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The Importance of Non-Uniform Geoelectric Fields in Calculating GIC Distributions

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Abstract—During the ascending phase of solar cycle 24 concern in the power industry regarding space weather has increased significantly. This is driving the development of software tools to estimate GIC distributions in power networks for a given uniform geoelectric field. Typically, geoelectric fields induced during space weather disturbances are spatially non-uniform. This paper shows that for accurate planning and development of mitigation strategies, GIC analysis software needs to allow for specification of non-uniform geoelectric fields. Further, the notion held by power utilities in mid and low-latitude locations that space weather does not pose any risk to their systems is questionable. In this paper a methodology is developed to estimate the distribution of GICs in a specified power network during a significant geomagnetic event at mid-latitudes.

Index Terms—Geomagnetic storms, GICs, space weather, geoelectric field

I. INTRODUCTION

THE phenomenon known as space weather has been understood to be a potential threat to power transmission systems for some decades now [1]. Solar-borne plasma ejections can at times interact with the magnetic field of the Earth and cause a chain of magneto-hydrodynamic and electromagnetic disturbances that induce electric fields in the Earth's surface referred to as "geoelectric" fields. These disturbances are referred to generally as geomagnetic storms. The induced geoelectric fields, which can often be coherent over hundreds of kilometers, drive Geomagnetically Induced Currents or GICs through systems of long grounded conductors such as power transmission networks and pipelines. In power networks the GICs will enter the system through the neutral points of grounded-wye transformers and if severe enough, cause the power transformers in the system to enter half-cycle saturation. The risks to the power system due to this latter phenomenon are well known and

documented [2], [3]. They include injection of harmonics into the system causing protection issues, flux leakage out of the core causing Eddy currents in parts of the machine and possible overheating of the windings or winding insulation to the point of severe damage, and the demand of large amounts of reactive power. The latter of these effects can potentially lead to voltage collapse of the entire system as famously occurred in Quebec, Canada in March of 1989 [4].

Previously the risk posed to power networks by space weather had only been considered important in high latitude countries due to their close proximity to the intense current systems of the auroral oval and the fact that resultant voltage stability issues were only reported from such regions. During recent years however, GICs in mid- and low-latitude power systems have been identified with other geomagnetic disturbance phenomena such as Sudden Impulse (SI) events [5]. These events are characterized by a sudden increase in the northward component of the geomagnetic field caused by a sharp rise in the solar wind dynamic pressure at the magnetopause and are often the precursor of a geomagnetic storm [6]. Further, it was demonstrated using Dissolved Gas Analysis, a diagnostic technique for assessing transformer winding health, that a number of transformers in South Africa failed due to damage sustained during geomagnetic storm activity several months prior [7]. These two findings have motivated the re-evaluation of the risk posed to power transmission networks by space weather in all regions of the world.

In order to assess this risk and develop mitigation strategies a power utility must be able to predict the distribution of GICs within their network for a given geomagnetic disturbance. Tools are currently being added to several commercial power system software packages which

will calculate distributions of GICs in power networks for specified geoelectric fields.

Presently, these tools are only able to perform these calculations for geoelectric fields which are spatially uniform [18]. Typically, geoelectric fields produced during space weather disturbances are spatially non-uniform. The spatial non-uniformity is caused by the structure of ionospheric current systems and the lateral inhomogeneities in the conductivity of the Earth such as the “coastal effect”.

In this paper a methodology for estimating GICs in power networks has been developed which incorporates non-uniform geoelectric fields. This has been used to investigate the error which may occur by estimating GIC distributions using uniform geoelectric fields compared with non-uniform fields. This paper also presents the GIC distribution modeled for a specified mid-latitude power network during a historically significant SI event.

In Section II the development of the methodology is explained. Specifically, the method for calculating GIC distributions, the use of geomagnetic data, the modeling of the geomagnetic coastal effect, and the verification of the methodology are discussed. In Section III GIC calculations for uniform and non-uniform geoelectric fields are compared for a specific event. In Section IV the GICs which would be generated by the SI event of March 1991 if it occurred today are investigated. In Section V the limitations of the methodology are described and the conclusions of the study are discussed in Section VI.

II. GIC ESTIMATION METHODOLOGY

A. Calculating GIC Distributions in Power Networks

GICs are slowly time varying signals with respect to the AC system and are therefore typically treated as DC currents. The calculation of their distribution in a power network, once the geoelectric fields driving them are known, is akin to the solution of a large circuit containing only DC voltage sources and resistances. The method used to perform these calculations is the Nodal Admittance Matrix Method [8].

A particular power transmission network was studied in the works of this paper; that which supplies much of the state of Queensland in Australia. Topological information, spatial data, and resistances for transformer windings, transmission lines and reactors were collected for this network. The resistance data required in GIC studies of power networks is described in [1]. Where possible, transformer winding resistances were collected from the original test reports and substation earth grid resistance test values were used.

To model the coupling between geoelectric fields and power networks accurately, a voltage source equivalent to the line integral of the geoelectric field under each transmission line must be placed in series with the transmission line [9]. In the case of a uniform geoelectric field this integral reduces to:

$$V_{AB} = \mathbf{r}_{AB} \cdot \mathbf{E} \quad (1)$$

In the case of non-uniform geoelectric fields, the line integral must be evaluated along each transmission line path. A sufficient approximation is to sum the dot products between small subsections of each transmission line and the average geoelectric field value over those subsections. For a transmission line between substations A and B , with N subsections between which significant variations in direction occur, the voltage source is given by:

$$V_{AB} = \int_A^B \mathbf{E}(\theta, \delta) \cdot d\mathbf{l} \approx \sum_i^N \mathbf{E}(\theta_i, \delta_i) \cdot \mathbf{l}_i \quad (2)$$

where the displacement vectors of each subsection are denoted by $\mathbf{l}_i$ and θ and δ denote the latitude and longitude of a given location respectively.

In this paper, geoelectric fields used in (1) are referred to as “uniform fields” and those used in (2) are referred to as “non-uniform fields”. All calculations in these studies were performed using MATLAB.

B. Estimating Geoelectric Fields using Geomagnetic Data

To model the GIC distributions in the Queensland transmission network resulting from given geomagnetic disturbance events it was necessary to estimate the geoelectric fields over this region for these events. Geomagnetic data provided by the Australian Bureau of Meteorology’s Ionospheric Prediction Service was used; three magnetic observatory sites in and around Queensland were chosen to obtain the best estimates of the fields across the region. All geomagnetic data used were of one second cadence making them more than capable of capturing all geomagnetic variations of interest [19].

The geoelectric field estimations were calculated using a finite-difference approximation to an integral equation relating the surface geoelectric field to a temporally varying geomagnetic field [10] given by:

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}} \int_{-\infty}^t \frac{dB_x}{dt'} \frac{1}{\sqrt{t-t'}} dt' \quad (3)$$

Equation (3) assumes the incident wave field is a plane wave and the conducting medium is homogenous and one dimensional. These assumptions have been shown to be reasonable [19] [12] in regions without strong conductivity gradients and/or below large scale ionospheric current systems. For the non-uniform field case, the geoelectric field estimations at each of the magnetometer locations were interpolated to the location of each transmission line subsection in the network. For the uniform field case, the geoelectric field estimation determined from the southernmost magnetic observatory site was assumed across the whole region.

C. Modeling the Geomagnetic Coastal Effect

Non-uniform geoelectric fields are induced during space weather disturbances in regions of horizontally varying

conductivity. Estimating the geoelectric fields over Queensland requires modeling the effects of non-uniform conductivities such as the “coastal effect” [17]. This results in an enhancement of the component of the geoelectric field which is perpendicular to a coastline in close proximity to that coastline as well as a reduction of the component which is parallel to it [11]. The coastal effect is a consequence of induction caused by currents induced in the highly conductive seawater and Earth beneath the sea. The potential between a generalized coastline and a short distance inland due to the perpendicular component of the geoelectric field during a geomagnetic disturbance is given by [11]:

$$V_u = \frac{2\mu_0^{1/4} x^{1/2}}{\sigma^4 \pi^2 \Gamma(3/4)} \int_0^t \frac{1}{(t-t')^{1/4}} \frac{\partial H_0(t')}{\partial t'} dt' \quad (4)$$

The parallel component of the geoelectric is given by [11]:

$$E_v = \frac{\mu_0^{3/4} x^{1/2}}{\sigma^4 \Gamma(1/4)} \int_0^t \frac{1}{(t-t')^{3/4}} \frac{\partial H_0(t')}{\partial t'} dt' \quad (5)$$

The subscripts u and v denote the directions perpendicular to and parallel with the coastline respectively and x is the shortest distance from a specified point to the coastline in meters. Refer to [11] for an explanation of the simplified conditions under which these equations were derived. It is assumed that the potential on the left hand side of (4) can be differentiated to yield an expression for E_u proportional to the inverse of the square root of x .

Equations (4) and (5) involve temporal integrals dependent on the time rate of change of the horizontal geomagnetic field. To avoid the repeated evaluation of these integrals at every transmission line subsection in the network the following simplified equations were used in the non-uniform field case:

$$E_u = \frac{\alpha E_u'}{\sqrt{x}} \quad (6)$$

$$E_v = \frac{E_v' \sqrt{x}}{\alpha} \quad (7)$$

where E_u' and E_v' are the $\hat{u}$ and $\hat{v}$ components of the horizontal geoelectric field in the absence of the coastline and α is defined as the coastal coefficient for this study. This variable was used to regulate the average distance inland over which the influence of the coastal effect extended. The coordinates of a series of locations along the Queensland coastline were used in part of the non-uniform field calculations to estimate the value of x at any given point in Queensland.

D. Verifying GIC Estimations against Measurements

During the latter half of 2012 a GIC measurement device was installed on one of the major power transformer neutral earth lines in the Queensland network. Data recorded by this device was available for verification of the estimation methodology developed. It was used to estimate GICs during three separate disturbances in 2012 for the uniform field case.

Fig. 1 shows the modeled GIC well correlated with the neutral line measurements for an SI event of 14th July 2012. The modeled GIC values plotted in green have been multiplied by a scaling factor of 17.8. Modeled and measured GICs were consistently different by a scale factor of ~ 18 .

Fig. 1. Comparison of measured GIC data (black) and estimated GIC (green) scaled up by a scaling factor of 17.8 for a period containing a Sudden Impulse on 14.07.2012

Two factors were considered likely for the existence of the discrepancy: the inappropriateness of the conductivity value used for the Earth beneath Queensland and the geomagnetic coastal effect being insufficiently modeled. The conductivity value initially used for the uniform field case was 0.03176 S/m; a depth-weighted average of a model for the Australian continent presented in [12]. It was however unclear how many of the layers of this model to calculate an average over since the depth of penetration of any electromagnetic disturbance is dependent on the frequency of that disturbance.

The induction studies of the Australian continent [16] were based on a conductivity model with an initial layer 150 kilometers thick and conductivity 0.001 S/m. This was taken to be a valid lower limit of the conductivity value used in the GIC estimations. Reducing the conductivity to this value did not account for the discrepancy. It is likely that insufficiently modeling the coastal effect has also contributed to the discrepancy. This is to be expected as the major transmission lines entering the substation at which the measured transformer is located are somewhat perpendicular to the Queensland coastline.

Using a coastal coefficient of 800 for four separate non-uniform field events, the conductivity values required to produce agreement between the modeled and measured GICs ranged from 0.00138 to 0.00178 S/m. The maximum inland distance of persistence of the coastal effect given this coastal coefficient was 640 kilometers. While this is likely to be in excess of the distances inland at which the coastal effect would actually be observable, reducing the coastal coefficient would have meant using conductivity values below the lower limit. Further, the literature contains no precise estimates of

the distances inland for which the coastal effect should persist, though it is thought to occur over hundreds of kilometers in general [13]. For a coastal coefficient of 800 the field components are only 25% and 10% larger than in the absence of the coastal effect at distances of 400 and 500 kms inland, respectively.

A coastal coefficient of 800 and a conductivity value of 0.00151 S/m are therefore considered appropriate for the non-uniform field case. For the uniform field case, the modeled GICs were scaled by a constant value to agree with the transformer measurements.

III. UNIFORM AND NON-UNIFORM FIELD COMPARISONS

On the 14th of June 2012 a transient in GIC was observable in the neutral of the measured transformer which coincided with an SI event. The NOAA (National Oceanic and Atmospheric Administration) Space Weather Prediction Centre confirmed the classification of the event as an SI event. GICs for each transformer in the network were estimated for both the uniform and non-uniform field cases. The formulae for the effective GICs in a power transformer were taken from [15]. Effective GIC was chosen as the quantity to be calculated in general because it is more closely related to transformer saturation than winding GIC.

The differences in modeled GICs for each transformer in the network for the uniform and non-uniform field cases for this event are plotted in blue in Fig. 2.

Fig. 2. Differences in effective GIC calculated using a uniform geoelectric field and a non-uniform geoelectric field for the Sudden Impulse of 14.07.2012

To indicate the significance of these differences, the positive and negative of the mean effective GIC calculated for the uniform field case has been plotted in red.

The effective GIC magnitudes for each transformer modeled for the uniform geoelectric field case differ substantially from those for the non-uniform field case. If the non-uniform field results are assumed more accurate, then the average error in the uniform field results would be approximately 150% of the mean effective GIC value. This was calculated using the root-mean square of the differences between the uniform and non-uniform field results.

Since a coastal coefficient of 800 is likely to be excessive, the above study was repeated with the coastal coefficient reduced to 330 so that the coastal effect only persisted inland for just over 100 kilometers. This is likely to be a conservative estimate for the level of influence of the coastal effect on geoelectric fields induced in Queensland. For this scenario, both the uniform and non-uniform field models used a conductivity of 0.03176 S/m and the uniform field results were not scaled. The results still showed significant differences between the uniform and non-uniform field estimates; the average error in the uniform field results were approximately 66% of the mean effective GIC value assuming the non-uniform field results as the more accurate.

It is therefore concluded that for a power network which lies within a few hundred kilometers of a coastline, as much of the Queensland network does, GIC distributions modeled assuming uniform geoelectric fields may be highly inaccurate. While the general magnitude of GICs estimated to be present may be approximately accurate their distribution, namely the hierarchy of transformers for which the effective GICs are the most severe, is likely to be incorrect.

IV. THE SI EVENT OF MARCH 24 1991

On the 24th March 1991 a large Sudden Impulse occurred which had a uniquely rapid rise time. Magnetometer data recorded at Birdsville and Weipa stations located in far southern and northern Queensland respectively was provided for this event by the International Centre for Space Weather Science and Education, Kyushu University, Japan [14].

The non-uniform field results for this event were obtained using a coastal coefficient of 800 and conductivity of 0.00151 S/m. The modeled GICs for this event are shown in Fig. 3 arranged in ascending order. Since the Queensland power transmission network was substantially less complex and interconnected in 1991, this calculation constitutes an estimation of the effective GICs which would be present in this network if the SI of 24th March 1991 occurred in the current day.

Fig. 3. Effective GICs for peak geoelectric field intensity during the SI of 24.03.1991 assorted in ascending order

For 66 of the 515 transformers included in the study the estimated effective GICs were in excess of 100 amperes. Though the effective GICs shown are total three phase GICs, three times the effective GICs flowing in each phase, this level of current is still significantly larger than that which is expected in networks at this latitude. For SI events such as these, GICs of these magnitudes would only be present in the network for a short period; of the order of minute(s). This is due to the geoelectric field's frequency dependence of the time varying geomagnetic field, with SIs typically having relatively short temporal widths. In such short timeframes it is unlikely that these GICs would significantly damage any healthy equipment, although voltage stability issues may occur in the network. Detailed studies of the saturation characteristics of each transformer in the network would need to be carried out to determine the likelihood of voltage collapse.

V. LIMITATIONS OF THE ESTIMATION METHODOLOGY

The GIC estimation methodology developed in this paper is subject to several factors which may reduce its validity. Firstly a one-dimensional, homogenous conductivity model was used to model the Earth beneath Queensland. The conductivity of the Earth is a function of both depth and lateral position in general. Secondly the model used for the coastal effect is considerably simplified. Finally, the location of the GIC measurement device was non-ideal in that it was located at a common path to ground between two major transmission lines instead of an outer node of the system. Any asymmetric error in the GICs estimated for these lines may have resulted in amplified errors in the scaling of the conductivity model and the coastal coefficient.

To verify the estimation methodology developed in these studies, several GIC measurement devices would need to be installed across the network and the agreement between measured and calculated GICs investigated at all sites.

VI. CONCLUSIONS

A methodology has been developed to estimate effective GIC distributions in the Queensland power transmission network; a network situated in a mid-latitude region. This methodology has been used to demonstrate the importance of realistic non-uniform geoelectric fields in accurately estimating effective GIC distributions. It was found that for the system studied, GICs modeled using a uniform field can result in average errors between 66% and 150% when compared to GICs obtained using a non-uniform field model. The methodology was also used to estimate the distribution of GICs that would be produced in the Queensland network if the Sudden Impulse of 24th March 1991 occurred in the present day. Many of the GICs estimated for this event were in excess of 100 amperes. These findings suggest that further investigations into space weather vulnerability of power utilities in mid and low-latitude regions are required.

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