The Potential for a GIC-inclusive State Estimator

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Abstract—**Power system state estimation is a key component of real-time monitoring, enabling extensive analysis and decision making for grid security and efficiency. One challenge that has seen recent interest involves the monitoring and mitigation of geomagnetically induced currents (GICs). These quasi-dc currents are the result of solar activity and can cause additional reactive power losses in transformers. The subsequent loss of reactive power support may result in voltage deviation at many buses. In a traditional state estimator, these voltage deviations may be masked by or attributed to incorrect estimations of generator reactive power output. Alternatively, the voltage state estimate may accumulate additional error, due to trying to match measurements to equations that do not represent the actual physical system and condition. This paper presents a case study that shows the need for state estimation models that consider GIC effects and analyzes the required increase in GIC-related measurements and models incurred therein.**

I. INTRODUCTION

It is widely known that solar storm events cause short term variation in magnetic fields in the atmosphere, resulting in electric fields over the surface of the earth. The presence of these electric fields induce quasi-dc currents flowing through long-distance transmission lines, neutral transformer groundings and the earth [1], [2]. Geomagnetically induced currents (GICs) can cause half cycle saturation of transformers and consequently affect the power grid with harmonics and reactive power losses [3]. The presence of harmonics in the system can result in the loss of reactive power support, such as static VAR compensators, and contribute to a total voltage collapse. The potential of geomagnetic disturbances (GMDs) to impact power grid operation has been known for decades and is receiving increased recognition as the North American Electric Reliability Corporation (NERC) has mandated assessments and plans for industry.

GICs flowing through the transformer neutral can have detrimental effects on the transformer and on overall system operation due to half cycle saturation of the transformer, leading to transformer heating, harmonics and additional reactive power losses. This can result in transformer damage and cause stability and reliability issues in the system [4], [5]. To better understand and mitigate these negative impacts, improved GIC modeling and monitoring is being initiated by electric power researchers and utility industries, see e.g., [6]–[9]. The effects of GMDs are typically modeled from a dc network analysis perspective [10]. Some of the necessary system information, such a transmission line impedances, are regularly needed for power system analysis, while some data, such as substation grounding resistance and transformer related constants, may not be known. There do exist techniques for improving substation grounding resistance models using estimation from GIC measurements [11], but at this time, there is generally a lack of measurement devices installed on the electric power grid to measure GIC-related quantities. In practice, only a small number of transformers are equipped with GIC neutral current monitors. Another key input for GIC analysis is the electric field, E. Rather than measuring it directly, electric field is often estimated from magnetic field measurements and earth conductivity profiles. These measurements are also limited in availability. Mitigation strategies, both from planning and operations perspectives, necessitate accurate models and increased metering, as well as the tools to effectively process that information. Similar to how power system state estimation (PSSE) is used to clean and consolidate data for use in other processes, comparable or augmented techniques for GIC-related values may soon find application among power system operators.

Provided good models exist, further studies can analyze the effects of GICs and develop control techniques to mitigate their effects. For example, the additional reactive power losses in the system can cause distortion and collapse of the voltage profile [5]. Regarding mitigation of the effects, short-term operational strategies are greatly reliant on visibility of the current system state, while long-term techniques still require accurate modeling and some measurement availability [12].

State estimation for transmission systems is an extensively studied topic with established algorithms that enables nearly real-time system status updates by processing measurement data. This situational awareness provides valuable inputs for management system functions for system security and control [13], [14]. To the best of the authors' knowledge, this is the first work to consider the effects of GMD on state estimation accuracy. Though the error varies with the measurement set, in general a traditional state estimator does not correctly account for the reactive power losses in transformers due to GICs.

This paper motivates a GIC-inclusive state estimator for an accurate assessment of the system state during GMD events. Using the UIUC 150 bus case [15], [16], the analysis shows that without considering the additional reactive power losses due to GICs in transformers the estimation can veer from the desired solution. In addition to motivating GIC-augmented models for state estimation, potential challenges of the endeavor are considered, such as lack of measurement

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observability, unknown measurement error models for new measurement types, and practical implementability. Future work will develop the proposed methods under the assumption that these shortcomings have been addressed.

The rest of the paper is organized as follows: Section II details the modeling of GICs from a dc analysis perspective as well as the traditional ac state estimator. Section III presents a motivating case for the inclusion of GIC modeling in the standard PSSE framework using analysis performed on the UIUC 150 bus case. Recommendations for an augmented and improved state estimator are explained in Section IV, while the conclusion is presented in Section V.

II. MODELING

A. DC GIC Modeling

The GIC injections are determined by solving the dc network described in [10],

$$\mathbf{I} = \mathbf{G}\mathbf{V} \tag{1}$$

where G is a square matrix of conductance values (in Siemens) augmented to include substation neutral buses and substation grounding resistances values. The vector $\mathbf{V}$ is comprised of the bus dc voltages as well as the substation neutral dc voltages induced by GICs. $\mathbf{I}$ is linear with respect to the electric field $\mathbf{E}$ and dependent on the length and direction of the transmission lines.

GIC flows from node n to node m are determined by

$$I_{nm} = g_{nm}(V_n - V_m) \tag{2}$$

where g_{mn} is the connecting line conductance. The effective GIC, $\mathcal{I}_t$, is the effective per phase current depending on transformer t. For simple cases, such as for GSU transformers, $\mathcal{I}_t$ is merely the current in the grounded (high-side) winding. Otherwise $\mathcal{I}_t$ depends on the current in both coils [10]. According to [6],

$$\mathcal{I}_t =\mid I_{H,t} + \frac{I_{L,t}}{a_t} \mid \tag{3}$$

where $I_{H,t}$ is the per phase GIC going into the high side winding, the series winding for an autotransformer, $I_{L,t}$ is the per phase GIC going into the low side of the transformer, and a_t is the transformer turns ratio. GIC flows through a transformer increase its reactive power losses linearly with respect to the effective GICs. The additional reactive power loss in Mvar is given by

$$Q_{loss,t} = k_t V_{pu,t} \mathcal{I}_t \tag{4}$$

where $V_{pu,t}$ is the per unit ac terminal voltage for transformer t, and k_t is a scalar specific to the transformer with units of Mvars/amp [17]. These losses due to the GICs in the dc network affect the ac network by drawing additional reactive power and generally lowering the system voltage profile. Future sections will highlight the effect that failing to account for GICs during a GMD can contribute to error in the state estimation process.

B. AC State Estimation Model

Standard PSSE programs are typically formulated as overdetermined systems of nonlinear equations, solved as a WLS problem [14]. For the state vector $\mathbf{x}$ with length n and measurement vector $\mathbf{z}$ with length m let

$$z_i = h_i(\mathbf{x}) + \mathbf{e_i} \tag{5}$$

be the (nonlinear) measurement model. The relationship between the ith measurement and the states $\mathbf{x}$ is captured in the function $h_i(\cdot)$ while e_i is the measurement error, assumed to have zero mean and variance σ_i^2. WLS state estimation is cast as an optimization problem with a quadratic objective and equality/inequality constraints representing power flow equations. Where the following measurements are typically included (if available): real and reactive power flow and injection, current magnitude flow and injection, voltage magnitude and angle difference, and turns ratio magnitude and phase shift angle (for transformers), the state variable $\mathbf{x}$ is often comprised of the nodal voltage, both magnitude and angle.

Iterative methods are the standard approach to solving the WLS state estimation problem formulated as the minimization of the unconstrained optimization problem.

$$\mathbf{J}(\mathbf{x}) = \frac{1}{2}\sum_{i=1}^{n} \frac{r_i^2}{\sigma_i^2} \tag{6}$$

where r_i is $z_i - h_i(\mathbf{x})$, the residual. The first-order optimality condition relates the Jacobian matrix $\mathbf{H}$, the (diagonal) weight matrix of measurement variances $\mathbf{R}$, and the residual $\mathbf{r}$. By Taylor series expansion and ignoring second-order terms, the Gauss Newton method is often used in practical implementations, following the iterative procedure

$$\mathbf{G}(\mathbf{x}^k)\Delta\mathbf{x}^k = \mathbf{H}^T(\mathbf{x}^k)\mathbf{R}^{-1}\mathbf{r}(\mathbf{x})$$
$$\mathbf{x}^{k+1} = \mathbf{x}^k + \Delta\mathbf{x}^k$$

where the gain matrix $\mathbf{G} = \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}$. Generally, $\mathbf{G} = \partial^2\mathbf{J}/\partial\mathbf{x}^2$ and the Newton Raphson method, with quadratic convergence, would include the second-order term of the Hessian. It should be noted that ill-conditioning and convergence issues can arise from factors such as the use of vastly varying weighting factors or topology and parameter errors. There exists a large collection of work dedicated to improving the numerical robustness of practical solutions [18], but those issues will not be addressed in this work.

C. GIC-Induced Reactive Power Losses

Consider a power network during a geomagnetic disturbance. The effective GICs induced in the transformers lead to reactive power losses, modeled at the transformer nominal high side bus. These losses affect reactive power flows in the system, in turn drawing more reactive power from the sources to maintain the voltage level. When monitoring such a system, these losses may not be accounted for or misattributed, depending on the measurement set. These modeling errors may manifest as topology errors or bad data skew, lowering the accuracy and credibility of the returned state.

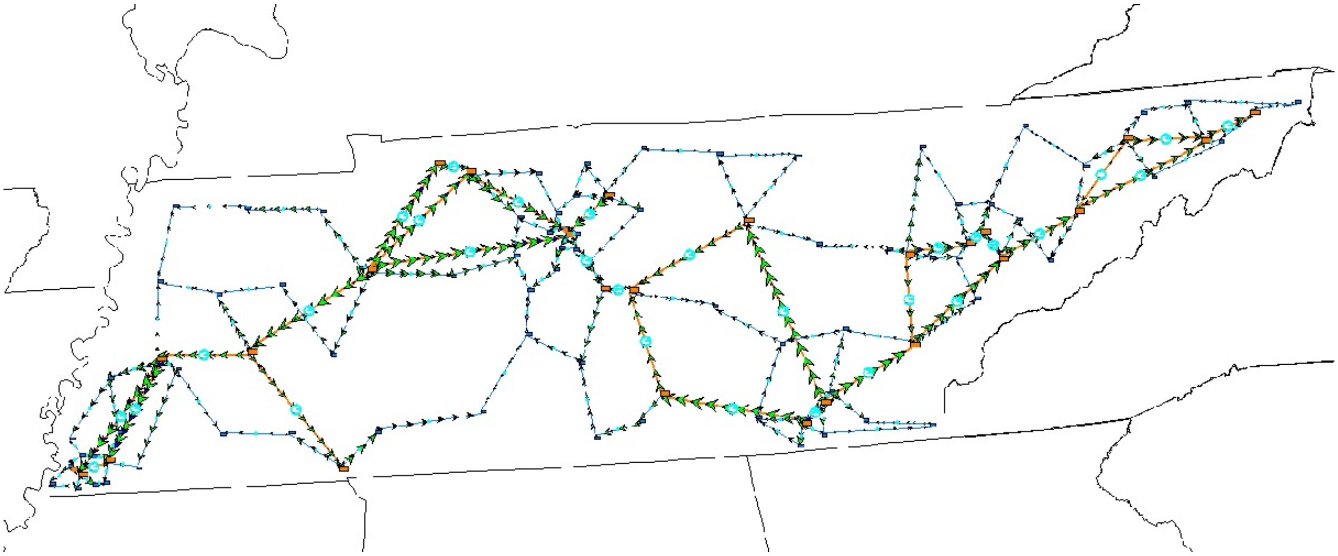

Fig. 1. One-line diagram of the 150 bus (synthetic) system

A bus reactive power injection measurement is a summation of all the transformer branch reactive power flows that include the reactive losses for transformers in their corresponding branches. For an increasing percentage of power injection measurements (and thus increasing number of inaccurately modeled bus injections), the error will be more, on average, as compared to increasing branch flow measurements.

III. MOTIVATING CASE AND RESULTS

A. *Test Case*

The following studies are performed on a 500/230 kV 150-bus synthetic system [16], depicted in Fig. 1. Electric fields of varying magnitude and direction are applied to the system using PowerWorld Simulator, by which the GIC flow is solved and the resulting GIC-induced reactive power losses are determined. The system power flow can then be solved including these additional losses. To generate artificially noisy measurements for use in the state estimator, the power flow results are exported and random Gaussian noise is superimposed in accordance with the following noise levels: $\sigma_i = 0.01$ for voltage magnitude measurements and $\sigma_i = 0.02$ for power flow and injection measurements. Because not every bus and line is monitored in real life, the set of available measurements is also randomized. The results only include those random measurements sets which provide sufficient coverage such that the system is solvable (observable). Across the different test scenarios, the percentage of the maximum number of available measurements actually used range from 55%-80% (power flow), 65%-100% (power injection), and up to 50% (voltage magnitude).

B. *GIC Effects on State Estimation Accuracy*

The changing magnetic fields that induce surface electric fields can produce electric fields of varying magnitudes and direction. In this work, it is sufficient to use a uniform electric field to illustrate the potential loss of accuracy in the estimate due to a GMD. First, the magnitude of the electric field is increased with a fixed direction $(50°)$. The average absolute error as a function of storm magnitude is shown in Fig. 2, where the error (the difference between the voltage magnitude estimate and the known actual voltage magnitude) is averaged over all the states over 100 simulations with random noise and (solvable) measurement sets. The maximum absolute error is also shown (Fig. 3). This illustrates the worst case scenario for a returned estimate and follows a similar (and expected) trend as seen in Fig. 2, where an increase in storm magnitude leads to increased reactive power losses and increased accumulated estimate error.

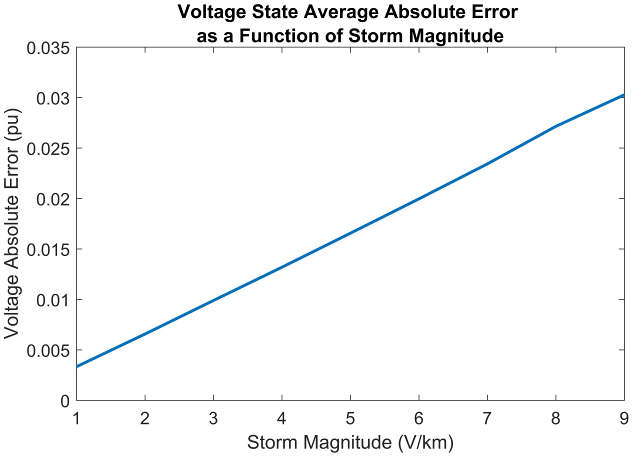

Fig. 2. The average absolute voltage error increases with increasing storm magnitude

Next, the direction of the electric field is varied from 0 to $360°$ while the magnitude remains at 4 V/km. Note that the error seems to follow a cyclical trend, which follows from the

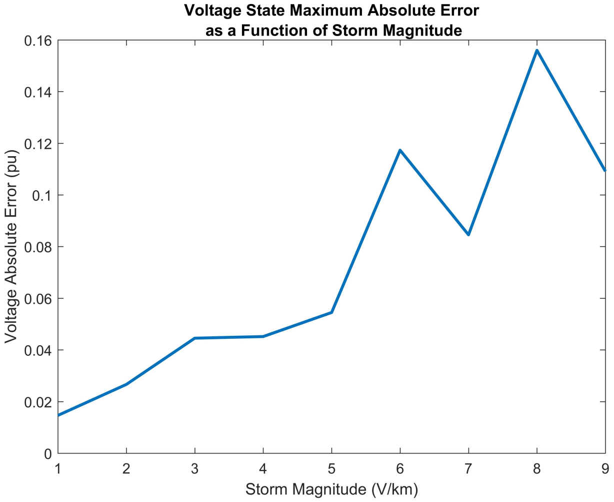

Fig. 3. The maximum absolute voltage error generally increases with increasing storm magnitude

fact that the induced GICs are greater on lines that are parallel to the storm direction.

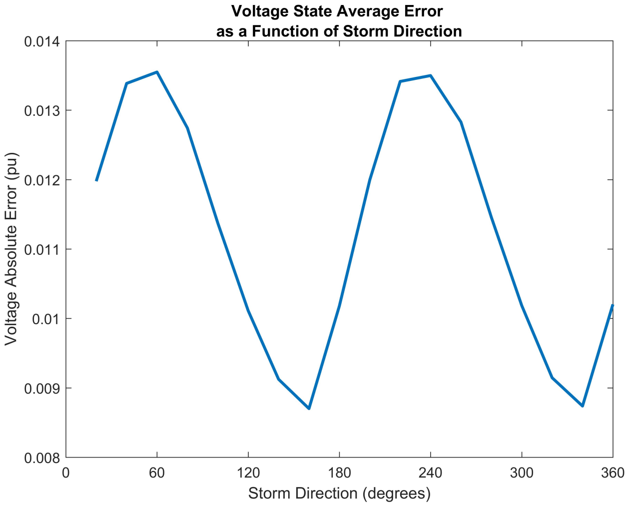

Fig. 4. The average absolute voltage error varies periodically with varying storm direction

Lastly, the storm magnitude and direction are held constant (4 V/km at 50°) while the ratio of power flow to power injection measurements are varied. Fig. 5 illustrates the phenomenon described in Section II-C, where including more power flows measurements (as opposed to power injection) improves the accuracy of the state estimator. Fig. 6 exhibits interesting behavior; it appears that due to the influence and strong coupling of the power flow measurements to the GIC-influenced voltage state, when all the power flow measurements are available, an especially noisy measurement has the potential to throw off the system state estimate.

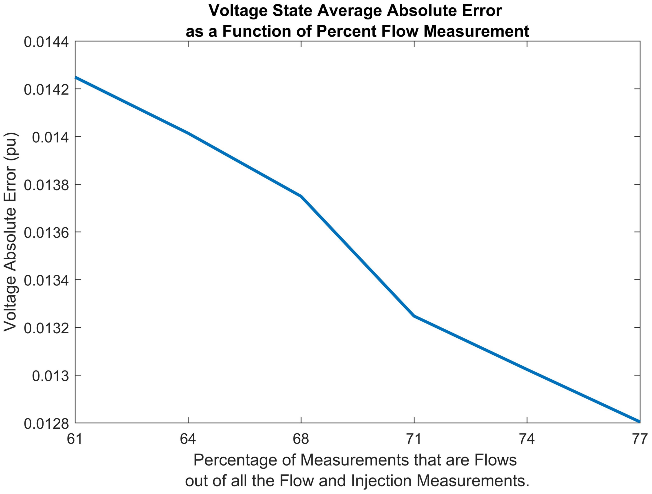

Fig. 5. The average absolute voltage error decreases as the percentage of the measurements which are power flow measurements (as opposed to power injection) increases

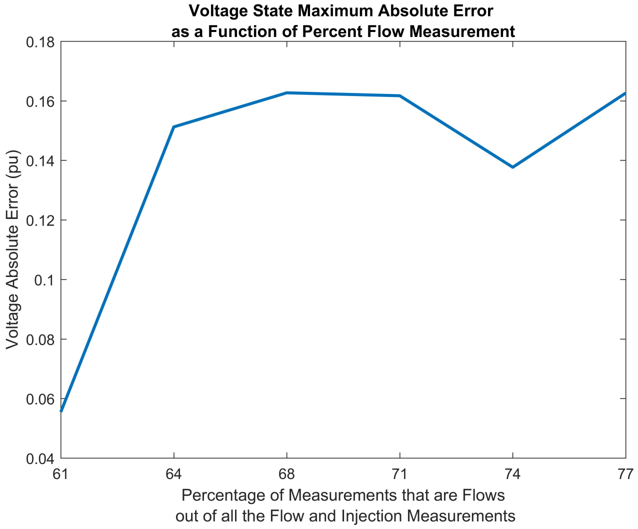

Fig. 6. The maximum absolute voltage error as a function of the percentage of the measurements which are power flow measurements

IV. RECOMMENDATIONS

As seen in the previous section, the ramifications for not considering GIC effects during state estimation are errors in the state estimate that can then propagate through other operational tools and processes. As it stands currently, there are modeling and metrology shortcomings that even with the intent to include GIC effects in the SE framework hinder the effective development and implementation of such programs. In this section, these issues are outlined and recommendations presented that would enable effective integration of GIC effects for improved SE results.

A. Network Model Considerations

There are several transformer parameters vital for GMD analysis that are not typically used in standard power flow studies. These values include winding resistances, configurations, and the k parameter. The k value especially is key for relating the effective transformer GICs to reactive power losses, according to Eq. 4. The accuracy of the SE results are dependent on knowing the accurate types and values of the transformers in the system. Additionally, the substation grounding resistance is needed to build the $\mathbf{G}$ matrix of Eq. 1. This value can be measured in the field, but it is a function of local earth and soil conditions and dependent on varying atmospheric conditions, i.e. temperature. System operators often estimate the value or use an outdated measurement. Techniques exist for estimating the substation grounding resistance, but they do require sufficient placement of GIC measurements [19]. There is also potential to use the same relationships for incorporating GIC reactive power losses into the standard ac state estimator to develop a time-varying estimator that can be leveraged to validate the substation grounding resistance values. Again, this requires at least as many GIC measurements as resistances to be estimated.

B. State Estimation Formulation Considerations

The ill-conditioning that occurs in traditional SE is often related to the squared form of the gain matrix, $\mathbf{H}^T\mathbf{H}$, and many methods have been developed to improve convergence characteristics. As SE methods are enhanced to include GIC effects, additional variables and even states (such as GIC neutral currents or electric field values) may be appended to the model. In the same way that the voltage magnitude and angle are often the state variable for transmission SE because in conjunction with the system parameters (admittance matrix) all other values of interest can be calculated, it is clear to see that including electric field values, GIC neutral currents, or induced voltages in the state vector would enable the same functionality. Existing techniques with respect to numerical conditioning may prove applicable, while new techniques for improving conditioning and computational efficiency may manifest with these additions.

C. Increased Measurement Availability

The biggest challenge for GIC-conscious SE is the lack of relevant measurements. While the availability of magnetic field data has increased in recent years, there are still portions of the United States that are not well-metered. The conductivity profiles used to transform magnetic field data to electric field data can also be improved with additional metering. GIC monitors installed on the grid are sparse and even then, the data is not always usable due to excessive noise. Though it is expensive to install and maintain meters, the potential afforded by the additional data could prove invaluable during a GMD when one considers the importance of an accurate system state for usage in other system operation and control tools. The development of useful tools, such as enhanced SE, can be used as motivation for utilities and system operators to invest in the necessary meters. The following sections outline specific concerns regarding increasing the number of available measurements.

1) System Observability: In the event that a GIC-related value, such as electric field or GIC neutral, becomes part of the state vector, it is vital that there are enough measurements well distributed across that network such that SE is possible. If there are not enough measurements or they are poorly distributed, the system is not observable. With the addition of states, it is important to determine the critical measurements, those that when removed turn the network unobservable. Algorithms for observability analysis are often either topological or numerical [20], [21] and new algorithms which take into account these GIC-related values will need to be developed.

2) Measurement Redundancy: Measurement redundancy is the ratio of the number of measurements to the number of states. For practical transmission systems, the redundancy is often between 1.7-2.2 [14] and lower for distribution systems. The higher the redundancy, the more likely the SE will effectively filter out measurement noise and additional techniques may be enacted to detect bad data or topology errors. Meter placement algorithms can be developed to improve both the observability and measurement redundancy.

3) Unknown Measurement Error Parameters: A key element of the WLS formulation is the weighting, related to variance σ_i^2 of the measurement error e_i. While there exists a general understanding of what these values are for typical power flow measurements such as voltage magnitude and power injections, these parameters for potential GIC-related values are more mysterious. This may be further complicated by the fact that while electric field would be a logical input for SE, the "measurement" would actually be based on a magnetometer measurement, with error, transformed into an electric field value via conductivity profiles and methods that may also add error. Future studies with real data would greatly enhance the understanding of appropriate error models for GIC values as measurements in SE.

V. CONCLUSION

In this paper a case study is used to show the importance of considering GIC effects in the traditional SE framework under GMD. For sufficiently large GICs, additional reactive power losses in grounded transformers affect the voltage profile. When these changes are not accounted for in the SE model, additional error in the system state is incurred. The paper also suggests directions for future work and notes the importance of increased metering to accomplish such future tasks. Enabled by new GIC-related data, the existing system models can be improved and validated with a broader and more accurate picture of the near-real time system state provided.

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