# ENERGIZING THE FUTURE! TEXAS SYNTHETIC GRID GEOMAGNETIC DISTURBANCES ANALYSIS

An Undergraduate Research Scholars Thesis

by

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# ABSTRACT

Energizing the Future! Texas Synthetic Grid Geomagnetic Disturbances Analysis

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The electrical grid is constantly evolving and it is essential to modify existing designs to assure preparation and safety for new threats such as geomagnetic disturbances (GMDs). It is necessary to maximize the functionality of the grid by utilizing the synthetic model of the Texas Interconnect. PowerWorld (visual software) was used to simulate the electrical grid and design modifications were integrated to the synthetic grid in order to withstand geomagnetic disturbance electric fields. It is necessary to conduct North American Electric Reliability Corporation (NERC) assessments to find the maximum effective geomagnetically induced current value for the worst case geoelectric field orientation. By simulating the disturbances on the power grid for the GMDs, the results will provide distinct solutions to threatening scenarios. It is essential to conduct such studies to predict the behavior of the grid to various natural phenomena and gather data to energize the future to create a more sustainable world.

## ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Thomas Overbye, for his guidance and support throughout the course of this research. I also would like to thank Komal Shetye and Adam Birchfield for their suggestions and advice throughout this year. Special thanks go to all my friends and colleagues and the Department of Electrical Engineering at Texas A&M University. Finally, I would like to thank my mother, father and sister for their constant encouragement and support for my undergraduate career and wishing me all the best in the future.

# CHAPTER I

# INTRODUCTION

In today's society, power consumption is continuously increasing and the electric grid is constantly in use. The grid's efficiency enables power distribution to homes, hospitals, businesses and companies. Electricity is universal and is used every day to entertain, provide information, and help individuals live more efficient lives. The electric power is symbolized as the heart of the world today. It would be devastating if the electric grid would be damaged due to natural disasters or hazardous threats.

## History

In March 1989, the entire province of Québec, Canada suffered an electrical power blackout [2] which was caused by a solar storm that lasted for twelve hours. This geomagnetic disturbance threat caused widespread outages. The Québec Grid collapsed and the solar storm also disrupted satellites in space for several hours. The aftermath of this event led to permanent damage of a transformer in New Jersey. The storm proved that individual transformers may be damaged from overheating. Approximately 9,450 MW of generation [3] was lost which caused a drastic drop of frequency at load center substations. Many utilities are considering geomagnetically induced current (GIC) measuring devices to be installed to receive the transformer's reactive power consumption [3]. Due to these catastrophic events, necessary predictions and measures must be taken in the case of a super storm striking today's power grids.

## Theory of Geomagnetic Disturbances

Geomagnetic Disturbances (GMDs) are caused by solar wind shock which affects the Earth's magnetic field. Geomagnetically induced currents (GICs) are also caused by solar flares ejected from the surface of the sun [4]. The changes of the magnetic field induce an electric field on the Earth. GMDs can severely disrupt operations of the electric grid by inducing various currents in the high voltage grid [4]. The impact is placed on transformers, communications and global positioning systems (GPS). There is a major concern that GMD events may adversely affect the equipment used in the transmission and distribution of electric power [5].

GMD events cause damage on transmission system assets [6] specifically the high voltage transformers. Additionally, the loss of reactive power leads to the potential for a voltage collapse [6]. The impact of GIC in the power flow can be formulated by solving the dc network: $I = GV.$ G represents the following: a real matrix with conductance values, conductance values that are determined by the parallel combination of three individual phases [6], includes substation grounding and neutral buses, and transformers that are modeled with the winding resistance to the substation neutral [6]. V represents the substation neutral dc voltages. For modeling these events, the GMD induced electric field variation can be viewed as dc voltage sources in the ground or as dc voltages in series with transmission lines. These dc voltage sources are represented in the I vector as Norton Equivalent currents.

In the past, GMD analysis tools were not readily available for power system engineers to use for assessments. It is clear that GMDs present a major problem to the electrical grid where large-scale blackouts lasting for months could occur due to voltage collapse or permanent transformer damage [4]. GIC values can be calculated using line resistance, substation geographic coordinates and grounding resistance, transformer configuration, and transformer coil winding resistances [6]. When GIC is integrated into a power flow analysis, the differences in reactive power losses and bus voltages can be analyzed to assess the risk of voltage instability and large-scale voltage collapse [6]. By simulating the disturbances on the power grid for the GMDs, the results will provide distinct solutions to various threating scenarios for the electric grid in order to create a resilient and secure future.

**North American Electricity Reliability Council (NERC) Work of 2012**

NERC conducted a special reliability assessment and published an interim report titled: Effects of Geomagnetic disturbances on the Bulk Power System in February of 2012. In this report, NERC provides key information regarding that GMD events have demonstrated their ability to disrupt the normal operations [2] of the power grid. The storm interaction with Earth and transmission lines are initiated with a solar flare which are originated from coronal mass ejections (CME). The CME interacts with the Earth's magnetic field and produces electrojets. The electrojets disturb the Earth's magnetic field which ultimately induces a voltage potential at Earth's surface [2]. This action produces GICs. The GICs interrupt the operations of power systems and may damage various equipment.

NERC explicitly states the two main risks of GICs entering the power system. The risks are the damage of transformers and the loss of reactive power support that could lead to voltage instability and power system collapse [2]. The report provides suggestions for power engineers to model bulk power systems for a future GMD event. The process is to determine the occurrence of the geomagnetic activity, calculate the electric fields experienced by the power system, and modeling the GIC produced [2]. By determining these factors, GMD characteristics are able to be measured and further analyzed to create optimized solutions. The February 2012 NERC report includes various strategies and recommendations to manage the effects of GMD events. The improvements on current simulation tools are important and crucial to investigate GMD impacts on the power grid.

# CHAPTER II

# METHODS

The main research methodology was to simulate the vulnerability of the Texas Synthetic Grid (TSG) by the impact of solar storms. The TSG acts as a large scale realistic test system which allows different and extreme scenarios to be simulated on the Earth's geomagnetic system. The advantage of using the TSG is that it provides a coordinate system platform to predict the data of threatening events. By using the TSG, changes can be made to test certain solutions for the case. The response of the TSG was captured by simulating GMD events. The simulations were conducted using PowerWorld [9], a visual software which enables the user to create various storm scenarios and analyze the response of the TSG.

In this study, the GIC Calculations tool was used and the calculation mode offered a field/voltage input option that was manipulated to simulate various solar storms. GIC calculations depend on the induced dc voltages in transmission lines, resistance of different system elements, and the various paths to the ground. For example, a simple GIC calculation can be computed by following Figure 1 [6]. In Figure 1, there are four buses and two substations. Bus 1 and Bus 2 are connected by a 765 kV line with a per phase resistance of 3 Ω. The grounded side of the coil for each of the transformers are 0.3 Ω. The substations' grounding resistance is 0.2 Ω. Assuming that the substations are at the same latitude and separated by 150 km (east to west) and an electrical field of 1 V/km was applied in the east to west direction, the total induced voltage in the transmission line is 150 V [6]. By solving a dc circuit, the transmission line and transformers are calculated in parallel. The total three phase resistance is 1 Ω and each transformer resistance is 0.1 Ω. Then, the previous resistance values are calculated with both of the substations' grounding resistance to provide the $I_{GIC,3phase}$ value in amps [6]. In Figure 1, the size and the direction of the brown arrows represent the direction and magnitude of the GIC flow [6].

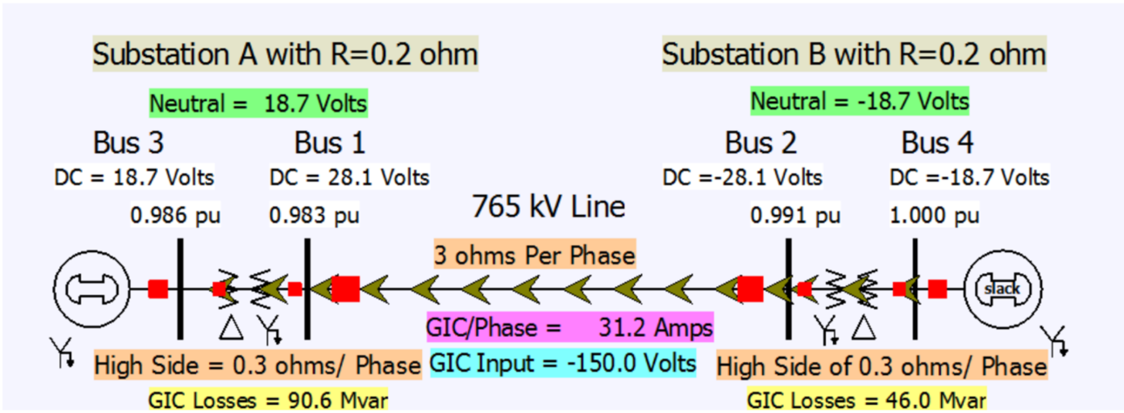



*Figure 1: GIC Example*

After the GICs have been calculated, the transformer reactive power losses are determined. The linear relationship of the reactive power losses can be demonstrated in the following equation: $Q_{loss} = V_{kv}kI_{GIC}$. $Q_{loss}$ represents the related reactive power loss in Mvar. $V_{kv}$ is the terminal voltage measured in kV and $I_{GIC}$ is the per phase in the transformer measured in amps. The transformer specific constant is $k$. In this study, power flow is calculated in per unit so the equation is rewritten as $Q_{loss} = V_{pu}KI_{GIC}$. $V_{pu}$ is the per unit voltage and $K$ has units Mvars/amp. $I_{GIC}$ measures the current in the grounded coil [6].

By simulating on the TSG, the model explored various parameters by calculating appropriate values for the system summary. The system summary displayed data for the total Mvar losses in a specified direction, total Mvar losses in a maximum direction, maximum direction in degrees, total Mvar losses in minimum direction, and minimum direction in degrees. Additionally, the GIC tool provides specific calculations for the areas, buses, generators, G-matrix, lines, line shunts, switched shunts, substations, and transformers for the case.

The GMD induced electric fields must correspond to a simulated GMD event or storm scenario generated by a simulator [4]. The NERC TPL-007-2 provides various parameters for a benchmark GMD event which includes a geospatially uniform GMD where the electric field magnitude varies with local earth resistivity and geomagnetic latitude [4]. The system generated uniform electric field models and provided the option to manipulate the magnitude corresponding to the parameters found in the NERC TPL-007-2 assessment.

The main concerns of this analysis to predict the storms are:

1) Large Scale Blackout due to voltage collapse
2) Permanent transformer damage due to overheating

These concerns were evaluated by conducting various assessments using the NERC TPL-007-2 Benchmark guide.

**NERC TPL-007-2**

The NERC Transmission System Planned Performance for Geomagnetic Disturbance Events or known as TPL-007-2 were used to abide the necessary requirements to analyze the GMD events in the various simulations. The benchmark evaluates various requirements which were necessary to consider to attain optimal data for the study.

The requirements cover planning coordinator information along with transmission planner documentation. There are eleven requirements in the NERC assessment for transmission system planned performance for geomagnetic disturbance events. The first task was to evaluate overall voltage per unit magnitude across the case by contouring the buses. The benchmark GMD vulnerability assessment begins with requirement four, which focuses on the system on peak load for at least one year within the near term transmission planning horizon and the system off peak load for at least one year within the near term transmission planning horizon. In this study, the maximum effective GIC values for the worst case geoelectric field orientations were analyzed. The main goal was to visualize and simulate the geomagnetic events across the TSG and to observe which areas were affected.

**GIC Power Flow Modeling**

The TSG was used as the synthetic power system model. Abiding by the parameters from the NERC TPL-007-2, two assessments were performed. The Benchmark GMD Vulnerability Assessment (based on Attachment 1) included the following conditions: reference maximum peak geoelectric field as 8 V/km and if the transformer GIC value is greater than 75 A, then a thermal heating analysis should be conducted. Similarly, the Supplemental GMD Vulnerability Assessment (based on Attachment 1) referred the following conditions: reference maximum peak geoelectric field as 12 V/km and if the transformer GIC value is greater than 85 A, then a thermal heating analysis should be conducted [10]. These assessments were set by the NERC as a standard. The simulations that were executed in this study implemented the peak values of 8 V/km and 12 V/km without the scaling factors. By conducting these simulations, an extreme GMD event analysis was able to be performed and analyzed on a synthetic system. The transformers that have a greater GIC value than the standard conditions were further studied by observing the animated flow. This process was implemented by utilizing the One Line Diagram tool, and selecting the custom float option. The animated flow option offers the ability to visualize GIC flow through the transformers to determine appropriate mitigation strategies.

The requirements (Requirement 5- Requirement 6) specified in TPL-007-2 provided the GIC flow information for the thermal impact assessment of transformers. Requirement 5 states the maximum effective GIC value for the worst case geoelectric field orientation must be further analyzed for the benchmark GMD event [10]. Requirement 6 describes suggested actions and supporting analysis to mitigate the impact of GICS [10]. Requirement 7 consists of developing a corrective action plan. These requirements were evaluated during the different storm simulations.

To visualize the storm, the contouring map option was used for different storm scenarios. The contouring map provided an overall voltage mapping of the case. The overall voltage contour and GIC animated flow provided key insight on the Texas Case to identify exact locations of vulnerability. The storms were simulated by changing the storm magnitude and the direction. The storm magnitudes were 3.11, 5, 8, and 12 V/km. The storm directions that were used were: 0 (east to west), 30, 45, 60 and 90 (north to south) degrees. The contour maps were a very important tool to use and pin point areas that have maximum GIC flowing creating a major threat to the power system.

In the GIC Analysis form, the GIC calculations were implemented into the power flow solution. To execute this condition, including GIC in the power flow must be selected to visualize the storm on the Texas case. After choosing the appropriate electric field model parameters and including GIC in the power flow were selected, the voltage contour was calculated and the animated GIC flow was initiated. The tables and results provided data that was calculated regarding the effect the GIC on areas, buses, generators, G-matrix, substations, lines, and transformers.

When modeling GMDs, there are two electric field approaches: uniform and non-uniform fields. In this study, the uniform field approach was integrated where the constant electric field is assumed and the maximum electric field can be changed along with the direction of the field. The calculation mode that was utilized was Single Snapshot. The Single Snapshot calculation offers to calculate the induced DC voltage in series with each transmission line at one time point. The network equations were calculated for the resulting DC network to the DC GIC currents for the entire system [6]. This study evaluated the overall voltage distribution of the case, transformer damage, and a corrective action plan was constructed to assess the different storm scenarios.

# CHAPTER III

# RESULTS

The results are composed of various storm scenarios that were simulated with different magnitudes and directions. For each storm simulation, the overall voltage distribution was analyzed to identify locations with near voltage collapse as the electric field strength increased. After each storm simulation, the transformer per phase effective GIC values were evaluated. The exact locations of the transformers were investigated to see the animated GIC flow, and identify the maximum effective GIC values for the worst case geoelectric field orientation. Additionally, the system summaries were assessed.

**Benchmark GMD Vulnerability Assessment**

The Benchmark GMD Vulnerability assessment's reference geoelectric field amplitude of 8 V/km was simulated in increasing storm directions from 0 to 90 degrees. As the storm direction increased, specific areas of the Texas case displayed regions of low voltages. Figure 2 depicts the the different storm directions and the region which is susceptible to voltage collapse that mostly occurs in Northeast Texas. When the storm direction is increased to 60 to 90 degrees, a blackout occurs. In this simulation, the worst case geoelectric field orientation before a blackout occurs is at 45 degrees. The advantage of visualizing the large scale system is that the actual locations of the damage can be assessed and confirmed with the transformer damage data.

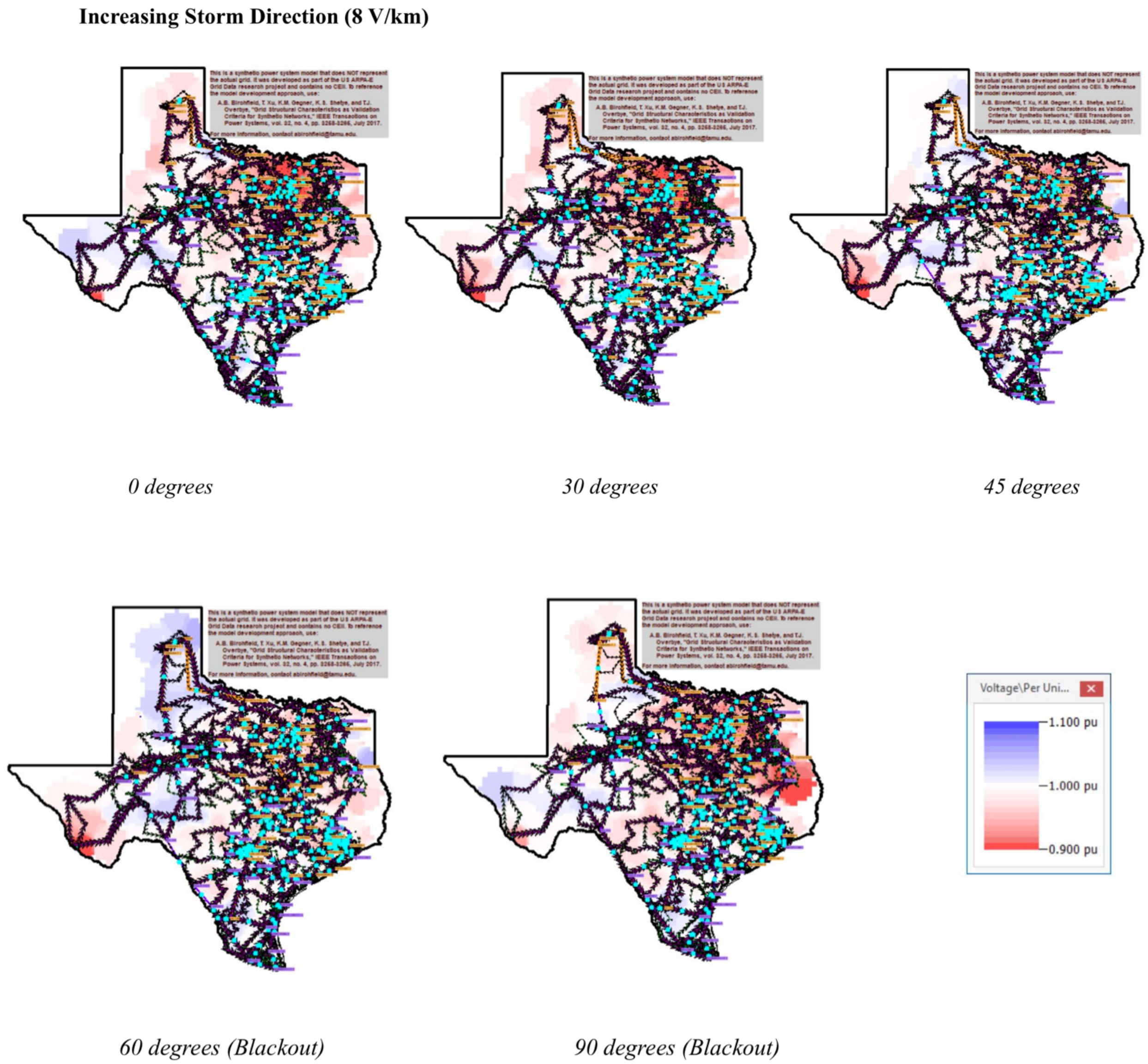
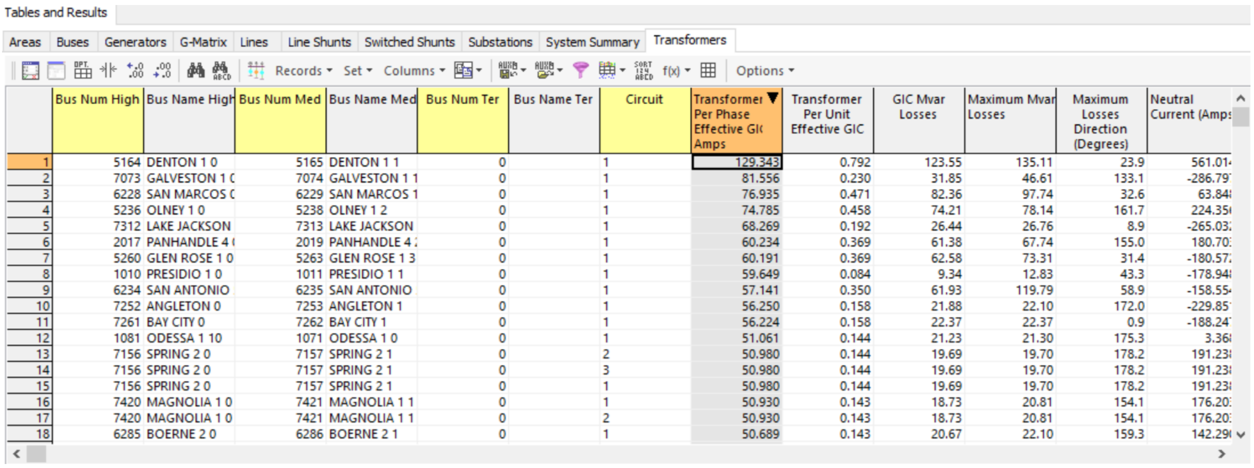



*Figure 2: Storm Direction at 8 V/km*

In Figure 2, the storm direction was increased from 0 to 90 degrees and as each of the orientations change, the synthetic grid can be analyzed to find the problem areas to fix and avoid blackouts. To create these solutions, the transformer damage must be analyzed to evaluate the GIC values. The transformer data was evaluated for each of the different magnitudes and storm directions. The three different magnitudes included 3.11 V/km, 5 V/km and 8 V/km for the first assessment. The first storm was investigated at 3.11 V/km and at 0 degrees.




| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 129.343 | 0.792 | 123.55 | 135.11 | 23.9 | 561.01 |
| 2 | 7073 | GALVESTON 1 ( | 7074 | GALVESTON 1 1 | 0 | | 1 | 81.556 | 0.230 | 31.85 | 46.61 | 133.1 | -286.79 |
| 3 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 76.935 | 0.471 | 82.36 | 97.74 | 32.6 | 63.84 |
| 4 | 5236 | OLNEY 1 0 | 5238 | OLNEY 1 2 | 0 | | 1 | 74.785 | 0.458 | 74.21 | 78.14 | 161.7 | 224.35 |
| 5 | 7312 | LAKE JACKSON | 7313 | LAKE JACKSON | 0 | | 1 | 68.269 | 0.192 | 26.44 | 26.76 | 8.9 | -265.03 |
| 6 | 2017 | PANHANDLE 4 ( | 2019 | PANHANDLE 4 | 0 | | 1 | 60.234 | 0.369 | 61.38 | 67.74 | 155.0 | 180.70 |
| 7 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 60.191 | 0.369 | 62.58 | 73.31 | 31.4 | -180.57 |
| 8 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 59.649 | 0.084 | 9.34 | 12.83 | 43.3 | -178.94 |
| 9 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 57.141 | 0.350 | 61.93 | 119.79 | 58.9 | -158.55 |
| 10 | 7252 | ANGLETON 0 | 7253 | ANGLETON 1 | 0 | | 1 | 56.250 | 0.158 | 21.88 | 22.10 | 172.0 | -229.85 |
| 11 | 7261 | BAY CITY 0 | 7262 | BAY CITY 1 | 0 | | 1 | 56.224 | 0.158 | 22.37 | 22.37 | 0.9 | -188.24 |
| 12 | 1081 | ODESSA 1 10 | 1071 | ODESSA 1 0 | 0 | | 1 | 51.061 | 0.144 | 21.23 | 21.30 | 175.3 | 3.36 |
| 13 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 2 | 50.980 | 0.144 | 19.69 | 19.70 | 178.2 | 191.23 |
| 14 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 3 | 50.980 | 0.144 | 19.69 | 19.70 | 178.2 | 191.23 |
| 15 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 1 | 50.980 | 0.144 | 19.69 | 19.70 | 178.2 | 191.23 |
| 16 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 1 | 50.930 | 0.143 | 18.73 | 20.81 | 154.1 | 176.20 |
| 17 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 2 | 50.930 | 0.143 | 18.73 | 20.81 | 154.1 | 176.20 |
| 18 | 6285 | BOERNE 2 0 | 6286 | BOERNE 2 1 | 0 | | 1 | 50.689 | 0.143 | 20.67 | 22.10 | 159.3 | 142.29 |

*Figure 3: 3.11 V/km at 0 Degrees Transformer Data*

In Figure 3, the Bus that suffered through the most GIC impact is Denton at 129.343 A per phase. Since, Denton had the highest value the area was further studied by zooming into the exact location in the case. Denton is located in Northeast Texas which showed the most visible impact by the storm.

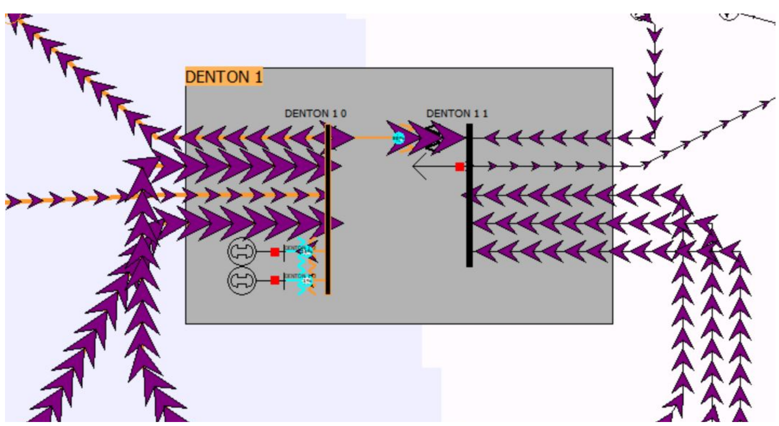
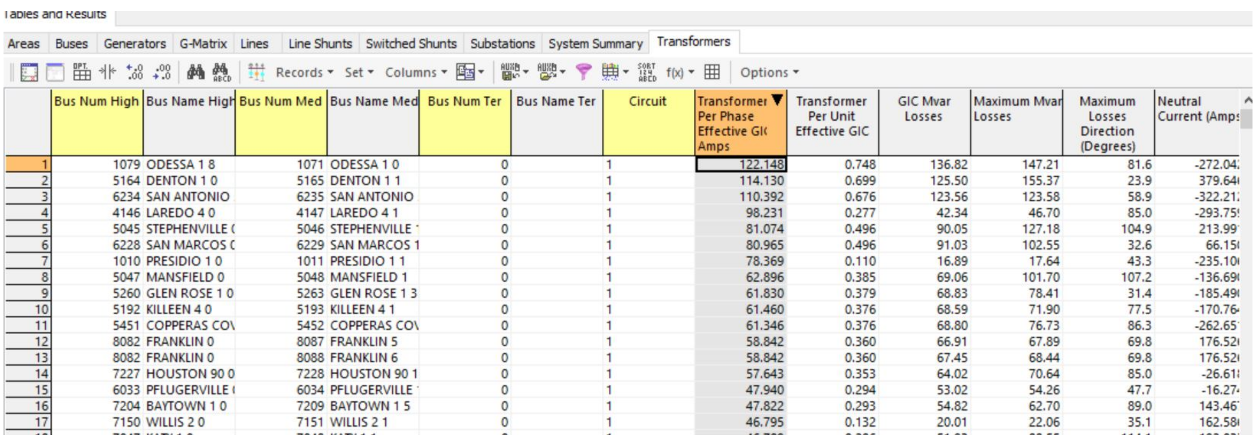



*Figure 4: DENTON Specific Location*

Figure 4 demonstrates the GIC animated flow at Denton. The size of the arrows represents the magnitude of the overall power flow. GICs flow along transmission lines and through transformer windings to ground wherever there is a present path for them to flow. When the area of Denton was analyzed, a key observation was noticed regarding the length of the transmission lines. The transmission lines were long and covered a lot of area which suggests that the GIC had an effective path to flow through and caused disturbances to the system. Due to this problem, a corrective action plan must be developed to mitigate the effects of GIC. As various simulations were conducted, the highest effective GIC value changed when the storm's electrical field was 3.11 V/km and the storm direction was 60 degrees.


Tables and Results

Areas | Buses | Generators | G-Matrix | Lines | Line Shunts | Switched Shunts | Substations | System Summary | Transformers

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1079 | ODESSA 1 8 | 1071 | ODESSA 1 0 | 0 | | 1 | 122.148 | 0.748 | 136.82 | 147.21 | 81.6 | -272.04 |
| 2 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 114.130 | 0.699 | 125.50 | 155.37 | 23.9 | 379.64 |
| 3 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 110.392 | 0.676 | 123.56 | 123.58 | 58.9 | -322.21 |
| 4 | 4146 | LAREDO 4 0 | 4147 | LAREDO 4 1 | 0 | | 1 | 98.231 | 0.277 | 42.34 | 46.70 | 85.0 | -293.75 |
| 5 | 5045 | STEPHENVILLE ( | 5046 | STEPHENVILLE | 0 | | 1 | 81.074 | 0.496 | 90.05 | 127.18 | 104.9 | 213.99 |
| 6 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 80.965 | 0.496 | 91.03 | 102.55 | 32.6 | 66.15 |
| 7 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 78.369 | 0.110 | 16.89 | 17.64 | 43.3 | -235.10 |
| 8 | 5047 | MANSFIELD 0 | 5048 | MANSFIELD 1 | 0 | | 1 | 62.896 | 0.385 | 69.06 | 101.70 | 107.2 | -136.69 |
| 9 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 61.830 | 0.379 | 68.83 | 78.41 | 31.4 | -185.49 |
| 10 | 5192 | KILLEEN 4 0 | 5193 | KILLEEN 4 1 | 0 | | 1 | 61.460 | 0.376 | 68.59 | 71.90 | 77.5 | -170.76 |
| 11 | 5451 | COPPERAS COV | 5452 | COPPERAS COV | 0 | | 1 | 61.346 | 0.376 | 68.80 | 76.73 | 86.3 | -262.65 |
| 12 | 8082 | FRANKLIN 0 | 8087 | FRANKLIN 5 | 0 | | 1 | 58.842 | 0.360 | 66.91 | 67.89 | 69.8 | 176.52 |
| 13 | 8082 | FRANKLIN 0 | 8088 | FRANKLIN 6 | 0 | | 1 | 58.842 | 0.360 | 67.45 | 68.44 | 69.8 | 176.52 |
| 14 | 7227 | HOUSTON 90 0 | 7228 | HOUSTON 90 1 | 0 | | 1 | 57.643 | 0.353 | 64.02 | 70.64 | 85.0 | -26.61 |
| 15 | 6033 | PFLUGERVILLE ( | 6034 | PFLUGERVILLE | 0 | | 1 | 47.940 | 0.294 | 53.02 | 54.26 | 47.7 | -16.27 |
| 16 | 7204 | BAYTOWN 1 0 | 7209 | BAYTOWN 1 5 | 0 | | 1 | 47.822 | 0.293 | 54.82 | 62.70 | 89.0 | 143.46 |
| 17 | 7150 | WILLIS 2 0 | 7151 | WILLIS 2 1 | 0 | | 1 | 46.795 | 0.132 | 20.01 | 22.06 | 35.1 | 162.58 |

*Figure 5: 3.11 V/km at 60 Degrees Transformer Data*

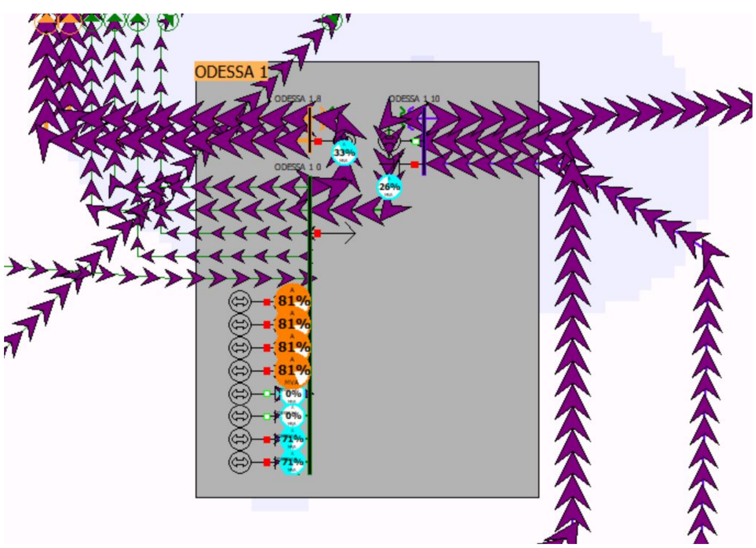



*Figure 6: ODESSA Specific Location*

Figure 5 and Figure 6 display the simulated storm at 3.11 V/km with 60 degrees storm direction. The highest GIC value changed from Denton to Odessa. Denton still had a high GIC value of 114.130 A per phase but Odessa had the highest value at 122.48 A. Figure 5 showed that the overall GIC animated flow for the system at the specific location. Odessa is located in Northwest Texas which displays a low voltage region at 3.11 V/km seen in Figure 6. The increasing electric field strength at 60 degrees can be seen in Figure 7. The voltage contouring maps help visualize the areas that would have the most chance of collapsing when a storm occurs.

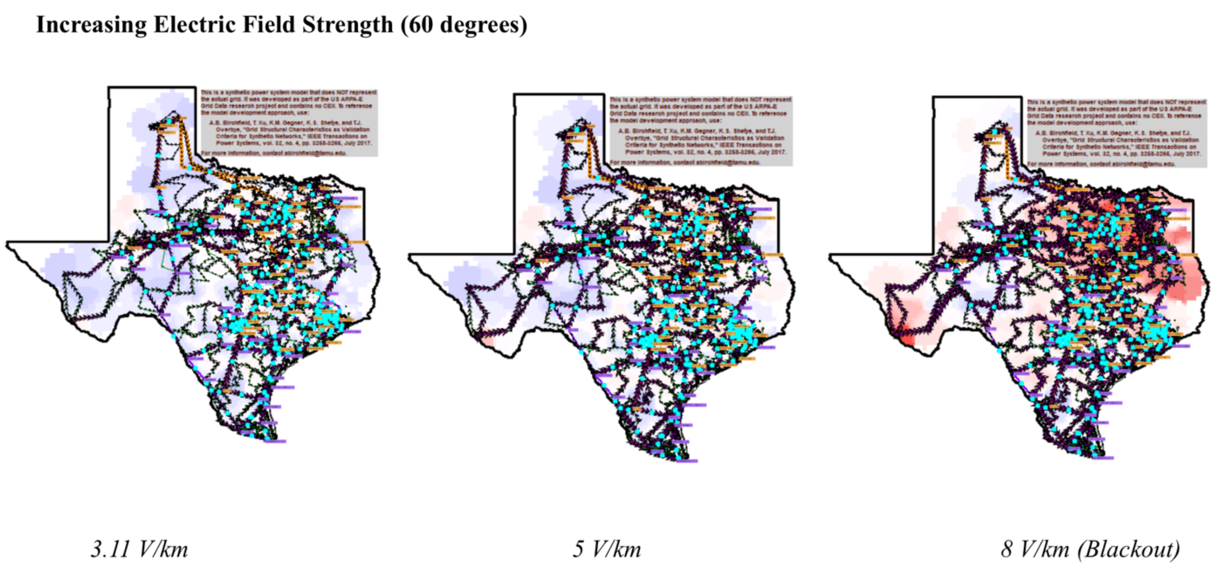
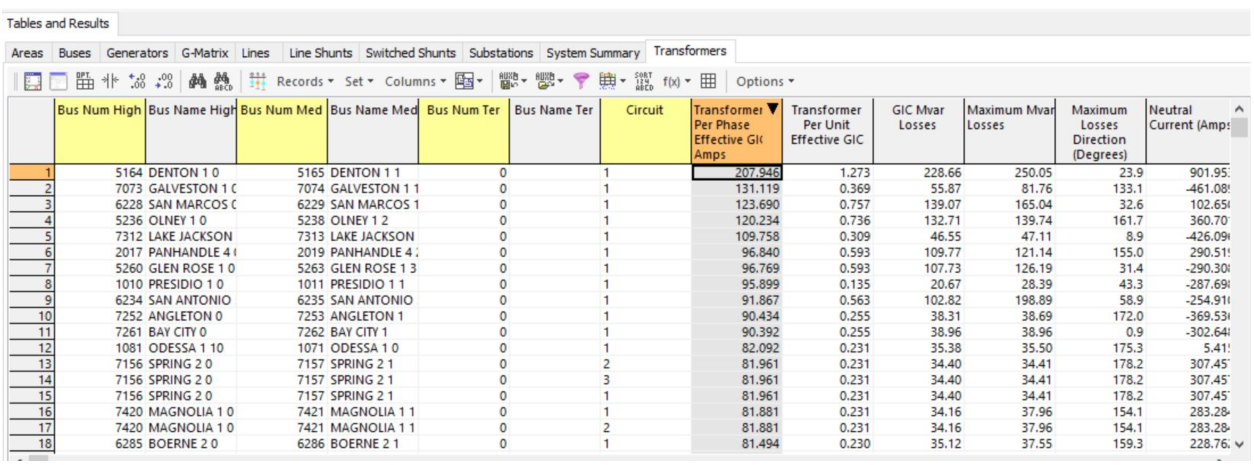



*Figure 7: Increasing Field Strength at (60 degrees)*

In this case, the transformer damage was evaluated and a solution to help minimize the problem would be to set up relay settings. By setting up the relay settings, the transformers would be tripped at certain times to continue appropriate power flow across the system. It is clear that the storm conditions selected of 8 V/km in all of the 0 to 90 degree events are very critical towards reliability violations and voltage collapse. The first blackout occurred at the 8 V/km and 60 degree directional storm.

Additionally, 5 V/km at 0 and 60 degrees' storms were assessed and the same areas were effected based on the GIC values. Both Denton and Odessa areas had the highest GIC value and compared to the 3.11 V/km storm, the values increased to 207.95 A and 196.58 A respectively (Figures 8 and 9). It was important to also evaluate the other areas such as Galveston, and San Marcos to locate the vulnerability. As the geoelectric field strength increased, the transformer GIC values significantly increased at the same areas. The increased values determine the necessity to create strategies to limit GIC flows.




| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 207.946 | 1.273 | 228.66 | 250.05 | 23.9 | 901.95 |
| 2 | 7073 | GALVESTON 1 ( | 7074 | GALVESTON 1 1 | 0 | | 1 | 131.119 | 0.369 | 55.87 | 81.76 | 133.1 | -461.08 |
| 3 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 123.690 | 0.757 | 139.07 | 165.04 | 32.6 | 102.65 |
| 4 | 5236 | OLNEY 1 0 | 5238 | OLNEY 1 2 | 0 | | 1 | 120.234 | 0.736 | 132.71 | 139.74 | 161.7 | 360.70 |
| 5 | 7312 | LAKE JACKSON | 7313 | LAKE JACKSON | 0 | | 1 | 109.758 | 0.309 | 46.55 | 47.11 | 8.9 | -426.09 |
| 6 | 2017 | PANHANDLE 4 ( | 2019 | PANHANDLE 4 : | 0 | | 1 | 96.840 | 0.593 | 109.77 | 121.14 | 155.0 | 290.51 |
| 7 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 96.769 | 0.593 | 107.73 | 126.19 | 31.4 | -290.30 |
| 8 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 95.899 | 0.135 | 20.67 | 28.39 | 43.3 | -287.69 |
| 9 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 91.867 | 0.563 | 102.82 | 198.89 | 58.9 | -254.91 |
| 10 | 7252 | ANGLETON 0 | 7253 | ANGLETON 1 | 0 | | 1 | 90.434 | 0.255 | 38.31 | 38.69 | 172.0 | -369.53 |
| 11 | 7261 | BAY CITY 0 | 7262 | BAY CITY 1 | 0 | | 1 | 90.392 | 0.255 | 38.96 | 38.96 | 0.9 | -302.64 |
| 12 | 1081 | ODESSA 1 10 | 1071 | ODESSA 1 0 | 0 | | 1 | 82.092 | 0.231 | 35.38 | 35.50 | 175.3 | 5.41 |
| 13 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 2 | 81.961 | 0.231 | 34.40 | 34.41 | 178.2 | 307.45 |
| 14 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 3 | 81.961 | 0.231 | 34.40 | 34.41 | 178.2 | 307.45 |
| 15 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 1 | 81.961 | 0.231 | 34.40 | 34.41 | 178.2 | 307.45 |
| 16 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 1 | 81.881 | 0.231 | 34.16 | 37.96 | 154.1 | 283.28 |
| 17 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 2 | 81.881 | 0.231 | 34.16 | 37.96 | 154.1 | 283.28 |
| 18 | 6285 | BOERNE 2 0 | 6286 | BOERNE 2 1 | 0 | | 1 | 81.494 | 0.230 | 35.12 | 37.55 | 159.3 | 228.76 |

*Figure 8: 5 V/km at 0 Degrees Transformer Data*

| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1079 | ODESSA 1 8 | 1071 | ODESSA 1 0 | 0 | | 1 | 196.578 | 1.204 | 220.19 | 236.91 | 81.6 | -437.80 |
| 2 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 183.674 | 1.125 | 201.97 | 250.05 | 23.9 | 610.98 |
| 3 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 177.659 | 1.088 | 198.85 | 198.89 | 58.9 | -518.55 |
| 4 | 4146 | LAREDO 4 0 | 4147 | LAREDO 4 1 | 0 | | 1 | 158.087 | 0.445 | 68.13 | 75.16 | 85.0 | -472.75 |
| 5 | 5045 | STEPHENVILLE ( | 5046 | STEPHENVILLE | 0 | | 1 | 130.475 | 0.799 | 144.92 | 204.68 | 104.9 | 344.38 |
| 6 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 130.301 | 0.798 | 146.50 | 165.04 | 32.6 | 106.45 |
| 7 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 126.122 | 0.178 | 27.18 | 28.39 | 43.3 | -378.36 |
| 8 | 5047 | MANSFIELD 0 | 5048 | MANSFIELD 1 | 0 | | 1 | 101.222 | 0.620 | 111.14 | 163.66 | 107.2 | -219.98 |
| 9 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 99.506 | 0.609 | 110.78 | 126.19 | 31.4 | -298.51 |
| 10 | 5192 | KILLEEN 4 0 | 5193 | KILLEEN 4 1 | 0 | | 1 | 98.910 | 0.606 | 110.39 | 115.72 | 77.5 | -274.81 |
| 11 | 5451 | COPPERAS CO\ | 5452 | COPPERAS CO\ | 0 | | 1 | 98.727 | 0.605 | 110.72 | 123.49 | 86.3 | -422.69 |
| 12 | 8082 | FRANKLIN 0 | 8087 | FRANKLIN 5 | 0 | | 1 | 94.697 | 0.580 | 107.68 | 109.26 | 69.8 | 284.09 |
| 13 | 8082 | FRANKLIN 0 | 8088 | FRANKLIN 6 | 0 | | 1 | 94.697 | 0.580 | 108.56 | 110.15 | 69.8 | 284.09 |
| 14 | 7227 | HOUSTON 90 0 | 7228 | HOUSTON 90 1 | 0 | | 1 | 92.767 | 0.568 | 103.03 | 113.68 | 85.0 | -42.83 |
| 15 | 6033 | PFLUGERVILLE ( | 6034 | PFLUGERVILLE | 0 | | 1 | 77.151 | 0.472 | 85.32 | 87.33 | 47.7 | -26.19 |
| 16 | 7204 | BAYTOWN 1 0 | 7209 | BAYTOWN 1 5 | 0 | | 1 | 76.963 | 0.471 | 88.23 | 100.90 | 89.0 | 230.88 |
| 17 | 7150 | WILLIS 2 0 | 7151 | WILLIS 2 1 | 0 | | 1 | 75.308 | 0.212 | 32.20 | 35.50 | 35.1 | 261.65 |
| 18 | 7047 | KATY 1 0 | 7048 | KATY 1 1 | 0 | | 1 | 75.170 | 0.460 | 83.58 | 142.51 | 114.1 | -309.04 |

*Figure 9: 5 V/km at 60 degrees Transformer Data*

Figure 10 and 11 exhibit the GIC values of the transformers per phase which are extremely high and dangerous for a system to function. The total system is overloaded with reactive power when GIC is present. When the voltage drops, the capacitors are charged and discharged which are connected to various breakers and relays. As GIC flows through the system, transformers create different even and odd harmonics. These harmonics create a negative impact on the relays. Due to this impact, the relays do not function properly and disrupt the breakers' proper operation. GMD events truly limit the power transfer capability and cause major power outages and power loss.

| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 332.714 | 2.037 | 365.85 | 400.08 | 23.9 | 1443.1 |
| 2 | 7073 | GALVESTON 1 ( | 7074 | GALVESTON 1 1 | 0 | | 1 | 209.790 | 0.591 | 89.39 | 130.82 | 133.1 | -737.7 |
| 3 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 197.904 | 1.212 | 222.51 | 264.06 | 32.6 | 164.2 |
| 4 | 5236 | OLNEY 1 0 | 5238 | OLNEY 1 2 | 0 | | 1 | 192.374 | 1.178 | 212.33 | 223.59 | 161.7 | 577.1 |
| 5 | 7312 | LAKE JACKSON | 7313 | LAKE JACKSON | 0 | | 1 | 175.613 | 0.495 | 74.48 | 75.38 | 8.9 | -681.7 |
| 6 | 2017 | PANHANDLE 4 ( | 2019 | PANHANDLE 4 | 0 | | 1 | 154.943 | 0.949 | 175.64 | 193.83 | 155.0 | 464.8 |
| 7 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 154.831 | 0.948 | 172.37 | 201.91 | 31.4 | -464.4 |
| 8 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 153.439 | 0.216 | 33.07 | 45.42 | 43.3 | -460.3 |
| 9 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 146.988 | 0.900 | 164.52 | 318.22 | 58.9 | -407.8 |
| 10 | 7252 | ANGLETON 0 | 7253 | ANGLETON 1 | 0 | | 1 | 144.695 | 0.408 | 61.30 | 61.90 | 172.0 | -591.2 |
| 11 | 7261 | BAY CITY 0 | 7262 | BAY CITY 1 | 0 | | 1 | 144.627 | 0.407 | 62.33 | 62.34 | 0.9 | -484.2 |
| 12 | 1081 | ODESSA 1 10 | 1071 | ODESSA 1 0 | 0 | | 1 | 131.347 | 0.370 | 56.61 | 56.80 | 175.3 | 8.66 |
| 13 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 2 | 131.138 | 0.369 | 55.03 | 55.06 | 178.2 | 491.9 |
| 14 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 3 | 131.138 | 0.369 | 55.03 | 55.06 | 178.2 | 491.9 |
| 15 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 1 | 131.138 | 0.369 | 55.03 | 55.06 | 178.2 | 491.9 |
| 16 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 1 | 131.009 | 0.369 | 54.66 | 60.74 | 154.1 | 453.2 |
| 17 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 2 | 131.009 | 0.369 | 54.66 | 60.74 | 154.1 | 453.2 |
| 18 | 6285 | BOERNE 2 0 | 6286 | BOERNE 2 1 | 0 | | 1 | 130.391 | 0.367 | 56.20 | 60.08 | 159.3 | 366.0 |

*Figure 10: 8 V/km at 0 degrees Transformer data*

Tables and Results

Areas | Buses | Generators | G-Matrix | Lines | Line Shunts | Switched Shunts | Substations | System Summary | Transformers

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1079 | ODESSA 1 8 | 1071 | ODESSA 1 0 | 0 | | 1 | 314.524 | 1.926 | 352.31 | 379.05 | 81.6 | -700.49 |
| 2 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 293.878 | 1.800 | 323.15 | 400.08 | 23.9 | 977.57 |
| 3 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 284.254 | 1.741 | 318.16 | 318.22 | 58.9 | -829.68 |
| 4 | 4146 | LAREDO 4 0 | 4147 | LAREDO 4 1 | 0 | | 1 | 252.939 | 0.713 | 109.01 | 120.25 | 85.0 | -756.41 |
| 5 | 5045 | STEPHENVILLE ( | 5046 | STEPHENVILLE | 0 | | 1 | 208.760 | 1.278 | 231.87 | 327.49 | 104.9 | 551.01 |
| 6 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 208.482 | 1.277 | 234.40 | 264.06 | 32.6 | 170.33 |
| 7 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 201.795 | 0.284 | 43.49 | 45.42 | 43.3 | -605.38 |
| 8 | 5047 | MANSFIELD 0 | 5048 | MANSFIELD 1 | 0 | | 1 | 161.955 | 0.992 | 177.82 | 261.86 | 107.2 | -351.97 |
| 9 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 159.209 | 0.975 | 177.25 | 201.91 | 31.4 | -477.62 |
| 10 | 5192 | KILLEEN 4 0 | 5193 | KILLEEN 4 1 | 0 | | 1 | 158.256 | 0.969 | 176.62 | 185.15 | 77.5 | -439.70 |
| 11 | 5451 | COPPERAS CO\ | 5452 | COPPERAS CO\ | 0 | | 1 | 157.963 | 0.967 | 177.15 | 197.58 | 86.3 | -676.31 |
| 12 | 8082 | FRANKLIN 0 | 8087 | FRANKLIN 5 | 0 | | 1 | 151.515 | 0.928 | 172.29 | 174.82 | 69.8 | 454.54 |
| 13 | 8082 | FRANKLIN 0 | 8088 | FRANKLIN 6 | 0 | | 1 | 151.515 | 0.928 | 173.69 | 176.24 | 69.8 | 454.54 |
| 14 | 7227 | HOUSTON 90 0 | 7228 | HOUSTON 90 1 | 0 | | 1 | 148.427 | 0.909 | 164.85 | 181.89 | 85.0 | -68.53 |
| 15 | 6033 | PFLUGERVILLE ( | 6034 | PFLUGERVILLE | 0 | | 1 | 123.442 | 0.756 | 136.51 | 139.73 | 47.7 | -41.90 |
| 16 | 7204 | BAYTOWN 1 0 | 7209 | BAYTOWN 1 5 | 0 | | 1 | 123.140 | 0.754 | 141.16 | 161.44 | 89.0 | 369.42 |
| 17 | 7150 | WILLIS 2 0 | 7151 | WILLIS 2 1 | 0 | | 1 | 120.494 | 0.339 | 51.53 | 56.80 | 35.1 | 418.65 |
| 18 | 7047 | KATY 1 0 | 7048 | KATY 1 1 | 0 | | 1 | 120.272 | 0.737 | 133.72 | 228.01 | 114.1 | -494.47 |

*Figure 11: 8 V/km at 60 degrees (Blackout) Transformer data*

**Supplemental GMD Vulnerability Assessment**

The supplemental GMD study was conducted using the peak geoelectric field at 12 V/km. When the storm was simulated at 0 degrees, the system could no longer supply the load resulting in a blackout.

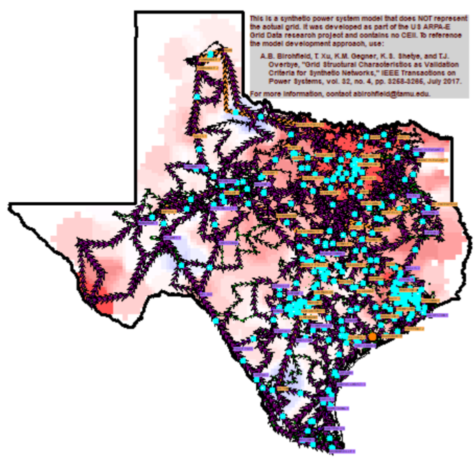
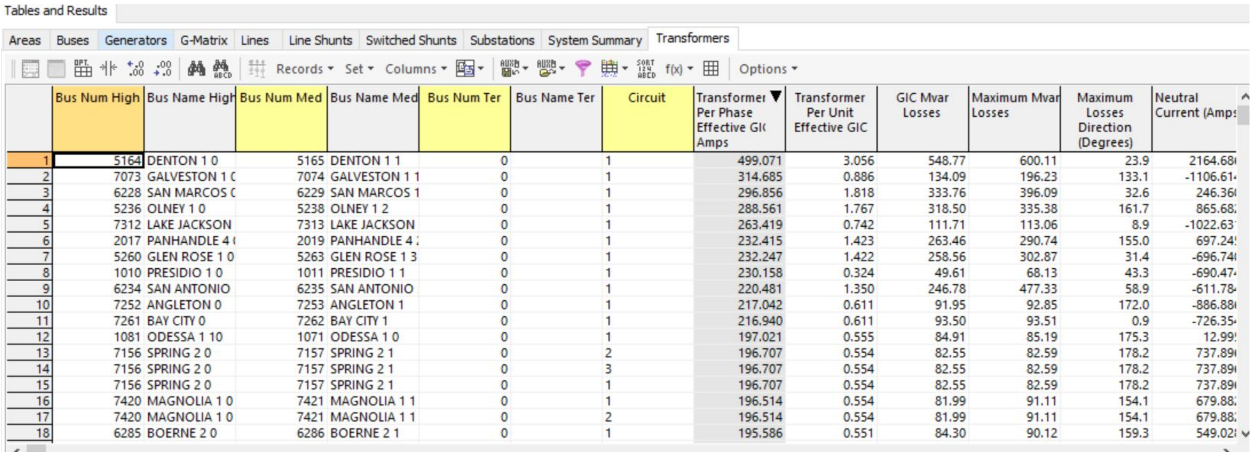



*Figure 12: 12 V/km at 0 Degrees (Blackout)*

Figure 12 truly shows the overall voltage drop and collapse which was spread across all of Texas. Southern Texas was the only location that did not get fully impacted by the storm. Northeast Texas was severely disrupted and Figure 13 depicts very high GIC values of the transformers per phase at 499.07 A at Denton.



Tables and Results

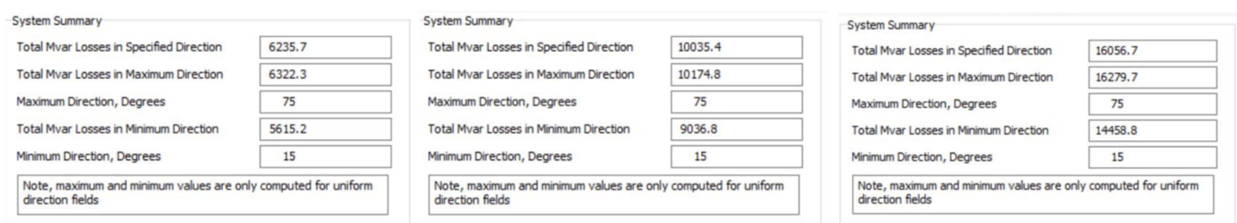
Areas | Buses | Generators | G-Matrix | Lines | Line Shunts | Switched Shunts | Substations | System Summary | Transformers

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5164 | DENTON 1 0 | 5165 | DENTON 1 1 | 0 | | 1 | 499.071 | 3.056 | 548.77 | 600.11 | 23.9 | 2164.68 |
| 2 | 7073 | GALVESTON 1 ( | 7074 | GALVESTON 1 1 | 0 | | 1 | 314.685 | 0.886 | 134.09 | 196.23 | 133.1 | -1106.61 |
| 3 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 296.856 | 1.818 | 333.76 | 396.09 | 32.6 | 246.36 |
| 4 | 5236 | OLNEY 1 0 | 5238 | OLNEY 1 2 | 0 | | 1 | 288.561 | 1.767 | 318.50 | 335.38 | 161.7 | 865.68 |
| 5 | 7312 | LAKE JACKSON | 7313 | LAKE JACKSON | 0 | | 1 | 263.419 | 0.742 | 111.71 | 113.06 | 8.9 | -1022.63 |
| 6 | 2017 | PANHANDLE 4 ( | 2019 | PANHANDLE 4 : | 0 | | 1 | 232.415 | 1.423 | 263.46 | 290.74 | 155.0 | 697.24 |
| 7 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 232.247 | 1.422 | 258.56 | 302.87 | 31.4 | -696.74 |
| 8 | 1010 | PRESIDIO 1 0 | 1011 | PRESIDIO 1 1 | 0 | | 1 | 230.158 | 0.324 | 49.61 | 68.13 | 43.3 | -690.47 |
| 9 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 220.481 | 1.350 | 246.78 | 477.33 | 58.9 | -611.78 |
| 10 | 7252 | ANGLETON 0 | 7253 | ANGLETON 1 | 0 | | 1 | 217.042 | 0.611 | 91.95 | 92.85 | 172.0 | -886.88 |
| 11 | 7261 | BAY CITY 0 | 7262 | BAY CITY 1 | 0 | | 1 | 216.940 | 0.611 | 93.50 | 93.51 | 0.9 | -726.35 |
| 12 | 1081 | ODESSA 1 10 | 1071 | ODESSA 1 0 | 0 | | 1 | 197.021 | 0.555 | 84.91 | 85.19 | 175.3 | 12.99 |
| 13 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 2 | 196.707 | 0.554 | 82.55 | 82.59 | 178.2 | 737.89 |
| 14 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 3 | 196.707 | 0.554 | 82.55 | 82.59 | 178.2 | 737.89 |
| 15 | 7156 | SPRING 2 0 | 7157 | SPRING 2 1 | 0 | | 1 | 196.707 | 0.554 | 82.55 | 82.59 | 178.2 | 737.89 |
| 16 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 1 | 196.514 | 0.554 | 81.99 | 91.11 | 154.1 | 679.88 |
| 17 | 7420 | MAGNOLIA 1 0 | 7421 | MAGNOLIA 1 1 | 0 | | 2 | 196.514 | 0.554 | 81.99 | 91.11 | 154.1 | 679.88 |
| 18 | 6285 | BOERNE 2 0 | 6286 | BOERNE 2 1 | 0 | | 1 | 195.586 | 0.551 | 84.30 | 90.12 | 159.3 | 549.02 |

*Figure 13: 12 V/km at 0 degrees Transformer data*

The system summaries (Figure 14) were assessed for each storm scenario specifically at 60 degrees. The data is associated with 60 degrees because it was the specific storm direction that caused the blackout at 8 V/km. The system summaries were evaluated for 3.11 V/km, 5 V/km, and 8 V/km. The key relationship that was observed was that the total Mvar losses in the specified direction increased, as the storm direction and electrical field strength were increased.




*3.11 V/km* *5.00 V/km* *8.00 V/km*

*Figure 14: System Summaries for Storms*

**Corrective Action Plan/ Mitigation Strategies**

Due to the storm impact on the system, it was important to develop ideas for a corrective action plan to minimize the overall power loss. GICs cause transformer heating and increased transformer reactive power losses. To mitigate the effect, DC current blocking devices should be implemented for protection. Current GIC blocking devices consists of capacitive or resistive circuits placed at the ground connection of transformers [11]. Capacitors that are placed in series on a transmission line block GICs on the lines. The blocking devices function by disconnecting the transformer neutral from the substation neutral.

Tables and Results

Areas | Buses | Generators | G-Matrix | Lines | Line Shunts | Switched Shunts | Substations | System Summary | Transformers

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

| | Bus Num High | Bus Name High | Bus Num Med | Bus Name Med | Bus Num Ter | Bus Name Ter | Circuit | Transformer Per Phase Effective GIC Amps | Transformer Per Unit Effective GIC | GIC Mvar Losses | Maximum Mvar Losses | Maximum Losses Direction (Degrees) | Neutral Current (Amps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1079 | ODESSA 1 8 | 1071 | ODESSA 1 0 | 0 | | 1 | 238.795 | 1.462 | 257.75 | 263.40 | 71.9 | 0.00 |
| 2 | 6228 | SAN MARCOS ( | 6229 | SAN MARCOS 1 | 0 | | 1 | 179.702 | 1.100 | 196.07 | 220.86 | 32.6 | 0.00 |
| 3 | 8082 | FRANKLIN 0 | 8088 | FRANKLIN 6 | 0 | | 1 | 148.753 | 0.911 | 167.71 | 170.05 | 69.5 | 446.26 |
| 4 | 8082 | FRANKLIN 0 | 8087 | FRANKLIN 5 | 0 | | 1 | 148.753 | 0.911 | 163.05 | 165.32 | 69.5 | 446.26 |
| 5 | 7227 | HOUSTON 90 0 | 7228 | HOUSTON 90 1 | 0 | | 1 | 148.428 | 0.909 | 159.80 | 176.31 | 85.0 | -68.54 |
| 6 | 5260 | GLEN ROSE 1 0 | 5263 | GLEN ROSE 1 3 | 0 | | 1 | 148.021 | 0.906 | 164.40 | 196.65 | 26.7 | -444.06 |
| 7 | 6235 | SAN ANTONIO | 6236 | SAN ANTONIO | 0 | | 1 | 137.158 | 0.386 | 55.76 | 55.76 | 60.6 | -528.43 |
| 8 | 6235 | SAN ANTONIO | 6236 | SAN ANTONIO | 0 | | 2 | 137.158 | 0.386 | 55.76 | 55.76 | 60.6 | -528.43 |
| 9 | 5464 | FRISCO 2 0 | 5465 | FRISCO 2 1 | 0 | | 1 | 135.852 | 0.832 | 143.81 | 201.36 | 15.6 | 587.55 |
| 10 | 6234 | SAN ANTONIO | 6235 | SAN ANTONIO | 0 | | 1 | 134.769 | 0.825 | 146.64 | 146.83 | 57.0 | 0.00 |
| 11 | 6033 | PFLUGERVILLE ( | 6034 | PFLUGERVILLE | 0 | | 1 | 127.592 | 0.781 | 136.83 | 139.45 | 48.9 | -53.03 |
| 12 | 7204 | BAYTOWN 1 0 | 7209 | BAYTOWN 1 5 | 0 | | 1 | 123.139 | 0.754 | 141.16 | 161.44 | 89.0 | 369.41 |
| 13 | 7150 | WILLIS 2 0 | 7151 | WILLIS 2 1 | 0 | | 1 | 120.481 | 0.339 | 49.50 | 54.57 | 35.1 | 418.61 |
| 14 | 7047 | KATY 1 0 | 7048 | KATY 1 1 | 0 | | 1 | 120.289 | 0.737 | 129.68 | 221.10 | 114.1 | -494.52 |
| 15 | 6308 | HONDO 0 | 6309 | HONDO 1 | 0 | | 1 | 118.396 | 0.334 | 48.05 | 66.51 | 103.7 | -514.85 |
| 16 | 7312 | LAKE JACKSON | 7313 | LAKE JACKSON | 0 | | 1 | 111.522 | 0.314 | 45.86 | 73.10 | 8.9 | -349.83 |
| 17 | 8158 | BRYAN 1 0 | 8159 | BRYAN 1 1 | 0 | | 1 | 109.733 | 0.672 | 119.54 | 229.66 | 118.6 | -265.57 |
| 18 | 1053 | MONAHANS 1 ( | 1047 | MONAHANS 1 ( | 0 | | 1 | 108.259 | 0.305 | 45.86 | 48.37 | 78.5 | -67.44 |

*Figure 15: GIC Blocking Approach*

Figure 15 shows that the GIC values for the transformers decreased after blocking 11 of the buses. The buses included Odessa, Stephenville, Copperas Cove, Laredo, San Antonio, Killeen San Marcos, Denton, Mansfield, and Presidio. These buses were chosen because previously to the blocking, they had the highest GIC values for the transformers.

The Mvar losses are important to consider when planning to place the blocking device. The blocking device principle goal is to inhibit the GIC from entering the transformer. In previous research studies, implementing blocking devices benefited the system by decreasing the total demand on the system [11]. The blocking device approach should be implemented since it mitigates the total system wide reactive power losses.

# CHAPTER IV

# CONCLUSION

Visualizing the GIC flow was very effective in this study and simulating the storm scenarios with different magnitudes provided a range of various worst geoelectric storm cases. Each storm direction presented a new scenario for a power system engineer to analyze using the system summary to prepare for future disasters.

**Future Optimized Solutions**

Based on the findings presented, GMD events truly cause damage and interrupt power system operations. The geographic locations of the GIC flow were found and were analyzed as the storm directions varied. It is seen that in the north part of Texas was the most affected. This visual representation of the current flow helps create a solution when a geomagnetic storm occurs. The north part of Texas would not have sufficient power to withstand normal grid operations. In that case, implementing a blocking device at specific transformers with the highest GIC values could be a solution.

In the future, more analysis will be conducted such as creating algorithms to add blocking devices. The blocking devices could be placed at the exact transformers that are the most vulnerable, and the GIC would not flow into those transformers. The GIC would try to find another path. This path would be to the other transformers that are not susceptible to the damage. Overall, this study exemplifies the importance to analyze different storm scenarios and to create a resilient grid for potential power deficiencies to occur in the future.

# REFERENCES

[1] Dunbar, Brian. “The Day the Sun Brought Darkness.” *NASA*, 13 May 2015. [Online].

[2] “Effects of Geomagnetic Disturbances on the Bulk Power System.” *North American Electric Reliability Corporation*, Feb. 2012. [Online].

[3] North American Electric Reliability Corporation and the United States Department of Energy, "High-Impact, Low-Frequency Event Risk to the North American Bulk Power System," Atlanta, GA, June, 2010.

[4] Overbye, Thomas. *Electric Power Grid Impacts of GMDs* (n.d.): n. pag. [Online].

[5] Overbye, Thomas. "Power Grid Geomagnetic Disturbance (GMD) Modeling with Transformer Neutral Blocking and Live Grid Testing Results." *CPE-Conferences/MIPSYCon-paper* (n.d.): n. pag. [Online].

[6] Overbye, Thomas J., et al. “Integration of Geomagnetic Disturbance Modeling into the Power Flow: A Methodology for Large-Scale System Studies.” *2012 North American Power Symposium (NAPS)*, 2012, doi:10.1109/naps.2012.6336365.

[7] Overbye, Thomas. “Theory of Geomagnetic Disturbances.” Web.

[8] "Protecting the World's Power Grid from a Catastrophic GMD Event." *IEEE Standards University*. [Online].

[9] “Simulator GIC.” *PowerWorld Corporation.,* [Online]

[10] TPL-007-2-Transmission System Planned Perforrmance for Geomagnetic Disturbance Events June, 2017.

[11] Zhu, Hao, and Tom Overbye. “Blocking Device Placement for Mitigating the Effects of Geomagnetically Induced Currents.” *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016, doi:10.1109/pesgm.2016.7741143.