When the lights go out...

Space weather stands out among natural hazards as one of the great unknowns, largely for its potential effect on modern technology. Alan Thomson and Jim Wild discuss the challenges in understanding the geomagnetic hazard to national power grids.

The impact of solar activity on human technology has been a cause for concern ever since the 19th century, when the Victorian telegraph system was disrupted by a massive geomagnetic storm. Although the ferocity of that 1859 event, triggered by a burst of solar activity observed by English astronomer Richard Carrington, has never been equalled, adverse "space weather" poses a risk to modern technologies both in space and on the ground. The recent disruption to European air traffic from the eruption of the Eyjafjallajökull volcano in Iceland served as a stark reminder that the everyday technologies on which our modern society depend are vulnerable to sudden and unexpected natural events. Indeed, many delegates at the 2010 National Astronomy Meeting in Glasgow, scientists whose daily work focuses on understanding the most awesome powerhouses of the universe, were left stranded by a natural event that posed no immediate threat to their health or safety but was a potentially major problem for the jet engines that had brought them to the meeting.

In many respects, this disruption arising from volcanic activity is analogous to the societal threats posed by space weather. The surface of the Earth is shielded from virtually all of the effects of space weather by our planet's strong magnetic field and dense atmosphere. Even the worst space weather disturbances have little or no direct impact on life on the surface of the Earth. But our advanced society depends upon an interlinked infrastructure of high-technology systems to deliver vital everyday services, chief among which is a reliable electricity generation system and distribution grid.

The Rishbeth Prize 2010

This article by Alan Thomson and Jim Wild, and the following one by Katie Turnbull, are both winners of the Rishbeth Prize for 2010. The prize is awarded to the best poster presentations at the Magnetosphere, Ionosphere and Solar–Terrestrial physics and UK Solar Physics annual meetings, which this year were held together with the National Astronomy Meeting in Glasgow. The prize is named in honour of the late Henry Rishbeth, founder member of MIST.

1: Failure in a large South African generator transformer, three weeks after the Halloween storm of 2003. The disruption of the winding and insulation by the arcing fault at the time of final failure is clear. The arcing fault also destroys evidence that might lead to a better understanding of the progression of damage after initiation by the geomagnetic current event. (From Thompson *et al.* 2010)

What are the effects?

There is much documented and anecdotal evidence of the effects of extreme space weather on the power systems of the developed world. Possibly the most frequently cited example of a damaging impact is the collapse of the Hydro Quebec power system on 13 March 1989. A severe geomagnetic storm shut down the complete Quebec high-voltage system in less than a minute, with significant knock-on economic cost and social disruption (Bolduc 2002). More recent storms, for example the October 2003 "Halloween" magnetic storm (which resulted in lower-latitude auroral activity including over the UK), are also known to have affected networks in Europe, North America, South Africa and elsewhere (e.g. Pulkkinen *et al.* 2005, Gaunt and Coetzee 2007, Thomson *et al.* 2005). Meanwhile, a recent study by the US National Research Council (2008) into the present-day economic impact of a repeat of the "Carrington Storm" of September 1859, has estimated the cost at \$1–2 trillion in the US alone in the first year after the storm, with full recovery taking between four and ten years, depending upon the level of damage to infrastructure.

It is well known that the impact of a coronal mass ejection (CME) on the Earth's protective magnetosphere can lead to a geomagnetic storm, dramatically boosting existing electrical currents in the magnetosphere. These current systems cause large magnetic variations, inducing electric fields in the solid Earth that, in turn, generate geomagnetically induced currents (GICs) in conducting pipes and wires. Once flowing through a power network, GICs are unwanted quasi-direct currents, superimposed on the alternating currents within the grid, unbalancing and damaging critical transformers.

Power grids at all latitudes, not only those in polar regions, are at risk from the natural hazard of GICs (figure 1). However, after entering a conducting network via grounding points, the different pathways taken by GICs are influenced by the electrical properties of each network. As such, the study of GIC impact on national power grids incorporates aspects of geophysics, solar physics, solar–terrestrial physics and power engineering. There is therefore considerable scope for cross-disciplinary engagement between solar-, space- and geophysicists and the power engineering community, to turn scientific understanding into practical tools for risk assessment and hazard mitigation.

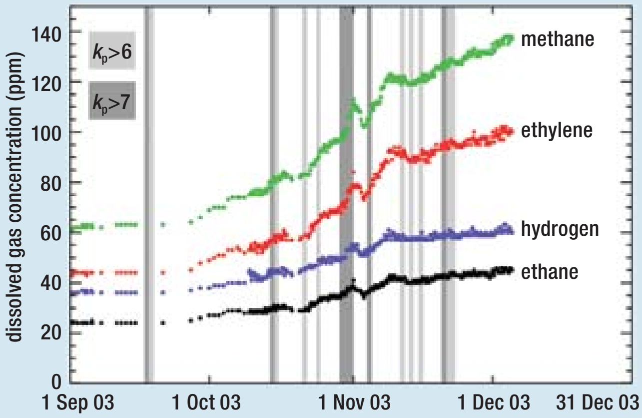
GIC workshop

In order to further this engagement, the University of Cape Town and the Hermanus Magnetic Observatory hosted a workshop in South Africa in December 2008 for a group of UK and South African scientists with GIC expertise. This workshop was funded by the Royal Society on behalf of the UK government, and by the National Research Foundation on behalf of the government of South Africa. One aim of the GIC workshop was the free exchange of ideas, insights and knowledge about the natural geomagnetic hazard and GIC risk in both developed and developing countries. A second aim of the workshop was to summarize the scientific and engineering "state of play" for the power engineering industry, for the public and for policy makers (Thomson *et al.* 2010). The workshop participants therefore compiled a short list of major points that they believed with some confidence that scientists and engineers do know about the GIC risk to electric power systems, as well as major things we still do not know (see page 5.24).

Compared with the "do knows" in our list, our "don't knows" may be more contentious within the scientific community. It may be debated which items are most important at present, while at the same time understanding that other issues might yet become more relevant. How-

Known knowns: 10 things we know about GICs

1. Solar storms (i.e. CMEs) that lead to high levels of GICs are statistically more likely during periods close to solar maximum and in the descending phase of the solar cycle, but they do also occur at all other times in the solar activity cycle.
2. The magnetospheric and ionospheric currents that drive GICs are different at different latitudes.
3. The dominant cause of GICs in power grids is the temporal rate of change of the Earth's magnetic field.
4. Interpolating the magnetic field from spatially distributed geomagnetic observations improves the prediction accuracy of GICs at any given point, even at mid-latitudes (e.g. Bernhardi *et al.* 2008). This is in comparison with predictions made from data from a single magnetic observatory, taken to be representative of the "regional" situation.
5. GICs are larger in countries and regions where the geology is generally more resistive (discussed, for example, in Pirjola and Viljanen 1991).
6. A multi-layered and laterally varying ground conductivity model gives better prediction of GICs than the simpler assumption of a homogeneous Earth (e.g. Ngwira *et al.* 2008, Thomson *et al.* 2005).
7. GICs have been demonstrated to affect power systems at all latitudes.
8. GICs can affect many power transformers simultaneously at multiple points across regional- and continental-scale networks.
9. Series capacitors in transmission lines may interrupt GIC flow in power networks, but are expensive. Some strategies involving capacitors may increase GIC and reactive power demands (e.g. Erinmez *et al.* 2002).
10. It is possible from transformer dissolved gas analysis to identify GIC-initiated damage before complete transformer failure occurs. This is especially true if the rate of gassing increases in widely separated transformers across a network (figure 2).



2: Results of dissolved gas analysis for a transformer in South Africa during the geomagnetically active period in late 2003, also showing intervals of k_P 6 and 7 level geomagnetic activity. This shows continued gas generation throughout the period. The ratios of different gases indicate low temperature degradation of paper insulation (which ultimately led to the transformer being removed from service). Similar trends were observed at several other sites across the South African grid throughout this period, suggesting that the damage was caused by a nationwide factor. (From Thompson *et al.* 2010)

Known unknowns: 10 things we don't know about GICs

1. What are the solar and interplanetary events and signatures that are most "geoeffective" in terms of GIC causation?
2. What characteristics of extreme geomagnetic storms pose the highest risk?
3. In predicting GICs, what is the contribution of each of the different components of the geomagnetic field and other parameters such as the ionospheric total electron content and the interplanetary magnetic field (e.g. Pulkkinen *et al.* 2006)?
4. What are the definitive spatial/temporal scales of the magnetospheric and ionospheric currents that drive significant GICs in grids?
5. What is an adequate number/distribution of magnetometers to model GICs?
6. Which information, given on what timescale, is most useful for any given power utility/authority to manage its GIC risk?
7. In modelling GICs in a power grid, what level of detail is required of Earth conductivity (as a 3-D model or otherwise)?
8. What are the characteristics of power transformers that determine their susceptibility to GICs and therefore determine the extent of damage sustained under different levels of GICs?
9. What are the transformer failure mechanisms after damage initiated by GICs?
10. Where should scientists go to access industry archives, particularly archives of GIC measurements obtained concurrently with network data (i.e. network configuration and connections, DC resistances of transmission lines and transformers and station earthing resistances)?

ever, by making progress on our "don't knows" we expect advances in the community's ability to monitor, model and predict the impacts of space weather and GICs on power grids.

Solar cycle 24 is just beginning and we can expect that the space-weather hazard to ground-based technologies will increase, just as it did during the up-turn of previous cycles. Wider discussion of these issues is required, not just within the international space-weather community, but also within industry and society. ●

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