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Improved methods for surface impedance estimation in modelling of geomagnetically induced currents in power networks.

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SUMMARY

Space Weather can adversely affect power transmission networks both through temporary outages caused by spurious tripping associated with the production of harmonics and increased VAR requirements resulting from geomagnetically induced quasi-DC currents (GICs) in power transformers, and through permanent damage to high voltage power transformers resulting from the half-cycle saturation and overheating associated with GICs. The prediction of potential GIC hot-spots in a power network should be considered in future planning in order to improve the security and reliability of electricity supply.

The geophysical step in modelling geomagnetically induced currents (GICs) has been shown to be a significant source of error in the modelling chain. This stems from the assumption that GICs in networks are related to an induced plane-wave geoelectric field, which is usually derived using limited knowledge of the Earth’s conductivity profile.

The surface impedance can be derived from an estimated conductivity profile, or from magnetotelluric measurements. By using both an interpolated magnetic field and interpolated surface impedance instead of data from a magnetometer station and magnetotelluric station nearest to the power line of interest the accuracy in the estimation of GICs can be significantly improved

This paper presents a new algorithm for the interpolation of the surface impedance to estimate the geo-electric field at locations distant from magnetotelluric observation stations. The plane wave assumption is quantified using a SECS interpolation of the magnetic field over South Africa and by deriving a regional geoelectric field using the improved interpolated surface impedance. Improved estimation of GICs in the power network allows for the development of a more accurate strategy for responding to and mitigating GICs.

KEYWORDS
Geomagnetically Induced Currents, Surface Impedance, Magnetotelluric Measurements.

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INTRODUCTION

Over the last two decades, a substantial research effort has been dedicated to show that Geomagnetically Induced Currents (GICs) do occur in the high voltage transmission networks in southern Africa. This has been complemented by the development of reliable models to estimate the flow of GICs in the power network and the deployment of measurement devices to measure GICs. Some of these includes the early works of Koen [1,2] in 2002 who modelled the flow of GICs in southern Africa. Some the assumptions made included the uniform plane wave electric field over the geographical region. In 2007, it was established that 400 kV transformers in South Africa were damaged during the 2003 Halloween storm [3]. Subsequently a major improvement in modelling GICs in southern Africa was achieved by the application of Spherical Equivalent Current Systems (SECS) [4]. To date, several statistical, geo-physical and engineering models have been developed which incrementally refine and improve the models used to predict, estimate and model GICs in southern Africa and propose mitigating strategies.

This study investigated the use of magnetic field interpolation and surface impedance interpolation to enhance the accuracy of predictions of the Geomagnetically Induced currents (GIC) in the South African Power network. The GICs are quasi-DC currents with a spectral range of 0.1 to 10 mHz [5,6].

Geomagnetic storms resulting from geomagnetic field disturbances following the impact of the solar wind on the Earth's geomagnetic field have been shown to have an adverse impact on several ground based technologies. The intense geomagnetic fluctuations associated with severe geomagnetic storms are known to give rise to significant GICs in power transmission grids [7]. High voltage power transformers of the interconnected power transmission system are known to be vulnerable to temporary and permanent damage due to geomagnetically induced currents (GICs) during extreme geomagnetic storms [8] such as the storms that occurred in October 2003 when the South African power network suffered severe damage due to GICs [9]. More so, the low resistance of high voltage transmission lines provides a suitable corridor for the flow of GICs in the transmission and distribution networks.

In order to mitigate the impact of geomagnetic disturbances on the South African power system, and promote a sustainable delivery of power, attempts are under way to improve the estimates of the GICs in the network. One recent work which can be advanced by the outcome of this research, is the work on the voltage stability analysis of the South African high voltage transmission network during a severe GMD[9]. The outcome of such a work will make it possible to identify and more accurately model hot spots in the transmission grid, to develop ways to attenuate and mitigate the effects GIC, thereby satisfying some of the requirements for a reliable power transmission network. The estimation of GICs from measurements or predictions [11] of the fluctuations in the geomagnetic field comprises two steps: The *geophysical step* which results in estimates of the geo-electric field along each power line, and the *engineering step* which applies these geo-electric field estimates to the network, to calculate the currents in each branch of the network and the currents that flow from neutral to ground in Y-connected power transformers with grounded neutral connections [12].

The geophysical step in the modelling of GICs comprises the convolution in the time domain of the magnetic field components along the power line, with the impulse response of the surface impedance. Alternatively the geo-electric field can be determined via a frequency-domain transformation in which the Fourier transform of the magnetic field is multiplied by the spectral components of the surface impedance to obtain the Fourier transform of the electric field components, and by then applying an inverse Fourier transform to the results. This process is illustrated in Figure 1.

The equation linking the Fourier transforms of the horizontal geomagnetic field components (B_x,B_y) to the corresponding Fourier Transforms of the geo-electric field components (E_x,E_y) is given in Equation 1.

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$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \frac{1}{\mu} \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} B_x(\omega) \\ B_y(\omega) \end{bmatrix} \quad (1)$$

Here Z_{xx}, Z_{xy}, Z_{yx}, and Z_{yy} are a set of complex numbers which express the tensor components of the surface impedance Z at the point of interest along the power line [14], ω is the frequency in radians/s and μ is the magnetic permeability of the ground, which is taken to be equal to that of free space. The values of the surface impedance tensor components are required at each of the frequencies in the Fourier transforms of the the horizontal geomagnetic field components (B_x,B_y). When data with a sampling interval of 1 minute is used, as is typically available from INTERMAGNET observatories, the frequencies at which the surface impedance values are required range from a few mHz to a maximum of 8 mHz. The frequencies at which the surface impedance components are derived from MT measurements, do not necessarily coincide with those in the B-field Fourier transform, and hence require some form of interpolation.

The surface impedance components are usually obtained from magnetotelluric (MT) measurements which make use of co-located instruments for measuring the horizontal components of the geomagnetic field and the horizontal components of the geo-electric field. Figure 2 shows the locations of the MT stations in Southern Africa where such measurements are made. These measurements are usually not made near power lines in order to reduce the potential impact on the MT measurements caused by power line fields, steel power line support structures and corona from high voltage lines. In order to find the surface impedance values under the power lines, a combination of two interpolation methods is proposed: First the variation of the surface impedance components with frequency is interpolated by means of a low order (typically 5th to 6th order) polynomial, and then the coefficients of the polynomials pertaining to each of the measurement locations are spatially interpolated using a Kriging method.

The assumptions made in the geophysical step in modelling GICs have been shown to be a significant source of error in the modelling chain. This stems from the assumption that GICs in networks are related to an induced plane-wave geoelectric field, which in turn is assumed to arise from a plane wave geomagnetic field over the region of interest.

Ideally the magnetic field components and the surface impedance values should apply to the locations along the power lines. In practice the magnetic field components are often taken as those from the nearest magnetic observatory and the surface impedance is derived from that of the nearest MT station or from some estimate of the conductivity structure of the Earth at the location of interest along the power lines.

This paper presents estimates of the errors in estimating the geomagnetic field away from the magnetic observatories by means of the method of Spherical Equivalent Current Systems (SECS) and proposes a method for interpolating the surface impedance to all locations along the power lines.

By using both an interpolated magnetic field and an interpolated surface impedance in the estimation of GICs, the accuracy can be significantly improved compared to using data from the nearest magnetometer station and nearest magnetotelluric (MT) station.

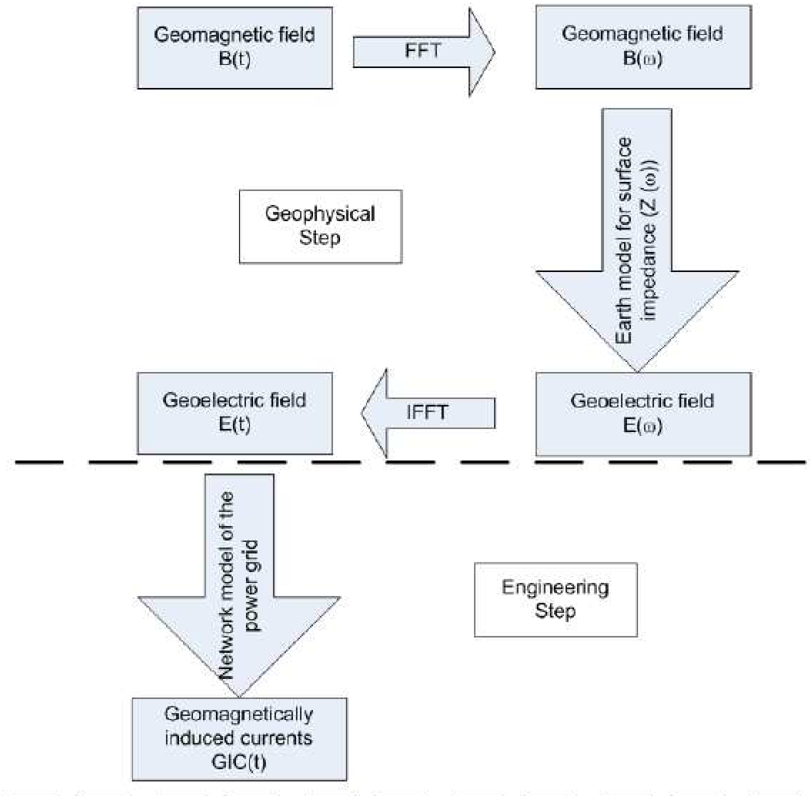

Figure 1. Frequency domain approach for finding the geo-electric field for the estimation of GICs in power lines from geomagnetic and surface impedance data. Adapted from (Zheng et al., 2013 [13]).

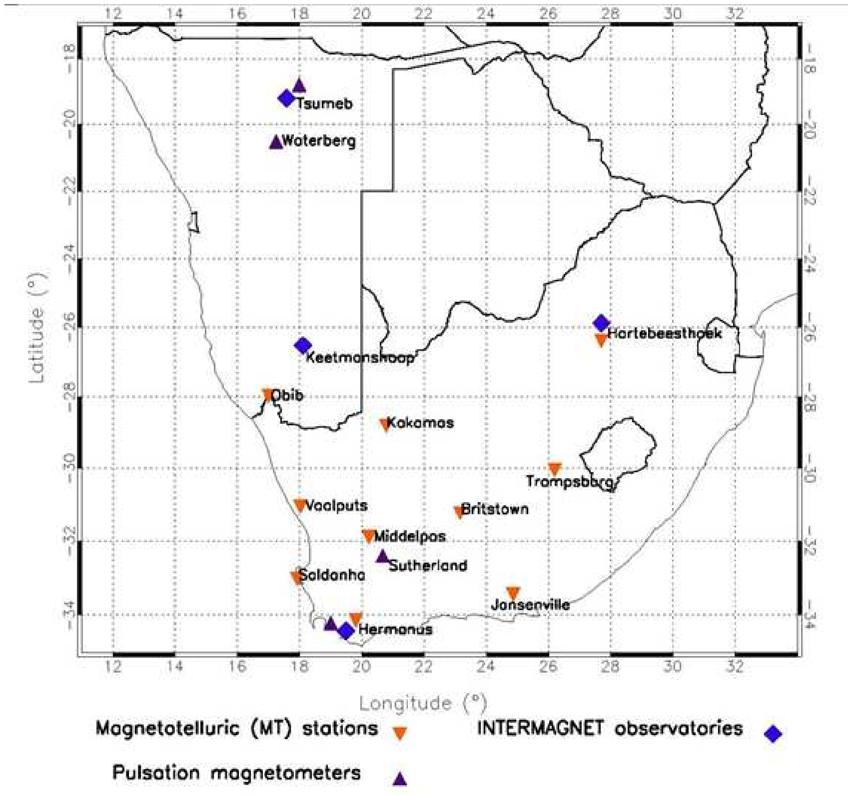

Figure 2. Locations of the INTERMAGNET magnetic observatories and magnetotelluric (MT) stations in Southern Africa which are used for the estimation of the surface impedance tensors at each location.

INTERPOLATION OF THE MAGNETIC FIELD USING SPHERICALLY EQUIVALENT CURRENT SYSTEMS

The Spherical Equivalent Current Systems (SECS) is a commonly used approach to find the magnetic field at the location of the power lines [15,16]. It estimates the characteristics of a hypothetical array of current elements in the ionosphere based on measurements of the geomagnetic field at several locations on the ground, typically at magnetic observatories. The SECS method then applies the Biot-Savart Law to the x- and y- components of the array of currents, to find the B_x, and B_y components, respectively, of the surface *B*-field at any coordinate of interest.

The accuracy of the interpolation method was estimated by comparing a simulated field for a whole day obtained by means of the University of Michigan Space Weather Modelling Forum (SWMF). The interpolated field components (dB_x/dt, and dB_y/dt) at a 2 x 2 grid of virtual observatories were derived from the simulated vector components of the total field at each of the four geomagnetic observatories in Southern Africa Hermanus (HER, 19.43°E,33.22°S), Hartebeesthoek (HBK, 25.88°E,27.70°S), Tsumeb (TSU, 19.20°E,17.58°S) and Keetmanshoop (KMH, 26.32°E,18.06°S). The simulated field was derived from solar wind parameters measured during the geomagnetic storm of 2003-11-20. For the comparison we use the time derivatives of the simulated field rather than the absolute values of the field, since the time derivative of the magnetic field is a better proxy of the electric field than the absolute values of the field and would thus be more relevant to the estimation of the interpolation error [17].

Figure 3 shows the results of this comparison. Note that the largest rms errors are about 6 nT/min and occur at locations furthest away from the observing stations.

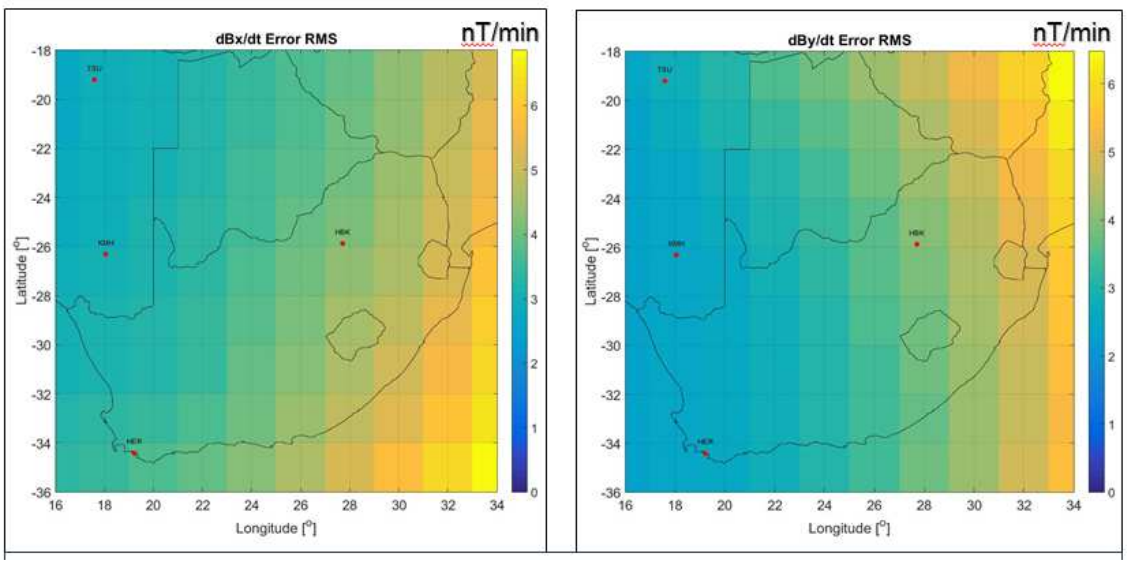

Figure 3. Plots of the RMS error, in nT/min, for *dBx/dt* (Left) and *dBy/dt* (Right) , between SWMF simulated and interpolated values, averaged over the duration of the simulated fields for the geomagnetic storm on 2003-11-20, at each point on a 2 x 2 degree grid. The locations of the INTERMAGNET magnetometer stations are shown on the maps. The simulated data from these stations were used for the interpolation using the SECS method.

INTERPOLATION OF SURFACE IMPEDANCE COMPONENTS

The surface impedance components were interpolated using polynomial approximations of each of the tensor components in Equation (1) (real and imaginary parts) and by subsequently doing a spatial interpolation of the polynomial coefficients.

Figure 4 shows the interpolation of the amplitude of the components of the surface impedance (Z_{xx}, Z_{xy}, Z_{yx}, and Z_{yy}) at a frequency of 10 mHz, corresponding to a period of 100 s, where data from four of the MT stations were used. These four MT stations were selected on the basis of the quality of their MT data and for having data that was measured over the same period of time. Measurements of MT data over the same time is not critical since the surface impedance values are not expected to have a significant variation over time. The surface impedance depends mostly on the deep-Earth conductivity due to the large skin depth at the mHz frequencies of the spectrum of the measured magnetic field used in the estimation of the electric field. The 5th order polynomial fit of the measured surface impedance vs. frequency facilitates the calculation of the surface impedance at any of the frequencies of the magnetic field spectrum for the frequency-by-frequency application of equation (1).

Notice that all four the surface impedance tensor components are higher at the coastal MT station than elsewhere.

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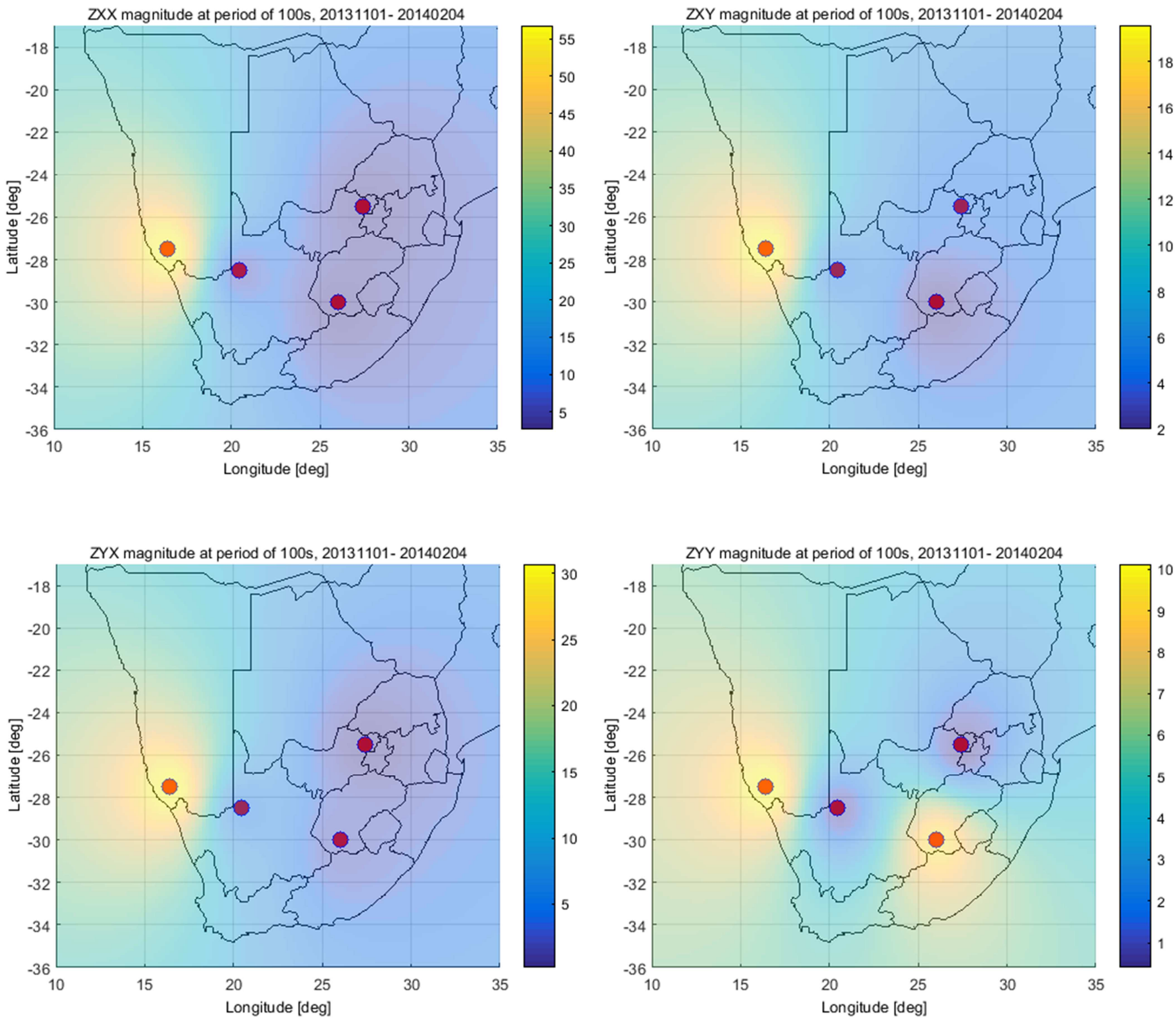

Figure 4. Examples of the interpolation of the surface impedance over Southern Africa based on the simultaneously measured surface impedance values at four MT stations Hartebeesthoek (27.42^{o}E, 25.53^{o}S), Obib (16.38^{o}E, 27.51^{o}S), Kakamas (20.46^{o}E, 28.49^{o}S) and Trompsburg(26.01^{o}E, 30.07^{o}S).

CONCLUSION

The results obtained with the interpolation of both the magnetic field and the surface impedance have proven the feasibility of these methods. The accuracy of the magnetic field interpolation has been verified using a simulated geomagnetic field derived from solar wind parameters during the geomagnetic storm of 2003-11-20.

The feasibility of using the new proposed method for the spatial interpolation of the surface impedance has been demonstrated. The method will be validated using surface impedance data from sites not used in the spatial interpolation. The improvement in the accuracy of GICs that can be obtained by means of the interpolation of the surface impedance components, still need to be verified through comparison with measured GICs.

Significant progress has been made in improving the estimation of GICs in the power network. This allows for the development of a more accurate strategy for responding to and mitigating the impact of GICs on the power transmission network.

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