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Geomagnetically Induced Currents in the Finnish Natural Gas Pipeline

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Abstract

Geomagnetically induced currents in the Finnish natural gas pipeline system are estimated assuming that the pipe is a straight infinite cylinder with an ideal coating buried in a homogeneous medium and that the geomagnetic disturbance is a plane wave. The current density between the pipe and the earth is calculated. During geomagnetic storms its value can be some $\mu A/m^2$ *thus exceeding the protection current density of the pipeline. Several special cases of practical significance are discussed: a horizontal change of the earth's conductivity, curves in the pipe, the effect of the earth's surface, the finite length of the pipe and holes in the insulation. In these cases it seems that the current density may be of the order of* mA/m^2 *or even more, but further studies are required.*

1. *Introduction*

According to Faraday's law of induction an electric field is always connected with temporal changes of the geomagnetic field. This electric field causes ohmic currents in all conductors. When these currents flow in man-made systems like power grids, gas or oil pipelines, they are called geomagnetically induced currents (GICs). The impact of geomagnetic disturbances on technological systems has been widely studied during recent years (e.g. *Albertson et al.*, 1973; *Albertson and Thorson*, 1974; *Albertson et al.*, 1974; *Boteler et al.*, 1982; *Boteler and Cookson*, 1986; *Brasse and Junge*, 1984; *Lanzerotti et al.*, 1979; *Lanzerotti*, 1979a, 1979b, 1981 and 1986; *Paulicas and Lanzerotti*, 1982; *Pirjola and Viljanen*, 1989; *Smart*, 1982). Geomagnetic induction in the Alaska pipeline has been discussed by *Campbell* (1978, 1980 and 1986).

Because Finland is situated at auroral latitudes the study of GICs is important here. Because geomagnetic variations are slow GICs are (quasi) dc currents. So only ohmic resistances of the conductors are taken into account (*Campbell*, 1978, p. 1171).

In pipelines currents between the pipe and the earth can cause corrosion and disturb the protection control against corrosion (*Campbell*, 1978, p. 1145; *Lanzerotti and Gregori*, 1986, p. 246). To avoid corrosion in the Finnish natural gas pipeline (Fig. 1) a protection system shown in Fig. 2 is used. The potential of the earth is kept higher than that of the pipeline to prevent currents to flow from the pipe to the earth.

The most critical areas are those where the insulation has been damaged. Then the resistance between the pipe and the earth is lower than elsewhere and currents are concentrated in these areas. Parallel currents in long pipes can be even hundreds of amperes (*Campbell*, 1980, p. 535-4). If these currents flow to the earth in a small area the local current density can be very high.

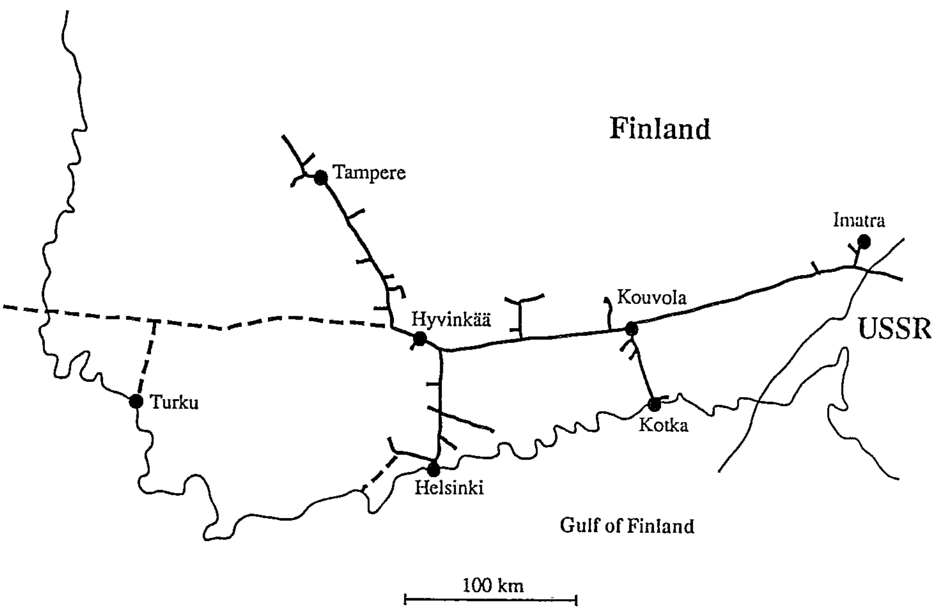

Fig. 1. Finnish natural gas pipeline in the end of 1986.

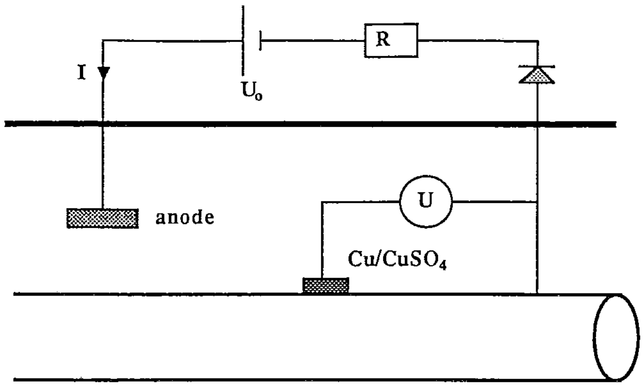

Fig. 2. Principle of the corrosion protection in the Finnish natural gas pipeline system. The voltage U_0 is regulated so that either the protection voltage U or the protection current I is constant.

In literature there are different data of the corrosion caused by GICs. According to *Campbell* (1978, p. 1167) and *Gideon* (1971, p. 9) it is not a problem at all. On the other hand, however, according to *Henriksen et al.* (1978) the corrosion due to GICs is a real problem. The latter also present a method that prevents corrosion almost perfectly. Anyway, geomagnetic variations cause difficulties in measuring the protection voltages.

The Finnish pipeline was previously considered by *Pirjola and Lehtinen* (1985) using the circuit theory of *Lehtinen and Pirjola* (1985). Assuming a perfect insulation they calculated currents in the earthings of the protection stations. However, their calculations are only the first approximations and should be greatly developed. They have namely assumed that the current can flow in either direction at protection stations which is not true (Fig. 2). Furthermore, the assumption of the perfect insulation is not good as will be seen later.

In this paper, GICs in pipelines are estimated theoretically. Especially the currents from the pipe to the earth are considered. The basic model is an infinite straight cylindrical conductor buried in a homogeneous medium. The geomagnetic disturbance is assumed to be a plane wave which propagates perpendicularly to the pipe.

A more realistic model for the ionospheric source causing the geomagnetic disturbance could be used but as the pipeline system lies in rather a small area, a plane wave model is sufficient. Assuming the medium around the pipe to be homogeneous means that the boundary between the earth and the air is neglected. This simplifying approximation is also studied in greater detail in this paper.

There are two separate cases: H-polarization (the primary magnetic field parallel to the pipe) and E-polarization (the primary electric field parallel to the pipe). In the H-polarization the current flows between the pipe and the earth, in the E-polarization parallel to the pipe. If the earth is not laterally homogeneous or the pipe not straight there is an radial electric field in the E-polarization, too.

The protection system is not taken into account in the calculations. Hence we get upper estimates for GICs. Statistics of GICs in pipelines are obtained by calculating the geoelectric field from measured geomagnetic data (*Viljanen and Pirjola*, 1989).

2. *Cylinder in a homogeneous medium*

2.1 H-polarization

2.1.1 Non-insulated cylinder

The pipeline is assumed to be an infinite hollow straight cylinder buried in a homogeneous infinite medium. The geomagnetic variation field is assumed to be a vertically propagating plane wave in the medium. The coordinate system used is shown in Fig. 3.

The time dependence is assumed to be harmonic ($e^{i\omega t}$). As usual, the physical fields are the real parts of the complex expressions. The general solution of the wave equation in the region 2 is

$$B_x(r,\phi) = \sum_{m=-\infty}^{\infty} (a_m J_m(kr) + b_m N_m(kr))e^{im\phi} , \tag{1}$$

where J_m and N_m are the Bessel and Neumann functions of order m. The imaginary part of the wave number $k=\sqrt{\omega^2\mu\varepsilon - i\omega\mu\sigma}$ is defined to be negative. The coefficients a_m and b_m are determined by boundary conditions. For details, see e.g. *Abramowitz and Stegun* (1972), *Arfken* (1985), *Jackson* (1975) or *Gradshteyn and Ryzhik* (1980).

In region 1 only the Bessel function is physical as the Neumann function has a singularity in the origin. In the region 3 it is practical to use the Hankel function of the second kind ($H^{(2)}=J-iN$):

$$B_x^3(r,\phi) = \sum_{m=-\infty}^{\infty} ((-1)^m B(\omega) J_m(k_3 r) + a_m^3 H_m^{(2)}(k_3 r))e^{im\phi}. \tag{2}$$

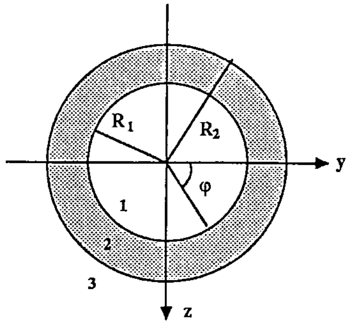

Fig. 3. Coordinates used in this paper.

The first term of the series is a downward propagating plane wave $e^{-ik_3 z}$ (*Arfken*, 1985, p. 573). Although the model does not take into account the boundary between the earth and the air, the amplitude $B(\omega)$ is assumed to equal the variation field measured on the earth's surface. The effect of the earth's surface is estimated in sections 2.1.4 and 2.2.4.

The Hankel function of second kind represents a wave reflecting from the pipe; it vanishes at infinity. The term $e^{-ik_3 z}$ increases exponentially when z decreases which is not physical. However, we can think that the study is restricted to values $z > -h$ ($h>0$).

The coefficients a and b are determined by the conditions that the tangential components of B/μ and E are continuous. Thus we get four equations from which we solve the coefficients using the known amplitude $B(\omega)$. The following abbreviations are used:

$$
\begin{aligned}
&\mu_{ij} = \mu_i/\mu_j, \quad k_{ij} = k_i/k_j, \\
&A_1 = J_m(k_1R_1), \quad A_2 = \mu_{12}J_m(k_2R_1), \quad A_3 = \mu_{12}N_m(k_2R_1), \\
&B_1 = J_m'(k_1R_1), \quad B_2 = k_{12}J_m'(k_2R_1), \quad B_3 = k_{12}N_m'(k_2R_1), \\
&C_2 = J_m(k_2R_2), \quad C_3 = N_m(k_2R_2), \quad C_4 = \mu_{23}H_m^{(2)}(k_3R_2), \\
&D_2 = J_m'(k_2R_2), \quad D_3 = N_m'(k_2R_2), \quad D_4 = k_{23}H_m^{(2)\prime}(k_3R_2), \\
&F_1 = (-1)^m\mu_{23}J_m(k_3R_2)B(\omega), \quad F_2 = (-1)^m k_{23}J_m'(k_3R_2)B(\omega), \\
&G = (A_1B_3 - A_3B_1)(C_2D_4 - C_4D_2) + (A_2B_1 - A_1B_2)(C_3D_4 - C_4D_3).
\end{aligned} \tag{3}
$$

A prime (') means differentiation with respect to the argument. The exact formulas of the field in each region in the H-polarization are then

$$B_x^1(r,\phi) = \sum_{m=-\infty}^{\infty} \frac{(A_2B_3 - A_3B_2)(D_4F_1 - C_4F_2)}{G} J_m(k_1r)e^{im\phi} \tag{4}$$

$$E_r^1(r,\phi) = \frac{\omega}{k_1^2 r} \sum_{m=-\infty}^{\infty} \frac{(A_2B_3 - A_3B_2)(D_4F_1 - C_4F_2)}{G} mJ_m(k_1r)e^{im\phi} \tag{5}$$

$$E_\phi^1(r,\phi) = \frac{i\omega}{k_1} \sum_{m=-\infty}^{\infty} \frac{(A_2B_3 - A_3B_2)(D_4F_1 - C_4F_2)}{G} J'_m(k_1r)e^{im\phi} \tag{6}$$

$$B_x^2(r,\phi) = \sum_{m=-\infty}^{\infty} \Big(\frac{A_1B_3 - A_3B_1}{G} J_m(k_2r) + \frac{A_2B_1 - A_1B_2}{G} N_m(k_2r) \Big)(D_4F_1 - C_4F_2)e^{im\phi} \tag{7}$$

$$E_r^2(r,\phi) = \frac{\omega}{k_2^2 r} \sum_{m=-\infty}^{\infty} \Big(\frac{A_1B_3 - A_3B_1}{G} J_m(k_2r) + \frac{A_2B_1 - A_1B_2}{G} N_m(k_2r) \Big)(D_4F_1 - C_4F_2)me^{im\phi} \tag{8}$$

$$E_\phi^2(r,\phi) = \frac{i\omega}{k_2} \sum_{m=-\infty}^{\infty} \Big(\frac{A_1B_3 - A_3B_1}{G} J'_m(k_2r) + \frac{A_2B_1 - A_1B_2}{G} N'_m(k_2r) \Big)(D_4F_1 - C_4F_2)e^{im\phi} \tag{9}$$

$$B_x^3(r,\phi) = \sum_{m=-\infty}^{\infty} \Big((-1)^m B(\omega) J_m(k_3r) + \frac{(A_1B_3 - A_3B_1)(D_2F_1 - C_2F_2) + (A_2B_1 - A_1B_2)(D_3F_1 - C_3F_2)}{G} H_m^{(2)}(k_3r) \Big) e^{im\phi} \tag{10}$$

$$E_r^3(r,\phi) = \frac{\omega}{k_3^2 r} \sum_{m=-\infty}^{\infty} m\Big((-1)^m B(\omega) J_m(k_3r) + \frac{(A_1B_3 - A_3B_1)(D_2F_1 - C_2F_2) + (A_2B_1 - A_1B_2)(D_3F_1 - C_3F_2)}{G} H_m^{(2)}(k_3r) \Big) e^{im\phi} \tag{11}$$

$$E^3_\phi(r,\phi) = \frac{i\omega}{k_3}\sum_{m=-\infty}^{\infty}\Big(({-1})^m B(\omega) J'_m(k_3 r) + \frac{(A_1B_3-A_3B_1)(D_2F_1-C_2F_2)+(A_2B_1-A_1B_2)(D_3F_1-C_3F_2)}{G} H^{(2)\prime}_m(k_3 r)\Big)e^{im\phi} \tag{12}$$

2.1.2 Current from a hollow non-insulated pipe to the earth

Before applications and results, some numerical values are given in table 1. The exact values of the permittivity of the steel, the insulator and the earth are unessential as they are included only in the displacement current term of the fourth Maxwell equation. This small term will be neglected later.

The permeability of the steel depends of its type and also on the external magnetic field. Some types can have the same permeability as the air. We have used a typical value in weak magnetic fields given in table books. However, in practical computations the value of the permeability is not very essential.

The conductivity of the insulator is given by the formula

$$\sigma = R_1 j(R_1)\ln(R_2/R_1)/U\,, \tag{13}$$

where R_1 is the distance from the axis of the pipe to the outer boundary of the steel, R_2 is the distance to the outer boundary of the insulator, j is the current density from the pipe to the earth and U is the pipe-to-earth voltage near the protection stations.

Table 1. Numerical values concerning the Finnish natural gas pipeline (SI units). The wave number k is calculated using a typical period 60 s for geomagnetic disturbances. The electromagnetic properties of the natural gas are assumed to be similar to those of the air. The thickness of the pipe is 7...12 mm and its radius $R(\approx R_1 \approx R_2)$ is about 0.3 m.

	natural gas	steel	insulator	earth
permeability	μ_o	$200\mu_o$	$2...3\mu_o$ *	μ_o
permittivity	ε_o	ε_o	$2...9\varepsilon_o$	$5...10\varepsilon_o$
conductivity	10^{-14} **	$4\cdot10^{6}$ *	10^{-8} *	$10^{-4}...10^{-3}$ ***
$\lvert k\rvert R$	$1\cdot10^{-10}$	3	$2\cdot10^{-8}$	$1\cdot10^{-6}...3\cdot10^{-6}$

*=Neste company, **=*Israel* (1971, pp. 95, 248), ***=*Jones et al.* (1983, p.48) and *Viljanen and Pirjola* (1989, p. 415).

In the old part of the Finnish system R_1 is about 35 cm, the thickness of the insulator (R_2–R_1) is 0.45 mm and $j \approx 30...50$ μA/m²; in the new part, respectively, 20...25 cm, 3 mm and 6 μA/m². The voltage U is about 1 V everywhere. (These values were obtained from the Neste company.) The conductivity of the insulator in the old part is thus $1.3...2.2 \cdot 10^{-8}$ $\Omega^{-1}m^{-1}$ and in the new part $1.8 \cdot 10^{-8}$ $\Omega^{-1}m^{-1}$. In calculations the value 10^{-8} $\Omega^{-1}m^{-1}$ will be used.

As concerns corrosion, the important quantity is the radial current density j_r from the pipe to the earth. Just outside the pipe it is

$$j_r^3(R_2,\phi) = \sigma E_r^3(R_2,\phi) . \tag{14}$$

When calculating $E_r^3(R_2,\phi)$ we use the fact that $|kR|$ is much smaller than unity if k is not the wave number of steel. Thus many expressions containing different Bessel functions become simpler (e.g. *Arfken*, 1985), and finally we obtain

$$j_r^3(R_2,\phi) = -2e^{i\pi/4}\sqrt{\omega\sigma_3/\mu_3}\cdot B(\omega)\cos\phi\cdot e^{i\omega t} . \tag{15}$$

If the earth is homogeneous and the geomagnetic disturbance is a plane wave the following relation holds on the earth's surface (e.g. *Cagniard*, 1953, p. 616):

$$\sqrt{\omega}\, B_x(\omega) = -e^{-i\pi/4}\sqrt{\sigma_3\mu_3}\, E_y(\omega) , \tag{16}$$

(similarly for B_y and $-E_x$) so that equation (15) gives in the time domain

$$j_r^3(R_2,\phi,t) = 2\sigma_3 E(t) \cos\phi . \tag{17}$$

Although we have not taken the earth's surface explicitly into account we assume that $E(t)$ equals the real geoelectric field on the earth's surface. The factor 2 is due to the fact that the normal component of the electric field doubles on the surface of a good conductor.

If the earth's conductivity is $\sigma_3 = 10^{-3}$ $\Omega^{-1}m^{-1}$ and that $|E| < 10$ V/km we get as an upper estimate $|j| < 20$ μA/m². The value 10 V/km for $|E|$ is very rare occurring only during the most intensive magnetic storms (*Sanders*, 1961).

2.1.3 Effect of the insulation

We now compare a non-insulated pipe (A) and an insulated pipe (B). To simplify calculations the pipe is not hollow now. Case A follows from equations (4)–(8) by setting the indices 1 and 2 equal. Using similar approximations as in 2.1.2 we get

$$j_r^3(R,\phi) = -2e^{i\pi/4}\sqrt{\omega\sigma_3/\mu_3}B(\omega)\cos\phi\,, \tag{18}$$

which is the same as (15). Case B is computationally similar to A. The radial current density in the boundary of steel and insulation is ($\omega > 0$)

$$j_r^2(R_1,\phi) \approx -\frac{4\omega\mu_2\sigma_2 B(\omega)\cos\phi}{\mu_3 k_3 (k_2 R_1)^2}\left(\frac{2}{(k_3 R_1)^2} + \frac{\mu_2}{\mu_3}\frac{R_2^2-R_1^2}{(k_2 R_1 R_2)^2}\right)^{-1}. \tag{19}$$

If we set $R_1=R_2$ and replace the index 3 by 2 we get the same result as for the non-insulated pipe. On the other hand, if we only replace the index 3 by 2 we do not get the correct limiting value. (This is unessential in our case as $R_1 \approx R_2$.) So in taking the limit one should be very careful.

The ratio between current densities of the insulated and non-insulated pipe is according to equations (18) and (19)

$$\Delta \approx \left(1 + \frac{\sigma_3}{2\sigma_2}\frac{R_2^2-R_1^2}{R_2^2}\right)^{-1}. \tag{20}$$

Using numerical values given in section 2.1.2 we see that Δ varies from 0.0008 to 0.07. This holds for a full pipe and certainly for a hollow pipe $\Delta < 0.1$, too.

If the insulation is damaged in some areas the radial current density can be at least ten times larger (equation (20)). This problem is studied in detail in section 2.2.6. In addition, the earth's real conductivity structure and the effect of the earth-air boundary should be taken into account. As the protection system is neglected, the estimates for radial currents describe the worst situation.

2.1.4 Effect of the earth's surface

Consider case A in section 2.1.3. The magnetic field outside the pipe ($r>R$) follows from equations (3) and (10) setting indices 1 and 2 equal. Using similar approximations as above we get

$$B_x^3(r,\phi) = B(\omega)\cdot(e^{-ik_3 z} - k_3 R/2)\,, \tag{21}$$

where the index 3 refers to the earth. The first term is the primary wave and the second term corresponds to the wave reflected from the pipe. As the pipe is located near the earth's surface we can estimate that $e^{-ik_3z} \approx 1$ which is much greater than $|k_3R|$. Hence the secondary magnetic field in the H-polarization can be neglected, and taking the earth's surface into account obviously does not affect much.

Currents in the earth flow perpendicularly to the pipe. Because the diameter of the pipe is small currents "do not have any use" of flowing along the pipe about a distance of one meter. Thus the current in the pipe remains small.

2.2 E-polarization

2.2.1 Parallel current

The above results concerning H-polarization are applicable with slight changes when studying the E-polarization. We define the abbreviations

$$
\begin{aligned}
&\mu_{ij} = \mu_i/\mu_j, \quad k_{ij} = k_i/k_j, \\
&A_1 = J_m(k_1R_1), \quad A_2 = J_m(k_2R_1), \quad A_3 = N_m(k_2R_1), \\
&B_1 = J_m'(k_1R_1), \quad B_2 = \mu_{12}k_{21}J_m'(k_2R_1), \quad B_3 = \mu_{12}k_{21}N_m'(k_2R_1), \\
&C_2 = J_m(k_2R_2), \quad C_3 = N_m(k_2R_2), \quad C_4 = H_m^{(2)}(k_3R_2), \\
&D_2 = J_m'(k_2R_2), \quad D_3 = N_m'(k_2R_2), \quad D_4 = \mu_{23}k_{32}H_m^{(2)\prime}(k_3R_2), \\
&F_1 = (-1)^m J_m(k_3R_2)E(\omega), \quad F_2 = (-1)^m \mu_{23}k_{32}J_m'(k_3R_2)E(\omega), \\
&G = (A_1B_3-A_3B_1)(C_2D_4-C_4D_2) + (A_2B_1-A_1B_2)(C_3D_4-C_4D_3).
\end{aligned}
\tag{22}
$$

The fields of the E-polarization can now be written making the following changes in the H-polarization (equations (4)-(12)):

$$
B_x \to E_x, \; B(\omega) \to E(\omega); \; E_r \to B_r = -k^2E_r/\omega^2; \; E_\phi \to B_\phi = -k^2E_\phi/\omega^2 \tag{23}
$$

For example, $B_r = -k^2E_r/\omega^2$ means that if the radial electric field E_r of the H-polarization is multiplied by $-k^2/\omega^2$ we get B_r in the E-polarization. $E(\omega)$ is assumed to equal the variation field measured on the earth's surface.

We will calculate the parallel current in the pipe in the following cases: (i) a full non-insulated pipe, (ii) a full insulated pipe and (iii) a hollow non-insulated pipe.

Case (i) has also been studied by *Pirjola* (1976) who has obtained the same results as we here. After reasonable approximations (cf. sect. 2.1.2) we get by integrating σ_1E over the cross-section of the pipe ($\omega > 0$)

$$I_1 = 2\pi R\sqrt{\frac{\sigma_1}{\omega\mu_1}}\ |E(\omega)|\frac{1}{|\ J_o(k_1R)/J_1(k_1R) + \mu_3k_1R(\ln(k_3R))/\mu_1\ |}\ , \tag{24}$$

where the index 1 refers to the pipe and the index 3 to the earth. The radius of the pipe is R. During typical magnetic storms $\omega \sim 2\pi/60\ s^{-1}$ and $E\sim1$ V/km and thus from (24) $I_1 \sim 2\cdot10^3$ A (when $\mu_1 \geq \mu_o$). This current causes a large secondary magnetic field and the effect of the earth-air boundary should be taken into account.

The current I_n can also be calculated in a straightforward manner, and after some approximations we get

$$\frac{I_1}{I_2} = 1 + \frac{\dfrac{\mu_2 J_1(k_1R_1)}{\mu_3}\ \ln\dfrac{R_1}{R_2}}{\dfrac{\mu_1 J_o(k_1R_1)}{\mu_3 k_1 R_1} + J_1(k_1R_1)\ln(k_3 R_1)}\ . \tag{25}$$

Using values $T > 60$ s, $\mu_1 \geq \mu_o$ and the same other values as above we get $\mu_2/\mu_3 \approx 3$, $|\ln(R_1/R_2)| < 0.015$, $|\mu_1/(\mu_3k_1R_1)| > 5$, $|\ln(k_3R_1)| \approx 15$ and $|J_o(k_1R_1)/J_1(k_1R_1)| \approx 1$. Then the ratio of the currents is $1\text{-}3\cdot10^{-3} < |I_1/I_2| < 1+3\cdot10^{-3}$, i.e. a thin insulation does not affect much parallel currents. Evidently the same is true also for a hollow pipe.

In the case (iii) functions containing arguments k_2R_2 are approximated using the Taylor's series:

$$f(k_2R_2) \approx f(k_2R_1) + k_2\Delta R f'(k_2R_1) \tag{26}$$

where $\Delta R = R_2 - R_1$ is the thickness of the pipe ($|k_2\Delta R| \leq 0.1$ according to Table 2.1). The current is then

$$I_3 = 2\pi\sigma_2(R_2-R_1)E(\omega)/f(R_1,R_2) \tag{27}$$

where

$$f(R_1,R_2) = 1 + (\mu_3/\mu_2)k_2^2R_2(R_2-R_1)\ln(k_3R_2)\ . \tag{28}$$

The second term of the right-hand side of (28) is of the order of 0.02 so that it is neglected. The final result in the time domain is, as one could also directly guess,

$$I_3(t) = 2\pi R_2(R_2-R_1)\sigma_2|E(t)| \,. \tag{29}$$

If $E < 10$ V/km the current is less than 1000 A.

Evidently the corrosion protection system has no remarkable effect on parallel currents. The earthing resistance of a protection station is on the average 0.86 Ω while the average resistance of the pipe between two stations is 0.22 Ω (*Pirjola and Lehtinen*, 1985, Tables 3 and 4). So the current flows along the pipe which is the "easier" way. This can be deduced indirectly of the calculations of Pirjola and Lehtinen, too.

On the contrary to the H-polarization, the currents "has use" of flowing along the pipe which is a very good conductor of infinite length parallel to the electric field. The current in the pipe is much larger than currents in the earth. For example, if the electric field is 1 V/km and the earth's conductivity $10^{-3}\ \Omega^{-1}m^{-1}$ then the current in the earth across an area 10 km·100 km is 1000 A. The current along the pipeline can be as large.

2.2.2 Horizontal change in the earth's conductivity

We now study a horizontal change of the earth's conductivity in the E-polarization (Fig. 4). The insulation is neglected so that we will obtain upper estimates. We assume that there is a fault in the earth. We also consider a more realistic situation than before by taking the earth's surface explicitly into account. In the present situation the electric field has a vertical component, too, but it does not cause parallel currents. It is noteworthy that the asymptotic electric field far from the fault depends on the earth's conductivity (e.g. *d'Erceville and Kunetz*, 1961). On the other hand, the asymptotic magnetic field on the earth's surface does not in practice depend on the conductivity (cf. *Pirjola*, 1982, (2.47) and (2.48) where $k \gg \omega/c$). Strictly speaking, we are not now considering the same kind of E-polarization as above.

At a long distance from the fault formula (29) is applicable. Due to the lateral change a current $\Delta I = I_2 - I_1$ flows into or from the pipe. In the time domain

$$|\Delta I(t)| = 2\pi R_2(R_2-R_1)\sigma|E_2(t)-E_1(t)| \,. \tag{30}$$

To estimate $E(t)$ we use the plane wave model assuming the earth to be homogeneous (i.e. the effect of the pipe is neglected). Then $E(t)$ is proportional to $1/\sqrt{\sigma}$ where σ is the conductivity of the region under consideration (e.g. Pirjola, 1982, ch. 2). Thus from eq. (30)

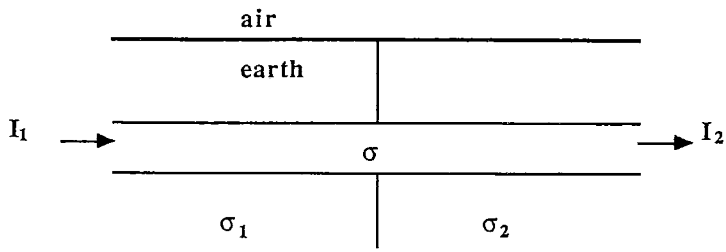

Fig. 4. Lateral change (fault) in the conductivity of the medium surrounding a hollow non-insulated pipe. Other electromagnetic properties are the same in regions 1 and 2.

$$|\Delta I(t)| = 2\pi R_2(R_2-R_1)\sigma|1-\sqrt{\sigma_1/\sigma_2}|\cdot|E_1(t)| \,. \tag{31}$$

We assume that $\sigma_1 < \sigma_2$ so that $|E_1(t)| > |E_2(t)|$. Using numerical values an upper estimate is obtained:

$$|\Delta I(t)| < 75\ A{\cdot}km/V{\cdot}|E_1(t)|. \tag{32}$$

So if $|E_1(t)| < 10$ V/km then $|\Delta I(t)| < 750$ A.

To calculate the current density flowing from the pipe we should know where the current flows out from the pipe. We estimate that the electromagnetic field changes significantly in a length scale determined by the skin depth of the earth ($\sqrt{2/(\omega\mu\sigma)}$), since in a homogeneous medium it is a practical length scale. So we assume that the length interval in which the current flows from the pipe is of the order of the skin depth.

If the period is 60 s and the earth's conductivity $10^{-4}\ldots10^{-3}\ \Omega^{-1}m^{-1}$ the skin depth is 120...400 km. If most of the current flows to the earth in a 400 km length the average current density is at most 1 mA/m^2. This is a very rough estimate since the length of the real pipe is usually less than 400 km.

The current density is not constant everywhere but it certainly has its largest value near the change of the conductivity. According to *d'Erceville and Kunetz* (1962) the horizontal electric field has a sharp discontinuity at the fault, and the flow into or out from the pipe could be concentrated near the fault. On the other hand, however, the existence of the high-conducting pipe may smooth the discontinuity. So it is very difficult to estimate the correct length scale, and an exact determination of the outflowing current density would require further studies. The "adjustment distance" discussed by *Jones* (1983) plays here an important role. Unfortunately, however, Jones does not give any explicit expression to it applicable now.

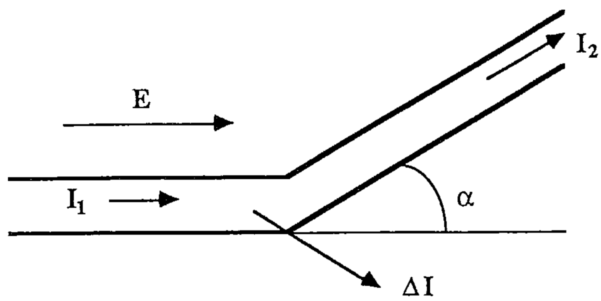

Fig. 5. Curve in the pipe. The electric field is assumed to be parallel to the part 1.

2.2.3 Effect of curves in the pipe

The effect of curves in the pipe are estimated in a similar way as the effect of the lateral change in the conductivity. Using symbols defined in Fig. 5 we get

$$\Delta I = (1 - \cos\alpha) I_1 . \tag{33}$$

Let us assume that current flows from the pipe in a length of the order of 100 km. If $|\alpha| \leq 10°$ and $|I_1| \leq 100$ A ($E < 1$ V/km) an estimate for the mean current density is at most 10 $\mu A/m^2$. There are also currents associated with the H-polarization which can increase the current between the pipe and the earth. However, the current density in the H-polarization is less than about 2 $\mu A/m^2$ when E < 1 V/km.

2.2.4 Effect of the earth's surface

Because in the E-polarization the parallel current in the pipe can be very large it is an important secondary source. The vicinity of the earth's surface can then have a significant effect. For example *Mahmoud et al.* (1981) and *Ogunade* (1986) have studied such a situation, but their results are quite complicated and difficult to apply to the present study.

We are going to study a simple case described in Fig. 6. The primary field propagating to the negative *z*-direction is a plane wave. The pipeline is replaced by a line current whose distance from the earth's surface is the same as that of the axis of the real pipe. Application of formulas given by *Pirjola* (1982, section 3.2) gives the electric field in the air:

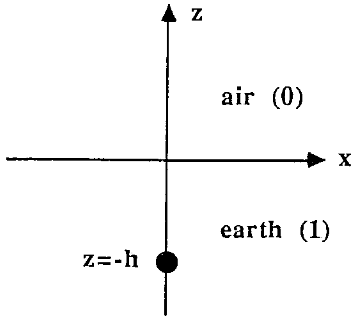

Fig. 6. A pipeline is approximated as a line current located at a depth h in the earth. Note that the coordinate system is not the same as previously.

$$E_{yo}(r,\omega) = \frac{\omega B(\omega)}{k_o} e^{ik_o z} + \int_{-\infty}^{\infty} db\, e^{ibx} G_o(b) e^{-K_o z} \tag{34}$$

where the first term is the primary field and the second is the secondary field caused by the earth and the pipe and

$$K_j = \sqrt{b^2 - k_j^2}\,,\ -\pi/2 < \arg K_j \leq \pi/2 \tag{35}$$

$$G_o(b) = -\frac{i\omega\mu_o I e^{-K_1 h}}{2\pi(K_o+K_1)} + \frac{\omega(1-k_1/k_o)B(\omega)}{k_o+k_1}\,\delta(b) \tag{36}$$

$B(\omega)$ is the amplitude of the primary magnetic field. In the previous text, it was assumed to be the total magnetic field on the earth's surface. In the plane wave model the primary and secondary magnetic fields are practically equal so that the total field is twice the primary field. As we do not take the earth's surface explicitly into account in other sections, it is evidently more physical to assume that $B(\omega)$ is the total field on the earth's surface.

In the static limit we can use the Biot and Savart law to estimate the secondary magnetic field caused by the pipe. Using values I=100 A, h=1 m we get for the secondary field the value 20000 nT which is much larger than the geomagnetic variation field without the cylinder.

However, the electric field is more important. As we will see later it is not affected as much as the magnetic field by the earth's surface. Without the earth's surface the current parallel to the pipe is according to equation (29)

$$I(t) = 2\pi R_2 (R_2 - R_1)\, \sigma_2 E(t) \tag{37}$$

where $E(t)$ is assumed to equal the electric field on the earth's surface.

To check formula (37) we use the Alaska pipeline studied by *Campbell* (1980). It has an average radius R_1=61 cm and a thickness 1.3 cm so that equation (37) gives $I(t)$ = 200 Akm/V·$E(t)$. According to *Campbell* (1980, Fig. 4) the experimental value at one site is 405 Akm/V. So equation (37) gives at least the correct order.

Additionally, as $|E|<1$ V/km, excluding the largest storms, the currents in the pipe are typically less than 200 A. This is in agreement with *Campbell'S* (1980) Figures 4 and 7. In these estimations we have not taken into account that the Alaska pipeline has earthings and that it is partially located above the earth's surface.

Consequently, when estimating the order of parallel currents we can omit the earth's surface. To understand this we consider the electric field at the origin. Using the fact that $|k_0| << |k_1|$ we can approximate (cf. *Pirjola*, 1982, section 3.3)

$$E_{yo}(0,\omega) \approx \frac{2\omega B(\omega)}{k_1} - \frac{i\omega\mu_o I}{\pi} \int_0^\infty db \frac{e^{-h\sqrt{b^2 + i\omega\mu_o\sigma_1}}}{b + \sqrt{b^2 + i\omega\mu_o\sigma_1}} \tag{38}$$

If the secondary field caused by the pipe (the integral) is at most as large as the field without the pipe we can neglect the earth's surface.

The physical secondary field of the pipe is

$$|E_{ysec}| = \frac{\omega\mu_o I}{\pi} \left| \sin\omega t \cdot \int_0^\infty db\, \mathrm{Re}F(b) + \cos\omega t \cdot \int_0^\infty db\, \mathrm{Im}F(b) \right| \tag{39}$$

where $F(b)$ is the integrand in equation (38). Using graphical integration we get an upper limit $|E_{ysec}| \le 20\omega\mu_0 I/\pi$. If $T \ge 60$ s then $|E_{ysec}| \le 8.4\cdot10^{-4}$ V/Akm·I; if $I \le 100$ A then $|E_{ysec}| \le 0.1$ V/km. Referring to the Alaska pipeline (*Campbell*, 1980, Fig. 4) we see that the secondary part is less than a half of the total field: a current of 100 amperes is possible if the electric field is larger than 0.2 V/km.

Consequently, if we are interested in currents flowing in the pipeline we can forget the earth's surface. On the other hand, if we are interested in the magnetic field we cannot neglect the surface.

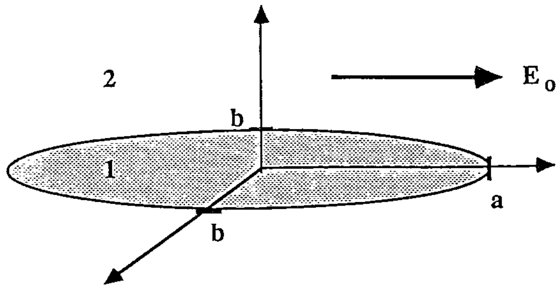

Fig. 7. Spheroid in an external constant electric field.

2.2.5 Effect of the finite length of the pipe

Kaufman and Keller (1981, section 9.3) have studied a prolate spheroid with a homogeneous conductivity in an external constant electric field E_0 (Fig. 7) parallel to the spheroid. When approximating a long pipe by a spheroid we set $a >> b$. In the case of the gas pipeline $\sigma_1 >> \sigma_2$, too, so that

$$\frac{E_1}{E_o} = (1 + \frac{\sigma_1 b^2}{\sigma_2 a^2}(\ln\frac{2a}{b} - 1))^{-1} \qquad (40)$$

where E_1 is the field inside the spheroid. Using values a=100 km, 20 cm $\leq b \leq$ 35 cm, $\sigma_1 = 4 \cdot 10^6\ \Omega^{-1}\mathrm{m}^{-1}$ and $10^{-4}\ \Omega^{-1}\mathrm{m}^{-1} \leq \sigma_2 \leq 10^{-3}\ \Omega^{-1}\mathrm{m}^{-1}$ we get $0.14 \leq E_1/E_o \leq 0.83$. The ratio (40) tends to unity when a increases. As it is quite near to unity, assuming the pipe to have an infinite length is not obviously too a poor approximation when estimating the orders of the currents.

Qualitatively, in the E-polarization the primary electric field "sees" the finite length of the pipe as a significant disturbance because its length is of the same order as the wave length of the field ($2\pi/|k|$). In the H-polarization the wave length of the primary field is much longer than the diameter of the pipe. Hence the assumption of the infinite length is evidently a better approximation in the H-polarization than in the E-polarization.

Because real pipes are finite the parallel currents are surely smaller than in an infinitely long pipe studied in this paper. On the other hand, near the ends of a finite pipe the current density between the earth and pipe can be very large. Observed currents in the Alaska pipeline can be hundreds of amperes (e.g. *Campbell*, 1980). The Finnish gas pipelines are not as long, but evidently currents of several amperes are possible here, too. For example, if a current I=1 A flows into a pipe of a length d=100 km and a radius

R=0.3 m the average current density from the pipe into the earth is $I/(\pi Rd) \approx 11\ \mu A/m^2$.

2.2.6 Single holes in the insulation of the pipe

To study a realistic situation the pipe is assumed to have a finite length and a hole in both ends of its insulation. If the insulation is otherwise perfect (i.e. it has an infinite resistivity) the earthing current is

$$I_e = V_0/2r_e \tag{41}$$

where V_0 is the geomagnetically induced voltage between the ends, and the resistance of the pipe is neglected because it is small compared to r_e (see below). To estimate the earthing resistance r_e, the hole is modelled by a spherical electrode buried in the homogeneous earth:

$$r_e = 1/(2\pi\sigma a) \tag{42}$$

where σ is the earth's conductivity and a is the radius of the electrode (*Sunde*, 1949, sect. 2). If $\sigma = 10^{-3}\ \Omega^{-1}m^{-1}$ and a=1 cm we get $r_e \sim 10^4\ \Omega$. As V_0 varies between 1 and 100 V then $I_e \sim 10^{-2}...10^{-4}$ A. The current density in the holes can thus be even 1...100 A/m^2. This value is very large compared to the other calculations. However, the protection current obviously tend to flow into the pipe through these holes, too. In any case, it is possible that the protection current density is not large enough everywhere. Because the insulation was assumed to be ideal the above estimation certainly gives an upper limit for the current density. Additional studies would clearly be required to obtain an accurate estimate for the real case, which may be much smaller.

In the H-polarization the current does not remarkably tend to flow to the pipe (see the end of section 2.1.4). Consequently, the currents through the holes are then evidently smaller than in the E-polarization.

3. *Statistics of geomagnetically induced electric fields and GICs*

3.1 Geomagnetically induced electric field

Geomagnetically induced electric fields on the earth's surface can be calculated assuming that the earth is homogeneous and the primary field is a vertically propagating plane wave (e.g. *Pirjola*, 1982; *Viljanen and Pirjola*, 1989). In Finland it is reasonable to use magnetic data from the Nurmijärvi Geophysical Observatory as it is located near the pipeline. The data consist of one-minute mean values.

The sign of the electric field is positive half a time and negative half a time on the average. According to the measurements of geomagnetically induced currents at the Huutokoski transformer in eastern Finland (*Pirjola*, 1983), GIC has sometimes kept its sign over one hour. So the sign of the electric field can behave in the same way, too.

The east component of the electric field (E_y) is

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_o\sigma}} \int_{-\infty}^{t} \frac{X'(u)}{\sqrt{t-u}}\, du \tag{43}$$

where σ is the earth's conductivity and X' the time derivative of the north component of the magnetic field (similarly for E_x and $-Y'$). To calculate the electric field at time t we have integrated the magnetic field 12 hours backwards.

The earth's (effective) conductivity is allowed to vary with the geomagnetic K-index. In this way we can get reliable statistics of GICs in the Finnish power system which is obviously true for the pipeline system, too. An explanation for this un-geophysical behaviour of the conductivity is given in *Viljanen and Pirjola* (1989, p. 418). However, their interpretation is just qualitative and should be improved by studying e.g. sheet currents with various widths.

Statistics of the horizontal geoelectric field is given in tables 2 and 4. In table 2, statistics is given according to the K-index of Nurmijärvi, and in table 4 the annual distribution calculated with the help of table 3 is shown. E_y is larger on the average as the variations of X are usually larger than those of Y. This is due to the fact that the ionospheric current systems tend to have an east-west direction.

Table 2. Statistics of the north (x) and east (y) components of the geoelectric field (absolute values). One percent corresponds 1.8 minutes (1 min 48 sec) when considering a three-hour time period for which the K-index is determined.

	K									
E_x (V/km)	0	1	2	3	4	5	6	7	8	9
0.0-0.1	100(%)	100	98.4	97.9	84.2	78.4	81.1	68.7	80.5	62.8
-0.2			1.0	2.2	13.9	16.7	15.2	21.2	12.8	18.8
-0.3			0.6		1.6	3.6	3.1	6.7	4.5	7.5
-0.4					0.3	1.1	0.5	1.8	1.3	4.0
-0.5					0.1	0.2	0.1	0.9	0.5	1.9
-0.6						0.03	0.03	0.5	0.2	1.9
-0.7								0.1	0.1	0.9
-0.8								0.1	0.1	0.8
-0.9										0.4
-1.0										0.3
-1.1										0.1
-1.2										0.1
1.2-2.9										0.5

	K									
E_y (V/km)	0	1	2	3	4	5	6	7	8	9
0.0-0.1	100	100	98.3	96.2	86.4	70.3	59.2	49.4	54.3	33.4
-0.2			1.5	3.6	12.3	22.6	24.4	27.5	23.9	24.1
-0.3			0.1	0.2	1.3	5.3	10.7	12.2	8.5	15.0
-0.4						1.1	3.9	5.7	4.9	8.4
-0.5						0.4	1.2	3.0	3.8	6.3
-0.6						0.2	0.4	1.0	1.8	3.3
-0.7						0.1	0.2	0.7	1.3	2.2
-0.8						0.1	0.1	0.3	0.6	1.8
-0.9							0.03	0.1	0.5	1.3
-1.0								0.03	0.4	0.8
-1.1								0.03		1.1
-1.2									0.1	0.4
-1.3										0.1
-1.4										0.3
-1.5										0.3
-1.6										0.1
-1.7										0.1
1.7-7.7										1.0

Table 3. Statistics of the K-index at the Nurmijärvi Geophysical Observatory (years 1976-1986). One percent corresponds 88 hours a year.

K	0	1	2	3	4	5	6	7	8	9
number of occurrence	317	753	863	586	251	90	38	13	6	3
%	10.9	25.8	29.6	20.1	8.6	3.1	1.3	0.4	0.2	0.1

Table 4. Statistics of the geoelectric field based on magnetic recordings at the Nurmijärvi Geophysical Observatory. If the electric field is larger than 0.8 V/km the percentage is less than 0.005.

E (V/km)	0.0-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8
E_x	96.3	3.1	0.6	0.1	0.02	0.01		
E_y	95.3	3.9	0.7	0.2	0.1	0.03	0.01	0.01

The magnetic data used for table 2 consist three-hour time periods from the year 1982 having a K-distribution as follows:

K	0	1	2	3	4	5	6	7	8	9
number of occurrence	-	1	8	15	12	18	22	17	9	10
total 112										

There are no events of K=0 but the "guesses" in the statistics are certainly correct.

3.2 Summary of the occurrence of GICs in an ideal pipeline system

The radial current density is according to equation (17) at most $|j| = 2\sigma|E(t)|$ where σ is the earth's conductivity. In Finland we can assume $\sigma < 10^{-3}\ \Omega^{-1}\text{m}^{-1}$. Then $|j| < 0.2\ \mu\text{A/m}^2$ with a probability 95% and $|j| < 1\ \mu\text{A/m}^2$ at least with a 99.9% probability referring to table 4. Due to the insulation (section 2.1.3) 1 $\mu\text{A/m}^2$ is evidently an absolute upper limit in the case of perfect insulation.

The parallel current in a hollow infinite pipe is of the order of $|I| < 100$ Akm/V$\cdot|E(t)|$ (equation (29)). Then $|I| < 10$ A with a probability 95% and $|I| < 100$ A at least with a probability 99.9%. If there are curves (section 2.2.3) the radial current density near them is over 1 $\mu\text{A/m}^2$ with a probability 5% and over 5 $\mu\text{A/m}^2$ with a probability 0.1%.

It must be strongly stressed that the above estimations concern ideal (or nearly ideal) situations. Some special cases important in practice are discussed below.

4. *Conclusions and discussion*

In the H-polarization, the current only has a radial component. If the pipe is not insulated the radial current density is less than 0.2 $\mu A/m^2$ with a probability 95 %. The largest possible value during the most intense magnetic storms can be 20 $\mu A/m^2$. So these current densities are nearly always less than the corrosion protection current densities. If the pipe has an unbroken insulation these values decrease by a factor of 10. If the insulation is damaged the currents are concentrated to such areas (section 2.2.6).

In the E-polarization, the current is parallel to the pipe and can be even of the order of 1000 A. If the conductivity of the surrounding medium is not the same everywhere a part of the current flows away from (or into) the pipe. Applying a simple estimation, the current density can then be of the order of 1 mA/m^2. If the pipe is not straight the current can flow to the earth near curves. The radial current density can then be over 10 $\mu A/m^2$ (section 2.2.3). According to a rough estimation, the current density through single holes in an otherwise perfect insulation can be even more than 1 A/m^2. Anyway, the protection currents also tend to flow through these holes so that they eliminate at least partly the harmful currents.

The basic model does not take the earth's surface into account. It can be shown that its effect can be neglected in the H-polarization (section 2.1.4). In the E-polarization there is a clear effect but the orders of magnitude are obviously obtained correctly (section 2.2.4). Consequently, in more accurate calculations the earth's surface should be taken into account. The assumption of an infinite length of the pipeline is shown to be reasonable at least in the H-polarization (section 2.2.5). In the E-polarization the parallel currents in a finite pipe are certainly smaller than has been estimated in this paper. On the other hand, the outflowing current density may be clearly larger than the average protection current (section 2.2.5).

The corrosion protection system is neglected. So the results are applicable in the worst situation when the protection system does not work. It is evident that the protection system and possible holes in the insulation are the most important aspects to be investigated in future work. To study the details more accurately, we should make better assumptions of the real geometry of the pipeline system, the protection system, the primary disturbances, the earth's conductivity and single holes in the insulation. We should also have measured data of geomagnetically induced currents or voltages from different parts of the pipeline system. Especially the study of E-polarization should be developed further.

Compared to the Finnish 400 kV power system, the pipeline system lies in quite a small area. So we can use simple models for the geomagnetic variation and the earth's conductivity when studying the pipeline system. The power grid, on other hand, covers southern and central Finland and is greatly affected by auroral currents. In the large area the earth's conductivity varies significantly, too. Thus we should use quite complex geophysical models to calculate the geoelectric field for the power system. The main difficulty in the pipeline system is its complex structure but the power system is in this sense simpler: after the geoelectric field is somehow determined, GICs are easily calculated.

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