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Key Points:

- A decade of even-order harmonic distortion data are used to investigate the impact of space weather on a power network
- In New Zealand four key substations containing single phase transformers act as sources of enhanced harmonic distortion
- The harmonic distortion is found to propagate into the nearby power network over 150–200 km distances, decaying at a rate of -0.0043 %km^{-1}

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Even-Order Harmonic Distortion Observations During Multiple Geomagnetic Disturbances: Investigation From New Zealand

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Abstract Large geomagnetic storms are a space weather hazard to power transmission networks due to the effects of Geomagnetically Induced Currents (GICs). GIC can negatively impact power transmission systems through the generation of even-order current and voltage harmonics due to half-cycle transformer saturation. This study investigates a decade of even-order voltage total harmonic distortion (hereon referred to as Even-Order Total Harmonic Distortion (ETHD)) observations provided by Transpower New Zealand Ltd., the national system operator. We make use of ETHD measurements at 139 locations throughout New Zealand, monitored at 377 separate circuit breakers, focusing on 10 large geomagnetic disturbances during the period 2013–2023. Analysis identified 5 key substations, which appeared to act as sources of ETHD. The majority of these substations include single phase transformer banks, and evidence of significant GIC magnitudes. The ETHD from the source substations was found to propagate into the surrounding network, with the percentage distortion typically decaying away over distances of 150–200 km locally, that is, at a rate of -0.0043 %km^{-1}. During the study period some significant changes occurred in the power network, that is, removal of the Halfway Bush (HWB) single phase bank transformer T4 in November 2017, and decommissioning of the New Plymouth substation in December 2019. Decommissioning of these two assets resulted in less ETHD occurring in the surrounding regions during subsequent geomagnetic storms. However, ETHD still increased at HWB with increasing levels of GIC, indicating that three phase transformer units were still susceptible to saturation, albeit with about 1/3 of the ETHD percentage exhibited by single phase transformers.

Plain Language Summary Space weather, triggered by solar storms, can lead to significant variations in the Earth's magnetic field. The magnetic variations are termed geomagnetic disturbances. Changing magnetic fields induce electric fields at the Earth's surface, causing unwanted currents to flow in electrical power transmission networks. These Geomagnetically Induced Currents (GICs), pose a hazard to network operations as they can cause networks to become destabilized, leading to blackouts and damage to transformers. One negative impact of GIC in a power network is the production of harmonics of the power transmission frequency (typically 50 or 60 Hz); such harmonics contributed to the blackout of the Québec power system in March 1989. In our paper we study harmonic distortion occurrence in the New Zealand power grid using measurements from 139 substations across the country during 10 geomagnetic storms. Analysis identified 5 key substations, which appeared to act as sources of harmonic distortion. The majority of these substations include a particular transformer design which is known to be more susceptible to GIC issues, as well as evidence of significant GIC.

1. Introduction

In recent years there has been growing interest from policy makers around the hazards posed by Space Weather to our deeply technologically connected society. One example is the report from UN Committee on the Peaceful Uses of Outer Space (United Nations, 2017). They noted that "The largest potential socioeconomic impacts arise from space weather driven Geomagnetically Induced Currents (GICs) in electrical power networks." This comment flows from hardware in electrical power transmission systems being disrupted, in some cases even permanently damaged, during significant geomagnetic storms that have occurred during the last 3 decades (approximately). This has occurred over a wide range of countries, with examples being Canada, New Zealand, Norway, South Africa, Sweden, and the United States of America.

The most extreme example of such a disruption occurred in the Canadian province of Québec during a geomagnetic disturbance (GMD) in 13–14 March 1989, where the power network was rapidly destabilized leading to a very wide-scale and long-lasting blackout (Béland & Small, 2004; Guillon et al., 2016). In modern societies, reliable electricity supply is vital. An extreme storm, expected to produce much larger GMD, is likely to collapse the electrical power grid in many locations across the world (e.g., Baker et al., 2008; JASON, 2011; Mac Manus, Rodger, Dalzell, et al., 2022; Oughton et al., 2017). The flow-down impacts from a major disruption are likely extreme and far reaching. Electrical power supply is the life-blood of modern economic and social systems. Disruptions will include extensive societal and economic impacts from loss of electrical power for essential services, businesses, and households.

Geomagnetically Induced Currents can adversely affect electrical power infrastructure through disruption to operations or hardware damage through multiple different routes (e.g., Boteler, 2015; Samuelsson, 2013), leading to system instabilities that can produce a voltage collapse and blackout. One of these routes is from harmonic distortion to the alternating current (AC) waveform due to saturated power grid transformers. The GIC, being quasi-direct current (DC), produces half-cycle saturation in transformers, leading to increased audible noise and excessive heating of transformers. Saturated transformers dissipate large quantities of power and also generate harmonics. The consequences of these impacts are incorrect operation of protective relays, voltage dips, changes in power flow, and possible system frequency shifts (EPRI, 1983). It is clear that GIC-produced harmonic distortion contributed significantly to the Hydro Québec blackout in 1989 (Guillon et al., 2016).

It is important to note how GIC causes asymmetric saturation and the production of harmonics (see, for example Arrillaga & Watson, 2003). When a transformer is subjected to higher than its rated AC voltage the peak magnetic flux can exceed the transformer core capabilities. This then leads to symmetric saturation and the production of odd-order harmonic components. While unwanted, this is a common issue faced in the design and operation of electrical power systems. In contrast, GIC provides a DC component in the transformer windings such that the transformer core saturates in only one direction, termed asymmetric saturation or "half-cycle" saturation. Because of the asymmetric nature of the current, half-cycle saturation results in even- and odd-order harmonic components (e.g., Boteler et al., 1989).

While harmonic distortion is clearly an important route by which space weather can produce hazards for electrical power networks, there is a limited amount of discussion and research into this in the scientific literature. This may reflect, in part, difficulties researchers experience in getting access to harmonic distortion data. At the same time, it appears that harmonic distortion levels are commonly collected by power-grid operators to monitor operations and power quality. In contrast, observations of GIC seem to be rare in most power systems, making that data set also very difficult to source for scientific research. The importance of this was emphasized in a recent study of changing harmonic distortion levels and GIC observations during two GMD in New Zealand (Rodger et al., 2020). Those authors stated: "We hence emphasize that GIC leading to asymmetric transformer saturation is one of the few ways to produce even harmonics, and as such even-order harmonic measurements should be a very valuable route to study space weather impacts on power networks." That comment is supported by the response of Hydro-Québec to the March 1989 blackout. Hydro-Québec introduced multiple monitoring systems to assist the system operators, including: real-time monitoring and control center reporting of voltage harmonics (9 substations), real-time monitoring and control center reporting of even harmonic distortion at (4 substations), and offline monitoring of voltage and current harmonics plus DC GIC observations (5 substations) (Guillon et al., 2016).

Over roughly the last decade, the mid-latitude south Pacific country of New Zealand has proved to be a valuable "laboratory" for studies into space weather GIC impacts. New Zealand is one of the few countries that have already experienced direct transformer damage from a large geomagnetic storm, with a transformer damaged beyond repair at the Halfway Bush (HWB) substation in Dunedin after the 6 November 2001 GMD (Béland & Small, 2004; Mac Manus et al., 2017; Marshall et al., 2012). New Zealand is unusual in that there is a long-lasting and relatively dense network of DC GIC observations available in parts of that country (Mac Manus et al., 2017; Rodger et al., 2020), with power grid operator staff willing and interested to collaborate with local researchers. The DC observations were originally deployed to monitor the operation of the high voltage DC link between New Zealand's main islands (see the discussion in Mac Manus et al., 2017), but the network is now being expanded to include space weather monitoring. All the real time DC observations are available in the system operations control room, and operational procedures have been developed to try to mitigate GIC impact during a GMD

(Divett et al., 2020; Mac Manus et al., 2023; Transpower, 2015). The New Zealand GIC data has allowed efforts to better investigate GIC drivers (Mac Manus et al., 2017), empirical estimates of likely extreme GIC magnitudes (Ingham et al., 2017; Rodger et al., 2017), and to show that GIC levels differ in the same storm between transformers in the same substation due to resistance differences between transformers and connections (Divett et al., 2018). Access to observation data, both GIC and detailed network layouts and resistances, have allowed theoretical modeling of time-varying GIC amplitudes at the transformer level to be developed (Divett et al., 2017, 2018; Mac Manus, Rodger, Ingham, et al., 2022; Mukhtar et al., 2020). This has recently culminated in an estimation of extreme storm GIC levels for a set of Carrington-storm level scenarios (Mac Manus, Rodger, Dalzell, et al., 2022) using the validated modeling, which found that there are at risk transformers across the country including major population centers at the northern and southern extremes of the country. These Carrington-storm level GIC scenarios have provided the basis of new mitigation planning (Mac Manus et al., 2023), producing a new operational space weather mitigation plan for the New Zealand power grid operator, Transpower New Zealand Ltd.

Transpower New Zealand also undertakes regular monitoring of harmonic distortion, and has provided observations for local space weather research. The harmonic distortion power quality measurements have comparatively low time resolution (10 min averages), but can still provide insights. A detailed examination of harmonic production in the HWB substation in Dunedin during the GMD of 7–8 September 2017 has been undertaken combining GIC measurements at that substation, magnetic field variations, and harmonic distortion observations made at both low time resolution by Transpower power quality monitoring systems and also at very high time resolution using a co-located VLF wideband radio receiver (Clilverd et al., 2018, 2020). These studies confirmed that high GIC lasting significant time periods (i.e., several minutes) produced clear increases in even-order harmonics, while higher but more short-lived GIC events produced no evidence of harmonic production. This is consistent with high averaged GIC levels leading to transformer saturation and even-order harmonic production, as expected from asymmetric saturation. Rodger et al. (2020) expanded on that work, examining even-order voltage harmonic distortion measurements made at 377 circuit breakers (CB) at 126 separate locations across both the North and South Island of New Zealand. That analysis showed that increased even-order voltage harmonic distortion occurred where there were significant GIC magnitudes which lasted over long time periods, consistent with the earlier findings for the single substation reported by Clilverd et al. (2018, 2020). However, these 126 location observations also demonstrated how GIC effects could be identified in even-order harmonic distortion monitoring for locations where no in-situ GIC measurements were present (e.g., the upper South Island or the majority of the North Island). This included substations in the northern part of the province of Taranaki in the North Island of New Zealand, a location approximately corresponding to Luxembourg City (Luxembourg) in Europe or Memphis (Tennessee) in North America.

In the current study we expand on the earlier work of Rodger et al. (2020) to examine multiple GMD and harmonic distortion observations across the New Zealand power transmission network. We also contrast the substation locations in New Zealand expected to have high GIC in an extreme GMD (Mac Manus, 2023; Mac Manus, Rodger, Dalzell, et al., 2022) with even-order voltage harmonic distortion observed during recent GMD.

2. Experimental Data Sets

2.1. New Zealand National Grid and GIC Observations

The New Zealand national grid stretches across both the North Island and South Island, and is made up of ∼11,000 km of high-voltage overhead transmission lines and ∼200 km of underground cables, connecting 170 substations (Transpower, 2021). The core high voltage transmission network operates at 220 kV, with a secondary network of 110 kV transmissions lines and a small amount of high voltage transmission at 66 kV to support smaller centers and generation (Mac Manus, 2023, Figures 5.9 and 5.11). Due to New Zealand's geographical location there are no connections to other countries power networks, unlike the situation in much of the world. The North and South Island are only connected by the 1430 A high voltage direct current (HVDC) link, operating at 350 kV, primarily used to bring hydro-electrically generated power from the South Island to the more populated North Island.

A detailed description of the New Zealand GIC measurements in the South Island has been previously reported (Mac Manus et al., 2017) and updated (Rodger et al., 2020). The following section is a very brief summary, and the reader is directed to the earlier studies for a more complete explanation.

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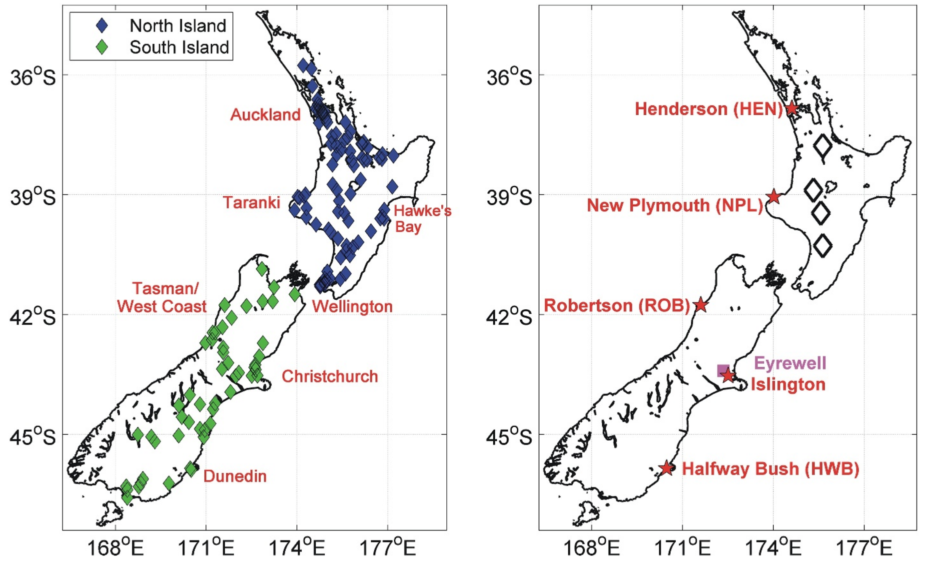

Figure 1. Left hand panel: Locations of the even-THD observations used in the current study. A total of 139 substations provide even-THD measurements in the time period considered (2013–2023), covering the entire Transpower electricity transmission network. Right hand panel: map of locations of specific substations of interest discussed in the text (red stars and white diamonds), as well as the Eyrewell magnetic observatory (magenta square).

Transpower New Zealand Limited has measured DC currents in multiple transformer neutral connections using Hall effect current transducers. These transducers are Liaisons Electroniques-Mécaniques (LEM) model LT 500 or LT 505, with about half of each in use, and a mix of -S and -T subtypes for both model cases. The primary purpose for the DC observations is monitoring stray currents when the HVDC link between the South and North Islands operates in earth return mode or with unbalanced currents on the conductors. For our purposes the LEM-provided DC measurements need to be corrected to remove the HVDC stray currents as described by Mac Manus et al. (2017), leaving only GIC. During GMD the typical LEM sampling rate is one measurement every 4 s. Due to the low time resolution of the harmonic distortion data, the GIC measurements will typically be down-sampled to 10 min averages, corresponding to the same time window as the harmonic distortion data.

2.2. New Zealand Harmonic Distortion Observations

In this study we examine all even-order voltage total harmonic distortion observations made by Transpower at CB in substations across New Zealand during a series of selected GMD (described in Section 3). Harmonic distortion observations are made at the majority of Transpower substations in New Zealand (i.e., transmission substations) using Schneider PowerLogic ION8800 m, which provide harmonic reporting up to the 63rd harmonic on both voltage and current inputs. The meters are capable of providing total, even-order, and odd-order harmonic recording. Transpower has provided us with power quality measurements including the harmonic distortion observations with 10 min time resolution made at 477 CB at 139 substations (with the number depending on the time period being considered). The locations of the harmonic distortion observations are shown in Figure 1, and include 88 substations in the North Island and 55 in the South Island. Measurements are available for most locations starting from near the end of 2013. The database we used ran through to April 2022 (with specific substations downloaded to allow analysis of GMD in early 2023, for which the observations were considered through to April 2023).

In Transpower's case the combined total, even, and odd-order harmonic distortion percentages are archived from each meter on each of the three phases with a 10 min time resolution. In the current study we focus only on the percentage distortion of the combination of all even-order harmonics monitored on the circuit breaker voltage input, which we term the Even-Order Total Harmonic Distortion (ETHD). This decision was made after looking at the odd-THD observations, and finding they did not seem to provide meaningful results linked to GMD; as expected following earlier analysis (e.g., Clilverd et al., 2018). As noted in Rodger et al. (2020), voltage harmonic distortion observed at a given monitoring location may not be locally generated, and is influenced by other substations linked to the given monitoring location by transmission lines. In contrast, current harmonic distortion observations provide a direct indication of the source from which the harmonics originate. Unfortunately, the Transpower phase current THD measurements do not discriminate between even and odd harmonics, but include both even and odd harmonics. As reported earlier, the total of both even and odd harmonic distortion does not respond in a useful way during space weather events (Clilverd et al., 2018; Rodger et al., 2020), and hence we restrict ourselves to the available even-order voltage THD (which we now refer to as ETHD). The influence of nearby substations is discussed further in Section 4.

Each substation includes multiple CB for which ETHD measurements are made, with separate measurements made on each of the 3 phases. In some locations there may only be 1 monitored CB at a location, but the maximum number is 30 with an average of 3–4 CBs monitored per substation location. Average ETHD values are provided for each phase at each CB with 10 min time intervals (i.e., 0–10, 10–20, 20–30, etc). The ETHD values are very similar across the 3 phases, as expected for a balanced three-phase system, and thus we take the mean of these values for each CB. Rodger et al. (2017) showed that the ETHD values could vary inside the same substation, but with the same time variation; this may be due to attenuation inside the substation linking different voltage levels. It is possible that this may be hidden in substations with few CB, such that averaging might "downgrade" the importance of the ETHD at a given substation. We therefore take the largest ETHD value amongst the CBs at a given time; we typically find that the CB which exhibits the highest ETHD in a given substation continues to show the highest ETHD over time during a GMD.

The process of taking the maximum ETHD value from the CBs in a given substation typically provides good quality information, but at some locations this is not the case. In the vast majority of New Zealand substations all the CB-ETHD values respond together, with only the magnitudes differing. This is the typical situation during GMD. In some fairly rare cases we find times unconnected with GMD where one or two CBs in a substation shows an ETHD increase, and the remaining CBs do not. These ETHD increases do not influence nearby connected substations, as is commonly seen during GMD (this is discussed more in Section 4). This type of non-GMD ETHD increase was identified as occurring in a set of substations in the North island running South to North and marked in the right hand panel of Figure 1 as white diamonds (from south to north the substations shown are Bunnythorpe, Tangiwai, Taumarunui, Hamilton). On consultation with Transpower we learned that these substations provide special traction services to the North Island Main Trunk electrified train services, and are thus different to the vast majority of New Zealand substations; our Transpower engineering colleagues indicate that ETHD increases occurring outside of GMD are most probably caused by rail operations near the substation. Such events are not particularly common, and have not impacted the GMD analysis described below. We note this effect, however, to emphasize that the situation is not quite as simple as indicated by Rodger et al. (2020).

2.3. New Zealand Magnetometer Observations

GMD observations are provided by the sole magnetic observatory in New Zealand, the Eyrewell (EYR) magnetometer operated by GNS Science, New Zealand. EYR is part of INTERMAGNET (http://www.intermagnet.org/). A detailed description of the construction of EYR one-minute averages of the horizontal component of the magnetic field, H, is given in Mac Manus et al. (2017). Due to the low time resolution of the harmonic distortion data, the EYR horizontal magnetic field measurements will typically be averaged to 10 min resolution over the same time window as the ETHD data.

2.4. Geomagnetic Disturbance (GMD) Events Examined

Previous studies have shown that the rate of change of the horizontal component of the magnetic field (H') was a good proxy for the observed GIC magnitude in New Zealand (e.g., Mac Manus et al., 2017), using measurements from the Eyrewell observatory. Rodger et al. (2020) also showed that the time variation of the 10 min averaged Eyrewell H' provided some indication of the time varying ETHD magnitudes across New Zealand. Based on this we selected a set of GMD using the EYR H' observations across the time window for which we have access to ETHD measurements. These GMD times are given in Table 1, which also includes the peak absolute horizontal rate of change measurements from EYR ($|H'|$) at both 1-min and 10-min time resolutions. Note there are other GMD which occurred during this time period which are not given in Table 1. That occurs due to missing data;

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Table 1
Geomagnetic Disturbances (GMD) Investigated in the Current Study

GMD time period [UT]	Max. $\|H'\|$ (nT/min) 1 min res.	Max. $\|H'\|$ (nT/min) 10 min res.
2 Oct 2013	85.6	10.8
17–18 Mar 2015	68.4	7.7
22–24 April 2017	18.7	7.5
7–9 Sept 2017	**33.3**	**12.0**
26–27 Aug 2018	**42.7**	**15.6**
27–28 Feb 2019	7.7	4.4
12–13 Oct 2021	32.1	5.8
3–4 Nov 2021	**31.6**	**16.2**
23–24 Mar 2023	18.2	8.6
23–25 Apr 2023	40.1	10.9

Note. The maximum rate of change of the horizontal component of the magnetic field (H') listed are based on observations from the Eyrewell (EYR) magnetic observatory, and are provided for 1- and 10- time resolution. The three largest GMD are highlighted in bold in this table, and also in Table 2.

there are a handful of unfortunate occurrences when a significant GMD occurs during a nationwide gap in THD data, for example, during 22 June 2015.

Three of the most important GMD in Table 1 are those of September 2017 (peak $|H'|$ of 33 nT/min at 1 min resolution), August 2018 (peak $|H'|$ of 43 nT/min), and November 2021 (peak $|H'|$ of 32 nT/min). These three storms are particularly useful because they have some of the highest peak $|H'|$ values in our time frame, whilst also occurring at times in between important changes to the power grid which impact our ETHD observations. They are shown in bold in Table 1. These are (a) On the 21 November 2017 the earthed single-phase HWB transformer number 4 (HWB T4) was taken out of service. (b) On 20 December 2019 the New Plymouth (NPL) substation, which contained at least one earthed single-phase transformer, was entirely decommissioned.

3. Even-Order Total Harmonic Distortion (ETHD) Variations

Outside of GMD periods, we see no coherent large spatial scale ETHD variations. Indeed, typically there are no significant ETHD changes in most locations. However, during a GMD all CBs show increases with the same time variation and these often appear to influence connected substations. As seen previously for September 2017 (Rodger et al., 2020), during a GMD there is a consistent ETHD time varying response across the vast majority of the monitored substations. Another source of ETHD increases local to a substation comes from spectral leakage from local ripple injection systems used to control domestic hot water heating systems in the local area. Once again, this is seen to be independent of GMD and is very localized, typically occurring at the same times of day over long time periods. There appear to be some other sources of local ETHD "spikes," and also offsets. We have not found they significantly detract from our GMD-focused analysis, and will mention work-arounds as they are applied.

3.1. Case Studies of Time Variations

Figure 2 shows examples of ETHD changes for two of the GMD considered, at a number of locations which show clear and strong responses in ETHD to GMD. The upper row of Figure 2 presents the rate of change of the horizontal component of the magnetic field measured at EYR (blue line), converted to 10 min time resolution. The following three rows are percentage ETHD changes (red lines) for 3 selected substations: HWB, NPL, and Robertson Street (ROB). The left hand column shows these variations for a GMD in September 2017, while the right hand column is for August 2018. The plots show there are typically strong correlations in the timing of changes in ETHD and EYR, with some correlation also in the magnitude of those changes, that is, a larger or smaller EYR 10 min resolution H' value will tend to produce larger or smaller ETHD at the same time resolution. However, it is not uncommon for the ETHD response to lag slightly behind the GIC response. A sudden spike in GIC magnitude will typically be seen in the ETHD in the same 10 min time window, or in the ETHD observations

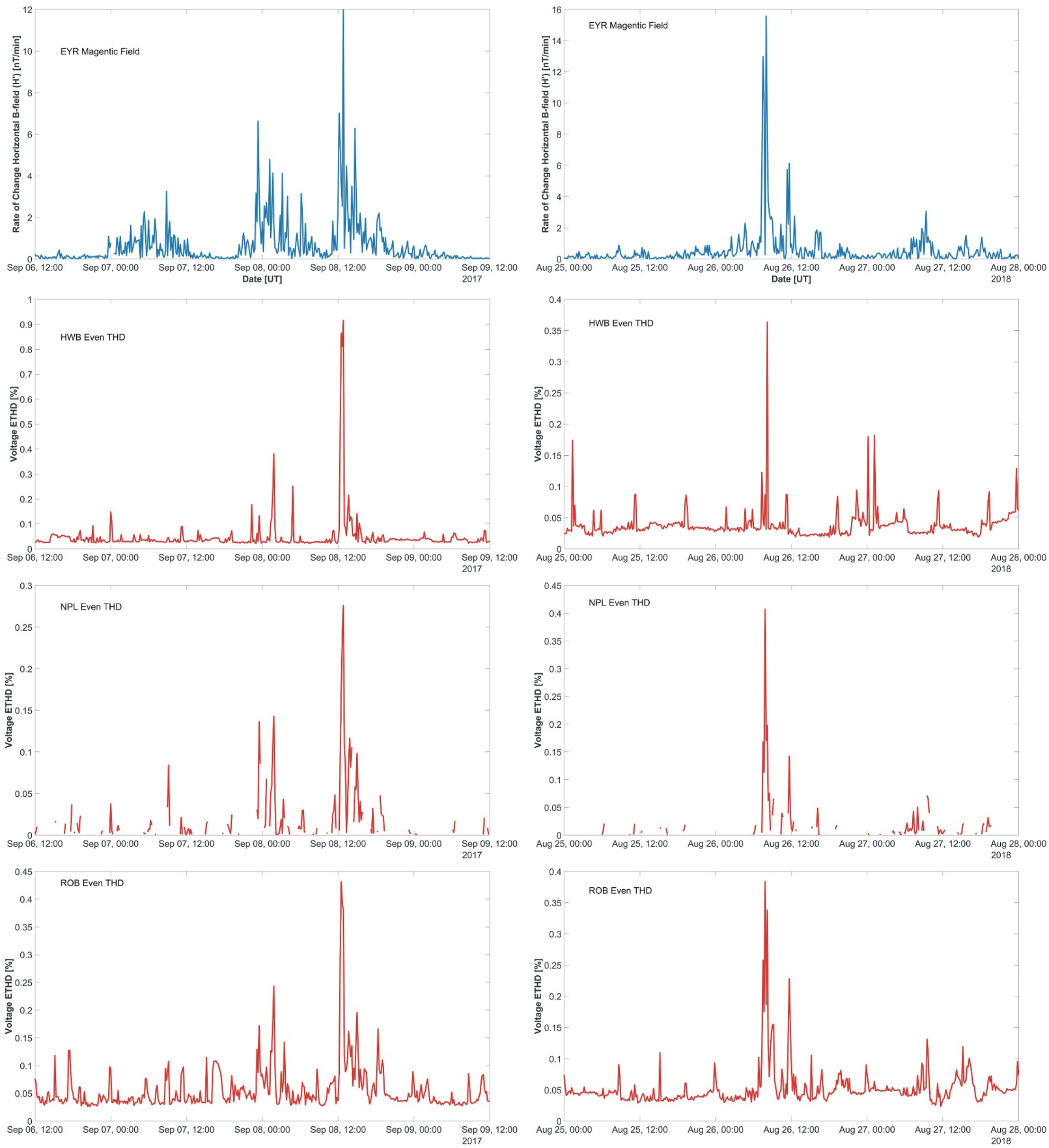

Figure 2. Time variation in the rate of change of the horizontal component of the EYR-observed magnetic field (upper row), and the variation in even order voltage THD measured at three different substations (lower three rows). The substations examined are Halfway Bush, New Plymouth, and ROB. The left hand column is a geomagnetic disturbance in September 2017, the right hand column is for August 2018. All data is shown with 10 min time resolution, the default for the THD observations.

in the 10 min period immediately following the GIC spike. This is likely due to time delays between the GIC spike and transformer core-saturation, which then produces ETHD.

The selected time periods and locations shown in Figure 2 are not the only locations in these storms with notable harmonic activity. We see similar patterns in ETHD "hot-spots" during other storms, with the amount of ETHD corresponding roughly to the level of geomagnetic activity. As reported by Rodger et al. (2020), GMD produce ETHD increases in multiple substations across the country. However, as will be shown below, the examination of multiple GMD over a longer time period in which significant network changes occurred indicates there is more complexity to the linkage that they reported.

3.2. Baseline Corrected New Zealand Wide Analysis

As can be seen in Figure 2, in many locations there is a fluctuating baseline value for ETHD, that is, the values often do not sit at zero percent outside of quiet times. In many locations a constant amount of ETHD is reported to be present, unrelated to GMD. These values tend to be small, but as they are clearly not due to GMD, we undertake data processing outlined below to remove these constant baselines. We speculate these baseline offsets are due to ETHD measuring errors, as the production of ETHD is unusual in a well run power network, as discussed in Rodger et al. (2020) (outside of the short time periods where transformers are initially energized (Watson & Arrillaga, 2018)). However, it is also possible that these locations include devices which only draw current on one half cycle of the AC wave. One example are half wave rectifiers, which would produce a long term near constant ETHD level. We also note that for a small number of substations the data quality is not good, which was also pointed out by Rodger et al. (2020), where the baselines vary considerably over time. There are several such locations in the central North Island (particularly around the city of Rotorua), which we speculate may be linked to equipment in the forestry and wood processing industry. Other examples where ETHD spikes unrelated to GMD can be produced are passing trains (discussed earlier) and spectral leakage from ripple control systems. During the manual inspection of ETHD around GMD periods these issues were obvious, as they were rare and very different from the main ETHD-variation which was clearly linked to GMD. Locations with such issues were excluded for further analysis, but the issue is mentioned for completeness and to assist future researchers.

In order to remove the impact of non-zero ETHD baselines, and to allow a better "like with like" comparison, our subsequent analysis is undertaken using ETHD percentage values after the baseline is removed. This is undertaken separately for each substation and GMD. The baseline is calculated as the mean ETHD value for a given substation for the time period of the GMD plus one day before and after the peak of the storm.

Figure 3 presents six example maps of the baseline-corrected ETHD values across New Zealand near the peak GMD 10 min periods for three significant GMD: September 2017, August 2018, and November 2021, that is, two examples per GMD. For each substation, the radius of the plotted ring is proportional to the magnitude of the baseline-corrected 10 min mean ETHD percentage value, where the value plotted is from the CB with the maximum for that substation (as discussed earlier). The time shown on each panel represents the end of the 10 min window over which the mean was taken. We use color to help discriminate between ring sizes: increases between 0% and 0.1% in ETHD (blue), 0.1%–0.3% ETHD (orange), and >0.3% ETHD (red). Black markers represent ETHD responses which are below the base-line, or no data. In each panel an additional subpanel is included which shows the time series of the magnetic field changes ($|H'|$, blue line), and a vertical red line marking the point in time corresponding to that map.

Figure 3 indicates that ETHD increases are seen in multiple locations in the South Island, particularly in Dunedin, but are also seen in multiple locations across the lower South Island, both north and south of Dunedin. ETHD increases are also seen in the South Island city of Christchurch, and surrounding areas. We note that high GIC magnitudes have previously been reported in both the Islington substations (Christchurch, particularly transformer number 6, i.e., ISL T6) (Divett et al., 2018; Mac Manus et al., 2017; Marshall, et al., 2012; Rodger et al., 2017). In addition, very high GIC has been reported in multiple transformers in the Dunedin substations of HWB and South Dunedin (e.g., Mac Manus et al., 2017; Mac Manus, Rodger, Ingham, et al., 2022; Rodger et al., 2017). This may, in part, help explain the significant ETHD increases seen in the Dunedin region, north and south of that city, and also around Christchurch. Significant ETHD increases are also seen in the Tasman/West Coast region of the upper South Island, and around Taranaki in the western North Island. There are also ETHD increases seen in New Zealand's biggest cities, Auckland and Wellington.

The middle panels of Figure 3 show baseline-corrected ETHD maps for two significant time periods during the 26 August 2018 GMD. A set of three single phase transformers in HWB, Dunedin (HWB T4), was decommissioned in November 2017, such that this GMD occurs after the last single phase transformer bank set earthed on the high voltage side was removed from Dunedin city. While high GIC are still observed in Dunedin city, at levels similar to those earlier measured at HWB T4, the levels of ETHD across the lower South Island are very different from that seen before HWB T4 was decommissioned. This single change has led to a dramatic decrease in ETHD levels in that part of New Zealand, indicating that HWB T4 might have been the source of much of that ETHD. Most of the other ETHD enhancement regions identified in the upper panels during the September 2017 GMD, particularly the West Coast of the South Island, Taranaki, and the Auckland region, are still seen during the August 2018 GMD.

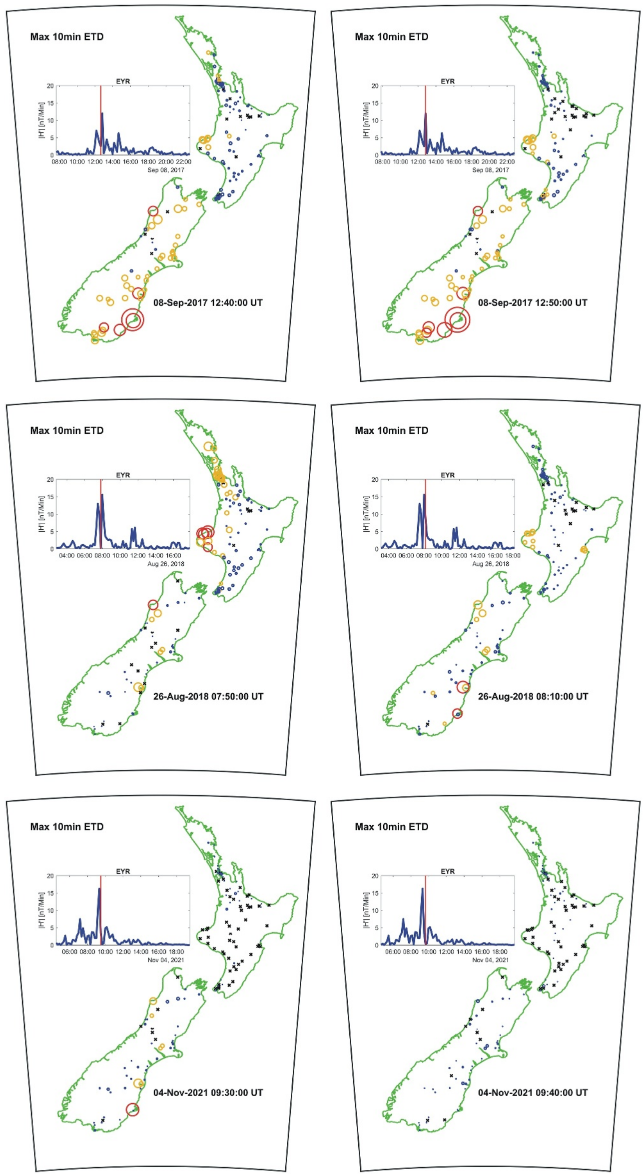

Figure 3. Maps showing the variation in baseline corrected Even-Order Total Harmonic Distortion (ETHD) for three significant geomagnetic disturbance (GMD) (see text for details), for two different selective time intervals per GMD. The colored rings show ETHD increases: between 0% and 0.1% in ETHD (blue), 0.1%–0.3% ETHD (orange), and >0.3% ETHD (red). Black crosses represent ETHD responses which are below the base-line, or no data. In each panel an additional subpanel is included, showing the time series of the magnetic field change (|*H*′|, blue line), and a red line marking the point in time corresponding to that map.

The lower panels of Figure 3 are maps during the November 2021 GMD. Once again, there is another dramatic decrease in ETHD relative to the earlier maps. This GMD occurred after the NPL substation was decommissioned in December 2019, removing another set of single phase transformers. For the last GMD example there are, again, some ETHD increases in the Dunedin region (but with little evidence across the lower South Island), some increases on the West Coast of the South Island and small increases in the Auckland region, but the dramatic feature on the North Island's west coast, Taranaki, essentially disappears. This demonstrates the importance of single phase units to ETHD production during these GMD, caused by that transformer type having lower GIC saturation thresholds than for 3 phase transformers (Dong et al., 2001; EPRI, 2014; NERC, 2013; Piccinelli & Krausmann, 2015).

From Figure 3 we identify 5 key substations to examine in more detail, with each appearing to be the primary generator of ETHD in their respective regions. These are HWB, Islington (ISL), Robertson Street (ROB), NPL, and Henderson (HEN). Note that in the Auckland region it is challenging to decide which substation might be the source of the ETHD observations. Henderson was selected as it was previously identified as a location with high GIC in GMD modeling (Mac Manus, Rodger, Dalzell, et al., 2022), and also because it contains multiple single phase transformers. We note that four of the five substations named above appear in the high GIC substations based on modeling reported in Figure 10 of Mac Manus et al. (2022b). The exception is Robertson Street (ROB) on the West Coast of the South Island. While this substation "stands out" in Figure 3, it has not been previously identified as an expected high GIC substation; nor does it contain any single phase transformers.

Table 2 summarizes the baseline-corrected ETHD response observed at each of the 5 key substations, for each of the 10 GMD examined in detail. Once again, we show in bold the three most significant GMD. A "yes" in the table indicates a clear ETHD response that is, by eye it is clear that ETHD at that substation responds to the GMD. "Unclear" means we are not confident. This often means there was small ETHD increases correlated with the peak of the storm which was not bigger than other ETHD increases occurring within ±1 day which were clearly not correlated with GMD. A "no" indicates nothing was seen, and "–" indicates no data was available for that location during the GMD in question. As is clear from Table 2, most of our substations of interest show clear ETHD increases for the selected GMD. Some of the clearest exceptions to this statement is for HWB from 28 Feb 2019 onwards, after the single phase transformers HWB T4 was decommissioned (November 2017), and for NPL from 12 Oct 2021 onwards, after the entire substation was decommissioned. It is important to note that the removal of HWB T4 has not stopped the occurrence of GMD-linked ETHD increases, as seen in Figure 3 and Table 2. However, the ETHD increases are not as clear or consistent since the removal of HWB T4.

4. ETHD Propagation From Source Substations

It appears that significant quantities of the GMD-ETHD increases are linked to well defined sources, potentially one single phase transformer bank with high GIC in a single substation. As noted earlier, voltage harmonics can propagate through a transmission network, allowing ETHD produced in one substation to influence large regions. The dramatic decrease in GMD-linked ETHD in the lower South Island after the removal of HWB T4, and ETHD in the mid and lower western North Island after the decommissioning of NPL are both strongly suggestive of single ETHD sources propagating over wide spatial zones.

Table 2
Geomagnetic Disturbances (GMD) Investigated in the Current Study Indicating if a Clear Even-Order Total Harmonic Distortion Response Is Observed at the Five Key Substations Identified in Section 3

GMD time period [UT]	HWB	NPL	ROB	ISL	HEN
2 Oct 2013	Yes	Yes	–	Yes	No
17–18 Mar 2015	Yes	Yes	Yes	Yes	Unclear
22–24 April 2017	Yes	Yes	–	Yes	Yes
7–9 Sept 2017	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
26–27 Aug 2018	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
27–28 Feb 2019	No	Yes	Yes	Yes	No
12–13 Oct 2021	Unclear	–	Yes	Yes	Yes
3–4 Nov 2021	**Yes**	–	**Yes**	**Yes**	**Yes**
23–24 Mar 2023	Yes	–	Yes	No	Yes
23–25 Apr 2023	No	–	Yes	No	Yes

Note. The substations are ordered from south to north, that is, moving equatorwards in the Southern Hemisphere. A "–" in the table refers to missing data.

4.1. Comparison GMD-Linked ETHD Changes to Network Grounding

Further evidence of significant propagation of voltage ETHD comes from the nature of the substations in which GMD-linked ETHD are observed around the substations we suspect are the sources. A good example is the increase of ETHD in the Taranaki region shown in Figure 3, starting near the NPL substation and going south along the coast toward Wellington (at the bottom of the North Island). In August 2018 the increases nearest NPL are red ETHD circles (i.e., >0.3% ETHD increase), generally decreasing to orange (0.1%–0.3% increase) and then blue circles (0%–0.1% increase), fairly steadily with distance from NPL. Importantly, there are ETHD increases seen in all of the substations along this transmission line. A map of the transmission lines and substations near NPL (and HWB and ROB) is shown in Figure 4. This figure also displays whether the substations include transformers which are earthed (or not) on the high voltage side (filled in red circles in Figure 4). Such earthing allows GIC to flow into the transformer windings, potentially producing core saturation and hence harmonic distortion. The other transformers (unfilled red circles in Figure 4) are not earthed on the high voltage side (66 kV or above), but only on the low-voltage local supply side. Further discussion on the earthing of New Zealand transformers in a GIC context can be found in Divett et al. (2018) and Mac Manus et al. (2022a).

The upper left panel of Figure 4 shows the substations with earthed (red filled in) and non-earthed transformers (red unfilled) going from NPL southwards toward Bunnythorpe (BPE). To avoid clutter, only the substations for which we have ETHD data along the NPL to BPE transmission line are labeled, as we will use these locations to analyze ETHD propagation along a power line. Recall that GIC will only flow into transformer cores for earthed substations, with examples being NPL, SFD, and BPE in this panel. As no GIC will flow into the cores of transformers at HWA, WVY, BRK, WGN, and MTN, the cores should not saturate, and thus no local harmonic production is expected. We conclude that the ETHD increases seen in the non-earthed substations have propagated down the transmission line from elsewhere; the most likely source is the NPL substation, as this substation included a set of earthed single phase transformers, and the region showed large GMD-linked ETHD increases maximized on NPL during its period of operation, which stopped once NPL was decommissioned.

The lower panel of Figure 4 is a similar map for the lower South Island, another region where clear GMD-linked ETHD increases were observed, and large changes after the removal of a single phase transformer bank (in this case HWB T4). Once again, in contrasting Figure 3 and the lower panel of Figure 4 we see evidence of ETHD increases in substations without earthed transformers (e.g., BAL, BDE, and EDN), as well as a large decrease in ETHD response after HWB T4 was decommissioned. This is, again, consistent with ETHD propagating in the transmission network.

The upper right panel of Figure 4 shows the transmission lines and grounding status for the West Coast region of the South Island, focused on Robertson Street (ROB) substation. Once again, there is evidence of propagating ETHD, potentially starting at ROB and seen at the non-earthed substations RFN and ATU. Uniquely, however, no transformers in the Robertson Street substation are earthed such that GIC can enter cores and cause local saturation. This apparent puzzle is addressed in Section 6.1.

4.2. Further Examination of GMD-Linked ETHD Propagation

As noted earlier, there is evidence of GMD-produced ETHD increases propagating down transmission lines, with decaying amplitudes along the line. We now investigate this in more detail.

Figure 5 shows examples of the baseline corrected ETHD-increases along the transmission line from NPL going southwards to MTN in the mid- and lower North Island (see Figure 4), that is, plotting the ETHD increases relative to distance along the transmission line from NPL. Four examples from 3 GMD are shown. The red line is a linear fit of the decay with distance, with the R^2 coefficient of determination given for each panel. As with the earlier maps in Figure 3, subplots are shown in each panel showing the time series of the magnetic field changes ($|H'|$, blue line), along with red lines marking the 10 min time window for this ETHD decay plot. In this case we

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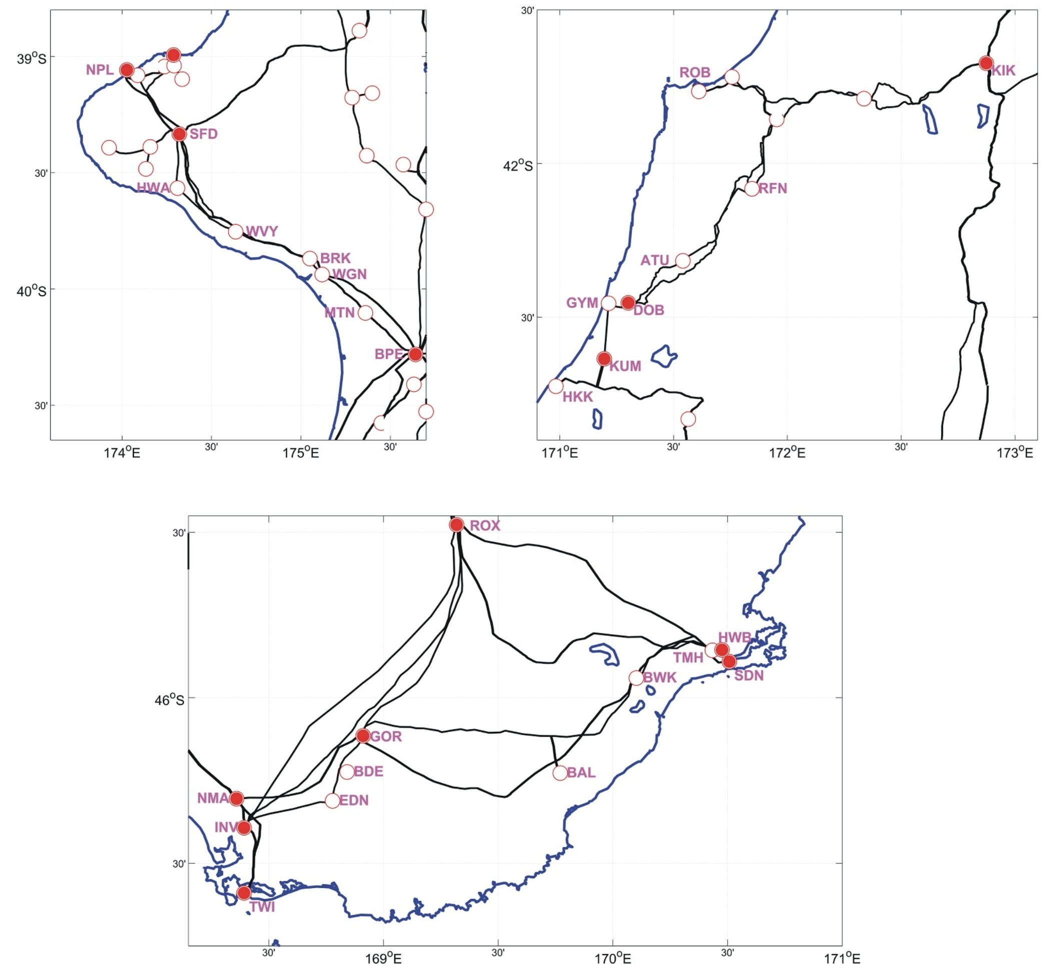

Figure 4. Maps showing the electrical transmission lines and substations in regions around three of our substations of interest. Substations containing transformers which are earthed such that will experience Geomagnetically Induced Current are shown in filled in red circles, effectively un-earthed substations are unfilled red circles. Substation locations are marked by their three-letter codes. Upper left panel: The mid-and lower North Island region from Taranaki. Upper right panel: Tasman/West Coast region of the South Island. Lower panel: The lower South Island.

limit ourselves to a study of the transmission line from NPL to MTN and do not include ETHD observations from BPE (Bunnythorpe). This is partly due to the electrified train issue mentioned earlier, but also as we suspect some ETHD propagation is occurring starting from the Wellington region, impacting BPE measurements. As can be seen in Figure 5, the ETHD decays in an approximately linear fashion with distance along the transmission line. We typically see quite good fits with quite high R^2 values. This is the common situation for this substation, and indeed for most events at many of our substations of interest (see Section 4.3). We note that the fits are not perfect. For example, in both examples from August 2018 HWA is above the ETHD level seen in SFD, which is closer to NPL. In contrast, in both April 2017 and September 2017 the observations from HWA fit much closer to the linear relationship. In general the behavior is fairly consistent; every time there is a significant ETHD response at NPL (>0.05% above baseline), it is found to decay in a roughly linear fashion along the transmission line to BPE. However, the spread of ETHD is likely to depend on the exact network state at that time, and hence will not be exactly the same from event to event.

Figure 6 investigates ETHD decay patterns in the lower South Island. Before the removal of HWB T4, strong ETHD increases are observed across the lower South Island, again with evidence of a roughly linear decrease with transmission line distance from the source substation. From October 2013 to September 2017 we see clear and approximately linear decay rates of ETHD with distance measured from HWB, confirming the relationship seen from NPL. After HWB T4 was decommissioned, the decay fits become weak or disappear. An example is shown

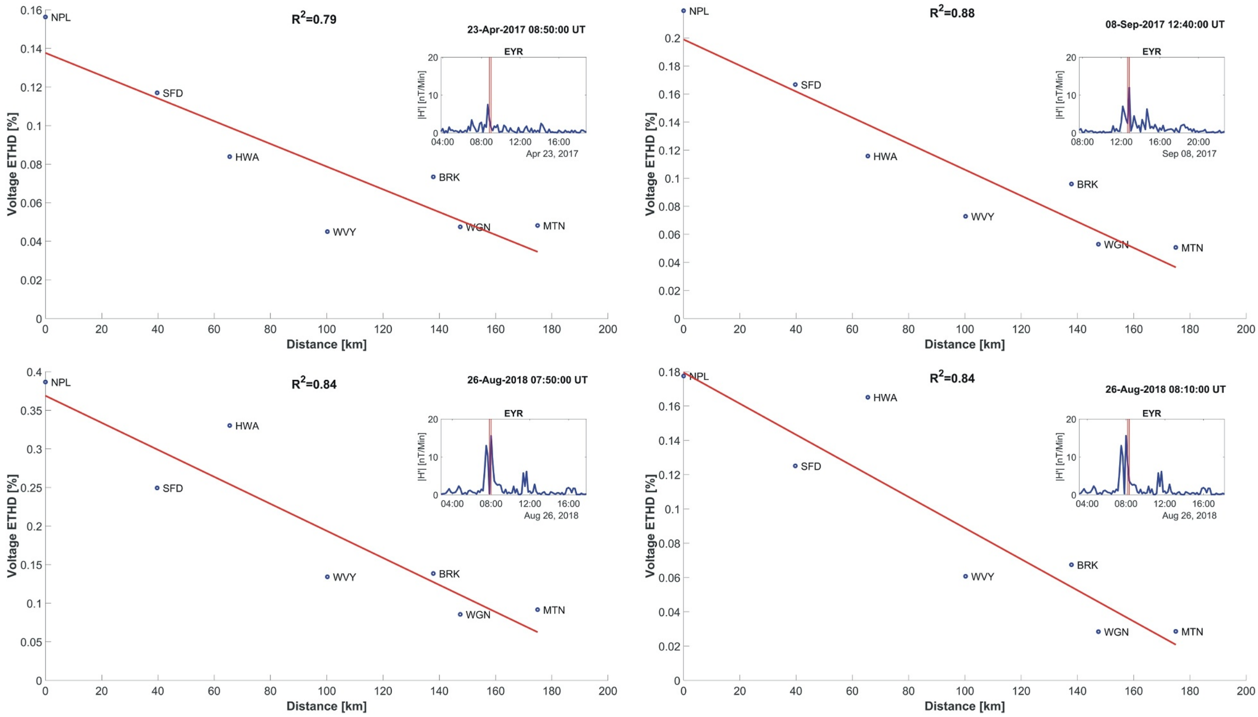

Figure 5. Investigating the decay of GMD-linked Even-Order Total Harmonic Distortion increases in the Taranaki region along the transmission line from New Plymouth to MTN (see the maps in Figure 4). We focus on four time periods in three different geomagnetic disturbance.

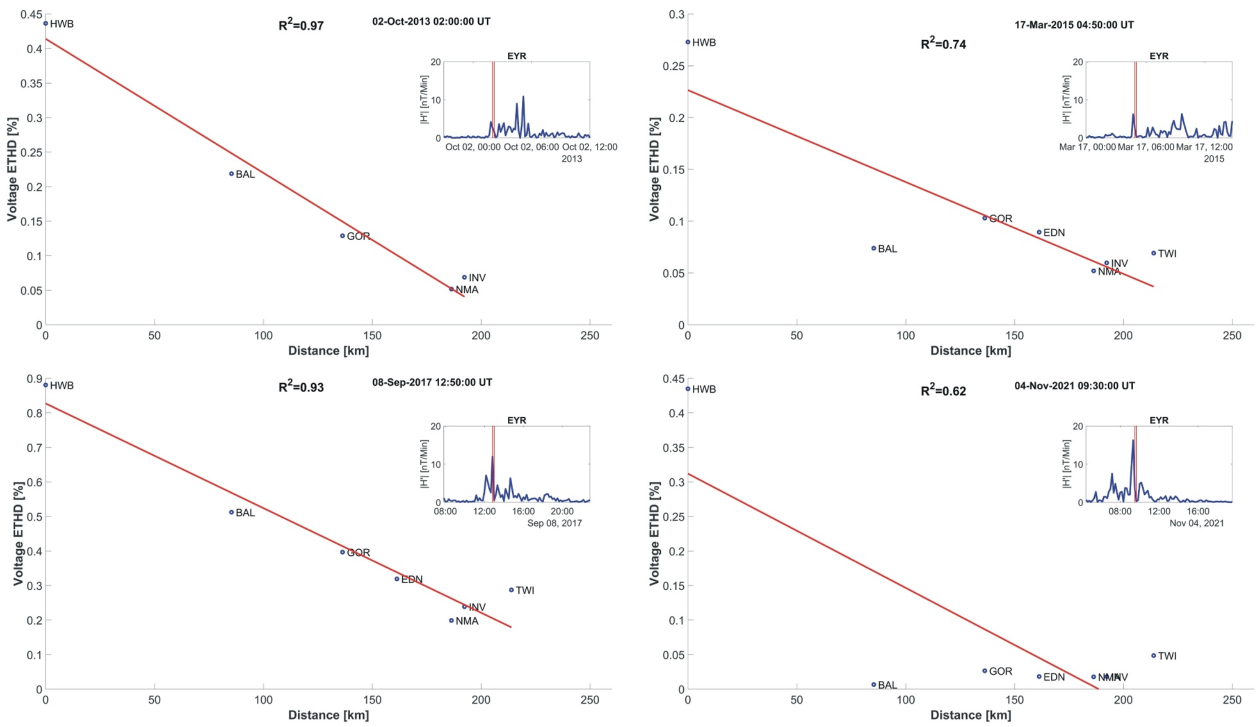

Figure 6. Investigating the decay of GMD-linked Even-Order Total Harmonic Distortion increases in the lower South Island region along the transmission line from Halfway Bush southwards toward INV/TWI, showing examples from four different geomagnetic disturbance.

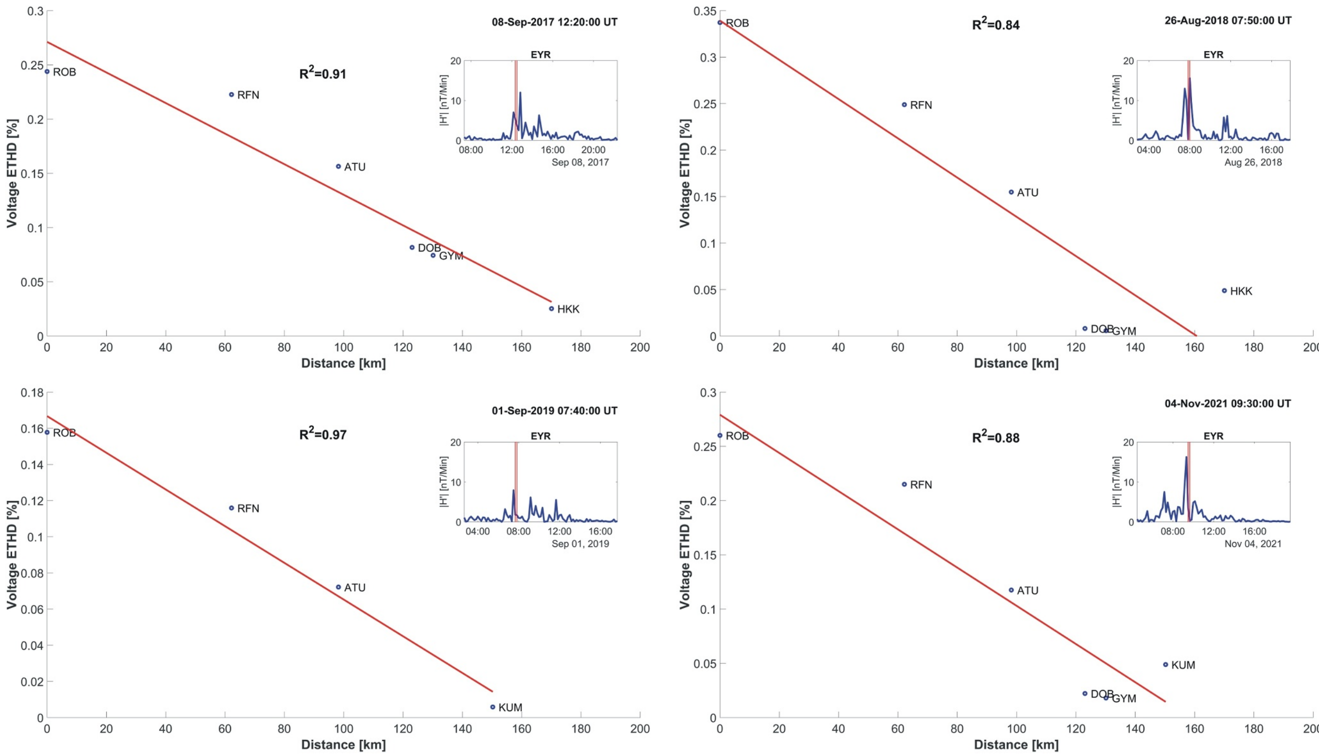

Figure 7. Investigating the decay of GMD-linked Even-Order Total Harmonic Distortion increases on the West Coast of the South Island. Here we focus on increases which may come from the ROB substation, looking at substations to the south. Examples are presented from four different geomagnetic disturbance.

in Figure 6, for the GMD in November 2021. While there is a strong ETHD increase observed at HWB, there is no evidence of propagation down the transmission line.

Note that TWI often appears to have higher ETHD levels than predicted. This may be due to TWI being a substation in which relatively high GIC are modeled (Mac Manus, Rodger, Dalzell, et al., 2022); another possibility is the aluminum smelter at TWI serviced by that substation. The smelter relies on specialist power transformers which have integrated power electronics rectifiers to produce the high DC currents needed for smelting. An alternative explanation is these systems are responding differently during GMD impacts.

Figures 5 and 6 showed evidence of GMD-linked ETHD increases propagating from NPL and HWB. In Figure 7 we consider the situation on the West Coast of the South Island in the same way, and investigate ETHD-increases around that substation. Of these, ROB substation has the highest ETHD values so is assumed to be acting as a source, and we examine how the ETHD values fall off with distance from ROB. As can be seen for the four examples of GMD periods in Figure 7, it does seem that ROB is acting as a source, much as was earlier seen for NPL and HWB. The R^2 coefficient of determination for the fitted decay with distance lines are rather good quality, with values >0.8 and often >0.9. Once again it appears as if ROB is acting as a source of ETHD, despite the lack of GIC at those transformers. We discuss this issue further in Section 6.

4.3. Summary: GMD-Linked ETHD Propagation

We have examined all our GMD events and the specific substations of interest for evidence of well-behaved ETHD propagation. Our criteria was a linear fit to the decay with distance with $R^2 \geq 0.7$ and a source ETHD ≥ 0.05% above baseline, plus a visual inspection of the decay which was convincing "by eye." The results of this examination are shown in Table 3. In this case a "yes" means the 3 criteria listed above. "Unclear" indicated the numerical criteria are met, but the visual inspection is not fully convincing. "No" indicates a lack of propagation evidence from the suggested source substation into the surrounding substations. As can be seen from Table 3 the clearest evidence of ETHD propagating away from a source substation is for ROB on the West Coast. NPL in the Taranaki region was a clear ETHD source causing propagating ETHD increases during GMD in

Table 3
Geomagnetic Disturbances (GMD) Investigated in the Current Study Indicating if a Well-Fit Propagating Even-Order Total Harmonic Distortion Response Is Observed, Focusing on the Five Key Substations

GMD time period [UT]	HWB	NPL	ROB	ISL	HEN
2 Oct 2013	Yes	Yes	Yes	No	No
17–18 Mar 2015	Yes	Yes	Yes	No	Unclear
22–24 April 2017	No	Yes	Unclear	No	No
7–9 Sept 2017	Yes	Yes	Yes	Yes	Yes
26–27 Aug 2018	Unclear	Yes	Yes	Unclear	Yes
27–28 Feb 2019	No	No	Yes	No	No
12–13 Oct 2021	No	No	Yes	No	No
3–4 Nov 2021	No	No	Yes	No	No
23–24 Mar 2023	No	No	Yes	No	No
23–25 Apr 2023	No	No	Unclear	No	No

Note. See text for details.

almost all the disturbances considered until the substation was decommissioned in December 2019 (the exception is the relatively small GMD on 27–28 Feb 2019). In contrast the situation for HWB and HEN is less clear; while both substations appear to have local GMD-linked ETHD increases (as described in Table 2), they do not always clearly propagate away from the source substation. In the case of ISL local GMD-linked ETHD increases are very common (as seen from Table 2), but it is rare to have clear examples of ETHD increases that appear to be sourced from this substation.

4.4. Examining ETHD Propagation With Distance

We now investigate the quality of the linear decay for propagating ETHD periods against the magnitude of the ETHD produced at the suspected source substation. Here we include events from all GMD where propagating ETHD is observed (noted by a "yes" in Table 3), for all the substations of interest. This is shown in the upper panel of Figure 8. This panel shows the relationship between the coefficient of determination (R^2), and the source ETHD percentage level. We see that for low values of source ETHD there is a wider range of R^2 values, but the average R^2 value becomes less variable as the ETHD magnitude increases (i.e., in larger GMD).

The middle panel of Figure 8 examines how the propagating ETHD magnitudes decay relative to the ETHD at the source substation, comparing all five selected substations. Here we examine the fitted linear decay rates of ETHD for each source substation (i.e., ETHD percentage per km along the transmission line) including multiple 10 min periods across all GMD where clearly propagating ETHD was observed. The fitted linear decay rates are compared with the ETHD found at the source substation. To create this panel we used all of the linear decay fits which had $R^2 \geq 0.7$, a y-intercept ETHD $\geq 0.05\%$, and a reasonable number of data points. We plot the y-intercepts of the decay fits, which are representative of the source ETHD (in %) at the substation of interest, on the x-axis of the panel, and the slopes of the decay fits on the y-axis. The steeper the lines shown on this panel, the faster the ETHD decays with distance along a transmission line for a certain level of ETHD at the source. This panel shows that the relationship for most source substations, especially for HWB, NPL, and ROB which have the most periods with good quality propagation activity, have a very consistent linear relationship between the ETHD at the source and the ETHD decay rate with distance. The R^2 value for linear fits for those points is $\geq$0.94. It seems reasonable these relationships could be extended to describe larger GMD when larger source ETHD increases would be expected. The ISL and HEN lines on this panel are limited to six and seven data points respectively, however these 13 data points are entirely consistent with the lines for other sub-stations, suggesting they would follow a similar pattern if extended to a larger GMD.

Data points on the yellow line representing ROB as a source fall consistently below the substations of interest, having a steeper slope of -0.00505 km^{-1}, compared to an average slope of the other four substations of -0.0043 km^{-1}. This means that ETHD increases, even if they were the same magnitude at the source, do not propagate as far from ROB as they do from the other substations. One possibility is that this is caused by ETHD changes at ROB being generated in a different way, as discussed later. However, the consistency of the ETHD fall-off on propagation from the other earthed substations suggest the decay rate of -0.0043 km^{-1} could be used to model such propagation during future, possible larger, events. Given the substations of interest are for very different locations it also seems reasonable that the observed decay rate could hold for all New Zealand substations. For example, the observed decay rates do not depend on whether the substation is connected by 110 or 220 kV transmission lines (as shown in the middle panel of Figure 8).

5. Correlation With Transformers Modeled to Have High GIC

5.1. Comparison With GIC Modeling

As briefly mentioned in the introduction Mac Manus et al. (2022b) recently used the New Zealand validated GIC model to investigate GIC hazard levels for a "Carrington class" GMD, based on the UK government "Reasonable Worst-Case Scenario" for a GMD (Hapgood et al., 2021). The Mac Manus et al. (2022b) study found the at-risk transformers were not localized to any specific region of New Zealand but extended across all regions and include

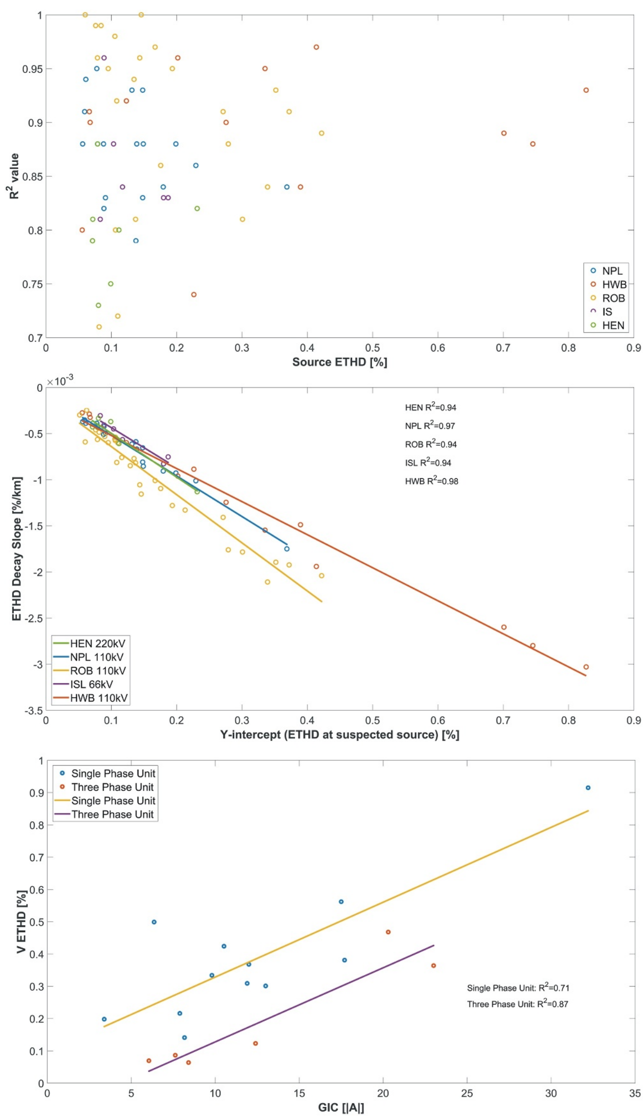

Figure 8. Further examination of Even-Order Total Harmonic Distortion (ETHD) propagating from the identified source substations. Upper panel: quality of the fitted linear decay against the magnitude of the ETHD produced at the suspected source substation. Middle Panel: Comparison of the fitted ETHD decays with distance depending on ETHD at the source substation. Lower panel: Comparing ETHD percentages observed at the Halfway Bush (HWB) substation depending on Geomagnetically Induced Current magnitude, before and after the HWB T4 unit was decommissioned in late November 2017.

most of the major population centers. Figure 10 of that study summarizes the locations of substations with the highest GIC magnitudes.

ETHD increases provide an independent way of confirming the GIC magnitude modeling described above. Some locations, particularly in the North Island, had no GIC monitoring data when the modeling was undertaken; such that the modeling relied on the network topology information from Transpower and GIC observations mostly from the lower and mid South Island (see the description in Mac Manus et al., 2022a). High currents are predicted in the HWB and ISL substations, and confirmed through GMD-linked ETHD increases but this modeling was strongly informed by GIC observations in those substations. However, modeling also predicted high currents should be present in the NPL substation (Mukhtar et al., 2020), as well as the HEN substation (Mac Manus, Rodger, Dalzell, et al., 2022), where no GIC measurements existed. The modeling results are consistent with the GMD-linked ETHD increases reported in the current study, providing additional confidence in the GIC modeling.

5.2. Single Phase Versus Three Phase Transformers and ETHD

The dramatic changes in GMD-linked ETHD occurrence when single phase units were removed (HWB and NPL) demonstrates the higher sensitivity of single phase transformers to GIC leading to ETHD production. When considering GIC danger levels using industry provided GIC thresholds of current magnitude and time, Mac Manus et al. (2022b) reported that thermal impacts would occur at much lower levels for a single phase transformer than a three-phase transformer. Clearly, the ETHD occurrence in the New Zealand network becomes much lower once the single phase units are removed, with remaining increases likely linked to single phase units in ISL and HEN. However, we note that ETHD increases do not stop in the HWB substation after the decommissioning of HWB T4, as seen in Figures 2 and 3, and Table 2. After HWB T4 is removed the remaining earthed transformers are three phase design, with lower sensitivity to GIC. However, currents in the remaining transformers in HWB and SDN are still large, with HWB T6 and SDN T2 having roughly the same peak GIC magnitudes as HWB T4 experienced (see for example, Figure 3 of Mac Manus et al. (2022a) or Table S9 from that paper). Continued GMD-linked ETHD increases observed at HWB, after the single phase transformers had been removed, indicates that the remaining three phase units were still being driven into partial saturation by the very large GIC magnitudes in the Dunedin substations. The lower panel of Figure 8 shows how GMD-linked ETHD increases depended on GIC magnitude before and after the HWB T4 unit was decommissioned in late November 2017. As expected, there is a marked decrease in ETHD after the single-phase unit is taken out of service. The same GIC magnitude observed in the main HWB transformers (HWB T4 beforehand, HWB T6 afterward) produces one-third the ETHD change once the single phase transformer is decommissioned, consistent with the findings in Clilverd et al. (2020) using VLF observations.

6. Discussion

6.1. ETHD Production From Roberson Street (ROB) Substation

As noted above, the Robertson Street (ROB) substation appears to act as a source of GMD-linked ETHD, despite there being no earthed transformers present in this substation (either single phase or three phase units). As well as checking this with Transpower New Zealand Ltd, the grid operator, we also communicated with the local owner of this substation, who confirmed the details we held (private communicate, Dale Ross, network manager, Buller

Electricity Ltd). As such, we have no evidence that GIC could be saturating transformers at this substation to produce the clearly observed harmonics.

The GMD-linked ETHD appearing from ROB is most likely caused by a resonance occurring in this substation, amplifying ETHD produced in some other substation, and causing ROB to act like an ETHD source. For the following discussion we direct the interested reader to the textbook Arrillaga and Watson (2003). A real-world substation includes a number of inductive and capacitive elements, which will have frequency dependent responses. The combined system of such elements, for example, in a substation, produces a power system with a resonant frequency (also known as the "natural" or "critical" frequency) dependant on the elements in the system. Such resonances can be identified by the application of nodal admittance matrix analysis (e.g., Amornvipas & Hofmann, 2010; Huang et al., 2007; Pană & Băloi, 2014). This analysis involves the generation of an N by N Nodal Admittance matrix, where N is the number of busses in the system being analyzed. In this context, a bus (or bus bar), usually located within a substation, is essentially a connector for multiple high voltage loads, and is fixed at a certain voltage. There can be multiple bus bars within a substation, for example, combinations of 66, 110, and 220 kV bus systems. Admittance is defined as the inverse of impedance, measured in Siemens. A higher admittance means it is easier for current to flow; admittance is more applicable to AC power systems than resistance as it takes into account other dynamic factors, such as reactance (Grainger & Stevenson, 1994). Nodal admittance matrix harmonic modeling allows one to identify resonant frequencies in a network. It is possible for the resonant frequency to overlap with the system operational frequency (or that of its harmonics), which then leads to power quality issues and can negatively impact equipment in the substation (e.g., Eghtedarpour et al., 2014; Lemieux, 1990).

The New Zealand Electricity Authority provides detailed data on the New Zealand electrical network to allow transmission engineers and technical analysts to undertake power systems analysis (Electricity Authority, 2023). These data were originally sourced from Transpower New Zealand Ltd, the system operator and are designed to be used by the DIgSILENT Powerfactory power system analysis software application. We have used Powerfactory to undertake Harmonic Modeling focused on the Robertson Street Substation, allowing resonances to be identified. The simulation process consisted of running a frequency sweep up to the tenth harmonic (500 Hz) and analyzing the impedance-frequency characteristic of the busbars connected to transmission lines going south-west and north-east of ROB substation. In a power system there are two different types of resonances; series and parallel. Series resonances at a specific bus bar are indicated by the admittance for the node sharply increasing around a certain frequency and the admittance sharply decreasing around a certain frequency for parallel resonance. Series resonances create current distortion and parallel resonances create voltage distortion. In the modeling loads were switched out of the simulation system to see their affect on the impedance frequency characteristic, and hence identify the combination of elements leading to the resonance. This analysis identified that the 33 kV busbar in the ROB substation has multiple parallel and series resonances around the sixth harmonic, providing a potential explanation for the GMD-linked ETHD appearing to come from ROB. As our measurements are of voltage ETHD, and show evidence of propagating harmonics, we conclude this is most likely due to parallel resonances leading to sixth order voltage harmonics.

One remaining question is the source of the ETHD which is apparently amplified by a resonance at the ROB substation. The best candidate which could be potential sources of the original ETHD is from the Kikiwa (KIK) earthed substation, shown to the east of ROB in Figure 4 (top right panel), ~100 km from ROB. Naively the best candidate might be thought to be the single phase unit at KIK (KIK T1). However, it is more likely that the source is the three phase unit at KIK (KIK T2), as modeling has shown it to be a transformer in the top 10 list for GIC magnitudes for New Zealand (Mac Manus, Rodger, Dalzell, et al., 2022, Table 2), with GIC magnitudes ~4 times higher than KIK T1. This is caused by the series winding resistances of KIK T2 being ~4 times smaller than KIK T1. KIK is not a large source for ETHD, but the observations indicate it has observable ETHD-levels during GMD, although lower than seen at ROB. For example, during the August 2018 GMD the KIK substation showed voltage ETHD peaks which were roughly one-third of the magnitude of those at ROB. There is additional evidence to support KIK as a potential ETHD source; while there is a fairly clear and consistent drop-off in ETHD magnitudes going "south" from ROB toward HKK (as seen in the upper right panel of Figure 4); this is not true going "east" of ROB toward KIK, potentially indicating that the combination of ROB and KIK interferes with the propagation pattern. Thus we conclude harmonic disturbances generated at the KIK substation resonate and are amplified at the 33 kV busbar in the ROB substation, producing the observed signature.

Note that we do not claim that this modeling does conclusively demonstrate that the apparent ROB source is a resonance, or that the original GMD-produced is from KIK T2. The New Zealand power system network detailed data has not been verified for use in harmonic studies at this point. The modeling provides a good indicator of likely harmonic resonances, but field work would be required to test the modeling and these conclusions. Such additional work is beyond the scope of the current study, but is under consideration for the future.

6.2. ETHD Increases in Henderson

The earlier work by Rodger et al. (2020) stimulated much interest by our industry partner, Transpower New Zealand. Previous to that research it was widely believed by the Transpower staff that the GIC hazard was confined to the lower South Island. Evidence that GMD-linked stressed transformers existed in the upper South Island and Taranaki region caused a major rethink and new appreciation of the space weather hazard. Early results from the extreme GMD modeling which identified the Henderson (HEN) substation in Auckland city as having high GIC also helped to break previous misconceptions (that work was eventually published as Mac Manus et al. (2022b)). The research reported here confirms GMD-linked ETHD increases in HEN, indicating transformers in New Zealand's largest city likely has a significant space weather risk. The Mac Manus et al. (2022b) GIC modeling and current ETHD analysis caused Transpower to install DC measuring instruments in the HEN substation. Recent G4-level geomagnetic storms have confirmed the occurrence of significant GIC at HEN, roughly one-quarter of that seen in Dunedin.

Evidence of significant GIC and ETHD increases (i.e., stressed transformers) in HEN suggests the space weather risk can extend significant distances equatorwards, even in a small country with relatively short power lines (when compared with Australia or South Africa, for example). We assume that global locations within these geomagnetic latitude ranges might possibly have high enough GIC to produce transformer saturation and harmonic production, that is, what occurs in New Zealand might happen elsewhere on Earth. Using the International Geomagnetic Reference Field, thirteenth Generation, revised in 2020 (Alken et al., 2021) we have found equivalent locations to HEN elsewhere on Earth to provide wider global context using the online geomagnetic coordinate calculator provided by the British Geological Survey (http://www.geomag.bgs.ac.uk/data_service/models_compass/coord_calc.html). The Henderson substation is located at 36.88° S, 174.63° E in geographic coordinates, which for epoch 2017 has a quasi-dipole latitude = −42.66° and a quasi-dipole longitude = 256.62° ($L = 1.85$). For Europe this is geomagnetically essentially equivalent to the city of Budapest (geographic: 47.50° N, 19.04° E, geomagnetic quasi-dipole: 42.64°, 93.54°), for North America both San Francisco, California (geographic: 37.78° N, 122.42° W, geomagnetic quasi-dipole: 42.82°, 302.63°), and Charleston, South Carolina (geographic: 32.78° N, 79.93° W, geomagnetic quasi-dipole: 42.28°, 355.79°), and for Asia the Russian city of Khabarovsk (geographic: 48.48° N, 135.07° E, geomagnetic quasi-dipole: 42.38°, 208.58°).

7. Summary

Space weather can adversely affect electrical power infrastructure through the generation of GIC and the production of harmonic distortion to the AC waveform generated by half-cycle saturation of transformers. Half-cycle saturation of transformers leads to even order harmonics, and thus investigating Even Total Harmonic Distortion (ETHD) during GMD can provide insights into the impact of space weather on an electrical network.

This is the second study to investigate ETHD occurrence in the New Zealand electrical network. Here we build on the earlier work (Rodger et al., 2020), which primarily focused on a single GMD. We expand that work to analysis ETHD changes across 10 GMD occurring from late 2013 to 2023, looking at ETHD changes monitored at 139 locations across the New Zealand power network. During that time some significant changes occurred in the power network, at locations known to be impacted by space weather: the removal of the HWB single phase transformer T4 in November 2017, and the decommissioning of the NPL substation in December 2019. NPL also contained an earthed single phase transformer. Following the decommissioning of those assets there were dramatic changes in GMD-linked ETHD increases at the HWB substation and also in substations which are within 150–200 km from both HWB and NPL substations. ETHD levels during GMD substantially decrease across the region after the equipment removal. We have identified 5 substations which appear to act as sources for GMD-linked ETHD, four of which are consistent with half cycle saturation by GIC at single phase units, which then propagates into the surrounding network. The nature of the propagation is consistent (i.e., roughly the same

ETHD decay with distance), which should allow future studies to model the propagation of ETHD across the power network in future events.

The analysis undertaken in the current study also shows that ETHD observations are not as simple and direct as was earlier concluded by Rodger et al. (2020). Some ETHD increases appear to occur outside of GMD, and are likely due to unbalanced loads due to poorly installed industrial equipment or electrical train drive systems. During GMD periods we also show evidence of a ETHD source substation which cannot be explained by locally stressed transformers at Robertson Street (ROB) on the West Coast of the South Island. It appears most likely this is due to resonances occurring inside this substation, due to ETHD increases produced elsewhere, Previous modeling studies have identified transformers in substations which are predicted to experience high-GIC during significant GMD. Some of these were locations for which GIC-observations had already identified this, but some were not. Examples of the latter are NPL and HEN, where we find significant ETHD sources, consistent with transformers stressed by GIC. The ETHD analysis in the current study helps independently confirm the extreme storm modeling of Mac Manus et al. (2022b). We have also shown evidence of stressed transformers sited in quite an equatorward location (HEN in Auckland), equivalent to Budapest or San Francisco in the Northern Hemisphere.

Data Availability Statement

Eyrewell magnetometer data availability is described at: https://intermagnet.org/metadata/#/ (select EYR) and https://intermagnet.org/new_data_download.html. The New Zealand LEM DC and harmonic distortion data 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 directly provide the New Zealand LEM DC data, derived GIC observations, or the harmonic distortion data. Requests for access to the measurements need to be made to Transpower New Zealand. At this time the contact point is Michael Dalzell (Michael.Dalzell@transpower.co.nz). We are very grateful for the substantial data access they have provided, noting this can be a challenge in the Space Weather field (Hapgood & Knipp, 2016).

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