Current **crisis**

The effects of geomagnetic storms have the potential to be damaging to power grids and costly to a nation's economy. Here, **Drs Ciaran Beggan**, **Alan Thomson** and **Gemma Kelly** discuss how accurately predicting geomagnetically induced currents reduces this risk



What is a coronal mass ejection (CME) and how does it lead to geomagnetically induced currents (GIC)?

A CME is essentially an explosive release of billions of tonnes of the solar atmosphere into space – a cloud of protons, ions and electrons, constrained by magnetic fields. If the CME is Earth-directed and the magnetic field of the CME connects with the Earth's in a particular orientation, energy is deposited into the upper atmosphere and throughout the large-scale magnetic field around the Earth. This energy causes large currents to flow in the upper atmosphere. We can sometimes see these currents, as in the aurora, and they generate a relatively large and continuously changing magnetic field which is detectable on the ground. It is the changing magnetic field that generates small electric currents in the ground because most rocks are somewhat conductive.

Can you describe the Carrington-type geomagnetic storm that struck the Earth in 1859 ?

In September 1859, an astronomer at the Kew Observatory in London called Richard Carrington observed two very bright regions emerge and disappear within a few minutes in a large sunspot on the Sun's surface – this is what we now call a solar flare. The magnetic recording equipment in Kew also showed a large deviation had occurred at the same time. Less than 20 hours later, an enormous geomagnetic storm hit the Earth, with observations of aurora at low latitudes (Italy and Cuba are often mentioned) which were bright enough to read a paper at night, according to accounts of the time. There were also reports of damaging effects on the telegraph network, such as battery fires and electric shocks to operators. The storm lasted several days.

How is your research contributing to the UK's ability to prepare for similar events?

The Carrington storm is notable not only for its magnitude, widely regarded as the most extreme event of the last 150 years, but also because there is limited surviving data which we can still analyse. However our analysis of known extreme events in existing European magnetic observatory data, published in 2011, quantified for the first time the likely magnitude of a one-in-100 and one-in-200-year space weather event. This research was subsequently used by the UK's National Grid Company to estimate the current exposure of and risk to the UK high voltage system, and the results were published by the Royal Academy of Engineering in a report on extreme space weather and its likely impacts on technologies. These results have informed much of the ongoing discussion within the UK Government concerning the risk to national infrastructure, as detailed in the National Risk Register.

Could you provide a real-world example of a GIC impacting a power grid?

The case that is generally cited is the failure of the Hydro-Québec power system on 13 March 1989, following rapid magnetic field changes due to a geomagnetic storm. A few hours after the storm started, large GICs caused a series of transformers in north east Canada to shut themselves down for protection. This triggered a chain reaction as other transformers became overloaded and led to the power grid collapsing. The total time from the shutdown of the first transformer to the collapse of the grid was only 90 seconds. Estimates of economic damage are difficult to make but it is believed to have cost the company CAD $12 million and left 5 million people without power in cold weather for around nine hours.

Why is it important to understand the effects of GICs on the UK power grid?

It is vital to know if the UK faces a societal or economic risk through the potential for widespread damage to its power infrastructure, should a large geomagnetic storm occur. A study such as ours can also help identify regions prone to large GICs – for example, outlying or isolated regions of the grid – so that the grid operator can be vigilant for signs of misbehaviour during a storm.

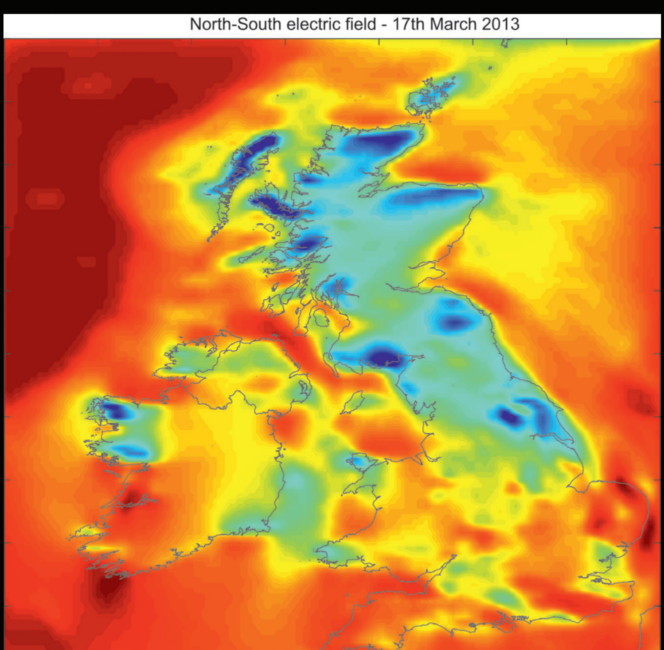
Preventing the power out

Since the creation of large-scale, interconnected power distribution networks, there has not been a geomagnetic superstorm to test them. As the likelihood of such an event increases, a team of geomagnetic researchers from the **British Geological Survey** is working to further our understanding of such phenomena and, crucially, to help preemptively protect our power grids against failure

THE MODERN WORLD takes the smooth operation of power distribution networks like the UK's National Grid completely for granted, to the extent that the economy is totally reliant on a guaranteed supply of electricity. While safeguarding the continual distribution of power is considered to be of paramount importance for governments across the world, episodes of damage to high-voltage transformers in the UK and South Africa, and power grid failure in Canada and Sweden from storms in 1989 and 2003 show that a better understanding of the threat is still required.

These power failures were all the result of geomagnetically induced currents (GICs) caused by large geomagnetic storms. Usually, GICs flow through the ground with relatively little effect, but if presented with a path of lower resistance, they will tend to pass through it. Unfortunately, along with pipelines, railways and telecommunication cables, high-voltage electricity transmission networks with their earthed transformers can provide just such a pathway. This leads to disruption of the transformers' optimal operation and, if the current is large enough, can trigger a domino-style switch-off across the network, bringing down the entire grid.

Concerns over future power failures are growing. Super storms like the Carrington Event of 1859 are thought to be rare, happening perhaps once in 200 years or more – if this is the case then it seems we are right to be wary. Furthermore, in the roughly 11-year cycle of solar activity that controls GIC activity on Earth, a long period of quiescence has just ended. While the coronal mass ejections (CMEs) which lead to GIC can occur at any time, in the build up to the solar maximum of 2013, it was timely to conduct research into GIC effects so that operators stand a better chance of avoiding grid failure.



Electric field map of the UK at the peak of a recent storm.

GEOPHYSICAL GEOLOGY

At the British Geological Survey (BGS), Edinburgh, a group including geophysicist Dr Ciaran Beggan is building on past research conducted at the institute to produce a comprehensive geophysical model of GICs in the UK. Their previous investigations were smaller-scale studies that sought to characterise GIC flow in central Scotland's electricity grid and a simplified version of the UK's power grid – and they have certainly proved useful. However, Beggan still did not know how large a geomagnetic storm would need to be to adversely affect the UK high-voltage network, or indeed the extent of possible GIC magnitudes.

The team was initially interested in exploring the worst case scenarios, but at the time more basic research was required to understand factors such as the flow and movement of GICs through the Earth's crust and within the power-grid itself. In order to achieve a reasonable geophysical model, research into how GICs are affected by the physical configuration of the National Grid, the conductivity of crustal rocks and the maximum rate of change in time-varying external magnetic fields was of fundamental importance.

TRANSMISSION TUNE-UPS

In order to map the spatial structure of the varying magnetic fields during a storm, Beggan turned to an interpolation technique called Spherical Elementary Current Systems (SECS) which, through the use of physical equations, provides more accurate mapping compared with other standard interpolation methods. When using data from 10 observatories and variometers in and around the UK, the SECS technique is particularly effective during periods of high geomagnetic activity, making it possible to estimate detailed spatial variance in the magnetic field. These maps show that strong external magnetic field activity is not, as might be assumed, confined to high latitudes, something which was dramatically demonstrated by the 1989 and 2003 episodes, both of which involved damage in low-latitude countries.

The existing 3D model of rock conductivity was first built in 1998 and needed an update. It was fairly detailed in the central lowlands of Scotland, but the rest of the UK was lacking any structure. Using data from aerial geophysical surveys such as the Tellus Project in Northern Ireland, which BGS helped analyse, and in conjunction with data from laboratory studies, colleague Dr David Beamish was able to estimate the conductivity of every rock type in the UK. "This gives us a very detailed map of electrical resistivity in the UK," states Beggan. With its addition, not only were the values of ground conductivity vastly improved, but the model also benefited from more accurate representations of coastlines and terrane boundaries.

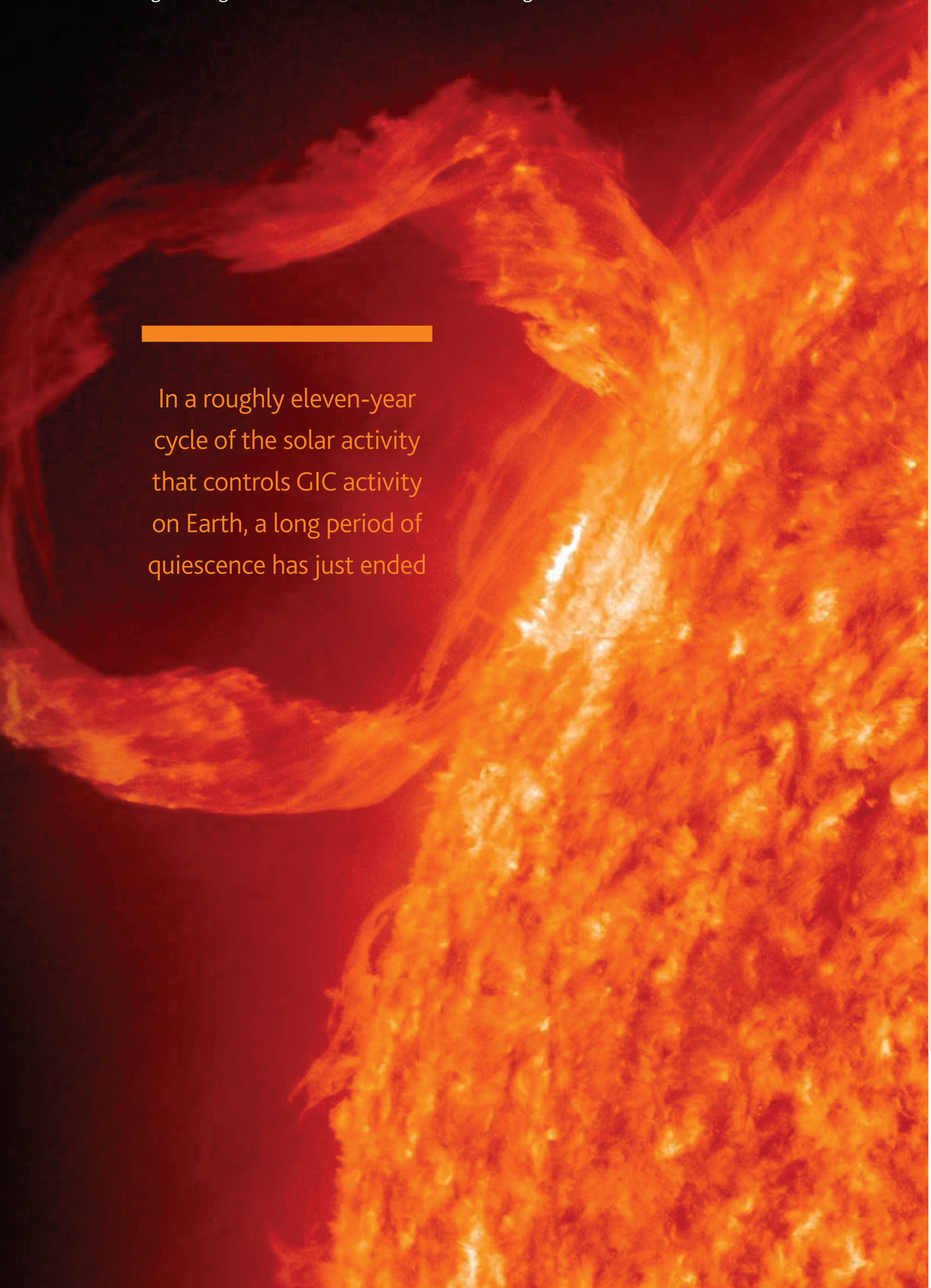
To attempt to understand how the configuration of the power grid affects GIC flow through it, a representation was developed using data received directly from National Grid UK Ltd on the position of transformers, linkage, line and earthing resistances to compute GIC at specific points. A set of mathematical equations is used to determine the electrical field induced in the conductive subsurface from the magnetic field. Once the team has a map of the induced electric field and the properties of the power transmission network, they can quickly calculate the expected GIC at each transformer.

MODEL BEHAVIOUR

In its present state, the electric field model correlates strongly with true values of the electric field derived from actual measurements at three UK observatory sites. During geomagnetic storms, the measurements appear reliable, though in less disturbed conditions effects local to the instruments come into play, causing discrepancies between the actual measurements and model predictions. In Scotland and Devon, for example, the measured data are influenced by rain (ie. soil moisture) and electric fields generated by tidal motion. Despite this, Beggan has confidence in the magnetic field extrapolation method, the conductivity map and the algorithms used for computing the electrical field during geomagnetic storms.

However, making sure the model is as robust as possible means that predictions of GIC flowing through transformers in the power grid need to be checked against measurements at transformers, which are not yet available. Once such instruments are in place and readings can be taken, the intention is to use the data to refine the high-voltage network model. When this stage is complete, final investigations into the distribution of GIC will begin, producing results that will inform the technical decision making of the power grid operators and regulators.

The BGS is also involved in a pan-European Seventh Framework Programme (FP7)-funded project called European Risk from Geomagnetically Induced Currents (EURISGIC), whose remit is to examine the wider risk across Europe. The EURISGIC group anticipates high-voltage networks are only set to get bigger and become increasingly more connected, thus exposing more systems to risk. With no geomagnetic superstorms having affected the Earth in over 150 years, Beggan's research could not have come at a better time for aiding the design of powergrid defence against GIC.



In a roughly eleven-year cycle of the solar activity that controls GIC activity on Earth, a long period of quiescence has just ended

INTELLIGENCE

GEOPHYSICAL MODELLING OF GEOMAGNETICALLY INDUCED CURRENTS IN THE UK

OBJECTIVES

To improve modelling and predictions of geomagnetically induced currents (GICs), with a view to minimising the impact on nationwide power grids.

KEY COLLABORATOR

Dr Andrew Richards, National Grid UK

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DR CIARAN BEGGAN is a geomagnetic researcher at the British Geological Survey, specialising in main field modelling, deep Earth processes and the flow of the outer core. Beggan has been working on GIC since he joined BGS in 2009, after completing a PhD at the University of Edinburgh, prior to that he worked as a systems engineer in the aerospace sector.

DR ALAN THOMSON is Head of Geomagnetism at the British Geological Survey and researcher in geomagnetism, particularly in ground-based and satellite magnetic data, magnetic field modelling, space weather and space climate and the geomagnetic hazard to technology. He has produced more than 60 scientific papers and technical reports, of which 30 have been published in peer-reviewed journals.

DR GEMMA KELLY is a postdoctoral Research Associate at the British Geological Survey, examining the hazard posed by space weather to the UK power system. She recently completed her PhD at the University of Liverpool where she employed innovative techniques using satellite magnetic data to help understand the effects of the auroral regions on main field models.

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