Assessment of GIC based on transfer function analysis

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Key Points:

- Transfer functions relating GIC measured at New Zealand substations to magnetic field variations at Eyrewell observatory are calculated
- Calculated transfer functions are able to accurately reproduce observed GIC during magnetic storms
- The GIC to be expected during a storm of the magnitude of the Carrington Event are estimated

Abstract

Transfer functions are calculated for periods between 2 and 1000 minutes between geomagnetically induced currents (GIC) measured at three transformers in the South Island of New Zealand and variations in the horizontal components of the geomagnetic field measured at the Eyrewell Observatory near Christchurch. Using an inverse Fourier Transform, the transfer functions allow the GIC expected in these transformers to be estimated for any variation of the inducing magnetic field. Comparison of the predicted GIC with measured GIC for individual geomagnetic storms shows remarkable agreement, although the lack of high frequency measurements of GIC and the need for interpolation of the measurements leads to a degree of underestimation of the peak GIC magnitude. An approximate correction for this is suggested. Calculation of the GIC for a magnetic storm in November 2001 which led to the failure of a transformer in Dunedin suggests that peak GIC were as large as about 80 A. Use of spectral scaling to estimate the likely GIC associated with a geomagnetic storm of the magnitude of the 1859 Carrington Event indicate that GIC of at least 10 times this magnitude may occur at some locations. Although the impact of changes to the transmission network on calculated transfer functions remains to be explored, it is suggested that the use of this technique may provide a useful check on estimates of GIC produced by other methods such as thin-sheet modelling.

Plain Language Summary

Rapid changes in Earth's magnetic field, such as occur during a magnetic storm, induce electric currents in the ground. These currents, known as geomagnetically induced currents (GIC), are able to enter a power transmission network through the ground connection of a substation transformer. Not only can such currents cause damage to transformers, but in extreme situations they may cause failure of the entire power transmission network. We relate measurements of GIC in the New Zealand power transmission network to variations in the magnetic field at a local magnetic observatory. This allows us to construct mathematical relationships between GIC and magnetic field variations which enable us to predict the magnitude of GIC that might occur in the event of a magnetic storm such as the so-called Carrington Event of 1859 – the largest such storm ever recorded. It is found that GIC of almost 1000 A might occur.

1 Introduction

The risk to electrical transmission networks posed by geomagnetically induced currents (GIC) is well known. GIC can lead to major damage both to individual transformers and to networks as a whole. The most significant such damage was that caused during a geomagnetic storm in March 1989 which resulted in the complete collapse of the Quebec hydroelectric transmission system [*Boteler*, 1994; *Bolduc*, 2002]. However, GIC have also been observed in low-geomagnetic latitude countries such as Australia [*Marshall et al.*, 2013], Brazil [*Trivedi et al.*, 2007], China [*Liu et al.*, 2009], New Zealand [*Marshall et al.*, 2012], South Africa [*Gaunt and Coetzee*, 2007], Spain [*Torta et al.*, 2012], and the United Kingdom [*Beamish et al.*, 2002], The most intense geomagnetic storm ever recorded was the so-called Carrington Event of 1-2 September 1859 resulting from the direct impact of coronal mass ejection (CME) plasma on Earth's magnetosphere. Geomagnetic storms of this magnitude are rare - although a similar magnitude CME occurred on 23 July 2012 it did not impact on Earth [*Baker et al.*, 2013]. Nevertheless the potential for an event such as the Carrington Event remains and with the increasing complexity and connectivity of transmission grids the ability to understand, predict and mitigate GIC becomes increasingly important.

A common approach to appraising the threat posed by GIC to an individual transmission network involves using the thin-sheet approach of *Vasseur and Weidelt* [1977] to model the electric fields induced at the surface of the Earth by geomagnetic variations. These are then in turn used as input into a model of the electric transmission network to calculate the resulting GIC. This method has been used to study GIC in France [*Kelly et al.*, 2016], Ireland [*Blake et al.*, 2016] and the UK [*Mackay*, 2003], as well as being recently applied in New Zealand [*Divett et al.*, 2017]. Although such modelling has the potential to allow investigation of mitigation strategies by testing the effect of modifications to the transmission network on GIC, it also has significant drawbacks. These primarily centre on the limitations on the validity of the thin-sheet modelling which not only restricts the period range of geomagnetic variations for which such calculations can be made, but also the spatial resolution that can be achieved. The construction of the thin-sheet model also requires a detailed model of the near-surface electrical conductivity of the region under study and its spatial variation. Information on the conductivity structure comes in general from a compilation of magnetotelluric (MT) measurements and information on local geological and tectonic structure.

MT measurements themselves, which relate the induced electric field to the time varying magnetic field, can also be used to directly predict the electric fields resulting from any geomagnetic variation. This approach is that being pursued by EarthScope [Bonner and Schultz, 2017], and a methodology for incorporating MT measurements into real time GIC prediction has recently been presented by *Kelbert et al.* [2017]. However, as the authors point out, the application of this to a complete transmission system requires not only a dense array of such measurements but also a model of the transmission network.

In this paper we present an alternative technique which allows the direct prediction of expected GIC at an individual location. This is based on a transfer function analysis of how measured GIC relate to recorded geomagnetic variations at a nearby geomagnetic observatory. As such it is dependent on the availability of a historic record of measured GIC. Also, as it applies to individual locations/transformers in a transmission network, it cannot be used to investigate GIC mitigation strategies. It does, however, allow the magnitude of GIC at individual locations of a network to be assessed and therefore provides an important tool in identifying those parts of a transmission network which are most at risk from GIC. New Zealand is fortunate in that Transpower New Zealand Ltd., who manage the national transmission network, have over many years monitored GIC at various substations, and in individual transformers, from measurements made by Hall effect current monitors (LEMs). These measurements provide a significant, and almost unique, database [Mac Manus et al., 2017] which allows for such a transfer function analysis. In what follows we first introduce the theory behind the transfer function analysis, before presenting the results of calculations of transfer functions between GIC at New Zealand substations in the lower part of the South Island and the horizontal components of the geomagnetic field as measured at the Eyrewell geomagnetic observatory. These transfer functions are then used to predict the GIC for a geomagnetic storm which occurred in 2014 and the predictions are compared to actual measurements. To account for apparent underestimation of GIC by the technique a possible correction is suggested after which the technique is used to predict the GIC for a storm in November 2001 during which transformer damage was actually observed. We also assess the likely magnitude of GIC from an event of similar magnitude to the Carrington Event, and finish with a discussion of the potential usefulness and limitations of the transfer function technique.

2 GIC Transfer function analysis

The approach taken is essentially the same as that taken by *Ingham* [1993] who investigated the corrosion risk to a natural gas pipeline by calculating transfer functions between the current produced in a synthetic leak in the pipe coating and the locally measured magnetic field variations. An estimate of the likelihood of sufficiently strong magnetic activity then permitted an estimate to be made of the probability of corrosion occurring should there be a break in the coating.

In the present case, mathematically, the GIC produced in an individual transformer of the power network can be regarded as the convolution of the time varying geomagnetic field with an impulse response function which represents a combination of the induction of electric fields in the conducting Earth by the changing magnetic field, and the manner in which these interact with the power transmission network. This is illustrated in Figure 1. In general, at mid-latitudes, it can be assumed that the electric fields are induced by the northwards (X) and eastwards (Y) horizontal components of the geomagnetic field and thus, following Fourier Transformation of time series of GIC and magnetic fields, in the frequency domain this relationship may be expressed as

$$C = AX + BY \tag{1}$$

where C, representing the GIC, X and Y the geomagnetic field components, and A and B the transfer functions, are all functions of frequency. Such a relationship is of the same kind as is used in geomagnetic induction studies to relate variations in the vertical component of the geomagnetic field to those in the horizontal components [*Unsworth*, 2007], and also in MT to relate a horizontal component of the electric field to the magnetic field. In this case A and B are elements of the impedance tensor. Although induction is a result of time variations in the magnetic field, considering a single angular frequency of variation it is simple to demonstrate that equation (1) is equivalent to a similar relationship between GIC and the rate of change of the fields

$$C = G \, dX/dt + H \, dYdt \tag{2}$$

in which the real and imaginary parts of the transfer functions *G* and *H* are related to those of *A* and *B* by $G_r = A_i/\omega$, $G_i = -A_r/\omega$, $H_r = B_i/\omega$, and $H_i = -B_r/\omega$, where ω is the angular frequency of the variation, and the subscripts *r* and *i* refer to real and imaginary parts of the transfer functions.

Calculation of the transfer functions A and B requires Fourier Transformation of simultaneous time series of GIC and the geomagnetic field and calculation from these of auto and cross-power spectra. When such spectra are averaged over a number of such time series the transfer functions can be calculated as

$$A = \frac{\langle CX^* \rangle \langle YY^* \rangle - \langle CY^* \rangle \langle YX^* \rangle}{\langle XX^* \rangle \langle YY^* \rangle - \langle XY^* \rangle \langle YX^* \rangle}$$
(3a)
$$B = \frac{\langle CY^* \rangle \langle XX^* \rangle - \langle CX^* \rangle \langle XY^* \rangle}{\langle XX^* \rangle \langle YY^* \rangle - \langle XY^* \rangle \langle YX^* \rangle}$$
(3b)

where $\langle XX^* \rangle$ represents an average autopower (in this case of X) and $\langle XY^* \rangle$ is an average cross-power (in this case between X and Y), the star representing a complex conjugate.

Once estimates of A and B have been obtained for a transformer or substation then for any time variation of the geomagnetic field they can be used to calculate the expected resulting GIC. This is done by using equation (1) to firstly calculate the expected frequency variation of GIC from the calculated transfer functions and the Fourier Transform of the geomagnetic field. Inverse Fourier Transformation of C then gives the expected time varying GIC.

A major question concerning the applicability of the calculated transfer functions is their robustness with respect to changes in the transmission network. This is discussed in more detail later, but for the following analyses it is assumed that the calculated transfer functions remain stable with time

3 Calculation of transfer functions

In the thin-sheet analysis of GIC in New Zealand's South Island presented by *Divett et al.* [2017] the southernmost part of the South Island, that closest to the auroral region, is also that for which the model of near surface conductance has the largest uncertainty. Therefore, as an example of the calculation of transfer functions and their ability to predict GIC, we concentrate on substations in this region. Initially GIC in transformer #2 at the South Dunedin (SDN) substation measured during a 10 day period from 13-22 March 2015 have been used in association with the measured geomagnetic field variations at the New Zealand geomagnetic observatory at Eyrewell near Christchurch. This time span includes the St Patrick's Day magnetic storm of 17-18 March 2015 – the most significant storm of that year. The locations of Eyrewell (EYR), SDN and other substations used in this study are given in Figure 2 which shows a map of the Transpower network in the South Island of New Zealand.

The observatory data used those available from INTERMAGNET are (http://www.intermagnet.org/) at a sampling interval of 1 minute. A detailed description of the New Zealand GIC observations can be found in Mac Manus et al. [2017]. The GIC recorded have a variable sampling rate that is generally some 10 s of seconds. However, during periods when the current is changing rapidly the sampling rate increases to approximately one sample every 4 seconds. Although more rapid variations of the geomagnetic field are likely to lead to larger magnitude GIC, the lack of a higher sampling rate outside of short limited periods of time means that for the transfer function analysis undertaken below the GIC data have been linearly interpolated to a 1 minute sampling. The effect of this on the calculated transfer functions and the ability to accurately predict GIC is discussed later. The magnetic observatory data (X and Y components) and the interpolated SDN GIC for this 10 day period are shown in Figure 3. Even on the scale shown in Figure 3 the visual correlation between the measured GIC and the horizontal magnetic field is striking, with the sudden storm commencement, clearly visible in X on 17 March, producing a peak GIC of around -15 A. (Note that the implication of the sign of the GIC – current into or out of the transformer – is unknown, but from the point of view of the risk posed the sign is unimportant.)

The GIC, X and Y time series shown in Figure 3 have been Fourier Transformed in 13 data sections each of 2048 points with a 50% overlap between adjacent sections. Each data section thus covers a period of just less than 1.5 days. Not only does this duration generally cover both the onset and main phase of a geomagnetic storm, it also allows transfer functions to be calculated to around 100 minutes period. Although such long period variations may not be important in inducing significant GIC, they do fall in the period range of variations that can be successfully modelled using the thin-sheet approach, and are therefore potentially useful in

comparing the results of the two techniques. Data in each section were de-trended and reduced to zero mean before Fourier Transformation. For each data section band averaging was carried out in the frequency domain to give estimates of auto and cross-powers at 13 frequencies, equally spaced on a logarithmic scale, and these estimates were then averaged over all data sections and used, as in equations (3a) and (3b), to give estimates of the transfer functions A and B. The resulting variations with period (in minutes) of the real and imaginary parts of A and B for SDN are shown in Figure 4.

As is shown in Figure 4, although the real and imaginary parts of the transfer functions suggest a smooth variation with period, there is considerable scatter in the values. This is particularly true for the imaginary parts of both A and B which are significantly smaller than the corresponding real parts. Given no major changes in the transmission network which might effect the relationship between GIC and the measured magnetic field, much improved estimates of the transfer functions can be obtained from carrying out the same procedure for a number of 10 day data sections and averaging the results. This has been done using 10 day data series covering the 10 most significant geomagnetic storms in 2015 as listed by <u>www.spaceweatherlive.com</u>. The significance of the storms is based on the Ap-index, which gives a measure of the geomagnetic field recorded at EYR for these storms are shown in Figure 5 and the times and dates of the data series used are listed in Table 1. The final averaged estimates of transfer functions A and B, with associated standard deviations, not only for transformer #2 at SDN, but also for transformer #5 at Invercargill (INV) and transformer #3 at Manapouri (MAN) are shown in Figure 6.

It is clear from Figure 6 that there are considerable differences in the transfer functions for the different locations. At SDN the real parts of both A (A_r) and B (B_r) are negative and become increasingly so at shorter period, whereas at both INV and MAN these parts of the transfer functions are both much smaller and, in general, tend to be positive. In terms of the direction of GIC at all three locations, this is in agreement with the results shown by Divett et al. [2017] based on thin-sheet modelling and the interaction of induced electric fields and the actual transmission network. That study suggested that, for field variations of 10 minutes period, the direction of GIC at SDN, on the east coast of the South Island, was opposite to that observed at INV and MAN on the south and west coasts respectively. As they do at SDN, the magnitude of both A_r and B_r at both INV and MAN tend to increase at shorter periods suggesting that at all three locations the availability of higher time resolution in the data would show that higher frequency geomagnetic variations are also instrumental in producing significant GIC. In contrast the imaginary parts of A (A_i) and B (B_i) at all three locations show a maximum in magnitude somewhere in the period range 3-10 minutes. At INV and MAN A_i and B_i are both very small, whereas at SDN the minima of around -0.1 to -0.2 A/nT is of comparable magnitude to the real parts of *A* and *B*.

The responsiveness of GIC to the orientation of the variations in the magnetic field is illustrated in Figure 7 which shows, for different periods of variation of the magnetic field, polar plots of the total magnitude of GIC produced by an assumed 100 nT variation in field oriented in different directions. Whereas *Torta et al.* [2014] suggested that the orientation of transmission lines relative to the induced electric fields is important in determining the magnitude of GIC, Figure 7 is in agreement with the thin-sheet modelling results of *Divett et al.* [2017] in showing that the largest GIC in the South Island of New Zealand are produced when the orientation of the geomagnetic field variations broadly aligns with the overall SW-NE geological trend of New Zealand associated with its location on the boundary of the Australian and Pacific tectonic plates.. For field variations of 2.1 minute period in this orientation, in response to a field variation of 100 nT GIC of nearly 40 A can be expected at SDN, while up to 10 A and 5 A can be expected at INV and MAN respectively. These magnitudes differ, however, from those found for a period of 10 minutes by *Divett et al.* [2017] whose results suggested smaller GIC at SDN than at either INV or MAN. Although these differences may well reflect the acknowledged uncertainty in the conductance model in the lower part of the South Island, they may well be partly explained by the fact that the largest GIC are clearly associated with much more rapid variations of the magnetic field than 600 seconds period.

4 Modelling of GIC

In principle, as is outlined above, the estimates of A and B for a particular transformer or substation can be used to calculate the GIC which will be observed due to any actual or hypothetical variation in the geomagnetic field. Following the same procedure as used in calculating transfer functions, a 2048 minute window of X and Y data are de-trended and reduced to zero mean before being Fourier Transformed. The transfer functions for the desired location, having been calculated only at 13 discrete periods, are fit by polynomials (e.g. for SDN with degree 5 polynomials for A_r , B_r and B_i , and degree 6 for A_i) which best replicate the smooth variations of the transfer functions. These fits are shown in Figure 6. Equation (1) is then used to calculate the expected GIC as a function of frequency of variation, C(f). Inverse Fourier Transformation of C(f) then yields the expected time variation in GIC for the time window in question.

As an example the variations in X and Y observed at EYR between 1200 UT 12 September 2014 and 2207 UT 13 September 2014 have been used. This 2048 minute time period encompasses a magnetic storm for which the decrease in X during the main phase was about 100 nT and followed a rapid increase in X, associated with the sudden storm commencement, of about 40 nT. Shown in Figure 8 are both, the measured GIC at SDN (middle panel), interpolated to 1 minute sampling as outlined above, and the GIC predicted from the transfer functions (upper panel). Visually, although the GIC predicted by equation (1) give an excellent reproduction of the actually observed temporal variation in GIC, it is apparent that the predicted GIC is generally smaller than that observed, with high frequency variations being particularly muted. These differences partly result from the interpolation of the irregularly sampled GIC data to a one minute sampling interval during the calculation of the transfer functions. However, the sampling interval of 1 minute also means that the shortest period variation that can be reconstructed is one of 2 minutes period, thus more rapid variations than this cannot be modelled. The effect of interpolation is illustrated for a simple case in Figure 9(a) which shows how linear interpolation of the non-uniform sampling of GIC (open circles) to a one minute sampling interval (grey squares) reduces the amplitude of high frequency variations in current which occur between 50 and 51 minutes. The use of multiple interpolated sequences in the calculation of the transfer functions consequently persistently underestimates the magnitude of rapid variations in GIC.

Objective assessments of how well the predicted GIC match the measurements are given by the correlation coefficient (ρ) and the performance parameter *P* defined by *Torta et al.* [2014, 2017] and *Marsal et al.* [2017]. The calculated correlation coefficient between the predicted and measured GIC for the example shown in Figure 8 is 0.813. However, as discussed by *Torta et al.* [2017], the same value of ρ will result from predicted values which are either scaled by a

constant factor or shifted by a constant value. In contrast P allows for predicted and measured values to have different standard deviations and means. P is defined as

$$P = 1 - \frac{1}{\sigma_m} \sqrt{\frac{\sum [(m_i - \overline{m}) - (p_i - \overline{p})]^2}{N}}$$
(4)

where m_i and p_i are the measured and predicted values of GIC respectively, with mean values of \overline{m} and \overline{p} . The summation is over the entire time series of N points, and σ_m is the standard deviation of the measured values. The value of P calculated for the measured and predicted GIC shown in Figure 8 is 0.37. By way of comparison, *Torta et al.* [2017] found values of between 0.45 and 0.68 for predictions of low amplitude GIC in a transformer at Vandellòs in Spain, based on the magnetotelluric impedance tensor. However, calculations of P for 256 minute subsections of the time series shown in Figure 8 yield higher values, comparable with that found by *Torta et al.* [2017], of between 0.40 and 0.60, for the first 1280 minutes of the time series when GIC variations are more significant. Lower values of P are found for the much quieter period between about 1200 and 1800 minutes. It can be concluded therefore that, notwithstanding the underestimation of values, for periods of significant GIC activity both the correlation coefficient and the performance parameter indicate that the use of transfer functions gives a good prediction of the expected GIC.

The systematic underestimation of GIC can be partially corrected for by taking a series of 2048 point data sections and, after using the calculated transfer functions to predict the GIC, plotting the measured GIC against the predicted values. This allows a mathematical relationship between them to be calculated. As an example, for SDN this has been done by using 2048 minute data sections from four further geomagnetic storms from 2013, listed in Table 2. Shown in Figure 9(b) is a plot of the measured GIC from these storms against the GIC predicted by the transfer function analysis. As was apparent from the GIC predicted for the 12-13 September 2014 storm, although low amplitude GIC are very well predicted, the transfer function analysis tends to underestimate the magnitude of GIC when these are larger than about 10 A. Such large GIC are typically associated with much more rapid field variations. A fit to the data shown in Figure 9(b), which gives a satisfactory fit to the data in the range of predicted GIC of -10 to +10 A, is given by a third degree polynomial relating the measured GIC (C_M) to the predicted GIC (C_P)

$$C_M = 0.002798C_P{}^3 + 0.03066C_P{}^2 + 1.237C_P + 0.1093$$
(5)

This fit has a value of R^2 of 0.726. Linear or quadratic fits noticeably underestimate the relationship between measured and predicted GIC for positive values of predicted GIC, while higher degree polynomials give negligible improvement in the fit. Nevertheless, it is apparent that there are relatively few data which are fitted which have either predicted or measured GIC outside the range of $-5 \leq \text{GIC} \leq +5 \text{ A}$.

This is largely a consequence of the absence of significant geomagnetic storms during solar cycle 24 and the fact that GIC measurements at SDN, INV, and MAN only commenced in 2012 or 2013, precluding the use of more significant storms in the calculation of the transfer functions. As a result the use of (5) outside the range of predicted GIC of -10 to +10 A may be highly inaccurate. Therefore, to avoid overestimating corrected GIC outside this range a conservative approach is to use the gradient of the fit and the value at $C_P = -15$ A and use linear extrapolation to estimate a correction to C_P for $C_P < -15$ A. A similar approach can be used to estimate a correction to C_P for values over +10 A. Although this is, admittedly, somewhat arbitrary, it does

serve to give potentially useful estimates of the maximum GIC that might be expected in given, or hypothesized, magnetic storms. Thus, an overall estimate correction for all predicted GIC values is given by

$$2.206C_{P} + 12.1 \qquad C_{P} < -15A$$

$$GIC_{corr} = 0.002798C_{P}^{-3} + 0.03066C_{P}^{-2} + 1.237C_{P} + 0.1093 \qquad -15A \le C_{P} \le 10A \qquad (6)$$

$$2.69C_{P} - 8.6 \qquad C_{P} > 10A$$

Applying this correction to the GIC predicted for the data from 12-13 September 2014 gives the result shown in the lower panel of Figure 8. Although there is some improvement in the match between the predicted GIC and the measured GIC, particularly in the large initial GIC associated with the sudden storm commencement and around t = 600 minutes, there is still a general underestimation of the magnitude of the GIC, particularly in regions where there are rapid variations, which can be attributed to the Nyquist cut-off. Over the entire 2048 point time series the performance parameter P (equation (4)) shows little improvement. However, for shorter time segments over the first 1280 minutes, where GIC are larger, it does improve significantly yielding values of up to 0.65, thus lending some validity to the correction.

5 GIC due to major storms

Having established the ability of transfer function analysis to give a good reproduction of observed GIC, it is of interest to look at the GIC expected to have been produced in historical magnetic storms. Within New Zealand the most significant incident of damage caused by GIC was during a magnetic storm on 6 November 2001. During this storm a transformer at the Halfway Bush (HWB) substation near Dunedin suffered a major internal flashover. Additionally alarms sounded at many other locations in the power network and a transformer in Christchurch went offline. This storm and the New Zealand impact has been discussed qualitatively in the scientific literature [*Béland and Small*, 2004], and was subsequently analysed in detail [*Marshall et al.*, 2012; *Mac Manus et al.*, 2017]. Given the close proximity of HWB to SDN the transfer functions for the two locations are expected to be broadly similar and therefore the GIC predicted at SDN during this storm may be taken as a guide to the GIC that actually occurred at HWB. However, implicit in such a calculation is an assumption that there were no major changes to the power transmission network between 2001 and 2015 which might result in changes to the transfer functions relating GIC to the magnetic field between the two dates.

The variations in X and Y measured at EYR over the time span 1700 UT 05 November to 0307 UT 07 November 2001 are shown in Figure 10. The storm initiated at 0153 UT 06 November with a rapid increase in X of about 200 nT which was followed by 2 to 3 hours of longer period field variations in both X and Y. The calculated GIC for SDN are also shown in Figure 10 and show a maximum GIC of about 40 A, in the negative sense, associated with the sudden storm commencement. The substorm activity following the onset of the storm produces variations in GIC between -15 and +10 A. Notwithstanding the limitations in the approximation for large magnitude GIC inherent in equation (4), the GIC predicted after this correction are also shown in Figure 10. The correction suggests that the maximum magnitude of GIC at the onset of the storm may well have been up to about 80 A. Allowing for the fact that the shortest period variation represented is 2 minutes it is likely that the peak GIC may well have been significantly larger than this. Subsequent variations in GIC between ± 20 A occur at periods of between 5 and 10 minutes.

Winter et al. [2017] have recently used a spectral scaling technique to estimate typical magnetic field variations at the Hartland (UK) observatory which might be associated with a magnetic storm comparable in magnitude to the Carrington Event of 1859. They used their derived field variations in association with electrical conductivity models for the UK to then estimate the likely variations in induced electric field which might drive GIC. This showed peak electric fields of up to 20 V/km. The use of transfer functions allows a similar approach to be used to give estimates of the size of GIC that might be produced by such an event. *Cid et al.* [2015] have identified the total horizontal magnetic field variation at the Tihany (THY) observatory in Hungary during a storm on 29-30 October 2003 as being very similar in form to those observed at Colaba (Bombay) during the Carrington Event itself. Colaba was the only record of field variations during the Carrington Event for which the magnetored id not saturate. To estimate GIC likely to occur during an event of this magnitude we have therefore taken the 1 minute sampled EYR horizontal field variations over a period of 2048 minutes from 0000 UT 29 October 2003 as a suitable magnetic record to which to apply the spectral scaling technique of *Winter et al.* [2017].

The first stage in such an analysis is to estimate, using a range of recent geomagnetic storms how the spectral power (P) in the horizontal field variations at EYR depends upon the period of variation (T) and the minimum value of *Dst* [*Winter et al.*, 2017]. Using the same storms as quoted by Winter et al. and fitting the log of spectral power as a afunction of the log of T and *Dst* yields the result

$$\log P = 2.1612\log T - 0.004121Dst_{\min} - 4.659$$
⁽⁵⁾

This allows the EYR power spectrum for the event in 2003 for which $Dst_{min} = -383$ nT to be scaled to an event of the size of the Carrington Event for which the estimated Dst_{min} was about - 1000 nT. The power spectrum for EYR is then further scaled by the ratio P_{EYR}/P_{ABG} for an event of $Dst_{min} = -1000$ nT, where P_{ABG} is the dependence of spectral power on T and Dst_{min} calculated for the modern day Bombay observatory at Alibag. The square root of the overall scaling as a function of period is applied to both the X and Y spectra for the 2003 storm and these are then used, as in equation (1), followed by application of an inverse Fourier Transform, to calculate the expected GIC. The results of this, without any correction as in (4), are shown for SDN, INV, and MAN in Figure 11.

It is apparent that, even allowing for the absence of shorter period field variations than 2 minutes, the expected GIC for an event of Carrington level are far in excess of anything that has actually been measured, or even predicted for the 2001 storm during which transformer failure occurred at HWB. The maximum magnitude of GIC predicted for SDN is in excess of 800 A, with considerable variations in the range of -500 to +500 A. At INV and MAN where GIC are typically measured to be much lower than those observed at SDN, peak GIC of about 200 and 100 A respectively are predicted.

Rodger et al. [2017] have given predictions for GIC at HWB during extreme storms by extrapolating relationships between the rate of change of the horizontal magnetic field at EYR (dH/dt) with GIC measured during a range of geomagnetic storms from 2001-2013. For example, the observed maximum rate of change, to 1 minute temporal resolution, of the horizontal field at EYR during a storm on 2 October 2013 was 85.6 nT/min, and this produced a measured peak GIC of 48.8 A. The maximum value dH/dt during the 6 November 2001 storm is quoted by *Rodger et al.* [2017] as 190.8 nT/min and this is consistent with giving a GIC of possibly larger

than 80 A as is predicted by the transfer function analysis. *Thomson et al.* [2011] estimated that at geomagnetic latitudes of 55-60° the maximum value for dH/dt for a storm of Carrington Event magnitude is of the order of several 1000 nT/min. Extrapolating their analysis to this rate of change *Rodger et al.* [2017] predicted peak GIC of at least up to 1000 A, again consistent with the estimates given for SDN by the transfer function analysis.

6 Discussion

The prediction of GIC using transfer functions calculated from measurements of GIC and magnetic observatory records during magnetic storms appears to give quite accurate reproductions of the measured currents. As such it is a powerful technique which, in association with other methods, can be used to identify the risk to individual substations and transformers from GIC during major geomagnetic events. An advantage of the method is that it does not require a knowledge of either the electrical conductivity structure of the region in which it is being applied, or of the actual power transmission network. To this extent it removes areas of uncertainty associated with the representation of these features.

There are, however, both weaknesses and uncertainties in the method. One weakness lies in the fact that most measurements of GIC which can be used in the calculation of transfer functions are recent and, furthermore, are during solar cycle 24 when there have been few geomagnetic storms which have produced large GIC. This introduces a level of uncertainty into how well the method will predict GIC resulting from large storms. This is compounded, at least in the data considered here, by the non-uniform and relatively large sampling interval which is used for measurement of GIC. As discussed above, this not only restricts the shortest period for which transfer functions can be calculated, but even at shortest period has a tendency to underestimate the magnitude of GIC. Although a correction for this underestimation can be applied it is acknowledged that it is, at best, only a rough approximation.

More significant is the unknown aspect of how changes to the transmission network will affect the calculated transfer functions. For individual transformers the grounding resistance is generally kept as low as possible and minor changes at transformer level are therefore likely to have an insignificant impact on the calculation of transfer functions compared to the statistical uncertainty involved in their calculation. In contrast, changes to the configuration of the network as a whole may result in changes to transfer functions at some, if not all, individual substations, which would clearly compromise the ability to predict GIC. How significant such changes might be is, *a-priori*, impossible to predict. The longest record of measurements of GIC in the New Zealand power network is from 2001-2016 at Islington (Figure 2), near Christchurch. Analysis of this record may elucidate any temporal changes in transfer functions associated with network changes, at least at the local level, and provide some indication of the impact of such changes.

Nevertheless, allowing for the stability of calculated transfer functions, application of the technique to all substations in a power network for which GIC measurements are available has some significant advantages. Not least of these is the potential to provide a check on both the magnitude and direction of GIC estimates provided by, for example, the thin-sheet modelling technique. This has already been illustrated by the mismatch between the transfer function and thin-sheet predictions for the amplitudes of GIC at SDN relative to INV and MAN. Additionally transfer functions are able to predict GIC at significantly shorter periods (higher frequencies) than is possible with thin-sheet modelling for which the validity is restricted by numerical

considerations. Availability of higher sampling rates for measurement of GIC would enhance this advantage.

Acknowledgments, Samples, and Data

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Figure 1. Production of GIC in a transformer/substation represented as a convolution of a time varying magnetic field with a combined impulse response for electromagnetic induction in the Earth and interaction of the induced electric fields with the power network.

Figure 2. Outline map of the South Island of New Zealand showing the Transpower New Zealand electrical transmission network (colored lines), the location of the substations with GIC observations used in the current study, and the location of the primary New Zealand magnetic observatory, Eyrewell.

Figure 3. GIC recorded at SDN from 13-22 March 2015 and the associated horizontal magnetic field variations at EYR.

Figure 4. Real (upper panels) and imaginary (lower panels) parts of the transfer functions A (blue circles) and B(red squares) for GIC observed at SDN transformer #2, calculated using the 10-day period of data in March 2015 shown in Figure 3.

Figure 5. Variations in the *X* component of the magnetic field observed at EYR for the 10 day periods listed in Table 1.

Figure 6. Calculated transfer functions and standard deviations for GIC observed at SDN (blue), INV (red), and MAN (black). The solid blue line show the fit of the polynomials used to interpolate the transfer functions.

Figure 7. Polar plots showing, for different periods of field variation, the magnitude of GIC produced at SDN, INV and MAN as a function of the orientation of the inducing field variations.

Figure 8. Predicted and measured GIC at SDN over 2048 minutes from 1200 UT 12 September 2014. Also shown are predicted GIC after correction as discussed in the text.

Figure 9. (a) Underestimation of rapidly varying GIC due to interpolation of non-uniformly sampled data (circles) to 1 minute uniform sampling (squares). (b) Plot of measured GIC against predicted GIC for the storms listed in Table 2. The solid line shows a third degree polynomial fit to the data.

Figure 10. Predicted and corrected GIC for SDN, and magnetic field variations at EYR during the magnetic storm of 5 November 2001 during which there was a transformer failure at nearby Halfway Bush (HWB) substation.

Figure 11. Predicted GIC at SDN, INV and MAN for a "synthetic" geomagnetic storm of the magnitude of the 1859 Carrington Event. As discussed in the text the "synthetic" storm is modelled on the event of 29 October 2003 and the time axis represents minutes after 0000 UT 29 October 2003.

Table 1. 10 day periods covering geomagnetic storms in 2015 used in the calculation of transfer functions.

1	0000 13 March – 2359 22 March 2015
2	0000 13 April – 2359 22 April 2015
3	0000 21 June – 2359 30 June 2015

4	0000 12 August - 2359 21 August 2015
5	0000 22 August – 2359 31 August 2015
6	0000 8 September – 2359 17 September 2015
7	0000 18 September – 2359 27 September 2015
8	0000 03 October - 2359 12 October 2015
9	0000 04 November – 2359 13 November 2015
10	0000 17 December – 2359 26 December 2015

Table 2. Geomagnetic storms in 2013 used to calculate a correction to predicted GIC.

1	0300 17 March - 1307 28 March 2013
2	1500 1 June – 0107 3 June 2013
3	0000 29 June – 1007 30 June 2013
4	0000 2 October – 1007 3 October 2013

Figure 1.

y(t) = x(t) * h(t)



Electromagnetic induction in earth and interaction of induced fields with transmission

network

Time varying geomagnetic field

GIC in transformer/ substation

Figure 2.



Figure 3.



Figure 4.





Figure 5.



Figure 6.



Figure 7.





	- 2.1m
_	— 5.3m
	- 13.2m
	— 33.3m
	- 83.5m
	- 209.8m
	- 527.1m

Figure 8.



Figure 9.





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Figure 10.



Figure 11.

