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1 Executive summary

When a coronal mass ejection (CME), a huge plasma cloud originating from the Sun, hits the Earth, it causes a space weather storm. Electrons in the Earth's magnetosphere cascade into the polar regions, creating currents that flow along the auroral oval. When these currents change in time an electric field will be induced in the ground. The electric field will act as a celestial battery driving currents in the ground and in man-made conductors such as communication cables, pipelines, electric power transmission grids and railway equipment. These currents, which thus constitute ground effects of space weather, are known as geomagnetically induced currents (GICs).

Normally a power system includes of Y-configurated transformers having the neutral point grounded and connected to 3-phase transmission lines in a network. When the AC supply is balanced and there are no geomagnetic disturbances the three phase currents add to zero in the neutral point of the transformer and no current is flowing to ground. GIC is, however, not balanced in the same way, and so it flows between the transmission lines and the ground through the transformer windings. This can cause severe problems to the transformers and the network. GICs have frequencies $\leq$ 1 Hz, which are very small compared to the 50 or 60 Hz AC in the power system. These currents can then be treated as near-DC. When geomagnetically induced currents flow through the transformer winding they will produce extra magnetisation and during the half-cycles when the AC is in the same direction the transformer may be saturated. The magnetic flux spreads out producing eddy currents that can cause hot spots which can damage the transformer. During the half-cycle saturation the magnetising current becomes distorted and increases significantly resulting in increased harmonics in the AC waveform. The enhanced content of harmonics can cause incorrect operation of protective relays, misoperation of equipment and may thus lead to disconnection of power lines. The reactive power demand is increased which, together with misoperation of protective relays, may cause a collapse of the entire system.

The history of GICs dates back about 150 years. The first observations were made in early telegraph devices, and later on in power systems. GICs have been recorded by the power industry during many years. The first documented case, occurred during a severe geomagnetic storm on Easter Sunday, March 24, 1940. On the US East coast many disturbances were noted. The most damaging GIC-event so far took place in March 1989. The entire province of Quebec experienced a blackout lasting about nine hours. A large transformer at a nuclear plant near the US east coast was damaged. On October 30, 2003, there was a power failure in Malmö in southern Sweden which caused an outage of 50000 customers lasting about 20-50min.

The goal of the project was to develop a forecast service to be used by electrical power companies to mitigate the effects of geomagnetically induced currents caused by the space weather. For this purpose Swedish power companies (ELFORSK, EON(Sydkraft) and Svenska Kraftnät) were identified as service users and who took active part in the project. The service developer and provider was the Swedish Institute of Space Physics in collaboration with the Finnish Meteorological Institute.

The project resulted in scientific articles, extended database, developed software, implemented web-based prototype service, and a cost-benefit analysis. The service was coordinated with the Space Weather European Network (SWENET). We delivered a real-time forecast/warning system and installed a monitoring magnetometer in the middle of the power grid considered. It was shown that the 10-min standard deviation GIC may be computed from a linear model using RMS $\Delta X$and ΔYat Brorfelde, Denmark and Uppsala, Sweden with a correlation of 0.926 ± 0.015. From recurrent neural network models, that are driven by the solar wind data, it was shown that the log RMS $\Delta X$and ΔYat the two locations may be predicted up to 30 min in advance with a correlation 0.78 ± 0.02 for both directions at BFE; 0.81 ± 0.02 and 0.80 ± 0.02 in the X- and Y-directions, respectively, at UPS. The most important inputs to the models are the 10-min averages of the solar wind magnetic field component B_z and velocity V, and the 10-min standard deviation of the proton number density σ_n. The average proton number density n had no influence. The predictions have been running on the web since the 1st of January 2004. The forecasts are also archived.

A COST Benefit Analysis was carried out by EFORSK. A warning and a monitoring system were recommended, based on the cost of effects of GICs and measures taken to mitigate the effects.

2 Definitions, acronyms and abbreviations

ACE Advanced Composition Explorer

CME Coronal Mass Ejection

ELFORSK Elforsk AB is owned jointly by Svensk Energi (Swedenergy) and Svenska Kraftnät (The Swedish National Grid). Its overall aim is to encourage and drive the industries joint research and development

ESA European Space Agency

FMI Finnish Meteorological Institute

GIC Geomagnetically Induced Current

IMAGE International Monitor for Auroral Geomagnetic Effects

IRF Swedish Institute of Space Physics

IRF-K Swedish Institute of Space Physics, Kiruna

IRF-L Swedish Institute of Space Physics, Lund

ISES International Space Environment Service

L1 Lagrangian point 1

OKG OKG AB (Oskarshamns Kraftgrupp AB) is a Swedish corporation who owns and operates three nuclear power reactors at Simpevarp near Oskarshamn, Sweden

RWC Regional Warning Center

SEC Space Environment Center

SOHO The Solar and Heliospheric Observatory

SWENET Space Weather European Network

URD User Requirements Document

WP Work package

A = Ampere

AE A geomagnetic index of the auroral electrojet

B = Magnetic flux density vector

$d\mathbf{B}/dt$ = time derivative of **B**

ΔH = Forward difference $\Delta H(t) = H(t+1) - H(t)$ of the magnetic field strength

Dst A measure of variation in the geomagnetic field due to the equatorial ring current

$\mathbf{E} = E_x e_x + E_y e_y$ horizontal electric field vector (x to the geographic north, y to the east)

Kp A 3-hourly planetary index of geomagnetic activity

kV = kilo Volt

MVAr = Mega Volt Ampere reactive

MW = Mega Watt

Ωm = Ohm-meter

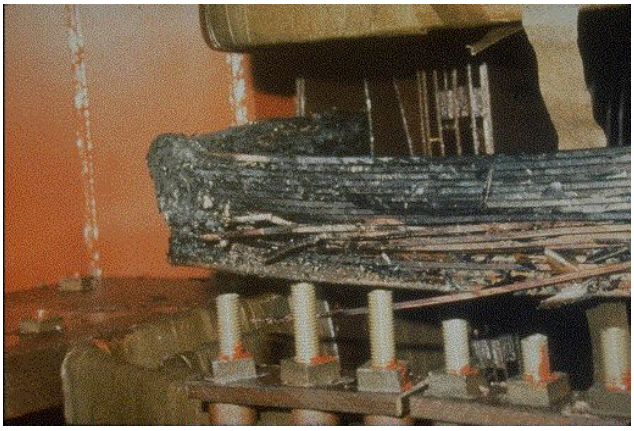

Figure 1: The figure shows a damaged 340 kV transformer at a nuclear plant on the Delaware River in New Jersey. The transformer was destroyed by the March 1989 magnetic storm.

3 Introduction

Space Weather refers to *Conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.* When a coronal mass ejection (CME), a huge plasma cloud, hits the Earth, electrons in the Earth's magnetosphere cascade into the polar regions, creating currents that flow along the auroral oval. The magnetic field from these currents induces a geomagnetically induced current (GIC) that can damage transformers and shut down power grid systems. GICs have been recorded by the power industry during many years (Kappenman, 1996 and Lundstedt, 2006). The first documented case, occurred on Easter Sunday, March 24, 1940. On the US East coast many disturbances were noted on March 24, such as misoperating relays and increased consumption of reactive power. A severe geomagnetic storm was the cause and the Ap index reached 207. The most serious solar-terrestrial event took place in March 1989. The entire province of Quebec experienced a blackout lasting about nine hours. A large generator step-up transformer at a nuclear plant on the US east coast was damaged (Fig.1). Also in Sweden many effects were noted (Fig. 2). Seven 130 kV-lines tripped. Fire alarms went on. Large fluctuations in the power transmission were noted.

The solar wind is continuously measured by the ACE spacecraft. The solar wind passes ACE about one hour before it hits Earth. Around midnight on September 24, 1998, the solar wind magnetic field turned strongly southward (Fig. 3). At the same time, there was a sudden increase in the density and the solar wind velocity. This behaviour is typical for a fast

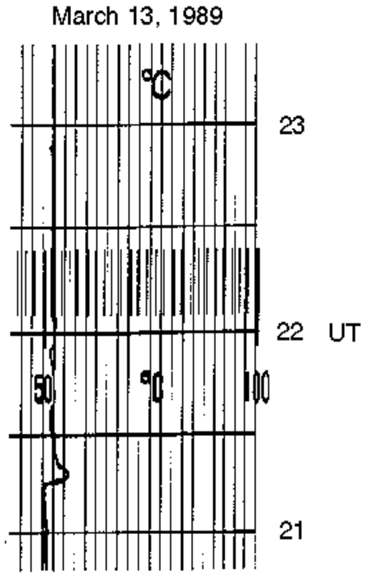

Figure 2: The figure shows a 5 C degree increase in the temperature of a rotor in a nuclear power plant in Sweden, caused by geomagnetically induced currents as a result of the severe geomagnetic storm of March 13, 1989.

CME.

In Figure 4 upper panel the resulting geomagnetically induced current of the CME as measured in the earthing of a transformer neutral in Sweden is shown. The transformer is connected to 400 kV grid in southern Sweden.The bottom panel of Figure 4 shows the geomagnetically induced pipe-to-soil voltage in a gas pipeline 300 km from the transformer.

Many other GIC events occurred during cycle 23 and the period of the GIC project. Particularly during the so called "Halloween events" in October 2003. Figure 5 shows how strong GICs (173 A) caused heating of the transformer oil in southern Sweden.

4 Main problems - proposed solution

Space weather causes geomagnetically induced currents. As mentioned in the introduction these GICs can damage transformers and shut down power grids. The power systems today are very large networks, consisting of thousands of substations, busses, transmission lines and transformers. Information about the system needs to be used as input to models which describe how such a system responds to a disturbance at the time of a space storm. The Swedish power industry has provided the information of the their power network (Fig. 6).

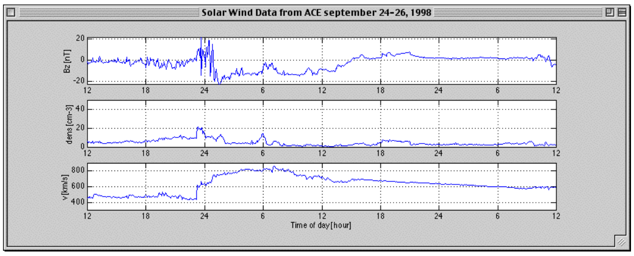

Figure 3: The figure shows the solar wind magnetic field z-component, the particle density, and the velocity for 2 days in September 1998.

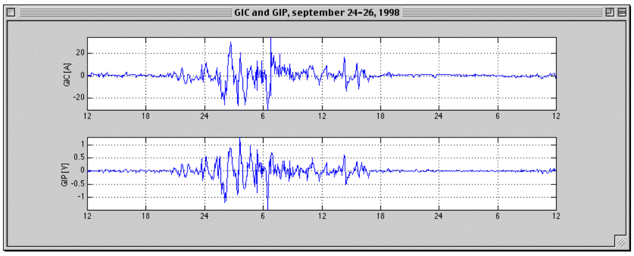

Figure 4: The geomagnetically induced current (GIC) and the geomagnetically induced pipe-to-soil voltage for the 2 days in September 1998.

Forecasts of GICs require access to real-time solar wind data, information about the network and a computed electric field for a region as close as possible to the node of the network of interest. If forecasts of GICs are available, then they will have the possibility of mitigating the effects of GIC. Power utilities also want average GIC and MVAr influence per zone. From this they can finally evaluate the cost benefits of using forecasts.

4.1 GIC data

From a previous study financed by Swedish power companies, titled "Forecasting and Calculating Geomagnetically Induced Currents", new GIC data were collected and studied (Kronfeldt,2002). Studies were also carried out to explore forecasting of the GICs. In the study (Kronfeldt, 2002) measured GIC data at a transformer at Simpevarp, Oskarshamn, Sweden, were collected. The data consist of one minute GIC recordings in units of Ampere (A). The dataset covers one month in 1998, and then continuously for readings over 3 A over 1999 and 2000. The dataset was partially cleaned from outliers and other artefacts. In this project the same dataset was used as described above. A more thorough analysis of the data was made to obtain a good dataset. Key events, such as changes of the power grid configuration, shall also be included in the dataset. Additional GIC data are available after

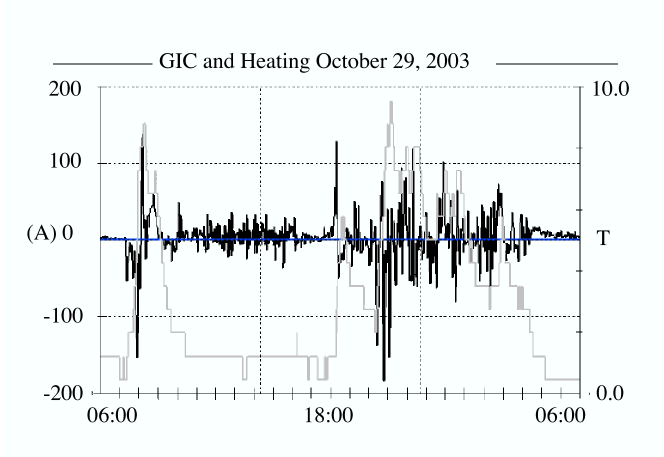

Figure 5: The measured GIC (black) and heating of transformer oil (grey) at a southern Swedish 400kV transformer during the Halloween events (Time is in Swedish local time (UT+1h)). Courtesy H. Swahn, E.ON-Sydkraft, Sweden.

2000 and at a few other sites in the south of Sweden during one month in 1998.

4.2 Computed geomagnetic data in south Sweden

The basic dataset is provided by the IMAGE magnetometer network, and data from a few other nearby sites can be added too. The high quality standards of IMAGE guarantee that the data are usable as such without any concern of annoying errors. Next, equivalent ionospheric currents are calculated using the method of spherical elementary current systems. This data set will be stored permanently, so it is straightforward to determine the ground magnetic field at any desired locations. A reasonable grid density is 50 km x 50 km, which is dense enough compared to typical distances between power system nodes. In this way a dataset with one minute resolution geomagnetic field data can be produced. The suggested spatial resolution of 50 km leads to a dataset with about 105 B-values every minute covering an area of 1000 km x 200 km. In the south of Sweden the closest magnetometer sites are at Lovö (18E,59N), Sweden, and Brorfelde (13E,56N), Denmark. For this project it would be desirable to set up a new site between these two locations to obtain a better geographical coverage. Such a site has been set up, close to Växjö (14E,57N) in Sweden.

4.3 Solar wind data

The ACE spacecraft has produced a dataset with high time resolution solar wind plasma and magnetic field data since 1997. The data we intend to use are one minute resolution data. The actual time resolution used for the

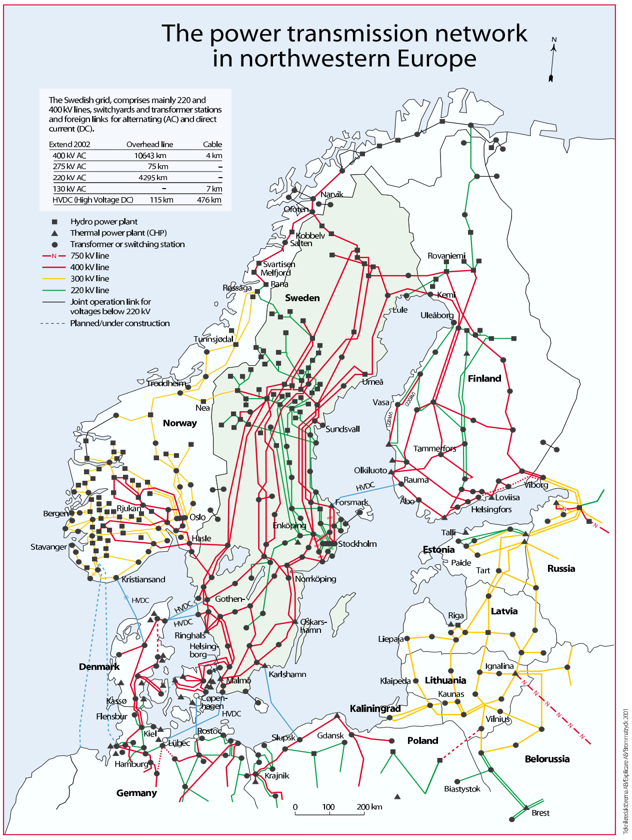

Figure 6: The power transmission network in Sweden and neighbouring countries. Courtesy ELFORSK.

model might be more than one minute, e.g. five or ten minutes, an issue that was explored in the project and is related to the accuracy of the final computation of GIC.

4.4 The horizontal geoelectric field

The key quantity in the calculation of geomagnetically induced currents is the horizontal geoelectric field at the earth's surface. The electric field does not depend on the technological conductor system in question, but is fully determined by the geophysical environment: ionospheric currents and the earth's conductivity. Consequently, once the electric field is known, it can be applied to any conductor system in the study area. It is handy to use pre-calculated model field sets to simulate GICs in different configurations of the conductor system. This is especially advantageous concerning frequently changing power networks. Because continuous geoelectric field recordings are not available in wide regions, the field must be calculated from other geophysical data. A powerful method is to use the simple relation between the local magnetic and electric fields determined by the plane wave surface impedance, which only depends on the local Earth's conductivity structure. A recently compiled set of conductivity models is available in Fennoscandia, so surface impedances can be readily determined. The ground magnetic field is measured at several sites in Fennoscandia (especially the IMAGE magnetometer network) and nearby regions, which makes it possible to derive equivalent ionospheric current systems. Then the magnetic field can be interpolated at a dense grid covering the area of the power system (or any other conductor system). Using appropriate conductivity models, the geoelectric field is then calculated in the selected grid. This is also a basic database with which GICs can be calculated in various power system configurations. GICs are calculated using a well established DC model. An important step is to compare model values to recorded ones, and then to further modify the earth's conductivity model for a reasonable fit.

4.5 Neural network model of dB/dt

The first step in the process of constructing a neural network model is to find suitable datasets that can be used for training, validation, and testing. The data should also be normalized to improve on the convergence towards an optimal model. Then a large number of models are trained in which various architectures are explored. The evolution of the geomagnetic field depends on the current state of the magnetosphere and the solar wind input. This type of dynamic systems can be modeled by time delayed and recurrent networks. Such models have been developed for geomagnetic indices, such as Kp (Boberg et al., 2000), Dst (Lundstedt et al., 2002), AE (Gleisner and Lundstedt, 2001a), and also for local magnetic field variations (Gleisner and Lundstedt, 2001b). The sampling rate range from 3 hours (Kp), 1 hour (Dst), 10 minutes (AE), and down to 5 minutes (local magnetic field). The prediction lead time is usually about one hour using a spacecraft at L1. Developing a model for the prediction of dB/dt from solar wind data is certainly possible based on the previous results, but it was clear this activity includes new research. The advantage of having a model forecasting dB/dt instead of B is that we do not need to consider slow variations, such as the quiet daily variation. Using data from the IMAGE magnetometer network we can compute a dataset of dB/dt values at any location in the south of Sweden with a spatial resolution of 50 km. The input to the model was the solar wind density, velocity, and magnetic field, together with the geographical location at which dB/dt should be forecasted. The appropriate time resolution need to be determined, although it is preferred to keep it as high as possible, e.g. one minute resolution. As the L1 point is situated about 1.5 million km upstream of the Earth the typical forecast lead time is one hour, based only on the convection of solar wind structures from L1.

For higher velocities the lead time can drop to about 25 minutes. The final desired accuracy of GICs will put constraints on how accurate the dB/dt forecasts must be. Both the timing of dB/dt structures and the amplitude must be considered when evaluating the forecasts. This will also lead to an estimate of the appropriate time resolution.

4.6 Forecasting local geomagnetic field and GIC

We proposed two possible approaches: A) Using solar wind data at L1 (ACE) a first model forecasts the time derivative of the geomagnetic field at given locations in southern Sweden (dB/dt). Then a second model uses the forecasted dB/dt, a description of the power grid layout, and ground conductivity data to compute the GICs. B) Using solar wind data at L1 (ACE) to forecast local ground field fluctuations. By using measured geomagnetically induced currents (GIC), from power grid transformer in southern Sweden, a relationship between the local geomagnetic field and GIC is found. This relation is then used to forecast GIC.

It was found that B) is suitable for forecasting, and A), with real-time data from Brorfelde and Uppsala, enables real-time simulations.

5 Offered solution

5.1 Database

Technical notes of WP 200 describes the database that is a part of the Project. The data have been identified in the *User Requirements Document.*

To support the model development and real-time operation a database was set up. As described in the URD, the forecast models shall be driven by solar wind data. The ground geomagnetic field shall be used to compute the ground electric field, and with knowledge about the power grid configuration and resistances the GIC shall be computed. Thus, the following basic data were included:

- solar wind data (16 second, 1 minute, and 64 second resolution),
- ground geomagnetic data (1 minute resolution),
- power grid data,
- GIC data (1 minute resolution).

In addition to this, intermediate data sets may be computed such as the geoelectric field.

To be able to compute the GIC accurately, a high temporal resolution is needed. Therefore, the data should be stored with an approximately one minute sampling rate or less, but the solar wind plasma data sets the lower limit at a 64 second sampling rate in practice.

We do not carry out any in-depth analysis of the data in this document, that was left to the technical notes of WP 300 and WP 400. However, we examine the quality of the data in terms of data gaps and coverage.

SQL stands for *Structured Query Language* and MySQL is an open source database management system. The history of MySQL begins in 1979 and in 1996 a binary distribution for Linux and Solaris was released. Today MySQL is implemented for all major platforms. MySQL is freely available under *GNU General Public License* (GPL), which means that it is free for in-house use.

The data in the database are organised in tables, where each table has a fixed number of columns and variable number of rows. A column corresponds to a physical parameter, e.g. solar wind speed, and a row corresponds to an observation. The time of an observation is a critical and unique parameter and is stored in the SQL DATETIME format. The format is "year-month-day hour:minute:second", e.g. "2003-12-22 12:45:04". It is also defined as a PRIMARY KEY which means that there can only be one row in a table with a specific time stamp.

The data are stored in a database called `gicpilot`. The database is selected with the command

```
mysql> use gicpilot
```

where `mysql> is` the MySQL command prompt. The database contains the tables that hold the data. The tables can be listed using the command

```
mysql> show tables;
```

which should produce an output.

5.2 Computation of GIC

The purpose of this study was to provide a routine tool for calculating geomagnetically induced currents (GIC) at Oskarshamn Simpevarp, in the southern part of the Swedish 400 kV power grid. As input we assume that geomagnetic recordings are available at the nearby region for calculating the geoelectric field. The necessary power grid information consists of the topology of the system and of the resistance values of the transformers, transmission lines and station groundings. The locations of the earthing points are an essential part of the topology information.

The initial geoelectric field was calculated assuming a 2-layer conductivity model of the earth: thickness of the upper layer 150 km and its resistivity 40 Ωm; the resistivity of the lower layer 0.4 Ωm. The geomagnetic field interpolated at a regular grid covering the power system was then multiplied by the surface impedance to get the geoelectric field.

GIC recordings were available at one site. Assuming a uniform electric field, the modelled GIC at this site is $GIC = (-53.3E_x + 150.9E_y)$ A km/V. Using four disturbed events, we found that multiplying the initial electric field by 3.96 gives the best fit of the model in the least-square sense. This yielded the median relative error of 58% when time steps with the measured GIC exceeding 5 A were considered.

5.3 Forecasting local geomagnetic field and GIC

The technical notes of WP 400 describe the models that will produce forecasts of the rate-of-change of the horizontal components of the local geomagnetic field in southern Sweden based on ACE real time solar wind data. Both the north-south (ΔX) and east-west (ΔY) directions are considered.

It is clear that predicting $\Delta H = (\Delta X, \Delta Y)$ with one minute resolution is with current knowledge impossible. Therefore, we motivate the use of temporal root-mean-square (RMS) ΔH formed over 10 minute intervals. A resolution of 10 minutes has been found to be a good trade off between high resolution and accurate forecasts. The optimal forecast lead time is 30 minutes and the correlation between model output and observed log RMS ΔH is approximately 0.80. The models forecast the 10-minute RMS ΔX and ΔY at Brorfelde (BFE: 11.67°E, 55.63°N), Denmark, and Uppsala (UPS: 17.35°E, 59.90°N), Sweden.

The magnetic field variations ΔH are interpolated over a dense grid covering southern Sweden using equivalent ionospheric currents. Based on the interpolated ΔH the electric field and thus the geomagnetically induced currents may be calculated for any given location. We have shown that the interpolated 10-minute RMS ΔH agrees with measurements from the two locations BFE and UPS. Therefore, the prediction model can be generalised to arbitrary locations.

Finally, we provide a linear model relating RMS ΔH at Brorfelde, Denmark, and Uppsala, Sweden, to RMS GIC at a single location. There is also a close linear relation between RMS GIC and MAX GIC, where the latter is the maximum GIC in a 10 minute interval. This is useful as an estimate of the maximum GIC that will occur (Wintoft, 2005).

5.4 Service implementation

The software is installed on a server maintained by IRF. GIC forecasts are accessible over the Internet (Fig. 7 and 8) (http://www.lund.irf.se/gicpilot/ and http://www.lund.irf.se/gicpilot/gicforecast/).

In order for the service to operate in real-time solar wind data are continuously needed. Currently the solar wind data from the ACE spacecraft are available with a couple of minutes time delay from SEC. At times of large solar storms, generating proton fluxes above a certain threshold, the

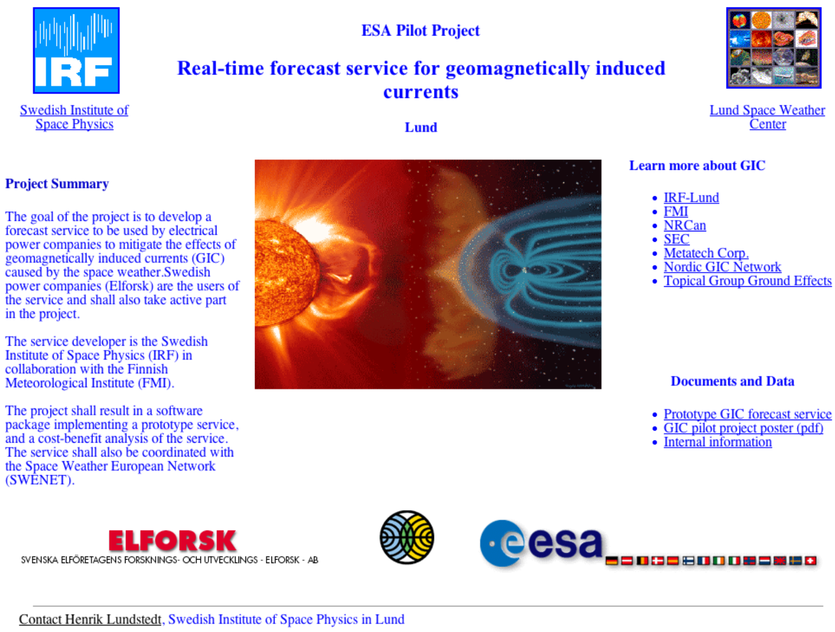

Figure 7: GIC project web page with link to forecast prototype page.

ACE plasma data are not reliable. However, it seems that the magnetic field data at those events are correct. SOHO plasma data are not available in real-time so the data can't be used for forecasts. However, the data are available after four or more hours. The data are stored in a SQL database. The GIC forecast web page includes also a link to RWC-Sweden for further solar-terrestrial information.

5.5 Cost-benefit analysis

In 1997-1999 Svenska Kraftnät, together with OKG and Vattenfall (part of the work), undertook a study, including monitoring, of Geomagnetically Induced Currents (GIC). The final report recommended that the results of the calculations should be verified in different ways, and that the value of an early warning system, as well as other measures, should be studied.

The aim of the cost-benefit analysis, carried of by ELFORSK (Skarp, 2003, Andreasson, 2005), was to study the benefits of the implementation of different measures to limit disturbances and damage in connection with GIC.

Four events (A, B, C, and D) were studied. A. Voltage collapse in all of Sweden, B. Regional voltage collapse, C. Serious damage to a system transformer and D. Serious damage to a power plant transformer.

The failure rate was estimated based on that a geomagnetic storm, caus-

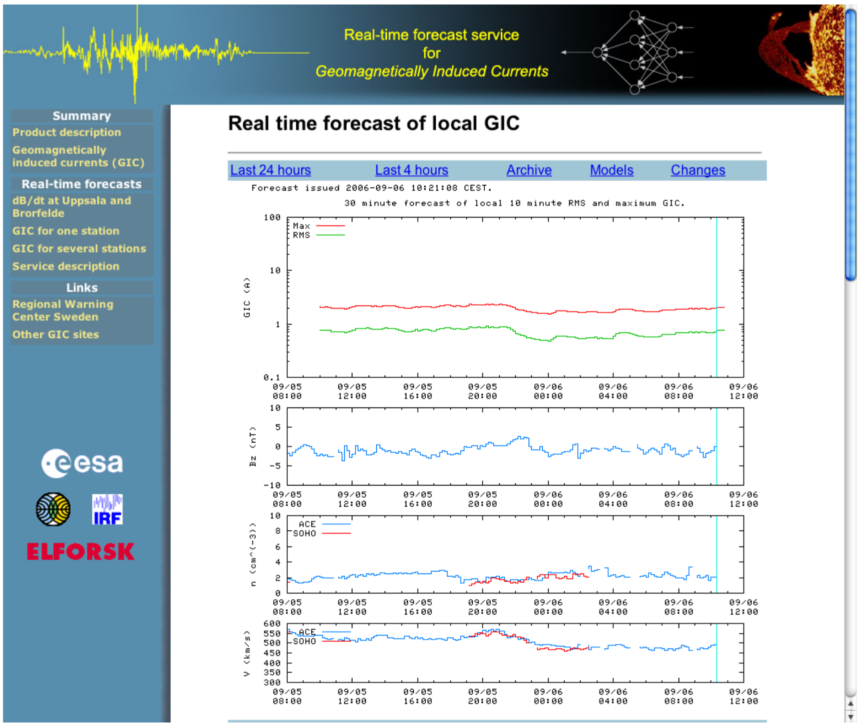

Figure 8: GIC forecast prototype web page.

ing an $E \geq 10V/km$, occurs once during a solar cycle. It was also assumed that the disturbance should occur during high load. A geomagnetic superstorm is defined by $Dst < -300nT$. The largest recent superstorm (1989, March 14, the Quebec event) reached $Dst = -589nT$. However, during the so called Carrington event, September 1-2, 1859, Dst reached $-1760nT$. Such storm most likely would have caused a high GIC value. Figure 9 also shows that effects and superstorms can occur any time during the sunspot cycle (Boteler, 2002). The estimates of the failure rates are therefore somewhat uncertain.

The cost of a disruption for the four cases was then estimated (Andreasson, 2005). The estimates for the four cases are summerized in Table below.

1 SEK (1/9.0 Euro)	Failure rate (times/100 year)	Averaged time of disturbance (h)	Cost of disruption (million SEK)
A	1.0	10	7 050
B	2.1	10	2 100
C	4.3	6	25
D	3.3	10	75.5

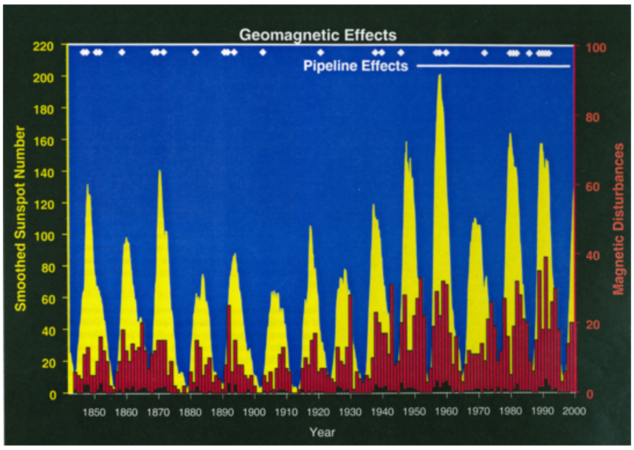

Figure 9: History of geomagnetic effects on ground technology. The diamonds indicate times of problems on telegraph systems, phone cables, and power systems. Telluric currents in pipelines have been reported for the last fifty years. Courtesy David Boteler.

Even if the failure rate is very low, the cost is very high. A warning system was estimated to cost only 2 MSEK plus an annual cost of 0.6 MSEK for operation and maintenance. Using a warning system it was estimated (Skarp, 2003) to reduced the cost by 78.66%, 74.98%, 78.33% and 79.96% for the four cases A-D.

The conclusion (Skarp, 2003) was therefore that there is a potential for public economy improvement by taking these measures to limit the risk of GIC-consequences.

It was recommended:

- a warning system of space weather storms
- a monitoring system of ground magnetic field variation and of GIC

Within the ESA GIC pilot project real-time forecasts of GICs were developed (Wintoft et al., 2006). These forecasts have been available on the web since September 2004 (http://solarwind.lund.irf.se/forecast/gic/). An archive of historic forecasts is also available.

The accuracy of the forecasts was tested for a real event in November 2004 (Wintoft et al., 2005). The forecasts about 30 min ahead of local 10 min RMS and maximum of GIC showed to be excellent compared to real-time GIC measurements at OKG (Fig. 10)

During the Halloween events 2003 (Lundstedt, 2006) a close collaboration with power operators took place. Continuous real-time warnings were given, based on SOHO/MDI/LASCO/EIT solar observations, solar wind

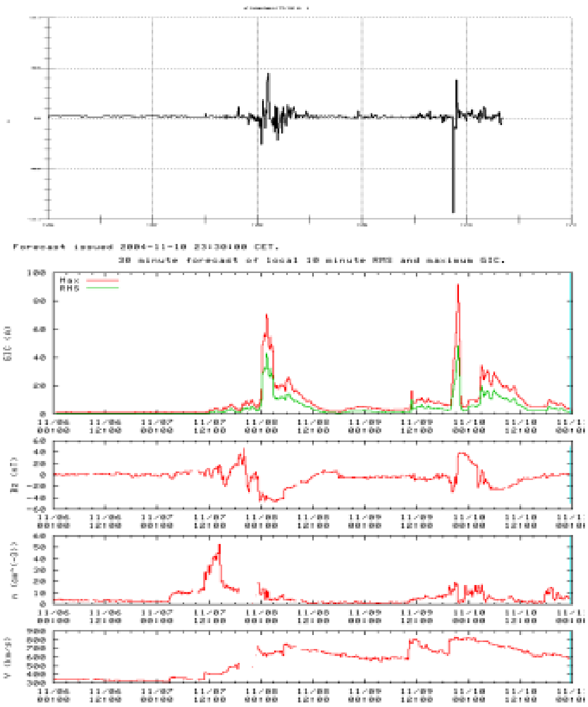

Figure 10: Measurements and forecasts of GICs November 6-11, 2004.

measurements by ACE, and geomagnetic field measurements. This information is available at RWC-Sweden of ISES, linked to on the GIC web page. Mitigating measures were taken based on these warnings of GIC and monitoring of GIC. Observations of solar activity on the Suns far-side, giving warnings two weeks ahead, played an important role during the Halloween events. The warnings drew their attention in the first place. When the active solar regions then appeared on Suns earth-side they were prepared. Continuous warnings and reports of activity were then given. Since they were prepared they could mitigate the effects. They lowered the distributed effect and could therefore manage higher values of geomagnetic induced currents. On October 30 at 20:07:15 the GICs however passed above 200A and that was too much. A power blackout occurred in Malmö (Fig. 11) (Lindahl, 2003).

ELFORSK reported that the reduction in the distributed effect, and herewith the loss of production, resulted in costs (for just one nuclear power plant) of about 0.5 million dollars. The forecasts and warnings made it possible to carry out mitigation measures and hereby reducing the costs considerably. The effects should have cost them much more otherwise.

Warnings have therefore shown to be of economically benefit, both based on the ELFORSK study and on real-world events.

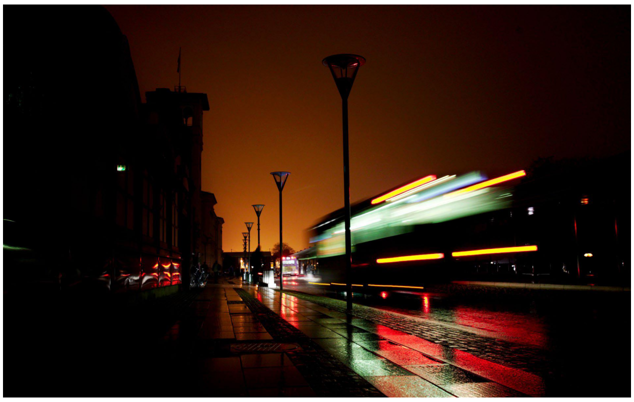

Figure 11: Power outage in Southern Sweden (Malmö), October 30, 2003. Courtesy Sydsvenskan.

The second recommendation, of the ELFORSK study, was to install a monitoring system. During the Halloween event OKG monitored the GIC. A new magnetometer, placed close to OKG in Risinge, is in operation (Lundmark, 2007). The magnetic field measurements will be available on the web in real-time. Based on these real-time measurements of the local geomagnetic field, accurate both nowcasts/forecasts have been made.

Local magnetic field measurements will therefore also facilitate a real-time monitoring system of GIC. A system that according to the ELFORSK study leads to cost benefits.

6 Concluding summary

The goal of the project was to develop a real-time prediction service to be used by electrical power companies to mitigate the effects of geomagnetically induced currents caused by space weather.

It was shown that the 10-min standard deviation GIC may be computed from a linear model using RMS $\Delta X$and ΔYat Brorfelde, Denmark, and Uppsala, Sweden with a correlation of 0.926 ± 0.015. From recurrent neural network models, that are driven by the solar wind data, it was shown that the log RMS $\Delta X$and ΔYat the two locations may be predicted up to 30 min in advance with a correlation 0.78 ± 0.02 for both directions at BFE; 0.81 ± 0.02 and 0.80 ± 0.02 in the X- and Y-directions, respectively, at UPS. The most important inputs to the models are the 10-min averages of the solar wind magnetic field component B_z and velocity V, and the 10-min standard deviation of the proton number density σ_n. The average proton number density n had no influence. The predictions have been running on the web since the 1st of January 2004. The forecasts are archived.

The project resulted in scientific articles (Lundstedt, 2006, Wintoft 2005, Wintoft et al., 2005, Pulkkinen et al., 2006), extended database, developed software, and implementing a prototype service.

The COST Benefit Analysis, carried out by Elforsk, showed that substantial amounts of money is to be earned by using a warning and monitoring system. This was based on the probability of having disturbances, and on considering carrying out measures to mitigate the effects and losses not taking any actions.

We have delivered a real-time warning system and installed a monitoring magnetometer.

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