GEOMAGNETICALLY INDUCED CURRENTS AT MID-LATITUDES

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INTRODUCTION

Eruptions from the sun are correlated with sunspot cycles peaking every 11 years. They disrupt the earth's dipole magnetic field and cause slowly varying currents in the ionosphere and magnetosphere. These currents induce quasi-dc currents called Geomagnetically Induced Currents (GICs) which flow through, disrupt and damage man-made systems including electric power systems.

The greatest GIC problems occur at high latitudes in or near the auroral zones. In these areas the geomagnetic storms are most intense and frequent since the ionospheric source is typically a localised electrojet. Countries at mid-latitude, such as South Africa, are located far from the magnetic pole and do not experience the same severity of geomagnetic disturbances as Canada or Scandinavia. GICs and their potential threat to network integrity are relatively unknown at mid latitudes. Until recently it was believed that electricity networks in mid-latitude regions are not affected by GICs [1]. Our research addresses this assumption, and provides insight into the incidence of GICs and the performance of the Southern African electricity transmission network.

THE EFFECT OF GICs ON TRANSFORMERS

A transformer core saturates under GIC bias, causing it to operate in the extremely non-linear portion of the core steel magnetisation (B-H) curve. When a large number of transformers experience saturation due to GICs, the system's reactive power demand increases significantly compared with the total load supplied by the transformer. Reactive power demands of this magnitude can cause severe system voltage excursions. At the same time, the change in size of the ferromagnetic material (magnetostriction) between saturated and unsaturated states at 100 times a second (at 50 Hz) causes heating, noise and mechanical vibration damage.

PRELIMINARY STUDY AND PAST SYSTEM EVENTS

An investigation of GIC modelling indicated that GICs could be expected in mid-latitude regions and an inspection of past system events found circumstantial evidence of damage by GICs to equipment on the power system [2]. Several trips and failures involving transformers and reactors, described as being of unknown cause, could be traced to periods of major geomagnetic activity. Based on these findings, research was initiated to:

- calculate the GICs expected throughout the Southern African grid to identify substations potentially most susceptible to damage, and
- monitor GICs and transformer saturation to provide measurements for verification of the calculations.

THEORETICAL CALCULATION OF GICs

The calculation of GICs in power networks is based on a method described by Lethinen and Pirjola [3] which considers separate geophysical and network calculations.

The geophysical calculation uses Maxwell's equations to calculate electric field strength components E_x and E_y in a region. Countries located at high latitudes beneath the auroral zone generally use a three dimensional model to calculate local earth surface potentials (ESP). It was unknown whether such detail would be necessary for countries at mid-latitude such as South Africa. Due to the great distances to these auroral zones it might be sufficient to assume an infinite current sheet with a spatially constant current density. It was assumed that the primary field is a vertically propagating plane wave and the earth's conductivity is uniform. The real situation is much more complex. Changes in the x component of the magnetic field generate an electric field in the y direction. Therefore measurements of B_x and dB_x/dt are used to calculate E_y, and measurements of B_y and dB_y/dt are used to calculate E_x.

The network calculation determines network constants a and b for each substation. This uses Ohm's and Kirchhoff's laws and Thevenin's theorem.

The results of the network and geophysical calculations are combined by calculating the GIC for each substation using the equation:

$$I_{GIC} = aE_x + bE_y \quad (1)$$

The analysis of the power system and electric fields calculates a total value of GIC current into the ground at each substation. Differences between calculated and actual results may arise from the following factors:

i. The GIC current will be shared among the transformers and reactors in any substation.
ii. The GIC current terminates (flows from the network through the neutral into the ground) at substations with separate winding transformers. In autotransformers some current can flow through the series (common) winding into the lower voltage network and terminate at other transformers and substations.
iii. The actual ground resistance at a substation could differ from the assumed value of 1000 Ω.m.
iv. The distance from the magnetic field measurement location to some of the substations could contribute to a difference between the local geomagnetic field and that measured.
v. The assumed plane wave approach to the calculation may not be accurate.

MEASUREMENT OF GEOMAGNETIC DISTURBANCES DURING 2001

The magnetic field changes of 13 March 1989 as recorded at the Hermanus Magnetic Observatory (HMO) were used to calculate the GICs expected in the transmission network and identify substations most exposed to potential damage. Monitoring equipment was installed on transformers in two of these substations, Hydra and Grassridge. Continuous measurements of field strength were recorded at the HMO, and of the transformer currents at the two substations.

Table 1 shows the major geomagnetic storms that occurred during 2001, based on measurements at the HMO. The severity of a storm is indicated by several parameters which do not entirely correspond with each other.

Table 1 Geomagnetic storms during 2001.

Date	**Max 3-hour K-index**	**ak - index**	**Maximum variation in the X, Y components of field [nT/min]**		**Minutes of field variation > 5nT/min**
			dX/dt max	**dY/dt max**	
31 Mar	7	106	31	21	368
11 Apr	7	57	16	13	154
12 Apr	7	34	12	5	22
25 Sep	7	31	31	16	38
6 Nov	7	62	53	17	107
24 Nov	9	112	47	29	357

Based on results from the modelling, network performance and actual current measurements, it appears that the following thresholds would identify the most significant events in terms of the effect on the power system [4]:

- Magnetic variance (dX/dt or dY/dt) > 30 nT /min
- K-index equal to or greater than 7 at least once for the day
- Ak index > 60 for the day

The storms on 31 March, 6 November and 24 November exceeded all three thresholds:

SCALING CONSTANTS

A comparison was made between the calculated results and data collected from the two monitored sites. The measurements are taken in the neutral of one transformer at each site. A scaling factor (k), shown in Table 2, was determined by balancing the areas and the GIC peaks of the measured and calculated graphs to be approximately equal.

Table 2 Scaling factors at two substations calculated for three significant storms.

Substation	**31 Mar 2001**	**6 Nov 2001**	**24 Nov 2001**
Grassridge	1.1	1.0	1.0
Hydra	8.9	7.1	7.3

Only one 400 kV autotransformer is installed at Grassridge. Some GIC current could flow into the 230 kV system, so k was expected to exceed 1. Lower earth resistivity than the 1000 Ω.m assumed may compensate the ‘leakage’.

There are four 400 kV transformers and three reactors at Hydra so k was expected to be approximately 7. However, the division of the GIC depends on the DC resistances and will be affected by the ratings of the units. The variation of the scaling factor at Hydra for different storms could be due to operational changes of the network between these dates.

CORRELATION BETWEEN ACTUAL AND CALCULATED RESULTS

Figures 1 and 2 illustrate the calculated (using k) and measured results for Grassridge and Hydra during two of the storms. The forms of the curves are qualitatively similar, and quantitative deviations are small. The backward and forward time shifts between measured and calculated peaks are also small.

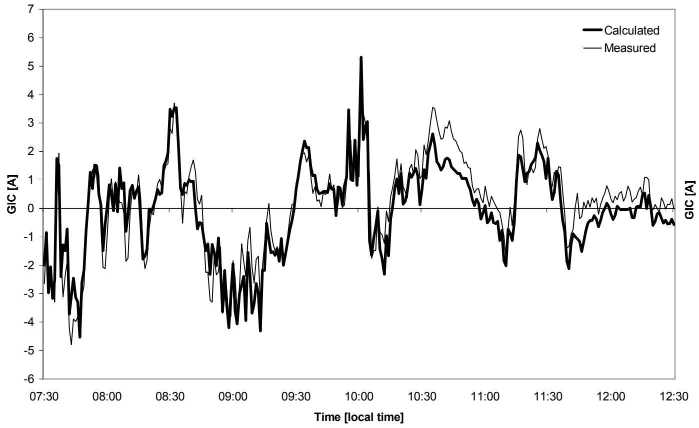

Fig. 1. Theoretical (a plane wave and homogenous earth) and measured earthing GIC at the Grassridge transformer on 31 March 2001.

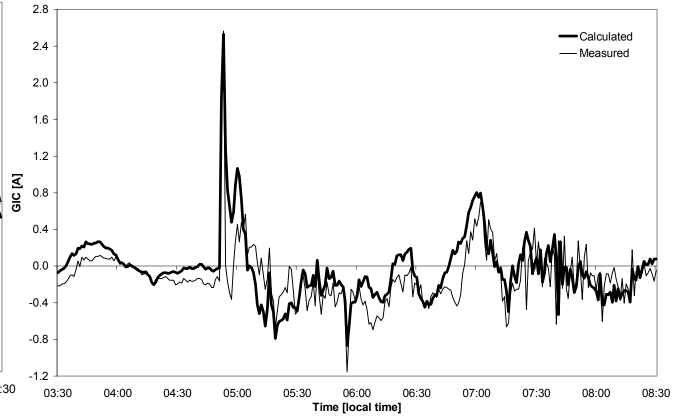

Fig. 2. Theoretical and measured values of GIC at the Hydra transformer on 6 November 2001.

Despite the distance of over 500 km from the HMO to both substations, the differences between the calculated and measured results is small. This indicates that the plane wave method assumed for the magnetic field is adequate in mid-latitude regions, unlike at higher latitudes where more complex modelling of the local magnetic field is needed.

CONDITION MONITORING OF EQUIPMENT

Condition monitoring of several transformers and reactors on the 400 kV network is routinely carried out using dissolved gas analysis. The presence of various gasses (ethane, ethylene and acetylene) indicates thermal damage corresponding to overheated oil and insulation hotspots. Correlation was found between geomagnetic storms and deterioration of the condition of transformers and reactors, to the extent of equipment failure [5]. Warnings of expected geomagnetic storms would allow network operators to take mitigating action to reduce such damage.

ISSUING GIC ALERTS FOR THE SOUTH AFRICAN ELECTRICITY UTILITY

Observation of an earth directed, full-halo Coronal mass Ejection (CME) by the Solar Heliospheric Observatory (SOHO) spacecraft is the basis of warnings of potential geomagnetic storms, with a lead time of 24 to 36 hours. The accuracy of these warnings is limited because a storm's severity depends on the alignment of the interplanetary magnetic field (IMF) and other conditions when the solar wind reaches the earth's magnetosphere. On the basis of experience from NOAA storm warnings and actual storm events in South Africa; a Level 1 warning is issued to Eskom National Control when the probability of a severe storm exceeds 40 %. Operators can review the applicable operational procedures.

Measurements on board the ACE (Advanced Composition Explorer) spacecraft provide warning of a geomagnetic storm with a lead-time of 15 to 60 minutes. A Level 2 warning can be issued to allow operators to choose an operational procedure according to the load at the time and return to service any available lines and transformers.

The maximum or Level 3 warning is issued from two sources at commencement of a geomagnetic storm. Real time geomagnetic field measurements at the HMO automatically initiate an alarm when the magnetic field change exceeds a predetermined rate based on previously calculated and measured GICs. The second source for a level 3 warning is actual data from GIC monitors at the two substations on the Eskom transmission network. Network operators could proceed immediately to switch according to a selected procedure.

Five alerts were sent to Eskom National Control during 2001, on 30 March, 11 April, 25 September and 5 November.

No warning was issued for the storm on 25 November 2001 because the advance warnings were not being monitored on the day. Continuous monitoring of solar activity and geomagnetic storm warnings is not implemented in Southern Africa at present, so storms occurring when the monitoring is neglected; especially over the weekend, could hit the network without any preparation.

GEOMAGNETIC STORM SEVERITY

The K-index and NOAA classification of storm severity are after-the-event measures and not directly related to the magnitude of GICs in networks. GICs are related to the variations in ionospheric currents and the magnetic field. An improved index for representing the severity of storms and, ideally, issuing warnings, will include:

- The magnitude of the magnetic field variation with time, which determines the electric field available to drive GICs. Variation exceeding 30 nT/min of the X or Y component appears to be significant in Southern Africa.
- The cumulative magnetic field variation as an indicator of the period of exposure of equipment to GICs. This value should be a moving average over a time period such as half an hour.

The severity of the effects of a storm also depend on the specific network topology. Therefore, a single index of GIC severity cannot apply for all utilities. A generic index will depend mostly on the magnetic variance with time and the storm duration. Utilities will then assess the storm effect on their networks. GICs can be calculated in real time on a standard computer with a continuous data feed from a magnetic observatory. However, the network response to the GICs, such as harmonics, reactive power flow and transformer overheating requires network data and better knowledge of transformers and reactors. Indicators could be used to characterise the level of disturbance to the network by GICs and the mitigation effect of changing the network configuration could be assessed.

CONCLUSION

The theoretical calculation of GICs in the Southern African Power Network and subsequent measurements showed that GICs are present during strong geomagnetic disturbances, despite the mid-latitude location.

GIC measurements compare well with calculations determining the earth surface potentials using a plane wave model. This indicates that the propagating plane wave method of calculating GICs is reasonably accurate for mid-latitude countries. Further work is needed to establish the distance over which magnetic field measurements at one location will be sufficient to calculate GICs at another.

A better index of geomagnetic storm severity related to the potential for damage to power systems would be useful, especially if the storm severity could be predicted.

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