Measurements of Earth potentials at Forsmark

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Abstract

The activity was initiated in order to study the structure of natural and man-made electrical and magnetic fields. Such electric currents can under certain circumstances interfere with scientific equipment submerged in boreholes.

The purpose of this activity is to measure the electric currents at depth and to achieve an understanding of their cause. The behavior of the three electric field components in the upper crust at a depth of 469–479 m was measured in the three boreholes KFM08A, KFM08C and KFM07A at Forsmark during the period July 3–17, 2006. In addition we measured the electric field on the surface directly above the boreholes KFM08A and KFM08C. Simultaneously we measured the three components of the magnetic field on the surface with two independent sensors for security reasons. We also take advantage of the magnetic field measurements at the geomagnetic observatory (Geological Survey of Sweden) at Fiby near Uppsala, which we use as a reference to the local measurements at Forsmark in order to separate possible man-made fields from natural fields.

The behaviour of the electric field at Forsmark turned out to be completely dominated by the disturbance from the High Voltage Direct Current (HVDC) grounding point at Fågelsundet, located some 30 km to the north of Forsmark. The effects of the natural field due to current systems in the ionosphere at a height of approximately 100 km could was only clearly seen on the horizontal magnetic field, whereas the vertical magnetic field and the three component electric field measured between the three boreholes were causatively related to the current from the HVDC cable.

The main conclusion of the experiment is that the observed voltage differences in and between boreholes in the Forsmark area can be explained as voltage drops due to injection of about 1,000 A strong currents at Fågelsundet. These voltage drops have an approximate radial distribution around Fågelsundet, and at Forsmark their magnitude is around 1 V/km in the horizontal direction but negligible in the vertical direction close to the surface. These voltages can in turn drive currents along the boreholes via grounding circuits connecting the various boreholes in the area. A simple way to avoid these currents is to disconnect the grounding circuits.

Sammanfattning

Denna aktivitet syftar till att studera strukturen av elektriska och magnetiska fält, orsakade av såväl naturliga fenomen som industriella installationer. Under vissa förhållanden kan sådana elektriska fält interferera med vetenskapliga instrument i borrhålen.

Syftet med detta projekt är att kartlägga elektriska strömmar mot djupet och att förstå deras uppkomst. Beteendet av de tre elektriska fältkomponenterna registrerades vid ett djup av 469–479 m i de tre borrhålen KFM08A, KFM08C and KFM07A under tiden 3–17 juli, 2006. Dessutom mättes det elektriska fältet på markytan nära borrhålen KFM08A och KFM08C och samtidigt därmed mättes även de tre magnetfältskomponenterna på markytan av säkerhetskål med två oberoende magnetometrar. Vi utnyttjade även registreringar av magnetfältet vid det geomagnetiska observatoriet i Fiby (Sveriges Geologiska Undersökning) i närheten av Uppsala, som referens för att kunna separera naturliga magnetfältsvariationer från människoskapade variationer.

Det elektriska fältet vid Forsmark visade sig att vara totalt dominerad av störningen från HVDC jordningspunkten i Fågelsundet, som ligger ca 30 km norr om Forsmark. De naturliga variationerna i det elektriska fältet beroende på strömmar i jonosfären på en höjd av ca 100 km kunde bara klart urskiljas på det horisontella magnetiska fältet, medan det vertikala fältet och de tre komponenterna av det elektriska fältet mellan de tre borrhålen var tydligt korrelerad med strömmen i HVDC kabeln.

Huvudkonklusionen av experimentet är att de observerade spänningsskillnaderna i och mellan borrhålen i Forsmark området kan förklaras som spänningsfall förorsakad av strömmar om ca 1 000 A i jordningspunkten i Fågelsundet. Dessa spänningsfall har approximativt ett radiellt beroende omkring Fågelsundet, och i Forsmark är deras amplitud ca 1 V/km i horisontell riktning, men försumbar i vertikal riktning i närheten av markytan. Dessa spänningar kan i sin tur driva strömmar längs borrhålen via jordningssystem som förbinder de olika borrhålen i området. Ett enkelt sätt att undvika dessa strömmar är att ta bort jordningssystemen.

Contents

1 Introduction

This document reports the results gained by measurements of earth potentials at Forsmark. The activity was not performed as a formal part of the site investigation at Forsmark, and the work was carried out in accordance with activity plan AP TD F130-06-028. In Table 1-1 the controlling document for performing this activity is specified. No method description exists for this method.

The activity aims at mapping Earth currents in the Forsmark area by means of Magnetotelluric (MT) measurements, i.e. simultaneous measurements of the electric and the magnetic field. The electromagnetic field derives from basically two sources: 1) the natural field due to large scale current systems in the Earth's ionosphere generated as a result of interaction between the Earth's static magnetic field and charged particles from the sun, 2) man-made current systems in power lines and grounding points and large consumers of electric power. The distinction between these two sources and their relative and absolute magnitude is a primary aim.

Two MT stations were set up at Forsmark during the period July 3–17, 2006, for simultaneous measurements of the electromagnetic field (see Figure 1-1 for a location map). The first one was placed with the three components of the electric field (or potential differences) measured in three boreholes and the second one coincided with the first one, but the two horizontal components of the electric field was measured directly on the surface to allow for a direct comparison with the horizontal components of the borehole measurements.

The borehole measurements were made in the three boreholes KFM08A, KFM08C, and KFM07A. In each borehole a Pb-PbCl$_2$ electrode was inserted as deep as possible using the available high quality cable in order to measure the potential differences between borehole pairs KFM08A–KFM07A and KFM08C–KFM08A, respectively. In addition we also measured the potential difference between the borehole and surface electrodes in borehole KFM08A; in this way we can estimate all three Cartesian components of the average electric field at borehole levels, i.e. approximately at a vertical depth of 500 m. All boreholes are about 1,000 m long, but the available electrode cables and the borehole inclination limited the depth of investigation to about 500 m.

We encountered some minor problems when lowering the electrodes into the upper part of the boreholes, but with repeated attempts we managed to overcome the small kinks found in the upper few tens of metres in the two boreholes KFM08A and KFM08C.

Table 1-1. Controlling documents for the performance of the activity.

Activity Plan	Number	Version
Mätningar av Jordpotentialer med magnetotellurik vid Forsmark	AP TD F130-06-028	1.0

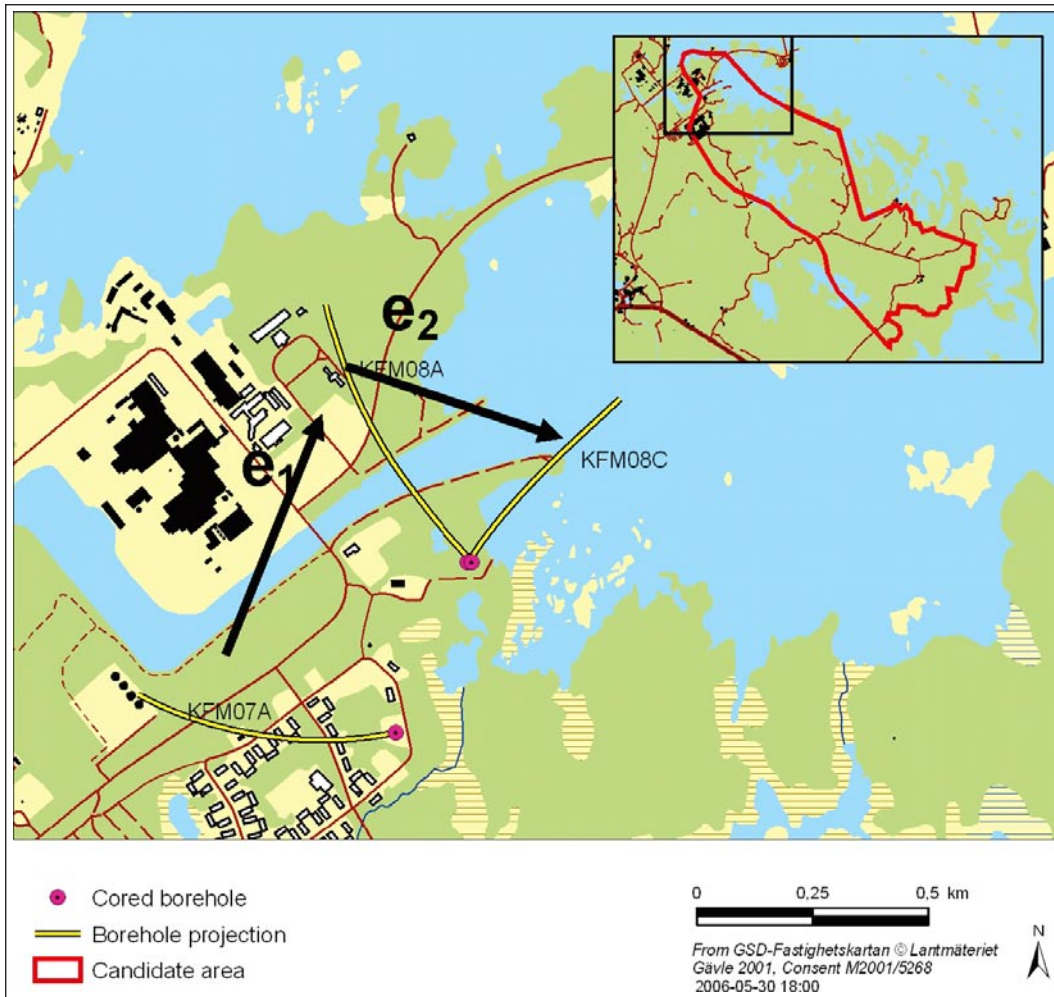***Figure 1-1.*** *Map showing the Forsmark area with the three boreholes KFM07A, KFM08A and KFM08C. Horizontal unit vectors **e₁** and **e₂** denote the directions of the measured horizontal electric field components in the boreholes.*

2 Objective and scope

Earth currents – natural or man made – are intimately related to the driving voltage gradients (electric fields) through Ohm's law, or conversely, voltage gradients result from current flow in conductive media. At the Earth's surface current flows parallel to the surface, because the electrical resistivity of the atmosphere can be regarded as infinite at the low frequencies (long periods) considered here. If the electrical resistivity does not vary laterally natural current flow at depth will still be horizontal, whereas man-made current flow can have both horizontal and substantial vertical components, depending on the distance to the sources, the depth of investigation and, not least, in the case of HVDC power lines the distance to anodes/cathodes and the layout of local grounding circuits around the sites under investigation.

In the real Earth – and especially in crystalline terrains like the Baltic Shield – numerous vertical or sub-vertical conductive fracture zones and mineralized zones can perturb current flow dramatically /1/. If current flows perpendicular to the zones, electrical charges are set up at the zone boundaries, whereby the electric field can become strongly enhanced or reduced, and strong vertical currents may result. On other hand, if current flows parallel to the zones the electric field is more or less unperturbed, but the resulting current in such conductive zones become magnified by the ratio between the electrical conductivity in the zone to the one outside in the intact crystalline bedrock. Pipelines or other electrically well-conducting structures will – if they are not isolated from the surrounding soils or rocks – act in the same way as conducting fracture zones /2, 3/, i.e. they can gather current from the surroundings. Such currents can cause corrosion on the installations.

In this work, for the first time, we studied the behavior of the three electric field components in the upper crust at a depth of 469–479 m, see Table 2-1. For this purpose we used three existing boreholes at Forsmark (see Figure 1-1). In addition we measured the electric field on the ground surface close to the boreholes KFM08A and KFM08C. Simultaneously we also measured the three components of the magnetic field on the ground surface with two independent sensors for security reasons. We also take advantage of the magnetic field registrations at the geomagnetic observatory (Geological Survey of Sweden) at Fiby, which we use as a reference to the local measurements at Forsmark in order to separate possible man-made fields from natural fields. In Table 2-1 we list all the field components that are measured, the bandwidths, duration and the equipment used.

Table 2-1. The measurement parameters for the Forsmark Earth potential experiment.

Measurement site	Field component	Bandwidth	Duration	Equipment
In borehole KFM07A	Potential at "South" point at 558 m borehole length.	30 s – DC	Ca 14 days	Pb-PbCl$_2$ electrode
In borehole KFM08A	Potential at "Central" point at 591 m borehole length.	30 s – DC	Ca 14 days	Pb-PbCl$_2$ electrode
In borehole KFM08C	Potential at "East" point at 560 m borehole length.	30 s – DC	Ca 14 days	Pb-PbCl$_2$ electrode
In borehole KFM08A	Potential at "Top" point at 2 m borehole length.	30 s – DC	Ca 14 days	Pb-PbCl$_2$ electrode
Near boreholes KFM08A KFM08C	Magnetic field, x-, y- and z-components.	30 s – DC	Ca 14 days	3-component fluxgate magnetometer
Near boreholes KFM08A KFM08C	Magnetic field (extra) x-, y- and z-components.	30 s – DC	Ca 14 days	3-component fluxgate magnetometer
Near boreholes KFM08A KFM08C	Horizontal electric field, x- and y- components.	300 Hz – DC	Ca 14 days	Pb-PbCl$_2$ electrodes

3 Equipment

3.1 Description of equipment

We used two sets of long period MagnetoTelluric (MT) equipment. The long period instruments use fluxgate magnetometers to cover the period band 30 s – DC. For measuring potential differences (or electric fields) we use pairs of identical Pb-$PbCl_2$ electrodes. Each instrument was fed by two 90 Ah car batteries, which were continuously recharged from 230 V mains. All signals are collected in a central box with signal conditioner, AD converter and data storage devices.

For the borehole measurements we used specially designed Pb-$PbCl_2$ electrodes that were directly mounted on special cables. Thus there is no external coupling between electrodes and cables. This makes the measurement system very robust under chemically active conditions that sometimes prevail in boreholes with high mineral content such as salt water. The special electrodes and cables were purchased separately by SKB with the idea that other groups or projects could make use of them in the future. They were used for the first time in July 2005 in a similar experiment at the Äspö site.

4   Execution

4.1   Execution of field work

The analogue signals from the electromagnetic sensors are connected directly to a 24 bit data logger with GPS timing. In this case we used three separate data loggers (each containing six channels) that were perfectly synchronised using accurate GPS clocks. One full five component measurement corresponding to borehole measurements of the horizontal electric and three component surface magnetic fields were recorded on one logger. A second full five component measurement corresponding to surface measurements of the horizontal electric and three components surface magnetic fields were recorded on a second logger. Finally the two "vertical" components of the electric field in the two boreholes were recorded on the third logger.

All sensors and data loggers were carefully buried to reduce as much as possible artificial signals from wind noise and daily temperature variations.

After installation of the two MT systems they were left to run for about 2 weeks. The state of health was monitored daily by mobile phone calls to the intelligent data loggers. No malfunctioning was detected at this stage.

4.2   Data handling/post processing

4.2.1   Data handling/post processing

The data were first treated as normal MT data for which we estimated the transfer functions related to the electrical conductivity/resistivity distribution at depth in the Earth's crust and upper mantle. The long period system can give reliable estimates of transfer functions for the band 30 s – DC only and we concentrate on this frequency band in our analysis. This is also the most important band from the point of view of Earth potentials, because high frequency changes in the potentials are small and are not believed to give rise to strong corrosion effects.

In the case of the Forsmark experiment it turned out that the disturbance from the HVDC grounding point was so dominant that the effects of the natural field due to current systems in the ionosphere at a height of approximately 100 km was only clearly seen on the horizontal magnetic field, whereas the vertical magnetic field and the three component electric field measured between the three boreholes were caused by the currents from the HVDC cable.

Right below the surface of the earth there can be no vertical electric field, because no current is passing through the air-earth interface. However, at greater depths, a vertical electric field can be set up as a result of charges generated when currents cross a contrast in electrical conductivity (resistivity). Current concentrations result from large-scale lateral variations in electrical conductivity at great depth due, for example to concentrations of massive graphitic schists. So, for the surface measurements only the horizontal component of the electric field need to be taken into account, but for borehole measurements, if there are strong lateral variations in electrical conductivity in the vicinity of the boreholes considered, then there can well be a vertical electric field, which in turn can drive vertical currents through the crust. As we shall see later we believe that the grounding system, connecting all borehole sites in the Forsmark area, causes a major distortion of the electric field so as to gather currents from depth and lead them through the grounding system.

In this experiment we, for the first time, explicitly measured the vertical electric field by inserting an extra electrode into the borehole KFM08A at a depth of only 2 m. In this way we can get an estimate of the average electric field in all three Cartesian directions. Especially it is of interest to study the vertical electric field because it gives unique information about possible man-made sources and/or lateral discontinuities in electrical conductivity in between the boreholes.

4.3 Analyses and interpretations

In the borehole measurements we have measured the three components of the average electric field (potential differences divided by distance) between the electrode positions in the central borehole and the two "E" and "S" boreholes. Let us denote the unit vectors pointing from "S" to "Center", from "Center" to "East" and from "Top" to "Center" by $\hat{\mathbf{e}}_1$, $\hat{\mathbf{e}}_2$ and $\hat{\mathbf{e}}_3$, respectively. Then the measured electric field, $\mathbf{E}^*$ can be expressed in terms of the three x- (North), y- (East) and z- (Downwards) components in the usual way as

$$\mathbf{E}^* = \begin{Bmatrix} E_1^* \\ E_2^* \\ E_3^* \end{Bmatrix} = \mathbf{R}^* \mathbf{E}^{\mathbf{b}} = \mathbf{R}^* \begin{Bmatrix} E_x^b \\ E_y^b \\ E_z^b \end{Bmatrix}$$

where the transformation matrix, $\mathbf{R}^*$ contains the projections of the unit vectors $\hat{\mathbf{e}}_1$, $\hat{\mathbf{e}}_2$ and $\hat{\mathbf{e}}_3$ onto the xyz-system, respectively, i.e.

$$\mathbf{R}^* = \begin{Bmatrix} \hat{\mathbf{e}}_1 \cdot \hat{\mathbf{x}} & \hat{\mathbf{e}}_1 \cdot \hat{\mathbf{y}} & \hat{\mathbf{e}}_1 \cdot \hat{\mathbf{z}} \\ \hat{\mathbf{e}}_2 \cdot \hat{\mathbf{x}} & \hat{\mathbf{e}}_2 \cdot \hat{\mathbf{y}} & \hat{\mathbf{e}}_2 \cdot \hat{\mathbf{z}} \\ \hat{\mathbf{e}}_3 \cdot \hat{\mathbf{x}} & \hat{\mathbf{e}}_3 \cdot \hat{\mathbf{y}} & \hat{\mathbf{e}}_3 \cdot \hat{\mathbf{z}} \end{Bmatrix}.$$

Then we have

$$\mathbf{E}^b = \begin{Bmatrix} E_x^b \\ E_y^b \\ E_z^b \end{Bmatrix} = \left[\mathbf{R}^* \right]^{-1} \begin{Bmatrix} E_1^* \\ E_2^* \\ E_3^* \end{Bmatrix} = \left[\mathbf{R}^* \right]^{-1} \mathbf{E}^*$$

Instead of representing the vertical electric field as impedance elements Z_{zx}^b and Z_{zy}^b it may be more convenient to represent it in terms of electric tipper elements, C^b and D^b as follows:

$$E_z^b = C^b E_x^b + D^b E_y^b$$

The vertical electric field is produced by scattering from 2D and 3D inhomogeneities close to or even at the surface. If this is the case, then the electric tipper elements C^b and D^b will be real and frequency independent and like the magnetic tipper elements they typically lie in the interval $[-1|1]$. Moreover, if the local structure is elongated in the x-direction then $|C^b|$ will be small in comparison to $|D^b|$. Thus, it becomes possible to uniquely identify an electric strike direction of the local structure by rotating the coordinate system until the tipper element $|C^b|$ is minimized. It is interesting to note that the so-determined strike direction should coincide with the strike direction of the local structure obtained from analyzing the horizontal impedance tensor in terms of a local and a regional conductivity structure /1/, but without the 90 degrees ambiguity of the latter. In this respect the electric tipper vector is analogous to the standard magnetic tipper vector, but the magnetic tipper vector is immune to the local conductivity structure in the long period limit.

During the analysis of the data it appeared that the vertical electric field was much greater than the horizontal electric field. This unexpected behavior is difficult to explain for the conductivity structures that are usually found in the subsurface. As we shall see later it is more likely that grounding circuits, acting as short circuits, connecting all the boreholes in the area allow for substantial vertical current flow close to the boreholes.

To conclude this section, the introduction of the borehole measurement of all three components of the electric field makes it possible to directly study the effect of local conductivity structures (including man-made short circuits) on the impedance tensor. Such local structures manifest themselves as frequency independent, real distortion matrices between borehole and surface impedances and frequency independent.

5 Nonconformities

We met little problems in measuring in the three boreholes at Forsmark during the 14 days period from July 3 to July 16, 2006. But the measurements of the surface electric fields were very unstable, most probably due to the extremely dry conditions during the time of the measurements. They show saturation, whereby it becomes difficult to obtain meaningful information from them. In this respect the borehole measurements showed very good stability and no significant drift.

For some reason which we do not understand the two vertical electric field components measured in the boreholes showed signs of short circuits early in the morning of July 11, 2006. However, this has no consequences for the conclusions that can be drawn from these measurements.

6 Results

6.1 The transfer functions from the borehole measurements

The geometry of the borehole measurements is given in Table 6.1. The measured potential differences between electrode positions in KFM07A–KFM08A and between KFM08A–KFM08C, respectively, are scaled by the distance between them to give the corresponding (average) electric field $\mathbf{E}^* = E_1^*\hat{\mathbf{e}}_1 + E_2^*\hat{\mathbf{e}}_2 + E_3^*\hat{\mathbf{e}}_3$. The unit vectors are displayed in Table 6-2.

The electric field was measured on the surface with electrode positions shown in Table 6-3.

Time series of the magnetic field components at the geomagnetic observatory at Fiby, run by the Geological Survey of Sweden, and the surface location at Forsmark close to boreholes KFM08A and KFM08C are shown in Figure 6-1. Notice that the horizontal components can be super-imposed onto each other nearly perfectly, illustrating the natural cause of these components. It can also be noticed that there were no magnetic storms during the period of measurements in July 2006; daily variations of plus minus 20 nTesla are typical. When comparing the vertical components of the magnetic field a clear difference can be noted. The vertical component at Forsmark exhibits jumps of as much as 100 nTesla in the beginning and smaller jumps throughout the measurement period.

Table 6-1. Location of the electrodes in the boreholes.

Id	Borehole	Borehole length	Northing-coordinate	Easting-coordinate	Vertical depth	Remarks
A	KFM07A	558 m	6700116	1630738	473	
B	KFM08A	591 m	6700763	1630988	481	
C	KFM08C	560 m	6700721	1631388	471	
D	KFM08A	2 m	6700495	1631196	2	

Table 6-2. Unit vectors between the downhole electrodes.

From	To	Unit vector	X	Y	Z	Distance
A	B	e_1	0.932545	0.360334	0.011531	693.8
B	C	e_2	–0.104300	0.993295	–0.024830	402.7
D	B	e_3	0.456093	–0.353980	0.815180	587.6

Table 6-3. Distances between surface electrodes.

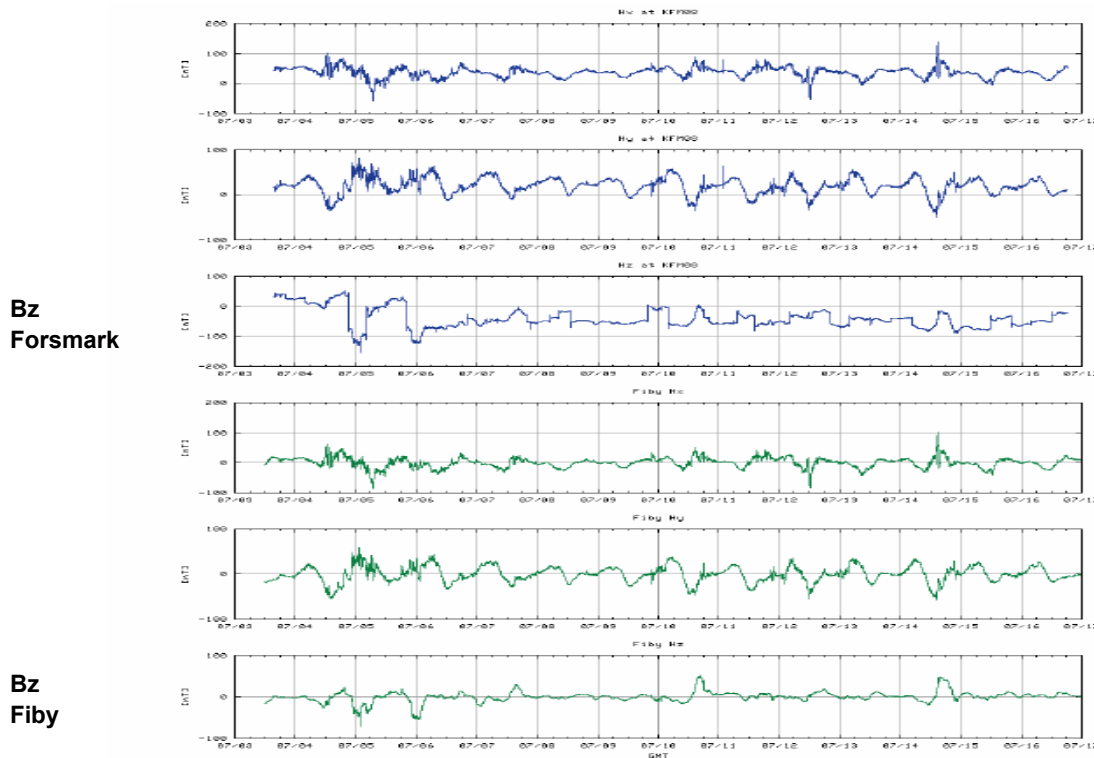| Electrode	Distance [m]	Total distance [m]	Remarks
Centre-North	44		Centre close to KFM08A and KFM08C
Centre-South	57		
North-South		101	
Centre-East	40		
Centre-West	49		
East-West		89	

Figure 6-1. *Variation in magnetic field components at Forsmark and the Geomagnetic Observatory at Fiby, Uppsala, during the period of measurement from July 3 to July 16, 2006 (Do not pay attention to the DC offsets at Forsmark).*

In Figure 6-2 we study in more detail the correlation between the time variations in the vertical magnetic field components in Fiby and Forsmark and the power variation in the Fenno-Skan cable. We first notice that the jump in vertical magnetic field at Forsmark of about 100 nTesla on July 4 has no counterpart on the Fiby record, but it is coincident with a power increase of 500 MW, corresponding to a DC current of 1,200 A. On the other hand on July 11 the Fiby and Forsmark magnetic components are well correlated when the power is constant.

In Figure 6-3 we show the long period variations of the horizontal electric field between the boreholes at a depth of approximately 500 m below the surface and the power variations in the Fenno-Skan HVDC cable during the measurement period. As with the vertical magnetic field there is a very strong correlation so that it can be safely stated without going into quantitative measures that the major part of electric variations is causally related to the DC current in the cable.

In Figure 6-4 we show the long period variations of the potential differences between electrode positions placed at a depth of about 470 m in the two boreholes KFM08A and KFM08C and electrodes placed about 2 m down in each borehole. Notice that the middle panel corresponding to borehole KFM08C shows the behaviour of a short circuit. We have found no explanation for this effect, but it is likely that the 10 m long cable connecting the "surface" electrode at borehole KMF08C to the data logger placed above borehole KMF08A is involved. Compared with the variations in the horizontal field variations from Figure 6-3 the vertical potential variations are about 4 times stronger with maximum amplitude of about 2,000 mV compared with 500 mV for the horizontal variations.
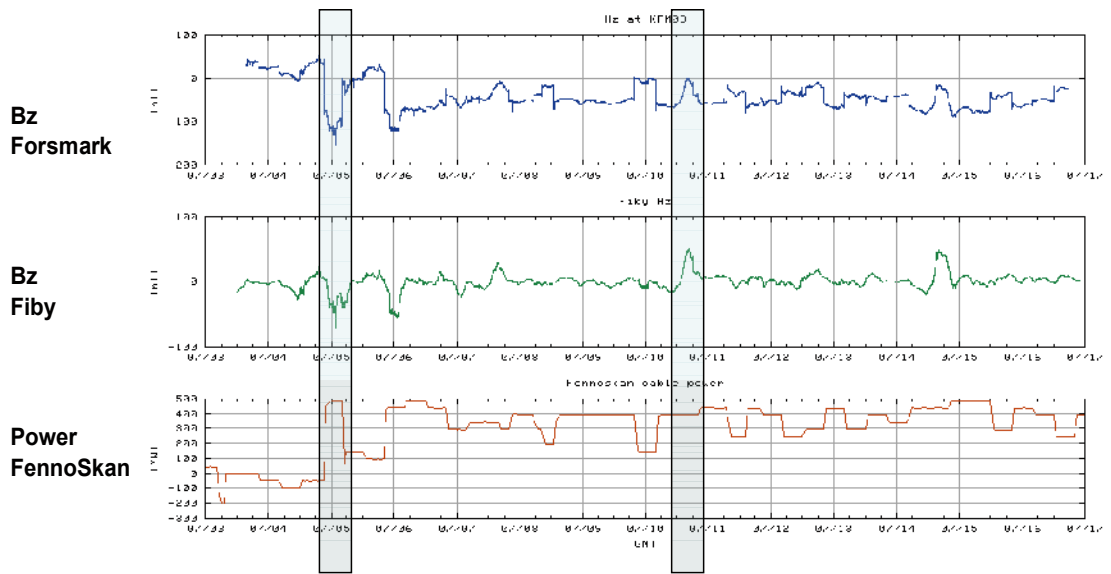
Figure 6-2. *Comparison between vertical magnetic field variations at Fiby and Forsmark and the variations of the power in the Fenno-Skan HVDC cable during the time period July 3 to July 16, 2006.*
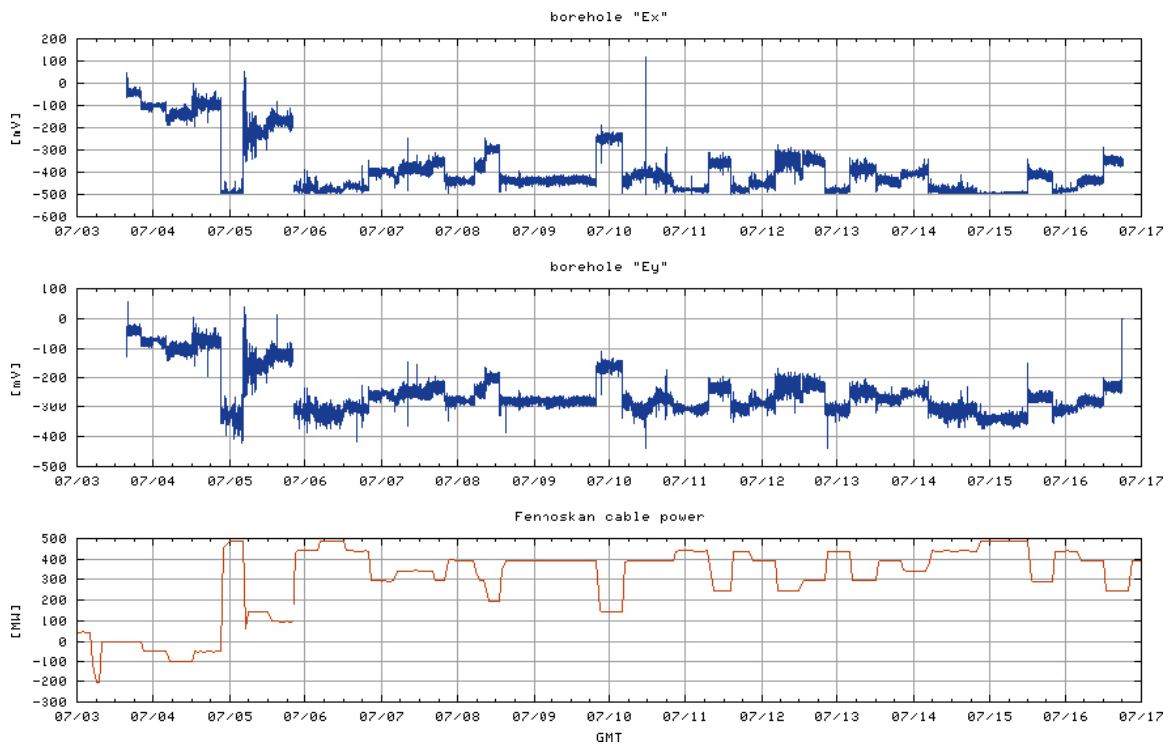

Figure 6-3. *Comparison between horizontal electric field variations at Forsmark and the variations of the power in the Fenno-Skan HVDC cable during the time period July 3 to July 16, 2006. The two horizontal fields were measured as potential differences between electrodes placed at depth of about 470 m in the two boreholes KFM08A/KFM07A and KFM08C/KFM07A.*
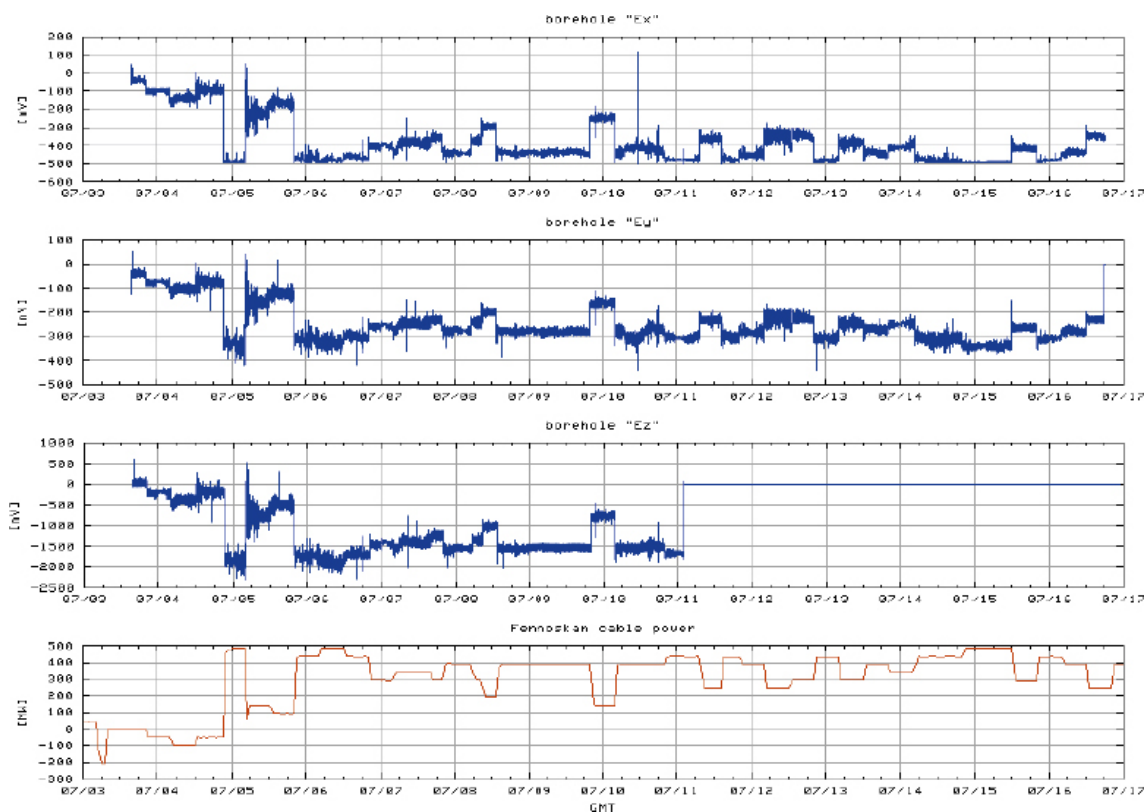
Figure 6-4. *Comparison between vertical electric field variations at Forsmark and the variations of the power in the Fenno-Skan HVDC cable during the time period July 3 to July 16, 2006. The two vertical fields were measured as potential differences between electrodes placed at depth of about 470 m in the two boreholes KFM08A and KFM08C and the surface at about 2 m depth in KFM08A. No explanation has been found for the short circuit observed on July 11 in electric component measured in KFM08C.*

Finally, in Figure 6-5 we show the variation of the horizontal electric field measured on the surface using a measurement setup that saturates at an amplitude of 500 mV. Ex and Ey denote the N-S and E-W components of the potential differences. Due to the extreme dry conditions during the time of measurements it seems that there is considerable drift in the measurements, especially in the E-W component. Since these potential differences are measured over distances of about 101 m and 89 m, respectively it seems that the E-W component is as strong as the vertical component when taking into account the difference in distance between the electrodes. However, the N-S component is significantly smaller and only shows a week coupling to the jumps observed in the E-W component.

It is thus clear that the major part of the electrical disturbances observed at Forsmark is related to the power in the Fenno-Skan HVDC cable. In the next section an attempt will be made to set up a model that, at least qualitatively, can explain these observations.

6.2   Electromagnetic disturbances from the Fenno-Skan DC cable

The Fenno-Skan cable carrries DC currents between Finland and Sweden. The sea and the Earth's crust are used to carry return currents. The position of the cable is shown in Figure 6-6. The distance from the grounding point north of the Forsmark power plant to the measurement points is approximately 30 km.
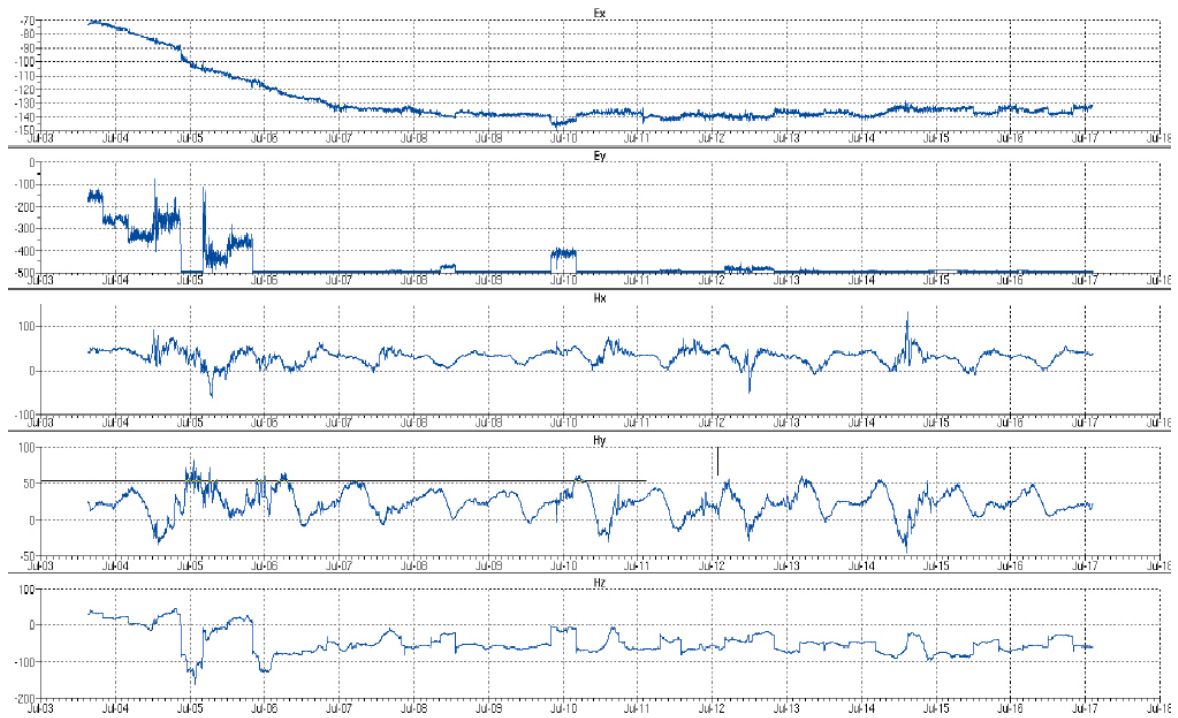
Figure 6-5. *The horizontal electric field variations at Forsmark measured on the surface centred around borehole KFM08A together with the three components of the magnetic field measured independently from that shown in Figure 6-1.*
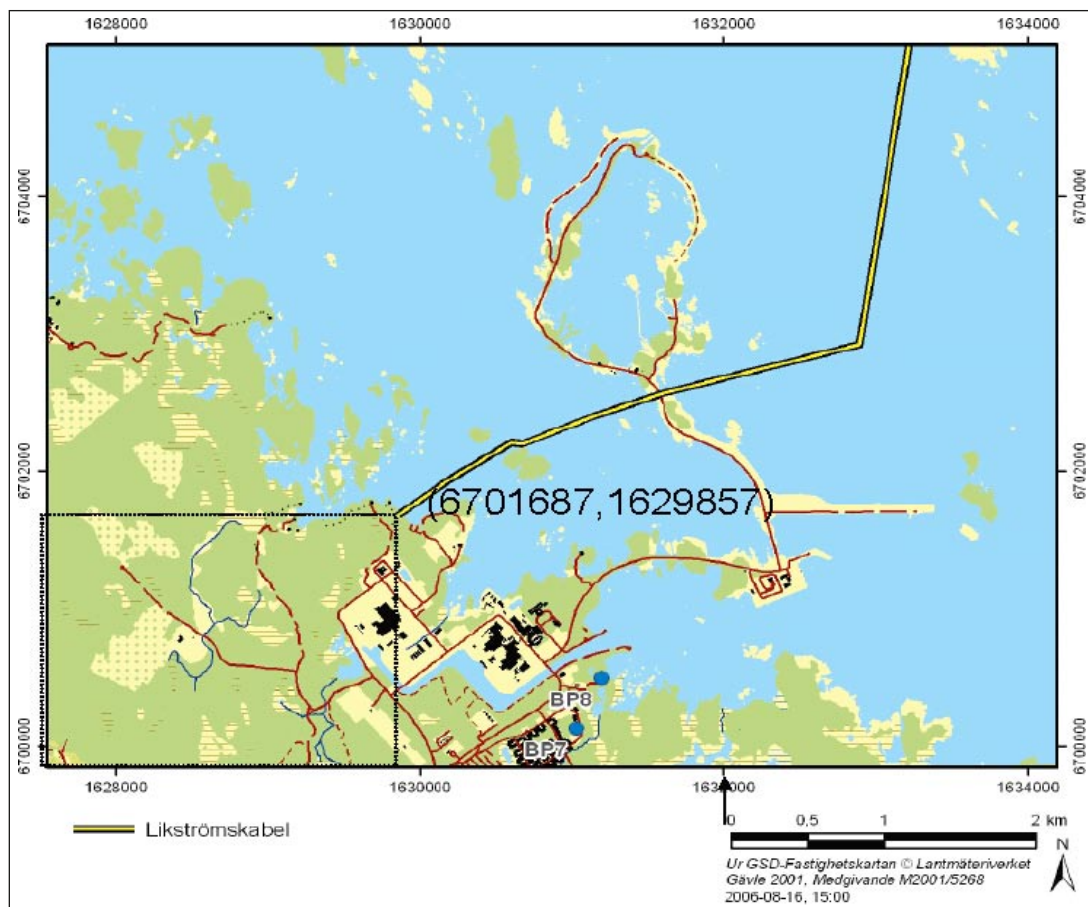

Figure 6-6. *The position of the Fenno-Skan HVDC cable in the Forsmark area. The grounding point (the anode) is located approximately 30 km to the north of Forsmark.*

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With effective resistivities between 1,000 and 10,000 Ohm-m (real resistivities in the bedrock is probably larger, but the conductive sea water will carry some of the currents) we can calculate the magnitude of the radially directed electric field in the Earth from the formula

$$E = \frac{\rho I}{2\pi r^2}$$

where I is the current, ρ is the electrical resistivity and r is the distance from the grounding point. At a distance of 30,000 m we find an electric field of

$$E = \frac{\rho I}{2\pi r^2} = \frac{(1,000\,|\,10,000)I}{2\pi \cdot 30,000^2} \left[V/m\right] \quad *$$

or

$$E/I = \frac{(1,000\,|\,10,000)}{2\pi \cdot 30,000^2}\left[V/m/A\right] = (0.2\,|\,2)\,\mu\text{V/m/A}$$

Hence, a field of 1 mV/m in the *horizontal* direction would require minimum currents in the range $(500\,|\,5,000)\,\text{A}$. This is in the range of the observed current load variations in the Fenno-Skan cable during the time of measurements. A similar calculation for the vertical direction indicates that for a potential difference of 2 V from the surface to the 500 m level a current in the range $(136\,|\,1,360)$ kA would be required, i.e. roughly one thousand times greater than the actual DC currents in the Fenno-Skan cable of about 1,000 A. Even, by taking into account that the Earth's crust is inhomogenous it is unlikely that such large voltages can be generated over a distance of 30 km.

We therefore need another model in order to explain the observed field variations. The model should explain the major features that have been observed:

1. The dominant vertical electric field of up to 2,000 mV at KFM08A and KFM08C in phase with the up to 500 MW power variations in the Fenno-Skan cable.

2. The horizontal electric field variations between sites KFM08A, KFM08C and KFM07A at a depth of about 470 m in phase with the power variations in the Fenno-Skan cable.

3. The disturbance of the vertical magnetic field measured on the surface a few tens of metres from borehole KMF08A within the steel fence of the site.

We believe that the model shown in Figure 6-7 can explain these features. Since there is no direct cable connection between the anode at Fågelsundet and the Forsmark site investigation area located 30 km away we need other ways of generating the necessary voltages.

At Forsmark, in contrast to the conditions at Äspö where similar measurements were carried out in 2005, all borehole sites, for safety reasons, are galvanically connected by a grounding circuit in order to keep them at the same potential. Since the electric field in the radial direction (normalized by the anode current) is of the order

$$E/I = \frac{(1,000\,|\,10,000)}{2\pi \cdot 30,000^2}\left[V/m/A\right] = (0.2\,|\,2)\,\mu\text{V/m/A}$$

and because the length of the grounding circuits is about 5,000 m we can expect to have driving voltages of about

$$(0.2\,|\,2)\,\mu\text{V/m/A} \cdot 1,000A \cdot 5,000m = (1\,|\,10)V$$

which are about the driving voltages necessary to get a vertical voltage difference of about 2 V caused by a current change of 1,000 A at the anode location.

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* In this and other formulas we use the vertical bar "|" to distinguish between two alternatives. In this case we distinguish between the resistivities 1,000 Ohm-m and 10,000 Ohm-m.
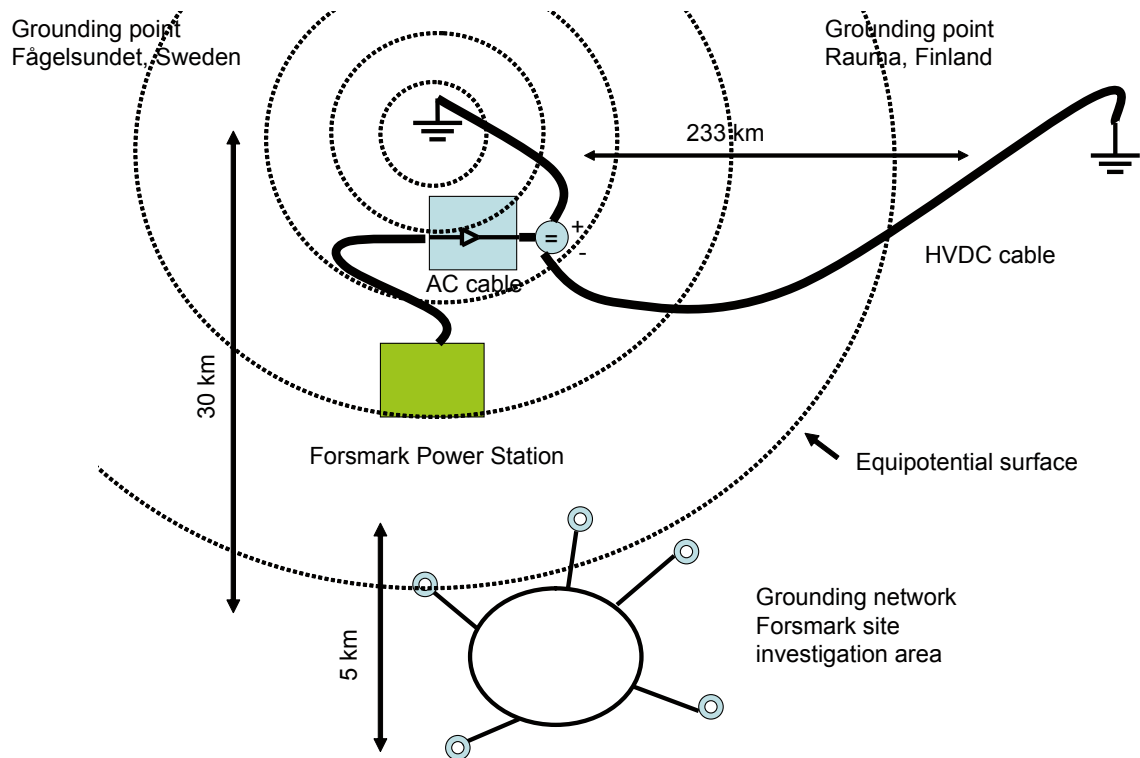
Figure 6-7. Model showing the variation of Earth potentials from the HVDC anode at Fågelsundet located about 30 km from Forsmark. The potential differences between the boreholes in the Forsmark area drive currents between the boreholes through the grounding circuit laid out on the surface to connect the borehole sites.

The measured horizontal voltage variation is smaller than that, but the horizontal distances between the downhole electrodes in the boreholes KFM08A–KFM08C and KFM07A–KFM08A are only 403 m and 694 m, respectively. This brings the measured voltage variations of maximum 500 mV to lie within the range predicted by the simple model.

The measured vertical magnetic field variations that correlate with the power variations amount to 100 nTesla. Such variations can be explained either as an effect of the 1,000 A variation in the DC power line itself or as due to stray currents in the grounding circuit lying close to the magnetic sensors.

Using an infinite line source model for the HVDC cable and a distance of 2 km (see Figure 6-6) from the line to the observation point at Drill Site 8, we find that for a current of 1,000 A the vertical magnetic field is perturbed by 100 nTesla.

Another contribution to the vertical magnetic field can come from the current in the grounding circuit. Take the distance from the observation point to the grounding circuit to be equal to 10 m and the current in the grounding circuit to be equal to 100 mA. Then for an infinite line source the vertical magnetic field is perturbed by 2 nTesla, far less than the observed 100 nTesla. We therefore conclude that the main contribution to the vertical magnetic field perturbation at Drill Site 8 is related directly to the current in the HVDC cable itself. The effect of the stray currents on the magnetic field is much smaller.

7 Discussion and conclusions

The simple model derived to explain the electric fields in the boreholes does not include effects of lateral conductivity changes in the crust or effects due to the conducting Baltic Sea. Lateral conductivity variations in the crust are primarily related to fracture systems whereby the electrical conductivity can increase by one or two orders of magnitude compared with the background values of crystalline rocks. However, fracture zones only occupy a vanishingly small volume compared with the volume involved in the conduction of currents from the source point at Fågelsundet and the observation points in the Forsmark area and besides they do not form a continuous conductor between source and receivers.

As for the effect of the Baltic Sea the situation is less clear since the sea forms a thin continuous conductor with a conductivity which is more than three orders of magnitude greater than that of normal crystalline rocks. This would cause a concentration of electrical current in the sea compared with the current in the crystalline basement, but since the distance from source to receiver is much greater than the thickness of sea water (30 km compared with a few tens of metres) the influence of the sea on the measured voltage differences is believed to be rather small. How small is difficult to say since this would require that a conductivity model in 3D be constructed, which was outside of the scope of this project.

The current injected into the sea at Fågelsundet is eventually gathered on the Finnish side of the Baltic Sea at Rauma. Since the distance between the two source points is much greater than the distance from Forsmark to Fågelsundet, it is a good approximation to assume that only the Fågelsundet electrode is active.

In conclusion the observed voltage differences in and between boreholes in the Forsmark area can be explained as voltage drops due to injection of about 1,000 A strong currents at Fågelsundet. These voltage drops have an approximate radial distribution around Fågelsundet, and at Forsmark their magnitude is around 1 V/km in the horizontal direction but negligible in the vertical direction close to the surface. These voltages can in turn drive currents along the boreholes via grounding circuits connecting the various boreholes in the area. A simple way to avoid these currents is to disconnect the grounding circuits.

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