When the lights go out

The impact of solar activity on human technology has been a cause for concern ever since the mid nineteenth century when the Victorian telegraph system was disrupted by a massive geomagnetic storm. Although the ferocity of that event in 1859, triggered by a burst of solar activity observed by English astronomer Richard Carrington, has never been equalled, adverse "space weather" poses a risk to many modern technologies both in space and on the ground. Alan Thomson and Jim Wild discuss the present-day challenges in understanding the geomagnetic hazard to national power grids

The recent disruption to European air traffic due to 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 held 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 threat to their immediate health or safety but was a potentially major hazard to the jet engines that power the modern aviation industry.

In many respects, this recent disruption due to 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 virtually no direct impact on life here 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.

There is much documented and anecdotal evidence of the effects of GICs on the power systems of the developed world. Possibly the most often cited example of a damaging impact is the collapse of the Hydro Quebec power system on 13th March 1989. A severe geomagnetic storm shut down the complete high voltage system of Quebec 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, Figure 1) 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 US alone in the first year after the storm, with full recovery taking between 4-10 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 flowing through the magnetosphere. These current systems cause large magnetic variations that induce electric fields in the solid Earth that, in turn, generate geomagnetically induced currents (GICs) that flow in conducting pipes and wires. Once flowing though a power network, GICs are unwanted quasi direct currents, superimposed on the alternating currents within the grid, unbalancing and damaging critical transformers.

It is clear that power grids at all latitudes, not only those located in the polar regions, are at risk from the natural hazard of GICs (Figure 2). 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 geo- physicists and the power engineering community, to turn scientific knowledge into practical tools for risk assessment and hazard mitigation.

In order to further this engagement, in December 2008 the University of Cape Town and the Hermanus Magnetic Observatory hosted a workshop in South Africa 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 on the natural geomagnetic hazard and on GIC risk in both developed and developing countries. A second aim of the workshop was to summarise 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 boxes on page X).

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 the present time, understanding that other issues might yet become more relevant. However, by making progress on our current '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 wider society.

Dr. Alan Thomson is the Head of the Geomagnetism Team at the British Geological Survey and is based in Edinburgh. Dr. Jim Wild is a Senior Lecturer in the Space Plasma Environment and Radio Science Group in the Department of Physics at Lancaster University.

Ten things we do 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) and 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. However, 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 trans- former failure occurs. This is especially true if the rate of gassing simultaneously increases in widely separated transformers across a network (Figure 3).

Ten 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 are the characteristics of extreme geomagnetic storms that pose the highest risk to power systems
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 is an appropriate level of detail required of Earth conductivity (as a 3D 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 subsequent to damage initiated by GICs?
10. Where should scientists go to access industry archives, particularly archives of any GIC measurements obtained concurrently with network data (i.e. network configuration and connections, DC resistances of transmission lines and transformers and station earthing resistances)?

Figure 1: An auroral display observed from Selsey, in the south of England (at 47.2°N magnetic north) on 31 October 2003 in the aftermath of the Halloween Storm. (Photo credit: Pete Lawrence, www.digitalsky.org.uk)

Figure 2: Failure in a large South African generator transformer three weeks after the Halloween storm of October 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.

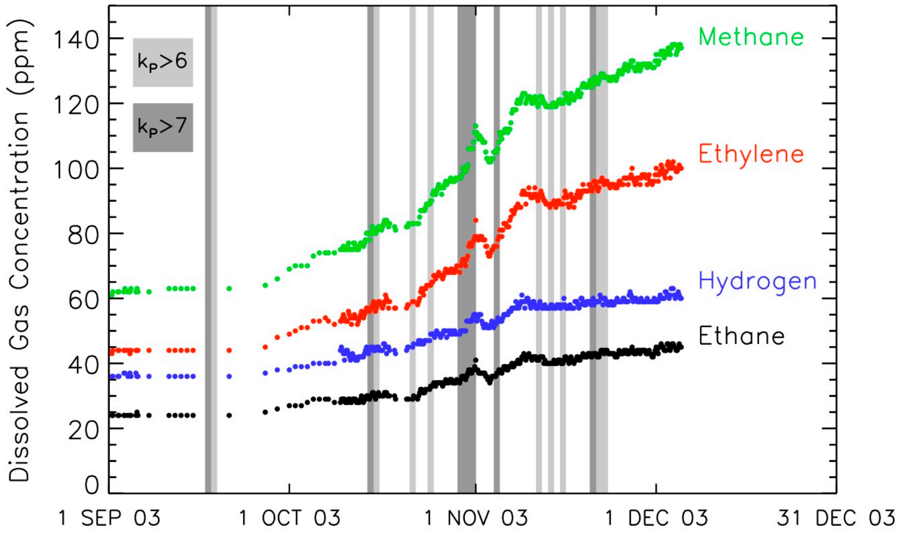

Figure 3: Results of dissolved gas analysis for a transformer in South Africa during the geomagnetically active period in late 2003. Intervals of K_P 6 and 7 level geomagnetic activity are also indicated. This shows continued gas generation throughout the period. The ratios of different gases indicates low temperature degradation of paper insulation (which ultimately lead 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.

References

Bernhardi, E.H., Cilliers, P.J., Gaunt, C.T. Improvement in the modelling of geomagnetically induced currents in South Africa. S. Afr. J. Sci. 104, 265–272, 2008.

Bolduc, L. GIC observations and studies in the Hydro-Quebec power system. J. Atmos. Sol.-Terr. Phys. 64, 1793–1802, doi:10.1016/S1364- 6826(02)00128-1), 2002.

Erinmez, I.A., Kappenman, J.G., Radasky, W.A. Management of the geomagnetically induced current risks on the National Grid Com- pany's electric power transmission system. J. Atmos. Sol.-Terr. Phys. 64, 743–756, 2002.

Gaunt, C.T., Coetzee, G. Transformer failures in regions incorrectly considered to have low GIC-risk. in: Proceedings of the IEEE Powertech Conference, July 2007, Lausanne, Switzerland, 2007.

Ngwira, C.M., Pulkkinen, A.A., McKinnell, L.-A., Cilliers, P.J. Improved modeling of geomagnetically induced currents in the South African power network. Space Weather 6, S11004, doi:10.1029/ 2008SW000408, 2008.

Pirjola, R.J., Viljanen, A.T. Geomagnetic induction in the Finnish 400 kV power system. Environmental and space electromagnetics, in: Kikuchi, H. (Ed.), Proceedings of the International URSI Symposium on Environmental and Space Electro-Magnetics, Tokyo, Japan, Septem- ber 4–6, 1989, Springer, Tokyo, Printed in Hong Kong, pp. 276–287 (Chapter 6.4), 1991.

Pulkkinen, A., Lindahl, S., Viljanen, A., Pirjola, R. Geomagnetic storm of 29–31 October 2003: geomagnetically induced currents and their relation to problems in the Swedish high voltage power transmission system. Space Weather 3, S08C03, doi:10.1029/2004SW000123, 2005.

Pulkkinen, A., Viljanen, A., Pirjola, R. Estimation of geomagnetically induced current levels from different input data. Space Weather 4 (8), S08005, doi:10.1029/2006SW000229, 2006.

Thomson, A.W.P., McKay, A.J., Clarke, E., Reay, S.J. Surface electric fields and geomagnetically induced currents in the Scottish power grid during the 30 October 2003 geomagnetic storm. Space Weather 3, S11002, doi:10.1029/2005SW000156), 2005.

Thomson, A.W.P, Gaunt, C.T., Cilliers, P.. Wild, J.A., Opperman, B., McKinnell, L.-A., Kotze, P., Ngwira, C.M., Lotz, S.I., Present day challenges in understanding the geomagnetic hazard to national power grids, Advances in Space Research, Volume 45, Issue 9, Special Issue: Recent Advances in Space Weather Monitoring, Modelling, and Forecasting, 3 May 2010, Pages 1182-1190, ISSN 0273-1177, DOI: 10.1016/j.asr.2009.11.023.

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