Undergraduate Research on Design Considerations for a GMD Mitigation System

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***Abstract*— Geomagnetic disturbances (GMDs) are the result of coronal mass ejections (CMEs) from the sun. CMEs, such as solar flares, alter the magnetic and electric field of the earth. These changes induce DC voltage sources superimposed on transmission lines. The voltages result in the introduction of quasi-DC geomagnetically induced currents (GICs) to the AC synchronous power grid. These currents can cause half cycle saturation of transformers, harmonics, reactive power losses, and in extreme situations, widespread power outages. In this work, a planning-based GMD mitigation strategy is developed for large power systems. GIC blocking devices and system topology are leveraged in the design of strategies and systems to maintain preferable system operations despite a GMD. Simulation cases based on GIC blocking device installation and islanding plans will be used to create a strategy to minimize the effects of GMDs on the power grid.**

I. Introduction

Electricity supports almost all aspects of modern life, including communication, transportation, water, and fuel availability. Solar weather can cause major disruptions to the electric power grid and damage power equipment such as high voltage transformers [1]. To prevent these effects, it is essential to have accurate methods to protect the power grid. Resilience can be defined as the “readiness of a critical infrastructure to withstand and recover from deliberate attacks, major accidents, or naturally occurring threats or incidents” [2]. An extreme event, such as a geomagnetic disturbance (GMD) with above 1 V/km, and the proposed actions to mitigate the resulting power system disruptions from the GMD storm play an important role in managing the resilience of the grid [2],[3]. One such protective measure is the implementation of geomagnetically induced current (GIC) blocking devices that are strategically placed using an algorithm to mitigate the effects of GMD events [4]. Islanding the grid by creating sections that can run independently in the event that one section is damaged, can also help increase grid resilience [5]. Providing a plan and strategy to protect the power grid will be of electric utility interest because of the potential to save time, money, and resources in the event of a solar storm.

In 1989, a major solar storm caused a power outage in Quebec, Canada. The entire Quebec power grid lost power for 12 hours; millions of people suddenly found themselves in darkness. The resulting aurora borealis effects could be seen as far south as Cuba [6],[7]. Although solar events of this magnitude are rare, developing preventative measures to prepare for GMD occurrences are of great interest to electric utilities.

The two main components of the proposed mitigation strategy are islanding the grid and developing a GIC blocking device placement algorithm. Simulation cases in PowerWorld will be created to demonstrate the effects of the mitigation strategy [8].

GMD mitigation systems will allow engineers to better understand and manage the effects of a GMD occurrence on the power grid. This project is intended to give electric utility companies viable strategies to mitigate the effects of a GMD. For this work, the Texas synthetic grid (TSG) 2000-bus case will be utilized to show the potential effects of a solar storm on the electric grid in Texas [9]. Two GMD scenarios will be observed. The first is a uniform field storm simulated at a magnitude of 3.14 V/km. The second scenario observed includes GMD storms simulated with hotspots. Hotspots are defined as localized geomagnetic disturbances that can cause increased GICs [10],[11]. While the phenomenon is still being studied, initial assessments indicate that the amplitude of the enhancement can be much higher than benchmark events, occurring over areas of up to 100km by 100km or more for 2-5 minutes. The impact of these enhancements has not been fully explored in earlier studies and has not yet been considered from a system design for resiliency perspective. A magnitude of 6.28 V/km was chosen for the hotspot simulation in addition to the uniform storm magnitude of the Dallas island case. Integrating hotspot simulation with an islanded grid can give better insight as to how the natural and manmade causes affect the resilience of the electric grid.

To prevent GMD storms from damaging high voltage transformers, which can be difficult and expensive to replace, a GIC blocking device can be installed in the transformer neutral to prevent the flow of GICs through the earth and power system. Installing GIC blocking devices throughout the grid can help build the resilience of the grid, but can be costly for utility companies to install [12]. There are only three companies in the US that manufacture GIC blocking devices, which can range from $25-500K each [13]. To secure the entire United States power grid against GMD impact, an excessive number of GIC blocking devices would need to be installed. Therefore, strategic algorithms for device placement are vital for increasing resilience while keeping costs low.

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During a GMD, utilities are focused on preventing permanent damage to high-voltage equipment such as transformers and transmission lines, as well as preventing widespread blackouts. The results of this simulated mitigation plan can inform electric utility companies as they plan a course-of-action against a GMD. The remainder of the paper is organized as follows. GIC effects and the proposed islanding and GIC blocking device placement techniques are outlined in Section II. The simulation scenarios are discussed in Section III. Section IV contains the results and the paper is summarized in Section V.

II. METHODOLOGY

The proposed mitigation system is intended to model a strategy that could be used by electric utilities to prevent blackouts and damage to major equipment in the power grid. Independently, an islanded grid will be designed such that each island is a self-sustaining grid and the placement of GIC blocking devices should lower the total reactive power losses. The mitigation plan will combine islanding and GIC blocking devices to form a system design improvement strategy that maintains grid operations and minimizes GMD effect. The benefit of the designs will be shown by comparing the GMD response of the improved cases with the response of a control case of the unaltered synthetic 2000 bus Texas case.

The goal of the GMD mitigation strategy is to observe the following:

1. Decrease in transformer reactive power losses compared to a control case.
2. Increase in the time that the grid remains energized during a GMD storm compared to a control case.

A. GIC Effects on Power Systems

During a GMD, coronal mass ejections (CMEs) can cause rapid disruptions to the magnetic field around the earth, resulting in changes in the electric field over the surface of the earth. Voltage potential is induced on the system transmission lines, calculated by integrating the electric field over the line length with respect to direction. By invoking Norton's equivalent, Kirchhoff's current law, and dc network analysis, the resulting GICs flowing between buses can be calculated. When flowing through transformers, GICs can cause half cycle saturation which leads to harmonics, transformer heating and damage, and reactive power losses [14],[15]. Suboptimal voltage profile due to additional reactive power consumption in the system is not desirable from an operations standpoint and can lead to voltage collapse in extreme cases. Preventing asset and system harm is enabled by blocking currents in tranformers and removing/redirecting currents through system reconfiguration.

B. GMD Mitigation Strategy Description

The design of an islanding scheme for the study system and the placement of GIC blocking devices will be combined to create various GMD mitigation strategies to be compared in simulation software.

1. Grid Islanding: The location of the grid islands will be based on generation, load, and line voltages in the area. The islands must be made so that the generation in the isolated area can support the load in the respective area.
2. GIC Blocking Device Placement: The mitigation plan will incorporate GIC blocking device placement with the islanding strategy to form an overall GMD mitigation strategy

C. Islanding Technique

The purpose of islanding the system is to mitigate the effects of a GMD. Islanding is electrically isolating parts of the system with the intent of preventing wide-scale blackouts and keeping the resulting parts of the grid energized [5]. Islanding can be especially beneficial during a GMD because the process of isolating parts of the system involves opening transmission lines. By opening high voltage transmission lines, the DC line voltage that results in GICs flowing in the system is no longer induced on that line.

The process by which islands for this system were created involved opening lines one by one and observing the effect on the system. Two cases were created: a Dallas island case and a Temple island case, named for the general area around which the island was created. This paper will primarily discuss the results of the Dallas island.

Initially, the focus was on high population areas, such that the areas affecting the most people remained energized. During the island creation process, the first lines to be opened were chosen to be lower voltage lines near the perimeter of the state which typically serve less load than densely populated cities. This was done to reduce the impact of the line opening while remaining geographically close to the area of focus, which in this case was the Dallas area. A bus per unit (pu) voltage color contour map in simulation allowed for visual observation of the impact on the system. Upon opening lines, the result with the lowest impact on the system was chosen to continue forming the perimeter of the island. The enclosed area also had to include enough generation to support the load of the area [5]. The Dallas island shown in Fig. 1 consists of 26,236 MW and 7433 Mvar of load with 27,006 MW and 3048 Mvar of generation. The remaining southern island consists of 40,872 MW and 11,580 Mvar of load with 41,757 MW and 7613 Mvar of generation. Thirty-three power lines were opened to isolate the northern half of the grid. This island scheme results in both isolated parts of the grid being similar in load and generation. The color voltage contour feature shown in Fig. 1 visually illustrates the bus pu voltage, where red is low pu voltage and blue is high pu voltage.

D. GIC Blocking Device Techniques

The purpose of this design strategy is to minimize the GIC effects of a GMD and thus prevent a blackout of the grid by locally optimizing the placement of GIC blocking devices throughout the TSG control case. GIC blocking devices are essentially small capacitors that are installed at the transformer neutral to prevent the flow of GICs between the neutral point and ground [12]. A placement algorithm was created to place

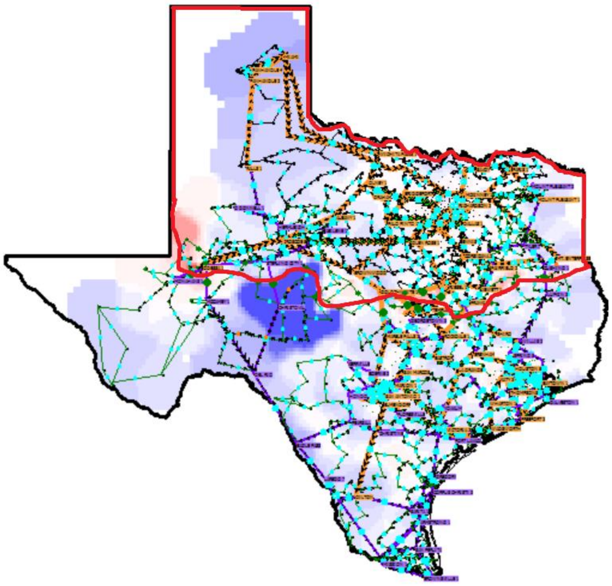

Fig. 1. A color voltage contour of the Dallas island Case, where the northern island perimeter is marked in red [16].

the GIC blocking devices on the transformers with the highest reactive power losses. This algorithm runs in conjunction with PowerWorld Simulator [8] using its SimAuto Feature [17] to place devices in the system model for any particular scenario.

E. Device Placement Algorithm

The algorithm can be described in the following procedure:

1. Sort transformers in ascending order based on reactive power losses
2. Store index of transformer that is right above or equal to reactive power loss threshold value μ to a variable *i* which will be used as a stopping criteria
3. Retrieves the last ten transformers with the highest reactive power losses from array
4. Places devices on transformers selected in 3.
5. Recalculates reactive power losses and re-sorts the transformers in ascending order based on reactive power losses
6. Adjust transformer index criteria based on re-sort
7. Repeat steps 3-6 until either the index of the last blocking device placed is less than or equal to *i* or there are no more transformers with reactive power losses greater than μ

The user has the option to set μ in which the program will place GIC blocking devices on all transformers above or until the stopping criteria *i* has been met.

III. Scenario

The GIC add-on feature in the simulation software was used to simulate GMD storms on the TSG for the Dallas island case. The Dallas island case was simulated with a GMD, the resulting GICs were included in the AC power flow, and the storm magnitude was increased until the simulation blacked out. The Dallas island case was able to withstand an electric field input of magnitude 3.14 V/km before the system could no longer withstand the additional reactive power losses and the system blacked out. The TSG control case was then simulated with a uniform storm magnitude and varying storm directions. It was concluded that a 90-degree storm had the biggest impact on the grid, as it resulted in the highest total reactive power losses. The direction of the storm was set to 90 degrees and was kept consistent throughout the remainding test scenarios.

A. Metrics and Validation

Validation of the proposed techniques will be measured by how well the proposed GMD mitigation strategy is able to mitigate the effects of a GMD event. The validation metrics for this project are as follows: a decrease in total reactive power losses after placement of devices compared to the initial total reactive power losses, the ability of the islands to withstand a higher storm magnitude before blackout after GIC blocking device placement, and the ability of the island case buses to remain energized for a longer period of time with the addition of GIC blocking devices during a transient stability simulation. Bus pu voltage was originally considered, as it is within ERCOT standards for buses to remain within 0.9-1.05 pu volts in the post-contingency state [15]. However, it was found that after the placement of devices on the island case, the number of buses in violation could increase compared to the original island case with no devices. An initial solution was to add additional GIC blocking devices manually to the transformers in the areas where there were buses in violation. This solution reduced the number of bus violations but made minimal difference in the total reactive power losses. Since the number of buses in violation only accounted for 1-1.5% of the total number of buses, it was concluded that for the purposes of this project, the focus would remain to reduce total reactive power losses due to installation costs.

B. Uniform Storm Case: Dallas Island

The Dallas island was simulated with a uniform storm magnitude of 3.14 V/km, the storm magnitude each case could withstand before the grid went to blackout. The proposed algorithm was utilized to place GIC blocking devices accordingly. The number of devices placed, as well as the reactive power loss improvement across three threshold values were recorded for this particular storm scenario.

C. Hotspot Scenarios

To determine the number of hotspot cases to simulate, a map of Texas with the latitude and longitude coordinates was utilized to place GMD hotspots in between every degree of longitude that spanned the width of Texas. Previously recorded GMD events and the corresponding hotspots that were observed recorded magnitudes of anywhere between 1.67-11.42 V/km, which were considered to be extreme cases [3],[11]. For the sake of creating a mitigation plan for these extreme cases, the hotspot storm magnitude was doubled in value from the uniform storm magnitude. This hotspot storm magnitude was kept constant throughout all cases. A total of 62 GMD hotspots were simulated at a storm magnitude of 6.28 V/km for both of the islanded cases. To test each case, a placement algorithm threshold of 50 Mvar, 60 Mvar, and 70 Mvar was implemented and tested. For each of these values, the program would place devices on transformers with reactive power losses at the specified threshold value or greater. The following threshold values were chosen due to the number of transformers with losses between 50 and 80 Mvar that did not have GIC blocking devices placed in an earlier study of manual placement of GIC blocking devices. To compare the difference in threshold values and the effectiveness of the algorithm based on the number of devices placed, three threshold values 10 Mvar apart were chosen to compare.

IV. Results

A. Islanding Results

Islanding does create dynamic disturbances to the system, which can lead to stability issues in some areas of the grid. However, one purpose of islanding is to prevent a complete black start situation and preserve a portion of the grid if there is a blackout. Since the simulation software used ends a simulation once any part of the grid blacks out, bus per unit voltages during a power flow analysis were analyzed to show the benefit of the islands during storms of varying magnitude.

It is expected that the bus pu voltage should be between 0.9 and 1.05, in accordance with NERC Steady State Voltage Standards [18]. The strategy as designed reduced voltage violations due to the GMD, see Fig. 2.

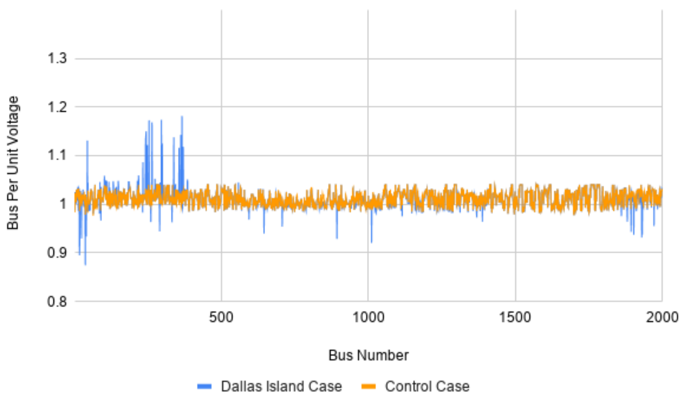

Fig. 2. Bus per unit voltages of Dallas island grid during no storm compared to a control case during no storm.

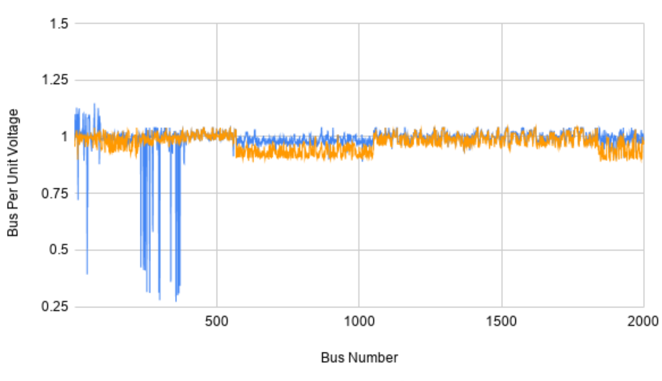

Fig. 3. Bus per unit voltages of Dallas island grid and a control case during a storm of 7.5 V/km

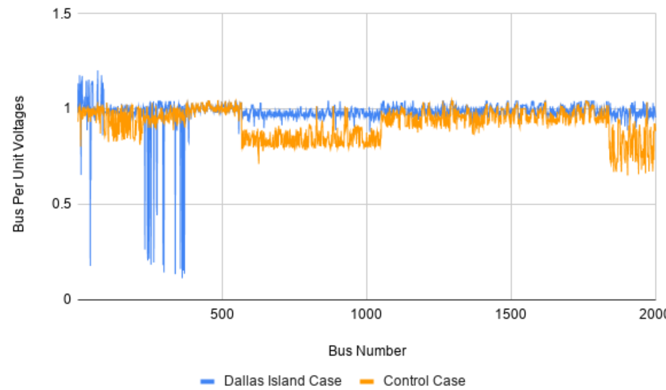

Fig. 4. Bus per unit voltages of Dallas island grid and a control case during a storm of 10.5 V/km

As the applied storm magnitude increased to 7.5 V/km in Fig. 3, and 10.5 V/km in Fig. 4, many of the buses of the islanded grid are still within the 0.9 and 1.05 range. The bus numbers along the x-axis are arranged by location. Buses 0 to 400 are located in West Texas, buses 400 to 1400 are in Central and South Texas, and buses 1400 to 2000 are located in East Texas and the Coast. While the area around West Texas does appear unstable, the goal of the islanding is to preserve the majority of the grid, preventing a black start situation.

B. Integrated Results: Uniform Storm Case

A uniform storm was applied to the Dallas island case and the algorithm was utilized to place GIC blocking devices for each reactive power loss threshold. The initial reactive power losses before placement of devices as well as the final reactive losses after placement were recorded. The reactive power loss *improvement* due to GIC blocking device placement is shown in Fig. 5.

C. Integrated Results: Dallas Island Case with Hotspots

A uniform storm was applied to the Dallas island case and several hotspot scenarios were simulated across the TSG. The algorithm was used to place GIC blocking devices for each reactive power loss threshold. Fig. 6 shows the number of devices placed per the algorithm with respect to hotspot location. The reactive power loss improvement due to GIC blocking device placement is shown in Fig. 7.

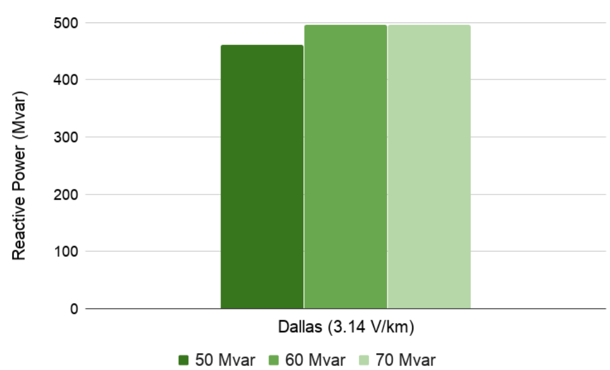

Fig. 5. Uniform Storm Case- Dallas island at a storm magnitude of 3.14 V/km the largest improvement in reactive power losses is seen at a threshold of 60 Mvar and 70 Mvar.

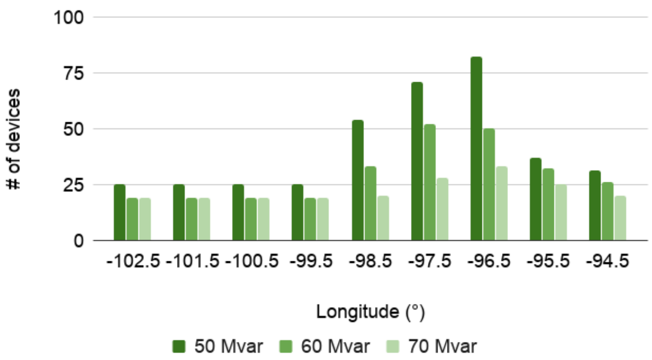

Fig. 6. Number of devices placement at 32.5 degrees longitude. In the Dallas/Fort Worth area where there is higher generation/load, the number of devices placed increases due to the increase in reactive power losses.

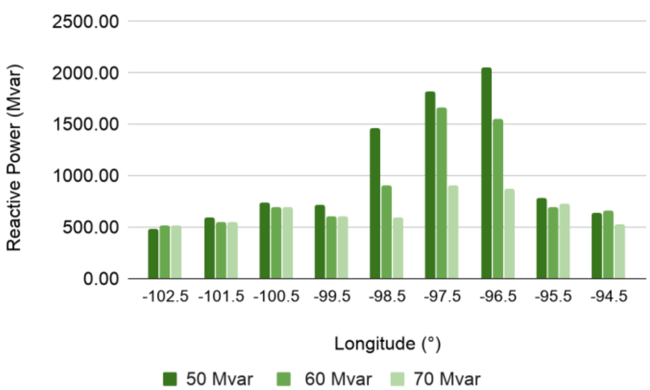

Fig. 7. Dallas island reactive power loss improvement at 32.5 degrees longitude with respect to the number of devices placed (Fig. 6).

As the hotspot is simulated at various coordinates across Texas, the reactive power loss improvement across threshold values is consistent until it approaches the Dallas/Fort Worth area. The greatest improvement in reactive power losses can be seen at the 50 Mvar threshold for a location of 32N, -96.5E, in the Dallas/Fort Worth area.

To observe the effect device placement has on the grid in regards to the storm magnitude the system can handle before blackout, a select number of hotspot scenarios that represented each area of Texas was chosen and the GMD storm magnitude was increased in increments of 0.2-0.5 V/km until the TSG

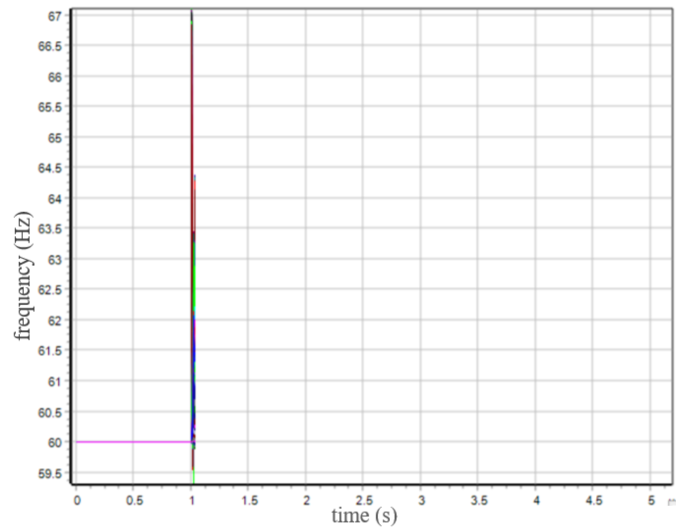

Fig. 8. Bus frequencies across the Dallas island case over time when 25 devices are *randomly* placed. A storm with magnitude 4 V/km is applied and the islands are made at 1 second.

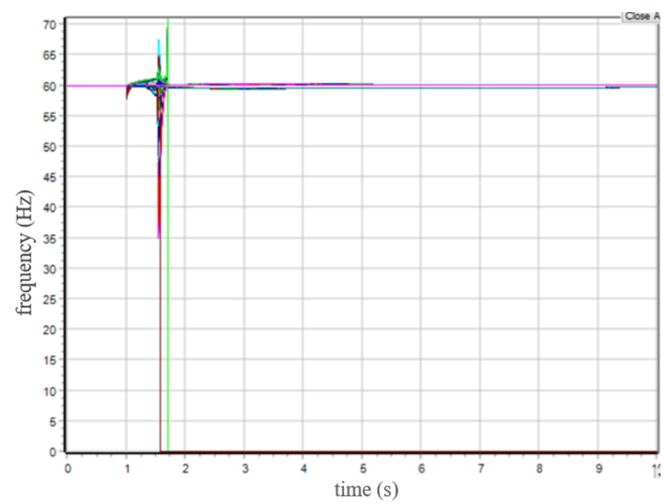

Fig. 9. Bus frequencies across the Dallas island case over time when 25 devices are *strategically* placed. A storm with magnitude 4 V/km is applied and the islands are made at 1 second.

blacked out. Based on the collected results, as seen in Table 1, each hotspot scenario was able to withstand a higher storm magnitude compared to the initial storm magnitude before device placement.

TABLE I
STORM MAGNITUDE AT BLACKOUT FOR DALLAS ISLAND CASE WITH HOTSPOTS

				50 Mvar Threshold		60 Mvar Threshold		70 Mvar Threshold	
Area of Texas	**Latitude (degrees)**	**Longitude (degrees)**	**Initial Storm (V/km)**	**Reactive Power Loss Improvement (Mvar)**	**Max Storm Magnitude (V/km)**	**Reactive Power Loss Improvement (Mvar)**	**Max Storm Magnitude (V/km)**	**Reactive Power Loss Improvement (Mvar)**	**Storm Magnitude (V/km)**
East Texas	30.5	-103.5	3.11	460.67	7.92	496.36	8.06	496.36	8.06
Panhandle	35.5	-100.5	3.14	463.52	7.90	500.58	8.08	500.58	8.08
Central Texas	29.5	-99.5	2.97	567.12	8.08	567.12	8.08	523.34	8.10
Dallas Area	32.5	-96.5	3.14	2052.71	9.26	1557.56	9.26	871.91	9.25
South Texas	28.5	-99.5	2.78	560.09	7.92	579.01	8.06	520.38	8.10

D. Transient Stability

To further validate the GIC blocking device placement algorithm, a transient stability simulation was completed. The bus frequencies were observed over time during a storm of 4 V/km. This magnitude was chosen because the Dallas island with no devices experiences a blackout at 3.14 V/km. A total of 25 devices were placed on the Dallas island case using the placement algorithm. On a separate case, 25 devices were arbitrarily placed throughout the Texas grid and simulated with the same storm magnitude of 4 V/km. With 25 arbitrarily placed devices the system blacks out at about 1.1 seconds (Fig. 8). In the case with 25 devices placed by the algorithm (Fig. 9), although some of the buses lose power, the system is able to remain energized for the entire duration of the 10 second simulation. The increase in the amount of time that the grid is energized demonstrates the benefit of the GIC blocking devices placement algorithm as opposed to adding the same number of devices arbitrarily.

V. Conclusion

This paper demonstrates the effects of implementing a planning-based mitigation strategy in the event of a GMD storm. Implementing islanding can increase the per unit voltages at buses in areas with localized reactive power losses due to a GMD. The GIC blocking device placement algorithm used on the TSG decreased the total reactive power losses during a GMD storm, as well as increased the amount of time the grid was able to withstand the storm before blacking out.

Electric utilities and operators can implement similar strategies to increase resilience on the electric grid, providing a mitigation system for GMD storms by increasing the amount of time operators have to maintain grid operations and increasing the reactive power capability of the grid. Future work includes more refined techniques for developing islands and improving the device placement algorithm, exploring different stopping criterion and problem objectives, such as incorporating bus pu voltage.

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