# MATGMD: A Tool for Enabling GMD Studies in MATLAB

Gandhali Prakash Juvekar, *Student Member, IEEE*, Katherine Davis, *Senior Member, IEEE*,
Department of Electrical and Computer Engineering
Texas A&M University, College Station, Texas 77840
Email: {gandhalijuvekar, katedavis}@tamu.edu

*Abstract*—Geomagnetic disturbance (GMD) has the potential to cause Geomagnetically Induced Currents (GICs) that disturb the power grid by circulating harmonics in the system. These quasi-dc currents give rise to additional reactive power losses in high-voltage transformers. Their combined presence can result in a loss of reactive power support that could even lead to a total voltage collapse. GMD events effecting the grid at such a scale render their study important. MATGMD is an open-source MATLAB® based package for Geomagnetic disturbance studies that provides tools for analyzing uniform electric field GMD events to extract crucial system information like transformer neutral currents, for one. Various such system values could be used for stability, mitigation or estimation studies by researchers, educators and students. Efforts have been made to make more system information available using as little input data as possible. This paper presents the details of the network modeling and the corresponding formulations used by MATGMD. It discusses the flexibility with which the GMD related system information can be extracted as per the need of the user depending on the nature of study to be carried out. Simulation results for two test cases are presented using techniques to compare them with output obtained from PowerWorld® Simulator.

## I. INTRODUCTION

This paper intends to introduce and inform, the academia and industry, about the open-source MATLAB based GMD package, called MATGMD developed by the authors. This tool aims at equipping power systems researchers and engineers with the ability to obtain important, GMD-related, dc system parameters during GMD events, with the observed uniform electric field, in MATLAB. Mitigation and reliability studies can be aided with the use of MATGMD for analysis. Currently, the analysis and simulations have been performed on the EPRI 20-bus case and the UIUC-150 bus case. The tool, MATGMD is actually inspired by MATPOWER which is a tool for steady-state operations, planning and analysis for power systems [1].

MATGMD is a set of MATLAB M-files designed in an attempt to give the user the best performance possible. The code is simple and efficient making it easy to understand. It can also be customized to fulfill the needs of the GMD study that the user intends to perform.

MATLAB is a popular and crucial tool for scientific computing. It is a high-level language suited for matrix computations with robust math libraries. It provides a GUI with exceptional visualization capabilities and also has an active community of both, users and developers [1]. Because of its powerful and high-level scientific computation capabilities, it is well suited for the numerical computations required for GMD related power system studies.

Before detailing the tool and it applications, it is necessary to understand the theory behind the occurrences of GICs. Solar coronal mass ejections (CMEs) can disturb the Earth's geomagnetic field. These geomagnetic disturbances causing rapidly varying magnetic field in turn induce electric fields over the surface of the earth. The presence of these electric fields drive quasi-dc currents flowing through long-distance transmission lines, neutral transformer groundings and the earth [2]–[4]. Geomagnetically induced currents (GICs) can cause half cycle saturation of transformers [5] and consequently affect the power grid with harmonics and reactive power losses [6]–[8]. 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 harmonics also cause transformer heating that can result in transformer damage and cause stability and reliability issues in the system [9], [10].

Past GMD events such as the 1989 Quebec blackout are examples that demonstrates the vulnerability of the highly interconnected and otherwise highly reliable North American power grid to solar storms [11]. Therefore, there have been several efforts towards improving GIC modeling, electric field estimation [12]–[17] and implementing GIC mitigation techniques for sustaining the secure and reliable delivery of electric power [2], [18]–[20]. GIC mitigation programs as per [6] includes monitoring and predicting space weather, GIC modeling and risk assessment, grid monitoring enhancement, GIC reduction devices, and designing operating procedures. The studies pertaining to modeling, mitigation and reliability for GMD events can be performed on MATLAB. The ease of performing these studies can be greatly aided by a tool that gives the dc system parameters.

The need for a tool that facilitates GMD studies arose while working on one such GIC modeling perspective - the Power System State Estimation (PSSE) problem on MATLAB, that is motivated by additional reactive power losses in transformers due to the presence of circulating GICs in the system as a result of a GMD event. During a GMD event, a traditional state estimator may show voltage deviations at many buses due to incorrect estimations of generator reactive power output. Thus, the state estimates may accumulate additional error, due to trying to match measurements to equations that do not

represent the actual system topology and condition [21]. The PSSE problem involves extracting various system values at dc level and information about the GICs at every high-voltage transformer in the system under study. The GMD tool was hence developed in an effort to aid with the extraction of the desired system information.

This paper details the traditional GIC modeling and its implementation in MATLAB. Two test cases: EPRI 20-bus case and UIUC 150-bus case have been used for validating the results. Potential challenges with modeling on MATLAB include the availability of input data, accuracy and credibility of input parameters like transformer high side and low side dc resistance, substation neutral dc resistance, line dc resistance, MATLAB rounding-off errors and practical implementability. Future work will focus on equipping the toolbox with the capability to perform GIC analysis with non-uniform electric field and make more test cases available for the same.

The rest of the paper is organized as follows: Section II details the modeling of GICs from a dc analysis perspective and describes the implementation process on MATLAB. Section III presents the results obtained upon using the tool for two cases - EPRI 20-bus case and UIUC 150-bus case and are verified using PowerWorld. Conclusions and future work are explained in Section IV.

## II. SYSTEM MODELING

This section details the system modeling for GMD events that result in GICs and explains the implementation in MATLAB for the tool. By Faraday's law, the changes caused during a GMD event in earth's magnetic field induce a geoelectric field above Earth's surface. The induced electric field is proportional to the rate of change in magnetic field and depends on the ground conductivity of the location. The tool currently uses a uniform electric field input which can be represented as $E = [E^N, E^E]^T$, where the superscripts $N$ and $E$ denote the north and east direction, respectively. Since the geoelectric field induces quasi-dc voltage in the transmission lines the GICs are modeled via a dc network analysis.

### A. Input file format

MATLAB uses M-files or MAT-files as data files which define and return output matrices. The M-file format is plain text that can be edited using any standard text editor. For the input files compatible with MATGMD, the output fields for the data files should be **Xmr**- *transformer dc information*, **Bus_dc**- *bus dc information*, **Substn**- *substation dc information*, **Lines**- *transmission line dc information*, **E**- *directional magnitudes of the uniform E field* and optionally **Ckt_n**- *circuit numbers for combined transformer and transmission line branches*, where all the fields are matrices. In the matrices, each row corresponds to a single transformer branch, bus, substation, line, E field direction, or circuit number. n_x, n_b, n_s and n_l correspond to the number of rows in **Xmr**, **Bus_dc**, **Substn** and **Lines** respectively. If the buses in the **Bus_dc** matrix indicate that the buses in the system are not numbered in

a consecutive manner they are then renumbered for further computations using function file, ext2int_dc.m.

### B. G matrix

*1) Theory:* For a transmission system, let $N^b$ be the number of buses excluding the buses connected to the generators that are grounded via the nearest substation and $N^s$ be the number of substations, which together form a set of nodes, $N : N^b \cup N^s$. Let $\mathcal{L}$ be the set of branches between the nodes $n$ and $m$ where, $(n, m) \subseteq N^b \times N^b$ which include transmission lines as well as buses that are connected by autotransformer series windings. Let $\mathcal{XL}$ be a set of pairs of bus nodes, $N^b$ and substation nodes, $N^s$ connected through transformer windings − high side windings for a delta−wye transformer, common winding for an autotransformer and both the windings for a wye−wye transformer which can be represented as $(n, m) \subseteq N^b \times N^s$. Together, $\mathcal{L}$ and $\mathcal{XL}$ comprise the edges, $\varepsilon$ represented as $(n, m) \subseteq N \times N$. For constructing the dc G matrix, let $g_{nm} = g_{mn}$ denote the equivalent conductance between $n$ and $m$ for any $(n, m) \in \varepsilon$. Similarly, let $g_{nn}$ represent the grounding conductance of the substation neutral for $n \in N^s$. Using these notations, we can construct G, an $N \times N$ matrix which is real and symmetric. It is important to note that all the conductance quantities have accounted for the three phases in parallel. The non-zero elements of G can be given by:

$$G_{mn} = \begin{cases} -g_{mn}, & \text{if } (n, m) \subseteq \varepsilon \\ \sum_{v \in N^n} g_{nv}, & \text{if } n = m \subseteq N^b \\ g_{nn} + \sum_{v \in N^n} g_{nv}, & \text{if } n = m \subseteq N^s \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

This G matrix computation is the first step in the dc network analysis during GMD events.

*2) MATLAB function file − G_mat.m:* The input to the function are matrices **Xmr**, **Bus_dc**, **Substn** and **Lines**. The output is the matrix **g**. The transformer high side dc conductance: Hcond, low side dc conductance: Mcond, substation neutral dc conductance: SCond and line dc conductance: LCond arrays are also obtained. A matrix, initialized to zero, of size N×N is assigned with labels depending on whether there's a line or transformer winding between two nodes $(n, m)$ pertaining to the element $(n, m)$ in the matrix. Next, the G matrix (**g**) is assigned the corresponding computed values according to (1). The rows and columns with all-zero values are eliminated and the final **g** matrix is obtained.

### C. Injection currents

*1) Theory:* We have discussed how change in Earth's magnetic field causes change in electric field on its surface. This electric field induces dc voltage along the transmission lines. Using the Norton equivalent, this induced voltage source on the lines can be converted to a dc current injection at buses connecting these lines. The voltage source is modeled in series with the transmission lines that result in the flow of GICs

through the system with a return path to via ground. This voltage source can be modeled as follows:

$$V_{nm} = E^N L_{nm}^N + E^E L_{nm}^E \qquad (2)$$

where, $V_{nm}$ is the induced dc voltage and $L_{nm}^N$ and $L_{nm}^E$ are the distances for the line between buses $n$ and $m$ in the north and east direction respectively. The Norton's equivalent of this induced dc voltage source is given by:

$$I_{nm} = V_{nm}/R_{nm} \qquad (3)$$

where, $I_{nm}$ is the dc injection current to bus $n$ and $R_{nm}$ is the resistance on the line between buses $n$ and $m$. Also, the equivalent current injection $I_{mn}$ to bus m equals to $-I_{nm}$. The overall injection current at a bus $n$ equals the summation of all the current injections at bus $n$ and using Kirchoff's law and is given by:

$$I_n = \sum_{(n,m) \in L} I_{nm} = \sum_{(n,m) \in L} \frac{E^N}{R_{nm}} L_{nm}^N + \frac{E^E}{R_{nm}} L_{nm}^E \qquad (4)$$

Notice that, for all the substations that are not directly connected by transmission lines, the injected current is simply $I_n$ = 0, $\forall n \in N^s$ Stacking (4) for all the N nodes:

$$\mathbf{I} := [I_1, ..., I_N]^T = \mathbf{HE} \qquad (5)$$

*2) MATLAB function file $-$ InjC.m:* The input to the function are matrices $\mathbf{E}$, $\mathbf{Bus\_dc}$, $\mathbf{Substn}$ and $\mathbf{Lines}$. The output is matrices $\mathbf{Iinj}$ and $\mathbf{GSU\_b}$. Injection current matrix of size N×1, $\mathbf{Iinj}$, is initialized to zero. Iterations equal to the number of buses, $N^b$, are carried out corresponding to each bus. For each iteration, two matrices are obtained for each bus containing the index number of the transmission lines in matrix $\mathbf{Lines}$: one when the bus is in the from side column and other when it is in the to side column. The lengths calculated to denote the number of instances. The lines under consideration are obtained and the location coordinates corresponding to their from side and to side buses are stored. Using these coordinates and the distance formula [22]:

$$L^N = (111.113 - 0.56 * cos(2\phi))\Delta lat \qquad (6)$$
$$L^E = (111.5065 - 0.1872 * cos(2\phi)) * cos(\phi)\Delta long \qquad (7)$$

the North and East direction distances, $L^N$ and $L^E$, can be computed. Here, $\Delta lat$ and $\Delta long$ are the differences between the latitude and longitude coordinates of the from and to substations respectively. $\phi$ is given as,

$$\phi = \frac{latA + latB}{2}$$

where, $latA$ and $latB$ correspond to the latitude coordinates of the from and to substations respectively. Using (4), the injection currents can be computed and stored in the matrix $\mathbf{Iinj}$. The buses with injection currents equal to zero are eliminated. These buses correspond the delta side of Generator Step Up Transformers (GSUs) and these buses are stored in matrix $\mathbf{GSU\_b}$. The substations, with injection currents equal to zero, are retained.

*D. DC Node Voltages*

*1) Theory:* In order to calculate the GICs flowing through transformers and substation neutrals, finding the dc node voltages is necessary. It is an intermediate step for GIC calculations but a crucial one. Let $V_n$ be then dc voltage at any bus or substation $n$. Concatenating all such nodes, we get $\mathbf{V} := [V_1, V_2, .., V_N]^T$, which from the dc power flow model is:

$$\mathbf{V} = \mathbf{G^{-1}I} \qquad (8)$$

where, $\mathbf{G}$ and $\mathbf{I}$ can be obtained from (1) and (5).

*2) MATLAB function file $-$ Vdcnodes.m:* The input to the function are matrices $\mathbf{g}$, $\mathbf{Iinj}$, $\mathbf{GSU\_b}$, $\mathbf{Bus\_dc}$ and $\mathbf{Substn}$. The output is matrix $\mathbf{Vnodes}$. Implementing (8), the dc node voltage at each non-GSU bus and substation is obtained. The obtained values are stored in the output matrix, $\mathbf{Vnodes}$.

*E. Substation and Transformer GICs*

*1) Theory:* The GIC flow at each substation $n$ can be obtained by Ohms law given by:

$$I_n^s = g_{nn}V_n, \forall n \in N^s \qquad (9)$$

The GICs are usually obtained at the transformer level. Depending on the type of transformer, the high-side and low-side transformer GIC currents can be obtained. The current flowing from bus $n$ to substation $m$ via the transformer in-between, which could be the wye side of a delta$-$wye transformer or either side for a wye$-$wye transformer or the low voltage side for an autotransformer is given by:

$$I_{nm}^T = g_{nm}(V_n - V_m), \forall n \in N^b, m \in N^s \qquad (10)$$

The current flowing through the series winding for an auto-transformer is given by:

$$I_{nm}^T = g_{nm}(V_n - V_m), \forall n \in N^b, m \in N^b \qquad (11)$$

where $n$ and $m$ correspond to the high-side bus and the low-side bus respectively. The transformer neutral current in the summation of the high side and the low side currents calculated using (10) and (11). Let $I_H$ and $I_L$ be the per phase high-side and the low-side currents for a transformer. The neutral current, $I_n^T$ is given by:

$$I_n^T = (I_H + I_L) * 3, \qquad (12)$$

These current values are of interest because GIC monitoring/measuring devices will record these and further analysis can be based largely on these transformer neutral currents. In addition to these values, the ratios of the high side and the low side currents to the transformer neutral current, $r_h$ and $r_l$ for the high side and low side respectively, can also be obtained using:

$$r_h = \frac{I_H * 3}{I_n^T}, r_l = \frac{I_L * 3}{I_n^T} \qquad (13)$$

which can be used for further analysis and calculations like the effective GIC currents.

*2) MATLAB function file − XmrI.m:* The input to the function are matrices **Xmr**, **Substn** and **Vnodes**. The output is matrices **Is**, **Itr**, **In** and **rt**. Using (9), the substation neutral currents are calculated and stored in **Is**. Using (10) and (11), the transformer high-side and low-side GICs are obtained and stored in matrix **Itr**. The neutral currents obtained by implementing (12) are stored in **In**. The ratios of high-side GICs and low-side GICs to neutral currents, $r_h$ and $r_l$ are computed using (13) and stored in **rt**.

### F. Effective GICs

*1) Theory:* The reactive power loss ($Q_{loss}$) in a transformer due to GICs is directly proportional to the effective GIC flowing through the corresponding transformer. The effective GIC of a transformer is dependent on the transformer parameter $a$ which is the transformer turns ratio. Let $t$ be the transformer being studied. The effective GIC per phase $I_{eff,t}$ is given by:

$$I_{eff,t} =\mid I_{H,t} + \frac{I_{L,t}}{a_t} \mid$$

where, $I_{H,t}$ is the transformer high side current per phase, $I_{L,t}$ is the transformer low side current per phase and $a_t$ is the transformer turns ratio.This can also be expressed as:

$$I_{eff,t} =\mid I_n^T (r_h + \frac{r_l}{a_t}) \mid \tag{14}$$

where $I_n^T$ is the transformer neutral current. Recall, $r_h$ and $r_l$ are the ratios of the high side and the low side currents to the transformer neutral current.

*2) MATLAB function file − Igiceff.m:* The input to the function are matrices **In**, **rt** and **Xmr**. The output is matrices **Igeff**. The transformer turns ratio, **alpha** is calculated and used in implementing (14) to calculated per phase effective GICs for each transformer which are stored in **Igeff**.

### G. Test case file

The test case files can be customized depending on the GMD related system parameters/values that need to be obtained. Different GMD studies target different system values for analysis and hence, the outputs of the test file are user dependent.

## III. RESULTS

As previously mentioned, the tool, MATGMD, has been used to analyze two systems: the EPRI 20-bus case and the UIUC 150-bus case. Electric field of uniform magnitude, $E = [1,0]^T$ is applied to the system. The input file file is constructed according to Section II. A and the matrices with system information is obtained. The tool is then used to calculate the transformer neutral currents. The answers are compared and verified using PowerWorld Simulator.
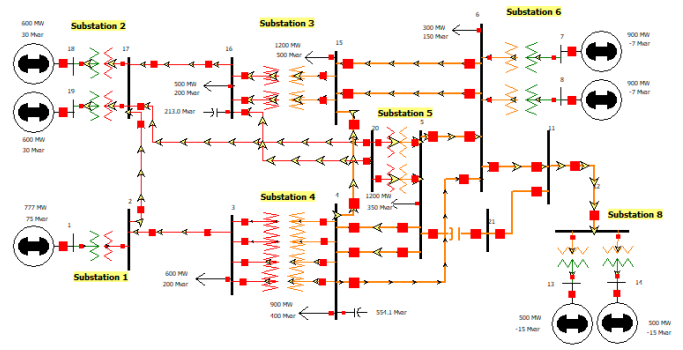


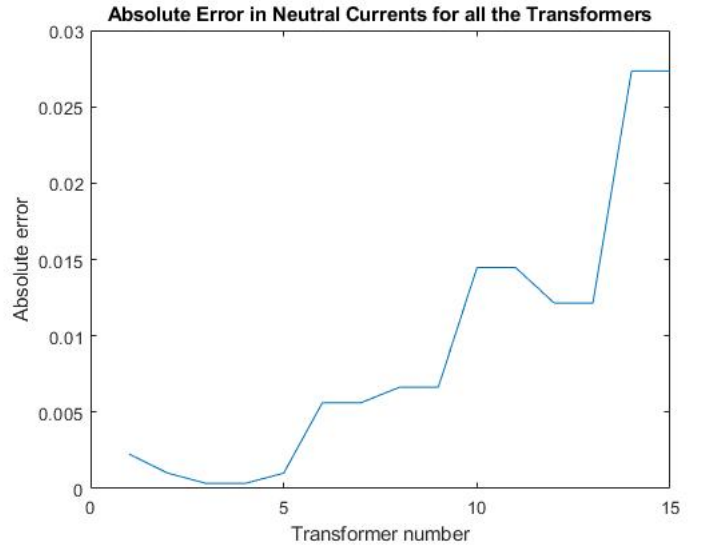Fig. 1. One-line diagram of the EPRI 20-bus system



Fig. 2. Plot of Absolute Error in Neutral Currents vs Transformer Number for EPRI 20-bus system
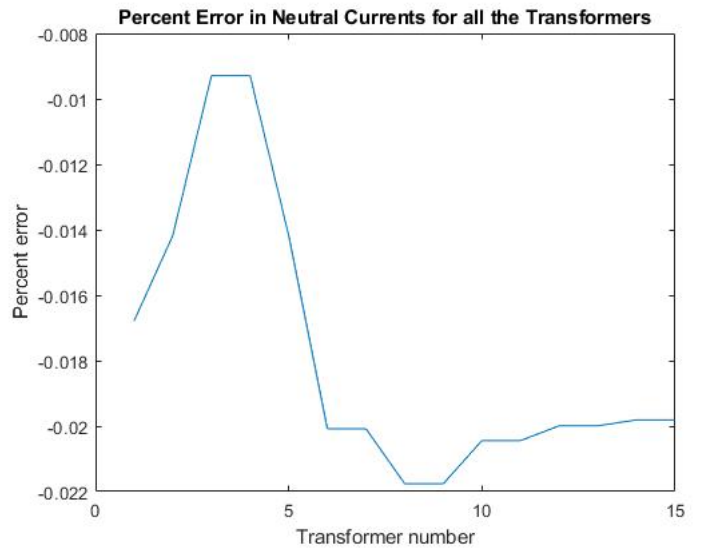


Fig. 3. Plot of Percent Error in Neutral Currents vs Transformer Number for EPRI 20-bus system
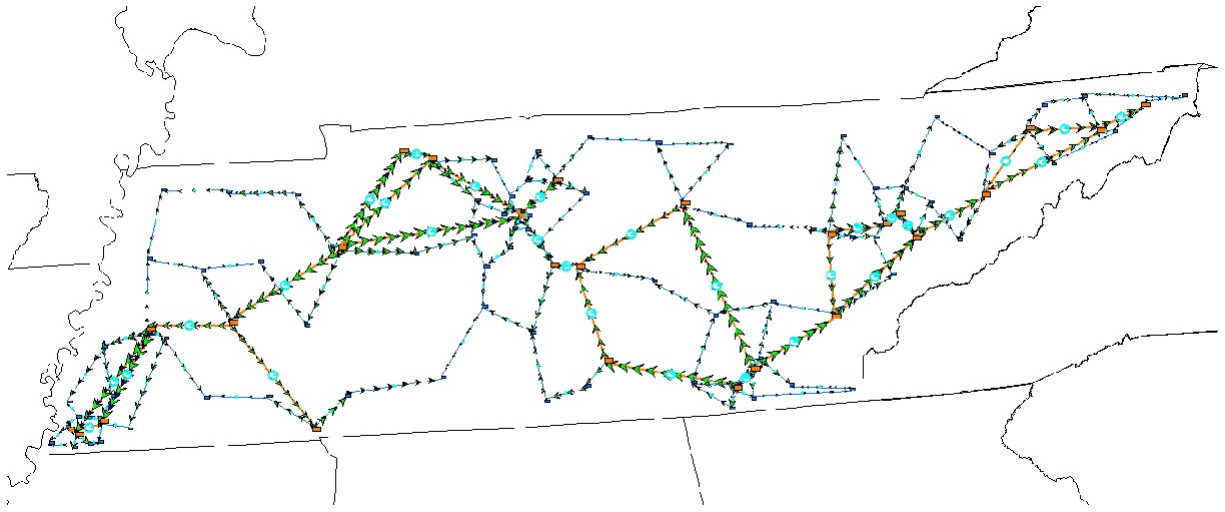
Fig. 4. One-line diagram of the 150-bus (synthetic) system

## A. EPRI 20-bus

The tool is used on the 500/345 kV 20-bus system depicted in Fig. 1. The plots in Fig. 2 and Fig. 3 depict the accuracy of transformer neutral currents, calculated in terms of absolute error and percent error with respect to the values obtained from PowerWorld respectively.

From the plots, Fig. 2 and Fig. 3, we can infer that - the absolute error, i.e.,

$$| I_{n,calculated} - I_{n,PowerWorld} |$$

reaches a maximum of 0.028A which is a small error value. This indicates how close the calculated values are to the actual values (obtained from PowerWorld). The percent error, i.e.,

$$((I_{n,calculated} - I_{n,PowerWorld})/I_{n,PowerWorld}) * 100$$

reaches a maximum magnitude of 0.021%

## B. UIUC 150-bus

The tool is used on the 500/345 kV 150-bus system depicted [23] in Fig. 4. The plots in Fig. 5 and Fig. 6 depict the accuracy of transformer neutral currents, calculated in terms of absolute error and percent error with respect to the values obtained from PowerWorld respectively.

From the plots, Fig. 5 and Fig. 6, we can infer that - the absolute error reaches a maximum of 0.018A which is a small value. The percent error reaches a maximum magnitude of 0.019%

Though the errors in both cases are minor, they can be attributed to the rounding error that arises because of differences in the rounding off for MATLAB and PowerWorld Simulator. MATLAB rounds off to four decimals irrespective to the number of digits in the input. This can skew the results away from the actual values. The rounding errors cascade for every computation and can accumulate deviating the final results. Nonetheless, the deviation is within acceptable limits and can be easily improved using better precision functions
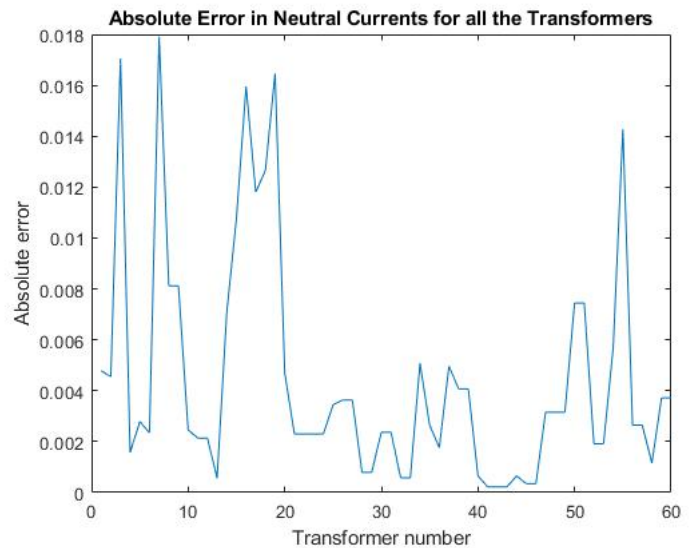


Fig. 5. Plot of Absolute Error in Neutral Currents vs Transformer Number for the UIUC-150 bus system

on MATLAB if the study demands accuracy. Another reason is the use of several MATLAB functions that have the ability to cause significant errors like the MATLAB function '$inv$'.

## IV. CONCLUSION

The tool, MATGMD, computes the system values relevant to GMD with an acceptable accuracy level. It can be used to compute values of various system parameters like the dc G matrix, injection currents, dc node voltages, transformer neutral currents and effective GIC currents. This information extracted for a system can be further utilized for various GMD studies pertaining to reliability, mitigation and estimation. For example, an on-going research to build a GIC-inclusive state estimator will be heavily benefited from MATGMD. One,
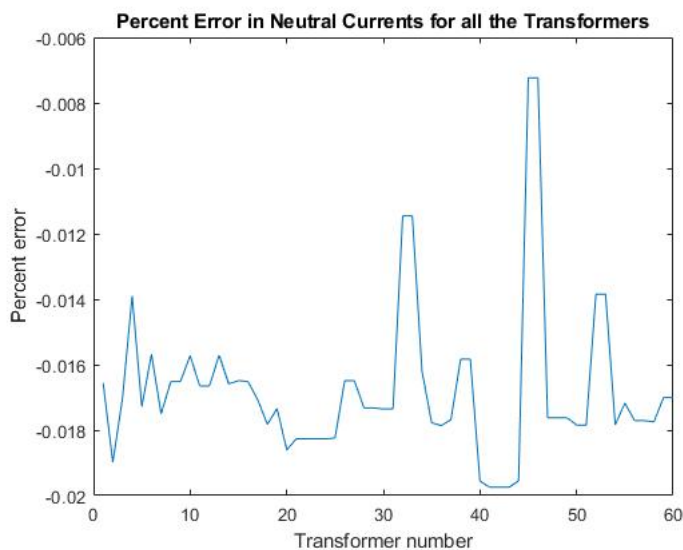
Fig. 6. Plot of Percent Error in Neutral Currents vs Transformer Number for the UIUC 150-bus system

because of it's ability to calculate the transformer neutral currents which can be used as an initial estimate.

This tool is equipped with calculating various parameters for a uniform electric field. But most GMD events result in non-uniform electric field and efforts are being taken to equip the toolbox with the ability to analyze the system for non-uniform electric field scenarios. This will increase the potential of MATGMD by many-folds increasing its applicability for various in-depth studies for GMD.

The MATGMD package can be found at https://github.com/gandhalijuvekar/MATGMD.

## REFERENCES

[1] R. D. Zimmerman, C. E. Murillo-Sánchez, R. J. Thomas *et al.*, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on power systems*, vol. 26, no. 1, pp. 12–19, 2011.

[2] J. Berge, L. Marti, and R. K. Varma, "Modeling and mitigation of geomagnetically induced currents on a realistic power system network," in *2011 IEEE Electrical Power and Energy Conference*, Oct 2011, pp. 485–490.

[3] D. H. Boteler and R. J. Pirjola, "Modelling geomagnetically induced currents produced by realistic and uniform electric fields," *IEEE Transactions on Power Delivery*, vol. 13, no. 4, pp. 1303–1308, Oct 1998.

[4] R. Pirjola, "Geomagnetically induced currents during magnetic storms," *IEEE Transactions on Plasma Science*, vol. 28, no. 6, pp. 1867–1873, 2000.

[5] V. D. Albertson *et al.*, "Geomagnetic disturbance causes and power system effects," in *1989 IEEE PES Meeting, Long Beach, CA*, 1989.

[6] "Effects of geomagnetic disturbances on the bulk power system," North American Electric Reliability Corporation (NERC), Tech. Rep., Feb 2012.

[7] P. R. Price, "Geomagnetically induced current effects on transformers," *IEEE Transactions on Power Delivery*, vol. 17, no. 4, pp. 1002–1008, 2002.

[8] X. Dong, Y. Liu, and J. Kappenman, "Comparative analysis of exciting current harmonics and reactive power consumption from gic saturated transformers," in *Power Engineering Society Winter Meeting, 2001. IEEE*, vol. 1. IEEE, 2001, pp. 318–322.

[9] 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*, vol. PAS-92, no. 2, pp. 471–477, March 1973.

[10] K. Shetye and T. Overbye, "Modeling and analysis of GMD effects on power systems: An overview of the impact on large-scale power systems." *IEEE Electrification Magazine*, vol. 3, no. 4, pp. 13–21, Dec 2015.

[11] L. Bolduc, "Gic observations and studies in the hydro-québec power system," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 64, no. 16, pp. 1793–1802, 2002.

[12] M. Kazerooni, H. Zhu, and T. J. Overbye, "Probabilistic modeling and reliability analysis for validating geomagnetically induced current data," in *North American Power Symposium (NAPS), 2013*. IEEE, 2013, pp. 1–6.

[13] M. Kazerooni, H. Zhu, T. J. Overbye, and D. A. Wojtczak, "Transmission system geomagnetically induced current model validation," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 2183–2192, 2017.

[14] T. J. Overbye, T. R. Hutchins, K. Shetye, J. Weber, and S. Dahman, "Integration of geomagnetic disturbance modeling into the power flow: A methodology for large-scale system studies," in *North American Power Symposium (NAPS), 2012*. IEEE, 2012, pp. 1–7.

[15] A. A. Trichtchenko, D. H. Boteler, and A. Foss, "Gic modelling for an overdetermined system," in *Canadian Conference on Electrical and Computer Engineering, 2006. CCECE'06*. IEEE, 2006, pp. 394–397.

[16] D. Boteler and R. Pirjola, "Comparison of methods for modelling geomagnetically induced currents," in *Annales Geophysicae*, vol. 32, no. 9. Copernicus GmbH, 2014, pp. 1177–1187.

[17] M. Kazerooni, H. Zhu, K. Shetye, and T. J. Overbye, "Estimation of geoelectric field for validating geomagnetic disturbance modeling," in *Power and Energy Conference at Illinois (PECI), 2013*. IEEE, 2013, pp. 218–224.

[18] H. Zhu and T. Overbye, "Blocking device placement for mitigating the effects of geomagnetically induced currents," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–1.

[19] J. Kappenman, S. Norr, G. Sweezy, D. Carlson, V. Albertson, J. Harder, and B. Damsky, "Gic mitigation: a neutral blocking/bypass device to prevent the flow of gic in power systems," *IEEE Transactions on Power Delivery*, vol. 6, no. 3, pp. 1271–1281, 1991.

[20] B. Kovan and F. De Leon, "Mitigation of geomagnetically induced currents by neutral switching," *IEEE Transactions on Power Delivery*, vol. 30, no. 4, pp. 1999–2006, 2015.

[21] C. Klauber, G. P. Juvekar, K. Davis, T. Overbye, and K. Shetye, "The potential for a gic-inclusive state estimator," in *North American Power Symposium (NAPS), 2018*. IEEE, 2018, pp. 1–6.

[22] A. Guide, "Computing geomagnetically-induced current in the bulk-power system, nerc. nerc."

[23] "UIUC 150-bus system." [Online]. Available: https://electricgrids.engr.tamu.edu/electric-grid-test-cases/uiuc-150-bus-system/