REDUCING UNCERTAINTY - AN ELECTRICITY UTILITY'S RESPONSE TO SEVERE SOLAR STORMS

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Abstract

Until recently, electricity utilities in mid- and low-latitude regions believed that solar storms had no (or only insignificant) effect on their power systems. Then it was noticed that the onset of damage in several large transformers, leading to their failure, correlated very closely with the Halloween storm of 2003. Only then did engineers start to understand that a very severe storm could have serious consequences outside the high-latitude regions.

There are many uncertainties in predicting the effects of solar storms on electrical systems. The severity and time of arrival of a storm are difficult to model; so are the geomagnetically induced currents (GICs) expected to flow in the power networks. Published information about the responses of different types of transformers to GICs is contradictory. Measurements of the abnormal power flows in networks during solar storms generally do not take into account the effects of the current distortion and unbalance, potentially giving misleading signals to the operators. And the normal requirement for optimum system management while allowing for the possibility of faults caused by lightning, birds and other causes all limit the capacity of system operators to respond to the threats of GICs.

A utility's response to the threat of damage by GICs depends on the expected frequency and magnitude of solar storms. Approaches adopted in high-latitude regions might not be appropriate where fewer storms are expected to reach damaging levels. The risks of an extreme storm cannot be ignored, and understanding the response mechanisms suitable for low-latitude regions has the capacity to inform power systems planners and operators worldwide.

Awareness of a Problem

Complexity contributes to uncertainty. Large power systems are complex, comprising many components and operating under variable conditions to meet the constantly changing requirements of the customers for power.

Components of the power system fail for diverse reasons, including ageing, corrosion, lightning and human interference. Redundancy is provided to reduce the effects of component failure, but still some customers' supplies are interrupted when too many fail and, in extreme situations, the collapse of a whole system causes widespread blackouts as in North America in 2003 and India in 2012.

A system with sufficient redundancy is able to continue supplying the customers in spite of an unexpected component failure, and is said to be operating in a normal state. The reserve margin, a term mostly used to describe generation capacity, represents the redundancy available to make up for the loss of any component, termed a contingency event. When the reserve margin is too small, the loss of one or more key components (generators, transformers and/or feeders) initiates interruptions. However, the real problem starts before the component or a combination of components is lost. External events, internal degradation and loading all contribute together to the likelihood that contingencies will exceed the compensation capacity of the reserve margin. Providing enormous reserve and redundancy is feasible but too costly. Therefore, system planners and operators need to find optimum conditions, continuously.

Planners and operators develop a good understanding of the most common problems and the most common operating conditions, so most decisions are based on average conditions. Less frequent phenomena are less well understood.

Geomagnetic storms severe enough to disrupt power systems are uncommon and, until recently, were thought to have no effect on power systems in low latitude regions. This is not really surprising, since the mechanisms leading to failure were relatively poorly understood. Investigations in South Africa during the 1990s, after the Quebec storm of 1989, found no evidence that geomagnetic storms were a problem. Both the power system and the effects of geomagnetic storms are complex and, with hindsight, the conclusions of those investigations are not surprising.

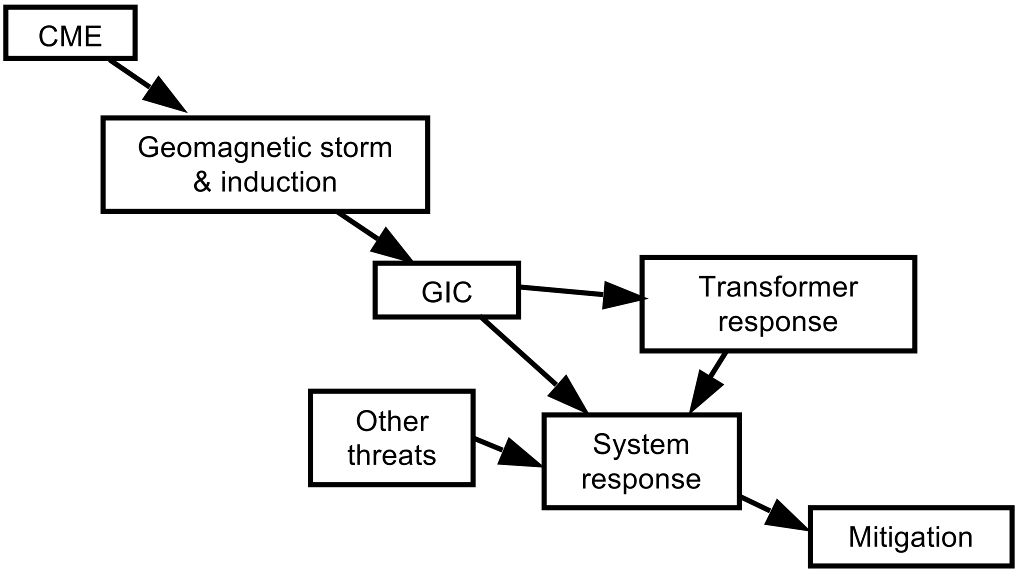
The Halloween storm of October 2003 led to a different conclusion - that solar events could affect power systems in low latitude regions. The conclusion that geomagnetically induced currents (GICs) could be a problem [Gaunt and Coetzee, 2007] was disputed. At the time the mechanisms of failures apparently initiated by GICs were not well understood and the failures that occurred were attributed to various other causes. The situation is outside the normal experience of system planners and operators and cannot be represented by average conditions. The complexity of predicting geomagnetic disturbances and their effects on power systems create substantial uncertainty for electricity utilities [Thomson et al., 2010]

This paper presents the findings of some research undertaken since 2007 to reduce that uncertainty.

A Model of the System

The system needing to be considered is greater than a power system. It includes the events that initiate GICs and extends to the possible responses of the utility. Figure 1 shows a model of the system used in our research.

Figure 1: Systems approach to GICs



The system has five sub-systems:

Space physics models the processes from a coronal mass ejection (CME) on the Sun to the disturbances of the Earth's magnetic field and the induction of the GICs in the power system.

Network analysis calculates the actual currents in the network's lines and transformers, including the effects of the transformer response.

Transformer engineering investigates the responses of the transformers to the induced currents, including the transient response to quasi-dc, the generation of harmonics that distort the power frequency sinusoidal voltages and currents, the processes of overheating, and the degradation and failure of the transformers.

Network reliability and cost assessment considers the performance of the network as a whole, affected by other threats as well as GICs, and the likely damage cost associated with any operating condition.

Decision support for network planners and system controllers models the implications of alternative approaches to preventing or mitigating the physical and financial damage that can be caused by GICs.

Space physics

Space physics addresses the key questions of how often and how severe the geomagnetic disturbances, usually generated by CMEs, are expected to be, and how big and when GICs are expected to flow in the power systems.

The magnitudes of the most severe disturbances in each solar cycle, measured or estimated as the peak geomagnetic intensity (3-hourly index aa), do not appear to vary much with the magnitudes of the solar cycles as measured by sunspot number. The peak sunspot number of the solar cycles when two of the most severe GMDs recorded (in 1859 and 1921) occurred were quite similar to that of the solar cycle expected to peak in 2013.

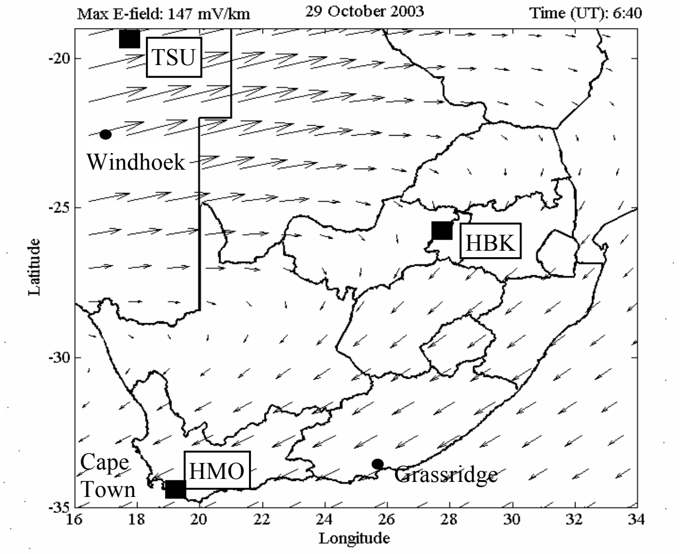
The frequency of extreme disturbances has been studied by various researchers [Thomson et al., 2011]. It is clear that several storms have been more severe than the Halloween storm that is believed to have been the initiator of significant damage to transformers in the South African power system during 2003. It is now over 150 years since the extreme storm known as the Carrington event, and the likelihood of another similar or larger disturbance is of great interest to power systems engineers.

Although probability distributions do not address the uncertainty of when severe and extreme events will occur, they do reduce the uncertainty in modelling the maximum likely stress on the power systems.

Building on work done in other countries, electric field interpolation techniques have been used to model the conditions in South Africa during geomagnetic disturbances. Figure 2 [Bernhardi et al., 2008] illustrates how non-uniform the field was at one stage of the Halloween storm and that it was closely aligned to the topology of the main transmission network. Similar maps at 2-minute intervals show the field was turbulent for several hours. Clearly, early assumptions of a uniform plane wave model were quite inaccurate. Figure 2 shows three of the magnetic observatories in Southern Africa at Hermanus, Hartebeeshoek, Tsumeb and another is now operational at Keetmanshoop, south of Windhoek.

The severity and characteristics of disturbances in South Africa might reasonably be expected to be similar to disturbances at other locations of similar geomagnetic latitude, such as in North America, Europe, China and Australia. However, the expectation is coarse and does not take into account the time of day and the possible interaction between the equatorial and polar ring currents during significant disturbances. Research on these aspects will be useful as a basis for comparing power system responses in the various regions, and further reducing uncertainty.

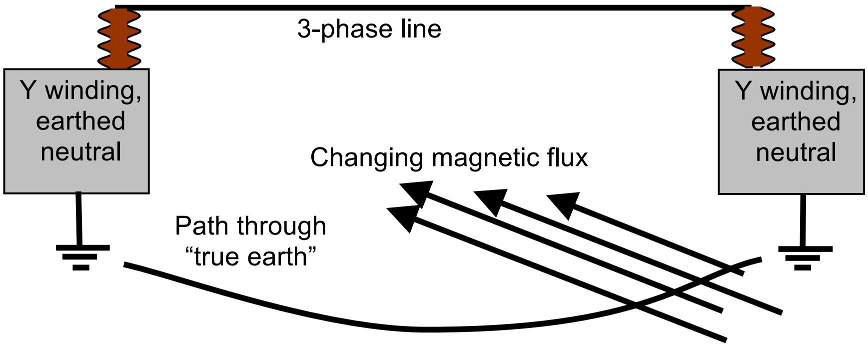
Figure 2: Grid of interpolated horizontal electric field over Southern Africa on 29 October 2003 at 06:40, calculated using measured magnetic fields at three observatories.



Space physics also contributes the models of induced current in the branches of the power system network connecting the nodes (substations) where transformers are installed with the neutral points earthed (grounded). GICs flow in loops illustrated in Figure 3 created by:

- the transmission line conductors,
- the transformers at each end that have the neutrals earthed for the purposes of safety, operations control, and reducing the cost of the transformers, and
- the path through the Earth, which has very low resistance and is often referred to as 'true earth'.

Figure 3: Induction of GICs in the power transmission system



The variation of the magnetic field, and thus the induced current, has a typical cycle time of minutes (~0.01 Hz), which is very slow compared with the rate of change of voltage and current in the power system (50 or 60 Hz). Therefore, power systems engineers often refer to GICs as being quasi-dc in their character, but it is important to realize that the currents do vary slowly.

Of course, post-event calculations of field conditions and induced currents are useful for research, but the operations control staff of an electricity utility need real-time data and, preferably, forecasts of storm onset and severity about six hours ahead. These models are not yet available. More accurate modelling based on measurements at the Lagrange Point L1, giving about 20 minutes warning during extreme events, would be useful in reducing uncertainty.

Network analysis

Network analysis, based on models of GIC induced in the overhead lines of the transmission network, calculates the currents expected to flow in the substation transformers. It is well known that the magnitudes of the induced currents in the lines and transformers depend on the characteristics of the geomagnetic disturbance, the resistivity of the ground and the network configuration (topology and conductor resistances). Until recently, the network analysis has not taken into account the time delay that arises from the charging of a large transformer - an inductance - by the quasi-dc GIC. The current in a large transformer will take a period of minutes to respond completely to a step change of induced voltage. As shown by the turbulent field modelling, the calculation of network and transformer currents is a dynamic process, and it is also influenced by the physical construction of the transformers. Three-phase 3- or 5-limb and single-phase transformers all respond differently to imposed GIC potentials, and the network analysis must take the differences into account.

New approaches to network calculations, from basic principles and based on mapping a disturbance to the response, are being attempted. Even small disturbances, such as have occurred several times already during the present solar cycle, produce measurable responses in the transformers. Reliable current measurements in the neutrals of many transformers in many parts of the network are needed to calibrate the calculations, and these are now being put in place. The new approaches, once tested on even small signals, could successfully model more intense disturbances.

Network analysis also calculates the power flow in the system, essential for understanding the network's capacity to maintain acceptable voltage conditions. It is widely known that GICs flowing in transformers increase the non-active (reactive) power required from the system [Molinski, 2002], explaining the unusual real and reactive power swings and voltage depressions observed during the Quebec storm [Kappenman, 1990]. More recent work has shown that, under conditions of distortion, unbalance and with dc components, a new definition and method of measuring apparent power and power factor is needed to allow potential voltage-instability conditions on a network to be interpreted correctly [Malengret and Gaunt, 2011, and companion papers]. Laboratory-scale measurements and simulations have shown that the power factor, reflecting the effective capacity of a system to deliver power, is substantially lower than indicated by conventional measurements when dc components flow in transformers [Gaunt and Malengret, 2012]. Since a recent NERC report on reliability concludes "*The most likely worst case system impact from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support simultaneous to a dramatic increase in reactive power demand*" [NERC, 2012], the new approach will help operators to identify the best system configurations.

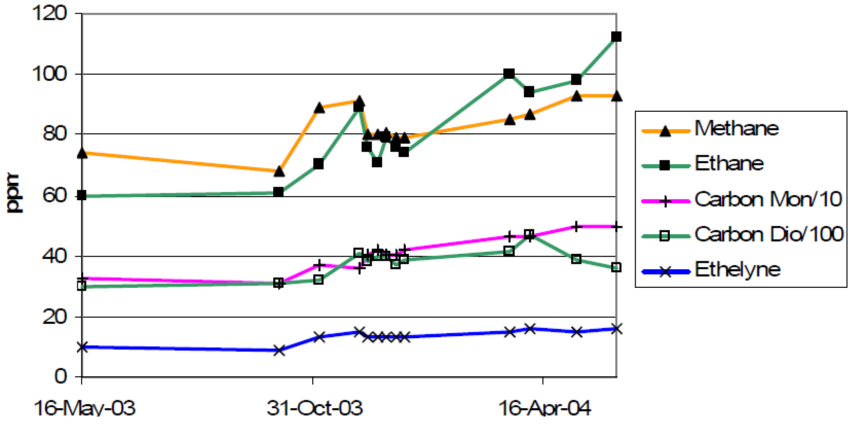
Transformer engineering

The GIC component of the current flowing in a transformer disturbs the normal power-frequency operation of the magnetic circuit, causing core saturation, increasing the leakage flux, and generating harmonic distortion and voltage unbalance. These effects in the transformers have the capacity to cause overheating and damage that depend on the design of the transformers and the load being carried, as well as on the magnitude, variation and duration of the induced currents. It is difficult to predict completely the damage likely in a transformer because of the many variables, but continual progress is being made in the modelling of currents, the heating effects, and transformer condition monitoring and fault investigation.

Damage to transformers is particularly complex. Although intense GMDs have been associated with physical melting of steel components of transformers [Kappenman, 1990], the nature of damage in transformers at mid-latitudes is quite different. It is postulated there are many different routes to failure, according to the conditions in the transformer at GIC commencement. For example, in appropriate conditions, bubbles can form within a winding if leakage flux and eddy currents cause rapid heating and change the moisture equilibrium between the oil and paper insulation. Flux shunts on the core overheated by leakage flux can burn the oil, also generating bubbles that are drawn into the winding by cooling flow. Bubbles are known to be sites for partial discharges that damage the paper insulation, and in a laboratory scale experiment it was found that partial discharge could be turned on and off by very small dc currents injected through a transformer [Oyedokun et al., 2011]. Alternatively, overheating is associated with sulphur deposition in some transformer oils, leading to a different mechanism of breakdown. Damage initiated by GICs might become self-sustaining, leading to progressive deterioration and eventually failure.

Several dissolved gas analysis (DGA) records from generator step-up transformers after the Halloween storm showed just the sort of trends that would be expected from these kinds of failure mechanisms. Figure 4 illustrates an increase of gas content starting around the date of the storm. Despite unloading the transformer for a period and filtering the oil in other transformers, seven units with this characteristic increase in dissolved gases starting at the end of October continued to failure within one year. The failed transformers were not especially old, and most were considered to be around half life at the time of failure.

Figure 4: DGA record of generator step-up transformer showing gassing starting end October

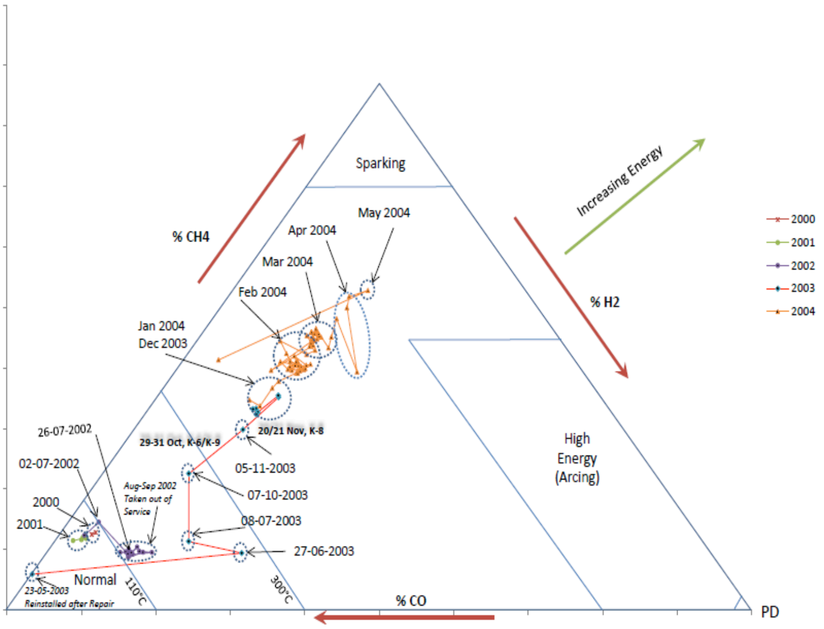


The interpretation of DGA records like the one shown in Figure 4 is time consuming and difficult, so the trajectories of some gases might even be omitted, especially when the damage caused by the GICs is not immediately evident. Therefore, the DGA measurements of the key gases associated with low energy degradation (hydrogen, methane and carbon dioxide) have been combined in a triangular representation of the transformer health [Moodley and Gaunt, 2012]. The low-energy degradation triangle, illustrated in Figure 5, clearly depicts the progress to failure of a 700 MVA GSU transformer. The analysis supports the conclusion that the Halloween storm contributed to the transformer's failure [Gaunt and Coetzee, 2007], but additionally a similar weaker response appears to have occurred after the small storms of 2001, and the GICs in November 2003 clearly accelerated the failure after the Halloween storm.

The trend towards failure illustrated in this example represents only one of the failure mechanisms that occur in transformers. Other characteristic patterns have been identified, associated with different failure processes in other transformers.

This new tool for transformer condition monitoring is easily automated for on-line dissolved gas monitoring. In the past, transformer failure prediction has been very uncertain, both generally and when caused by GICs, but now can be substantially improved.

Figure 5: Low-energy degradation triangle for transformer health assessment [Moodley and Gaunt, 2012]



Network reliability and cost assessment

Transformers are not the only components in the network disrupted by the effects of geomagnetic disturbances. The distortion of the power frequency voltage and current can affect capacitors, protection relays and the non-active (previously called reactive) power flow essential for network voltage stability. GPS-based communication and protection may mal-operate or fail if the satellites lose lock as might occur during severe events. GIC warning systems dependent on internet-based systems might similarly not perform reliably.

In addition, system operators need always to consider the effects of all other causes of coincident component and system failure. In South Africa the dominant external causes of faults on the main transmission system are birds, lightning, fires and pollution, together accounting for nearly 90% of all line faults [Minnaar et al. 2012]. GICs are uncommon initiators of faults, although the effects may be widespread. Further, exposures of systems to geomagnetic disturbances are of very limited duration relative to the life of the power system assets. Therefore, new techniques are needed to analyse the multiple contingency effects associated with both large power systems and the simultaneous exposure of many components to the threat of GICs.

Lightning, birds, fires and pollution all have distinct seasonal and time of day patterns. The demand on the system exhibits similar patterns. Based on these properties, a time-dependant probabilistic approach has been developed for reliability analysis. Defining four seasons and four times of day, the vulnerability of components to all adverse external threats is modelled by Beta probability density functions for each season- and time-period [Minnaar et al. 2012]. A consistent approach can then be taken to Monte Carlo modelling of system failure for both planning and operations [Edimu et al., 2012]. The approach copes effectively with the time-dependant correlation between threats and demand.

The costs of interruptions to customers can be applied to the output of the reliability (or failure) analysis. Surveys have identified that interruption costs also correlate with business activity levels according to the seasons and time of day and can also be represented by Beta probability density functions. The costs of interruptions at each busbar are aggregated for the customer mix. The aggregate cost is combined with the probability of failure at each busbar, allowing the total value at risk to be identified for the system configuration. The total cost is also a Beta probability distribution, from which singular values can be extracted for a given level of confidence (or risk) [Dzobo et al., 2011].

Decision support

The whole combination of the five sub-systems can be used for testing the cost-effectiveness of various approaches to preventing or mitigating the effects of GICs in power systems. The integrated approach is needed because the system is large and complex and characterised by uncertainty. Understanding the implications of any decision is beyond the scope of more simple, disconnected 'solutions'.

For example, the flow of GICs in a power system can be interrupted by installing series capacitors in the lines making up the network. Although this is costly, causes redistribution of GICs in circuits that are not blocked, and might introduce problems of sub-synchronous resonance, the expense is justified in regions where GICs are sufficiently common to justify the cost of protecting the assets. In low latitude regions, such as South Africa, the solution could work, but cannot be justified financially, so alternatives must be considered. However, such alternatives have not been implemented widely, so there is little experience available locally or internationally to guide the decision-making. In the absence of that experience or other ways to find the best solutions to the problems of transformer failure and the threat of an extreme storm, a completely integrated approach, as described, is needed.

An advantage of the modular design of the integrated system is that the modules can be developed in parallel. Further, as the ways of dealing with the complexity within each module are improved, the whole system becomes incrementally better at guiding the various decisions, including the final outputs for planning and operations.

Benefits

Another advantage of taking a systems approach to the threat of solar storms is that the whole is greater than the sum of the parts. The above descriptions of sub-systems show that the approaches have been conceived to feed into each other, so the whole system moves raw data from various sources towards decision support. At the same time, each process has outputs that feed into completely different systems. A few examples must suffice to illustrate the extra benefits derived from the research.

The work on the definition and measurement of power under non-ideal conditions was initiated by twin needs - to design power electronic controllers to correct power quality problems and connect renewable energy sources to the grid, and to understand better the performance of power systems in the presence of GICs.

The low-energy degradation triangle was developed to address specifically the uncertainty about the mechanisms of failure of transformers in our region. The need was evident because transformer failures were too many to be coincidental and yet could not be fully explained by what was known about GICs. The solution conceived to analyse what was happening turns out to be a tool suitable also for the early detection of low-energy degradation and warning of incipient failure. The tool can be incorporated, virtually unchanged, in standard programmes for transformer condition monitoring and asset management.

As knowledge of the transformer degradation processes improved, a better understanding was gained of the most relevant parameters of geomagnetic disturbances. Without interfering in the scientific research of space physicists, the definition of distinct applications has provoked new approaches for some of that research.

We determined that reliability analysis could be improved by adopting a 16-cell, time-based matrix of inputs to reduce the complexity of dealing with continuous functions in Monte Carlo simulations. At the same time, the output can be modelled as a probability to be interpreted with a level of confidence. The approach required classifying existing failure data in a new way, which has had spin-off already in identifying ways to improve transmission system reliability. The same time-dependant approach allowed reliability analysis to be applied to long term planning and short term (6-hours periods) operations control using closely related algorithms, common input data and consistent interpretation of the results of simulations.

Although developed to address specifically the uncertainties of high impact, low frequency GIC events, several of the techniques provide new tools suitable for extreme events other than those related to GICs, as well as for normal, every day planning and control.

Finally, from the point of view of a university, the research has served as a vehicle for the intellectual training of a relatively large number of students, several of whom have already found responsible positions in industry.

Implementation

There is still a gap between having a plan or design and having a working project in place. The plan was conceived in 2004 and design has progressed according to the availability of resources - both funds and people. Many problems have been solved in the process. The work has also identified new possibilities for improvement in this project and applying the evolving techniques in other projects.

Completely new algorithms and tools have been developed and tested as far as is possible using limited data. Much of the work has already been published in various forms for critical review. However, the real benefits will only be realised when the design is put into use. We do not underestimate the effort required to ensure that every practical detail is working properly.

It is also recognised that implementation of a warning and mitigation system for responding to extreme geomagnetic events is not trivial. In addition to the algorithms, techniques and understanding already developed, there is a need for instrumentation, communications and procedures to use the information derived from on-line monitoring and reliability analysis, and for training the utilities' personnel.

Conclusion

We still do not know when the next extreme geomagnetic storm will arrive, but the research so far has provided two key results to supplement the work of others:

> the processes from CME to power system failure can be formulated in a large but coherent model to analyse the complexity and manage the uncertainty; and
>
> the improved understanding allows better responses to the threats of severe and extreme geomagnetic storms to be planned in advance and in ways that were not envisaged in March 1989 and October 2003.

Research of this nature cannot prevent emergencies, but can help in mitigating and managing the outcomes more effectively.

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