Real-Time Monitoring Applications for the Power Grid under Geomagnetic Disturbances

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***Abstract*—Prior research on the impact of geomagnetic disturbances (GMD) on the electric grid has mainly focused on improving GMD modeling for off-line analyses. Given the recent industry emphasis on monitoring the earth's magnetic field and geomagnetically induced currents (GIC), this paper describes a real-time GMD monitoring system. The real-time magnetic field measurements come from a network of six magnetometers installed in the US State of Texas. The paper focuses on the real-time GIC monitoring application implemented in a simulation environment, which could be extended to the real grid. The magnetic field measurements are coupled with ground conductivity models to calculate real-time electric fields, which are passed to a grid model to estimate and visualize GICs in real-time. Results are demonstrated on a synthetic but realistic and publicly available model of the Texas grid. The simulation environment is interactive with communication capabilities, making operational control and GMD mitigation possible in the near future.**

***Index Terms*—geomagnetic disturbance (GMD), geomagnetically induced currents (GICs), magnetometers, real-time monitoring, visualization**

I. Introduction

Quasi-dc geomagnetically induced currents (GICs) induced in the power grid by geomagnetic disturbances (GMDs) can cause half-cycle saturation in transformers, leading to harmonics, heating, and increased reactive power losses. Voltage collapse has been recognized as the key risk posed by GMDs to the grid [1]. Hence, GMD assessments of power systems have become important, and mandated by regulatory bodies [2]. Recognizing this, research on modeling GICs in power systems has progressed significantly, with several offline tools developed and available to study large systems [3]–[7]. Some of these also include ground conductivity models to convert magnetic field, B, into geoelectric field, E.

However, there are relatively few papers on the implementation of such tools in an online environment with monitoring and control, apart from [8], [9]. For instance, Hydro-One's real-time GIC solver [10] used actual system configuration, and supervisory control and data acquisition (SCADA) information from the network management system and real-time B measurements from the Ottawa magnetometer as input. Mitigation measures were pre-planned using a large number of offline studies. Recently, with the increasing deployment of GMD and GIC sensors, more utilities have started incorporating this data in their online environment. The utility operating the largest transmission system in the US uses a PI Historian database to store GMD monitoring data for creating real-time displays for operators and post-event analysis [11]. Operating procedures and visualization tools are developed and refined based on monitoring data such as the US National Oceanic and Atmospheric Administration (NOAA) GMD alerts, magnetic field measurements, transformer GICs and reactive power losses, temperature rise, harmonics, etc. At another utility, the state estimator is tuned to address potential issues that can be caused by GMD-induced losses [12]. They also have tools to visualize their real-time, GIC-related data such as GICs from monitors installed at critical locations.

There are likely more real-time implementations currently available or under development. However such tools often tend to be proprietary, or confidential due to security concerns. Thus, the details of the underlying techniques remain undisclosed to the engineering and research community at large. To address this gap, this paper describes the implementation of a real-time GIC monitoring system that makes use of real-world B measurements, and a synthetic, simulated power grid.

There are more factors behind the need for online monitoring and analysis tools for GMDs. Offline studies with conceivable contingencies are important to assess and mitigate the GMD threat. They can be used to plan corrective actions in advance, after studying a variety of scenarios (i.e. operational mitigation). However, experiencing and responding to an actual, severe GMD event can be a different challenge altogether, especially when a scenario or a cascade of events occur, which were not analyzed before. This is quite possible, given that strong GMDs are rare (or yet to come), and so there is no precedent or post event analyses to help guide future operations in such cases.

Regardless, the importance of GMD and GIC monitoring is coming to light in recent times, with the recognition that existing systems are quite minimal or under-developed and there is a need for good monitoring, visualization, and analysis tools in the grid operations time frame. With this in view, this paper describes an implementation of a real-time GMD monitoring system. The different components of this system are described using a 2000-bus synthetic but realistic test system, based on the footprint of the US state of Texas [13]. A key reason behind choosing this test system is that the authors have deployed magnetometers around Texas to acquire B measurements for research purposes.

Section II describes this network that forms the basis of the monitoring system and how these B measurements are used to calculate E. Section III describes the GIC Simulation and Visualization Environment, starting from, wherein these E estimates are fed to the Texas grid model, in order to estimate GICs from the real-time B measurements. Visualization methods for transformer GICs are also discussed, with the paper summarized in Section IV.

II. Magnetic and Electric Fields

A. Magnetometer Measurements

Variations in the geomagnetic field during space weather events are measured using a magnetometer. In this case, we use real-time B measurements from the Texas A&M University Magnetometer Network (TAMUMN) [14]. Fig. 1 shows the locations of the installations. The B data is transmitted in real-time ($<$1 second latency). The goal of this paper is not to describe the complete measurement system but to demonstrate how such measurements can be used in estimating GICs in real-time for eventual use in operations and mitigation in, perhaps, a utility environment.

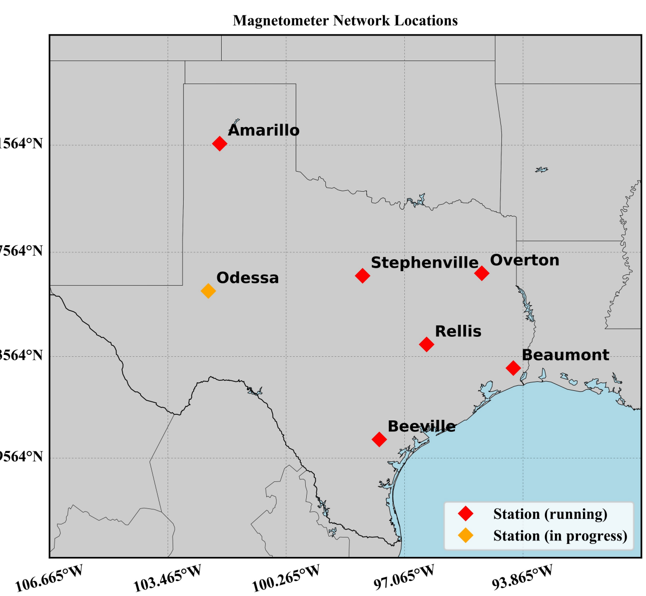


Fig. 1. Magnetometer Network Locations: Amarillo (AMR), Beaumont (BMT), Beeville (BVL), Overton (OVR), RELLIS (RLS), and Stephenville (STP). Odessa (ODS) station in Far West Texas was installed under a prior project; its data will be added to the TAMUMN shortly

The sensor at the heart of the system is a triaxial fluxgate magnetometer [15]. These low-noise sensors produce a set of voltages proportional to the observed magnetic field strength. The magnetometer data acquisition system produces a 1-Hz 3-component vector sample of the geomagnetic field, which is transmitted in real time to a database archive hosted on a cloud-based virtual machine. The B measurements from these sites are used to calculate E for the Texas footprint as they are the key inputs to the grid model (and the actual grid) that produce GICs. The methodology behind this is described next.

B. Electric Field Calculations

The induced E is estimated using the cloud-based AVERT™ commercial software application [16], with all sensors in the TAMUMN providing input. The calculation method is derived from standard techniques (e.g., [17]) applied in the frequency domain, described in [18]. To produce the E across the analysis region, the B is interpolated in frequency bands using krigging techniques [19], with empirically-determined interpolation lengths [20], [21]. The ground response is given by the surface impedance calculated from the regional "one-dimensional" ground response models used in the North American Electric Reliability Corporation (NERC) TPL-007 standard [2], using a plane-wave approximation. Updated ground response models in Texas will be incorporated as they are validated [21] and made publicly available.

From this method, the E is estimated on a 0.5-degree grid spacing, and provided in a binary file format called *.B3D [22], updated once per minute. The new data are immediately available for access through AVERT's Python API. Fig. 2 visualizes the surface E amplitude estimated for the Texas footprint with the 0.5-degree grid spacing. The colors represent the variation in the E magnitude, on a magnetically quiet day. This combined B measurement and E estimation system can be used in conjunction with not only a simulated testbed environment, but also potentially in actual utility control room operations for GMD situational awareness.

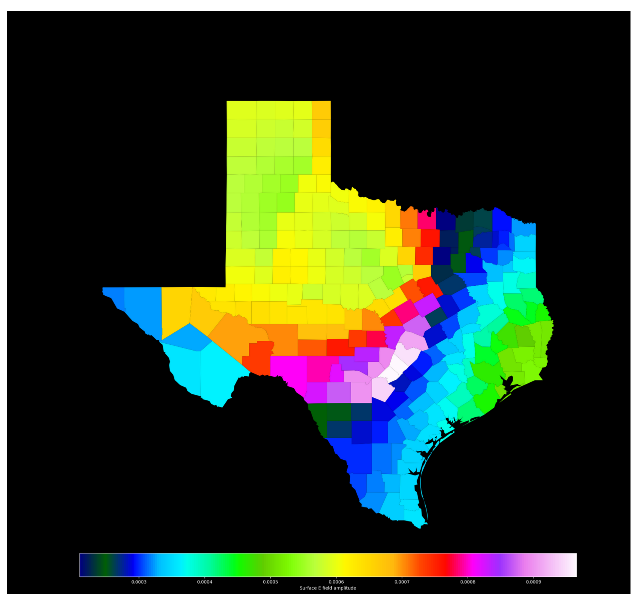


Fig. 2. Surface electric field amplitude

III. GIC Simulation and Visualization

A. Converting Electric Field to GIC

In the event of a GMD, the actual power grid would be subjected to the spatio-temporally varying electric field, which can be estimated by the process described so far. This electric field induces GICs in the grid. To model this phenomenon, we input the estimated E into a model of the power grid. The effect of non-uniform electric fields in the power grid model is represented as a dc voltage induced in series with the transmission lines [23], [24]. To calculate the GMD-induced voltage U_k on a transmission line k, the electric field is integrated over the line's length as,

$$U_k = \int_R \vec{E}.\vec{dl} \tag{1}$$

where R is the geographic route of the line, $\vec{E}$ is the electric field along this route, and $\vec{dl}$ is the incremental line segment.

Referring to Figure 2, E is estimated over the footprint of the analysis region by dividing it into a two-dimensional spatial grid (not to be confused with the power grid) of $0.5° \times 0.5°$ latitude and longitude. There is also a third dimension of time since this is a spatio-temporally varying electric field. Transmission lines are divided into segments contained in the squares or blocks of the spatial E grid. Each such spatial block b could be experiencing a different electric field, creating a vector E of length $2b$ of the electric field components (i.e. North and East). The distance components L_N and and L_E associated with each line are separated to represent the portion of the line in each block. Hence, (1) can be used block wise to calculate the induced dc voltage in each of the blocks by using the following expression,

$$U_b = E_{b,N} L_{b,N} + E_{b,E} L_{b,E} \tag{2}$$

where U_b is the GMD-induced dc voltage in the part of the line in block b, $E_{b,N}$ ($E_{b,E}$) is the northward (eastward) electric field over b, and $L_{b,N}$ ($L_{b,E}$) is the northward (eastward) line length. The total dc voltage induced in each line is then found by the summation of the dc voltages induced in its block segments. The linearity of these calculations make them extremely fast.

Next the set of the GMD-induced dc voltages in the lines is passed to the same power system model, however in a real-time simulation framework, henceforth referred to as the Dynamic Simulator (DS) described in [25], [26]. The DS runs a full transient stability simulation, in real-time, for up to thousands of buses. The motivation to use the DS is that it enables interactive simulations through a client-server system, paving the way for extension of this work, from monitoring to control and GMD mitigation. The DS includes modeling to perform GIC calculations, described below.

The induced dc voltages on all transmission lines are converted into Norton equivalent current injections at the buses. The total current injection can then be found via Kirchhoff's current law; the resulting vector is given by $\mathbf{I} = \mathbf{HE}$, where $\mathbf{H}$ depends on the length, resistance, and orientation of the lines. The width of $\mathbf{H}$ depends on the number of grid blocks. The solution vector $\mathbf{V}$ containing the dc voltages at substation neutrals and all the buses is then found by,

$$\mathbf{V} = \mathbf{G}^{-1}\mathbf{I}. \tag{3}$$

where $\mathbf{G}$, is built from the dc model of the power system, consisting of dc resistance values of the transmission lines, transformer winding resistances, and substation grounding resistances [27]. GIC flows throughout the grid are then derived from $\mathbf{V}$, the key results being the GIC flow in transformers.

The time step of the underlying dynamic simulation in the DS usually ranges from 4 to 16 msec (i.e. 1/4 to 1 cycle), which is typical of a power system transient stability simulation. However, knowing that the E does not vary on the same scale, it is updated every 60 sec. While higher frequency B fluctuations can contribute up to 50% of the peak E magnitude in areas of higher geological complexity [28], in Texas it is likely that longer period fluctuations ($>$ 1 min) are the primary contribution. It is interesting to note that the E calculation is based on 1-second cadence B, even though the update time for the output is every minute.

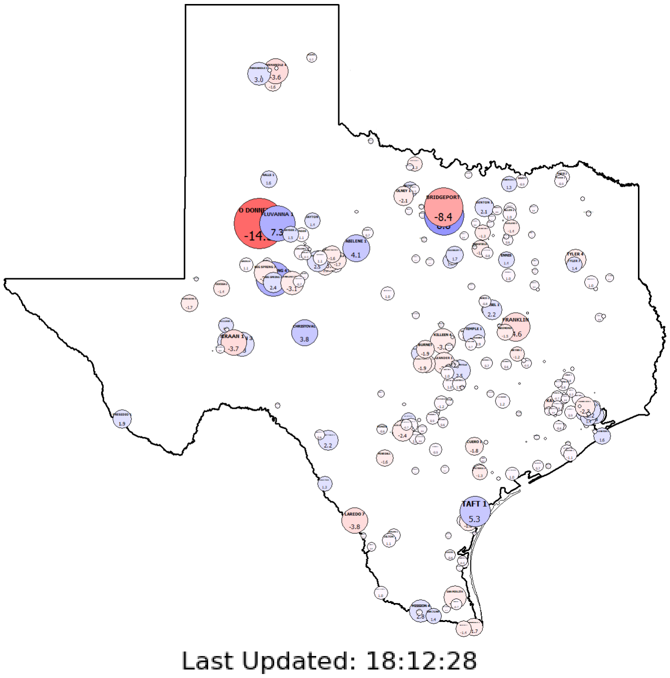
B. Data Communication

For post-event or offline analysis, a B3D file or other electric field input can be uploaded to the power system model of interest and the resulting time varying series of voltage inputs saved with the model. To run time-varying input simulations where the inputs are not known ahead of time, i.e., real-time, requires leveraging the communication capabilities between the different softwares. Interacting with a commercial GIC package such as PowerWorld Simulator is aided by the SimAuto functionality and the Python package Easy SimAuto (ESA) [29]. SimAuto commands automate applying a B3D file received from AVERT as electric field input, running a GIC simulation and procuring the resulting dc voltage values for every line in the system at the moment. This information is then passed to the DS to set the GMD-induced dc voltage for a particular branch identified by bus and circuit number. These values are then integrated into the GIC model in (3).

C. GIC Visualization

A key part of this monitoring work is the visualization of different measurements and estimates such as B and E which have been discussed so far. Visualization for power system control centers often incorporates color contours to show value variation and animated arrows to display flow directions. Large displays may be geographically-based, enabling a consistent and intuitive overview to inspire a rapid response. Based on these principles, the visualization of the estimated real-time GICs is described below.

1) Geographic Data Views (GDVs): GDVs are designed to dynamically provide visualization of power system quantities, anchored in geographic information [30]. Symbols representing power systems information are placed according to their related geographic information. Symbol size, color, and shape can be used to communicate characteristics of the underlying information. As GICs are inherently location-sensitive and the corresponding geographic data already required, GDVs can be effectively used for GIC visualization. After setting up



Substation Name	GIC Amps to Neutral
O DONNELL 2	-14.48
POOLVILLE	8.82
BRIDGEPORT	-8.43
FLUVANNA 1	7.26
BIG SPRING 4	6.77
TAFT 1	5.31
FRANKLIN	-4.61
ABILENE 1	4.08
CHRISTOVAL	3.84
LAREDO 7	-3.77

Fig. 3. Real-time GIC visualization for the Texas footprint using GDVs. Table that updates with the DS interface to display substation names corresponding to the transformers with the largest magnitude neutral currents.

how the magnitude and sign of GIC to neutral values will be represented, the DS display will update as new information is provided or calculated in simulation. For this particular display, larger circles correspond to greater magnitude currents, while the color fill (red or blue) corresponds to the direction of the flow (negative or positive, respectively). The display begins to update every minute, in correspondence with the update rate of the electric field information. The transfer of information and re-rendering of the display takes less than 10 seconds, so a greater refresh rate is feasible if desired. Furthermore, to provide operators with additional insight, as they may not have the same intuition about GMD effects as they do about normal grid operations, a client provides a table of substations ranked by largest magnitude of GIC to neutral transformer current. It also shows the last updated time and an electric field multiplier, if used for demonstration purposes as

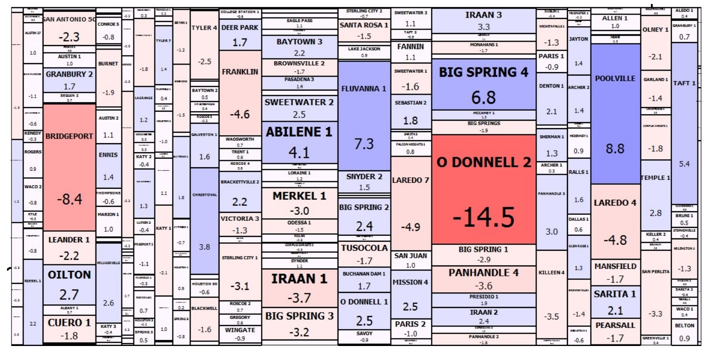


Fig. 4. Pseudo-geographic mosaic display of the real-time GICs

the electric field during quiet periods is too small to produce noticeable GICs. Fig. 3 shows an actual GDV display at a snapshot in time during a quiet period. The substations with the transformers with the largest currents are also provided.

2) Pseudo-geographic Mosaic Display: A new method for wide-area visualization of grid information known as pseudo-geographic mosaic displays (PGMDs) is also used [31]. This method leverages dynamically created GDVs and arranges them to maximize the usage of the display space while maintaining some semblance of the geographic anchoring of the information. Similar to GDVs, the color hue indicates the direction of the current flow, while the color intensity and box size indicates the magnitude. Fig. 4 shows an actual PGMD display at the same snapshot in time as shown in Fig. 3.

D. Overall Monitoring System

The overall GIC real-time monitoring system can be summarized as shown in Fig. 5. The real-time B measurements are collected from each magnetometer in the TAMUMN every second and uploaded to a cloud-based server where the data is used to calculate E every 60 seconds. This is converted into the B3D format and fed to the Texas 2000 power system model to calculate the line induced dc voltages. These voltages are communicated to the DS to calculate system GICs in real time, where one can also visualize these values through techniques including geographic methods. The GICs simulated from real-time B measurements discussed so far could be compared with measured GICs for model validation. GIC measurements from transformers could be added to this monitoring system to include more measurements. This can also help in applications such as GIC estimation which does make use of system measurements. Since GIC estimation has been already covered in depth by the authors in [32], [33], it is beyond the scope of this paper and hence not included in the discussion.

IV. Summary

The paper has presented a methodology and an example implementation of a real-time GMD monitoring system, focusing on visualizing system GICs in a real-time environment. It has made use of a realistic power grid test system, an actual magnetometer data network, and sophisticated power system simulation tools to incorporate and communicate different

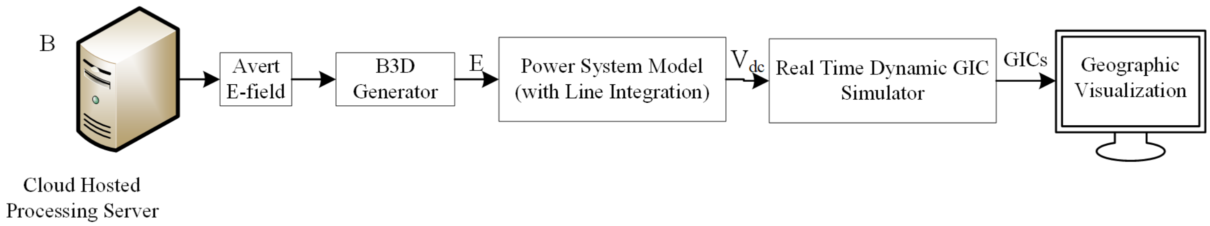


Fig. 5. Real-Time Monitoring and Simulation System

measurements and values. Work is ongoing to extend this framework to real-time monitoring and control, aided by online analyses to better inform operator decisions. A major benefit of using the DS in this system is its communication capabilities that simulate a more realistic power system operating environment including topology changes, and enable users to interact with the grid and take actions, making it suitable for education, research, and training.

Acknowledgment

This paper is based on work funded by the NSF Grant 1916142, the State of Texas under the Governor's University Research Initiative, and the Texas A&M University.

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