Project EURISGIC: UK Regional GIC Studies

(Technical Note D1.3)

Earth Hazards and Systems Programme

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Project EURISGIC: UK Regional GIC Studies
(Technical Note D1.3)

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Composite image of Coronal Mass Ejection from the Sun (Dec 2003). Courtesy of SOHO consortium. SOHO is a project of international cooperation between ESA and NASA.

Bibliographical reference

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of the EURISGIC project (NEE4272SF and NEE3710F) into geomagnetically induced currents in the high voltage UK power system. We report on model developments since 2010, including a re-evaluation of the October 2003 impact on the UK grid system and an analysis of the impact of hypothetical extreme space weather events on the grid.

Acknowledgements

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1 Scope

The main objective of Work Package 1 of the EURISGIC project (see website eurisgic.eu) is to:

“Compile a DC description of the European high-voltage power network and update existing GIC modelling software. Compile (for validation and comparison) two regional models (UK and NW Russia).”

This document is a technical note (deliverable item 1.3) on task 2a of this work package:

“Regional model: Analyse the UK power network to determine GIC ‘hot spots’ under hypothetical and real-event source fields; test model outputs in respect of sensitivity to grid changes and against existing GIC measurements.”

In Section 2 we briefly review the UK geophysical understanding and modelling considerations prior to project start. In Section 3 we then detail modifications to the modelling code undertaken during the project and identify where the high voltage grid model is changed from previous published versions. In Section 4 we re-analyse, with the new grid model, the October 2003 ‘Halloween’ event as a recent worst case and draw conclusions on the grid ‘hot spots’ during this event, in relation to measured GIC data. Finally, hypothetical worst case space weather events are developed and applied to the new grid model in Section 5.

2 Background

Over more than ten years BGS has developed geophysical and other mathematical models that have allowed detail study of the GIC hazard to the UK power system. These prior models are described in this Section.

2.1 CONDUCTIVITY MODEL OF THE UK

The BGS model of the conductivity of the crust and upper mantle reflects the setting of the UK within the shallow continental shelf of North West Europe and the deeper ocean of the Atlantic to the west. It also recognises the tectonic complexity of the regional lithosphere, for example in comparison with the shield regions of Fennoscandia and Canada; regions from where much of the published models and literature on geomagnetically induced currents (GIC) originates. The conductivity model used in published work prior to project start is that of Beamish et al (2002), based on Beamish (1998) and Beamish (1997), and augmented as described in Thomson et al (2005), which in turn was based on McKay (2003). Summary details on the UK conductivity model are provided in the companion technical note (Beamish and Thomson, 2012).

In short, the prior conductivity model consists of the 2D surface conductivity of the entire region, including the water column and offshore bathymetry. Onshore the UK conductivity structure is split into six different geological terranes (i.e. distinct upper crustal zones). In addition, the model also includes a single 11 layer 1D model of the lower crust and mantle, under the UK, therefore adding a third dimension. The maximum depth of this 1D model is 1000km.

Figure 2-1 shows the surface conductance model (that is, the product of conductivity and thickness). The model is has a spatial resolution of 1/12th of a degree and extends from 12°W to 2°E in longitude and from 50°N to 60°N in latitude.
It can be observed from Figure 2-1 that while the conductance model is fairly complex overall, the geological representation onshore is relatively simple, except around the Midland Valley of Scotland (where considerable effort has been made to measure the conductivity structure, see McKay, 2003, in particular). Outside this region the conductivity structure is less accurately sampled. However, it must be pointed out that strongest of the electric field gradients occur along coastlines where differences in the sea-water and land conductivities are largest.

2.2 SURFACE ELECTRIC FIELD MODEL

The interaction of the external magnetic field with the conductive Earth is approximated by ‘thin-sheet’ modelling; this determines the electric field arising at a particular frequency from the layers of conductive material in the sub-surface.

The thin-sheet modelling code used in this study is based upon the work of Vasseur and Weidelt (1977). Using a series of appropriate Green’s functions and integrals, the thin–sheet approximation can be used to model the likely influence of near surface conductivity contrasts in the context of regional induction. Hence, a thin–sheet model includes the effect lateral conductivity variations have on redistributing regional or “normal” currents induced elsewhere (e.g. oceans or shelf seas). However, a number of assumptions and approximations are made to ensure that the thin-sheet model remains valid.

The various layers of the model can be considered to act as filters with each layer responding as a function of the period of the input field, as well as its own relative resistivity. Deeper layers respond to longer periods, while the shallower layers respond to shorter periods. Much greater detail can be found in Beamish et al. (2002) and McKay (2003).
2.3 A MODEL OF THE UK POWER NETWORK

The UK grid model at the EURISGIC project start is based upon information in the National Grid Seven Year Statement 2008\(^1\) (SYS08) and was derived by Turnbull (2011). This simplified grid models only the 400kV and 275kV networks and consists of 252 nodes together with 379 connections. The transformer resistances are fixed at 0.5\(\Omega\) and the earthing resistance is set to 0.1\(\Omega\). Line resistances are calculated based on the length of the connections between nodes.

GIC along power transmission lines are calculated using the matrix equation as set out in Lehtinen and Pirjola (1985):

\[
I = (1+Y.Z)^{-1}.J
\]

where \(J\) is the geo-voltage between nodes, \(Z\) is the impedance matrix, \(Y\) is the network admittance matrix and \(I\) is the GIC at each node. Input data about the network is used to calculate \(Y\) and \(Z\). The geo-voltage \(J\) is calculated by interpolating the electric field grid onto the power transmission lines and integrating along the line. The GIC at each node on the grid is then given by \(I\).

Note that when modelling real-world data, to compute the total GIC at each node, all periods would be summed, as would the resultant components of the orthogonal X and Y electric fields values.

However, in this study it is assumed that all the energy is concentrated into a single period – a scenario which is physically unrealistic. However this is a necessary, simplifying assumption. Future work may address more physically realistic source field distributions in the frequency domain.

\(^1\) http://www.nationalgrid.com/uk/sys_08/
3 Upgrade of the UK Geophysical and Grid Models

Improvements have been made to the BGS modelling code in the following areas.

1. Use of ‘Spherical Elementary Current System’ (SECS) modelling:
   - To provide a more physical interpolation of the external magnetic field variations driving the electric fields and GIC flows. This uses data typically from observatories and variometers shown in Figure 3-1.
   - Existing BGS SECS code has been rewritten into modules.
   - Improved use has been made of Matlab, which provides a ~50x speed improvement.
   - For each minute, the magnetic field is interpolated at each point in the grid. We then assume that the field has a specific period (e.g. 360s) and solve for the electric field for that minute, assuming it is of a fixed frequency.

2. E-Field thin-sheet modelling:
   - Full parallelised computation of Green’s functions has been implemented on a high performance computing cluster.
   - The integration of conductivity now occurs over all surface grid points in the model (previously this was integration over just the 25 closest points).
   - Parallelised computation of model time-steps has been introduced, improving processing time linearly with the number of cores available on the cluster.

Figure 3-1: Observatory (in capital letters) and variometer (mixed case) data sites used in the SECS interpolation model of external magnetic field variations.
It now takes about 10-12 minutes per time step (i.e. per minute) as there are multiple iterations in the thin sheet code. Most of the time (>95%) is taken up by the thin sheet part. The SECS module takes <10 seconds to run, and the GIC code then takes between 10 and 60 seconds depending on how many connections and nodes. For the simple grid it takes 10 seconds.

4 Re-analysis of the Halloween 2003 Event

The 29-31 October 2003 (Halloween) storm in the UK was extensively considered in Thomson et al (2005). Figure 4-1 and 4-2 show the peak surface electric field in the UK and GIC flows in the Scottish grid, respectively, at the height of the Halloween storm (taken from Thomson et al, 2005).

The GIC and surface $E$-field modelling work reported by Thomson et al (2005) used an inducing field orientated slightly east (5 degrees) of north-south, corresponding to the observed field perturbation direction at the Eskdalemuir observatory at the time of the peak of the storm (21:20, 30th October, 2003). The magnitude of the perturbing ($H$) field was estimated to be 1400 nT, with a period of about 360 seconds, across the middle of the UK, again based on measurements from the Eskdalemuir observatory. However a simple north-south $H$-field latitude taper was also employed, as the field variation in the north of the UK was 2-3 times that in the south. Data from the three UK magnetic observatories were therefore used to provide both the representative amplitude ($H=1400$ nT in Central Scotland) and the taper.

Peak surface electric fields of ~5 V/km were estimated (compared with ~0.1 V/km on a magnetically quiet day). The degree of structure in the surface electric field, estimated by Thomson et al, and shown in Figure 4-1, reflects the complexity of the underlying conductivity model in the Southern Scotland and Northern England regions. Elsewhere the $E$-field model is relatively smoother.

![Figure 4-1: Modelled peak surface electric field at 21:20 on 30th October 2003](image-url)
At the 21:20 storm peak (Figure 4-2), the maximum GIC recorded at the Strathaven (in west Central Scotland) transformer substation was -40A, though the modelled GIC was -20A. But the modelled GIC then reduced to around -40A within one minute, providing support both for the models and the assumptions made.

Using the improved external field (SECS) and electric field models (Section 3) the Halloween event has now been re-analysed. Magnetic field data from four observatories and four variometers located around the North Sea were used to compute the external field using the SECS method. In contrast to the method used in the previous study, it can be argued that the modelled field better represents the true field, rather than being based on a single data point (Eskdalemuir) with an assumed spatial structure.

Figures 4-3 to 4-7 show snapshots of the X component of the magnetic field (top left), electric field (lower left) and GIC variations (right panel) that are estimated for this storm, at 5-minute intervals through the peak in storm activity.

In Figure 4-3, the external field strength is relatively low at 21:10 (though still much larger than on a quiet day) but rapidly doubles in intensity over the course of ten minutes. By 21:20 (Figure 4-5) the modelled strength of the X component has changed from +/-1000 nT (at 21:10) to +/-3000nT across the UK, while maximum electric field strength peaks at 5 V/km in parts of Scotland. Extremely large GIC are computed across Scotland and the middle of England, driven by the very large differences in potential between the north and south of the island, where the electric field is small (< 1 V/km).
Figure 4-3: Modelled peak external magnetic field variations, surface electric field, and GIC flow in the high voltage UK grid, at 21:10 on 30th October 2003. GIC flow to Earth is indicated in red. X, Y is in the magnetic north, east direction.

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Figure 4-6: Modelled peak external magnetic field variations, surface electric field, and GIC flow in the high voltage UK grid, at 21:25 on 30th October 2003. GIC flow to Earth is indicated in red. X, Y is in the magnetic north, east direction.
Figure 4-7: Modelled peak external magnetic field variations, surface electric field, and GIC flow in the high voltage UK grid, at 21:30 on 30th October 2003. GIC flow to Earth is indicated in red. X, Y is in the magnetic north, east direction.

In Figure 4-6, the external magnetic field actually increases in strength over the following five minutes across the entire UK. The electric field peaks at 5 V/km across much of the UK. However, note that the GIC in Scotland and northern England, on average, decrease compared to 21:20 but the GIC in the south-western part of England increase in strength. By 21:30 (Figure 4-7), the magnetic field has decreased over most of the UK. However, although the electric field is still large (5 V/km in northern Scotland), the gradient of the electric field across the UK is not as extreme as at 21:20 and hence the overall GIC are not as large.

In comparison with Figures 4-1 and 4-2 we note the following:

- The UK grid contains more earthing points than the Scottish Power network.
- The GIC are computed using the entire UK grid. This changes the topology of the network, of course, giving rise to different behaviour at the edges of the electrical grid.
- The external magnetic field is computed using SECS which leads to a different model of the spatial variation of the field strength. The electric field computed in Figure 4-1 code is much larger than in Figure 4-5. This is due to (a) the different external magnetic model and (b) the enlarged area of integration in the updated thin sheet modelling code.
- In figure 4-5, the electric field peaks at about 5 V/km in places, but is on average about 3 V/km across most of Scotland. In Figure 4-2, much of Scotland has an electric field of 5 V/km.

In conclusion, the revised modelling shows that additional complexity in the input and modelling produces first order similarities to the simpler modelling but produces more subtle output.
5 Worst Case Scenarios in the UK Grid

In this section we examine the impact of Geomagnetically Induced Currents (GIC), during extreme space weather, on a simplified model of the high voltage UK power grid for 2010. GIC are driven by rapid changes in the strength of the magnetic field external to the Earth (usually known as ‘dB/dt’). Electric fields are produced in the ground by the interaction between this changing magnetic field, the shallow shelf-seas and the conductivity structure of the Earth. A technique known as the ‘thin-sheet approximation’ allows us to determine the electric field at the Earth’s surface, which in turn allows the calculation of GIC in the earthing connections of high voltage transformers within the grid.

Likely extreme dB/dt for the UK for 100 and 200 year return periods have recently been extrapolated from measured observatory data, using a generalised Pareto distribution statistical model (Thomson et al. 2011). This statistical model essentially characterises the dB/dt caused by the auroral electrojet: an electrical current system in the ionosphere largely responsible for magnetic storms and large dB/dt. Using the statistical model, we construct and analyse 28 ‘worst case’ dB/dt scenarios.

Two models of a large auroral electrojet are produced. The first electrojet model is a ‘top-hat’ function, extending from 53° to 63°N in geomagnetic latitude. The second is a Tapered Cosine model extending between 48° and 68°N in geomagnetic latitude. Two orientations of the electrojet are modelled; the first aligned roughly east-west across the UK, the second approximately aligned N-S along the UK. Three extreme values of the horizontal (H) magnetic field change are modelled: dH/dt = 1000 nT/min, 3000 nT/min and 5000 nT/min. The conductivity model responds differently at different frequencies to these magnetic field changes.

A simplified version of the UK power grid exists for 2010 (Turnbull, 2010; Turnbull, 2011), which has been upgraded as discussed in Section 3. This consists of 252 earth nodes together with 379 straight line inter-connections. We use this model to integrate the estimated surface electric field along each length of the 400kV and 275kV electrical networks to derive the expected GIC at each transformer node. We quote the resulting GIC as the total current flowing in the three phases of the system.

As a large number of assumptions and approximations are required to produce the estimated GIC contained in this report, it should be noted that the results are probably best considered as indicative of where major GIC tend to flow in and out of the power grid, and are more qualitative rather than fully quantitative.

That said, our conclusions are that ‘corner’ nodes of the grid and those nodes linked by long north-south aligned connections are most likely to experience large GIC. GIC of tens to hundreds of Amps (in some locations) are possible, for the worst cases considered. Simulations of the flow of GIC in power grids require geomagnetic data with a sampling of seconds to minutes. Such data, in digital form, have only been continuously available in the UK since around 1983. Prior to 1983 analogue measurements recorded on paper extend back to the 1840s. This long time series of data contain major magnetic storms, such as the ‘Carrington Event’ of September 1859 and the 21st May 1921 storm.

In the digital era severe magnetic storms occurred in March 1989, November 1991 and October 2003. Studies, such as Turnbull (2010) and McKay (2003), have modelled the impact of these storms on versions of the high voltage transmission system of the UK. It is also known that measured GIC reached 42A in the UK in the October 2003 event and that damage was sustained by two transformers in the March 1989 event. Thomson et al. (2005) showed that the measured
GIC for the 2003 event was reasonably reproduced by the geophysical model of Beamish et al. (2002) and McKay (2003), constructed for the Central Scotland region.

The key magnetic parameter in the ‘GIC problem’ is the time rate of change of the magnetic field, denoted $dB/dt$, and particularly its component in the horizontal plane $dH/dt$. Values of $dH/dt$ are readily extracted from the digital archive, and usually expressed as nT/minute. However, prior to this digital era, there is limited knowledge of how large $dH/dt$ could have been, for example in 1859 and 1921, or for that matter how large it could be in the future.

Thomson et al. (2011) therefore attempted to estimate likely 100 and 200 year maxima in $dH/dt$. By using a sample of 28 European observatories they found that $dH/dt$ increases with magnetic latitude, but that there is a distinct peak in the magnitude of $dH/dt$ around 55-60°N, associated with an enhanced ionospheric current system known as the auroral electrojet.

The table below is extracted from Thomson et al. (2011) and gives the predicted range in activity between 55-60°N at 100 years and 200 years return period. The data in parentheses are the equivalent figures when one European observatory is excluded from the analysis, regarded as ‘anomalous’, as discussed by Thomson et al. (2011).

These figures are used as the basis for the work in the rest of this report and are in a latitude range appropriate for assessing the space weather hazard to grounded infrastructure on the UK mainland.

<table>
<thead>
<tr>
<th></th>
<th>$dH/dt$ (nT/min)</th>
<th>$H$ (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>100 Year Return</strong></td>
<td>1000-4000 (1500-4000)</td>
<td>2000-5000 (4000-5000)</td>
</tr>
<tr>
<td><strong>200 Year Return</strong></td>
<td>1000-6000 (2000-6000)</td>
<td>3000-6500 (4500-6500)</td>
</tr>
</tbody>
</table>

Table 1: Estimated 100 and 200 year maxima in $dH/dt$ and $H$ between 55 and 60 geomagnetic degrees north summarised from Figures 5 and 6 of Thomson et al. (2011). Figures in parentheses apply where Valentia observatory data (Ireland) are excluded as anomalous.

There are four major components to the modelling of GIC: (1) measurement and modelling of the magnetic field, (2) modelling the conductivity structure of the region, (3) computation of the electric field from (1) and (2) and finally (4) integration of the electric field differences in a connected power grid to provide GIC at each node.

Further information on each of these stages is given in Section 2 and 3 and is discussed in more depth in Beamish and Thomson (2012), Beamish et al. (2002), Bolduc (2002), Thomson et al. (2005), Wik et al. (2008) and Turnbull (2010).

### 5.1 MODELLING OF THE MAGNETIC FIELD

Two models of the auroral electrojet were created. The first electrojet model consists of a ‘top-hat’ function, extending from 53° to 63°N in geomagnetic latitude. The second is a Tapered Cosine model extending between 48° and 68°N in geomagnetic latitude. The latitude range was suggested from Thomson et al. (2011). Both the Top Hat model and the Tapered Cosine have similar volumes (i.e. as integrated under the curves). Figure 5-1 shows the extent of the electrojet models in geomagnetic latitude. The models were created on a square grid in geomagnetic coordinates and then rotated 10° counter-clockwise to match the approximate position of the electrojet in the UK. The electrojet grids were cropped and sub-sampled to $1/12^{th}$ of a degree to match the grid-spacing of the conductivity model (next Section).
The reason for the two different models is to examine if the gradient (slope) of the magnetic field affects the GIC. The Top Hat model gives a very extreme gradient at its edges while the Tapered Cosine model has gentler gradient throughout.

Two orientations of the auroral electrojet were modelled; the first was aligned geomagnetically east-west across the UK, and in order to produce an orthogonal magnetic field direction, a second set of grids were produced (and approximately aligned along the central axis of the UK). To scale the electrojet model magnetic fields to the correct size in nanoteslas (nT), some results from recent BGS research into the application of Extreme Value statistical theory to European magnetic observatories were applied (Thomson et al., 2011).

The expected 100 and 200 year return levels of the change of the horizontal component of the magnetic field \( \frac{dH}{dt} \) are given in Table 1. The largest measured digital \( \frac{dH}{dt} \) for the UK is around 1100 nT/min (in 1991). Therefore as representative models of these extreme variations we choose to use 1000 nT/min, 3000 nT/min and 5000 nT/min in the analysis. This approximately represents, according to current understanding, the expected maximum in \( \frac{dH}{dt} \) in around 30, 100 and 200 years. Hence these values were chosen to scale the values of the magnetic field in the electrojet model grids.

However the results of Thomson et al. (2011) show that in Europe the extremes in \( H \) (sometimes referred to as ‘delta-\( H \’) itself are highly unlikely to exceed 10,000 nT even once every 200 years. We therefore use this as a maximum cut-off for the value of \( H_0 \), which is defined below. For this reason 3000 nT/min and 5000 nT/min changes do not seem to be physically reasonable as ‘worst cases’ for electrojets varying with periods longer than about 10 minutes. (However we retain 5000 nT/min for a 10-minute period electrojet for comparison purposes.)

To convert the rate of change to equivalent root-mean-square input horizontal field, we assumed the field was changing sinusoidally with time, \( t \). Hence the input field strength \( H_0 \) can be computed using the approximation:

\[
\frac{dH}{dt} = \sqrt{2.\pi}.H_0/T,
\]

where \( H = H_0\sin(2.\pi.t/T) \). \( H_0 \) is the strength of the field from the electrojet and \( T \) is the period of electrojet variation (in minutes). If we assign \( T = 2 \) minutes, this leads to magnetic field input
strengths \( H_0 \) of approximately 450 nT, 1350 nT and 2250 nT for \( dH/dt = 1000 \) nT/min, 3000 nT/min and 5000 nT/min.

The starting grid models are multiplied by these values to scale them to the magnetic field strength before combining them with the conductivity model to calculate the electric field strength at each point across the UK mainland.

Source fields input to the conductivity model therefore comprised twelve different scenarios:

- 2 electrojet models (Top Hat and Tapered Cosine)
- 2 orientations (as geomagnetically E-W and N-S aligned electrojets)
- 3 \( dH/dt \) scaling values

Each scenario was run through the conductivity model with one of three periods: 120, 600 or 1800 seconds, for a total of 28 model outputs.

<table>
<thead>
<tr>
<th>( dH/dt ) (nT/min)</th>
<th>Period (minutes)</th>
<th>Electrojet Field Strength ( (H_0) ) (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>2</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2275</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>3820</td>
</tr>
<tr>
<td>3000</td>
<td>2</td>
<td>1350</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>6825</td>
</tr>
<tr>
<td>5000</td>
<td>2</td>
<td>2250</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>11375</td>
</tr>
</tbody>
</table>

Table 2: Static input fields to the conductivity model. \( H_0 \) of 6825 nT and 11375 nT are regarded as unlikely physical scenarios. The latter in particular is not considered further.

The most extreme GIC will be associated the largest electric field, in this case at a period of 1800 seconds, with a N-S alignment of the electrojet (i.e. electric field gradients aligned with the longest sections of power line connections), from a \( dH/dt \) of 5000 nT/min.

5.2 RESULTS

The electric field for each of the 28 idealised scenarios was computed using the thin-sheet approximation (see Sections 2.1 and 2.2) and then the GIC at each node point in the network was calculated (Section 2.3).

Figure 5-2 to Figure 5-7 shows the impact of the two electrojet ‘shape functions’ and the electrojet period of oscillation, in terms of electric fields and estimated GIC. Positive (red) values indicate GIC leaving the power grid and entering the ground. Negative (blue) values show current flowing from the ground into the power grid. These figures are the total GIC per transformer, i.e. three times the per-phase GIC. Measured GIC (e.g. by National Grid or by Scottish Power) are the per-phase GIC, one third of the total GIC. This should be remembered when comparing modelled and measured data.

The twenty nodes where the largest GIC occurs at each period are listed in Table 3 to Table 5. A full listing of the computed GIC at each of the 252 nodes for the 120 second period electrojet is given in Appendix 1.
5.2.1 Periods of 120 seconds

At this period GIC will be tend to associated with the surface layers of the Earth, rather than penetrating deeper into the lower crust and upper mantle.

As expected, the largest GIC are associated with the largest magnetic field changes. Figure 5-2 shows the electric field generated from a magnetic field of 2250 nT in the X (North) direction. The induced electric field is in the E-W direction. The grid model has few long E-W power lines, so the larger GIC are in Wales and the Midland Valley of Scotland.

Much larger GIC occur when a similar magnitude magnetic field occurs in a north-south aligned direction. In Figure 5-3, the electric field is aligned approximately along the central axis of the UK, where the longest power lines run. Consequently, very large GIC occur in northern Scotland and around Anglesey for example.

In Figure 5-4 and Figure 5-5 the Top Hat electrojet model is shown. The GIC are slightly larger than the Tapered Cosine model, as magnetic field is more concentrated over the UK. Note that in reality, the electrojet current density tends to look more like a tapered cosine.

![Figure 5-2: Input: Tapered Cosine electrojet; X component of the magnetic field; dH/dt = 5000nT/min](image)

Figure 5-2: Input: Tapered Cosine electrojet; X component of the magnetic field; dH/dt = 5000nT/min
Figure 5-3: Input: Tapered Cosine electrojet; Y component of the magnetic field; $\frac{dH}{dt} = 5000\text{nT/min}$

Figure 5-4: Input: Top Hat electrojet; X component of the magnetic field; $\frac{dH}{dt} = 5000\text{nT/min}$
5.2.2 Periods of 600 seconds

Longer period fields penetrate into the lower crust and mantle. This results in a larger surface electric field and hence larger GIC on average.

Figure 5-6 and Figure 5-7 show the GIC generated from the 10 minute period with an input magnetic field of $H = 6825\text{nT}$ or $dH/dt = 3000\text{nT/min}$ (c.f. Table 1). Note, the GIC are much larger compared with the figures in the previous section, though the $dH/dt$ is of course different. For example, the GIC at Aberthaw (near Cardiff) change from -142A to -245A, while at Smeaton (near Edinburgh) the GIC changes from -21A to -44A.
Figure 5-6: Input: Tapered Cosine electrojet; X component of the magnetic field; $dH/dt = 3000\text{nT/min}$
5.2.3 Summary Tables

The following tables (Table 3 to Table 5) give the twenty largest estimated GIC (i.e. total from the three phases) in the modelled power grid.

In each table are listed the latitude and longitude of the node used in the study and the approximate location name. The station number is an arbitrary number used in the modelling process to differentiate stations. The GIC for each variation period are given based upon the twelve combinations of modelling scenario: by electrojet type, by different \( \frac{dH}{dt} \) and then by orientation of the electrojet (approximately east-west \([X]\) or north-south \([Y]\)).

Note that the locations of the substations do not match exactly with station locations as supplied by National Grid in a more recent set of spreadsheets detailing the network. This is probably due to the simplified network model containing out-of-date data, or truncating/rounding of the latitude or longitude numbers. This also causes uncertainty in some areas where transformers are close together.
<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Number</th>
<th>1000nT/min</th>
<th>3000nT/min</th>
<th>5000nT/min</th>
<th>1000nT/min</th>
<th>3000nT/min</th>
<th>5000nT/min</th>
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<td>Y</td>
<td>X</td>
<td>Y</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Mybster/Thurso</td>
<td>64</td>
<td>8.64</td>
<td>125.69</td>
<td>25.92</td>
<td>377.06</td>
<td>43.19</td>
<td>628.43</td>
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<td>Redmoss</td>
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<td>20.64</td>
<td>153.04</td>
<td>34.41</td>
<td>255.07</td>
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<tr>
<td>Dunbar</td>
<td>222</td>
<td>4.56</td>
<td>40.21</td>
<td>13.67</td>
<td>120.62</td>
<td>22.79</td>
<td>201.03</td>
</tr>
<tr>
<td>Norton</td>
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<td>20.99</td>
<td>8.78</td>
<td>62.97</td>
<td>14.64</td>
<td>104.95</td>
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<tr>
<td>Peterhead</td>
<td>174</td>
<td>1.86</td>
<td>35.14</td>
<td>5.59</td>
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<td>9.32</td>
<td>175.71</td>
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<tr>
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<td>11.71</td>
<td>87.85</td>
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<td>146.41</td>
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<td>38.11</td>
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<td>190.54</td>
</tr>
<tr>
<td>Keadby</td>
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<td>1.21</td>
<td>13.41</td>
<td>3.64</td>
<td>40.23</td>
<td>6.06</td>
<td>67.05</td>
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<tr>
<td>Bridgend</td>
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<td>1.10</td>
<td>24.55</td>
<td>3.29</td>
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<td>5.49</td>
<td>122.77</td>
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<tr>
<td>Wylfa</td>
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<tr>
<td>Hinkley</td>
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<td>16.30</td>
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<td>48.89</td>
<td>68.40</td>
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<td>-5.01</td>
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<td>-99.89</td>
<td>-21.67</td>
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<td>-41.73</td>
<td>-10.23</td>
<td>-125.18</td>
<td>-17.06</td>
<td>-208.63</td>
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<td>-85.33</td>
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<td>-142.21</td>
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<tr>
<td>Bishops</td>
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<td>-6.87</td>
<td>-28.51</td>
<td>-20.61</td>
<td>-85.52</td>
<td>-34.35</td>
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<tr>
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<td>-42.85</td>
<td>-7.05</td>
<td>-128.55</td>
<td>-11.74</td>
<td>-214.24</td>
</tr>
</tbody>
</table>

Table 3: The twenty largest GIC (in Amps) generated by an electrojet with 2 minute (or 120 second) variation period.
Table 4: The twenty largest GIC (in Amps) generated by an electrojet with 10 minute (or 600 second) variation period. NB: though included, 5000 nT/min is regarded as physically unrealistic at this period, as it requires a $H_0$ which is inconsistent with Table 1 and Thomson et al. (2011).
<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Number</th>
<th>Tapered Cosine Model</th>
<th>Top Hat Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Mybster/Thurso</td>
<td>64</td>
<td>30.04</td>
<td>572.69</td>
</tr>
<tr>
<td>Cottam</td>
<td>49</td>
<td>7.75</td>
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<td>189</td>
<td>42.94</td>
<td>117.04</td>
</tr>
<tr>
<td>Keadby</td>
<td>120</td>
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<td>96.88</td>
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<tr>
<td>Redmoss</td>
<td>128</td>
<td>22.38</td>
<td>199.50</td>
</tr>
<tr>
<td>Dunbar</td>
<td>222</td>
<td>115.03</td>
<td>164.04</td>
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<td>Hinkley</td>
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<td>47.47</td>
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<td>74</td>
<td>32.07</td>
<td>183.38</td>
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<td>Peterhead</td>
<td>174</td>
<td>3.65</td>
<td>67.94</td>
</tr>
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<td>Staythorpe</td>
<td>208</td>
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<td>Indian</td>
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<td>-121.58</td>
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<tr>
<td>Feckenham</td>
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<td>-41.46</td>
<td>-160.46</td>
</tr>
</tbody>
</table>

Table 5: The twenty largest GIC (in Amps) generated by an electrojet with 1800 second (30 minute) variation period. NB: 3000 and 5000 nT/min variations are regarded as inconsistent with Table 1 and Thomson et al. (2011).
5.3 DISCUSSION

The results reported here are first attempts at determining the impact on the UK power grid of the worst-cases of space weather that we can expect in up to 200 years.

The analysis will need to be refined in the future. For example it is assumed that all the energy in the auroral electrojet is concentrated into a particular frequency, which is unphysical, but makes the problem manageable. Also scientific advances may change the appreciation of what constitutes a ‘worst case’, either in terms of \(\frac{dH}{dt}\) or in terms of the significance of other variables. Moreover the grid itself changes over time and even the model here is simplified with respect to the current situation at 2010/2011.

However the current modelling does show consistently that the same 23 locations are at risk from particularly large GIC. These are identified in Figure 5-8, with the ‘top twenty hot spots’ and their risk levels detailed in Tables 3-5.

Figure 5-8: Locations of the transformer nodes with the largest GIC risk. Also shown are the locations of the BGS UK magnetic observatory monitoring network (LER: Lerwick, ESK: Eskdalemuir, HAD: Hartland)
In summary from Tables 3-5 we note the following:

- The dominant east-west electrojet orientation produces total GIC of order tens, in some instances hundreds of Amps at the twenty most at-risk transformer locations.
- The ‘tapered cosine’ form assumed for the electrojet is arguably a more physical distribution of electrical current in the ionosphere, but results in typically lower GIC than the broader, ‘Top Hat’ model.
- The sign of GIC (+/-) is not important in terms of its impact on a transformer.
- Any North-South component to the electrojet over the UK will markedly increase the GIC flowing in transformer earths. This GIC can be an order of magnitude greater than that for an east-west oriented electrojet, i.e. of order hundreds of Amps.
- Longer period variations with significant magnitude (e.g. > 3000nT/min) are physically less and less realistic, as noted in section 2, but could produce large GIC if realised.
- We model and present results for a 5000 nT/min, 10 minute period electrojet. However it is doubtful (from Table 2 and the discussion in Section 3) that this is a physically realistic scenario and we would therefore caution against its use as any kind of ‘standard’.

Although model outputs (in Tables 3-5) are described in terms of approximately east-west (called ‘X’) and north-south (called ‘Y’) scenarios, the dominant electrojet orientation is in the east-west (geomagnetic) direction, particularly over any prolonged periods. Over shorter intervals there can be more of a north-south component to the electrojet where, as noted above, the risk to the system will become temporarily larger.

In order to calculate the GIC at any node in the grid, $n$, for intermediate orientations of the electrojet, away from the east-west orientation, one can use:

$$GIC_{\theta}(n) = GIC_{E-W}(n) \times \cos(\theta) + GIC_{N-S}(n) \times \sin(\theta)$$

where $E-W/N-S$ denotes the GIC calculated in the east-west and north-south directions respectively (i.e. X and Y in Tables 3-5) and $\theta$ is a positive angle for the electrojet measured from the E-W direction, up to ninety degrees.

Given that $GIC_{N-S}$ can be ten times larger than $GIC_{E-W}$, it only requires $\theta$ of order 6 degrees or more for the second term to begin to dominate the first. This is seen in measured magnetometer data during storms.

Some final, more general comments and caveats:

- The geophysical model (i.e. description of the conductivity of the UK and of its neighbouring seas) probably needs further work, specifically to improve the model over England and Wales. Fine-scale spatial detail could also be improved.
- The geophysical model of the auroral electrojet is idealised. It is not physically likely that a single frequency electrojet can exist. However it provides some indication of grid response. Also, the electrojet parameters (location, width) assume that the analysis of Thomson et al. (2011) is correct.
- The electrical model of the grid is simple and needs further work. Not least in terms of the resistances, transformer characteristics and the role of the lower voltage system (132kV and below) in distributing GIC. The current model assumes one line between nodes and one node per transformer substation, as well as common resistances for all components.
- In Figure 5-8 we show the locations of the UK magnetic observatories. Real-time, quality controlled data and data products, from these observatories is provided by BGS as monitoring data and can be used to assess the hazard to the UK power system.
6 Conclusions

The UK power grid is a complex network, which is constantly evolving (as is demonstrated in Turnbull, 2011, where the effect of adding and removing transmission lines from the UK system is tested).

The model we have used in this work is undoubtedly simplified, for example in respect of the fact that it contains only the 400 kV and 275 kV portions of the system. There is an extensive 132 kV system, particularly in Scotland, where significant GIC could be generated in an area of moderately high geomagnetic latitude and resistive terrain. The model as it currently stands also does not include the electrical links to the generator plant connected to the system. There are also, in the ‘real’ system, DC links to France, Netherlands, Ireland and, in the future, to Norway. None of these are represented in the existing grid model. From discussion with industry representatives it may be that the GIC impact of magnetic storms may be restricted to harmonic generation on either side of AC:DC convertors. However this is not clear and more work is suggested. System impacts, such as the transformer VAR (volts-amps reactive) demand during storms, are also not represented.

So the grid model is limited in its use for system operators. However it does provide clues as to the likely locations and order of magnitude estimates of the GIC that can flow in the UK system as a result of real and hypothetical storms. This is what has been shown in this work and in this report. Future studies will address the shortcomings of the existing models, including that of the UK conductivity model (see Beamish and Thomson, 2012, for more on this).
References

British Geological Survey holds many of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://envirolib.bgs.ac.uk.


