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Implementing Geomagnetically Induced Currents Mitigation During the May 2024 "Gannon" G5 Storm: Research Informed Response by the New Zealand Power Network

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Key Points:

- The May 2024 "Gannon storm" produced the largest magnetic field variations (nT/min) measured in New Zealand since digital recordings began
- During the Gannon storm the New Zealand-wide electricity grid GIC mitigation strategy was implemented for the first time
- Measured GIC levels were the largest values ever recorded in New Zealand but were reduced at key hotspot locations due to mitigation

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Abstract In early May 2024 ∼6 Coronal Mass Ejections were launched toward the Earth in short succession. This triggered the G5 "Gannon" geomagnetic storm lasting from ∼17 UT on 10 May 2024 to ∼9 UT on 12 May 2024. Auroral displays were seen around the world including at lower latitudes than previous geomagnetic disturbances this century. Magnetic field variations measured at multiple sites in New Zealand exceeded values observed over the past 30 years. In 2022, following many years of industry-research collaboration, an updated and enhanced "All of New Zealand" Geomagnetically Induced Current (GIC) mitigation strategy was developed. This strategy involves targeted line disconnections to reconfigure the network. The goal of this approach is to reduce GIC magnitudes and durations at the most at risk transformers, while still maintaining the continuous supply of power. Following training of control room staff, this strategy was declared operational in mid-2023. Once disturbance levels reached the G5 threshold during the Gannon storm Transpower control room staff followed the planned procedure and implemented the mitigation strategy for the first time. There was no impact to New Zealand's electrical supply from this storm. GIC was measured at more than 70 transformers throughout the New Zealand power grid. Peak GICs observed after the mitigation strategy was in place reached ∼113 A at a transformer in the city of Dunedin. Without mitigation, modeling shows that a peak GIC of ∼200 A through the neutral would have occurred, exacerbated by the tripping of a transformer at a neighboring substation.

Plain Language Summary The Gannon storm of May 2024 was host to the largest geomagnetic storm to impact New Zealand in approximately 20 years. In this study we report the response taken during this storm by the New Zealand power network, including mitigation efforts undertaken. Peak GICs observed exceeded 100 A. Modeling shows these would have exceeded 200 A without the mitigation efforts. There were no negative impact to the New Zealand power network or supply to customers. Understanding how the power network responds during geomagnetic storms is crucial when developing a response plan for the much larger extreme storms which may pose a severe risk to power network operation in the future.

1. Introduction

Solar activity phenomena such as coronal mass ejections colliding with the Earth's magnetosphere can lead to large geomagnetic storms which pose a threat to power transmission networks. Rapid fluctuations in the Earth's external magnetic field induces currents in the ionosphere and geoelectric fields in the conducting surface of the Earth. This induces currents through long, high-voltage power lines (Divett et al., 2017, 2020; Vasseur & Weidelt, 1977) which flow into the Earth via neutral connections on high voltage transformers (Mac Manus, Rodger, Ingham, et al., 2022). GICs can lead to various issues for power systems and other infrastructure, such as damage to transformers and other equipment, voltage instability, and power outages (e.g., D. Boteler, 2015; Samuelsson, 2013). In severe cases, Geomagnetically Induced Currents (GICs) could result in large-scale blackouts and significant disruptions to critical infrastructure (Council, 2008; JASON, 2011; Oughton et al., 2017). The most well-known extreme geomagnetic event is the Carrington event of September 1859 (Carrington, 1859), though other notable instances include the May 1921 event (Gibbs, 1921; Hapgood, 2019) and the "Carrington-like" event in July 2012, which narrowly missed Earth (Ngwira et al., 2013).

The solar activity of the most recent solar cycle has exceeded all prior forecasts. The monthly sunspot number has reached higher values than initially predicted (Nandy, 2021). Since the Halloween storm of 2003, the past 20 years has seen largely mild geomagnetic conditions, but solar cycle 25 has produced frequent solar flares and coronal mass ejections and will likely cause further geomagnetic storms and potentially severe space weather events in the next few years. Large events like the Gannon storm provide a key opportunity to understand the impact on a global and local scale that might arise from an extreme event in the future.

Given enough warning of the arrival at Earth of a large geomagnetic storm event, two potential network configuration styles could be adopted. One is to increase power generation in order to provide any increase in reactive power that a network might need for stability if transformers are experiencing large GIC. Another configuration strategy is to act to reduce the levels of GIC experienced by key transformers in the network. This has the advantage of reducing the likelihood of damage to transformer assets and reduce the reactive power demand as well. Transpower in New Zealand have adopted this latter mitigation strategy (Mac Manus et al., 2023). However, any mitigation strategy can be undermined by unexpected network configuration changes, potentially brought on by the geomagnetic storm itself, and an understanding of the possible evolution of the network is important in planning for extreme events.

In this study the impact of configuration changes in the New Zealand power network that occurred during the Gannon Storm are investigated. During periods of peak geomagnetic disturbance network configuration changes both increased and decreased GIC at key transformer locations. Modeling of the network changes is used to provide a framework for the measurements of GIC flowing in hotspot transformers to be put into context, and are used to indicate the GIC levels that could have occurred had no changes taken place. In Section 2, we present a description of the experimental data sets measured during the Gannon storm. Following this, in Section 3 we provide a brief description of the modeling method used in this study to model GIC in New Zealand. In Section 4 we describe the mitigation strategy developed to reduce GIC impact in New Zealand. The timeline of the Gannon storm is summarized in Section 5 while observations and modeling results are discussed in Section 6. Final remarks can be found in Section 7.

2. Experimental Data Sets

2.1. GIC Observations

Transpower NZ Ltd, the New Zealand High Voltage electricity transmission system owner and operator, has been measuring, and archiving observations of transformer neutral current values from quasi-DC current measuring devices (LEM) at many transformers. This has occurred from multiple South Island locations since 2001 with more observing locations added over time. Now, LEM installation sites approximately span the full length of New Zealand. Beginning with 36 transformers at 13 substations in 2001 the GIC observations have expanded to 93 transformers at 28 substations as of October 2024 (see Figure 1). In many substations more than one LEM is installed, independently monitoring each transformer. An extensive description of the New Zealand DC observations are given in Mac Manus et al. (2017) and Rodger et al. (2020). The LEM archiving software alters the recorded data time resolution depending on the level of change detected in the observations, as discussed in Clilverd et al. (2020). During periods of fast-changing measurements the time resolution is at its highest level of 4-s for most transformers, but during less active periods the time resolution could be tens of seconds. In this current study we down-sample all the GIC observations to 1-min resolution, for consistency, but also to reflect the limitations of the modeling code (Divett et al., 2020).

2.2. Geomagnetic Field Data

The geomagnetic observatory in New Zealand is located at Eyrewell (EYR) (43.474°S, 172.393°E; green circle in Figure 2). It is part of INTERMAGNET (https://intermagnet.github.io/) and is operated by GNS Science, New Zealand.

As part of the Solar Tsunamis research project we have also set up a chain of five variometer sites to help capture the different geomagnetic conditions occurring over the range of latitudes and longitudes covered by New Zealand. These consist of two in the North Island (Donnelly and Oakview), two in the South Island (Swampy and Awarua) and one on the Chatham Islands approximately 800 km east of New Zealand's South Island (see Figure 2). Together these 5 variometers are termed the Magnetometer Array for New Zealand Aotearoa (MANA);

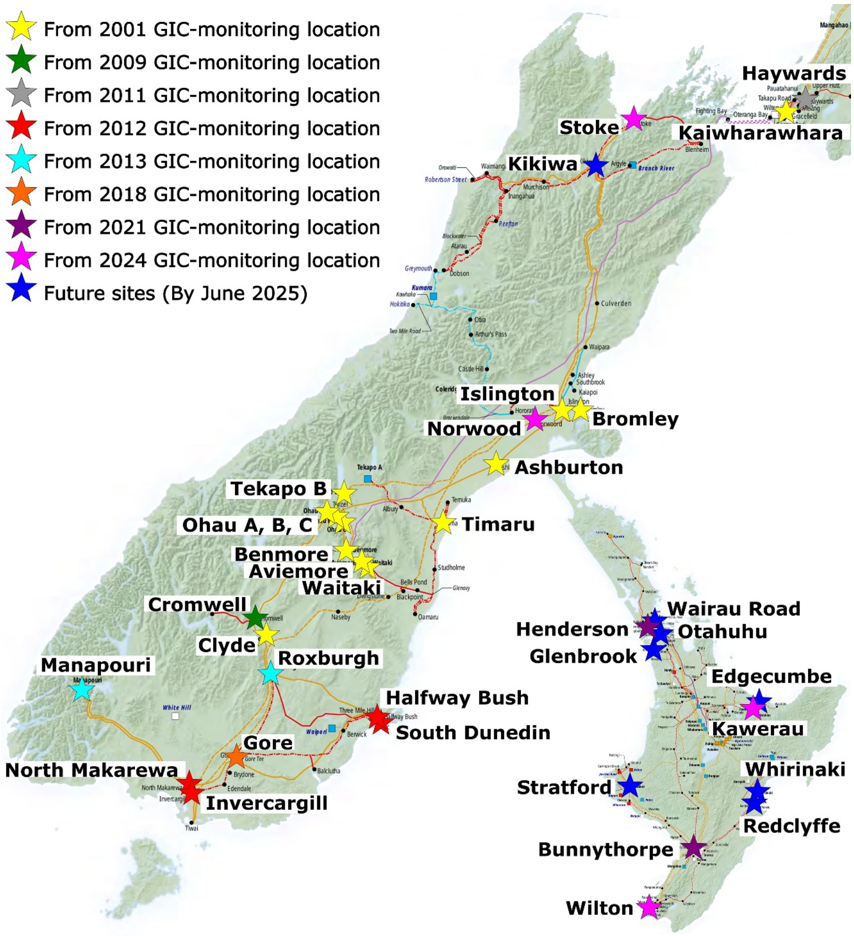

Figure 1. Location of substations with DC monitoring equipment are given by the colored stars. Colored lines indicate the routes of transmission lines of various voltages (66 kV = light blue, 110 kV = red, 220 kV = orange) including the High Voltage Direct Current (HVDC) link shown in purple (350 kV) connecting the North and South Island electrical networks.

MANA, along with the Eyrewell magnetometer, provides the magnetic field coverage required across New Zealand to capture the time and spatially varying geomagnetic conditions.

3. Modeling Method

Over the years, numerous studies have focused on modeling GIC in New Zealand, with the majority employing the thin sheet model (Divett et al., 2017, 2018, 2020; Mac Manus, Rodger, Dalzell, et al., 2022; Mac Manus, Rodger, Ingham, et al., 2022). These studies have relied on the large Transpower data set of GIC observations for model validation. Rodger et al. (2020) demonstrated a strong correlation between Total Harmonic Distortion (THD) and model GIC outputs in the South Island, while also identifying potential concern areas in the North Island where GIC measurements did not exist in 2020. Ingham et al. (2017) used Magnetotelluric (MT) measurements in New Zealand to develop transfer functions, predicting GIC at key transformers in the South Island during geomagnetic storms. Mukhtar et al. (2020) applied MT measurements to calculate GIC in the North Island, confirming high current levels in transformers that showed THD increases, as reported by Rodger et al. (2020). Based on these predictive results, Transpower was able to validate the harmonic measurements from its Power Quality metering installations and subsequently justify the installation of additional GIC LEM units at these newly identified higher risk sites.

The approach used in the current study is a thin sheet model similar to that explained in Section 2 of Mac Manus, Rodger, Ingham, et al. (2022). Here, we will give a short summary of the modeling approaches and address any areas which differ from that study.

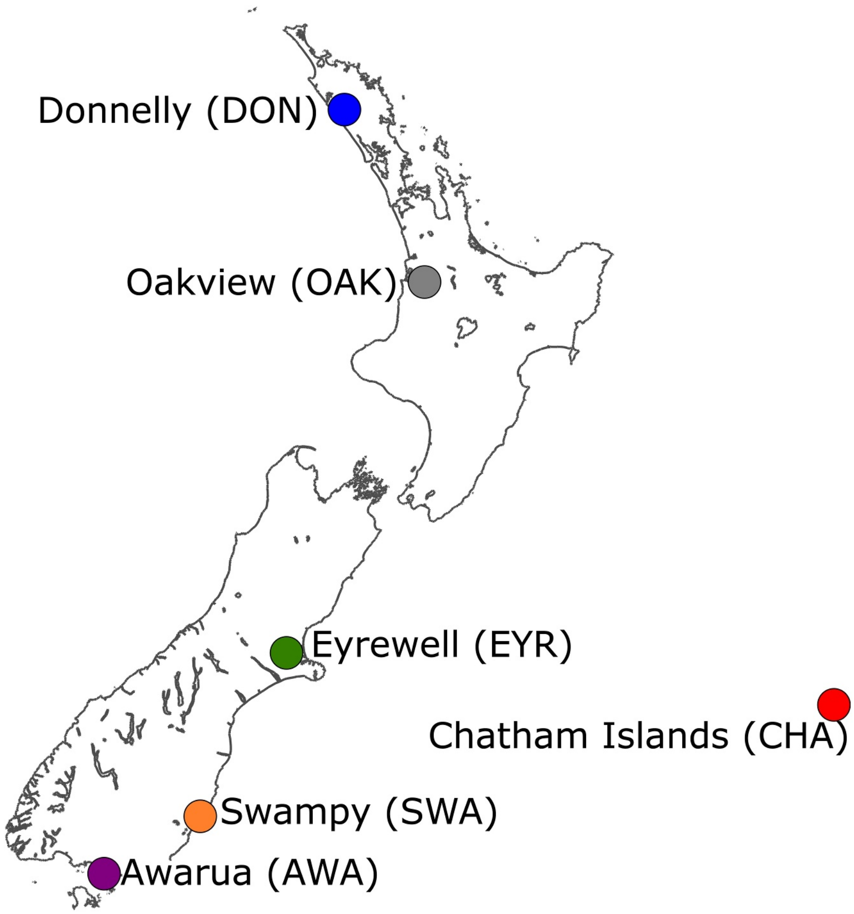

Figure 2. Location of the 5 MANA variometers and the Eyrewell (EYR) magnetic observatory.

3.1. Ground Conductance Model

A Thin-Sheet Conductance (TSC) model of New Zealand and its surrounding ocean is employed to calculate the electric field. The TSC modeling method, developed by Vasseur and Weidelt (1977), utilizes a grid with cells spaced one-sixth of a degree apart (approximately 20 km). Each grid cell represents the integrated conductance of the upper 20 km of the crust, reflecting the on-land conductance. The model's underlying structure consists of four layers, with resistivities of 1,000, 10,000, 100, and 1 Ω/m at depth boundaries of 20, 60, and 320 km, respectively (see Figure 1 in Mac Manus, Rodger, Ingham, et al. (2022)).

3.2. Geomagnetic Field

The geomagnetic field input is derived from the magnetic field measurements outlined in Section 2.2. Maps of the magnetic field across the model region are generated for each minute of the storm period under investigation, utilizing spherical elementary current systems (SECS) to interpolate between the six measurement locations (Amm, 1997). We use a spatial resolution of 0.5° and set the ionospheric current sheet at a height of 110 km above the surface. These parameters were selected as they work well for other mid-latitude countries at a similar geomagnetic latitude (Malone-Leigh et al., 2023; McLay & Beggan, 2010). The resulting magnetic field maps have a 1-min cadence and a resolution of 0.1 nT. The X component (positive toward geographic north) and the Y component (positive toward the east) are used as inputs for the thin sheet model, with values applied to each cell in the model domain. This is an update to previous modeling in Mac Manus, Rodger, Dalzell, et al. (2022), Mac Manus, Rodger, Ingham, et al. (2022) which utilized a single magnetic observatory at Eyrewell and multiple different geomagnetic latitude variation methods to account for the expected regional differences based on geomagnetic latitude.

3.3. Geoelectric Field

Electric fields are induced at the Earth's surface due to the interaction of temporal changes in the magnetic field with the electrically resistive Earth. As such the regional variations in the magnitude and orientation of the magnetic field along with the regional variations in Earth resistivity affects the magnitude and orientation of the electric field. Similar to Section 2.3 in Mac Manus, Rodger, Ingham, et al. (2022), the valid period range is not restricted, covering durations from 2 min (corresponding to the Nyquist frequency) up to the full length of the modeled geomagnetic disturbance period (1,440 min). This stretches the numerical limitations of the thin-sheet model but comparison of modeled and observed GIC justifies this approach.

3.4. GIC Model

The New Zealand high-voltage AC power network consists of a series of transmission lines connecting the ∼190 substations. These substations contains ∼590 transformers of which ∼55% are solidly earthed, providing a path to ground for GIC to flow. In this study, the high voltage DC (HVDC) link connecting the North and South islands is not represented in the model, electrically isolating the two networks from each other.

GIC is modeled through each transformer winding and transmission line following the approach outlined by Lehtinen and Pirjola (1985) and modified by D. H. Boteler and Pirjola (2014). A comprehensive explanation of this process is provided in Section 2.4 of Mac Manus, Rodger, Ingham, et al. (2022) and the references cited therein.

In order to model GIC accurately, sufficient detail of the power network is required. This ranges from the obvious such as knowing the location of substations, how many transformers are present there and understanding how these substations are connected to each other through a series of transmission lines, to the more complex and often difficult to obtain transformer and transmission line resistances information along with identifying which transformers are earthed.

4. Mitigation Procedure

4.1. Extreme Storm Modeling in New Zealand

Extreme storm modeling for the New Zealand power network was presented in Mac Manus, Rodger, Dalzell, et al. (2022). In that study, several extreme storm scenarios were modeled covering a range of magnetic field time signatures and latitude variations. The authors found that between 13% and 35% of transformers experienced damaging levels of GIC magnitudes for extended periods of time. They also identified that these transformers span the whole geographic range of New Zealand as opposed to being isolated to the lower latitudes of the South Island, stressing the need for a New Zealand wide mitigation strategy covering all regions of the country.

4.2. Transpower 2022 New Zealand (TP2022NZ) Mitigation Strategy

In November 2001, a geomagnetic storm damaged a transformer in the city of Dunedin beyond the point of repair (Béland & Small, 2004; Mac Manus et al., 2017; Marshall et al., 2012). This was the driving factor for the development of a mitigation procedure by Transpower in the early 2000s. The purpose being to provide network control room staff a method to follow such that high levels of GIC in lower South Island transformers can be managed (Transpower, 2023). Following the finding of Mac Manus, Rodger, Dalzell, et al. (2022), it became clear that an improved mitigation strategy is required, one that address the full national network. In response, a new mitigation strategy, called the Transpower 2022 New Zealand (TP2022NZ) mitigation strategy, was created in partnership with Transpower during a site visit in August 2022. During this visit, the space weather research team worked directly with Transpower system operators in their simulation room, engaging in real-time discussions on potential mitigation modifications. While the research team initially proposed the suggestions, they were refined through ongoing collaboration as the discussions progressed. These proposed suggestions were immediately tested within Transpower's network simulation model, enabling the system operators to assess whether network stability and power distribution remained unaffected. Similarly, suggestions from Transpower system operators were tested in real time with the GIC model, ensuring they effectively reduced GIC levels.

The complete TP2022NZ mitigation strategy consists of 24 line disconnections, as well as the disconnection of the series winding of one transformer (GOR), which halts GIC flow between the 110 and 220 kV nodes at GOR.

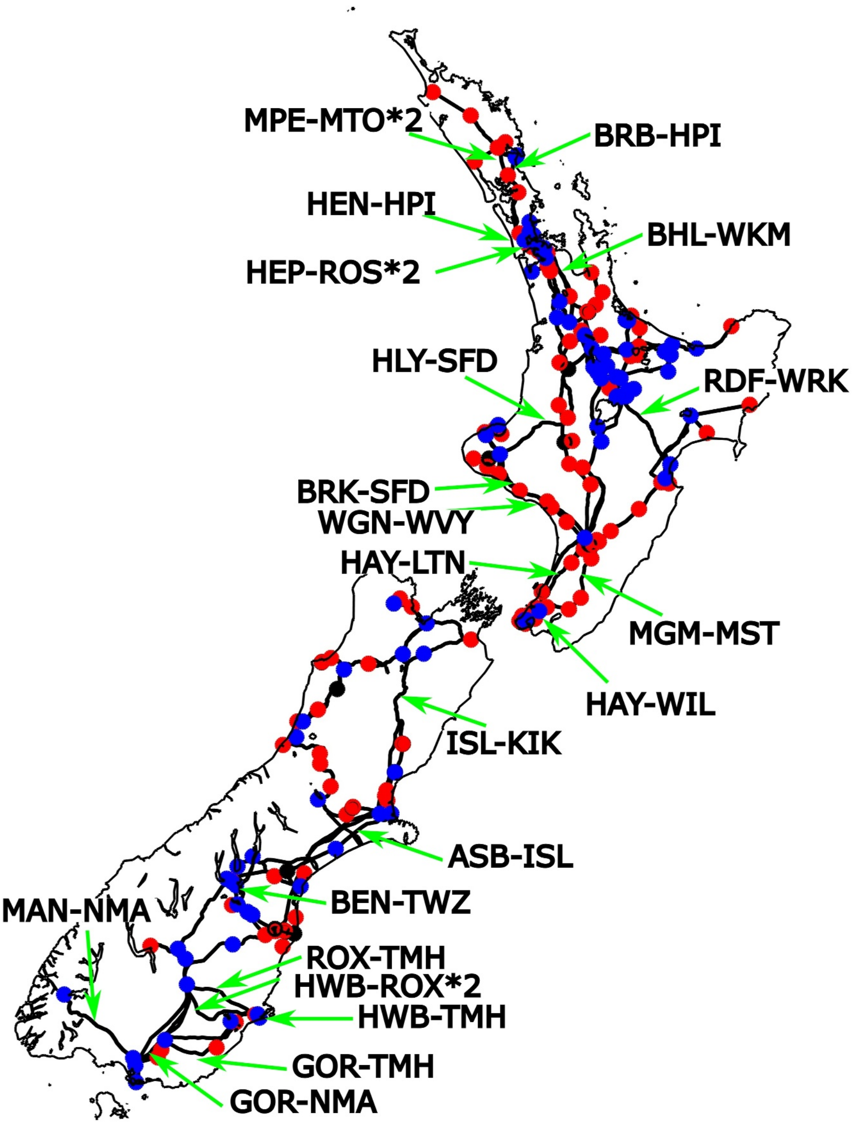

Figure 3. TP2022NZ mitigation strategy showing the approximate location of disconnected equipment. Earthed substations are represented by blue circles while unearthed substations and T-junctions are given by red and black circles. The "*2" indicates two transmission lines have been disconnected.

Several of the transmission lines disconnected in this plan are the only direct connections between two substations. A major advantage of working directly with our industry partners, Transpower in real time was the ability to quickly assess whether transmission lines could be safely disconnected without compromising the security and stability of the network. The act of disconnecting transmission lines that serve as the only connection between two substations was a consideration that the research team would not have anticipated without Transpower's network expertise. The locations of the disconnected transmission lines under the TP2022NZ mitigation strategy are displayed in Figure 3.

Under the TP2022NZ mitigation strategy, modeling shows the total sum of the substation average 60-min mean GIC across the network decreased by 16% compared to the original non-mitigated network. Overall, 27 out of the 30 transformers most at risk, based on average 60-min mean GIC, showed reductions in GIC under the TP2022NZ mitigation strategy (Mac Manus et al., 2023).

5. The Gannon Storm

5.1. From Sun to Earth

Between 10 May and 13 May 2024, during solar cycle 25, a sequence of intense solar storms, including extreme solar flares and geomagnetic storm activity took place. The resulting geomagnetic storm, named "the Gannon storm" in honor of Dr Jennifer L. Gannon, a key figure in space weather research who passed away in early May 2024 (Pulkkinen et al., 2024), resulted in the largest magnetic field variation in New Zealand since March 1989. It generated auroras at much lower latitudes than usual in both the Northern and Southern Hemispheres. A detailed description of the solar activity of May 2024 is provided in Spogli et al. (2024).

5.2. Initial Beginnings (G4)

Beginning at ∼17 UT on 10 May 2024, large magnetic field perturbations were observed for approximately 36 hr. By 17:44 UT, the NOAA Space Weather Prediction Center (SWPC) issued an Alert for a G4 geomagnetic disturbance (GMD). Early on in this GMD South Dunedin #2 transformer (SDN T2) located in the city of Dunedin, tripped out (17:28 UT). Under high temperatures inside transformers sulfur atoms are released from the transformer oil, which builds up like a flakey rust layer. It is believed some of this layer flaked off and fell between contacts in the on load tap changer switch where an electrical flash over occurred. Thus the tripping is not believed to be directly due to the Gannon storm, rather the result of sulfur atoms accumulating over time. As SDN T2 is one of only three high voltage-earthed transformers in Dunedin, this boosted GIC at the nearby Halfway Bush (HWB) substation due to the Whack-A-Mole effect (see Section 7 of Mac Manus et al. (2023)). With the tripping of SDN T2 and the declaration of a G4 GMD, Transpower was closely monitoring the situation in New Zealand. At approximately 21:00 UT on 10 May 2024 Transpower declared a Grid Emergency Notice (GEN) and activated the South Island switching strategy, which is the South Island component of the "all of New Zealand" TP2022NZ mitigation strategy. It took approximately 10 min for this to be enacted by the network control-room staff.

5.3. Upgrade to G5

At 23:34 UT on 10 May 2024 SWPC issued an Alert for a G5 GMD. The threshold was reached at 22:54 UT and the alert email arrived to the New Zealand subscribers at 23:43 UT, 49 min after the threshold crossing. Transpower declared a GEN G5 GMD Event at 00:01 UT on 11 May. This triggered the Transpower protocol to enact the new NZ-wide GIC mitigation strategy, for the first time. Within 90 min of this occurring, an online meeting occurred over Teams consisting of ∼190 electricity industry members (distribution, generation, and Transpower as system operators) as well as space weather researchers from the University of Otago. Concerns over the risk to other transformer assets were raised in the wake of the outage at SDN T2.

5.4. Changes in the Grid During the Gannon GMD Event

As noted above during the Gannon GMD event a number of network Grid modifications were carried out. As well as the unintended removal of SDN T2, there was also mitigation applied. Initially mitigation was applied to the South Island (starting from 21:08–21:17 UT on the 10 May) and then to the North Island approximately 3 hr later once a G5 alert was declared (starting from 00:03–00:13 UT on 11 May). This mitigation enacted was not exactly the TP2022NZ mitigation strategy described in Section 4.2 and shown in Figure 3. The control room staff have the ability to modify the mitigation strategy and make network changes depending on its state at the time of the GMD. For example, the control staff will take into account outages due to transmission line maintenance or other network alterations and respond accordingly. Figure 4 show the actual changes implemented during the May 2024 Gannon GMD event.

6. Discussion

6.1. MANA Magnetic Observations

Throughout the storm geomagnetic field variations were observed from the five MANA sites as well the Eyrewell geomagnetic observatory, as described in Section 2.2. Figure 5 shows the absolute horizontal rate of change of the magnetic field ($|H|'$) from these six locations. The figure shows two significant spikes at ∼08:50 UT and ∼12:29 UT on 11 May 2024. The largest spikes observed in the North Island MANA sites occurred much earlier at ∼22:37 UT on 10 May 2024. The H' values observed at the six monitoring locations for these 3 time periods are

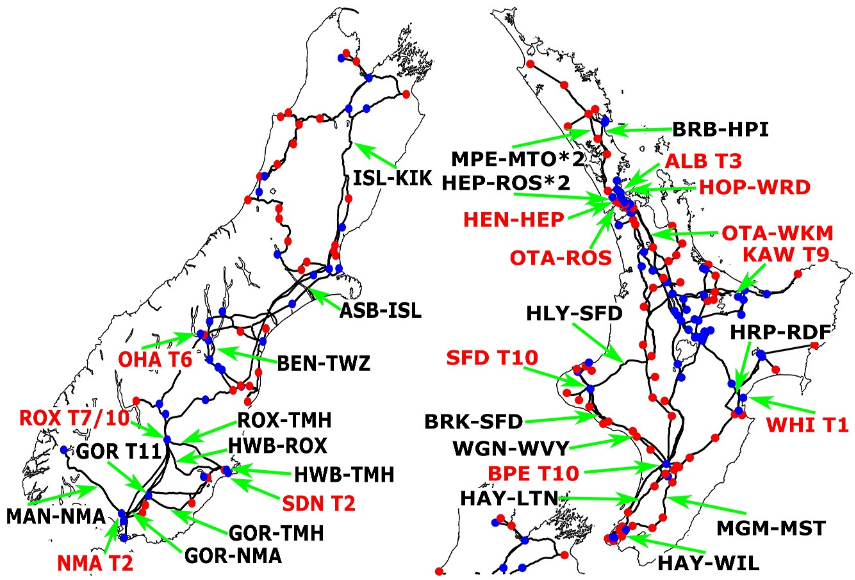

Figure 4. Mitigation and outages that occurred during the May 2024 "Gannon" storm. Assets marked in red are additional disconnections/removals which are not part of the official TP2022NZ mitigation strategy. These are largely due to other network situations and not an attempt at mitigation.

given in Table 1. The approximation for the times is to allow for the 1–3 min difference in peak $|H|'$ depending on the location of the magnetometer. The largest value measured was 478 nT/min at the Awarua variometer located at the very south of New Zealand at ∼12:29 UT. The value of 321 nT/min at the Eyrewell magnetic observatory is the largest since digital records began in the early 1990s, exceeding the previous largest value of 191 nT/min in November 2001.

6.2. GIC Observations Nationwide

During the May 2024 "Gannon" storm, Transpower was measuring GIC at multiple transformers across a number of substations. In Figure 6 we show the maximum observed GIC at each monitored transformer during this event. The GIC values shown corresponds to the measurements at their original resolution prior to being down sampled to 1-min. The largest observed value occurred at the Halfway Bush transformer #6 (HWB T6) with a measurement of 112.7 A. This is the largest reported New Zealand GIC measurement at any transformer since observations began in 2001. A number of other locations experienced GIC larger than ∼50 A including HWB T3 (99.3 A), Islington transformer #6 (ISL T6, 50.2 A) and Timaru #5 (TIM T5, 49.5 A). All four of these transformers exceed the previous largest measured GIC in New Zealand of 48.9 A measured at the now decommissioned HWB T4 transformer during a geomagnetic storm in September 2017 (Mac Manus, Rodger, Ingham, et al., 2022). A further 12 transformers experienced in excess of 20 A during the Gannon GMD event.

When looking at the GIC levels during the three spikes discussed in Section 6.1 we can see some interesting variations which are shown in Figure 7. The transformers ISL T6 and TIM T5 show the largest GIC values during Spike 2 (middle panel of Figure 7). This spike leads to the largest $|H|'$ value at the Eyrewell magnetometer (as seen in Figure 5 and the insert); EYR is closest to ISL T6 and TIM T5. In a similar way, HWB T3 and HWB T6 measured the largest GIC during Spike 3 (upper panel of Figure 7) at which time the nearby Swampy variometer records the largest rate of change. However, this relationship is not seen at HEN T1 (located in-between Donnelly and Oakview) as the GIC during Spike 1 is rather low, with large GIC occurring during spike 2 and 3 (lower panel in Figure 7).

Figure 7 includes the times for which the South Island and North Island mitigation strategies were enacted. While it is not obvious through a "by eye" examination of the GIC magnitudes shown in this figure, the mitigation leads to significant decreases in GIC levels. While not clear by eye, this can be demonstrated through modeling as outlined in the next section.

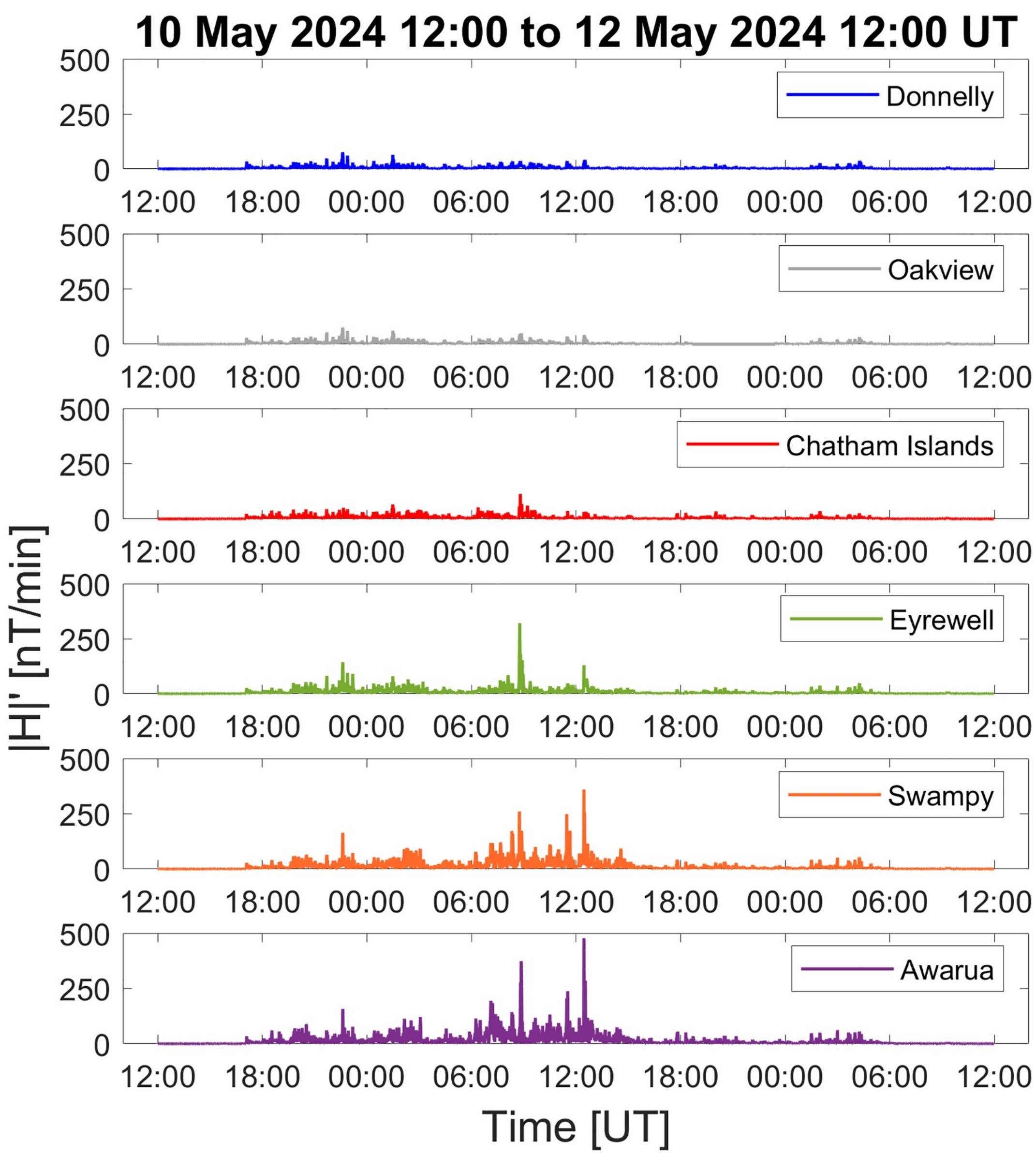

Figure 5. Absolute Horizontal rate of change of the magnetic field ($|H|'$) from the five MANA sites and the Eyrewell magnetic observatory.

Table 1
Absolute Horizontal Rate of Change of the Magnetic Field From Five MANA Sites and the Eyrewell Magnetic Observatory at Three Key Time Periods

Observation site	~22:37 UT 10 May Spike 1 [nT/min]	~08:50 UT 11 May Spike 2 [nT/min]	~12:29 UT 11 May Spike 3 [nT/min]
Donnelly	75	36	41
Oakview	76	50	41
Chatham Islands	51	113	32
Eyrewell	144	321	130
Swampy	164	260	360
Awarua	158	374	478

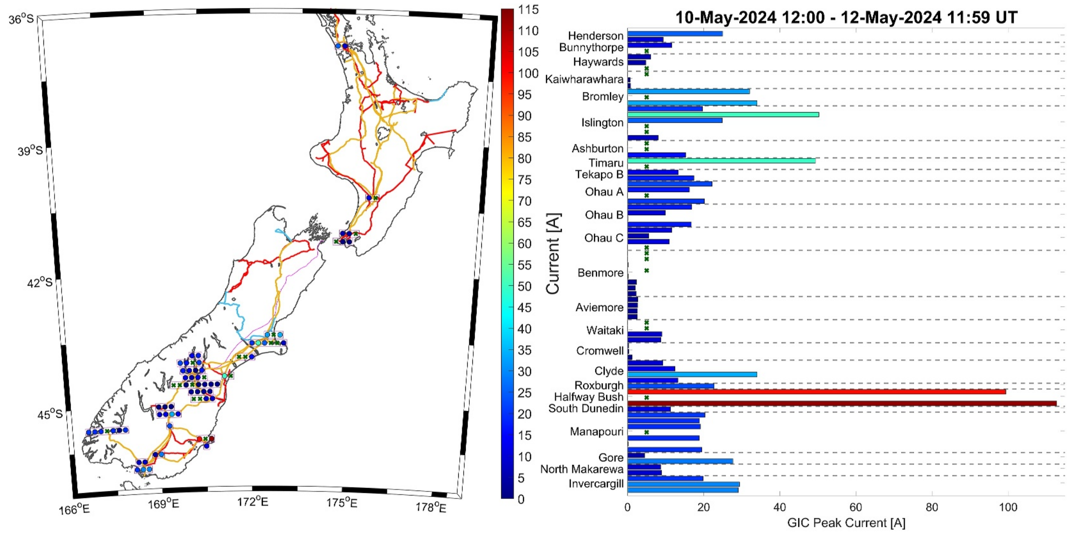

Figure 6. Magnitudes of the peak GIC observed during the May 2024 “Gannon” geomagnetic disturbance event at the original time resolution. On the left, a geographical map including the transmission lines. Each box represents a substation, with Colored circles for the individual transformer measurements. On the right, a bar plot indicating the magnitudes of transformer GIC. The black dotted lines separate the individual substations inside of which multiple transformers may be monitored. The green crosses in both panels mark transformers which had no LEM observations during the event.

6.3. Thin-Sheet GIC Modeling

Regarding the GIC modeling results, there are three different network cases to consider. First we have the real-world case that occurred during the Gannon storm consisting of: Case A the mitigated grid network with the SDN T2 outage including any additional network changes due to planned maintenance and other operational impacts. Secondly we have Case B, the typical network grid for which SDN T2 remains in service. Finally we have the typical network grid configuration but with only the SDN T2 outage, which we term Case C. This last case represents the likely worst-case scenario which might have occurred without mitigation.

In Figure 8 we present the modeled GIC at HWB T3. We see that the best agreement with the observations comes from the mitigation scenario with the SDN T2 outage (i.e., the real-world conditions experienced during the Gannon storm we called Case A). The model produces a maximum absolute 1-min GIC value of 66.7 A which is consistent with the measured 64.8 A at the same 1-min resolution. Utilizing the peak GIC observations at their original resolution of 4 s we can predict a peak mitigated model value of 102 A, which again compares well to the measured peak of 99 A. The Figure also shows that for the worst case scenario in which mitigation is not implemented, yet the outage at SDN T2 still occurs (i.e., Case C), a modeled 4-s estimate of 200 A is found. This shows that by implementing the mitigation strategy, GIC at HWB T3 was reduced by ∼50%, demonstrating the value of the mitigation strategy in the event of an extreme space weather event.

It is worth noting that the GIC modeling at most locations shows good agreement between the modeled and observed GIC. One key exception is the Invercargill (INV) substation located at the bottom of the South Island, where all modeling scenarios show much larger GIC than observed, and poor agreement with the time variation. The reason for this discrepancy is still under investigation, but does not significantly impact our conclusions concerning the value of the mitigation approach.

Other substations showed GIC magnitude increases and decreases due to the implementation of the mitigation strategy. Of the 91 earthed substations in New Zealand, 30 have 1-min GIC magnitude decreases averaging to 18% (12 A) when comparing Case A relative to the Case C modeling. In contrast 14 show average increases of 16% (3 A). The remaining 47 do not change, by design. Sub-divided by Island, of the 34 earthed substation in the South Island, 20 decrease on average by 17% (13 A) while only 3 increase, with these changes only being by 8% (2 A). For the North Island, of the 57 earthed substations 10 decrease on average by 21% (10 A) while 11 increase by 18% (3 A). While there are a number of transformers for which the modeling indicates GIC magnitudes increase when mitigation is applied the magnitude of the increase is significantly smaller (3 A on average) when compared

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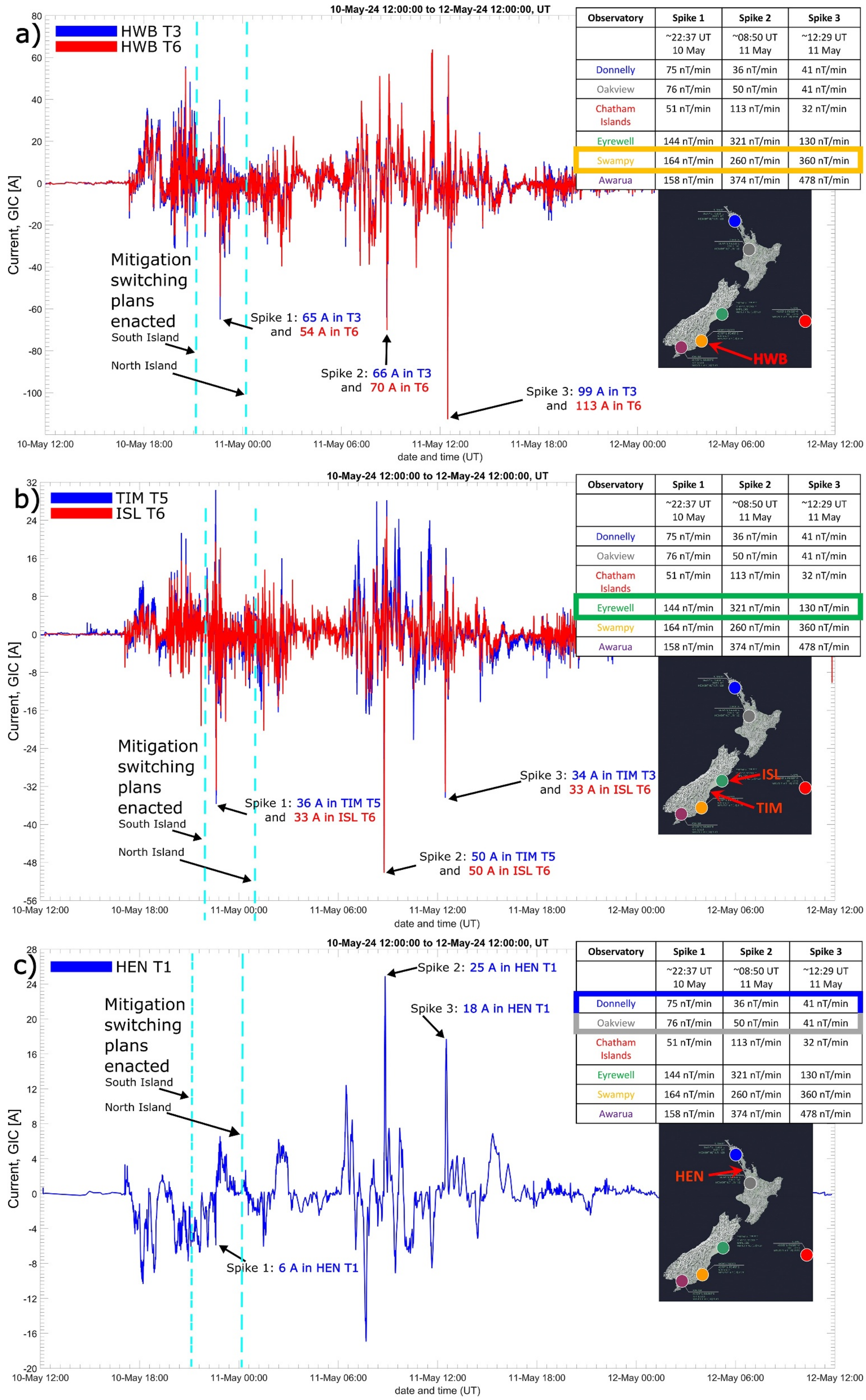

Figure 7. GIC time series for transformers at the Halfway Bush (HWB) substation (panel a), Islington (ISL) and Timaru (TIM) substations (panel b), and the Henderson (HEN) substation (panel c). On the right of each panel, the MANA and EYR magnetic field H' is shown for the three key spikes along with a figure showing the location of the MANA variometers and EYR magnetometer, color coded for each location along with the approximate location of the substations in question.

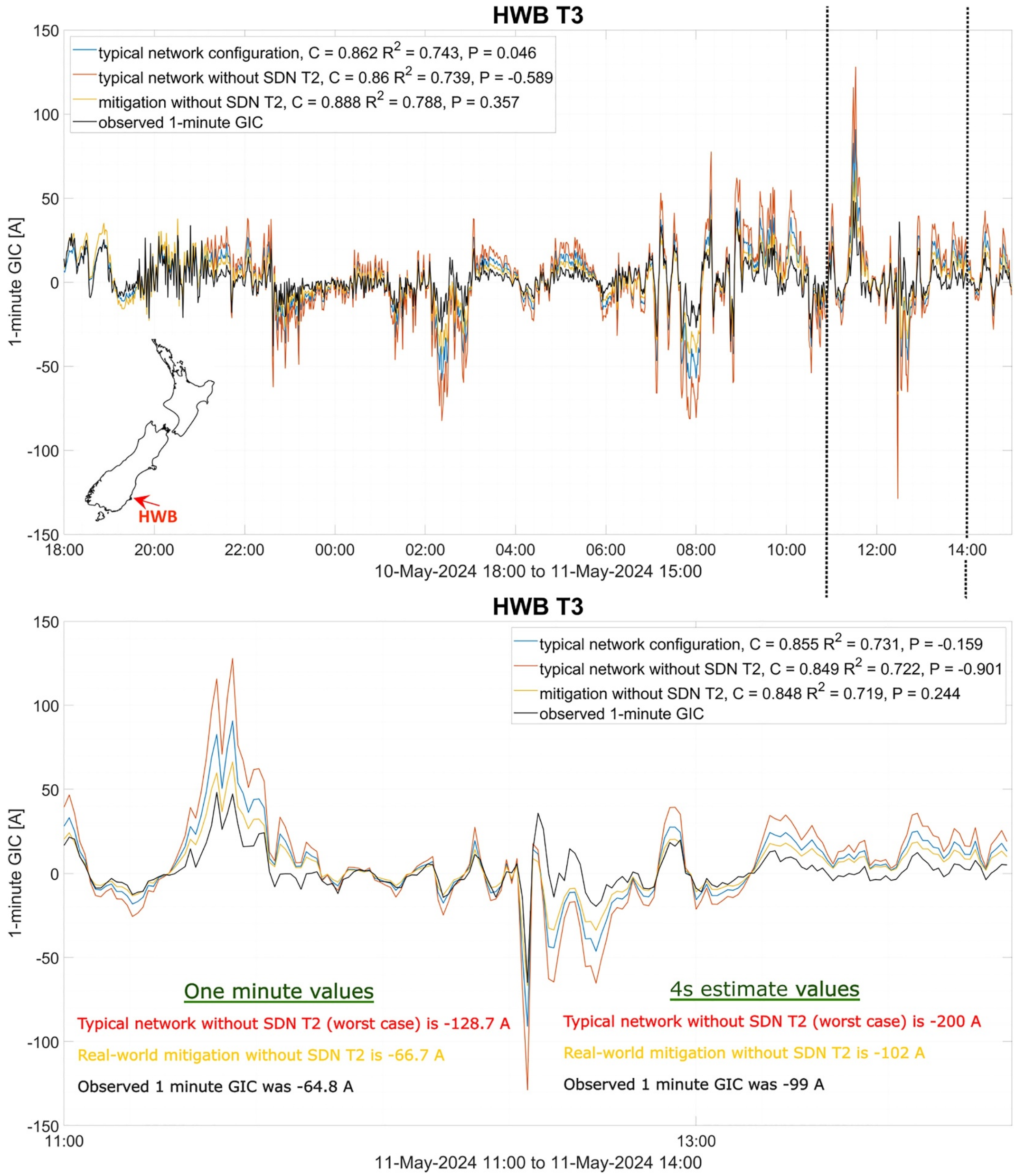

Figure 8. Modeled GIC at the Halfway Bush #3 transformer (HWB T3) for the three network scenarios described. The top panel shows a wider time range while the bottom panel is a zoomed in image of the region indicated by the dotted lines. In both panels, C is the correlation coefficient, R^2 is the r-squared value and P is the performance parameter defined by Equation 1 of Marsal and Torta (2019).

to the many substations that decrease by on average 12 A, a value four times as large. The locations where we model increases are also substations that already have a low magnitude of GIC, such that the comparatively small increases in GIC do not provide significant increases to the likely GIC hazard level of that transformer. In comparison those substations that show decreases are locations which initially have large magnitudes of GIC and thus are at a greater risk of GIC-related damages leading to space weather impact on the power network.

In Figure 9 we show the change in peak 1-min GIC at earthed substations due to the implementation of the mitigation strategy (i.e., Case A- Case C). Substations for which the change is greater than 10% and 5 A are highlighted. In both cases SDN T2 is offline so these changes are solely due to mitigation. The mitigation scenario decreases the GIC at "hotspots" without making it worse elsewhere. This highlights how the significant impacts

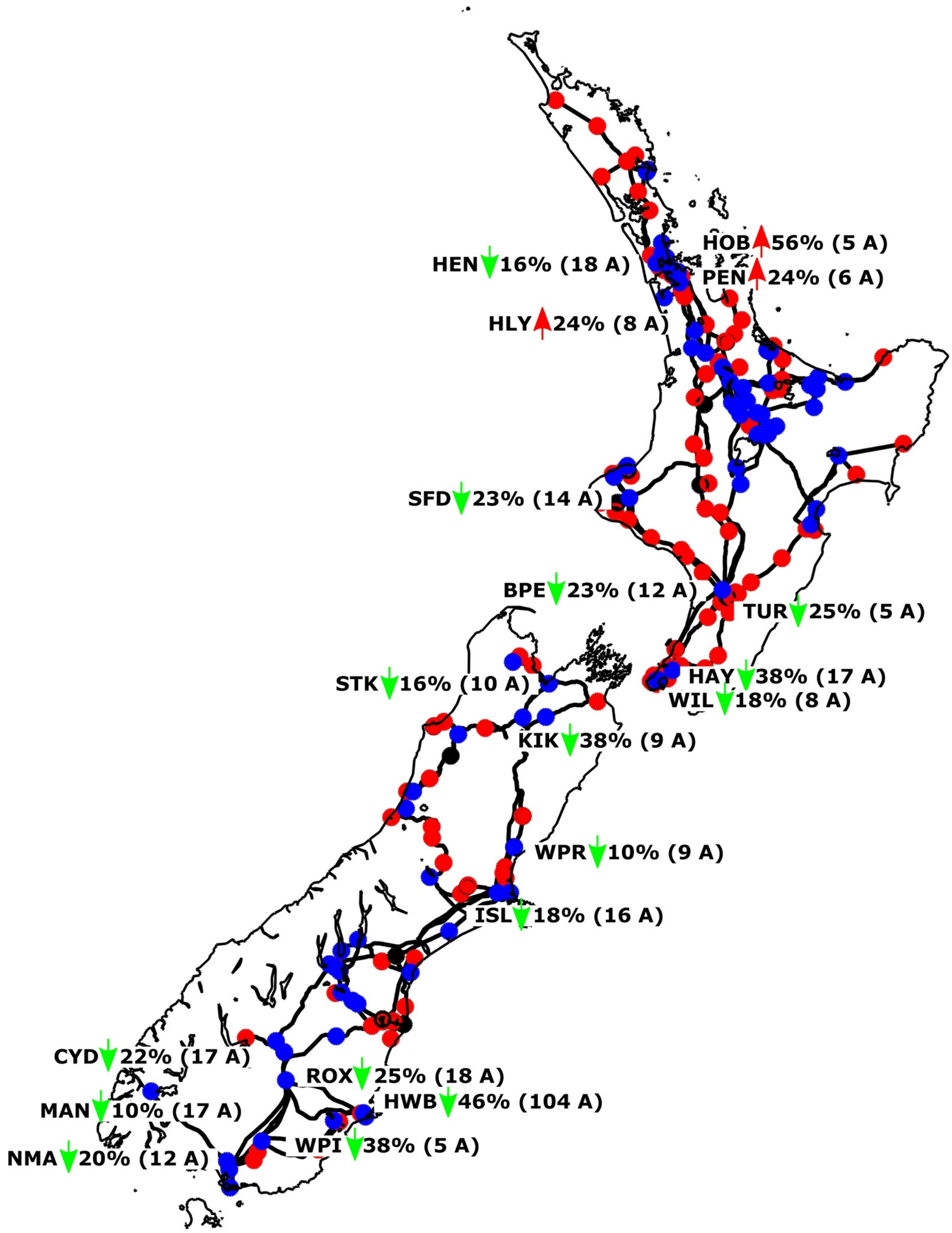

Figure 9. Change in peak 1-min GIC at earthed substations due to the implementation of the mitigation strategy. Substations for which the change is greater than 10% and 5 A are shown. In both cases SDN T2 is offline so these changes are solely due to mitigation.

from the mitigation are decreases in GIC with a small number of the locations plotted showing slight increases. While the GIC modeled and observed during this GMD are not particularly large outside of HWB, the Gannon storm was not an extreme event; despite being the biggest GMD in some decades it was only approximately 10% of our extreme storm scenario (Mac Manus, Rodger, Dalzell, et al., 2022).

The outage of the SDN T2 transformers was an unexpected occurrence which, for good reason, caused a large amount of concern for the electricity industry in New Zealand. From a GIC perspective, modeling shows that the loss of SDN T2 resulted in GIC at the nearby Halfway Bush (HWB) substation approximately doubling in value. HWB was expected to experience the largest amount of GIC even if SDN T2 remained in service so any further increase here is concerning. Below shows the estimated 4-s modeled GIC at HWB T3 for a number of network scenarios, noting that Case A, represents what actually happened during the Gannon GMD, generating 99 A GIC at peak. The others are possible alternative scenarios.

- Real-world network with mitigation with SDN T2 = 51 A.
- Case A: Real-world network with mitigation without SDN T2 = 102 A.
- Case B: Typical network without mitigation and with SDN T2 = 140 A.
- Case C: Typical network without mitigation and without SDN T2 = 200 A.

This shows that despite the outage at SDN T2 the mitigation strategy (Case A) lowered the GIC at HWB T3 to levels lower than those which would have been expected without mitigation if SDN T2 had remained in service (i.e., typical network configuration, Case B). Modeling also showed negligible increases and decreases (less than 5%) at half a dozen other nearby substations.

6.4. Comparison With NERC Benchmark

The North American Electric Reliability Corporation (NERC) has developed a "benchmark" geomagnetic disturbance scenario to help US and Canadian grid operators examine their risk from extreme space weather events. The purpose of the benchmark GMD is to "provide a defined event for assessing system performance during a low probability, high magnitude GMD event" (NERC, 2016). The benchmark GMD event defines the geomagnetic field values to be used to compute GIC flows for a GMD Vulnerability Assessment. The NERC benchmark GMD uses the time variation of the March 1989 event as observed from a magnetometer in Ottawa, but scaled upwards so the geoelectric field induced is 8 V/km, as this was estimated to be a 1:100 years level GMD (NERC, 2016). The reference geomagnetic latitude was 60°, and a formula provided to scale the reference geomagnetic field waveshape to other latitudes was provided in Appendix 2 of the Benchmark description document, "obtained from a large number of global geomagnetic field observations of all major geomagnetic storms since the late 1980s." For 60° geomagnetic latitude the benchmark GMD H' peaks at ~1,600 nT/min (1 min resolution) (NERC, 2016). However, if we use Appendix 2 formula to scale the reference geomagnetic field time-variation to the geomagnetic latitude of EYR, the benchmark predicts a maximum H' of ~310 nT/min. This is smaller than the peak change observed at EYR during the Gannon storm (321 nT/min), which is widely recognized as not being representative of a 1:100 years disturbance. Elvidge and Themens (2025) concluded that the Gannon storm has an expected return period for magnitude of a 1-in-12.5 years event and for duration a 1-in-41 years event. We note that the UK government reasonable worst case scenario for New Zealand-like latitudes is 4,000–5,000 nT/min (Hapgood et al., 2021), considerably larger than the NERC Benchmark Scenario.

6.5. Mitigation Plan Flexibility

One might wonder at the level of flexibility in the mitigation plan used for the New Zealand power transmission network, for example, if different plans are needed for different storms due to changing geomagnetic orientations leading to very different geoelectric field directions (and hence GIC magnitudes). We have modeled a variety of different theoretical extreme storm scenarios and the time-varying GIC they produce in the New Zealand network. These storm scenarios were based on different real-world observed storms with differing magnetic field magnitude and orientations, scaled to the same maximum level (following the approach outlined in Mac Manus, Rodger, Dalzell, et al. (2022)). We find that the same transformers consistently experience the largest GIC magnitudes and durations in all the differing scenarios. As such the mitigation plan was developed with those hot spot transformers in mind. When modeling the implications of the mitigation plan, we find consistent GIC percentage decreases at the key transformers, regardless of the geomagnetic storm scenario we use in the modeling. When looking at the electric field orientations in New Zealand there is a preferred alignment, predominantly for the South Island of New Zealand, despite very different magnetic orientations (Divett et al., 2017). This is likely the cause of the consistent GIC hotspots in New Zealand across multiple storm scenarios. As such it is not viewed as necessary to change the mitigation plan from storm to storm based on magnetic field orientation. There is, however, flexibility available in the mitigation plan, largely through the Transpower control room staff having the ability to modify the network changes to accommodate the specific system conditions and the network configurations and needs of the system at the time. As outlined above as there is no practical difference between differing storms on the system apart from magnitude and for operational management consistency, it is not useful to change the mitigation plan from storm to storm due to magnetic field orientation. The present switching mitigation plan is utilized as it reduces the GIC magnitude for little effort and no cost compared to physical hardware mitigation. To improve the systems protection further in a practical and economic manner we are in the process of devising alternative mitigation approaches and combinations such as capacitor blockers installed on key transformers and considering separating the network into individual smaller "isolated islands" to reduce the contribution of GIC induced from the long transmission lines that traverse much of New Zealand.

6.6. Electricity Industry Space Weather Working Group (EISWWG)

The Electricity Industry Space Weather Working Group (EISWWG) was established in July 2023 (Transpower, 2024). The goals of the EISWWG are to develop a coordinated operational response plan to extreme space weather events and the threat they can pose to the New Zealand's electricity system. Membership includes multiple industry groups and generators that own and operate aspects of the New Zealand power network and each organization works to:

- Increase their technical understanding of the effects of GICs on their own assets;
- Assess their assets limitations and understand how they interact and effect the assets of others;
- Prepare their own internal response plan;
- Integrate their own plan and contribute to a joint industry wide operational response plan.

Aspects of the industry groups own business response plans have been incorporated into the new joint industry response plan. These include event triggers, pre-impact coordination, identification of asset owner equipment removal levels, Government co-ordination, demand management, and reference to restoration sequences.

Extreme storm modeling for New Zealand, the mitigation strategy and also the Gannon-storm response, are now being discussed and built upon through the EISWWG. The group of industry engineers from the main generating companies as well as the network system operator seek advice from scientific researchers from academia. The Gannon-storm response produced significant reflection from the EISWWG as outlines in their report on the Gannon GMD (Transpower, 2024).

Key learning from industry identified after that GMD were:

- Operational data is critical to success but currently limited. Industry needs more LEM devices on their transformers to monitor GIC.
- Industry need reliable and well-informed forecasting, ideally with a 2 hr ahead window, and advice of space weather impacts to our power system if we are to take meaningful action during an extreme event.
- Having no New Zealand specific space weather monitoring, forecasting and advice service presents a risk to the electricity industry and other sectors who could be impacted by solar storms. This information is key to providing situational awareness leading up to and in response to an extreme solar storm.
- Being able to understand the criteria to identify when the storm has passed and a resumption to normal operation.

7. Summary

Following years of collaboration with the New Zealand High Voltage electricity system owner and operator, Transpower Ltd, we have developed a GIC mitigation strategy for use during G5-class geomagnetic storms. This involves targeted line disconnections to decrease GIC magnitudes at specific transformers of national importance or at those deemed a high risk to GIC related damages. This mitigation strategy was enacted for the first time during the May 2024 "Gannon" storm. At the primary GIC hotspot in the city of Dunedin, observed currents peaked at over 100 A in each of the two transformers at the Halfway Bush (HWB) substation. These high current levels were enhanced due to the tripping out of SDN T2 during the early phases of the storm. Without mitigation, modeling shows that the peak currents would have been closer to 200 A. Overall the application of the mitigation lead to decreases in GIC magnitude at hotspots and only small increases at other transformers. Following the end of the Gannon storm, the disconnected lines were returned to service and no loss of power to consumers was experienced.

While the Gannon storm was large the New Zealand electricity industry and government bodies are preparing for a much larger extreme storm (Mac Manus, Rodger, Dalzell, et al., 2022). The mitigation strategy in Mac Manus et al. (2023) was developed for storms much larger than the Gannon storm, however it provided a good opportunity to test the effectiveness of the mitigation strategy during a real-world large geomagnetic disturbance.

Data Availability Statement

The New Zealand electrical transmission network's DC characteristics were provided to us by Transpower New Zealand with caveats and restrictions. This includes requirements of permission before all publications and presentations. In addition, we are unable to provide the New Zealand network characteristics due to commercial sensitivity. Requests for access to these characteristics need to be made to Transpower New Zealand. At this time the contact point is Andrew Renton (Andrew.Renton@transpower.co.nz).

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