Estimating the Electric Field From Geomagnetically Induced Currents

Nicole C. LoGiudice, Jonathan M. Snodgrass, Thomas J. Overbye
Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX
{nicolelogiudice30; snodgrass; overbye}@tamu.edu

***Abstract*—This paper presents a weighted least squares algorithm to find the electric field during geomagnetic disturbances (GMDs) using geomagnetically induced current (GIC) measurements. Estimation of the electric field requires familiarity with the grid's layout, including but not limited to, transformer types, conductances, and line orientations. The algorithm is tested using the 2000 bus synthetic Texas case. The results show that not only can the electric field be accurately estimated using only GIC neutral measurements, but that only eight GIC neutral measurements are required.**

***Index Terms*—Geomagnetic Disturbances (GMDs), Geomagnetically Induced Currents (GICs), Electric Field, Weighted Least Squares (WLS)**

I. INTRODUCTION

Geomagnetic Disturbances (GMDs), produced by solar activity, cause fluctuations within the Earth's magnetic field. This alteration in the magnetic field induces quasi-dc electric fields across the Earth's surface that are dependent upon the Earth's conductivity. Created by the electric fields, Geomagnetically induced currents (GICs) flow through the Earth and high voltage transmission lines connected to grounded transformers [1]. The immediate risks of GMDs include half-cycle saturation in transformers creating harmonics, heating in the transformers, and increased reactive power losses [2]. These three initial responses could lead to two key risks of GMDs to the electrical grid, potential damage of transformers and voltage collapse [3], [4], [5]. Real world examples of grid instability have occurred like the famous 1859 Carrington Event, the 1989 GMD event where the Hydro Quebec power grid collapsed, and in 2003 where a blackout occurred in the Swedish grid due to a GMD event [5], [6], [7]. Considering the possible effects of GMDs, it is important to monitor and study GMDs. NERC has released transmission standards for monitoring during GMD events in TPD-007-1 and FERC has approved of this standard while also mandating that all GIC and magnetometer data be shared via NERC in FERC order No. 830 [8], [9], [10]. Due to the high cost of GIC measurement devices and magnetometers, it is important to know how many devices are truly necessary to minimize costs while still ensuring accuracy.

This paper focuses on estimating the electric field through the use of GIC measurements. At a few locations currently, the electric field is calculated from the magnetic field, measured by magnetometers, in conjunction with ground conductivity maps [11], [12]. The purpose of this paper is to investigate the extent to which the electric field can be estimated using only GIC measurement devices. Because GICs are directly induced from the electric field, they can also be used to estimate the electric field. Due to the system being over-determined and the linear relationship between the electric field and quasi-DC GIC measurements, non iterative linear state estimation is used.

This paper consists of five sections. Section II covers an overview of DC state estimation and explains how the electric field is calculated from the neutral currents in transformers. Then, utilizing these calculations, create an electric field state estimation problem using GICs as measurements, with [13] as a building block. Section III goes over a state estimation example utilizing the synthetic 2000 bus Texas case. Section IV compiles the results from the study. Section V summarizes and presents areas for future work.

II. ELECTRIC FIELD STATE ESTIMATION FORMULATION

A. Traditional Electrical Grid State Estimation

Traditionally, state estimation is utilized to find the voltage magnitudes and angles throughout the grid [14], [15]. The measurements are taken from phasor measurement units while also having the MW output of generators, ultimately making the system over-determined when the two measurements do not exactly line up for the expected states. State estimation is used to produce the most likely values of nonlinear equations. The state estimation formula is as follows:

$$z_i = h_i(x) + e_i \tag{1}$$

where h_i is the relationship of the *i*th measurement with the state x. e_i is the *i*th measurement error and z_i is the *i*th measurement.

The authors gratefully acknowledge the financial assistance received from the U.S. Department of Energy, Office of Cybersecurity, Energy Security, and Emergency Response (DOE-CESER), and Pacific Northwest National Laboratory (PNNL) for work conducted under Master Agreement 401273, Task Order 610876.

Presented at the 2024 IEEE Kansas Power and Energy Conference (KPEC), Manhattan, KS, April 2024.

979-8-3503-7240-3/24/$31.00 ©2024 IEEE

To solve the state estimation problem, weighted least squared (WLS) is utilized. WLS will minimize the measurement residuals after weighing each of the measurements. Therefore, WLS is especially useful when wanting to give different weights to certain measurements dependent upon their error. So, the more accurate measurements are more important when minimizing the residuals. The resulting estimated states found using WLS state estimation is

$$\boldsymbol{x} = (\boldsymbol{h}^{\boldsymbol{T}}\boldsymbol{R}^{-1}\boldsymbol{h})^{-1}\boldsymbol{h}^{\boldsymbol{T}}\boldsymbol{R}^{-1}\boldsymbol{z} \tag{2}$$

where **R** is the weight matrix that includes the measurement error covariances. Within this matrix, the diagonal values of $\boldsymbol{R}$, R_{ii}, are equal to σ^2 and all other values are zero. Due to the non-linearity of the power equations, the WLS solution is found via an iterative process.

B. Electric Field and GICs Relationship

The calculations to find neutral GIC from the electric field are covered in [13] and are summarized in this section. First, the induced DC bus and substation neutral voltage is found by solving the DC network using

$$\boldsymbol{V} = \boldsymbol{G}^{-1}\boldsymbol{I} = \boldsymbol{G}^{-1}\boldsymbol{H}\boldsymbol{E} \tag{3}$$

where **V** is based on the north/east components of transmission lines and the electric field. Converting the induced voltages to Norton's Equivalent, then to DC current injections, find the total current injections by Kirchhoff's current law, $\boldsymbol{I} = \boldsymbol{H}\boldsymbol{E}$. Where **H** is dependent upon the length, resistance, and orientation of the lines and **G** is the line conductance values that are altered to include substation grounding resistance values. The path the current injections travel through includes the earth, grounded transformers, and connecting transmission lines. The GIC flow from node n to node m (transformer neutrals) is then found by

$$I_{nm} = g_{nm}(V_n - V_m) \tag{4}$$

where g_{nm} is the connecting line conductance found from the G matrix. The current is dependent upon the transformer types and configurations. So, I_n is the transformer neutral GIC currents

$$\boldsymbol{I_n} = \boldsymbol{\Phi_n}\boldsymbol{G}^{-1}\boldsymbol{H}\boldsymbol{E} \tag{5}$$

where $\boldsymbol{\Phi_n}$ is a sparse matrix of transformer conductance entries included to ensure the different types of transformers are accounted for. Equation (5) is the relationship between the GIC neutral currents and electric field.

C. Electric Field State Estimation

Electric Field state estimation has been done, however magnetometers are also utilized as measurements, as seen in [13]. Due to the linear relationship of the quasi-DC GICs to the electric field, they can be used to estimate the electric field and the state estimation is no longer an iterative process. Examples and implementation of linear state estimators are included in [16], [17], [18]. Utilizing the relationship between the electric field and GICs found in Equation (5) and setting it equal to the measurements over the states, the **h** equation in Equation (1) and Equation (2) is found:

$$\boldsymbol{h} = \frac{\boldsymbol{I_n}}{\boldsymbol{E}} = \boldsymbol{\Phi_n}\boldsymbol{G}^{-1}\boldsymbol{H} \tag{6}$$

Note, that **h** is a matrix with l rows, where l is the number of GIC measurements. One concern with state estimation is observability, as at least the same number of measurements as states is needed. The estimation will derive the Northern and Eastern directions of the electric field, so at least two GIC-neutral measurements will be needed. It is also worth noting that the G matrix is never fully inverted, but instead inverted using sparse matrix methods, therefore the process is relatively easy and short.

III. 2000 BUS EXAMPLE CASE

This section describes an example of estimating electric fields from GIC netural measurements using the synthetic 2000 bus Texas case [19], [20]. The synthetic 2000 bus case was chosen due to it representing the 'overall core' response of an electrical grid while still being on the smaller bus count to limit the complexity and time it takes to compute state estimation (the number of rows in the h matrix for state estimation is dependent upon the number of GIC neutral measurements from grounded transformers). The 2000 bus case has 861 transformers, therefore the h matrix in Equation 5 has a maximum row length of 861. All of the needed values in Equation 5 are found from the 2000 bus Texas case.

To increase the granularity of the estimated electric field while still allowing for overestimated values within each zone, the footprint of Texas is divided into five different zones. The GIC measurements are not placed into the five different zones equally instead, the zones are designed to match the 1-D conductivity map, found from [21].

The location of which GICs to be used as measurements are randomized throughout the different zones. There are multiple iterations using the same number of measurements but with randomized locations, state estimation is completed, then the average of the error is taken over all iterations. This is done to obtain an understanding of how well that specific number of measurements does at estimating the electric field for the grid, regardless of the locations picked.

For the simulation, the electric field is assumed to be non time varying, in reality it is quasi-DC, however to depict whether the GIC neutral measurements can accurately estimate an electric field, a constant electric field is satisfactory. Nonetheless, the electric field is going to be different across the state of Texas, so different electric fields' magnitudes and directions are also tested between the different zones.

To produce more 'realistic' results, two more different simulations are performed: without noise added onto the GIC neutral measurements and with noise added. The noise added onto the GIC neutral measurements simulate sensor noise, when applicable, are Gaussian with a mean of zero

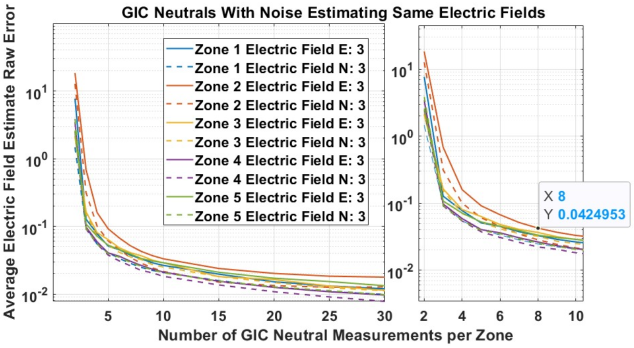

Fig. 1. Constant Electric Field for each Zone, State Estimation Residuals after 1000 iterations for different amounts of GIC Neutral Measurements with added noise

and a deviation of one. It is important to perform these two different simulations to understand whether the estimated values' deviation from the true values are caused by error due to estimating the electric field using only GIC measurements or noise from the GIC neutral measurements.

IV. RESULTS

A. Same Electric Field throughout Zones

State estimation using GIC measurements without noise and the same electric field throughout all the zones represents whether the electric field can theoretically be estimated from GIC measurements. The results found that while the minimum required measurements for observability in state estimation per zone is two, it is much more accurate to use three.

In reality, there will never be perfect measurements, so it is important to also study the GIC measurements with noise. Another simulation included GIC measurements with noise where it was seen that as the number of GIC measurements utilized decreases, the Electric Field state estimation accuracy also decreases. The results revealed that there is a significant increase in error when the number of GIC neutral measurements drops below eight. Figure 1 shows that electric field estimation that utilizes over eight GIC neutral measurements is below 0.05 V/m average deviation over 1000 iterations. The true electric field values are to the right of each label in the legend in V/m and the y-axis is the raw error in V/m ($|estimated - true|$). So, the electric field can be accurately estimated utilizing only GIC neutral measurements when the electric field is constant throughout all zones with at least eight GIC measurements utilized within each zone.

B. Different Electric Fields throughout Zones

Another reality is that the electric field will not be constant throughout the entire state of Texas, therefore the simulation needs to replicate estimating different electric fields across different zones. The results will depict whether the GICs are affected by the different electric fields in other zones enough to affect the accuracy of the estimation within its own zone.

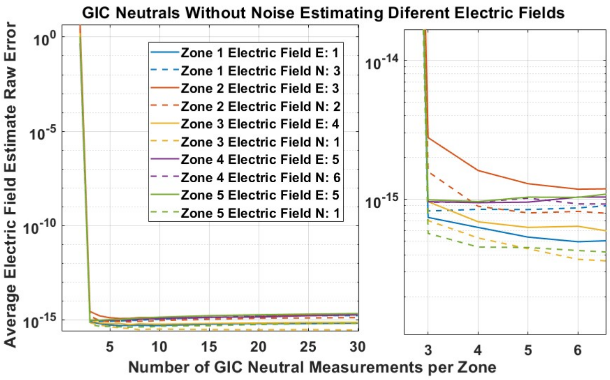

Fig. 2. Different Electric Field for each Zone, State Estimation Residuals after 1000 iterations for different amounts of GIC Neutral Measurements without added noise

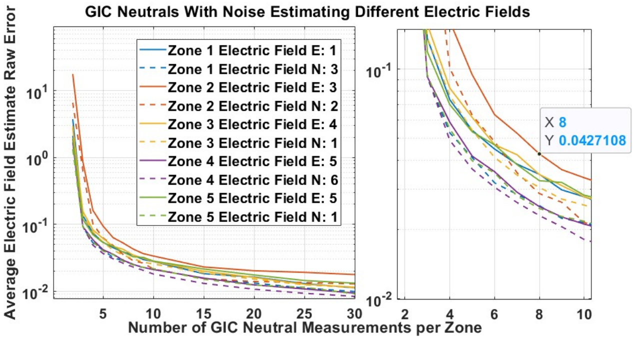

Fig. 3. Different Electric Field for each Zone, State Estimation Residuals after 1000 iterations for different amounts of GIC Neutral Measurements with added noise

Figure 2 shows the results when the GIC measurements are exactly known with different constant electric field values between the zones. Even with the different electric field values between the zones, the estimation has very low deviation and high accuracy when using at least three measurements, which is the same conclusion when using a constant electric field. Receiving the same results verifies that estimating the electric field using GIC measurements requires at the very least, three measurements within each zone.

While the overall accuracy did not change when introducing different electric field magnitudes and directions, the accuracy of specific directions within each zone fluctuated slightly. Note how in Figure 1 zone four had the lowest error for North and East directions, while in Figure 2 it is now in the upper half of the group. The zone's error is affected by the direction and magnitude of the electric field, but it does not affect the error to a significant degree. Most likely, the zones that have higher error, have transmission lines traveling perpendicular to the electric field direction and a combination of shorter lines that span parallel to the electric field [22]. Ultimately, while the error will fluctuate slightly, due to a change in the angle and magnitude of the electric field, it does not make estimating the electric field unreliable when using three or more measurements.

Constant electric fields throughout all of Texas and perfectly linear GICs will never appear in real life, so the electric field is varied throughout the different zones and noise is added to all GIC measurements in this simulation. When including different electric fields across the zones, the deviations were very similar to Figure 1. Figure 3 shows the deviations of each zone and direction as the number of GIC neutral measurements change. The order of the lines, concerning highest/lowest error, did change slightly, which again points to some zones being stronger at detecting certain angles than others. This could point to some zones requiring more measurements than others to obtain the same degree of accuracy. However, the overall error of the different zones was not significantly affected by the different electric fields.

Knowing the minimum value of GIC neutral measurements required to create an accurate electric field estimation within each zone on a synthetic grid is an important stepping stone to estimating the electric field using the actual grid. As seen in Figure 3, the measurements required to acquire an error of less than 0.05 V/m for all electric field estimations, is eight measurements per zone. The ability to accurately estimate the electric field using GIC measurements creates more fluidity, simplicity, and options concerning which instruments can be used to calculate the electric field during GMD events when magnetometers are not available.

V. SUMMARY AND FUTURE WORKS

Geomagnetic disturbances (GMDs) alter the Earth's magnetic field, inducing electric fields that create geomagnetically induced currents (GICs) within grounded transformers across transmission lines. Due to the possible affects of GICs, transformer heating, harmonics, reactive power loss, and voltage instability, it is important to monitor them. To help accurately monitor GMD events, this paper proposes utilizing GIC sensors as measurements within state estimation to find the electric field. It is found that the electric field can be accurately estimated within 0.05 V/m throughout the state of Texas when the footprint is split into five different zones and eight GIC neutral measurements are utilized within each zone.

For future work, it was not looked into how large of a deviation is considered acceptable when estimating electric fields. The estimated electric field would be utilized to calculate the GIC neutral values that were not measured throughout the system. The number of GIC neutral values to be calculated is not consistent across each zone, therefore some zones could require more accuracy than others.

It was also seen that some zones require more measurements than others to acquire the same amount of precision, and vice versa. The right mix of the number of measurements within each zone should be found. Then, the optimal number of zones within the footprint of Texas, based on the number of GIC neutral values needed, could be obtained.

Estimating the electric field using GIC measurements could also be used to verify conductivity maps. This would require magnetometer and GIC neutral measurements within a real GMD event. An estimated conductivity map could be produced by mapping the estimated electric field values (from the GIC measurements) to the magnetic field from magnetometers. The conductivity maps could then be compared to the estimated conductivity map.

REFERENCES

[1] V. D. Albertson, J. M. Thorson, R. E. Clayton, and S. C. Tripathy, "Solar-induced-currents in power systems: Cause and effects," *IEEE Transactions on Power Apparatus and Systems*, no. 2, pp. 471–477, 1973.

[2] V. Albertson, J. Kappenman, N. Mohan, and G. Skarbakka, "Load-flow studies in the presence of geomagnetically-induced currents," *IEEE transactions on power apparatus and systems*, no. 2, pp. 594–607, 1981.

[3] "Effects of geomagnetic disturbances on the bulk power system," *North American Electric Reliability Corporation (NERC)*, 2012.

[4] "High-impact, low-frequency event risk to the north american bulk power system," *North American Electric Reliability Corporation (NERC)*, 2010.

[5] M. H. MacAlester and W. Murtagh, "Extreme space weather impact: An emergency management perspective," *Space Weather*, vol. 12, no. 8, pp. 530–537, 2014.

[6] N. Homeier and L. Wei, "Solar storm risk to the north american electric grid," *Dept. Atmos. Environ. Res.(AER), Lloyd's Atmos. Environ. Res., Lexington, MA, USA, Tech. Rep*, 2013.

[7] A. Pulkkinen, S. Lindahl, A. Viljanen, and R. Pirjola, "Geomagnetic storm of 29–31 october 2003: Geomagnetically induced currents and their relation to problems in the swedish high-voltage power transmission system," *Space weather*, vol. 3, no. 8, 2005.

[8] "TPL-007-1 Transmission system planned performance for geomagnetic disturbance events," *North American Electric Reliability Corporation (NERC)*, 2014.

[9] "TPL-007-2 Transmission system planned performance for geomagnetic disturbance events," *North American Electric Reliability Corporation (NERC)*, 2017.

[10] "Reliability standard for transmission system planned performance for geomagnetic disturbance events," *Federal Energy Regulatory Commission (FERC)*, 2015.

[11] L. Marti, A. Rezaei-Zare, and D. Boteler, "Calculation of induced electric field during a geomagnetic storm using recursive convolution," *IEEE Transactions on Power Delivery*, vol. 29, no. 2, pp. 802–807, 2014.

[12] M. D. Butala, M. Kazerooni, J. J. Makela, F. Kamalabadi, J. L. Gannon, H. Zhu, and T. J. Overbye, "Modeling geomagnetically induced currents from magnetometer measurements: Spatial scale assessed with reference measurements," *Space Weather*, vol. 15, no. 10, pp. 1357–1372, 2017.

[13] C. Klauber, K. Shetye, T. J. Overbye, and K. Davis, "A gic estimator for electric grid monitoring during geomagnetic disturbances," *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4847–4855, 2020.

[14] A. Abur and A. G. Exposito, *Power system state estimation: theory and implementation*. CRC press, 2004.

[15] A. Monticelli, "Electric power system state estimation," *Proceedings of the IEEE*, vol. 88, no. 2, pp. 262–282, 2000.

[16] T. Yang, H. Sun, and A. Bose, "Transition to a two-level linear state estimator—part ii: Algorithm," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 54–62, 2010.

[17] L. Zhang, A. Bose, A. Jampala, V. Madani, and J. Giri, "Design, testing, and implementation of a linear state estimator in a real power system," *IEEE transactions on Smart Grid*, vol. 8, no. 4, pp. 1782–1789, 2016.

[18] K. D. Jones, J. S. Thorp, and R. M. Gardner, "Three-phase linear state estimation using phasor measurements," in *2013 IEEE Power & Energy Society General Meeting*. IEEE, 2013, pp. 1–5.

[19] (2016) Texas 2000-bus system. [Online]. Available: https://electricgrids.engr.tamu.edu/electric-grid-test-cases/activsg2000/

[20] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye, "Grid structural characteristics as validation criteria for synthetic networks," *IEEE Transactions on power systems*, vol. 32, no. 4, pp. 3258–3265, 2016.

[21] P. Fernberg, "One-dimensional earth resistivity models for selected areas of continental united states and alaska," *EPRI technical update*, vol. 1026430, pp. 1–190, 2012.

[22] Y. Zhang, K. S. Shetye, A. B. Birchfield, and T. J. Overbye, "Grid impact evaluation of localized geomagnetic field enhancements using sensitivity analysis," in *2019 North American Power Symposium (NAPS)*. IEEE, 2019, pp. 1–6.