# Evaluation of full impact of Carrington – equivalent GMD Event on Power Transformers on New Zealand's Transmission Network

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***Abstract*— GIC flow system studies performed by the "Solar Tsunami" team in New Zealand determined that, under a Reference GMD equivalent to the 1859 Carrington event, transformers on New Zealand's Transmission Power Network (Transpower) would be subjected to levels of GIC that are much higher than those expected for transformers in North America when subjected to NERC's Benchmark GMD. As a result, Transpower requested Hitachi Energy perform an evaluation of the full impact of this Reference GMD on Transpower's fleet of large power transformers. The evaluation included determining the degree of Susceptibility of each of the transformers on the fleet to different effects of GIC, as well as the evaluation of the magnetic and thermal impact of GIC on these transformers. The GIC Susceptibility evaluation showed that all transformers on the fleet would need to be evaluated for the magnetic impact of GIC, while 65% of these transformers would be exposed to thermal impact of GIC. For the magnetic impact, additional VAR Demand and current harmonics were calculated vs. level of GIC. For the thermal evaluation, hot spot temperatures of main windings, Tertiary windings (caused by circulating currents) and structural parts, were calculated for both NERC's Reference GIC signature and the signature recorded by Transpower during May 2024's Gannon GMD. This paper presents results of the full GIC fleet assessment undertaken.**

***Index Terms*—GMD, GIC, Latitude, kV Rating, Soil Conductivity**

## I. Introduction

New Zealand is a mid-latitude country (35-47°S) of two major islands and a long coastline of 9,300 miles. Located on the Pacific "Ring of Fire", it is a seismically active country that needs to plan for various natural hazards including power system impacts from Space weather Geomagnetically Induced Currents (GIC). Transpower is the owner and operator of the high voltage (HV) electricity transmission system and manages 178 substations, approximately 7,000 miles of 66/110/220kV transmission lines, a 400-mile long 1,200 MW HVDC Bi-Pole link, multiple FACTs devices, and a fleet of 455 transformer banks of which 180 are two winding and Auto transformers with High Voltage (HV) wye-connected windings.

In 2001, a transformer at Transpower's Halfway Bush substation, Fig.1, in the South Island city of Dunedin (45° 55'S) failed during a low-level GMD storm [1]. This episode encouraged Transpower to review its understanding of the phenomenon. First indications that Transpower's network may be more exposed were highlighted when reviewing nationwide Revenue Meter Power Quality data from across the country showing a high correlation of even order harmonic production during GMD events. In 2016, the New Zealand Government funded a research program "Solar Tsunamis" to provide sound science basis for the impacts of space weather and enabling the development of an industry-wide response plan to significant solar events. The "Solar Tsunami" team includes subject area experts at Transpower and the University of Otago (UoU), as well as national and international partners. Transpower reviewed GIC Standards, such as NERC TPL007 [2], comparing it to more recent findings and selected a worst-case scenario with magnetic field changes of 4,000 nT/min. This level is equivalent in magnitude to the 1859 Carrington GMD and was chosen as it is consistent with the United Kingdom (UK) range of reasonable worst-case events between 1:100-1:200 years [3]-[5]. This range is considered appropriate to New Zealand as like the UK, it is an island landmass, at similar geomagnetic latitude, and has a long coastline in relation to land area. For comparison, the recently experienced May 2024 "Gannon" storm had observed field changes of 370-420nT/min which is approximately 1/10$^{th}$ of the worst-case GMD event selected by Transpower for the Reference storm. Also, this Reference GMD storm is about 4 times the intensity of NERC's 1-in-a-100-year Benchmark GMD.

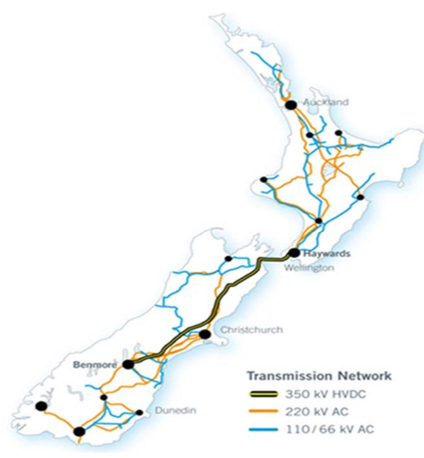


Fig. 1. Transpower Transmission Network

## II. GIC System Flow Studies

The Solar Tsunami team performed GIC System studies to determine the highest levels of GIC that the Transpower transformer fleet would be exposed to under the chosen Reference GMD storm. Table I below presents the 10 highest calculated GIC peak values for transformers on the

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Transpower system. The Table demonstrates the very high levels of GIC that Transpower transformers would be subjected to under the reference GMD. These levels are more than an order of magnitude higher than corresponding transformers subjected to NERC's 1-in-a-100-year Benchmark GMD in North American. This difference is caused by the fact that New Zealand consists of two islands, has special soil electrical conductivity characteristics, and most transmission lines extend North – South vertically for large distances.

Table I
10 highest calculated GIC levels for Transpower Transformers

| **Substation** | **SDN** | **HWB** | **ISL** | **TIW** | **BPT** |
|---|---|---|---|---|---|
| GIC, Amps | 1234 | 852 | 346 | 337 | 308 |
| **Substation** | **TIM** | **NMA** | **SFD** | **OHB** | **TKB** |
| GIC, Amps | 300 | 291 | 290 | 283 | 245 |

The Solar Tsunami team validated the calculated GIC levels, against Transpower's 20 years of archived GIC measurements from 99 transformers at 31 sites [4]-[5]. Upon completing this GIC level validation, Transpower requested the Hitachi GIC team to perform a full GIC assessment of their fleet of power transformers. This assessment and the process undertaken on the Transpower fleet of transformers are presented in sections III – VI of this paper.

## III. Performing GIC Fleet Assessment

The Hitachi Energy process of performing GIC assessment of a fleet of power Transformers involves the following steps:

Step 1: Performing a GIC Susceptibility analysis of the transformers in order to determine which transformers would be susceptible to Magnetic and / or Thermal impact of GIC when exposed to the Reference GMD storm.

Step 2: Performing the Magnetic GIC Assessment of identified transformers

Step 3: Performing the Thermal impact of GIC on main windings and structural parts of identified transformers

Step 4: Performing the Thermal impact of GIC on Tertiary windings of identified Autotransformers

## IV. GIC Susceptibility Analysis

The total GIC Susceptibility of a power transformer to effects of GIC is determined by the combination of the following two types of GIC susceptibilities:

1. Its "Design – based" susceptibility, which defines the degree and magnitude of susceptibility of the individual design to effects of GIC as determined by its electrical and design parameters. In this assessment, the transformers on the fleet are divided into 4 Design Classifications [6], namely, Transformers not susceptible to effects of GIC, Transformers least susceptible to core saturation but susceptible to high magnetizing current, Transformers susceptible to core saturation and possible structural parts overheating, and Transformers susceptible to core saturation, as well as possible damaging Tertiary windings and significant structural parts overheating.

2. Its "GIC – Level" susceptibility, which is based on the expected magnitude of the GIC levels which the transformer would be subjected to under the Reference GMD event. This is determined by factors such as the kV rating of the transformer, the geographic location of the transformer (latitude, altitude, and proximity to large masses of water), the conductivity of the soil where the transformer is located, and configuration of the power system which the transformer is part of. The process of evaluating transformer GIC level-based susceptibility divides transformers into the following 3 exposure categories:

High: ≥ 75 Amps / phase

Medium: > 15 Amps / phase, but < 75 Amps / phase

Low: ≤ 15 Amps per phase

From these two susceptibilities, the "Total GIC susceptibility" of a transformer is determined as described in Reference [6]. As a result of this assessment process, a transformer would belong to one of the following 4 categories of the degree of "Total GIC Susceptibility":

Category I: Transformers that would have practically no, or minimal, susceptibility to effects of GIC, and therefore, no further action needs to be taken.

Category II: Transformers that have a low level of susceptibility to thermal effects of GIC and, thus, only magnetic assessment would need to be performed.

Category III: Transformers that have a medium level of susceptibility to effects of GIC and therefore, both magnetic and thermal assessment of structural parts would be needed.

Category IV: Transformers that have a high level of susceptibility to thermal effects of GIC. For these transformers, both magnetic and thermal impact of GIC on main windings, Tertiary windings, and structural parts would need to be performed.

Table II below presents a summary of the results of the GIC Susceptibility assessment performed on Transpower's fleet of power transformers. The table shows that all transformers on the fleet require GIC Magnetic Assessment while 25 % require GIC Thermal Assessment of main windings & structural parts only, and 45 % of the transformers require assessment of thermal impact of GIC on main windings, tertiary windings, and structural parts.

Table II
Summary of results of the GIC Susceptibility evaluation of Transpower's fleet of Transformers to effects of GIC

| Number of Transformers | Categories of Total GIC Susceptibility | | | | |
|---|---|---|---|---|---|
| | I | II | III | IV | Total |
| Count | 0 | 43 | 31 | 50 | 124 |
| % of Total | 0 % | 35 % | 25 % | 40 % | 100 % |

## V. GIC Magnetic Fleet Assessment

A proper study of the vulnerability of a power system to a GMD event requires accurate information of the GIC flow in the system as well as accurate calculation of the resulting:

1. Additional VAR Demand by transformers on the system, caused by this GIC

2. Current harmonics injected into the power system, by each transformer on the fleet, due to GIC

### A. Calculated Additional VAR Demand

Calculation of the additional VAR Demand, performed for Transpower fleet of transformers, used Hitachi Energy's method of calculations that were developed based on rigorous magnetic modelling of core form and shell form transformers of the full range of kV & MVA ratings, different designs, 1-phase & 3-phase, different core types, etc. [7]. Calculated values of the Additional VAR Demand are presented in Table III below for the 5 transformers on the Transpower fleet with the highest levels of GIC. These values are compared with corresponding values calculated using a simplified method commonly used by the industry [2]. The table shows significant differences between corresponding values of VAR Demand. Also, it was found that the Total VAR Demand for the Transpower system, calculated using the "Hitachi Energy" method, is more than 40 % higher than values calculated by the Simplified method (3032 vs. 2156 MVAR). The simplified method, used by industry, has a number of inaccuracies and significant approximations [7]. Obviously, having more accurate values of the VAR Demand is critical for studying the system vulnerability to GMDs and determining corrective actions.

Table III

Calculated Values of Additional VAR Demand

| Transformer # | Hitachi Energy | Simplified Method |
|---|---|---|
| 1 | 290 | 136 |
| 2 | 176 | 79 |
| 3 | 36 | 110 |
| 4 | 35 | 109 |
| 5 | 21 | 64 |

Finally, it is worth noting that, upon examining GIC signatures recorded at different geographical locations of the different substations on the Transpower System, the highest peaks of GIC occur at different times, Fig. 2. Therefore, highest levels of VAR Demand would not add up and hence, the total VAR Demand on a system would be lower, or much lower, than calculated by adding the highest VAR Demands of all transformers on the System. The same would apply to current harmonics injected into the system by these transformers.

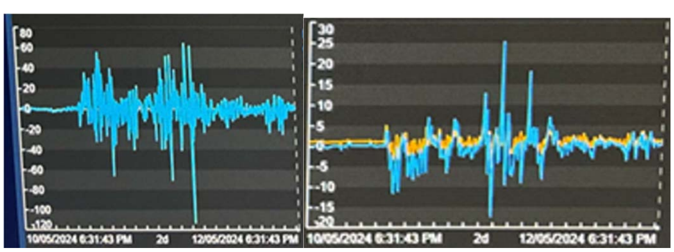



Fig. 2. Times of highest GIC Peaks at 2 different locations

### B. Calculated Current Harmonics

When transformers are subjected to GIC during a GMD event, core saturation results in a very high magnetizing current pulse (one per cycle per phase). The frequency spectrum of this magnetizing current contains both even and odd harmonics. Transformers inject these current harmonics into the power system, which in turn can cause protection relay mis operations, overstress of capacitor banks, electrical resonances, etc., eventually leading to system collapse and blackouts. Calculated values of the first 3 current harmonics are presented in Table IV below, again for the 5 transformers on the Transpower fleet with the highest levels of GIC. The table demonstrates the very high levels of these harmonics. Hence, Power system studies will need to be performed to examine the impact of these current harmonics on the power system and its components.

Table IV

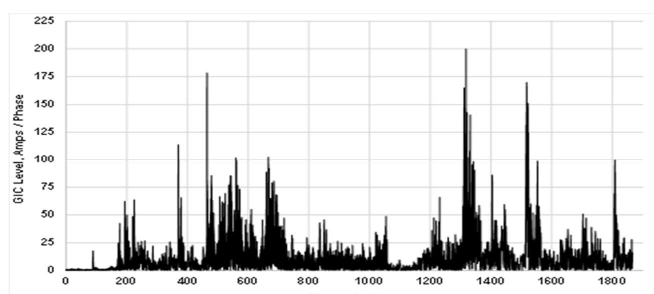
Calculated values of Current harmonics

| Transformer | 2nd harmonic | 3rd harmonic | 4th harmonic |
|---|---|---|---|
| 1 | 516 | 438 | 262 |
| 2 | 309 | 252 | 151 |
| 3 | 194 | 90 | 18 |
| 4 | 192 | 90 | 19 |
| 5 | 149 | 85 | 31 |

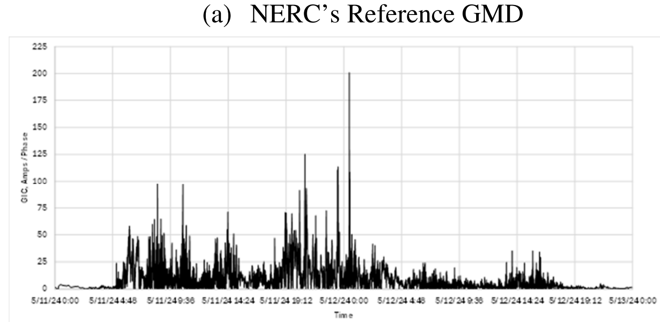
## VI. GIC Thermal Fleet Assessment

### A. Thermal impact of GIC on Main Windings

Table V below presents a summary of the calculated hot-spot temperatures of the High Voltage windings of 4 transformers when subjected to NERC's Reference GIC Signature with GIC peaks corresponding to the Transpower Reference 1-in-a-100 years GMD storm, Fig 3(a). The Table also presents the corresponding hot spot temperatures when these transformers are subjected to the GIC Signature measured on these transformers during May 2024 Gannon GMD but with the GIC levels again corresponding to the Transpower Reference GMD event, Fig 3(b). In all of these calculations, the transformers were assumed to be operating at full load at the time it is subjected to GIC.




(a) NERC's Reference GMD



(b) Gannon GMD

Fig. 3. GIC Signatures used in the GIC Thermal Calculations

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The table shows that, in general, the winding hot spot temperatures are below the allowed temperatures under GMD scenarios [8]. Some of the transformers experience higher temperatures with the NERC Signature and some with the Gannon Signature.

Table V
Calculated hot spot temperatures of HV windings

| Transformer | NERC Signature | Gannon Signature |
|---|---|---|
| 1 | 112 | 154 |
| 2 | 129 | 118 |
| 3 | 115 | 119 |
| 4 | 167 | 151 |

### *B. Thermal impact of GIC on Tertiary Windings*

Previous studies performed on the thermal impact of GIC on power Transformers have shown that the thermal impact on Tertiary windings is very different in nature [9]. Therefore, it would require special magnetic modelling to determine magnitudes and wave shapes of circulating currents developing in Tertiary windings as a consequence of core saturation of one phase at a time at different times on the cycle caused by GIC.

Fig. 4 below presents an example of calculated wave-shape of the circulating current developing in the tertiary winding of a transformer that has the 3-limb core type. The circulating 3-phase current is characterized by high peak pulses, 3 per cycle. This current causes additional losses in the windings. If sufficiently high, it could result in damaging winding overheating in low MVA rating Tertiary windings.

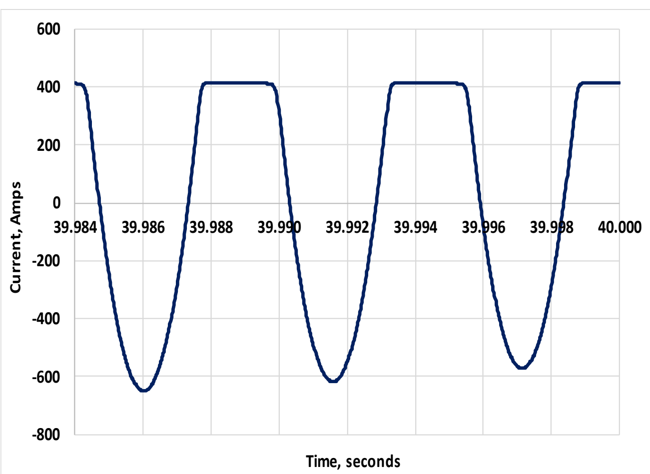


Fig. 4. Calculated waveshape of circulating current developing in the tertiary winding of a Power Transformer

Calculations showed that the majority of Transpower's fleet of transformers, would not experience large increases in Tertiary winding hot spot temperature. The highest temperatures observed were for a 150 MVA Autotransformer located on the South Island. Calculated hot spot temperature is shown in Fig. 5 below and shows a maximum temperature of 131.4 °C which is a temperature increase of 29.2 K due to GIC and is again much lower than the temperature allowed (160 °C) by the IEEE GMD Guide for windings of power transformers subjected to GIC [8].

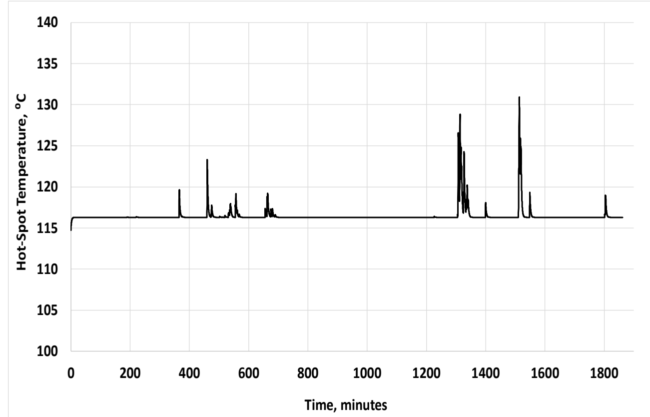


Fig. 5. Calculated hot Spot Temperature of the Tertiary winding of a 220 kV / 150 MVA 3-Phase transformer

### *C. Thermal impact of GIC on Structural Parts*

GIC thermal assessment of Transpower's transformers was performed using Hitachi Energy's Universal GIC Thermal models. These models were developed using results of detailed non-linear magnetic circuit modelling of over sixty 1-Phase and 3-Phase Core Form Transformers of different types (GSU, Autos, and non-Autos), all different core types, and different combinations of MVA & kV Ratings. A normalization technique, that is based on the physics of how transformer parameters impact the thermal response of transformers to GIC, was the tool used to develop the final form of these Universal GIC Thermal Models. These include models for the following parameters for Flitch plates (Tie Plates):

- Steady State Thermal Gradient, Time Constant, and hot spot temperature
- For 3-phase Core Form Transformers with the 3-limb core type, GIC level that causes core saturation, referred to as "Ics".

The thermal calculations were performed for 119 transformers / transformer banks on the fleet when these transformers are subjected to NERC's Reference GIC signature with values of highest peak GIC pulse that each of these transformers are expected to be exposed to under the 1-in-100-year Transpower Reference GMD event. Fig. 6 below presents calculated hot spot temperatures of structural parts of the Power Transformer Bank at Halfway Bush, which is susceptible to the second highest level of GIC in the Transpower system. The figure shows very high levels of hot spot temperatures beyond what is allowed under GMD scenarios.

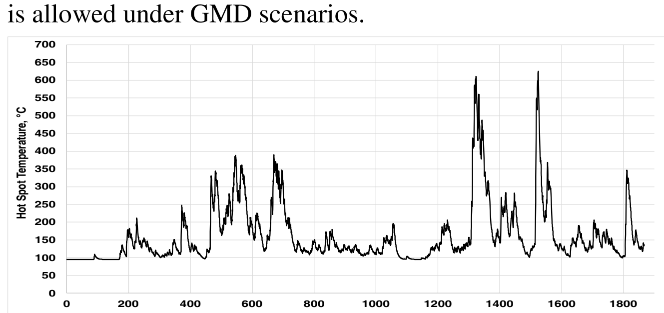


Fig. 6. Calculated GIC Thermal impact on Power Transformers at Halfway Bush

Fig. 7 presents calculated structural parts hot spot temperatures (for 27 transformers / transformer banks on the Transpower system) exceeding the allowed 200 °C when subjected to GIC. The data shows the following:

- 13 of the 27 transformers have structural parts hot spot temperatures that exceed the 200 °C limit by a few 10's of degrees. For these, the short duration of these temperatures should not cause any significant degradation of the transformer insulation and therefore do not represent an increase of risk of a dielectric failure.
- 12 of the 27 transformers have structural parts hot spot temperatures that exceed the 200 °C limit by more than a few 10's of degrees. Even with the short duration of these temperatures, these transformers would experience some degradation of their insulation and could be at some risk of dielectric failure under the Transpower Reference GMD Storm used in the calculations of the GIC levels.
- 2 transformers have calculated hot spot temperatures that would cause the production of significant oil bubbles, that could cause catastrophic dielectric failure of these units. To mitigate this from happening, these 2 units would definitely require a GIC Blocking device to eliminate the thermal impact of these currents. As stated earlier, such high levels of GIC would result in very high winding hot spot temperatures, and a high risk of these transformers experiencing damaging winding overheating and subsequent failure. Alternatively, these two transformers could be taken out of service in case a major GMD event is expected.

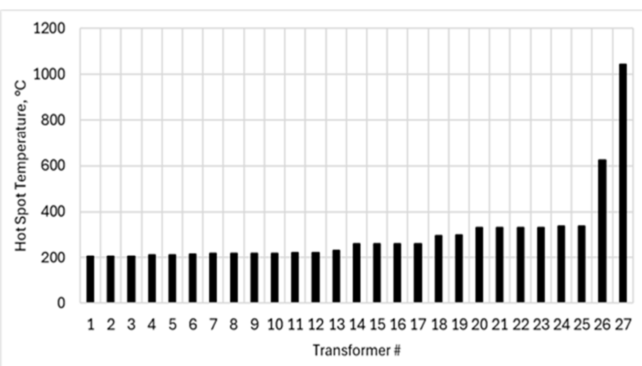


Fig. 7. Calculated highest structural parts hot spot temperatures

## VII. Acknowledgment

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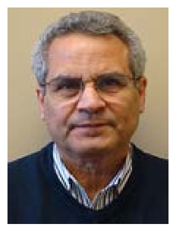
## IX. Biographies



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