# MONITORING GEOMAGNETICALLY INDUCED CURRENTS IN THE SCOTTISH POWER GRID


**Alan W P Thomson[(1)], Toby D G Clark[(1)], Ellen Clarke[(1)]**
**Allan McKay[(2)]**

[(1)]*British Geological Survey, West Mains Road, Edinburgh EH9 3LA, UK,*
*Email: a.thomson@bgs.ac.uk, t.clark@bgs.ac.uk, e.clarke@bgs.ac.uk*
[(2)]*Department of Geology and Geophysics, University of Edinburgh, West Mains Road, Edinburgh EH9, UK,*
*Email: allan.mckay@glg.ed.ac.uk*



## ABSTRACT

During magnetic storms, induced electric fields in the ground can result in currents flowing through the neutral earth connections of transformers in power grid systems. These geomagnetically induced currents (GIC) can result in damage to transformers, potentially a major expense to power companies. Scottish Power plc and the British Geological Survey (BGS) have established a system for monitoring GICs and associated geomagnetic disturbances in the part of the UK power grid operated by Scottish Power. We describe various aspects of this system, used routinely since the beginning of 2000 by Scottish Power in its daily grid operations. This paper also includes some examples of calculated and measured GIC during significant magnetic storms. These are shown in relation to measurements made at Eskdalemuir magnetic observatory, which is the nearest observatory to the GIC monitoring sites. Current scientific analysis of GIC and magnetic data in the UK are also described.


## 1. MONITORING GIC AND GEOMAGNETIC ACTIVITY

The BGS/Scottish Power monitoring service involves the provision of hourly geomagnetic activity indices from the three UK magnetic observatories direct to the grid control centre at Scottish Power. The index chosen for this purpose is the hourly standard deviation (*HSD*) in the North (*X*) and East (*Y*) components of the geomagnetic field. These data are considered an appropriate measure of local geomagnetic activity, as the standard deviation in the field is a proxy for the power in magnetic field variations that drive surface electric fields and GIC. It is also simple to compute in near real-time. The data are normally processed at the Edinburgh office of BGS (for quality control purposes). However Scottish Power can access the data directly from the observatories in the event of rare problems in Edinburgh. Data provision has been essentially 100% reliable since 2000, with the added back up of BGS consultancy available during normal working hours.

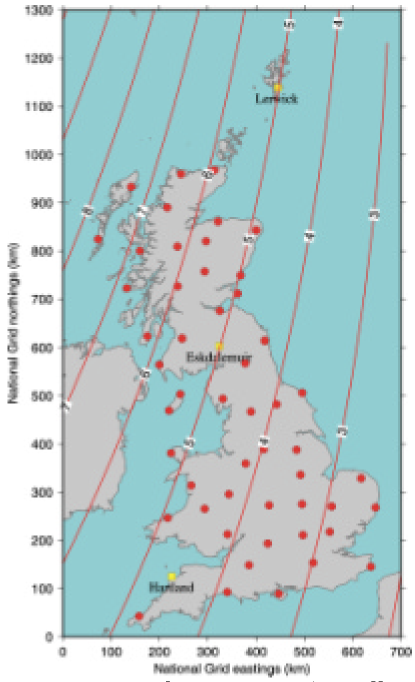


**Fig. 1**. UK magnetic observatories (in yellow). Also shown is the UK magnetic repeat station network (red). Overlain are contours of magnetic declination for 2001 (degrees west of true north).

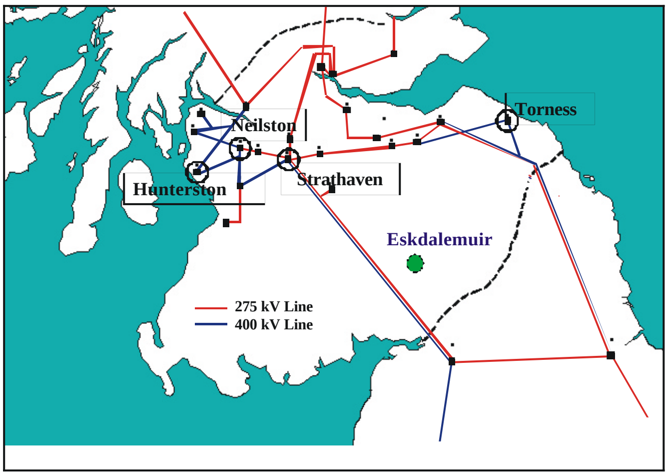


**Fig. 2**. The high voltage Scottish Power grid, in relation to Central Scotland and Eskdalmuir observatory.

The locations of the UK permanent magnetic observatories are shown in Fig. 1. Eskdalemuir (approximately 100 km South of Edinburgh) is the closest observatory to the part of the UK power grid managed by Scottish Power. Fig.2 shows a typical layout (in 2000) of the high voltage part of the Scottish grid. There are long high voltage lines connecting south to England and to Northern Scotland up the eastern half of the country.

Beginning in January 2000, real-time measurements of GIC have been made in the grid. GIC monitoring equipment was installed on the network at four main transformer sites – Hunterston, Neilston, Torness and, more recently, at Strathaven (see Fig. 2). The GIC equipment comprises a Hall effect probe sampling the magnetic field resulting from quasi-DC currents in the Earth line of one major transformer at each site (see Fig. 3).

**Fig. 3**. Hall effect probe (white box) on transformer Earth line (copper) at Hunterston power station. Engineer (lower left) included for scale.

Measured GIC data are available from these sites at grid control. BGS *HSD* data are then used by system engineers to verify that any increased DC current observed is geomagnetically induced. Scottish Power has grid management procedures to deal with the occurrence of significant GIC, above a nominal threshold of 5 A. Advanced warning (by BGS – see below) of the likelihood of major magnetic storms may also impact on day-to-day planning for grid maintenance.

A geomagnetic activity prediction service is provided by BGS and comprises a qualitative geomagnetic forecast of global activity levels for the next three 24-hour (mid-day to mid-day) periods. This is issued each morning. The forecaster makes use of as much public domain information as possible. Particular attention is paid to resources on the web sites of the Space Environment Center (SEC), USA and the IPS Radio and Space Services, Australia, as well as data, information, knowledge and analysis tools developed by BGS staff. Also included in the daily forecast is an interpretation of what may happen locally in the UK depending on the local time of arrival of solar wind disturbances.

## 2. GIC MEASUREMENTS DURING MAGNETIC STORMS

Examples of data collected during a recent magnetic storm are shown in Figs. 4 and 5. The rapid rise and fall of *HSD* is evident as is the close correlation between field rate of change (best at Eskdalemuir) and the time varying GIC. Phase relationships between measured currents may be frequency dependent (see later) and the largest GIC are generally seen at Neilston. Note that the peak currents in this case were seen during the storm commencement. One-second magnetic data are also available from the observatories.

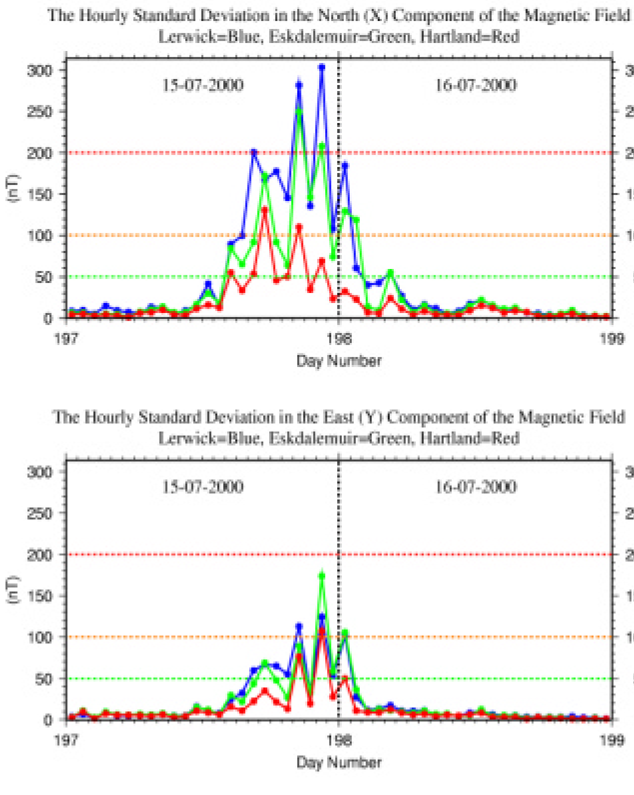


**Fig. 4**. *HSD* during the 'Bastille Day' magnetic storm of 2000.

The dashed lines in Fig. 4 denote approximate thresholds for active, minor and major storm levels. One can see that activity levels tend to become greater with higher latitude, as might have been expected. However during some major storms in the past the highest *HSD* was recorded at Eskdalemuir, rather than at Lerwick. Note also that *HSD* in the North component is larger, symptomatic of a predominantly East-West ionospheric current. Again, this is a common observation.

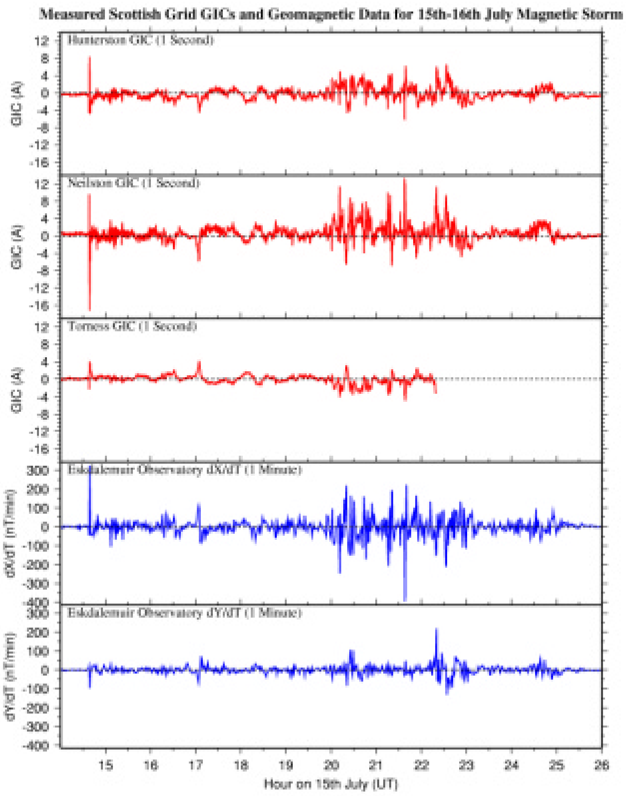


**Fig. 5**. Scottish grid GIC and field rate-of-change at Eskdalemuir, during the 'Bastille Day' magnetic storm of 2000.

## 3. ONGOING SCIENTIFIC STUDIES OF GIC IN THE UK

Given simultaneous recording of both the local magnetic field and GIC, a transfer function that relates, for example, the field at Eskdalemuir and GIC at Neilston can be derived, as in Fig. 6. This can then be used to estimate GIC during other time intervals for which data are unavailable.

One of the largest magnetic storms, in terms of intensity and rates of change of the field, occurred in March 1989. The Eskdalemuir/Neilston transfer function has been used to estimate the likely size of Neilston GIC given the type of storm conditions experienced in March 1989. The maximum rate of change of the magnetic field experienced at Eskdalemuir during the 1989 storm was approximately 800 nT/min. The output of the Neilston transfer function suggests that a GIC of approximately 28A may have occurred as a result, see Fig. 7.

Note that these are one-minute (average) data – the data are effectively low pass filtered. We may expect, based on recent experience, that GIC, second to second, will be significantly higher. Further work is needed in order to establish any dependence of such transfer functions on source field conditions and perhaps power grid configuration.

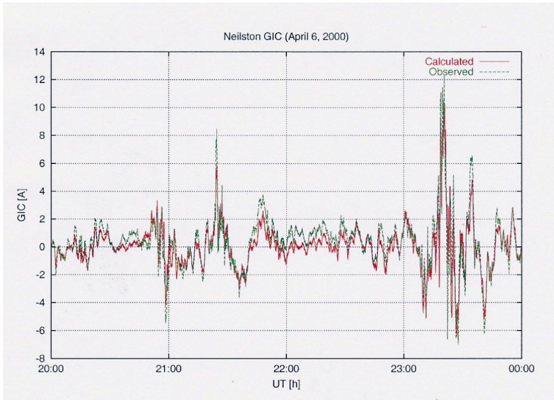


**Fig. 6.** Measured and calculated GIC at Neilston, 20:00-00:00 UT, 6th April 2000. The GIC time series is formed by multiplying (in the frequency domain) the magnetic time series with the transfer function.

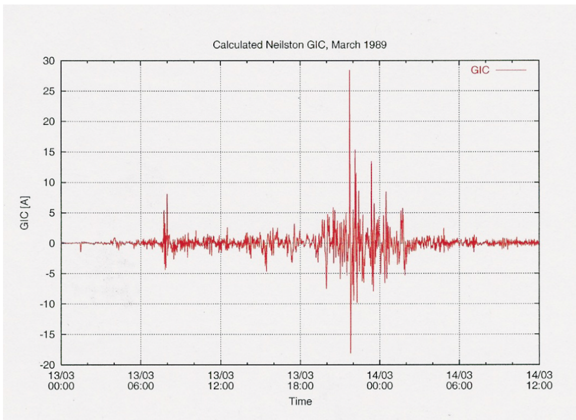


**Fig. 7.** GIC calculated at Neilston using the Eskdalemuir - Neilston transfer function used in Fig. 6. Period shown is 00:00-12:00 UT, 13/14 March 1989.

A spectral analysis of the 6th April 2000 storm GIC data has also been undertaken. This produced an interesting phase relationship between Hunterston and Neilston GIC. Phase is found to vary with frequency: currents aren't simply in-phase or out of phase. Hunterston and Neilston appear to be 180 degrees out of phase from DC to periods of the order of 100s. For periods shorter than this a phase shift of approximately 90 degrees occurs. This relationship is constant in time given sufficient signal power. Ideally this result needs to be confirmed in future examples, as it has implications for DC network models of power grids in the presence of GIC.

A representative conductivity model of the UK is required if the prediction of currents flowing in power grids is to be possible. Electromagnetic investigations of the United Kingdom have consistently shown that the deep ocean and shelf seas greatly influence the observed electromagnetic fields at periods comparable to those of GIC. Thus, the period range of interest and configuration of electric fields (established experimentally) suggests that the thin-sheet approximation in 3D electromagnetic modeling may be well suited to investigating UK GIC.

Preliminary thin-sheet modeling of the UK electric field has been undertaken to assess the suitability of the method and available algorithms. Modeling has initially been restricted to examining the influence of the coastal conductivity contrast on the pattern of induced currents in the UK. The real part of the *X* (geographic North) component of the surface electric field when the polarisation of the inducing magnetic field is parallel to geographic North is shown in Fig. 8.

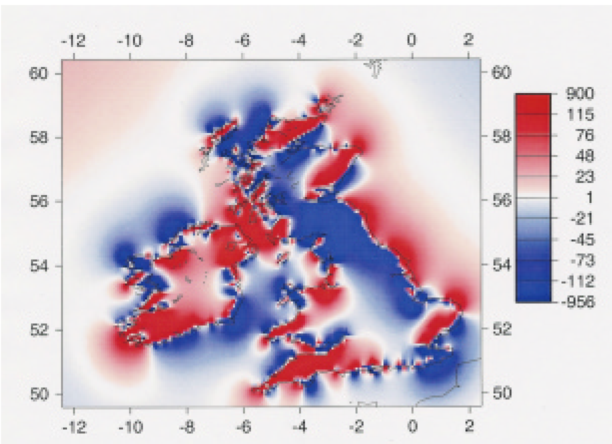


**Fig. 8.** *X* component of electric field [$10^{-4}$ V/km] given inducing magnetic field $\boldsymbol{H}$ = 1 A/m (equivalent to a 1257 nT sinusoidal ionospheric field) and period T=450s.

The coastal enhancement of the electric field is clear. Also worth noting is the influence of coastline geometry: the polarity of the electric field along coastline boundaries depends on the orientation of the coastline relative to the regional current flow, in this case East-West. Interestingly the surface electric field can have same polarity on opposite coasts and this may explain the observation that Hunterston and Torness often have in-phase GIC.

Further work is underway to include shelf-sea bathymetry, on-shore conductivity variations and to assess the relative importance of these factors with regard to the main coastal conductivity contrast. Thin-sheet modeling offers the opportunity to include both non-uniform source fields and geology. Future work should include both realistic conductivity structure and ionospheric current models.

## 4. CONCLUSIONS

The simultaneous monitoring of GIC and geomagnetic variations has been continuous in Scotland since 2000. BGS have continuously provided *HSD* index data to Scottish Power during this time and have received GIC data for subsequent analysis.

Scientific developments that are ongoing include:

1. Construction of UK GIC:field transfer function relationships.
2. Estimates of peak GIC (or at least a lower bound on the maxima) seen in historically great magnetic storms.
3. Detailed surface electric field modelling.

In the future we intend to investigate realistic ionospheric source fields and combine these with the surface electric field model to compute GIC flowing in the grid. A crucial test of the accuracy of such models will be the degree to which they conform to measured GIC data. This research is being carried out in association with the Finnish Meteorological Institute.

## 5. ACKNOWLEDGEMENTS

We would like to acknowledge the helpful discussions on various aspects of GIC with Scottish Power plc, Strathkelvin House, Campsie Road, Kirkintilloch, Glasgow G66 1RN. A number of present and past BGS staff have contributed to the smooth operation of the monitoring and forecasting service in the past two years. We would like to acknowledge the important contributions of Jess King, Sarah Reay and Pamela White. The scientific studies described in Section 3 would not have been possible without the data and technical support provided by Tom Cummings and Tom Breckenridge of Scottish Power. This paper is published by permission of the Director, BGS (NERC).