Mitigating disastrous electricity system failures initiated by GICs

Hypotheses and protocols

A research project enabled by a grant from the Open Philanthropy Project to the University of Cape Town.

The Open Philanthropy Project identifies outstanding giving opportunities, makes grants, follows the results, and publishes its findings. Its mission is to give as effectively as it can and share the findings openly so that anyone can build on them.

Background to the GIC mitigation project

Concern has arisen in many countries about the potentially massive disruption of electricity supply systems (and other infrastructure) caused by geomagnetic disturbances (GMDs) initiated by explosions on the Sun, called coronal mass ejections. Disruptions of GMD origin are part of a group of threats to society called high impact, low frequency events. Scientific research since 1989 has provided substantial insight into the nature, magnitude and probability of such an event. There is general consensus that the impact of an extreme event on electricity networks, arising from the geomagnetically induced currents (GICs) induced by the GMD, would be very severe and possibly catastrophic for modern society in many countries.

The engineering approach to such a problem would be to make changes to the design and operation of large power systems to reduce the severity of an impact, giving careful attention to the costs and benefits of such changes. However, studies of the phenomenon have exposed some significant weaknesses in the understanding of the problems and the suitability of the available analytical methods [1, 2].

The purpose of the proposed research at the University of Cape Town (UCT) is to improve knowledge of the effects of GICs on electrical power systems that will inform decisions about mitigating those effects, and that may also be applied more widely in the planning and operation of power systems for events other than those caused by GMDs and GICs.

This report defines the main components of the project by describing the objective and approach, the work packages, resources and budget, overall deliverables and outputs, and the ethical issues.

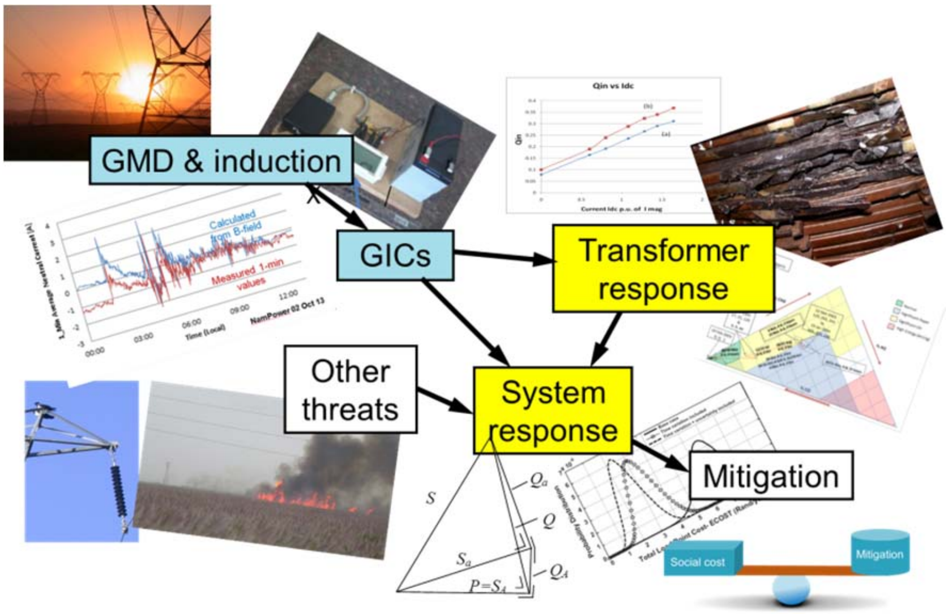
Objective and Approach

Based on the premise that improved knowledge of the performance of transformers and power systems in the presence of GICs will enable better choice of approaches, including preparedness and early warning, to mitigate the potentially disastrous effects of GICs, we will examine opportunities for interventions from studies of the following:

- ***The character of GMDs and GICs, and their effects on transformers and power systems***
- ***The reliability of power systems, taking into account concurrent stresses, and the economic impacts of interruptions***
- ***Decision aids to assess mitigation options***

Our approach to this objective is illustrated in the following figure and comprises six work packages:

1. characteristics of GMDs and GICs
2. the transformer response to GICs
3. power system voltage stability under distorted conditions
4. transformer degradation and failure prediction
5. costs of failures and interruptions of supply; and
6. a GIC mitigation decision-aid.



Relationships between work packages of the proposed research

Each of the proposed activities builds on past and current work and anticipates collaboration with other researchers at UCT and other institutions, with the purpose of improving understanding and decision-making.

Much of the study is in the form of observational, descriptive and analytical research, from which testable hypotheses will be developed and provisional mitigating interventions proposed, and, where possible, tested. Full testing of the hypotheses presented will not be possible within the scope of the new project, nor will it be possible to examine in real life the impact of the solutions proposed, particularly those that relate to rare or exceptional events. In the meantime, the project's contributions will be directed to helping regulators and utilities to make decisions and will form a valuable platform for ongoing research, which may be of critical importance to society when these extreme events occur.

To date, UCT researchers, assisted by postgraduate students, have carried out research in each of the areas to be studied. Separate project teams will be assigned to each of six work packages. In addition the work will benefit from established and active collaborations with researchers in other institutions, most prominent of which is with the Space Science Directorate of the South African National Space Agency (SANSA). New collaborations will be established in areas in which additional expertise is required.

For various reasons, including the need to implement better systems before the statistical risk of an extreme event increases again in the next solar cycle – probably from about 2021, the work planned to start on all packages in December 2016, with substantial completion within three years.

Work Packages

Each work package studies a characteristic of GICs or their effects on power systems and is directed towards providing analytical tools and data that will assist electricity system planners and operators to improve the resilience of their systems.

Each package can be studied to characterise data and processes within it, and the outputs of one package may be inputs to another.

In the following descriptions of each work package, some background (with references to existing UCT outputs), one or more working hypotheses (for testing the validity of the concepts), a preliminary research protocol, and the available resources (researchers and budget) are provided.

WP1: Characteristics of extreme GMDs and GICs

Background

The greatest interest is in severe and extreme GMDs but they occur infrequently. Therefore, modelling of the likelihood of and conditions expected in extreme storms must be based on measurements of smaller disturbances and a supportable basis of extrapolation.

Several models exist already:

- models of disturbance magnitude using various indicators
- models of the relationship between GMD and GIC

- models to extrapolate GMDs and GICs to severe and extreme occurrences

These models are complex and characterised by uncertainty in respect of one or more parameters. Among other things, the implications for power systems appear to depend on maximum intensity and the duration of a GIC, both of which should be reflected in the derived parameters.

We will build on substantial work done in South Africa and Namibia, mainly by researchers based at UCT and SANSA [3-14].

Lower cost measuring instruments will be developed and deployed to collect more data than is presently available. Also, measurements of GMDs and/or GICs in different parts of the world will be used to analyse the effects of latitude/time of day and ground conductivity. Statistical extrapolations of measurements to extreme events will be reviewed and adapted.

Outputs from this work package will be inputs to WP 2, 3, 4 and 6.

Hypotheses

H1a A statistically-based relationship between GMD and GIC, with results as useful as or better than those derived from detailed, theoretically based calculations of the frequency response of 3D, layered-ground conductivity and the transient response of transformers, can be identified for every grounded network node and used for both long-term planning of networks and real-time monitoring during GMDs.

H1b Low cost measurement of GICs in transformer neutrals and in transmission lines can provide data useful for planning and operational monitoring.

H1c Statistical extrapolations of GMDs and GICs to extreme, multi-day events can be derived from existing and new data, and expressed in the form of probabilistic models of extreme values, storm duration, and time-integrated magnitudes.

Protocol

Develop lower cost neutral and differential magnetometer instruments to measure GICs in transformers and lines. Extend liaison with NamPower, the Namibian electricity utility (with a large but topologically simple network) to install the instruments and collect data by which to characterise the GICs induced by GMDs.

Use existing magnetometer data to analyse geomagnetic variation with longitude, latitude and time of day, and model potential exposure during possible multi-day solar storms – using data from magnetic observatories and utilities and, as necessary, in collaboration with scientists and engineers in other countries.

Use measurements of solar surface activity, solar wind plasma and magnetic field, and geomagnetic data sets to develop forecasting models of acceptable accuracy for operational warning of GMD intensity.

Using locally and internationally available data, develop practical models of the links between geo-effective CMEs and GMDs, and between GMDs and GICs that can be extended to extreme events distinguished by maximum intensity and time- or duration-weighted magnitudes, and show by tests (still to be defined) that the models are sufficiently (defined?) accurate for practical application to mitigation studies and power system operational awareness.

Resources

Researchers: S Lotz, PJ Cilliers (both at SANSA), DT Oyedokun, CT Gaunt, 1 PhD candidate, 1 Masters student, collaboration with NamPower.

Budget: US$111'195

WP2: Transformer response to GICs

Background

GICs (low freq. quasi-DC) in transformers generate harmonics, unbalance, and a requirement for the system to supply non-active power - vars (Q). Capacitor banks and SVCs correct Q by storing energy to control out-of-phase V-I. Harmonic distortion and unbalance trip capacitor banks and SVCs to protect them. Such conditions initiated the voltage collapse of the Hydro-Quebec power system in 1989. Therefore, a good understanding of the electrical responses of transformers to GICs is required. Preliminary work in South Africa includes simulation and practical tests of transformers with different core structures [17-21], and rigorous measurement of Q [22, 23] in accordance with the General Power Theory described in greater detail in WP3.

According to NERC, voltage stability collapse of power systems exposed to extreme GMD events is of the greatest concern in North America, and the risk of transformer damage is negligible for GICs below 75 A/ph (225 A in the neutral). On the other hand, there are multiple records of transformer damage initiated by GICs, from USA, UK and South Africa. Nevertheless, FERC found in its Final Rule TPL-007 (Sep 2016) that the data compiled in South Africa was inadequately specific. Foundational work done at UCT [24] to develop an early indicator of low energy degradation in generator step up transformers (GSUs), possibly but not exclusively associated with GICs, can be combined with calculations of GICs in the transmission system to determine an evidence-based threshold of transformer degradation in the presence of GICs.

Outputs from this work package will be inputs to WP 3, 4 and 6.

Hypotheses

H2a Tests on model transformers and extension of the results to power transformers with suitable transformer equivalent circuit and FEM simulations will improve the conventional models of the reactive power requirement in transformers conducting GICs.

H2b Thresholds of GICs initiating damage in transformers , based on identifiable mechanisms of degradation, can be determined from the practical records of transformer degradation leading to relatively early failure, and calculation of the associated GICs.

Protocol

Extend the experimental and computer modelling work (2 PhD students ending this year) presently focusing on single-phase four-limb (3x1p-4L) transformers with a test transformer (supplied at no cost to UCT by Royal Smit Transformers, Netherlands), testing facilities at Eskom (used at no cost), and software (provided by Infolytica, under an academic licence) to transformers of other core configurations.

Determine by measurement and numerical simulation the transformer's harmonics generation and Q response under various conditions and develop better models (equivalent circuits and parameters) of transformer electrical response in the presence of GICs, taking into consideration the effects of GICs on joint performance.

Review all relevant records of the Halloween Storm and earlier GMD events to assess the damage to transformers in Southern Africa and establish a specific value for the magnitude/duration of GICs that appear to have initiated damage, according to the transformer core type and condition at the time of the GMD prior to failure.

Resources

Researchers: DT Oyedokun, CT Gaunt, 4 Masters students.

Budget: US$90'320

WP3: Power system stability in the presence of harmonic and dc components

Background

An essential component of the past work at UCT on the effects of GICs on transformers and power systems has been the development of a General Power Theory (GPT) that accommodates distortion, unbalance and dc components [25-31].

It is widely believed that the reactive power demand of transformers exposed to dc components is linear with the magnitude of dc, with a gradient determined by the core structure of the transformer. Preliminary tests on bench scale transformers, applying the GPT to the definition of the apparent power and non-active power indicates some deviation from the conventional view.

Most power system stability analysis [32, 33] depends on a conventional definition of apparent power and reactive power derived on the basis of sinusoidal waveforms and adjusted for harmonics. However, the full effects of distortion, unbalance and dc components are not included. Since these decrease the power factor, they also decrease the voltage stability of networks, especially under extreme conditions, to an extent that has not been tested. Our preliminary assessments indicate the effects might be significant.

Outputs from this work package will be inputs to WP 5 and 6.

Hypothesis

H3 GICs generate distortion and unbalance which, together with the quasi-dc component of the GICs, reduce the voltage stability of power systems affected by GICs more than is indicated by conventional load flow studies.

Protocol

Liaise with the research groups led by Prof Tom Overbye (presently at University of Illinois at Urbana-Champagne, and PowerWorld software) and Dr Barry Rawn at Brunel University London to investigate the increased system losses and decreased stability of power systems in the presence of harmonics and DC components when using rigorous power theory, compared with conventional power theory. Identify whether a simple correction factor can be applied to conventional calculations.

Measure/derive typical ratios of phase wire to neutral wire resistances needed for application of the GPT and assess whether they are typical on most high voltage power systems.

Apply the 'new' models of various types of transformers' non-active power requirements to assess 'in principle' the effects on voltage stability of the application of the GPT and the change in risk of voltage collapse according to the power system model adopted. Determine the extent to which the GPT can be applied to the modelling of the Hydro-Quebec collapse in 1989 and whether the voltage profile as published is more consistent with conventional analysis or analysis based on the GPT.

Include the practical performance of capacitor bank switching and tap-changer operation in analysis of the response of systems to rapid changes in GICs. Assess whether there is an increased risk of small signal instability associated with sub-synchronous resonance or other operating performance problems in networks with series capacitor compensated lines.

The investigation of system stability will not include the effects of GICs and harmonics on power system protection relaying – we believe such studies are being considered elsewhere.

Resources

Researchers: KA Folly, M Malengret, DT Oyedokun, CT Gaunt, 1 Doctoral candidate, 1 Masters student, collaboration with T Overbye, B Rawn.

Budget: US$97'305

WP4: Transformer degradation and failure prediction

Background

In the investigation of the transformer failures that occurred after the Halloween storm in 2003, our preliminary work on the interpretation of transformer condition monitoring data established that early signs of degradation could be identified from the dissolved gas analysis (DGA) data sampled and collected from large transformers by most utilities. Variability in the raw data makes interpretation difficult, but focusing on the gases most related to low energy degradation led to a new method interpretation called the Low Energy Degradation Triangle (LEDT). Application to the records of many failed and healthy transformers gave insight into some of the mechanisms that might initiate eventual failure [34-38].

The proposed work will examine additional techniques in the analysis or conventionally available data and the numerical modelling of the probability of failure.

(Note: There is a possibility that long periods of exposure to relatively small GICs – such as induced by high speed solar wind from coronal holes (CHSS) – or nearby HVDC lines might be significant, so low current exposure should not be ignored in magnitude/duration models.)

Outputs from this work package will be inputs to WP 2, 5 and 6.

Hypotheses

H4a Conventional measurements of transformer oil DGA, moisture and temperature can provide statistically significant condition-based estimates of failure probability.

H4b The reduction of the lifetime of a transformer can be assessed from the GICs to which it is exposed and selected parameters of a transformer and its condition, based on identified degradation processes initiated by GICs and leading to relatively early failure.

H4c The approach underlying the LEDT for mineral oil filled transformers can be extended to vegetable oils.

Protocol

Review existing records of transformer DGA and failures to develop a transformer failure prediction model for use in reliability studies. Determine whether the failure prediction model accuracy is improved for planning or operations or both by extending the LEDT approach to a supplementary vector of medium energy degradation.

Collaborate with large utilities (and possibly data companies) to increase the data set of transformer condition measurements (DGA+) and failures, and to build and test failure probability models of GSU and transmission transformers, based on condition assessment.

Identify cases of transformer degradation towards failure that followed severe GIC and long duration CHSS events and determine whether the degradation profiles from the DGA data correlate with processes consistent with initiation by GICs.

Determine from basic principles what modifications are needed to the LEDT for transformers insulated with mineral oils to adapt the approach for transformers filled with vegetable oils.

Resources

Researchers: CT Gaunt, 2 Masters students.

Budget: US$47’260

WP5: Costs of failure and interruptions of supply

Background

There are many different approaches to assessing the costs of damage to electricity systems and interruptions of supply. Some assess only the costs incurred by utilities, others only the costs incurred by various classes of customers, and others the costs incurred by society as a whole. Past research at UCT has focused on the costs incurred by customers.

To accommodate the sensitivity of costs to the time and season of interruptions, reliability analysis of power systems was related to the fault incidence through the time-dependent probability analysis [39-49].

The customers' costs of interruptions can be assessed by survey and clustering of various classes of customers and representing the results as probability distributions. These cost estimates can be aggregated to various levels and applied to specific nodes of power systems or a system as a whole [50-61].

Cost estimates prepared for one country cannot be applied directly to another country. Also, the various approaches do not lead to compatible results, nor results that are applied easily to decision-making by utilities and regulators.

The research will explore approaches to the collection, analysis and application of data relating to degradation, failure and interruptions of supply relevant to various levels of decision-making in different countries. It will determine and test some of the approaches in specific contexts to demonstrate the feasibility of the applications.

Collaboration with energy economists in other countries will be needed.

Outputs from this work package will be inputs to WP 6.

Hypotheses

H5a Internally consistent approaches to estimating the costs of degradation, failure and interruptions of supply can be identified for both utilities and regulators, taking into account their needs for taking different decisions.

H5b The applicability of proposed approaches can be demonstrated by using existing data and, using suitable guidelines, collecting more data where required.

Protocol

Review existing approaches to determining direct and economic (including indirect) costs of interruptions from isolated, short interruptions to widespread interruptions for many hours or days. Identify the factors introducing inconsistencies between the estimated costs and how they can be removed or compensated. Ensure the differences between developed and developing countries are incorporated.

Collate available data on damage costs, costs of interruptions and mitigation costs (including mitigation by customers and utilities). Determine the sufficiency of the available data and the potential benefit of collecting more data.

Prepare guidelines for the collection of data to support the modelling the costs of disruption caused by power failures. Test the suitability of the guidelines by collecting sample data. (The actual collection of complete data as would be required by utilities and regulators in various countries is beyond the scope of this research.)

Develop a rigorous approach to identifying consistently the costs of interruptions (in a format compatible with application to decision-making, as identified in WP6). Test the approach to cost estimation using the already existing and newly collected data.

The financial and economic consequences of degradation initiated in generators exposed to high values of harmonics developed in transformers carrying GICs will not be included in the research, as too little is known at this stage to quantify the technical relationships between the GIC, transformer design, and generator behaviour when the levels of harmonics significantly exceed normal ratings.

Resources

Researchers: K Awodele, CT Gaunt, 3 Masters students.

Budget: US$76'450

WP6: Overall reliability and value impact model of a system

Background

The mitigation of the effects of GICs on power systems has been a desired outcome of our research from the beginning [62]. The potential exposure of power systems to extreme events, the effects of transformers' and system's responses to GICs on the reliability of a power system, and the costs incurred by damage and disruption together establish a probabilistically-defined value at risk (V@R) for an electricity supply system.

On the other hand, diverse system modifications and operational procedures, all of which incur costs, can reduce the effects of GICs on power systems, and can be implemented to reduce the V@R. While some approaches to mitigation might emerge as being generally most effective, utilities need to determine the cost-benefit relationship of the best approaches to mitigation of risk for their systems [63].

The research is directed to improving an overall reliability and V@R decision-aiding model that has been identified in preliminary form for application in operations centres and for network planning. A computer-based model should bring together the engineering and economic impact in terms of costs and benefits.

Hypotheses

H6a An integrated computer-based model can compare the probabilistic V@R with the costs of mitigation to guide practical decision-making; the inputs to the model being based completely on existing information and approaches and the additional information and approaches to data preparation developed in this research.

H6b The practical usability of the decision-aiding model can be demonstrated.

Protocol

Identify the various techniques for mitigation together with their costs and effectiveness, and develop a standard approach to comparing the disruption impact that could arise from GICs with the potential value of the benefit of mitigation, with the objective of reducing the total V@R to a minimum.

With collaboration sought from one or more system control centres and network planning departments of utilities, identify the critical information required to be clearly noticeable to the operators and planners responsible for mitigation of the effects of GICs, in order to reduce error (including input data, wrong deductions or inaction) in using the models, and develop suitable graphical user interfaces (GUIs), tools, displays and guidelines for the model.

Complete a working computer-based model and demonstrate that its functions are consistent with the overall approach of this research project and the needs of utilities and regulators.

Resources

Researchers: KA Folly, CT Gaunt, 1 Doctoral student.

Budget: US$70’895

Overall Deliverables and Outputs

The research findings will be disseminated through conference presentations, and publications in conference proceedings and peer-reviewed journals.

The training of students is a key component of the proposed research. It is expected that 14 postgraduate research students will participate in the project and they be awarded 11 Masters and three Doctoral degrees. Their academic reports will be published by UCT.

Assessments of the progress of the research project will be published regularly by the Open Philanthropy Project.

Research Ethics

The research requires no experiments on people or communities.

Data collected to assess interruption costs may include specific location. Where it is necessary to collect individual data in such a way, the identification of specific location and cost will be kept separately from other data. All survey data will be published only in an aggregated and analysed form to prevent individual identification.

Raw data collected from utilities will be kept confidential unless it is placed in the public domain by the originator, since it can have commercial implications. Only aggregated and processed data will be published and will be linked to the originator only with permission.

All data generated in the research, belonging to UCT and used to establish research findings will be available on request. However, in some experiments high frequency sampling will be needed and the raw data will not necessarily be stored after the derived measurements are recorded. All test and measurement protocols will be recorded with sufficient detail needed for repeatability.

All researchers engaged on the project are required to sign non-disclosure agreements.

References

1 Thomson AWP, Gaunt CT, Cilliers P, Wild JA, Opperman B, McKinnell L-A, Kotze P, Ngwira CM, Lotz SI, 2009, Present Day Challenges in Understanding the Geomagnetic Hazard to National Power Grids, Advances in Space Research (2009), volume 45, issue 9, year 2010, pp. 1182 - 1190, doi: 10.1016/j.asr.2009.11.023

2 Gaunt CT, 2015: Comments on Notice of Proposed Rulemaking on Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events in Docket No. RM15-11-000, July. elibrary.ferc.gov/idmws/common/opennat.asp?fileID=13940218.

WP1: Character of extreme GMDs

3 Koen J, Gaunt CT, Britten AC, 2000: The effect of geomagnetically induced currents in the South African power network. Proceedings 9th South African Universities Power Engineering Conference (SAUPEC), Durban, January, p176-181.

4 Koen J, Gaunt C T, 2001. Geomagnetically induced currents in the Southern African power network. Proceedings 4th Cigré Southern African Regional Conference, Cape Town 1-5 October, Paper no 41.

5 Koen J, Gaunt C T, 2002. Geomagnetically induced currents at mid-latitudes. URSI, Maastricht, August.

6 Koen J, Gaunt C T, 2002. Disturbances in the Southern African power network due to geomagnetically induced currents. Cigré Session, Paper 36-206, Paris, August.

7 Koen J, Gaunt CT, 2003. Geomagnetically induced currents in the Southern African electricity transmission network. IEEE Powertech, Bologna, June.

8 Bernhardi E, Cilliers PJ, Gaunt CT, 2007: Modelling the effect of space weather and on geomagnetically induced currents in Southern Africa, 52nd Annual Conference of the South African Institute of Physics, University of Witwatersrand, 3-6 July.

9 Bernhardi EH, Tjimbandi TA, Cilliers PJ, Gaunt CT, 2008: Improved calculation of geomagnetically induced currents in power networks in low-latitude regions. Power Systems Computation Conference, paper 677, Glasgow, July.

10 Bernhardi EH, Cilliers PJ, Gaunt CT, 2008: Improving the modelling of geomagnetically induced currents in southern Africa. SA Journal of Science, vol104, no 7/8, pp265-272, July/August. ISSN 0038-2353.

11 Ngwira, CM, McKinnell L-A, Cilliers PJ, Viljanen A, Pirjola R, 2009: Limitations of the modeling of geomagnetically induced currents in the South African power network, Space Weather, 7, S10002, doi:10.1029/2009SW000478

12 Ngwira CM, McKinnell L-A, Cilliers PJ, 2011: Geomagnetic activity indicators for geomagnetically induced current studies in South Africa. Adv. in Space Research, vol. 48, pp 529–534.

12 Simon MN, Oyedokun DT, Gaunt CT, 2013: Calculations of geomagnetically induced currents (GICs) in the Namibian transmission network. Southern African Universities' Power Engineering Conference, p29-32, Potchefstroom, January.

13 Oyedokun DT, Simon MN, Gaunt CT, 2013: Introduction of a more detailed calculation of geomagnetically induced currents in transmission networks. Southern African Universities' Power Engineering Conference, p211-215, Potchefstroom, January.

14 Matandirotya E, Cilliers PJ, Van Zyl RR, Oyedokun DT, de Villiers J, 2016: Differential magnetometer method applied to measurement of geomagnetically induced currents in Southern African power networks. Space Weather, 14, 221–232, doi:10.1002/2015SW001289.

15 DW Danskin, SI Lotz, 2015, Analysis of geomagnetic hourly ranges. Space Weather. doi: 10.1002/2015SW001184.

16 Gaunt CT, 2015: Why space weather is relevant to electrical power systems. AGU Space Weather, doi: 10.1002/2015SW001306

WP2: Transformer response to GICs

17 Amuanyena LAT, Gaunt CT, 2003. Effects of geomagnetically induced currents (gics) on power transformers and reactors. Proceedings 12th Southern African Universities Power Engineering Conference (SAUPEC), Pretoria, January.

18 Heindl M, Beltle M, Reuter M, Schneider D, Tenbohlen S, Oyedokun DT, Gaunt CT, 2011: Investigation of GIC related effects on power transformers using modern diagnostic methods. XVII International Symposium on High Voltage Engineering, Hannover, August.

19 Oyedokun DT, Gaunt CT, Tenbohlen S, Heindl M, Beltle M, ReuterM, Schneider D, 2011: Laboratory Test for GIC Effects on Power Transformers. XVII International Symposium on High Voltage Engineering, Hannover, August.

20 Borrill LD, Chisepo HK, Gaunt CT, 2016: Measurements with dc components in laboratory transformers show equivalent circuit models need core joint details. IEEE PowerCon, Wollongong, Australia.

21 Chisepo HK, Borrill LD, Gaunt CT, 2016: Measurements and finite element model of transformer with direct current component. 5th International Advanced Research Workshop on Transformers, La Toja Island, Spain

22 Chisepo HK, Gaunt CT, Oyedokun DT, 2013: Testing the response of laboratory bench transformers to geomagnetically induced-like currents. Southern African Universities' Power Engineering Conference, p37-42, Potchefstroom, January.

23 O'Donoghue P, Gaunt CT, 2010, Non-active power in a transformer carrying geomagnetically induced currents. Proceedings 19th Southern African Universities Power Engineering Conference (SAUPEC), Johannesburg, January.

24 Moodley N, Gaunt CT, 2012: Developing a power transformer low energy degradation assessment triangle. IEEE PowerAfrica Conference, Johannesburg.

WP3: Power system stability in the presence of harmonic and dc components

25 Malengret M, Gaunt CT, 2005: Definition of apparent power in poly-phase systems Proceedings 14th Southern African Universities Power Engineering Conference (SAUPEC), Johannesburg, January.

26 Malengret M, Gaunt CT, 2008: Decomposition of Currents in Three- and Four-Wire Systems., IEEE Trans on Instrumentation and Measurement, Vol: 57, Issue 5, pp 963-972, May, ISSN: 0018-9456

27 Malengret M, Gaunt CT, 2011: General theory of instantaneous power for multi-phase systems with distortion, unbalance and direct current components. Electr. Power Syst. Res., doi:10.1016/j.epsr.2011.05.016 (Volume 81, pp 1897-1904)

28 Malengret M, Gaunt CT, 2011: General theory of average power for multi-phase systems with distortion, unbalance and direct current components. Electr. Power Syst. Res., doi:10.1016/j.epsr.2011.11.020 (Volume 84, Pages 224-230)

29 Gaunt CT, Malengret M, 2012: Why we use the term non-active power, and how it can be measured under non-ideal power supply conditions. IEEE PowerAfrica Conference, Johannesburg.

30 Gaunt CT, Malengret M, 2013: True power factor metering for m-wire power systems with distortion, unbalance and direct current components. Electr. Power Syst. Res., http://dx.doi.org/10.1016/j.epsr.2012.07.019, (Volume 95, pp140-147)

31 Malengret M, Gaunt CT, 2014: Using Thévenin equivalents to improve electricity delivery efficiency in AC and DC systems. Proc 22nd Conf on Domestic Use of Energy (DUE 2014), 31 March - 2 April 2014, Cape Town, South Africa. ISBN 9780992204143.

32 Pretorius B, Gaunt CT, 2005: Preliminary analysis of reliability of electric power systems with changes of load and system configuration. Proceedings 14th Southern African Universities Power Engineering Conference (SAUPEC), Johannesburg, January.

33 Jakoet A, Oyedokun DT, Gaunt CT, Cilliers PJ, 2016: Preliminary modeling of geomagnetically induced currents in South Africa using PowerWorld simulator, IEEE PowerAfrica, Livingstone.

WP4: Transformer degradation and failure prediction

34 Geldenhuis L, Jagers J, Gaunt CT, 2007: Large power transformer reliability improvement in Eskom Distribution. International Conference on Electricity Distribution (CIRED), Vienna, May.

35 Gaunt CT, Coetzee G, 2007: Transformer failures in regions incorrectly considered to have low GIC-risk. IEEE PowerTech, Lausanne, July.

36 Jagers JN, Khosa J, De Klerk PJ, Gaunt CT, 2007: Transformer reliability and condition assessment in a South African utility. 15th International Symposium on High Voltage Engineering, Ljubljana, Slovenia, August.

37 Moodley N, Gaunt CT, 2011: Energy Dissipations within power transformers. Proceedings 20th Southern African Universities Power Engineering Conference (SAUPEC), Cape Town, July.

38 Moodley N, Gaunt CT, Low energy degradation triangle for power transformer health assessment. (Submitted)

WP5: Costs of degradation, failure and interruptions of supply

39 Cross N, Herman R, Gaunt CT, 2006: A preliminary investigation into the value of the beta pdf in power system reliability modelling. Proceedings 15th Southern African Universities Power Engineering Conference (SAUPEC), Durban, January.

40 Cross N, Herman R, Gaunt CT, 2006: Investigating the usefulness of the beta pdf to describe parameters in reliability analyses. Probabilistic Methods Applied to Power Systems (PMAPS), Stockholm, June.

41 Gaunt CT, 2007: Causes of faults on a transmission line in Mozambique – case study. 7th International Conference of Power System Operation and Planning, Cape Town, January p103. ISBN 978-0-7992-2363-7

42 Edimu M, Gaunt CT, Herman R 2011: Using probability distribution functions in reliability analyses. Electric Power Systems Research, Vol 81, Issue 4, April, pp 915-921.

43 Herman R, Gaunt CT, Edimu M, 2011: Procedure for Investigating the Planned and Operational Reliability of Transmission Networks with GICs. IASTED Conference on Power and Energy Systems, Crete, June.

44 Edimu M, Herman R, Gaunt CT, 2011: Applying probability distribution functions to model system failures due to adverse weather. Power Systems Computation Conference, paper 439, Stockholm, August.

45 Edimu M, Herman R, Gaunt CT, 2012: Applying a probabilistic approach to transmission network reliability assessment. Probabilistic Methods Applied to Power Systems (PMAPS), Istanbul, June.

46 Minnaar UJ, Gaunt CT, Nicolls F, 2012. Characterisation of power system events on South African transmission power lines. Electr. Power Syst. Res., doi:10.1016/j.epsr.2012.01.015 (Vol 88, July 2012, pp 25-32)

47 Edimu M, Herman R, Gaunt CT, 2013: Impact of a network's component failure model on the perception of its reliability. Southern African Universities' Power Engineering Conference, p200-205, Potchefstroom, January.

48 Edimu M, Alvehag K, Gaunt CT, Herman R, 2013: Analyzing the performance of a time-dependent probabilistic approach for bulk network reliability assessment. Electr. Power Syst. Res., http://dx.doi.org/10.1016/j.epsr.2013.06.016 (Volume 104, pp 156-163).

49 Minnaar UJ, Nicolls F, Gaunt CT, 2016: Automating transmission line fault root cause analysis. IEEE Transactions on Power Delivery. doi 10.1109/TPWRD.2015.2503478.

50 Herman R, Gaunt CT, Minnaar U, Koch R, 2007: Direct and indirect estimation of domestic customer interruption costs: considerations and preliminary results. Cigré SC-C6 Colloquium on Electricity for rural socio-economic development, Langkawi, May.

51 Herman R, Gaunt CT, 2008: Direct and indirect measurement of residential and commercial CIC: preliminary findings from South African surveys. Probabilistic Methods Applied to Power Systems (PMAPS), Puerto Rico, May.

52 Dzobo O, Gaunt CT, Herman R, Saulo MJ, 2010: The effect of backup power supply on calculation of reliability cost and worth indices in power distribution system planning. Third IASTED African Conference on Power and Energy Systems, Gaborone, September.

53 Herman R, Gaunt CT, 2010: Direct and indirect measurement of residential and commercial CIC: preliminary findings from South African surveys. Probabilistic Methods Applied to Power Systems (PMAPS), Singapore, June.

54 Awodele KO, Gaunt CT, Herman R, 2010, A review of customer interruption cost modelling for regulatory decision making. Proceedings 19th Southern African Universities Power Engineering Conference (SAUPEC), Johannesburg, January.

55 Herman R, Gaunt CT, Edimu M, Dzobo O, 2010, Developing a probabilistic reliability assessment process in South Africa using CIC surveys. Proceedings 19th Southern African Universities Power Engineering Conference (SAUPEC), Johannesburg, January.

56 Dzobo O, Gaunt CT, Herman R, Saulo MJ, 2011: The effect of business activity level on customer interruption estimation. Proceedings 20th Southern African Universities Power Engineering Conference (SAUPEC), Cape Town, July.

57 Dzobo O, Gaunt CT, Herman R, 2012: Customer interruption costs (CICs) for composite power system reliability analysis. Probabilistic Methods Applied to Power Systems (PMAPS), Istanbul, June.

58 Dzobo O, Gaunt CT, Herman R, 2012: Investigating the use of probability distribution functions in reliability-worth analysis of electric power systems. Int J Electr Power Energ Syst (2012), doi:10.1016/j.ijepes.2011.12.013 (Volume 37, Issue 1, May 2012, pp 110-116)

59 Dzobo O, Gaunt CT, Herman R, 2012: Reliability worth assessment of electricity customers: a South African case study. Journal of Energy in Southern Africa, vol 23, no 3, Aug, pp31-39

60 Dzobo O, Alvehag K, Gaunt CT, Herman R, 2014: Multi-dimensional customer segmentation model for power system reliability-worth analysis. International Journal of Electrical Power and Energy Systems, Vol 62, Nov 2014, pp 532–539. . doi: 10.1016/j.ijepes.2014.04.066

61 Herman R, Gaunt CT, 2016: Probabilistic estimation of power system interruption impact using time element matrices. IEEE PES GM, Boston.

WP6: Overall reliability and value impact model of a system

62 Koen J, Gaunt CT, 2000: Mitigation of geomagnetically induced currents in the Eskom Main Transmission network. Proceedings SA Power Systems Protection Conference, Johannesburg, November, p85-88.

63 Gaunt CT, 2014: Reducing uncertainty – responses for electricity utilities to severe solar storms. J. Space Weather Space Clim., 2014, 4, A01. doi: 10.1051/swsc/2013058

CT Gaunt

Project Leader

University of Cape Town

25 October 2016.