Corrosion potential measurements have indicated that borehole casing in some cases is in galvanic contact with power supply ground (boreholes KFM01C and KFM05A). The short distance between ground mats and the borehole casing will however result in rather moderate electric resistance between the objects also for the other boreholes. The drill site groundings may thus act as local current sources also involving the borehole casings to a greater or lesser extent.

5.2 Cathodic protection systems

Earth currents can potentially cause corrosion if the current is channelled through a metallic object. The corrosion will take place where the current leaves the object. It is therefore possible to protect an object by placing it at low electric potential so that it always will act as a current sink, i.e. electric current will preferably enter the object but not leave it. This can be done by either connecting the object to a sacrificial anode that is made out of a less noble metal or by connecting it to the negative terminal of a DC current source. The cathodic protection system is therefore a source of earth currents of its own and may affect other objects in the vicinity. The injected current is however usually of rather moderate magnitude. The anode and the cathode will be at fairly short distance from each other so that their effects usually cancel each other away from the installation, unless the protected object is of large dimensions. In such a case it is possible that the effective current sink can be at considerable distance from the source.

Active corrosion protection systems have been installed on monitoring equipment at several of the drill sites at Forsmark. The protected objects are the central steel rods that run through the centres of the holes. Those rods are however quite long, extending to several hundred metres depth in the ground. It is therefore difficult to predict at what depths the current actually will be collected. The depth of current collection will also change if the external electric potential field is changed, e.g. due to change of polarity at the Fågelsundet electrode or if protection systems at other boreholes are connected/disconnected. It cannot be ruled out as a possibility that one protected borehole installation draws current from a neighbouring hole at depth. This might happen for different holes at the same drill site, but some holes at different drill sites are also located not very far from each other towards depth like e.g. KFM04A–KFM01A or KFM07A–KFM09B.

5.3 Conceptualization of current paths at drill sites

Some possible current paths involving metallic objects at the drill sites at Forsmark are discussed in this section. The situation is likely to vary from one drill site to another and also between different holes at the same site. Figure 5-1 shows the principal installation in a monitored borehole. More detailed descriptions can be found in Sandberg (2014). The uppermost part of the hole has metallic casing and hosts the monitoring equipment. The instruments are connected to different sections in the lower, open part of the borehole. The equipment is mounted on a stainless steel rod that runs from the surface to the deepest monitored section. The steel rod is insulated with a Teflon coating down to the uppermost section, but the coating may become damaged leaving the metallic rod in electric contact with the surrounding.

Figure 5-2 shows the different earth current sources that may interact with metallic equipment in a borehole for the situation where Fenno-Skan 2 is in operation, i.e. the Fågelsundet electrode is used as a cathode. A borehole in the vicinity of the Forsmark power plant is also assumed. Natural spontaneous potentials have been neglected. The primary electric potential field due to the electrode at Fågelsundet is also not considered in the figure. The earth current sources are:

1. Current is injected to ground by the grounding system of the major AC power lines that connects Forsmark with the Swedish power grid. The current drawn from the Fågelsundet electrode will set Forsmark at a lower potential compared to other grounding points in the 400 kV AC grid. Current will thus be drawn from remote grounding points and injected at Forsmark. These earth currents may be channelled through the casing of boreholes and through the central steel rod of the borehole. Eventually such currents will leave the metallic structures and may then cause corrosion.
2. The drill sites at Forsmark have an inter-connected grounding grid. The injection of current at the groundings at the substation (cf. #1 above) will cause a potential field that is over-printed on the primary potential field caused by the Fågelsundet electrode. This will set drill sites close to the substation (e.g. sites 7, 8 and 9) at higher electric potential compared to sites further away (e.g. sites 2 and 10). Current will therefore be drawn from the former drill-sites and injected at the latter ones. The drill site grounds will thus act as tertiary current sources or sinks. Current might be channelled through the borehole casing and through the borehole steel rod towards the drill site ground. The local effect (potential gradient) of these current sources might be stronger than the primary effect from the HVDC electrode or the secondary effect of substation grounds at some drill sites, especially at shallow depth.
3. Cathodic protection systems are connected to most of the monitoring boreholes at Forsmark. The central steel rod is connected as a cathode to a DC current source with an anode at some distance away from the drill site. The central rod will thus be at low electric potential and it will act as a current sink. The resistance between the steel rod and the borehole casing might however be quite low and for some borehole they are known to be in galvanic contact with each other (boreholes KFM01B, KFM02A, KFM05A, KFM06B and KFM08B). A significant part of the protection current drawn from the surrounding formation might therefore be channelled through the borehole casing before entering the protected rod. It is also possible that some current is drawn through drill site ground from other drill sites if the resistance is low between central rod-casing-drill site ground. It should also be pointed out that the protected object is several hundred metres long and located in a potential gradient field when the HVDC electrode is in operation. The resistivity of the surrounding rock volume and hence the ability to supply current will vary with depth. It is therefore difficult to predict where current will enter the rod and it might even happen that current leaves the rod at some location.
4. Neighbouring boreholes are also connected to cathodic protection systems. The borehole collars at a drill site are quite close to each other. Some boreholes from different drill sites are at rather short distance from each other at large depth (e.g. KFM04A–KFM01A or KFM07A–KFM09B). Some current might therefore be channelled through the central rod or the borehole casing to supply current to the protection system of a neighbouring hole.

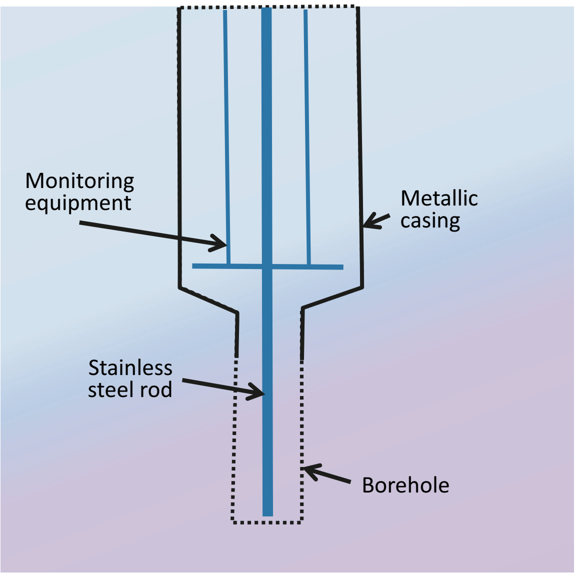

***Figure 5-1.** Sketch showing the principal design of a deep monitoring borehole. The upper part is of larger diameter and with metallic casing. The lower part is open. A steel rod is located at the centre of the hole. Monitoring equipment is positioned in the cased part of the hole and is connected through tubes to measurement sections in the lower part. The sections are hydraulically isolated from one another with inflatable rubber packers.*

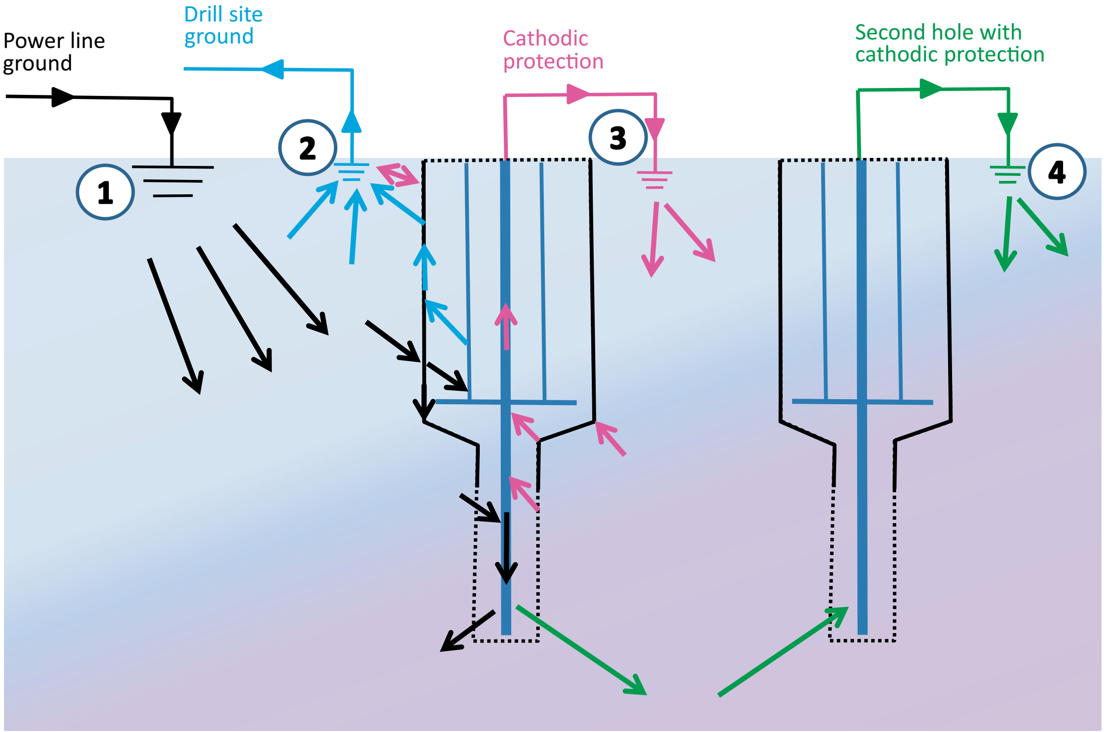

***Figure 5-2.** Conceptual sketch of local earth current sources at a drill site near the power plant (e.g. drill site 7, 8 or 9). Fenno-Skan 2 in operation and thus the Fågelsundet electrode operating as a cathode is assumed. 1) Current injected at groundings at the substation and power plant. 2) Current drawn by the grounding grid that inter-connects the drill sites. 3) Cathodic protection system of the borehole monitoring equipment. 4) Cathodic protection system of a neighbouring borehole. See text for explanations.*

Figure 5-3 shows the different earth current sources that may interact with metallic equipment in a borehole for the situation where Fenno-Skan 1 is in operation, i.e. the Fågelsundet electrode is used as an anode. A borehole in the vicinity of the Forsmark power plant is assumed. The current sources that directly or indirectly are related to the HVDC electrode are the same as in Figure 5-2 but with opposite polarity.

1. Current is drawn from ground by the grounding system of the major AC power lines that connects Forsmark with the Swedish power grid. The current injected at the Fågelsundet electrode will set Forsmark at a higher potential compared to other grounding points in the AC grid. Current will thus be injected at remote grounding points and drawn from Forsmark. These earth currents may be channelled through the casing of boreholes and through the central steel rod of the borehole. At some point such currents will leave the metallic structures and may then cause corrosion.
2. The current drawn from the groundings at the AC substation will cause a potential field that is over-printed on the primary potential field caused by the Fågelsundet electrode. This will set drill sites close to the substation (e.g. sites 7, 8 and 9) at lower electric potential compared to sites further away (e.g. sites 2 and 10). Current will therefore be injected at the former drill-sites and drawn from the latter ones. The drill site grounds will thus act as tertiary current sources or sinks. Current might be channelled through the borehole casing and through the borehole steel rod. The local effect (potential gradient) of these current sources might be stronger than the primary effect from the HVDC electrode or the secondary effect of substation grounds.
3. Cathodic protection systems will set the central rod of the borehole at low electric potential. The tuning of the protection system is difficult since the ambient electric potential gradient will change polarity depending on which HVDC pole is in operation. The net current at the HVDC electrode may also be close to zero if both poles are in operation.
4. Current may be channelled through metallic objects in a borehole to supply current to the protection system of a neighbouring borehole.

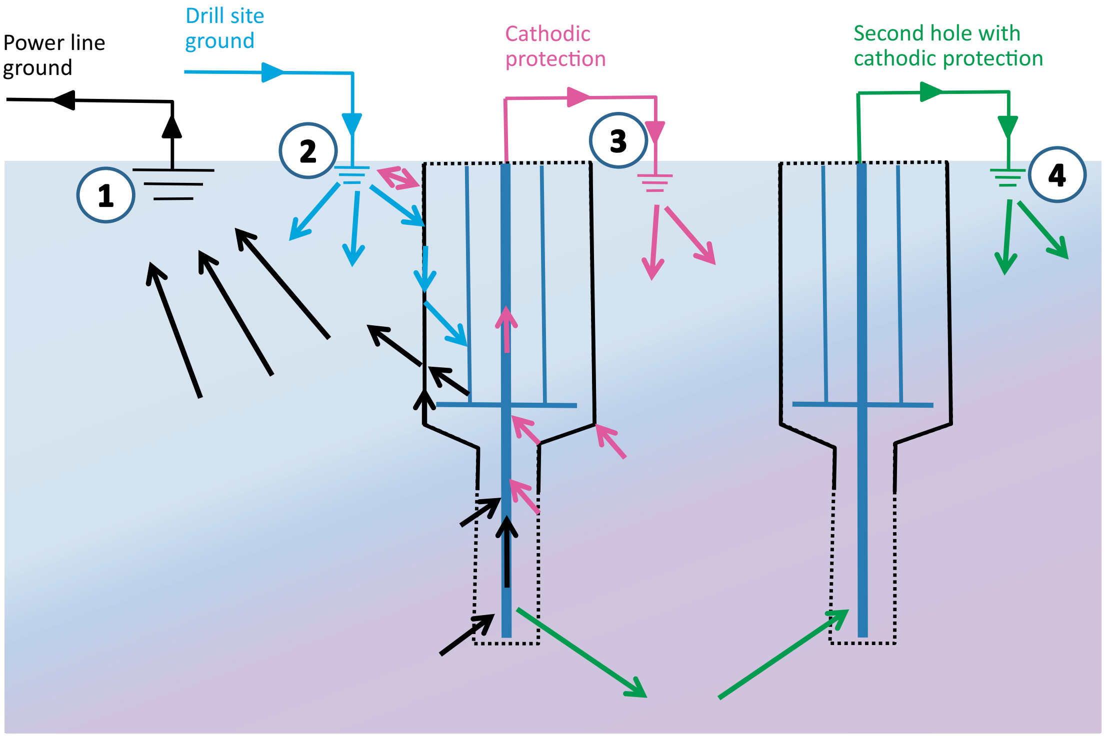

Figure 5-3. Conceptual sketch of local earth current sources at a drill site near the power plant (e.g. drill site 7, 8 or 9). Fenno-Skan 1 in operation and thus the Fågelsundet electrode operating as an anode is assumed. 1) Current drawn at groundings at the substation and power plant. 2) Current injected by the grounding grid that inter-connects the drill sites. 3) Cathodic protection system of the borehole monitoring equipment. 4) Cathodic protection system of a neighbouring borehole. See text for explanations.

6 Measurements of electric fields

Measurements of electric potentials in the ground are referred to as SP (spontaneous potential) measurements in the following text, since that is the common term used in geophysical literature. It is however obvious that the measurements do not make any distinction about the source to the potentials, that may be natural or anthropogenic.

6.1 Geophysical borehole logging

Geophysical borehole logging was carried out as a standard investigation during the site investigation for a deep repository at Forsmark. The resistivity tool Century 8044 was one borehole probe that was used. It measures the electric resistivity of the rock formation, but the SP is measured as a by-product. The SP was measured with a reference electrode on the ground surface. A number of things should be considered when SP data from the borehole loggings are looked at:

- The SP logging was a by-product from the resistivity logging and the SP logging was therefore not covered by any method description.
- There is no documentation about the status of the Fenno-Skan HVDC link in the logging reports. No efforts have been made in the present work to find out how much current that was injected at the Fågelsundet electrode during the respective loggings. The borehole loggings were carried out before Fenno-Skan 2 was in operation, so the electrode can only have been active as an anode.
- The reference electrode for the logging was usually placed quite close to the borehole collar. The measurements may therefore have been influenced by corrosion potentials from the borehole casing, effects from the local grounding grid etc. The absolute levels for the potentials are therefore of no real use. It is also not possible to compare the potential levels between different boreholes.
- The logging was usually carried out shortly after the completion of the drilling of the hole. The borehole water was therefore not at equilibrium with the pore water of the surrounding rock formation. Near-hole diffusion and redox potentials may therefore be overprinted on ambient earth current potentials.
- Potential differences due to telluric currents may overprint SP logging results, but the magnitude of such signals is expected to be small unless magnetic storms are active[3]. Records from magnetic observatory data have not been compared with the logging results.

In spite of the above listed factors it is obvious that there are some systematic results in the SP loggings. Results from two boreholes, (KFM07C and KFM08D) located fairly close to the power plant and the main substation at Forsmark, are shown in Figures 6-1 and 6-2. There is a clear positive SP gradient with respect to depth in both boreholes of around 1.5 V/km. Similar results were obtained in other boreholes in the vicinity of the power plant and substation (e.g. KFM07B, KFM08A, KFM08C, KFM09A and KFM09B). SP logging results from boreholes at larger distance from the power plant (KFM06A and KFM10A) can be seen in Figures 6-3 and 6-4. A positive gradient with depth can be seen for KFM06A, but it is of considerably smaller magnitude compared to KFM07C and KFM08D. It can also be noted that no borehole logging during the site investigation at Oskarshamn resulted in positive SP gradients similar to those in Figures 6-1 and 6-2.

The logging results can hardly be explained by natural electric fields. Natural potential differences are expected to have magnitudes of no more than a few tens of millivolts in an area like Forsmark. It is also difficult to explain the results as the effect from current injected at the Fågelsundet electrode. The electrode can only have acted as an anode during the site investigation programme, i.e. current was injected into the ground. Even though the resistivity structure of the rock volume around Fågelsundet-Forsmark not is fully known, it is very difficult to imagine any structure that would

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[3] Telluric signals have been monitored at Forsmark (Pedersen et al. 2008, Pedersen et al. 2013) and the telluric electric fields were found to be very weak in comparison to fields of anthropogenic origin, primarily related to use of the electrode at Fågelsundet.

transfer current from the electrode to the Forsmark area from below, corresponding to an increased potential with depth in the boreholes. Contrary, modelling shows that the sea water tend to be at a high electric potential due to current injected at Fågelsundet (see Section 4.2), and electric current is distributed to the rock volume in the vicinity of the sea from above. The spatial correlation between holes with significant vertical electric potential gradients and the Forsmark power plant suggests some local cathodic DC source, quite likely a secondary effect from current injection at Fågelsundet (cf. Section 7.1). Assuming an effective bulk resistivity of the local soil/bedrock/sea water of 1 500 to 3 000 Ωm, a cathodic current source with a magnitude of around 5 to 15 A at the power plant would explain potential gradients as those seen in Figures 6-1 and 6-2. A precise estimate of the source strength is however not possible with present knowledge.

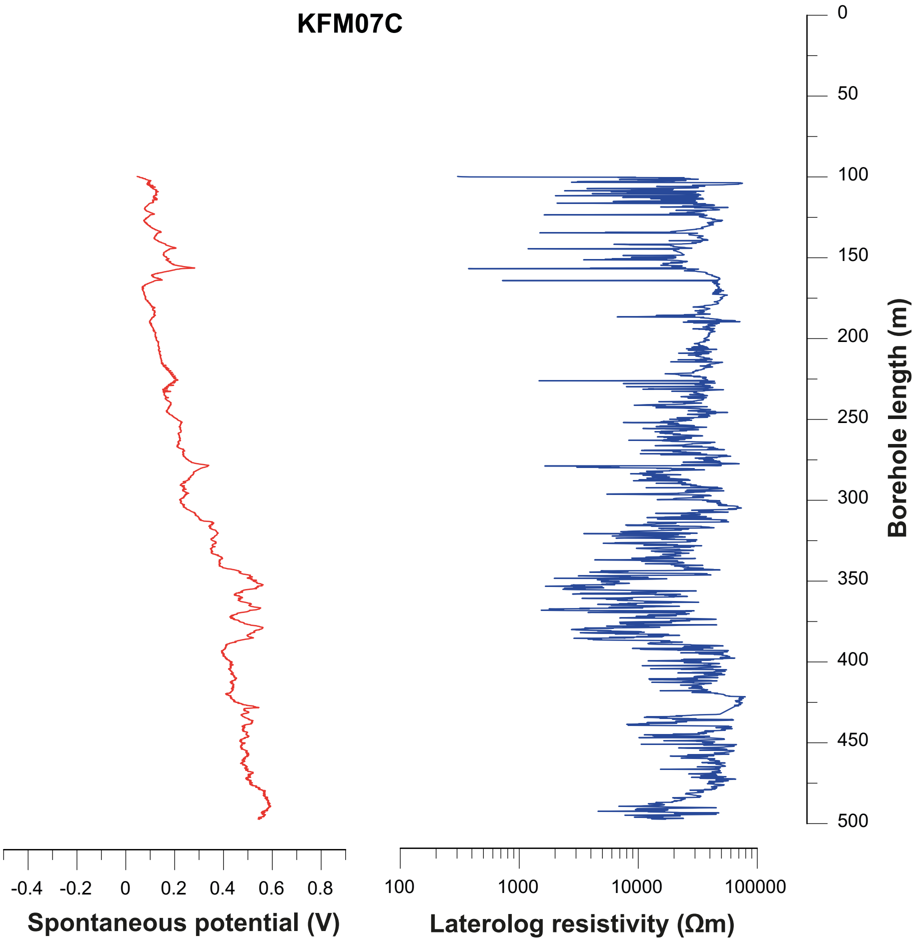

Figure 6-1. *Geophysical borehole logging results from KFM07C (Nielsen and Ringaard 2007a). Left: SP log with reference electrode on the surface. Right: Laterolog apparent resistivity.*

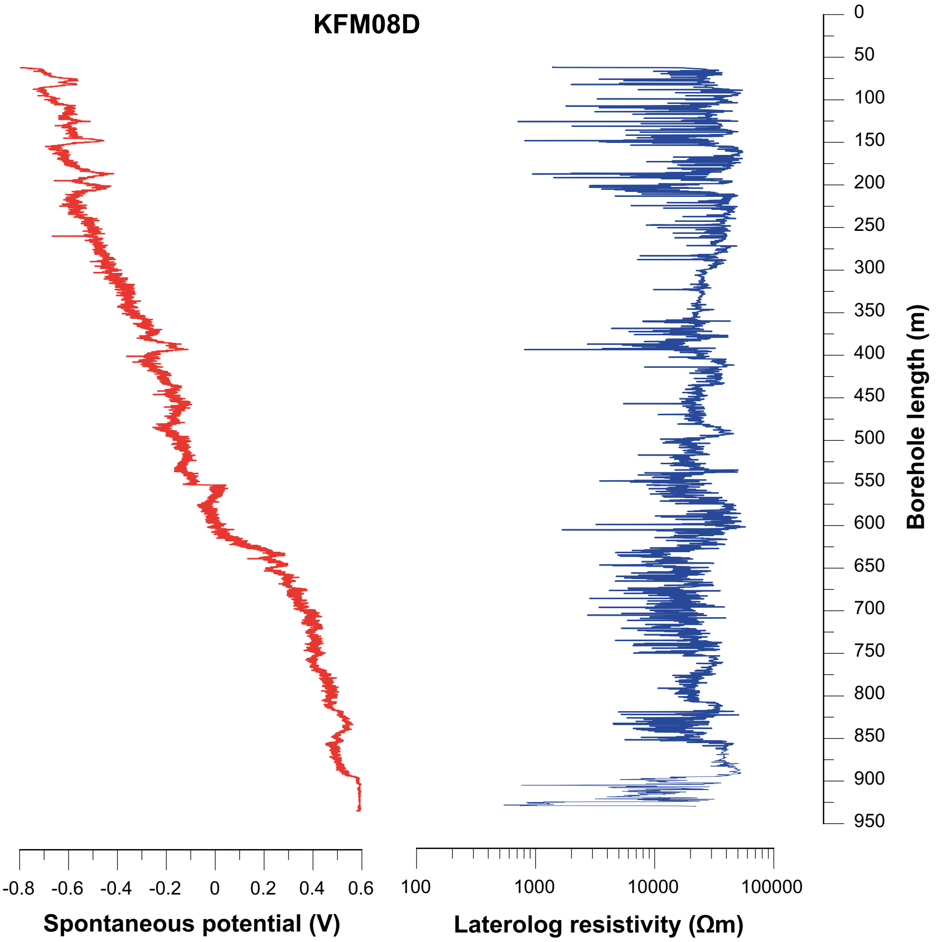

***Figure 6‑2.** Geophysical borehole logging results from KFM08D (Nielsen and Ringaard 2007c). Left: SP log with reference electrode on the surface. Right: Laterolog apparent resistivity.*

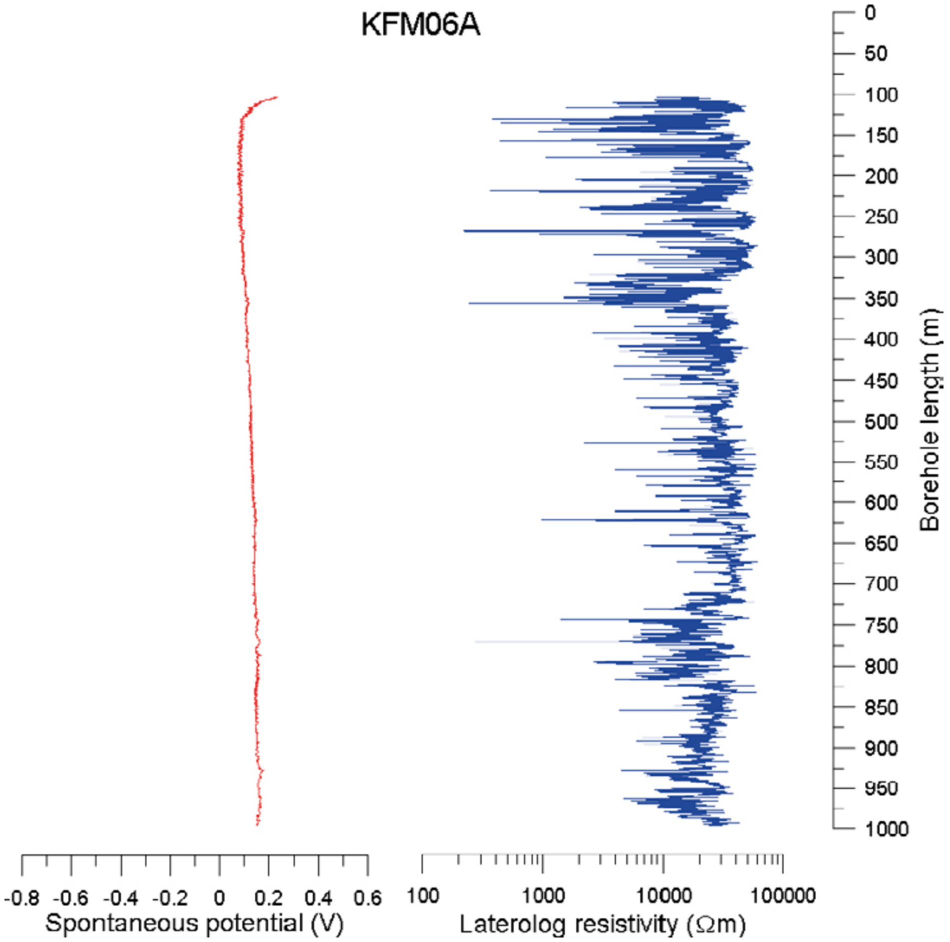

Figure 6-3. *Geophysical borehole logging results from KFM06A (Nielsen et al. 2005). Left: SP log with reference electrode on the surface. Right: Laterolog apparent resistivity.*

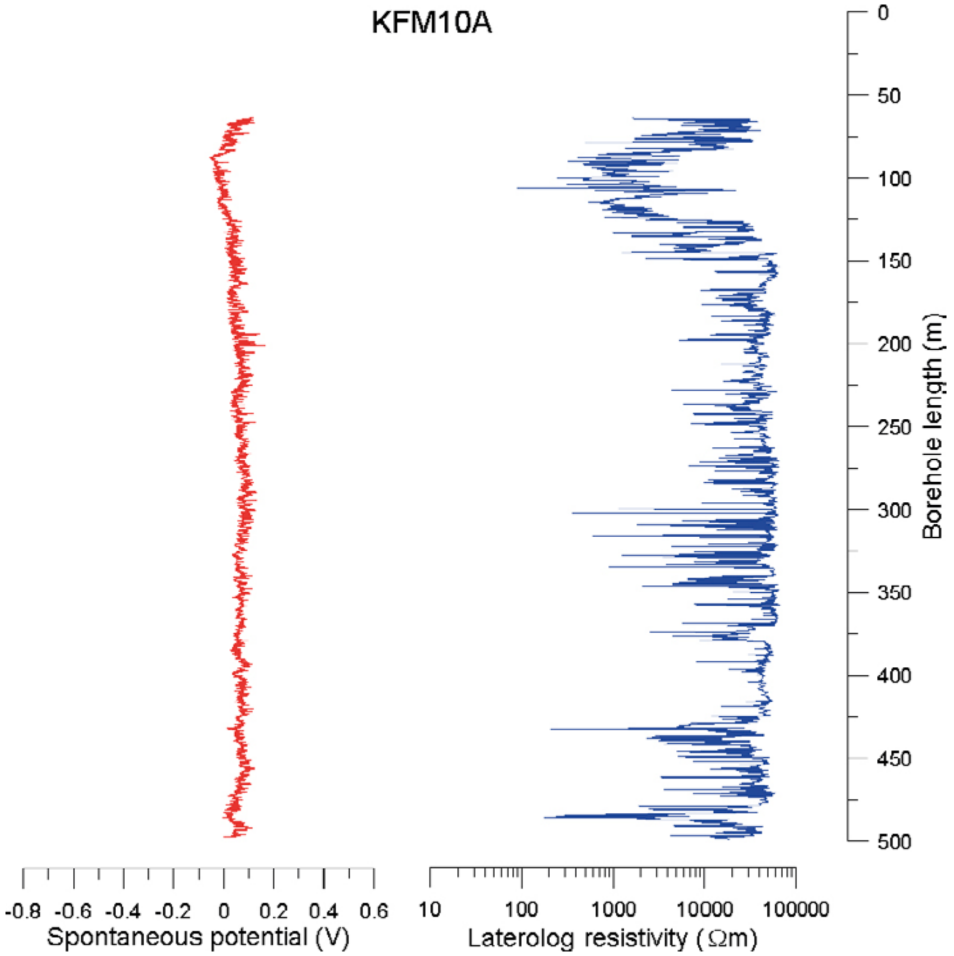

Figure 6-4. *Geophysical borehole logging results from KFM10A (Nielsen and Ringaard 2007b). Left: SP log with reference electrode on the surface. Right: Laterolog apparent resistivity.*

6.2 Measurements at drill site 4 and surroundings

Corrosion problems have been observed on monitoring equipment in a number of the deep boreholes at Forsmark. The problems were first observed in the borehole KFM04A. Different types of measurements were therefore carried out in the borehole and on the surface around the drill site. Results have been presented in Nissen et al. (2005). A number of investigations were carried out to investigate the conditions including:

- SP measurements on the surface around the drill site.
- SP measurements along a profile from drill site 4 towards drill site 1 (Figure 6-5).
- Monitoring of SP in KFM04A.
- Monitoring of SP gradient with a specially designed probe in KFM04A, KFM07A and KFM08A (Figure 6-6).
- Measurements of current at different positions in the grounding grid that connects the different drill sites.
- Monitoring of the current in the grounding grid at a position between drill site 4 and drill site 10 (Figure 6-7).

The different measurements are briefly summarized and commented below.

The SP measurements on the surface reveal a very strong positive SP anomaly at the drill site (Figure 6-5 and contour map in Nissen at al. 2005). Metallic structures like e.g. the borehole casing can hardly explain such an anomaly since metallic objects tend to create negative SP anomalies. One possibility is that the local grounding grid acted as an anode that injected current around drill site 4 during the measurements. That might have happened if the grid was connected to some other location at higher electric potential. The SP increases by around 400 mV from a background level at drill site 4 towards drill site 1. There is no documentation in Nissen et al. (2005) about the status of the Fågelsundet electrode during the measurements. It is therefore not possible to say if the results seen in Figure 6-5 are affected by the electrode or not.

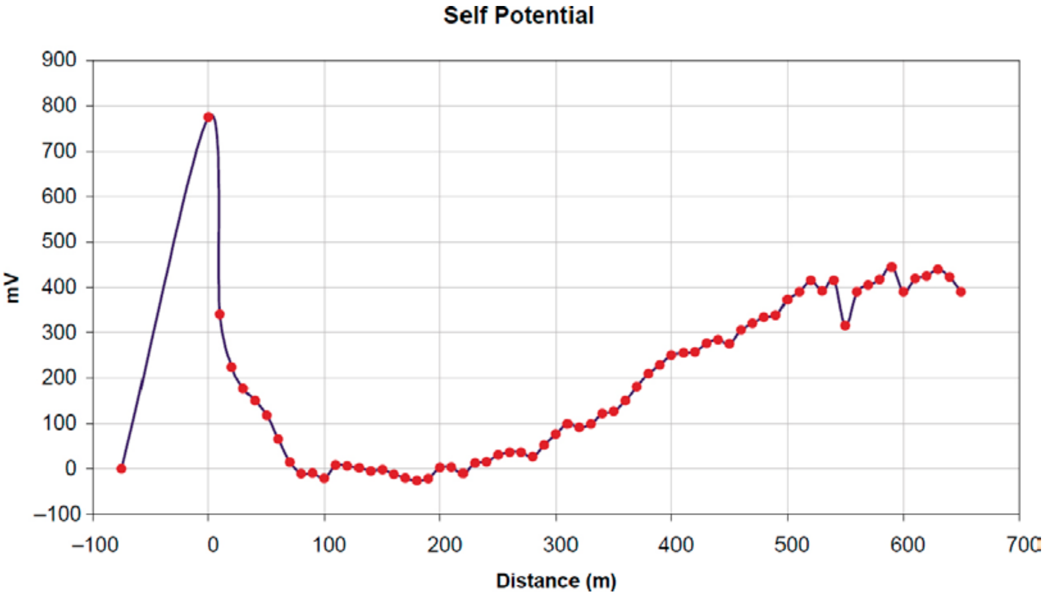

Figure 6-5. SP results from Nissen et al. (2005). The profile runs from drill site 4 to drill site 1. The first point at position −75 m is the reference and is by definition at potential zero. The peak anomaly at position 0 is at drill site 4. The SP level is around 400 mV higher towards drill site 1 compared to the background level around drill site 4.

Nissen et al. (2005) describes the design of a gradient SP probe for downhole measurements. The distance between the electrodes of the probe was 1.5 m. Measurements were carried out in the boreholes KFM04A (Figure 6-6), KFM07A and KFM08A as time series. It is not documented in Nissen et al. (2005) if any tests were made of bias between the upper and lower electrode of the probe. The absolute levels of the recorded data might therefore be uncertain. Correlations with the injected current at the Fågelsundet electrode can however be made. The transmitted power of Fenno-Skan is shown in Figure 6-6. Note that the current goes from Finland to Sweden and is injected into ground at Fågelsundet irrespective of negative or positive power transmission (the measurements were carried out before the construction of Fenno-Skan 2). Full power (500 MW) corresponds to an injected current of 1 250 A. The effect of the injected current is approximately –1 mV/m/kA according to the recordings in Figure 6-6, i.e. the potential decreases with depth when current is injected at the electrode. It should be noted that the recorded potential gradient is dependent on the local conditions at the measurement location. The SP at 232 m depth was also logged with a reference on the surface, around 75 m from the borehole. That logging resulted in a much weaker influence from the Fenno-Skan current, probably because the increased potential in the borehole was balanced by a similar increase at the surface caused by current injection via the grounding grid at the drill site.

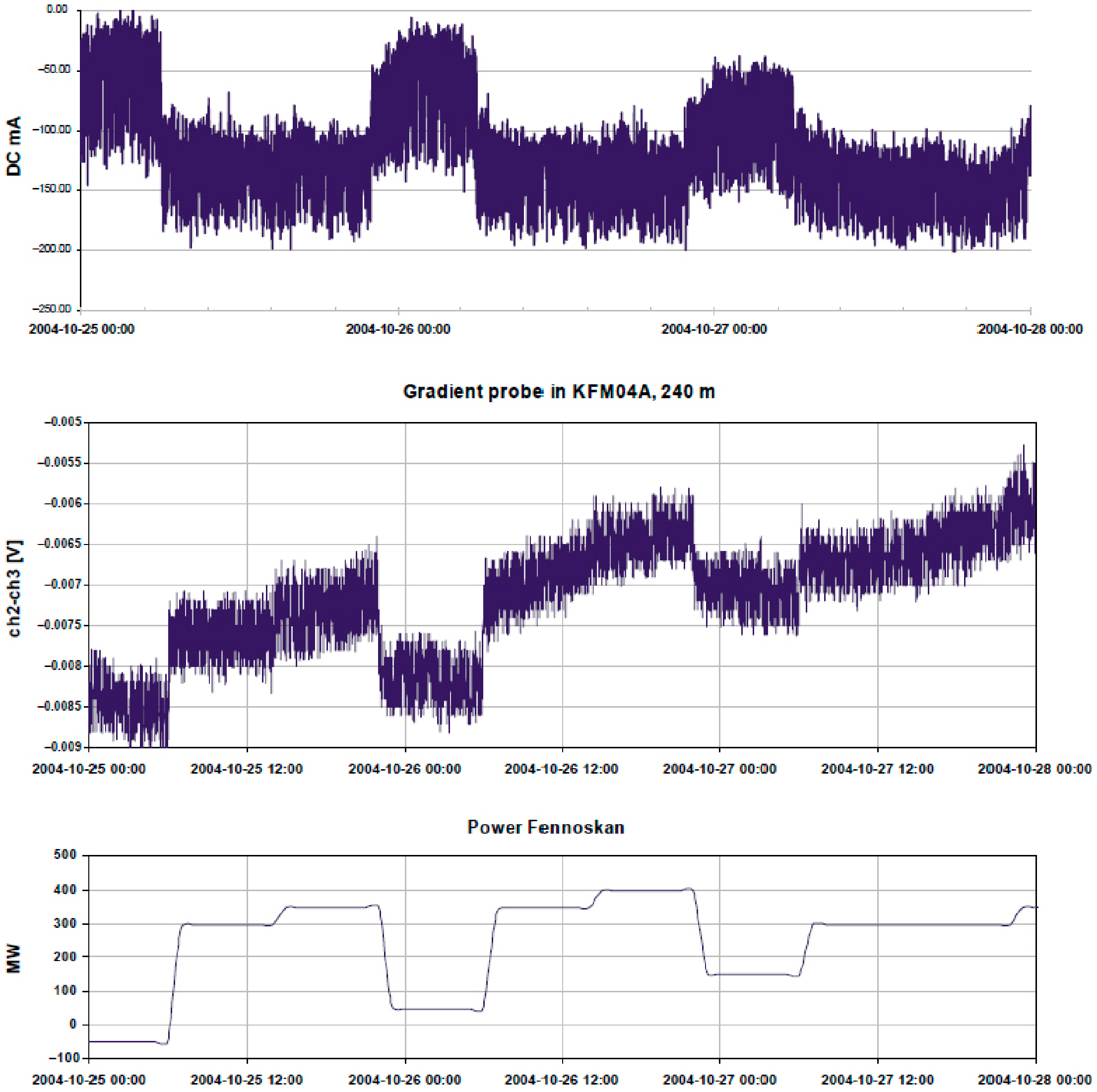

Figure 6-6. *Time series data from Nissen et al. (2005). From top to bottom: Current in grounding grid wire between drill sites 4 and 10, SP difference over 1.5 m at 240 m depth in borehole KFM04A, power transmission of Fenno-Skan HVDC link (at 400 kV). Ch2 corresponds to the lower electrode of the gradient probe and ch3 corresponds to the upper electrode.*

The current at a position in the grounding grid between drill site 4 and drill site 10 was logged during the same time period as the SP gradient in KFM04A (Figure 6-6). The current is around −50 mA when no current is injected at the Fågelsundet electrode. According to Nissen et al. (2005) the polarity is defined in such a way that the current direction is towards drill site 4. The effect of the injection of current at Fågelsundet is to increase the current with around 120 mA/kA. The current flow in the local grounding grid must be caused by a difference in potential between drill site 4 and other parts of the area, where drill site 4 is at lower potential. This potential difference appears to increase when current is injected at Fågelsundet.

6.3 Measurements of current in grounding wires

Measurements of the DC current magnitude at different positions in the local grounding grid are presented in Nissen et al. (2005). The measurements were carried out at two different occasions in September–October 2004. The Fenno-Skan link was out of operation on September 29 and the link was transmitting 480 MW on October 4, corresponding to injection of 1 200 A at Fågelsundet. Figure 6-7 is redrawn from Nissen et al. (2005) and shows the magnitudes of measured currents. The direction of the current during operation of Fenno-Skan is indicated by the red arrows, except for the readings by drill site 2 where the polarity was not possible to determine and the direction is inferred. The location corresponding to the time series recording in Figure 6-6 is shown in Figure 6-7 with a blue circle. The numbers at the arrows in Figure 6-7 indicate the current magnitude at the corresponding position in the grounding grid with current injected at Fågelsundet (before commas) and with no current injected at Fågelsundet (after commas).

The largest influence from current injection at Fågelsundet is to increase current flowing from drill site 2 towards drill sites 10, 4, 1 and 5 (Figure 6-7) with the largest reading being 175 mA (drill site 10 was not constructed at the time of measurements but it has been included in Figure 6-7 for reference). The 162 mA reading to the south of drill site 2 is most likely directed towards drill site 10 to agree with the readings taken further south-west. Drill sites 5 and 6 are fairly close to each other, separated by Lake Bolundsfjärden. Assuming that the potential difference between drill sites 5 and 6 is smaller than the potential difference between drill sites 6 and 2, the 110 mA reading taken north of drill site 2 represents current flowing towards drill site 6. Current is thus picked up around drill site 2

Figure 6-7. *Measured DC currents in wires of the grounding grid that connects the drill sites (redrawn from Nissen et al. 2005). Numbers are given in mA with values before commas representing a situation with Fenno-Skan transferring 480 MW and the values after the commas representing Fenno-Skan out of operation. Magenta arrows indicate inferred current directions.*

and transmitted to the sites further west. The injection of current at Fågelsundet thus appears to set drill site 2 at a higher potential compared to the other sites, in spite of the fact that drill site 2 is the site at largest distance from the electrode. This is difficult to explain with any resistivity model of the ground. A cathodic current source closer to the power plant is a more reasonable explanation. Such a current source might of course be a secondary one, e.g. a grounding grid node drawing current from the ground and transmitting it to a distant location at lower potential.

6.4 Measurements between boreholes

Time series measurements between boreholes have been carried out at two occasions by Uppsala University (Pedersen et al. 2008, 2013). The measurements presented in Pedersen et al. (2008) were carried out with two horizontal bipoles at around 475 m vertical depth (Figure 6-8), in almost perpendicular directions (KFM08A to KFM08C and KFM08A to KFM07A respectively). The potential difference was also measured between the electrodes at depth and a shallow electrode at around 2 m depth in the holes. The shallow electrodes are thus located inside metallic casing and the absolute values of the potentials might be affected. The shallow electrode is also likely to be affected by currents in the local grounding grid that connects the drill sites at Forsmark.

The potential differences showed strong correlation with the injected current at Fågelsundet. The potential gradient along vector e_1 in Figure 6-8 was approximately 460 mV/km/kA and the gradient along vector e_2 was approximately 520 mV/km/kA. The direction of the potential gradient due to current injected at Fågelsundet thus appears to be directed towards north-east at 475 m depth, i.e. the current in the ground is directed towards south-west.

Figure 6-8. Monitoring of the electric field was carried out between the boreholes KFM07A–KFM08A and KFM08A–KFM08C respectively at a vertical depth of around 475m during a period 2006 (Pedersen et al. 2008).

The measurements also indicate a potential gradient that is uncorrelated to the current injected at Fågelsundet. That gradient is around 190 mV/km/kA for both vectors e_1 and e_2 (Figure 6-8). The uncorrelated gradient is thus in roughly the same direction as the one correlated to the current injected at Fågelsundet.

The gradient down the borehole KFM08A can be estimated to around −1 400 mV/km/kA, the potential decreases with depth due to an injected current at Fågelsundet. It is however possible that those measurements are strongly affected by currents carried by the local grounding grid that connects the drill sites at Forsmark.

Measurements presented in Pedersen et al. (2013) were carried out at around 90 m depth below ground in two sets of boreholes forming almost perpendicular dipoles (Figure 6-9). One set of boreholes were on the pier close to SFR and the other set of boreholes was on land fairly close to the power plant. Potential gradients correlated with current in the Fågelsundet electrode were estimated to 0.42 V/km/kA at the pier and 1.84 V/km/kA on land by the power plant. The direction of the gradients was close to east-west for both locations, i.e. almost perpendicular to the radial vector from the Fågelsundet electrode. No estimates of the vertical gradients were made.

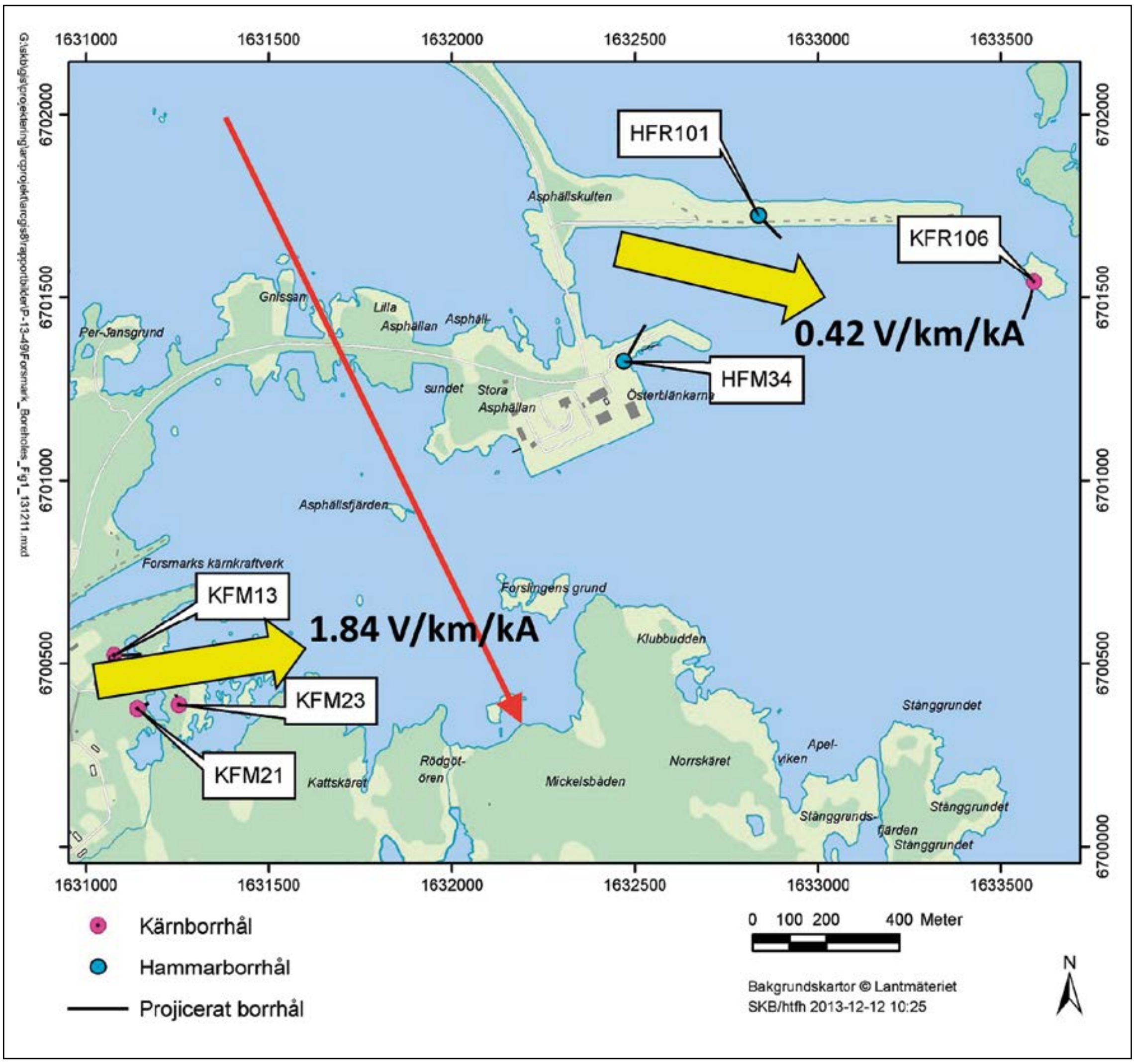

Figure 6-9. Monitoring of the electric field was carried out between the boreholes KFM21–KFM13, KFM21–KFM23, HFR101–HFM34 and HFR101–KFR106 respectively at a vertical depth of around 90 m during a period 2013 (Pedersen et al. 2013).

A significant potential gradient that was uncorrelated to the current through the Fågelsundet electrode was recorded on the land site. The cause to this gradient is not known. It is possible that it is related to the cathodic protection system at drill site 8, but it is also possible that some DC source at the power plant has affected the measurements.

6.5 Profiling by Swerea Kimab

Swerea Kimab carried out potential measurements in a project where corrosion of reinforcement in concrete constructions was studied (Sandberg et al. 2009). The outlet tunnels from Forsmark plants 1, 2 and 3 were investigated and potential measurements were therefore carried out on ground surface from the power plant to the tunnel outlets at the pier (Figure 6-10). The measurements were carried out with a power load of 506 to 512 MW on the Fenno-Skan link, corresponding to an injected current of 1 280 A at the Fågelsundet electrode. Interpolated contours are shown in Figure 6-10. The positions of such contours are of course uncertain away from actual measurement locations. There is a potential difference of around 5 V from the main substation at Forsmark to the tunnel outlet on the pier. The potential gradient is almost perpendicular to the directional vector towards Fågelsundet. Even if the resistivity structure of the ground can perturb the electrical field considerably; it seems unlikely that the measured potentials are caused directly by the current injected by the Fågelsundet electrode. The effect of a secondary cathodic source at the substation and power plant over-printed on the primary field from the Fågelsundet electrode is a more likely explanation. The strength of such a secondary current source can be estimated to around 15 to 25 A if the effective bulk resistivity of the rock/soil/water is assumed to be between 1 500 and 3 000 Ωm.

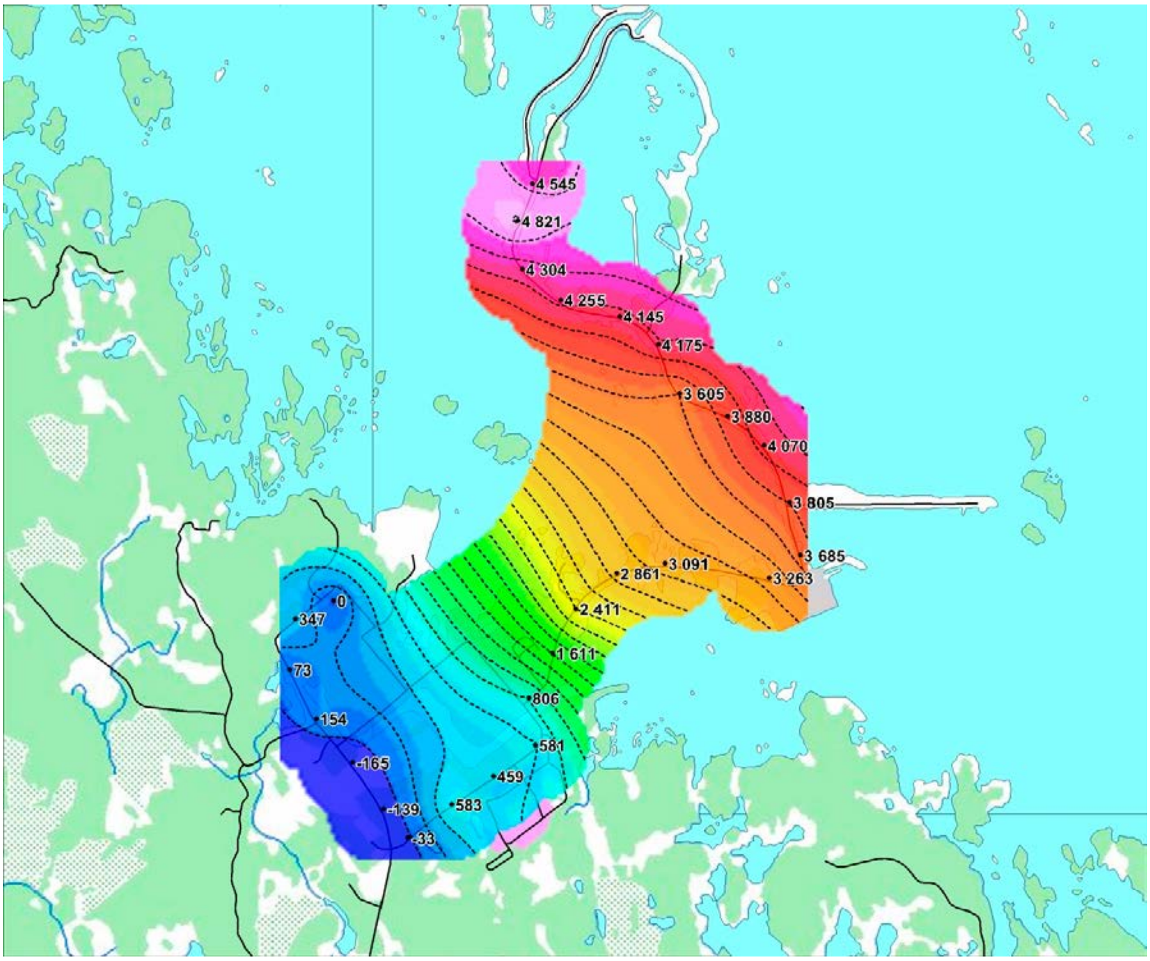

Figure 6-10. Potential measurements in mV with a reference by the Forsmark 3 power plant (redrawn from Sandberg et al. 2009). The measurements were carried out during injection of around 1 280 A current at Fågelsundet. Interpolated contours are shown with dashed black lines. The contour interval is 200 mV.

7 Discussion, Conclusions and Recommendations

7.1 Conceptual model for earth currents in the Forsmark area

No single measurement campaign has fully mapped and characterized the electrical field around Forsmark. The Fågelsundet electrode is a main source to electrical fields, but also other sources exist. Figures 7-1 to 7-4 illustrate conceptually how the electrode creates electrical fields around Forsmark.

The description below is valid for operation of Fenno-Skan 1. The same description is valid for Fenno-Skan 2 but with opposite polarity for the fields. With Fenno-Skan 1 in operation, current is transmitted from Finland to Sweden through a subsea cable (Figure 7-1). The injection of current into the ground/sea at Fågelsundet creates a potential field that is illustrated by green contour lines in Figure 7-1. The distance between Fågelsundet and Forsmark is such that the electric field mainly is affected by current conduction in the sea water and in the upper part of the earth's crust. The distance from Forsmark to the electrode in Finland is however so large that the current will penetrate to the lower crust and upper mantle before it reaches Forsmark. The distance from the electrode in Finland is only a few tens of km from a major mid-crustal conductor (Korja et al. 2002). Minor, presumably graphite bearing, shallow bodies also exist closer to the electrode. The current to (from) that electrode is therefore expected to be channelled through the mid-crustal conductor and the influence at Forsmark is expected to be negligible. The electric potential was measured along a planned route for a gas pipeline not far from the Fenno-Skan cable. The results can be found in Jonsson et al. (1992) and they are in agreement with the sketched contour lines in Figure 7-1.

Figure 7-2 is a conceptualized image of the situation around Forsmark. Sketched contour lines illustrate the electric potential field due to current injection at Fågelsundet. Warm colours (semi-transparent) represent high potentials and cold colours represent low potentials. The AC lines that transmit power from the Forsmark power plant have both safety and functional grounding. This is accomplished by a top conductor at the line towers and a buried ground conductor along the line (Figure 7-3). The substation at Forsmark also has functional and safety grounding connected to the station ground mat. Even if the grounds of the substation and the AC lines are separated by spark gaps, the resistance between AC line grounds and the substation ground mat is expected to be low. For this discussion the above groundings can be treated as a single grounding at the substation that is connected to remote grounds via the top and buried conductors of the AC lines.

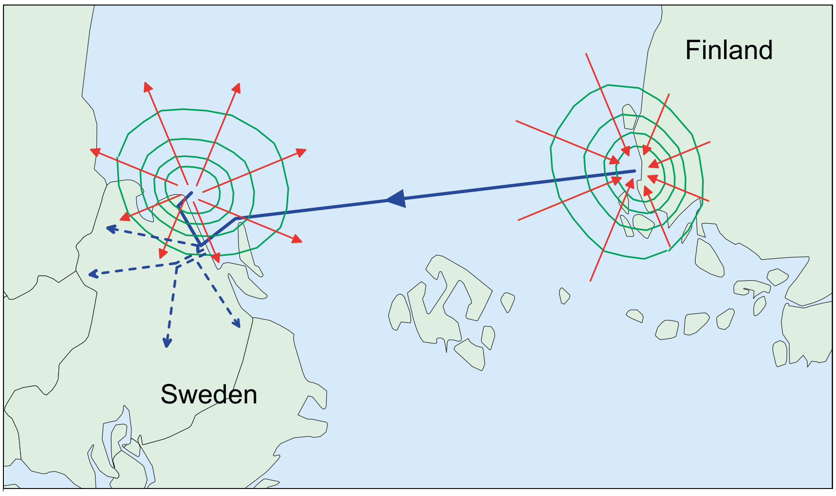

Figure 7-1. Map illustrating the principal current flow of the Fenno-Skan HVDC link, assuming current flow from Finland to Sweden (Fenno-Skan 1 in use) and the use of the Fågelsundet electrode as an anode. The solid blue line shows the HVDC cable and the electrode line. Red arrows illustrate the current direction in the ground. Green lines are (sketched) potential contours. Dashed blue lines are high-voltage AC lines connected to the Swedish power grid and with top and earth conductors grounded at Forsmark.

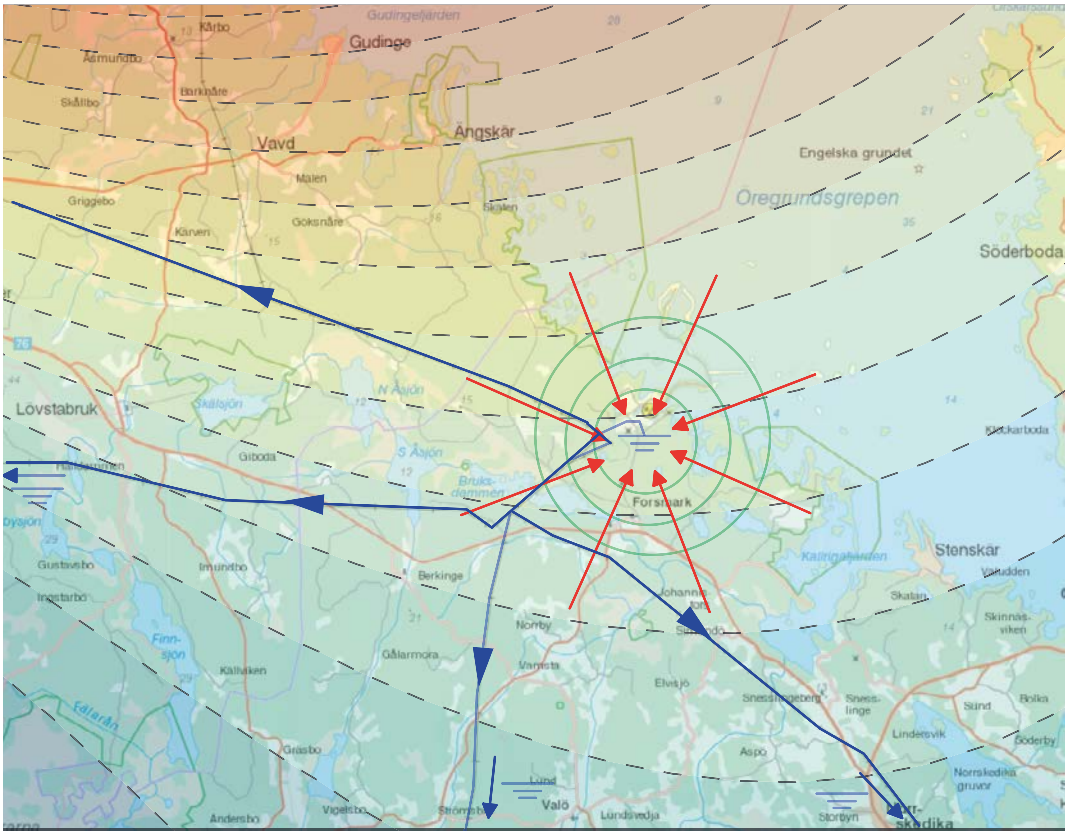

Figure 7-2. *Map of the Forsmark area with sketched primary potential contours due to current injection at Fågelsundet. Solid blue lines are high-voltage AC lines connected to the Swedish power grid with conductors grounded at Forsmark. Red arrows illustrate the current direction in the ground due to current picked up by the grounded conductors. Green lines are (sketched) potential contours due to the secondary effect of the grounded AC line top and buried conductors.*

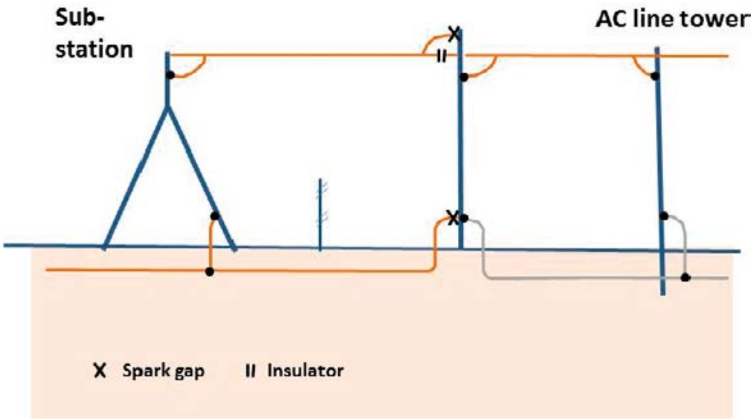

Figure 7-3. *Example of how top conductors and buried ground conductors may be connected at the end of an AC line and the interface to a substation (Svenska kraftnät 2012). Different arrangements of spark gaps and insulators are possible. Phase conductors are not shown.*

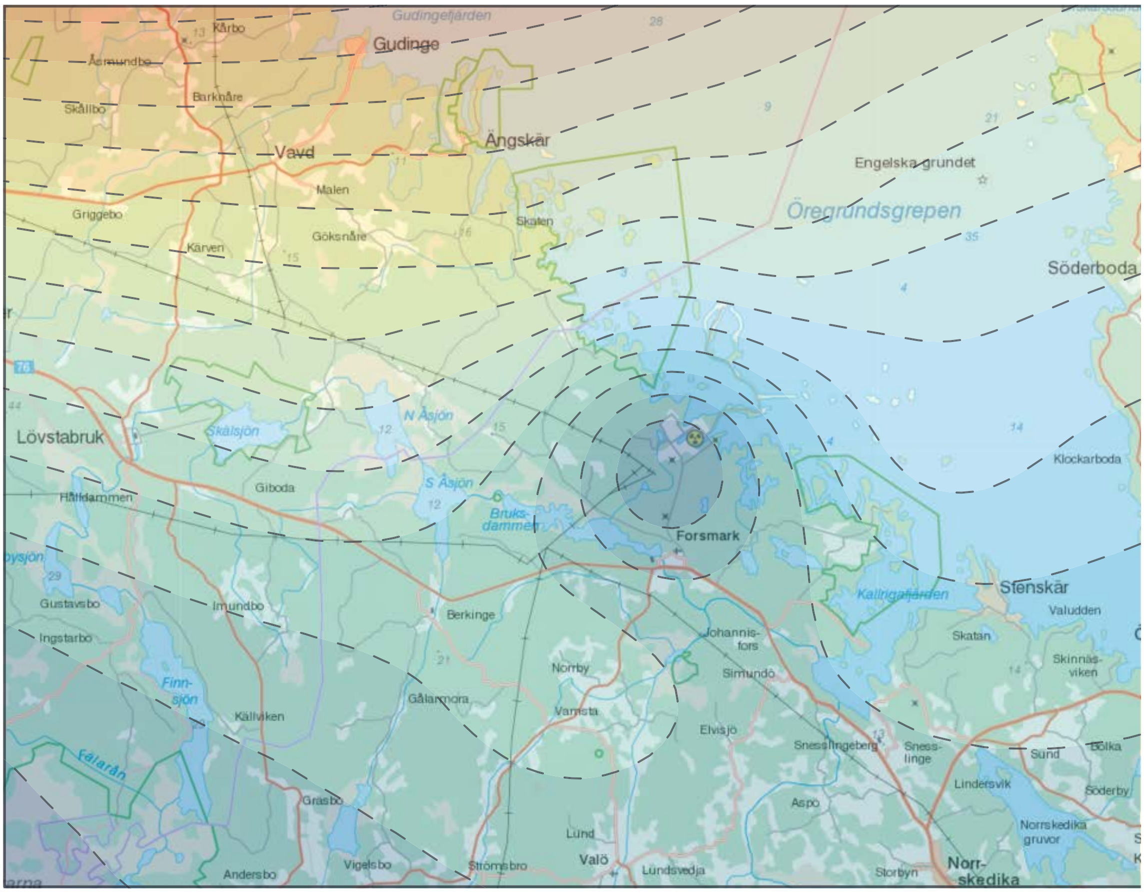

***Figure 7-4.** Map of the Forsmark area with sketched potential contours due to current injection at Fågelsundet and current transmission along grounded AC line top conductors (cf. Figure 7-2).*

The grounding at Forsmark will be at an elevated potential due to current injection at Fågelsundet (Figure 7-2). Current will therefore be drawn from the ground and transmitted via the AC lines to remote positions at lower (zero) potential as proposed by B. Sandberg 2009. The grounding at Forsmark will thus act as a secondary cathode and the current drawn from ground will create an electric field that is overprinted on the primary field due to the Fågelsundet electrode. The secondary electric field is sketched as green contours in Figure 7-2. The magnitude of the current that is drawn from ground depends on the effective grounding resistance and the primary electric potential. The electric potential field at Forsmark, due to the Fågelsundet electrode and the overprinted secondary field due to grounded AC lines, is sketched in Figure 7-4.

The local situation at Forsmark is illustrated in Figure 7-5 with the combined primary and secondary electric potential field shown with contours. The electric potential is expected to have a local minimum around the substation and the power plant. The potential gradient, including a vertical component, is thus expected to be rather high in the close vicinity of that minimum, which is also confirmed by measurements (cf. Chapter 6). The locations of drill sites are marked in Figure 7-5. It can be noted that drill sites towards east are expected to be at a higher electric potential compared to drill sites towards west. The drill sites are inter-connected with a local grounding grid. Current injection at Fågelsundet, and the secondary effect of the grounded AC lines, is thus expected to set e.g. drill site 2 at higher potential compared to e.g. drill sites 7, 8 and 9. Current will thus be drawn from ground at drill site 2 and it is expected that current is injected to ground at sites 7, 8 and 9. It is also expected that current will be injected at drill site 6 since that site is only connected to the local grid via site 2. The situation at sites 1, 4, 5 and 10 is difficult to predict since the effective grounding resistance of the sites might vary. It should be noticed that the map in Figure 6-7 is based on measurements that were carried out before the construction of drill sites 7, 8, 9 and 10 (Nissen et al. 2005). The current drawn from and injected to ground at the drill sites will create a tertiary electric field that is probably not of any major overall significance, but can have a local and rather shallow effect around the drill sites that is significant. Cathodic protection systems are also expected to have a significant effect on the local electric field at the drill sites.

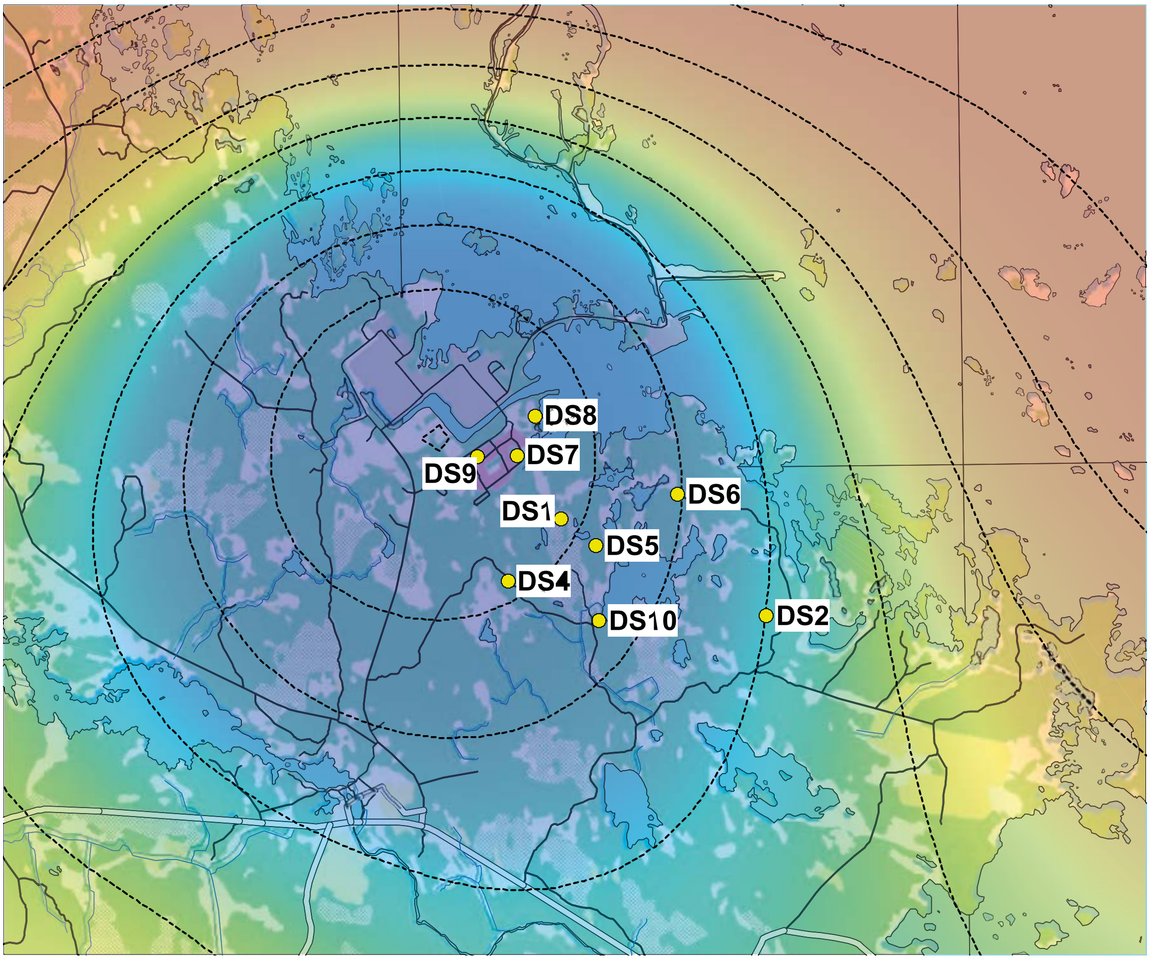

***Figure 7-5.** Detail of the map in Figure 7-4 illustrating that the drill sites at Forsmark will be at different electric potentials due to current injection at Fågelsundet. The drill sites are inter-connected via a local protective grounding grid. Currents are expected to flow in the grid from sites at high potential (e.g. drill site 2) towards sites at lower potential (e.g. drill sites 7, 8 and 9).*

The description above is conceptual and to some extent hypothetical, but the conclusions fit available data quite well. It is however recommended that some of the assumptions are tested by field measurements, which is discussed in Section 7.3 below.

7.2 Conclusions

Different factors that affect earth currents have been reviewed in this report. The most important source to electric fields and earth currents is the Fenno-Skan HVDC link through the use of the electrode at Fågelsundet during monopolar or unbalanced bipolar operation. The earth currents due to the electrode appear to set groundings in different positions of the power grid, as well as local protective grounding grids, at different potentials. This will have as a result that current is drawn from ground at positions with high potential and injected to ground at positions with low potential. These secondary (and tertiary) current sources will perturb the primary electric field.

Corrosion problems have been observed on monitoring equipment in a number of the deep boreholes at Forsmark. Earth currents from the Fågelsundet electrode are likely to be one major source to these corrosion problems. It also appears as the problems have become worse since the commissioning of Fenno-Skan 2 and the use of the Fågelsundet electrode as a cathode. Corrosion problems have however also been observed during periods when Fenno-Skan has been out of service. It is likely that other earth current sources exist in the area, most likely within the power plant complex. Corrosion problems have also been observed at SFR.

Cathodic protection systems have been installed at the drill sites. They have however not been effective in all cases. It is however not easy to tune the protection systems. It should be realized that the metallic objects that are protected have an extent of several hundred metres towards depth and that they are at locations with strong potential gradients. The ambient electric potential may vary with more than one volt over the protected structure. The potential gradient will also flip polarity when the Fågelsundet electrode changes from anode operation to cathode or vice versa. It is also likely that the protection systems for different boreholes interact with each other, especially at drill sites 7, 8 and 9 that are close to each other and where the ambient potential gradient is of large magnitude.

Earth current may also be caused by natural sources like hydraulic, salinity and other chemical gradients. The geological environment in Forsmark is however such that such earth currents are expected to be of minor importance. Telluric currents, i.e. time-varying natural currents, can have components that are of very low frequencies. The source to such currents is e.g. the Earth (including the conductive sea) rotation in the radiation of charged particles from the sun. This will induce currents that have a 24 hour cycle. The magnitude of telluric currents is however fairly weak and they are not expected to be a significant cause to corrosion.

7.3 Recommended investigations

The sources to earth currents and the distribution of electric fields due to such sources are not fully known in the Forsmark area. A number of different investigations are therefore recommended:

- It is indicated by several investigations that protective grounding systems act as secondary sources to earth currents. A review of the grounding systems and how they are interconnected is therefore recommended.
- Secondary currents appear to flow in the grounding systems. The magnitude of such currents, correlated and un-correlated with Fenno-Skan, should be investigated. If possible, the grounding conductors of the AC power lines should be monitored for some time. The grounding grid of the drill sites should also be monitored as well as local grounding grids at SFR.
- The electric potential distribution around Forsmark has never been mapped, except for some individual profiles. A complete mapping of the field is probably complicated, but a number of profiles are recommended. The measurements must be correlated with the current through the Fågelsundet electrode.
- The vertical gradient of the primary electric field at Forsmark and SFR is not well known. Loggings in deep holes indicate a significant gradient, but the measurements are affected by several uncertainties. New SP loggings are recommended when holes become available, i.e. when monitoring equipment is temporally removed from a hole. Reference electrodes should then be placed along the surface projected trace of the hole so that the true vertical gradient can be estimated.
- Monitoring equipment in several deep drillholes has corroded. The cause to the corrosion is not fully understood although earth currents can be suspected as one cause. Investigations related to these problems are ongoing and should continue.
- Cathodic protection systems have been installed at the drill sites. The installations were however done before the commissioning of Fenno-Skan 2 and the use of the Fågelsundet electrode as a cathode. The effectiveness of the systems should therefore be evaluated and the parameters of the system should possibly be adjusted.
- Continuous monitoring of ground currents does not seem motivated at the moment. However, any major change in electrical infrastructure around Forsmark that possibly could affect ground currents will motivate new measurements.
- A plan for measurements of earth currents during the construction of a deep repository should be prepared. Such measurements might include SP loggings in pilot boreholes and monitoring of electric infrastructure.
- The design of functional and protective grounding of power supply during construction of the deep repository should take transferred potentials and earth currents into account.
- Investigations should be made about the discrepancy in levels between resistivity borehole logging results and other resistivity measurements.

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SKBdoc documents will be submitted upon request to document@skb.se.

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