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Recordings of Geomagnetically Induced Currents in the Finnish Natural Gas Pipeline -- Summary of an 11-year Period

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Abstract

Geomagnetically induced currents (GIC) in the Finnish natural gas pipeline at Mäntsälä in southern Finland have been measured since November 1998. The time series covers now approximately one sunspot cycle, including the highly active year 2003 and, on the other hand, the exceptionally quiet year 2009. This short report provides an overview of GIC statistics during the 11-year period. The most active period was 29–31 October 2003 with the maximum GIC of 57 A, whereas the deepest solar cycle minimum in 2007–2009 was very quiet with the maximum GIC of only 4.7 A.

Key words: geomagnetic activity, geomagnetic induction, GIC, space weather

1. Introduction

Geomagnetically induced currents (GIC) belong to space weather phenomena, which may have adverse effects on technological systems (e.g., *Boteler et al.* (1998); *National Research Council* (2008)). Today GIC concern mostly power transmission grids (e.g., *Kappenman* (2005); *Molinski* (2002)) and gas or oil pipelines (e.g., *Campbell* (1980); *Gummow* (2002); *Hejda* and *Bochnicek* (2005)), but there is also some evidence about problems in railways (*Kasinski*, 2007).

This short report gives an overview of the recordings of GIC in the Finnish natural gas pipeline since November 1998. Since the measurement technique as well as modelling of GIC in a buried pipeline has been extensively described in previous papers (*Pulkkinen*, 2001a,b), we will only very briefly discuss these basics here. The main purpose of this paper is to publish, for the first time, statistics of GIC during an 11-year period approximately corresponding to one sunspot cycle.

2. *GIC statistics*

2.1 *Background*

The measurement of GIC is based on the use of two magnetometers, one just above the pipe and another at the Nurmijärvi Geophysical Observatory about 40 km southwestward of Mäntsälä (*Pulkkinen et al.* (2001b); see also Fig. 1). The Nurmijärvi recording describes the natural variation of the geomagnetic field, which is subtracted from the variation measured at Mäntsälä. The difference is then due to GIC flowing along the pipe.

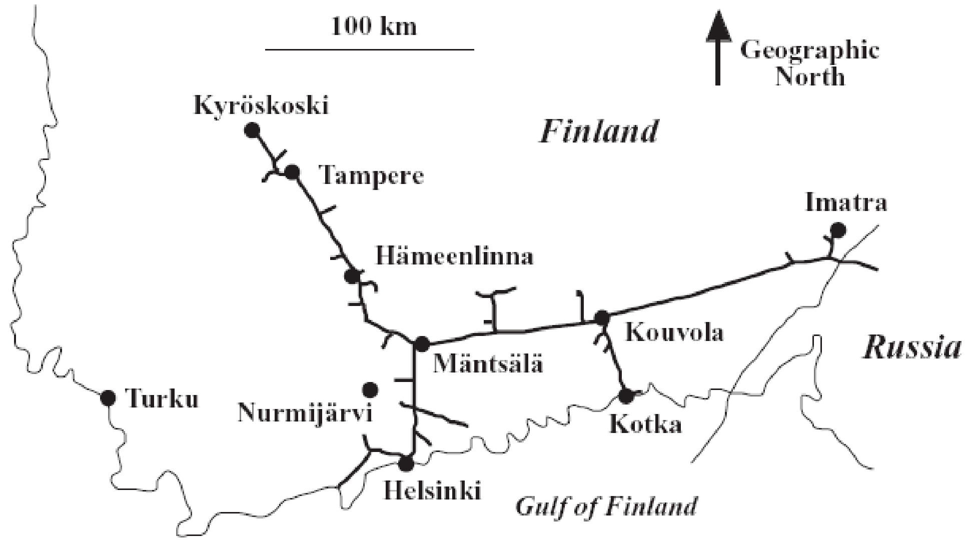

Fig. 1. Finnish natural gas pipeline. The GIC recording site is at Mäntsälä, and a geomagnetic observatory is located at Nurmijärvi. The map presents the situation in the beginning of the GIC measurements in 1998, after which there have been some additional constructions like new parallel sections and short branches. The pipeline system continues to Russia up to Siberia.

GIC are driven by the horizontal geoelectric field associated with temporal variations of the magnetic field. The electric field is seldom measured directly, but it can be calculated by using geomagnetic recordings and a model of the earth's conductivity. Knowing the geoelectric field and the geometry of the pipe together with its electromagnetic properties, GIC can be then determined as shown by *Pulkkinen et al.* (2001a), and further applied by *Viljanen et al.* (2006). *Pulkkinen et al.* (2007) present additional refinements of the modelling technique.

2.2 *Description of the data*

Recordings of GIC at the Mäntsälä compressor station were started on 19 November 1998. The measuring site remained the same until 18 May 2005, when a shift of a couple of hundred metres was necessary due to reconstructions at the station. At the first recording site, the pipe section was quite exactly parallel to the geographic east-west direction. At the present place, the pipe section is tilted about 30 degrees counterclockwise from the eastward direction. However, model calculations show that the GIC time series is still quite uniform, although GIC at the present site are about 15 % larger than previously.

GIC values are saved as 10 s averages, and magnetic field data at the same sampling rate are available from Nurmijärvi. The recording system is automatic, and on-site visits are made only when needed for maintenance. The GIC dataset has some gaps, but the number of missing highly-active periods is fortunately small. We can also fill such gaps by modelled values as will be demonstrated in the following section. The data quality has occasionally suffered from unidentified external (probably man-made) disturbances, which cause noise up to about 1 A. However, during magnetic storms, GIC can reach even several tens of amperes, which clearly exceeds the noise level. As follows from Faraday's law of induction, the time derivative of the (horizontal) magnetic field provides a proxy of the induced electric field driving the current in the pipe. An example of the recorded GIC is shown in Fig. 2. Although the amplitude of the current is rather small, this event is an especially elegant demonstration of geomagnetic induction. A practical rule of thumb applicable at this site is that GIC follows the negative of dX/dt at Nurmijärvi (time derivative of the northward magnetic field), which in turn is a proxy for the eastward electric field. As a side note we remark, that in some special geological conditions elsewhere in the world, GIC may follow more closely the field variation B instead of its time derivative (*Watari et al.*, 2009). However, the situation illustrated in Fig. 2 seems to be much more common.

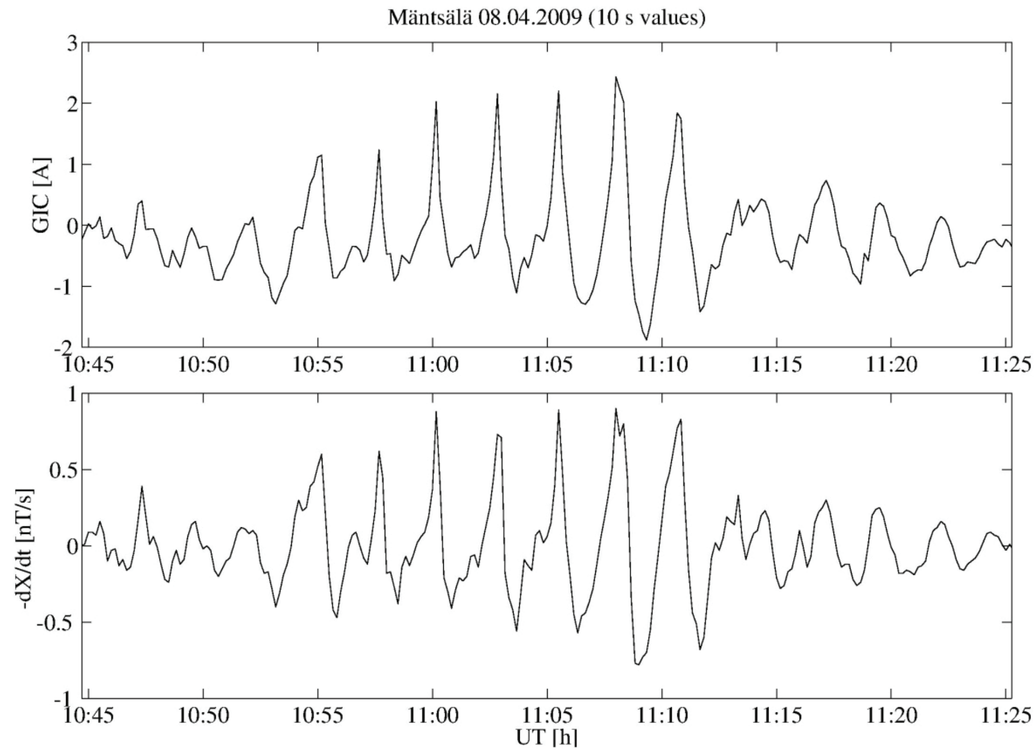

Fig. 2. GIC at Mäntsälä and the time derivative of the northward magnetic field (*dX/dt*) at Nurmijärvi on 8 April 2009. Note that actually −*dX/dt* is plotted to emphasise its similarity to GIC. Positive GIC flows eastward from Mäntsälä.

Quick-look plots showing GIC and the time derivative of the magnetic field at Nurmijärvi are available at the website http://space.fmi.fi/gic/gicdata/gasum index.html. The Finnish Meteorological Institute operates a nowcasting service GIC Now! (*Viljanen et al*., 2006), which is available at http://aurora.fmi.fi/gic_service/.

2.3 Statistics of GIC

Concerning the effects of GIC on technological conductor systems, there are two simple measures to characterise the daily activity level. The maximum GIC is an evident indicator, which is especially relevant to power systems being prone to immediate effects due to large GIC. On the other hand, possible effects due to an increased corrosion in pipelines are cumulative rather than caused by single short-term GIC peaks. Then a better activity measure is obviously the number of GIC values exceeding a given limit. However, single GIC peaks should be identified during control measurements of the corrosion protection system. In practice, such surveys should not be carried out during geomagnetically active times.

We will use two standard indices of geomagnetic activity: K and A_k. The K index is a 3-hour quasi-logarithmic local indicator of the geomagnetic activity relative to an assumed quiet-day curve for the recording site. It measures the deviation of the more disturbed horizontal component on the scale from 0 to 9 (*Rangarayan*, 1989). The A_k index (from 0 to 400) is the mean value of the equivalent amplitudes derived from the eight K indices of a day. We define a magnetic storm as a day when the A_k index at Nurmijärvi is at least 30. An overview of geomagnetic and GIC activity in 1996–2009 is shown in Fig. 3. Most of the storms occurred around or after the sunspot maximum in 2000. In 2007–2008, there were only four stormy days, during which A_k was just slightly above 30. There were no storms at all in 2009. As Fig. 3 shows, the occurrence of large GIC days, as defined by the daily maximum, follows that of magnetic storms.

The largest GIC values per year are listed in Table 1. The very low activity in 2007–2009 is prominent. We have excluded 1998, since there are data of only about 1.5 months of the rather quiet period in the end of the year. The largest values measured then was 4.8 A.

Table 1. The largest GIC per year at Mäntsälä.

year	1999	2000	2001	2002	2003	2004
GIC (A)	13.0	30.1	32.0	28.1	57.0	42.8
year	2005	2006	2007	2008	2009	
GIC (A)	27.5	14.2	4.7	4.7	2.8	

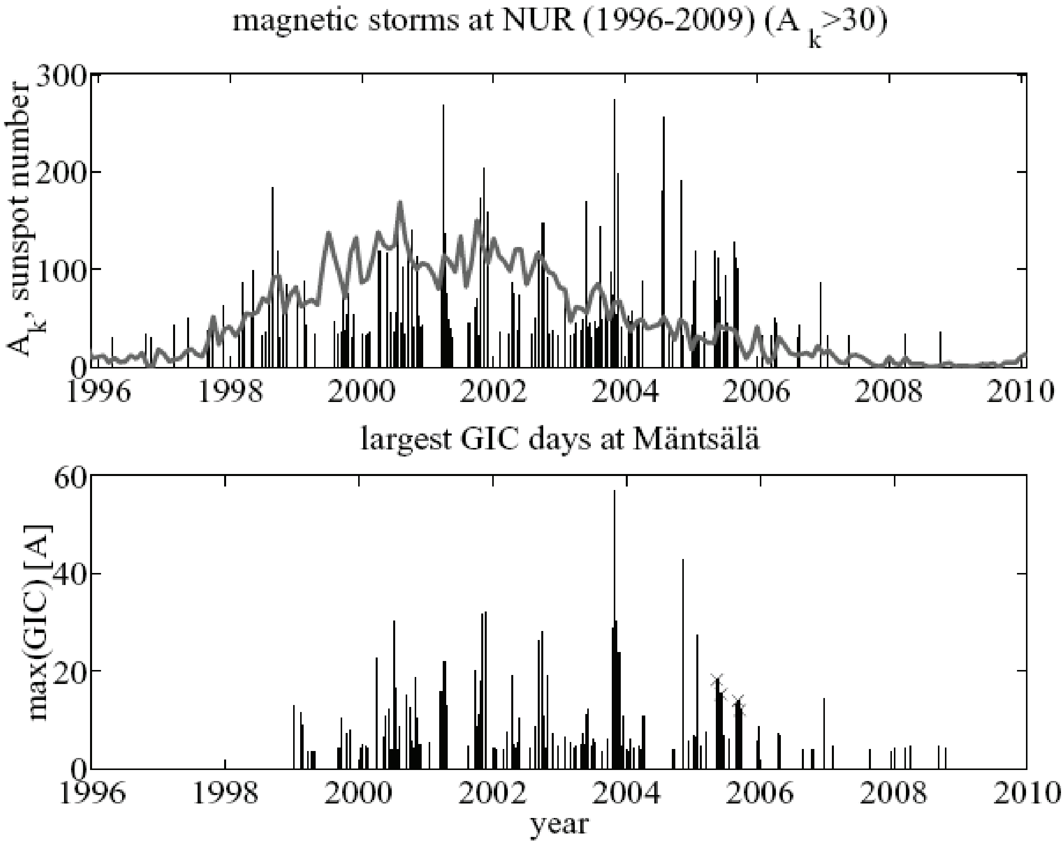

Fig. 3. Upper panel: Monthly sunspot number (uniform grey curve) and the Nurmijärvi A_k index (bars) when exceeding 30, classified as a stormy day. There were 222 stormy days at Nurmijärvi in 1999–2009. Lower panel: the 222 largest GIC days in 1999–2009 according to the daily maximum shown as bars. See the text concerning missing GIC data of four stormy days in 2005. The modelled maximum GIC is shown for these events marked by a cross at the top of each bar.

We present two lists of large GIC days in Tables 2–3. Table 2 gives the ranking list of the largest daily values. The A_k and K indices from Nurmijärvi give a reference based on standard indices. We also present the number of large time derivatives of the horizontal magnetic field vector ($d\mathbf{H}/dt$) on the particular day. Table 3 lists the days with the largest number of GIC values exceeding 5 A. We note that only the absolute value of GIC is significant in this context.

Table 2 shows that the largest GIC values occur typically during very disturbed magnetic periods as defined by $K = 9$, with only two exceptions. All days in Table 2 occur around or after the sunspot maximum in 2000. The ”Halloween” storm on 29–31 October 2003 is clearly the most significant event, and 7–9 November 2004 is another prominent sequence. The list in Table 2 might be a little different if there had been GIC recordings already since the sunspot minimum in 1996, because there were some major storms especially earlier in 1998.

Table 2. The largest GIC days at Mäntsälä in 1998–2009 according to the daily 10-s maximum (in amperes). A_k is the daily magnetic activity index at Nurmijärvi, and K is the 3-hour index at the time of the maximum GIC. The last column gives the number of 10-s time derivatives of the horizontal magnetic field vector ($|d\mathbf{H}/dt|$) exceeding 1 nT/s at Nurmijärvi.

rank	UT day	max(|GIC|)	A_k	K	#($\|d\mathbf{H}/dt\|$)
01.	20031029	57.0	274	9	4094
02.	20031030	48.8	224	9	2039
03.	20041109	42.8	189	9	946
04.	20041107	34.8	92	9	412
05.	20011124	32.0	158	8	1326
06.	20011106	31.6	203	9	1045
07.	20031031	30.3	151	9	2337
08.	20000715	30.1	157	9	1195
09.	20041108	29.1	191	9	1631
10.	20031014	28.7	97	9	124
11.	20021001	28.1	147	9	560
12.	20050121	27.5	118	9	1039
13.	20020907	26.4	118	9	316
14.	20020908	24.5	67	9	213
15.	20031120	23.8	198	9	1142
16.	20000406	22.7	119	9	618
17.	20010411	21.8	137	9	620
18.	20010925	20.3	60	9	187
19.	20021024	19.0	91	9	109
20.	20020417	19.0	86	6	84

Sorting GIC storms according to the number of large daily values (Table 3) does not much change the general picture. The daily A_k index seems to be quite a good proxy for this kind of GIC activity, although there is no direct relationship. Now, 29 October 2003 is even more striking than in Table 2. Again, the stormiest days occur in 2000 or later. There is also one major event in December 2006 when the sunspot number was already small. This gives just a reminder of the well-known fact that the plain sunspot number is not a good measure for magnetic or GIC activity (cf., for example, Fig. 5 in *Pulkkinen et al.* (2001c)).

There are a few magnetic storms with no GIC data due to technical problems at the measuring site, but this does not cause any prominent bias in statistics. The evidently largest missing events occurred on four days in May–September 2005, when A_k reached values of 100–119 at Nurmijärvi. According to model calculations, the maximum GIC during these days varied from 12.1 (11 Sep. 2005) to 18.3 A (8 May 2005). Even the largest one of these is slightly below the last top record in Table 2.

Table 3. The largest GIC days at Mäntsälä in 1998–2009 according to the daily number of 10-s GIC values exceeding 5 A. The other quantities are the as in Table 2.

rank	UT day	#(|GIC|)	A_k	#(|$d\mathbf{H}/dt$|)
01.	20031029	1934	274	4094
02.	20031030	878	224	2039
03.	20041108	833	191	1631
04.	20031031	829	151	2337
05.	20031120	667	198	1142
06.	20011106	579	203	1045
07.	20000715	549	157	1195
08.	20011124	515	158	1326
09.	20041109	450	189	946
10.	20010331	399	268	1545
11.	20021001	343	147	560
12.	20050121	326	118	1039
13.	20010411	304	137	620
14.	20041110	278	177	937
15.	20030529	276	170	608
16.	20061215	254	86	368
17.	20041107	205	92	412
18.	20011021	198	118	461
19.	20000917	168	83	465
20.	20000918	164	116	1026

3. *Conclusions*

The 11-year recording of GIC in the Finnish natural gas pipeline provides the longest timeseries of such measurements according to our knowledge. The data provide a unique set for verifying theoretical models used for calculating GIC and pipe-to-soil voltages in pipelines. Thanks to these data, we have been able to prepare a reliable nowcast service based on real-time recordings of the geomagnetic field. Using a magnetometer in the GIC measurement is also technically convenient, since there is no need to interfere directly with the pipe. The same method is also applicable for recording GIC in a power transmission line as was done in Finland in 1991–92 (*Viljanen and Pirjola*, 1994).

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References

Boteler, D.H., R.J. Pirjola and H. Nevanlinna, 1998. The effects of geomagnetic disturbances on electrical systems at the earth's surface. *Adv. Space Res.*, **22**, 17–27.

Campbell, W.H., 1980. Observation of electric currents in the Alaska oil pipeline resulting from auroral electrojet current sources. *Geophys. J. R. Astron. Soc.*, **61**, 437–449.

Gummow, R.A., 2002. GIC effects on pipeline corrosion control systems. *J. Atmos. Sol.-Terr. Phys.*, **64**, 1755–1764.

Hejda, P. and J. Bochnicek, 2005. Geomagnetically induced pipe-to-soil voltages in the Czech oil pipelines during October-November 2003. *Ann. Geophys.*, **23**, 3089–3093, SRef-ID: 1432-0576/ag/2005-23-3089.

Kappenman, J.G., 2005. An overview of the impulsive geomagnetic field disturbances and power grid impacts associated with the violent Sun- Earth connection events of 29-31 October 2003 and a comparative evaluation with other contemporary storms. *Space Weather*, **3**, S08C01, doi:10.1029/2004SW000128.

Kasinski, V.V., N.G. Ptitsyna, N.N. Lyahov, M.I. Tyasto, G. Villoresi and N. Iucci, 2007. Effect of Geomagnetic Disturbances on the Operation of Railroad Automated Mechanisms and Telemechanics. *Geomagn. Aeron.*, **47**, 676–680.

Molinski, T.S., 2002: Why utilities respect geomagnetically induced currents. *J. Atmos. Sol.-Terr. Phys.*, **64**, 1765–1778.

National Research Council, 2008. Severe Space Weather Events – Understanding Societal and Economic Impacts: A Workshop Report.The National Academies Press, Washington, DC. Also available at http://www.nap.edu/catalog/12507.html

Pulkkinen, A., R. Pirjola, D. Boteler, A. Viljanen and I. Yegorov, 2001a. Modelling of space weather effects on pipelines. *J. Appl. Geophys.*, **48**, 233–256.

Pulkkinen, A., A. Viljanen, K. Pajunpää and R. Pirjola, 2001b. Recordings and occurrence of geomagnetically induced currents in the Finnish natural gas pipeline network. *J. Appl. Geophys.*, **48**, 219–231.

Pulkkinen, T.I., H. Nevanlinna, P.J. Pulkkinen and M. Lockwood, 2001c. The Sun-Earth connection in time scales from years to decades and centuries. *Space Sci. Rev.*, **95**, 625–637.

Pulkkinen, A., R. Pirjola and A. Viljanen, 2007. Determination of ground conductivity and system parameters for optimal modeling of geomagnetically induced current flow in technological systems. *Earth Planets Space*, **59**, 999–1006.

Rangarayan, G.K., 1989. *Indices of Geomagnetic Activity, in: Geomagnetism*, Volume 3 (ed. J.A. Jacobs), Academic Press, 323–384.

Viljanen, A. and R. Pirjola, 1994. Geomagnetically induced currents in the Finnish high-voltage power system – a geophysical review.*Surv. Geophys.*, **15**, 383–408.

Viljanen, A., A. Pulkkinen, R. Pirjola, K. Pajunpää, P. Posio and A. Koistinen, 2006. Recordings of geomagnetically induced currents and a nowcasting service of the Finnish natural gas pipeline system. *Space Weather*, **4**, S10004, doi:10.1029 /2006SW000234.

Watari, S., M. Kunitake, K. Kitamura, T. Hori, T. Kikuchi, K. Shiokawa, N. Nishitani, R. Kataoka, Y. Kamide, T. Aso, Y. Watanabe and Y. Tsuneta, 2009. Measure– ments of geomagnetically induced current in a power grid in Hokkaido. Japan, *Space Weather*, **7**, S03002, doi:10.1029/2008SW000417.