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Geomagnetically induced currents in the New Zealand power network

R. A. Marshall,[1] M. Dalzell,[2] C. L. Waters,[3] P. Goldthorpe,[3] and E. A. Smith[1,4]

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[1] Adverse space weather conditions have been shown to be directly responsible for faults within power networks at high latitudes. A number of studies have also shown space weather to impact power networks at lower latitudes, although most of these studies show increases in GIC activity within networks not directly related to hardware faults. This study examines a GIC event that occurred in New Zealand's South Island power network on 6th November 2001. A transformer failure that occurred during this day is shown to be associated with a change in the solar wind dynamic pressure of nearly 20 nPa. Measurements of GICs recorded on the neutral lines of transformers across the Transpower network during this event show good correlation with a GIC-index, a proxy for the geoelectric field that drives GIC. Comparison of this event with GIC activity observed in the Transpower network during large space weather storms such as the "2003 Halloween storm," suggests that solar wind shocks and associated geomagnetic sudden impulse (SI) events may be as hazardous to middle latitude power networks as GIC activity occurring during the main phase of large storms. Further, this study suggests that the latitudinal dependence of the impacts of SI events on power systems differs from that observed during large main phase storms. This study also highlights the importance of operating procedures for large space weather events, even at middle latitude locations.

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1. Introduction

[2] The impacts of Geomagnetically Induced Currents (GICs) on power networks at high latitudes have been studied for a number of decades [*Boteler et al.*, 1998; *Viljanen et al.*, 1999; *Lam et al.*, 2002; *Béland and Small*, 2004; *Kappenman*, 2005; *Pirjola*, 2005; *Pulkkinen et al.*, 2005; *Wik et al.*, 2009]. At high latitudes, GICs are typically the result of the relatively intense magnetospheric and ionospheric current systems such as the auroral electroject, substorm current wedge, and smaller scale horizontal currents associated with the Birkeland current circuit [*Viljanen*, 1997; *Pulkkinen et al.*, 2003, 2005].

[3] More recently, studies have shown GICs to also be of concern to power networks at lower latitudes [*Kappenman*, 2003; *Gaunt and Coetzee*, 2007; *Trivedi et al.*, 2007; *Liu et al.*, 2009a, 2009b; *Ngwira et al.*, 2009; *Watari et al.*, 2009]. *Gaunt and Coetzee* [2007] showed an increase in dissolved gas analysis (DGA) measurements in a number of transformers in South Africa (~29°S, 24°E GG) following significant geomagnetic storm activity, resulting in transformer deterioration and eventual failure.

[4] At lower latitudes, magnetospheric and ionospheric current systems such as the magnetopause current, ring current, and equatorial electrojet are also considered as possible sources of time varying magnetic fields responsible for GICs hazardous to power networks [*Kappenman*, 2003; *Watari et al.*, 2009; *Pulkkinen et al.*, 2012]. *Kappenman* [2003] discussed the impact of geomagnetic sudden impulses (SIs) and their effect on the magnitude and period of magnetic field variations from the magnetopause currents, compared with auroral substorm signatures. The author suggested that SIs are one of the more important sources for large GICs that occur at middle latitudes, reporting some of the largest GICs measured in the U.S. have been due to SI events. *Pulkkinen et al.* [2012] suggested that a confined enhancement of the maximum computed geoelectric field and the time derivative of the horizontal magnetic field for two stations near the magnetic equator may be due to the equatorial electrojet.

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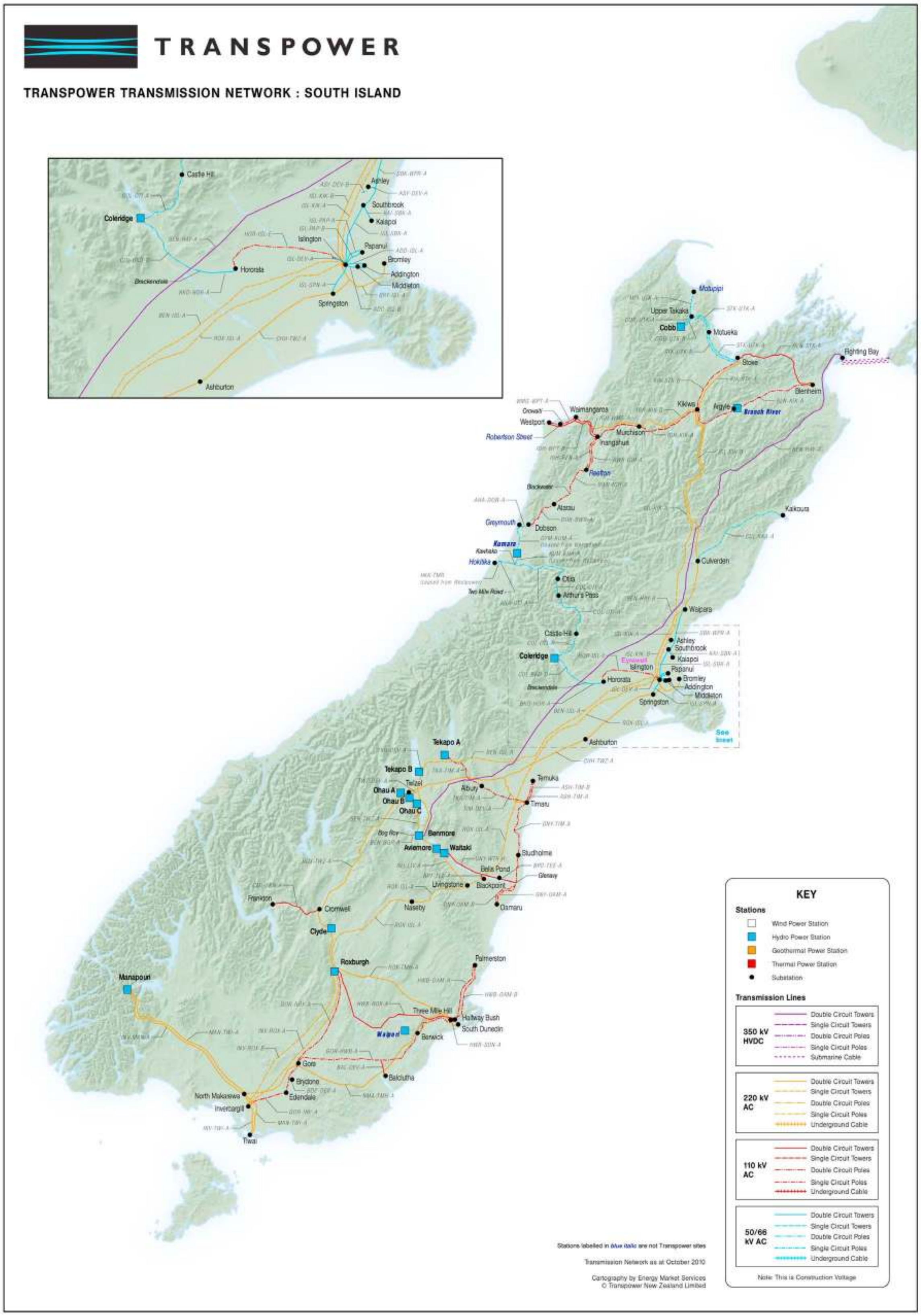
TRANSPOWER
TRANSPOWER TRANSMISSION NETWORK : SOUTH ISLAND
Castle Hill
Coleridge
Ashley
Southbrook
Kaiapoi
Islington
Papanui
Bromley
Addington
Middleton
Hororata
Brackendale
Springston
Ashburton
Motupipi
Upper Takaka
Cobb
Motueka
Fighting Bay
Stoke
Blenheim
Kikiwa
Argyle
Branch River
Orowaiti
Waimangaroa
Westport
Robertson Street
Murchison
Inangahua
Reefton
Blackwater
Atarau
Greymouth
Dobson
Kumara
Kawhaka
Hokitika
Two Mile Road
Otira
Arthur's Pass
Kaikoura
Culverden
Waipara
Castle Hill
Eyrewell
See inset
Tekapo A
Tekapo B
Twizel
Ohau A
Ohau B
Ohau C
Albury
Temuka
Timaru
Bog Roy
Benmore
Aviemore
Waitaki
Studholme
Bells Pond
Glenavy
Livingstone
Blackpoint
Naseby
Oamaru
Frankton
Cromwell
Clyde
Roxburgh
Palmerston
Manapouri
Three Mile Hill
Halfway Bush
South Dunedin
Waipori
Berwick
Gore
Balclutha
Brydone
Edendale
North Makarewa
Invercargill
Tiwai
KEY
Stations
Wind Power Station
Hydro Power Station
Geothermal Power Station
Thermal Power Station
Substation
Transmission Lines
350 kV HVDC
Double Circuit Towers
Single Circuit Towers
Double Circuit Poles
Single Circuit Poles
Submarine Cable
220 kV AC
Double Circuit Towers
Single Circuit Towers
Double Circuit Poles
Single Circuit Poles
Underground Cable
110 kV AC
Double Circuit Towers
Single Circuit Towers
Double Circuit Poles
Single Circuit Poles
Underground Cable
50/66 kV AC
Double Circuit Towers
Single Circuit Towers
Double Circuit Poles
Single Circuit Poles
Underground Cable
Note: This is Construction Voltage
Stations labelled in blue italic are not Transpower sites
Transmission Network as at October 2010
Cartography by Energy Market Services
© Transpower New Zealand Limited

Figure 1

[5] *Béland and Small* [2004] reported that the power network in New Zealand had historically been considered relatively safe from GIC activity due to its relatively short line lengths, predominant north-south line orientation, and middle latitude location. This perception altered following a transformer fault that occurred on New Zealand's South Island during the geomagnetic storm of 6th November, 2001. This paper examines this event in some detail and compares GICs measured in the transformer neutral lines with a GIC-index (a proxy for the geoelectric field that drives GICs). This event is further analyzed in terms of other space weather data and compared with other significant space weather events in order to examine the relative role of the various magnetospheric and ionospheric current systems at these latitudes.

2. Data Analysis

[6] The New Zealand (NZ) power transmission network is owned and operated by Transpower Limited. Generation is predominantly Hydro and Thermal, with smaller contributions from Geothermal, Wind, and Cogeneration. A High Voltage DC (HVDC) link connects the North and South Islands. Figure 1 shows the NZ South Island transmission network in detail. When the HVDC link is operated with unbalanced pole currents, the difference in current must return via the land/shore electrodes and the earth/sea between the North and South Islands. A small amount of this Earth current strays into the South Island alternating current (AC) transmission lines by entering and exiting grounded, "wye" connected power system transformers. The flow of these direct currents (DC) through the power transformers, if sufficiently large, can cause half wave saturation in the power transformers. This can result in increased reactive power and incorrect protection operation on the power system. As a consequence, Transpower have designed and installed neutral earthing resistors and DC current measuring devices (referred to as LEMs) on grid connected transformers vulnerable to stray DC currents from the HVDC link (see Table 1 for installation sites).

[7] The transformer neutral current values measured by the LEMs have been used in the evaluation of DC models to provide an improved understanding of the flow of HVDC link return currents in the AC system [*Dalzell*, 2011]. The transformer neutral current measurements are used in this paper to compare with a proxy for the geoelectric field, the driver of GICs. Typically, data are obtained from a number of transformers at each of the installation sites indicated in Table 1. It can be seen from Figure 1 that some installation sites are power stations and some are substations. The monitoring sites are primarily located toward the center of New Zealand's South Island, nearer to the HVDC land electrode at Bog Roy (8 km away from the HVDC converter station at Benmore).

[8] The GIC-indices used as a proxy for the geoelectric field are derived according to the method described by *Marshall et al.* [2011]. This method involves applying a frequency domain filter that is essentially the "surface impedance" for a uniform half-space unity conductivity model. Typically, a complete day of 1 min sampled single component geomagnetic field data is transformed into the frequency domain, filtered, and reverse transformed. The GIC-index is the absolute value of the reverse transformed data. Geomagnetic field variations measured in the north-south direction (x-component) were used to calculate the $\mathrm{GIC_y}$-indices as a proxy for the east-west geoelectric field (y-direction). Only the results of the correlation analysis obtained using $\mathrm{GIC_y}$-indices are presented as the results obtained using $\mathrm{GIC_x}$-indices were typically lower. Appropriate combination of NS and EW fields would most likely improve correlation values, however, the values obtained using only $\mathrm{GIC_y}$-indices are considered sufficient to illustrate the points presented in this paper. Geomagnetic field data obtained from the Eyrewell magnetic observatory (43.422S, 172.355E), located about 30 km northwest of Christchurch on New Zealand's South Island, were used to calculate the $\mathrm{GIC_y}$-indices. The $\mathrm{GIC_y}$-indices were compared with the absolute value of transformer neutral currents measured at various locations given in Table 1 recorded over the same time intervals. The sample periods of both the magnetometer and the transformer neutral data sets are 1 min. *Pulkkinen et al.* [2012] discuss the implications of increased sampling of data sets for GIC analysis. It is likely that using increased sampling would result in higher correlation values and increased amplitudes of peak GICs. However, for the purposes of this study the 1-min samples are considered adequate.

3. Results

[9] Figures 2a–2d show time series plots of $\mathrm{GIC_y}$-index and absolute values of the transformer neutral current measured at stations spanning the monitoring network from north to south, Islington and Ashburton substations, and Ohau(A) and Clyde power stations respectively. Figure 2 shows data recorded 1400–2200 (LT) on 6th November 2001. The correlation coefficients between the $\mathrm{GIC_y}$-index and each of the transformer neutral currents were: 0.93 (Islington substation); 0.81 (Ashburton substation); 0.86, 0.86, 0.53 for Ohau A power station transformers T5,T6, and T7 respectively and 0.85 and 0.86 for Clyde power station transformers T1 and T3 respectively. Some monitors were reporting 0A DC during this event. A transformer which is out of service for scheduled maintenance for example will report 0A DC current. However, at almost all monitored

Figure 1. Map of New Zealand's South Island power transmission network. The approximate location of the geomagnetic observatory at Eyrewell is shown in pink with precise latitude and longitude given in the text. All copyright remains with Transpower New Zealand Limited.

Table 1. Definitions of Some of the Acronyms and Terminology Used in This Study (in Alphabetical Order)[a]

Term	Definition
Alstom	Manufacturer of ISL SVC
AC	Alternating Current
ASB	Ashburton*
AVI	Aviemore*
BDE	Brydone
BEN	Benmore Power Station* (located near southern HVDC terminal station)
BRY	Bromley*
Buchholz	A device fitted to a transformer which detects internal pressure spikes
Cap	Capacitor
CLU	Clutha River Hydro Scheme
CML	Cromwell*
CYD	Clyde Power Station*
HBC	Halfway Bush Control Centre
HWB	Halfway Bush
HVDC	High Voltage Direct Current Link
ISL	Islington*
kV	Kilovolts
KWA	Kaiwharawhara* (North Island, Wellington)
MCC	Meridian Control Centre (manages OHA, OHB, OHC, TKB, MAN, BEN)
MW	Power in Megawatts
NCC	National Control Centre
NER	Neutral Earthing Resistor (fitted to transformer neutrals)
OHA	Ohau A Power Station*
OHB	Ohau B Power Station*
OHC	Ohau C Power Station*
Pole 2, half pole	Part of the HVDC Link (made up of Pole 2 and 2 half poles)
Red phase	The power grid is made up of three different phases; Red, Yellow, and Blue. A single phase bank of transformers such as HWB T4 is made up of three units; one for each phase
RTS	Return To Service
ROX	Roxburgh Power Station
SC	Security Co-ordinator (part of NCC)
SI	South Island
SVC	Static VAr Compensator - A device which dynamically supplies or absorbs reactive power
T4, T10	Transformers
TIM	Timaru*
TKB	Tekapo B Power Station*
TOC	Transfer of Operational Control
TWD	Tailwater Depressed - a method of operating hydro generators. In this configuration they can supply or absorb reactive power but not generate real power
VAr	Reactive Power
WTK	Waitaki*

[a] The asterisks indicate locations where transformer neutral DC currents are monitored.

stations there was at least one transformer neutral current that showed similar amplitude trends to the GIC_y-index in the time series data with good correlation so the trends shown in Figure 2 are representative of most other monitored locations. The relatively poor correlation value of transformer T7 at Ohau A power station is considered partly due to erroneous data during the first 1–1.5 h of Figure 2c when the data were initially flat-line and then decreased leading up to, and during, the large spike in GIC_y-index. The correlation coefficient calculated with this section of data removed for Ohau A transformer T7 was 0.64.

[10] Some of the larger GICs measured by the monitoring system during this event coincided with the large spike in GIC_y-index that occurred at 14:52 (LT) with the largest being approximately 22.5 Amps measured at the Islington substation. The peak current as recorded from 20 s sampled data (not shown) was 27.4 Amps. Not all transformer neutral monitors within the network recorded currents as large as those shown in Figure 2. A full network analysis may establish whether the largest currents were observed at the anticipated locations. This analysis is a future study and beyond the scope of this paper.

[11] Figure 3 shows the solar wind speed and density as measured by the SOHO satellite proton monitor and the calculated solar wind dynamic pressure. The ACE satellite data were unavailable for this event. The large step-like change in dynamic pressure of approximately 18 nPa at

Figure 2. Time series of GIC_y-index and absolute values of the transformer neutral currents measured during 6th November 2001 at (a) Islington substation, (b) Ashburton substation, (c) Ohau A power station, and (d) Clyde power station. Data is shown for the period 1400–2200 (LT).

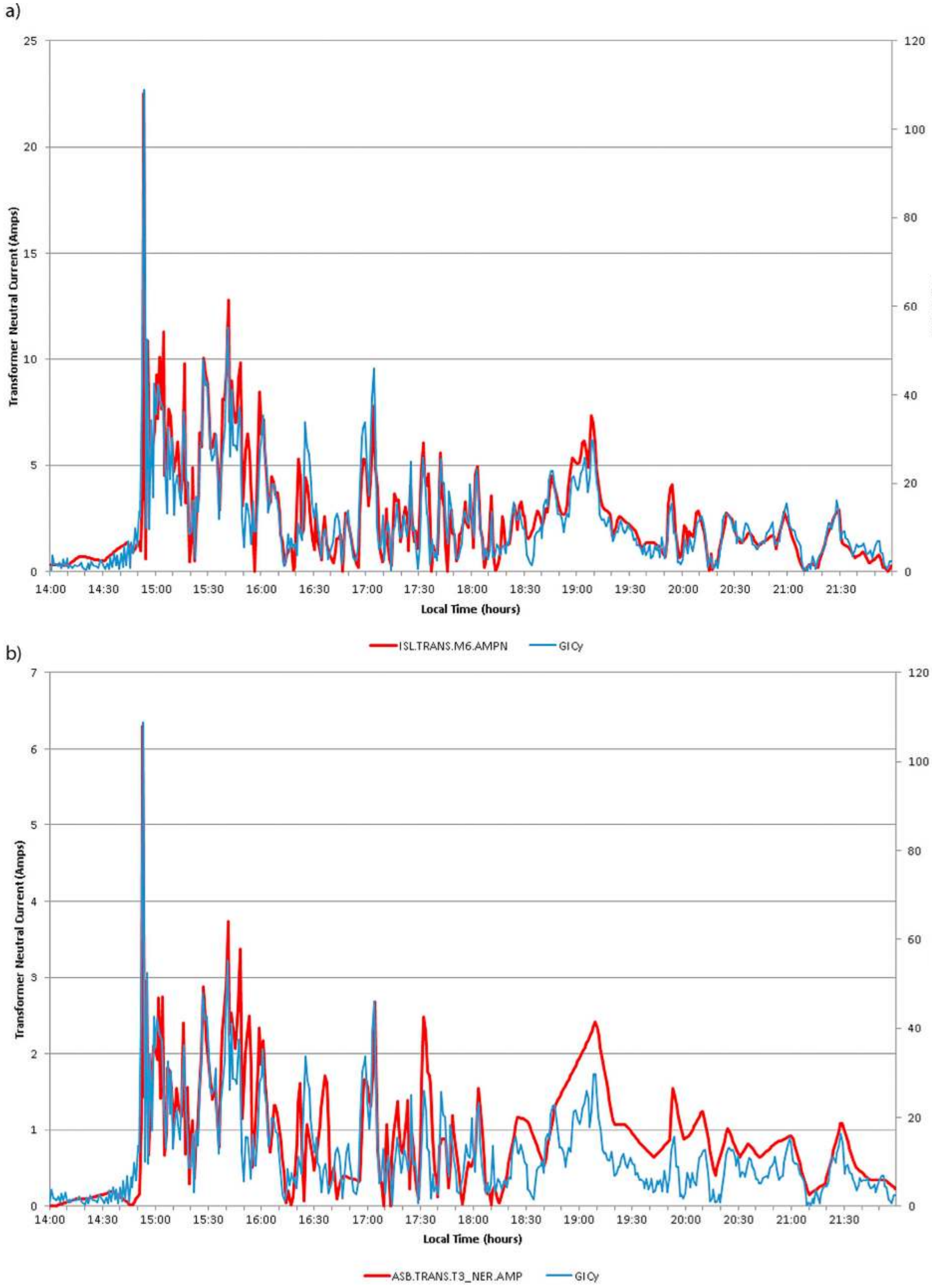
a)
Transformer Neutral Current (Amps)
0
5
10
15
20
25
GICy-Index
0
20
40
60
80
100
120
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
Local Time (hours)
ISL.TRANS.M6.AMPN
GICy
b)
Transformer Neutral Current (Amps)
0
1
2
3
4
5
6
7
GICy-Index
0
20
40
60
80
100
120
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
Local Time (hours)
ASB.TRANS.T3_NER.AMP
GICy

Figure 2

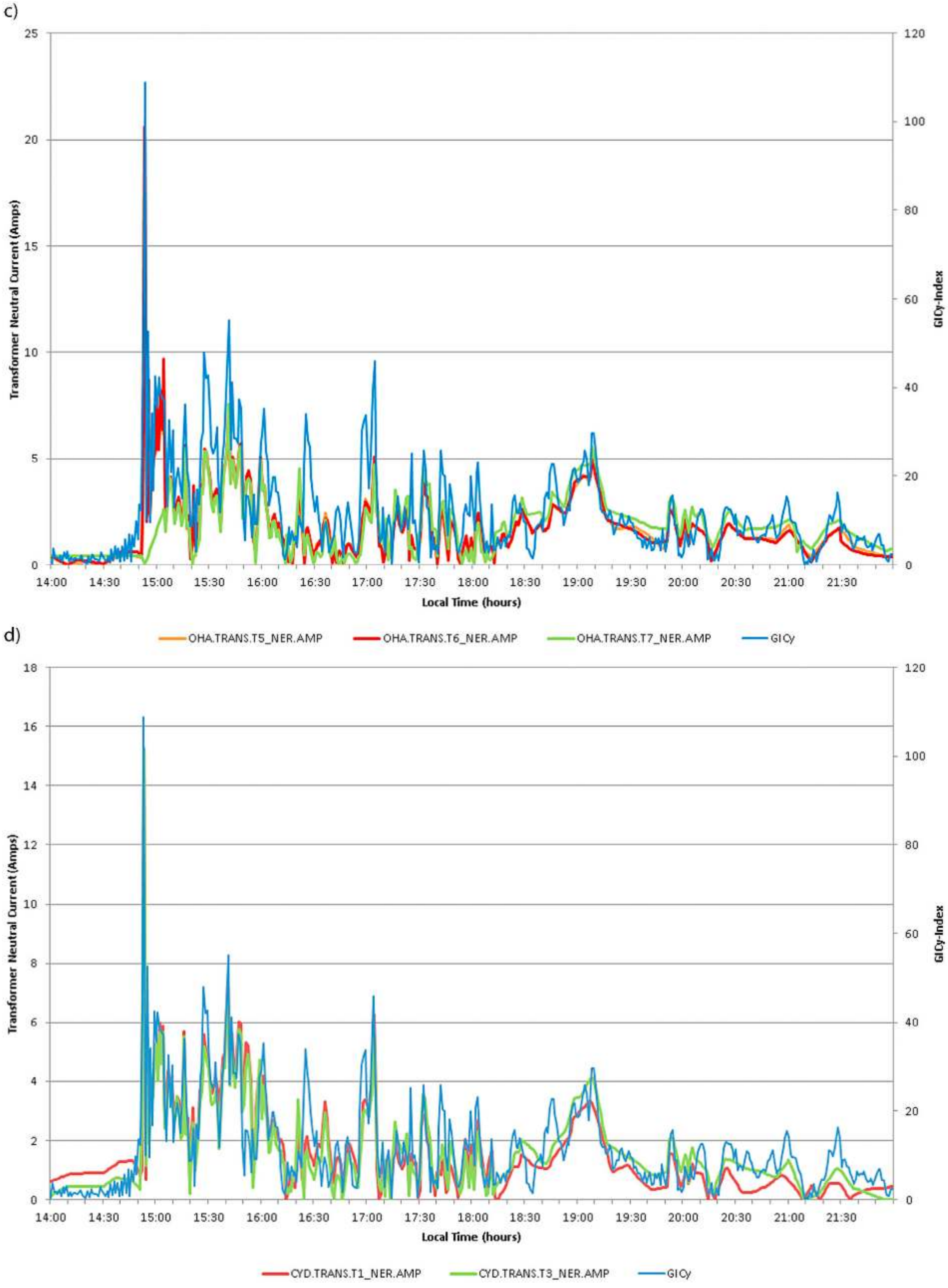

Figure 2. (continued)

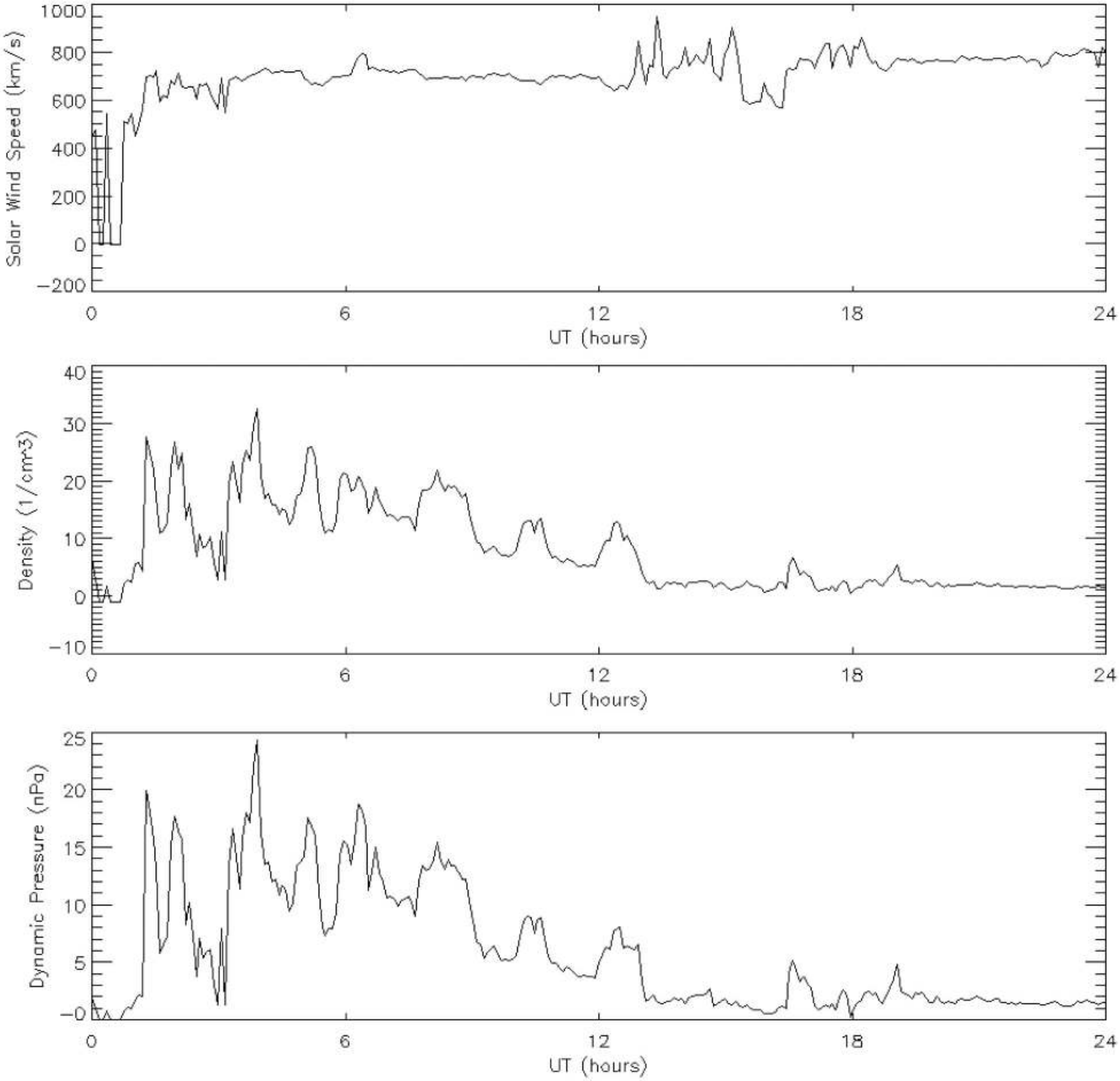

Figure 3. Solar wind data recorded by the SOHO satellite during 6th November 2001 (UT = NZST − 13). (top) The bulk solar wind velocity, (middle) the density, and (bottom) the dynamic pressure calculated from these two parameters.

01:20 UT is associated with the sudden impulse in the geomagnetic field x-component data and the corresponding large GIC$_y$-index at 14:52 LT (01:52 UT) as shown in Figure 4. The SOHO satellite was located ~197 Re sunward and the density enhancement propagated at a solar wind speed of ~700 km/s gives an approximate transit time to the magnetopause of ~30 min. Table 2 shows a summary of the Transpower events log from the National and Regional Control Centers during this event. It can be seen that tripping of the SVC system at Islington and the tripping of transformer T4 at Halfway Bush coincides with the SI related GIC$_y$-index. Within the following hour there were a number of alarms and components tripped, including a transformer fault and subsequent failure. This also occurred during increased levels of geomagnetic activity and GIC-indices. There were no monitors at Halfway Bush. Transpower have recently approved the installation of further GIC monitors in the more southern parts of New

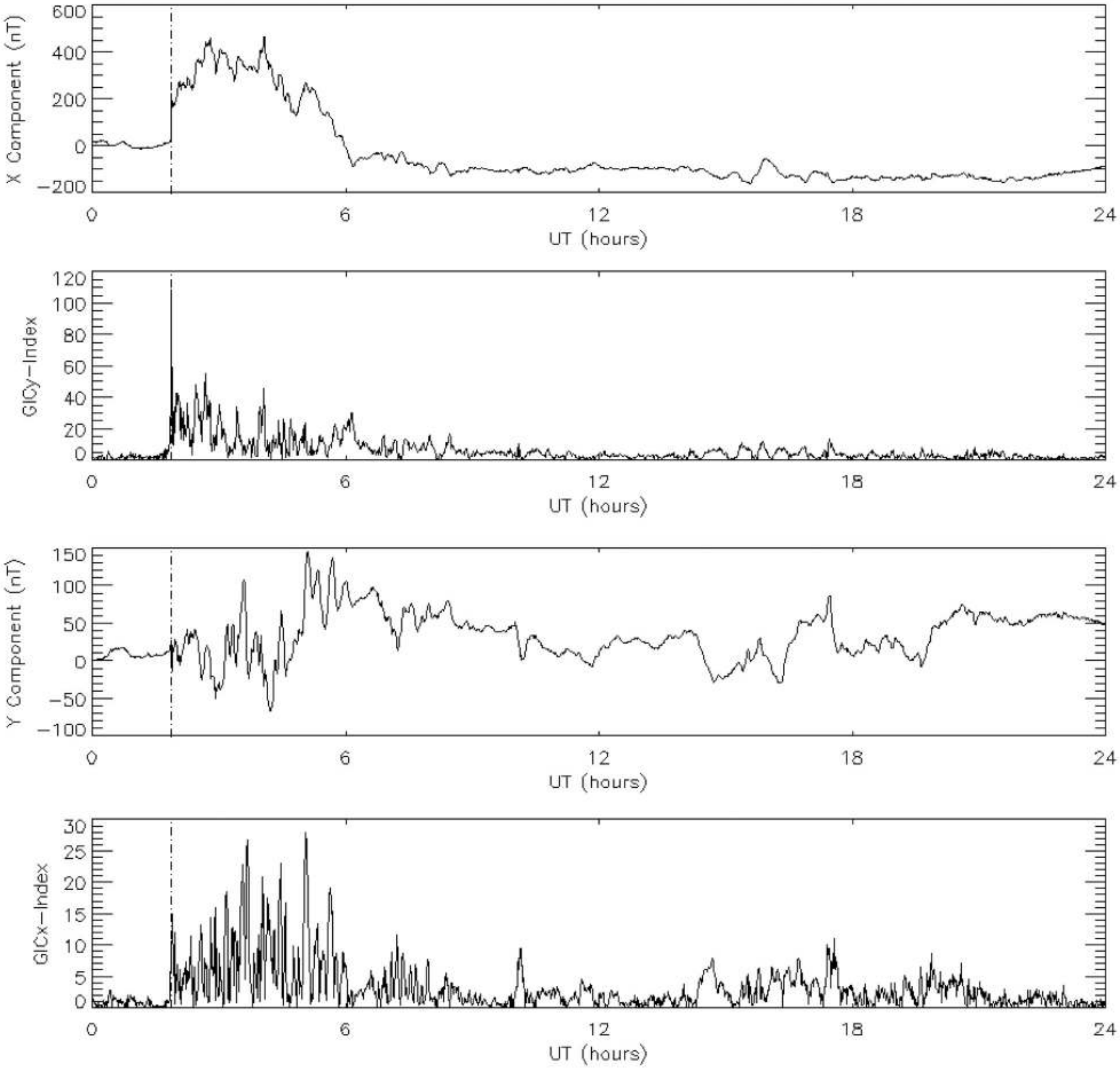

Figure 4. Time series and derived GIC indices obtained from the Eyrewell magnetometer in New Zealand for 6 November 2001. The vertical dashed line indicates the time of power system failure.

Zealand's South Island in order to improve understanding of the GIC phenomena and to increase network security.

4. Discussion

[12] The impacts of the "2003 Halloween storm" on various technologies have been well documented [*Barbieri and Mahmot*, 2004; *Webb and Allen*, 2004]. This storm was generally considered one of the larger events of solar cycle 23 [*Cliver and Svalgaard*, 2004] and resulted in loss of electricity supply for a period of 1 h in the Swedish power system [*Pulkkinen et al.*, 2005; *Wik et al.*, 2009]. The planetary A-index (Ap) for the Halloween storm days of 29–31 October 2003 were 204, 191, and 116 respectively, with Dst-index minima of −353 nT and −383 nT occurring at 01 UT and 23 UT on 30 October (14 LT 30 October and 12 LT 31 October respectively). The geomagnetic storm of 6th November 2001 produced an Ap of 142 and a minimum Dst-index of −292 nT. Comparison of these geomagnetic activity indicators suggests the 6th November 2001 storm

Table 2. Summary of Transpower's Event Log for 6th November 2001 Event[a]

Date/Time	Description
06-Nov-01, 14:52:00	HWB T4 and ISL SVC tripped. Many South Island transformer NER alarms. HVDC running OK in balanced mode. HVDC load 216MW with Pole 2 and a half pole in service
06-Nov-01, 14:52:00	Buchholz trip
06-Nov-01, 14:53:00	Red phase caused the tripping. D2 protection flag. Maintenance contractor advised
06-Nov-01, 14:53:00	Buchholz trip. SC advised. HBC to call out contractors
06-Nov-01, 15:08:00	Trip. Alstom called out. SC advised
06-Nov-01, 15:25:00	SI NER alarms reset
06-Nov-01, 15:26:00	T4 tripped at HWB. Ohau unit transformers NER saturation. ISL SVC tripped. Unknown cause. Requested CLU max VArs at ROX 110 kV, Extra machine started. Third cap switched in at BDE. Requested extra machines on OHA, OHB, OHC running on TWD to alleviate NER transformer saturation
06-Nov-01, 15:27:00	TKB, CYD, OHA, OHB NER alarms
06-Nov-01, 15:34:00	TOC (Internal transformer fault, explosion vents blown)
06-Nov-01, 15:34:00	HBC advise Red phase unit indicates internal fault. SC told
06-Nov-01, 15:46:00	RTS
06-Nov-01, 16:09:00	Further to 15:26 incident. ISL SVC reconnected. Fourth cap in at BDE
06-Nov-01, 16:32:00	Expected return 07-11-01 09:00 SC told
06-Nov-01, 17:00:00	Further to 15:26 incident. NER saturation alleviated. MCC advised to disconnect extra machines at OHA, OHB, OHC. Voltage manageable at HWB. AC constraint within block applied to ROX 110 kV. CLU advised extra machine can be disconnected at ROX 110 kV as VAr output sufficient on 1 machine.
06-Nov-01, 17:05:00	TKB, CYD, OHA, OHB NER alarms reset

[a] Acronym definitions are given in Table 1. Data from Transpower New Zealand Limited.

was less severe than the Halloween storm in many aspects. However, the impact on New Zealand's power network was significant. *Béland and Small* [2004] suggest that the failure of Transformer T4 at Halfway Bush may have also been due to deterioration from cumulative exposure to GICs, faults and overloads, with the 6th November 2001 event being the final contributor.

[13] For comparison, plots analogous to Figure 2a for the "Halloween storm" event of 29–31 October 2003 for Islington are shown in Figure 5. The correlation coefficients for Figures 5a–5c were 0.90, 0.86 and 0.78. The similarities in time series and high correlation coefficients indicate that the geoelectric field proxy (GIC_y-index) is an excellent predictor of measured GIC. The relatively lower correlation value of Figure 5c is considered likely due to the large current spikes in the latter half of the day which are not observed in the GIC_y-index. Figure 5 shows that the maximum amplitude of the measured GIC at Islington during this storm occurred during the current spikes on 31 October and was approximately 23.4 Amps. Comparison of Figure 5 with Figure 2a indicates that the maximum measured GIC associated with the large SI of 6th November 2001 is comparable with the maximum measured GIC observed during the "Halloween storm." The event logs for the Halloween storm (not shown) reveal that although there were many alarms and relatively elevated neutral current measurements, no apparent damage was sustained by the network. Mitigating action taken by Transpower during the "Halloween storm" may have also contributed to the reduced severity of impact of this storm to the New Zealand power network. Some of these actions were: to operate the HVDC link with balanced pole currents in addition to reducing HVDC power transfer; to cease live-line work being carried out on South Island circuits so these can be taken out of service quickly if required; and to reconfigure the South Island grid to be less susceptible to GIC including removing transmission lines from service and disconnecting/connecting power transformers at key sites. The mitigating actions were taken in response to geomagnetic activity warnings, alerts, and network monitoring alarms, and in accordance with procedures [*Transpower*, 2011] implemented as a consequence of damage sustained during the 6th November 2001 event.

[14] Further comparisons between the 6th November 2001 event and the "Halloween storm" may be made by comparing magnetic field measurements, often used to monitor changes in space weather at the ground [*Viljanen et al.*, 1999, 2001; *Kappenman*, 2005, 2006; *Pulkkinen et al.*, 2005, 2012; *Wik et al.*, 2009; *Liu et al.*, 2009a, 2009b]. The magnetometer data respond to overhead ionosphere current and magnetosphere current systems, where the time rate of change of the magnetic field is used to estimate the magnitude of GICs [*Viljanen et al.*, 2001]. Magnetometer data sampled at 1 min intervals are commonly available. The time rate of change may be calculated from field component (b_x, b_y, b_z) change per minute or as a total change (B) per minute. *Kappenman* [2005] and *Trichtchenko and Boteler* [2004] discuss the benefits of db/dt data over more traditional geomagnetic indices such as the K-index when studying GICs.

[15] *Viljanen* [1997] presented db/dt values for each field component as a function of latitude using auroral latitude stations over the period 1991–1992. *Kappenman* [2001] presented contours of dB/dt as a function of latitude for the March 1989 event. *Pulkkinen et al.* [2012] presented plots of the geoelectric field, dH/dt and ΔH with latitude for both the March 1989 and 2003 Halloween storms. All these studies showed an approximate order of magnitude

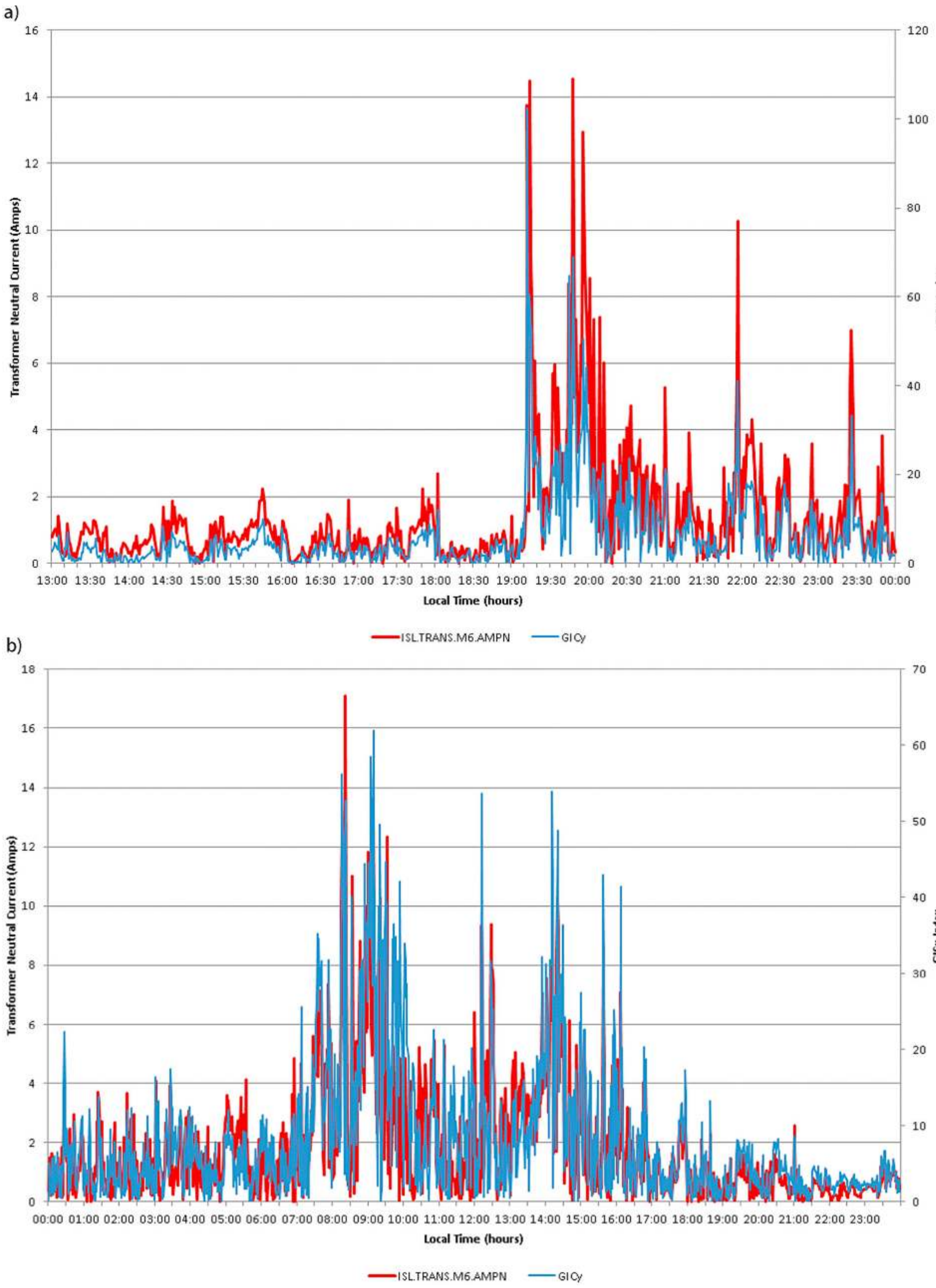
a)
Transformer Neutral Current (Amps)
0
2
4
6
8
10
12
14
16
GICy-Index
0
20
40
60
80
100
120
13:00 13:30 14:00 14:30 15:00 15:30 16:00 16:30 17:00 17:30 18:00 18:30 19:00 19:30 20:00 20:30 21:00 21:30 22:00 22:30 23:00 23:30 00:00
Local Time (hours)
ISL.TRANS.M6.AMPN
GICy
b)
Transformer Neutral Current (Amps)
0
2
4
6
8
10
12
14
16
18
GICy-Index
0
10
20
30
40
50
60
70
00:00 01:00 02:00 03:00 04:00 05:00 06:00 07:00 08:00 09:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00
Local Time (hours)
ISL.TRANS.M6.AMPN
GICy

Figure 5

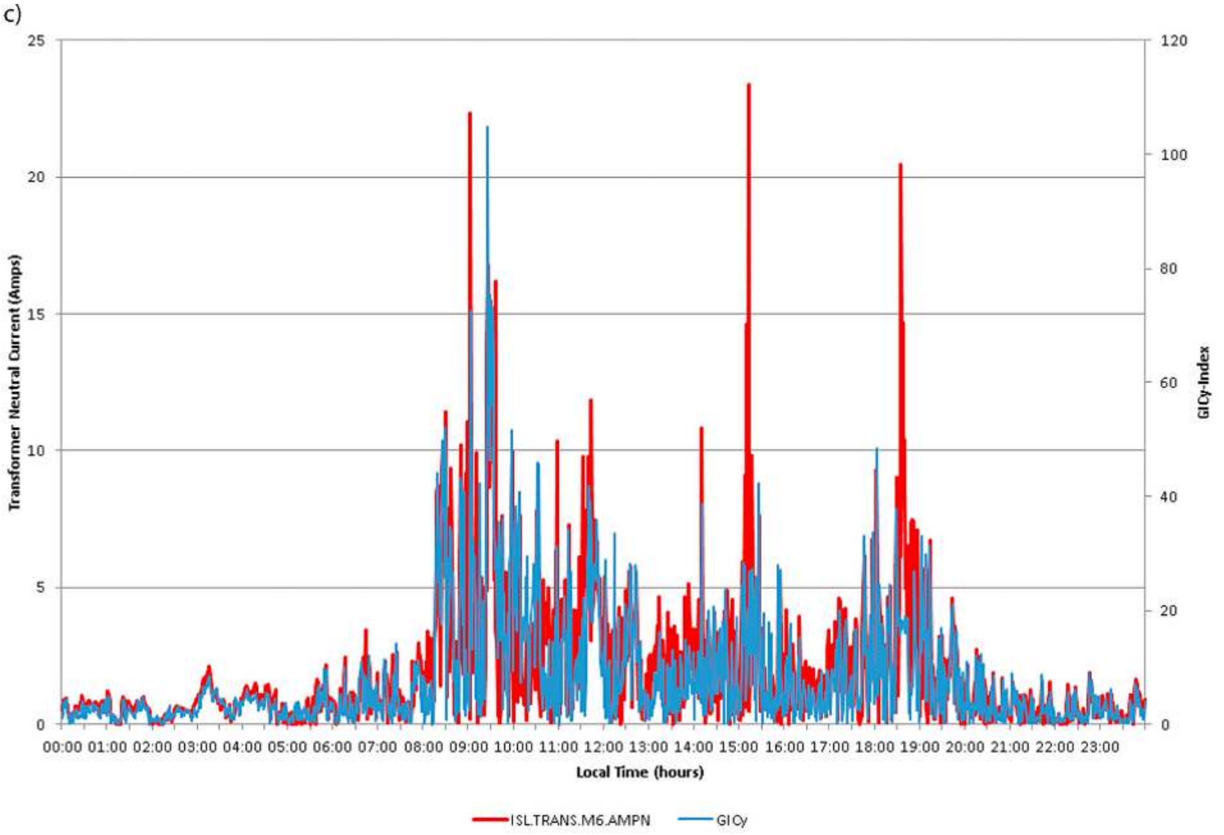

Figure 5. (continued)

decrease in db/dt transitioning from auroral latitudes to middle latitudes. Figure 6a is reproduced from *Pulkkinen et al.* [2012] and shows the maximum time rate of change of horizontal magnetic field intensity with latitude derived from a large latitudinal array of stations during the 2003 Halloween storm. Figure 6b shows an analogous plot (southern hemisphere data only) for the SI event of 6th November 2001 derived from the stations in Table 3. Although the data are somewhat more sparse compared with Figure 6a, there does not appear to be the order of magnitude decrease transitioning from high latitudes to middle latitudes. The values obtained for the SI event of Figure 6b show less variation with latitude than that exhibited in Figure 6a which typifies a large main phase storm. This suggests that some of the trends determined from studies of GICs that occur during large storms may not necessarily apply to GICs produced as the result of large SI events, i.e., a different latitudinal dependence may be expected depending on whether the field values are dominated by dynamics of the auroral or magnetopause currents.

[16] These results suggest that large changes in solar wind dynamic pressure producing enhanced magnetopause currents and associated geomagnetic SIs may pose threats to power networks at middle latitudes at least equally significant to those occurring during the geomagnetic storm main phase produced by auroral currents. This has been suggested previously by *Kappenman* [2003]. Sudden Impulse events are typically more global in nature than auroral current signatures and affect a range of latitude covering a large percentage of the world's population. Further, the latitudinal dependence of the impacts of these events on power systems differs from that observed during large main phase storms.

[17] Shocks in the solar wind, and the resultant SI, are some of the more impulsive transients in the solar wind, and provide little lead time for power networks to react to in situ satellite data (if available). Forecasting of the solar wind speed and density associated with large CMEs may prove important in providing sufficient lead times for this type of space weather phenomena. Further studies of SI events such as their relation to associated solar wind

Figure 5. Time series of GIC$_y$-index and absolute values of the transformer neutral currents measured at the Islington substation during (a) 29, (b) 30, and (c) 31 October 2003 (NZST).

shocks, their possible extremes, and the latitude dependence of their signatures, may also provide a better understanding of the possible impacts to low-middle latitude power networks. Further, the mitigating actions taken by Transpower during the Halloween storm also highlights the importance of operating procedures for large space weather events, even at middle latitude locations.

5. Conclusion

[18] This study examines a GIC event that occurred in New Zealand's South Island power network on 6th November 2001. A transformer failure that occurred during this day is shown to be associated with a change in the solar wind dynamic pressure of nearly 20 nPa. Measurements of GICs recorded on the neutral lines of transformers across the Transpower network during this event show good correlation with a GIC-index, a proxy for the geoelectric field that drives GIC. Comparison of this event with GIC activity observed in the Transpower network during large space weather storms such as the "2003 Halloween storm," suggests that solar wind shocks and associated geomagnetic sudden impulse (SI) events may be as hazardous to middle latitude power networks as GIC activity occurring during the main phase of large storms. Further, this study suggests that the latitudinal dependence of the impacts of SI events on power systems differs from that observed during large main phase storms. This study also highlights the importance of operating procedures for large space weather events, even at middle latitude locations.

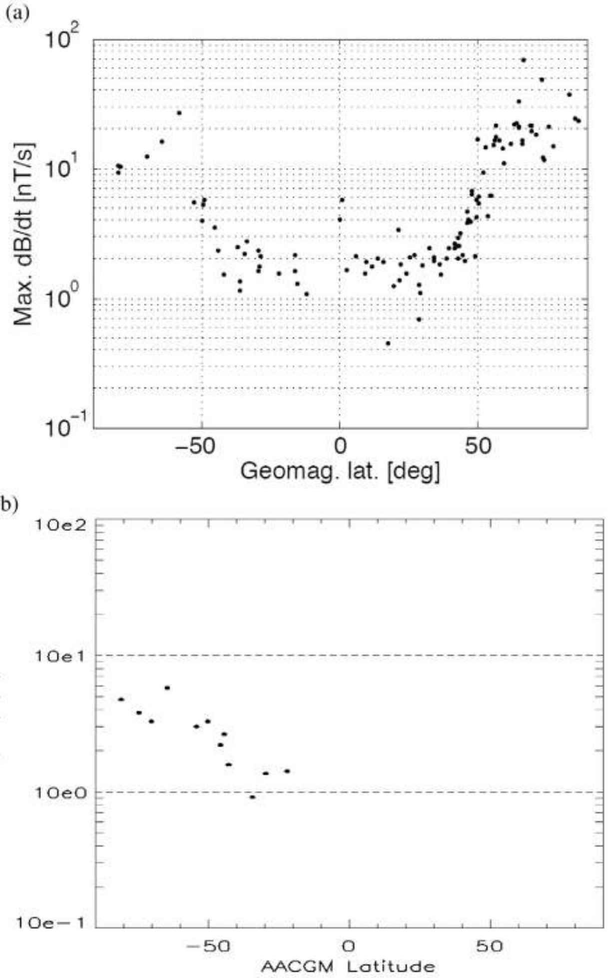

Figure 6. Maximum time rate of change of horizontal magnetic field intensity in nT/sec as a function of latitude for (a) the "Halloween storm" of 29–31 October 2003 (reproduced from *Pulkkinen et al.* [2012]) and (b) the sudden impulse event of 6th November 2001 as determined from the stations in Table 3.

Table 3. List of Stations and Their Coordinates Used to Derive the Time Derivative of Geomagnetic Field Data for Figure 6b[a]

Station	GG Latitude	GG Longitude	ACCGM Lat.	ACCGM Long.
Darwin	12′ 27″S	130′ 50″E	−21.96	157.3
Charters Towers	20′ 6″S	146′ 16″E	−29.5	139.8
Alice Springs	23′ 42″S	133′ 52″E	−34.3	153.2
Gnangara	31′ 46″S	115′ 51″E	−44.3	173.5
Newcastle	32′ 55″S	151′ 45″E	−42.7	131.1
Canberra	35′ 18″S	149′19″E	−45.6	133.6
Hobart	42′ 52″S	147′ 19″E	−54.1	133.5
Eyrewell	43′ 24″S	172′ 24″E	−50.1	103.7
Macquarie Island	54′ 30″S	158′ 57″E	−64.5	111.9
Casey	66′ 17″S	110′ 31″E	−80.8	155.7
Mawson	67′ 36″S	62′ 52″E	−70.1	89.8
Davis	68′ 35″S	77′ 58″E	−74.5	99.6

[a] Geographic (GG) latitude and longitude coordinates are given in degrees and minutes and the Altitude Adjusted Corrected Geomagnetic (AACGM) coordinates are given as decimals with negative values for south and west.

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