Using Large Scale Synthetic Systems for Undergraduate Research in Electric Grid Islanding

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Abstract— **Natural disasters have long posed a threat to electric grids. This paper considers how islanding can be used to improve electric grid resiliency to such events. Specifically the paper provides an example of undergraduate research applying the concept of islanding to a Texas-sized synthetic grid. The results show that islanding the synthetic grid successfully protects it from a complete blackout, and maintains full functionality for all portions of the electric grid in the absence of an event.**

Index Terms— **Intentional islanding, predetermined islanding, undergraduate research, synthetic grid**

I. Introduction

In 2017, Texas witnessed the devastation that can be caused by severe weather. Hurricane Harvey brought flood and ruin to coastal Texas cities. The damage caused by the storm was estimated to cost up to $180 billion. On Monday August 28, 2017 almost 300,000 Texans were without power [1]. Another frequent threat in Texas is winter ice storms. In 2011, the extreme ice caused 152 power generation plants to go offline in Texas, causing outages across the state [2]. With the increasing frequency of severe weather as well as higher load demands, grids need strategies to avoid weather-related blackouts.

Hurricanes and tornadoes are capable of knocking down power lines with their extreme wind speeds. The flooding from rain storms can cause outages due to the water seeping into the electrical components at substations and plants, which then takes time to be either cleaned and dried or replaced. Customers can even have individual outages if the salt from flood water gets into their houses' meters. Ice storms can cause accumulations on power lines, weighing them down and breaking the pole or snapping the lines. Droughts can cause forest fires, or kill trees due to lack of water, providing a threat to lines located close enough to be taken down by a fallen tree. Natural disasters are the top causes for power outages across the globe. Resiliency to natural disasters is an issue for many grids.

In this paper, which is based on undergraduate research by the first author, a synthetic model of the Texas grid is used to evaluate the effectiveness of islanding on improving the resiliency of a system faced with extreme weather events. Synthetic power grids are fictitious data sets designed to match characteristics of actual grids. Because much actual power system data is confidential energy infrastructure information (CEII), it is often subject to non-disclosure agreements and cannot be freely shared. The purpose of synthetic grids is to spur innovation by providing fully public test cases that are realistic and similar in size and complexity to actual grids.

The test case used here comes from [3, 4], and covers the geographic footprint of the Electric Reliability Council of Texas (ERCOT) with a 2000-bus system. It was built according to the synthesis methodology of [3, 4]. This method starts with public information about energy and population in the geographic region, then generates a transmission line topology to match power flow, topological, and other constraints. Though the system is fictitious, it is realistic and contains detailed modeling such as geographic coordinates and transient stability dynamics models, which were designed according to the method of [5]. These dynamics models are important for the transient stability simulations performed in this paper.

This paper provides an application of synthetic power grids to undergraduate research. Synthetic grids are particularly suited to education, and both undergraduate or graduate research because they are realistic, geographically contextualized, and free from confidential information. This paper focuses on the 2000-bus Texas Synthetic Grid (TSG) as a test case for studying intentional islanding to improve grid resilience. The case associated with this paper is publicly available online [6].

II. Current Meothods: Grid Hardening

There are a wide variety of different methods for improving grid resilience. A 2017 U.S. National Academies approach summaries some of these approaches stating, "Building the transmission and distribution network to withstand greater physical stresses can help prevent or mitigate the catastrophic effects of major events [7]." This section refers to enhancing the robustness of the grid through physical means, often

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referred to as “grid hardening”. First, tree trimming is enforced so that trees do not fell lines or cause shorts, especially when transmission lines sag during heavy loads. After the August 14, 2003 blackout in the Northeast United States, new standards for vegetation management were enforced [8]. Undergrounding transmission and distribution lines is common in urban areas, and protects against storms. However, it can be many times more expensive to install, harder to repair, and is not immune to flooding from seismic disturbances. Building reinforced or dead-end towers is done to prevent the cascading effect of fallen poles. Most transmission line towers are unable to support broken lines, as they are made to have equal weight of the line on both sides to keep them upright. Therefore, dead-end towers exist to stop a domino effect of fallen lines. Another practice is to place redundant transmission lines, in case one is damaged. Cost must be considered when implementing all these solutions. With infinite money, for example, we could reinforce all the towers. In addition to grid hardening, the industry also uses interdisciplinary methods including statistics and meteorology to focus hardening efforts on weather-prone areas, communication and control techniques to island or restore microgrids, and interdependence studies to plan infrastructure [9]. Multiple papers have already been published on transmission line planning, such as [10, 11]. However, often these hardening methods are applied on a case by case basis rather than according to a pre-determined solution. This is why the focus of this paper is on intentional islanding, a technique which can be applied systematically, simulated, and studied.

III. What Makes a Grid Resilient

Figure 1 shows a common graphic for illustrating grid resilience according to each phase of an event. It is called the Resilience Trapezoid. The source paper of this image states, “Defensive islanding enhances the resilience of the system during extreme events (Phase I) by mitigating their impact on the power system” [12]. The important parts of this statement are that islanding is only helpful in Phase I, because it is implemented during an event to lessen the spread of negative effects. It has no direct contribution to the other two phases which take place after the event occurs. The other focus in this statement is the term “extreme events.” Because overloaded lines that are tripped during a standard event are reconnected soon after, the end of Phase I would look the same with or without islanding. In fact, islanding could even cause more lines to need reconnection. However, in an extreme event that knocks out enough generation and transmission to cause large blackouts, islanding could improve the resilience of Phase I by cutting the blackout area in half, or less.

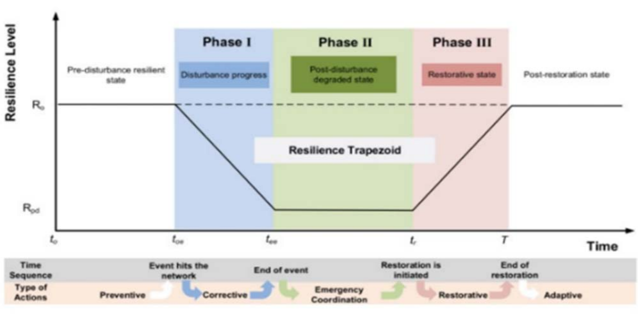

Figure 1. Conceptual resilience trapezoid associated to an event [12]

The proposed islanding for the synthetic TSG is evaluated in the Results section according to the standards set by previous resilience metrics, as described above. Islanding schemes are only recommended if they improve the resilience of the grid at the end of Phase I of the Resilience Trapezoid.

Currently, a common industry approach for implementing any type of islanding is to create pre-determined islands, which is also what is considered in this paper. A number of papers have been written on creating intentional islands using algorithms based on weather data and risk factors—a technique called adaptive islanding. Some focus on smaller-scale microgrids and load shedding techniques in response to weather events [13, 14, 15]. Others focus on algorithm-based islanding for larger interconnections [12, 16]. The scenario considered in this paper, although not algorithm-based, serves to show that larger sized synthetic models can be used effectively for undergraduate research to predict the impact of islanding on systems similar to large scale interconnections. After showing the success of the pre-determined islanding approach, future research could be to test algorithms like the ones discussed in these papers on synthetic grid models in order to support their integration into the education and perhaps industry practice.

IV. Islanding the Synthetic Model

This section describes a case study on intentional islanding for the 2000-bus TSG [3,6]. The commercial tool PowerWorld was used for the simulations [17,19]. Figure 2 shows a oneline of the TSG. It is important to note that while the figure 2 oneline covers a similar geographic footprint to the actual ERCOT grid and serves a similar population density, its transmission system is entirely different and was actually designed using different nominal transmission system voltages. However, for the undergraduate research application considered here it is more than adequate to show the potentially advantages of defensive islanding. The cyan and white areas on the oneline represent the two pre-determined locations for islanding.

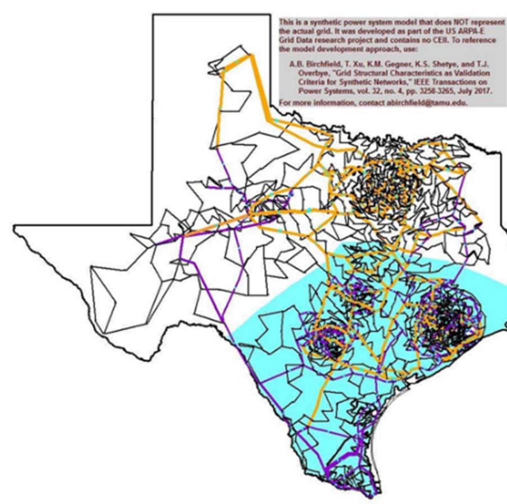

Figure 2. Islands on the synthetic grid model

To create electrically viable islands it is necessary to consider a number of factors: the amount of load vs generation in an area (so the island is self-sustaining), the total amount of load and generation in an area (so the island is not too small or large relative to the other), and the number of transmission lines that need to be opened in order to create the island (the least number is best). After analysis of the obstacles described, and some design iterations, the islands shown in figure 2 were obtained. The northern island contains 898 buses and 27,779 MW of generation. The southern island contains 1102 buses, and 40, 985 MW of generation. When a simulation is run on the grid, the islands are self-sustaining.

Before using islanding to potentially prevent a system-wide blackout, it is essential to demonstrate that the islands can handle the initial separation and then remain stable while operating independently. In North America, all power grids operate at a frequency of 60 Hz. Faults or events in the grid can cause fluctuation in which the frequency will either oscillate and eventually taper back to 60 Hz, or diverge because the disruption was too extreme. Separating the islands from each other inevitably causes some fluctuation in the bus voltage frequency and magnitudes. Fortunately, the transient stability results show that this case is within an acceptable amount, and the frequency and voltage stabilize after approximately 20 seconds. Figure 3 shows the frequency of some randomly selected buses in the North island and the South island. Figure 4 shows the frequency at all buses on the grid model, with the frequency of both islands plotted together for comparison. The separation of the islands occurs at 1 second in the simulation.

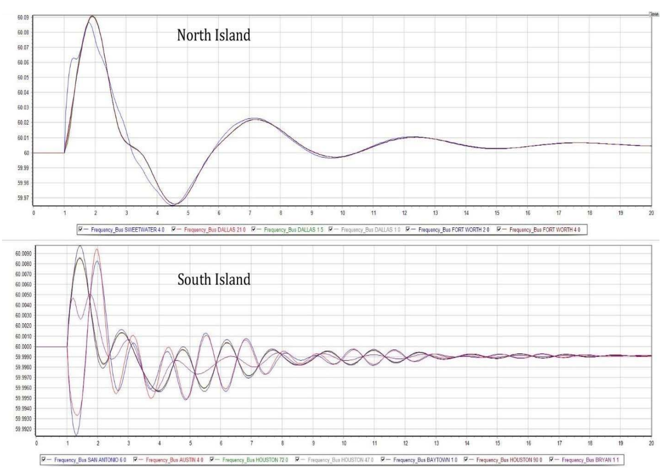

Figure 3. Frequency (Hz) of some buses in North and South islands.

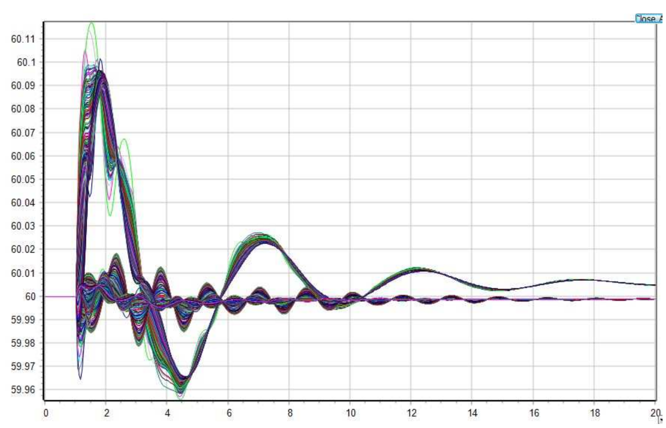

Figure 4. Frequency (Hz) at all buses.

From these figures it is apparent that the North island experiences a more extreme reaction to the separation of the grid. Its maximum frequency reaches an average of 60.1 Hz, while that of the South island reaches only 60.02 Hz. Figure 4 also shows that the two islands do not stabilize around the same final frequency. While the South island almost returns to the desired 60 Hz, the North island is slightly higher at 60.005 Hz (the frequency does not always return to 60 Hz in the transient stability simulation because it only models the governor droop control, and not the slower automatic generation control). This supports the conclusion that the North island could be considered less optimal, with a poorer matchup of load and generation. It also the smaller island, with about 2/3 the amount of MW generation that South island has, so it is more vulnerable to fluctuation. However, these are all acceptable results for a power grid and will not cause any major issues to the overall functionality.

V. Blackout Simulation

This section demonstrates the benefits of islanding by simulating an extreme weather event. The event here consists of a tornado impacting Northeast Texas resulting in the opening of three 500 kV transmission lines connected. For this scenario without islanding the entire grid eventually blacks out. However, once the islands are created and stabilized, the same scenario only causes a blackout in the North island. This is shown in Figures 5 and 6 which are bus contour maps of the bus voltage frequency [20] at the end of the simulation with blue being above 60 Hz and red below; dark red is used to indicate areas that blacked-out. Figure 7 shows the frequency of some buses in each island. At slightly after ten seconds the North island has load shed due to undervoltage relays, which soon results in generator trips on overspeed and an eventual blackout; the South island's frequency is unaffected and continues stabilizing.

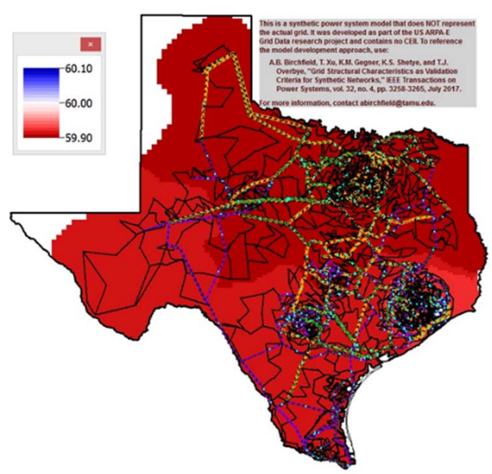

Figure 5. Blackout due to generation loss in Northeast.

Although no blackout at all is, of course, preferred, it is clearly preferable for at least a portion of the system to remain energized. Having one portion functioning is also extremely helpful in restarting the portion that is blacked-out. The portion with power can reconnect to the other side when the contingency event is over and provide power to generators to restart that section of the grid. By creating more than two islands, even more of the state could be saved from blackout by the same event. There are countless ways to implement islanding to protect the grid.

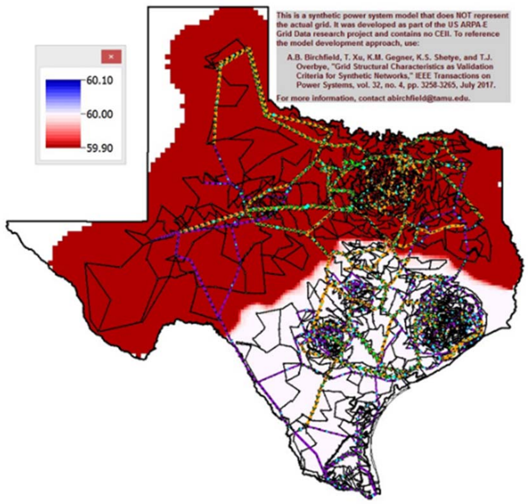

Figure 6. Blackout reduced by islanding.

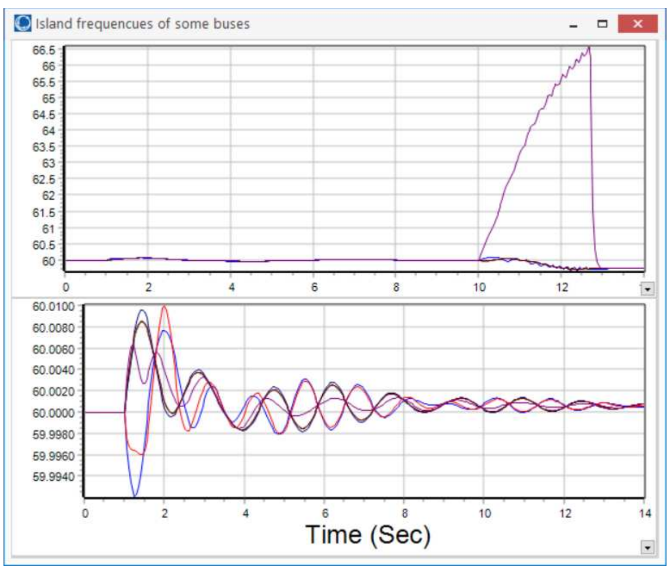

Figure 7. Frequency (Hz) of North vs South island

VI. FAIL-TO-ISLAND SCENARIO

An important issue to consider when islanding is what if it doesn't work? The reason to implement islanding is to prevent a blackout based, perhaps, on an upcoming weather condition. However, it would be even worse to cause a blackout by trying to use islanding and failing. This is a potential issue if one of the lines necessary to separate the islands fails to open. In that case, the closed line will cause an inter-area oscillation that is exacerbated by having only a relatively high-impedance path between the two islands. If the line opens, the islands can continue to stabilize as separate entities. The longer the line stays closed, however, the more unstable the entire grid becomes, which puts it in an even more vulnerable position for when the natural disaster hits. Figures 8 and 9 show the effects of high voltage and low voltage line failing to open, respectively.

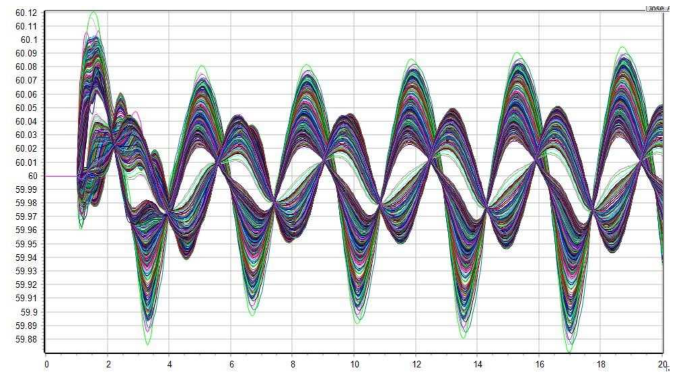

Figure 8. Frequency (Hz) when a high voltage line fails to open

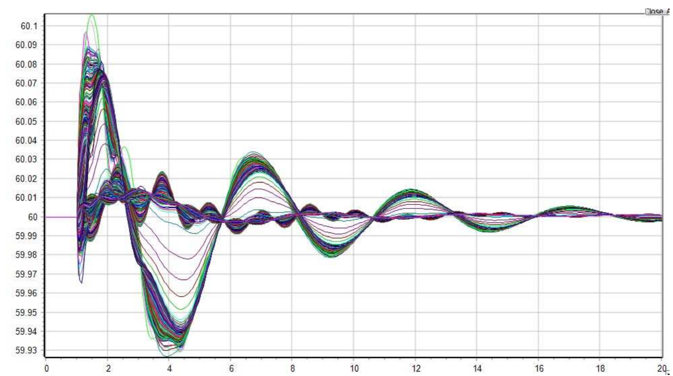

Figure 9. Frequency (Hz) when a low voltage line fails to open

For context, the low-voltage line was carrying 67 MW before islanding, and the high voltage line was carrying 560 MW. The graph of frequency when the low-voltage line fails to open looks similar to when all lines open. This shows that the case is able to recover, and takes only a few seconds longer to stabilize than in the case of completely successful islanding. In the high-voltage case of Figure 8, however, it is clear that the island "tug-o-war" is happening, with increasing magnitude (i.e., negative damping) as time progresses. These results suggest that high-voltage lines should be given the most attention when implementing islanding, and should be confirmed as opened with priority over lower voltage lines.

VII. CHOOSING WHERE TO ISLAND: INTERFACE STUDY

The predetermined island scenario discussed in this paper is just one example of how to set up islands. It is also possible to island the grid in an East-West configuration rather than North-South, to have more than two islands, etc. Therefore, the above example of a successful island was used to conduct a study to help inform the future placement of islands. Using the interface tool in PowerWorld, the net power (MW) across the interface of the two islands can be observed. To clarify, this is the power flow across the islands before they are split apart. The flow across the interface afterwards should of course be zero. In the unaltered case used in the rest of this paper, the net flow across the islands from North to South is 41.3 MW (before separation). The frequency for this case is shown in Figure 4. Although many of the individual lines connecting the two portions carry more than 41 MW, the total transfer when added together is relatively small, which is why this area is suitable for islanding. A small power exchange between the interface of islands means that they are well suited to operate independently. To determine what range of power across the interface is acceptable for islanding, some generation on the TSG was incrementally adjusted to alter the net power transfer. The following figures all correspond to the fluctuation in frequency of the North island when separated, because it is the more affected island. Figures 10 and 11 show how the interface flow affects the highest and lowest frequencies reached by the island before stabilizing. Figure 12 shows how the interface flow affects the equilibrium frequency to which the island stabilizes. Ideally, both islands would stabilize to 60 Hz. For the case used in the rest of this paper (with 41 MW of initial interface flow), the South island stabilizes to 60 Hz, and the North is slightly higher at 60.05 Hz. Figure 12 shows that larger interface flows cause the islands to stabilize farther from 60 Hz and farther from each other. This causes issues for reconnecting the islands. Another metric to consider is the time required for islands to stabilize. However, this study showed that interface flow did not affect stabilization time. Of course, regardless automatic generation control (AGC) would eventually restore the frequency to nominal for both islands.

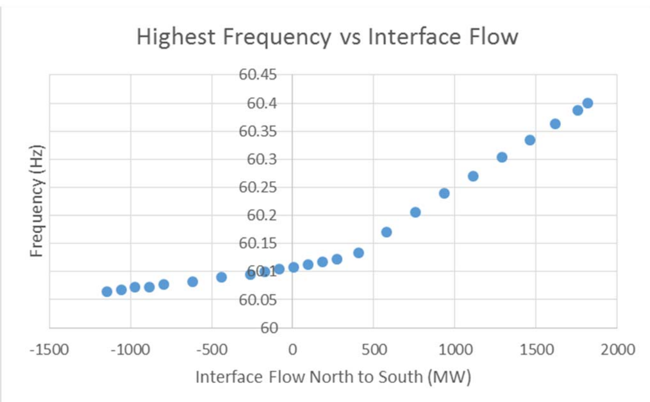

Figure 10. Highest frequency (Hz) vs interface flow (MW) of North Island.

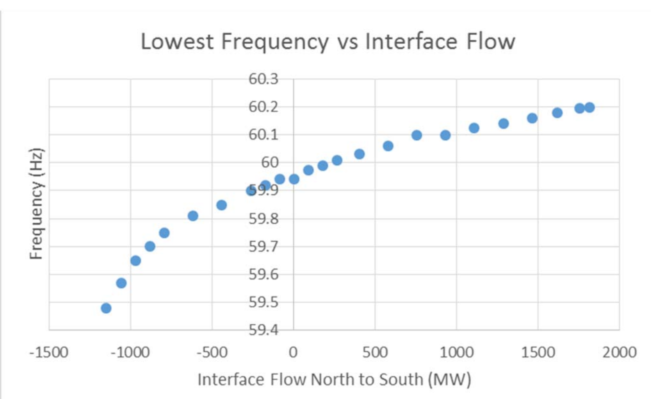

Figure 11. Lowest frequency (Hz) vs interface flow (MW) of North Island.

The final frequency in Figure 12 jumps up during the leftmost three data points because the case is setup to trip a small percentage of the load when the frequency goes below 59.7 Hz. This can be seen at about 2.7 s in Figure 12. Aside from that adjustment, the final frequency is a linear function of the interface flow because of the droop characteristics of the governors. Again, after AGC the frequency would be restored to nominal. Beyond -1150 MW of interface flow from North to South, the North island of the TSG fails to stabilize and blacks out. Figure 11 shows the change in lowest frequency as the interface flow approaches this point—it breaks the linear trend and decreases quickly when approaching the point of failure. This point occurs at an interface flow that is approximately 4.1% of the total generation capacity in the North island. Also note in Figure 13, which is close to the point of failure, how far apart the two island frequencies stabilize.

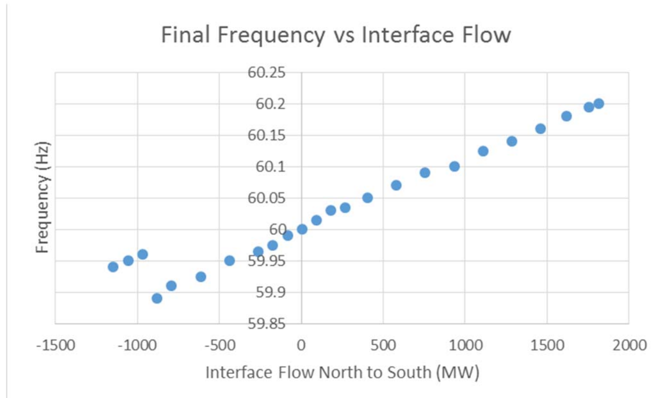

Figure 12. Final frequency (Hz) vs interface flow (MW) of North Island.

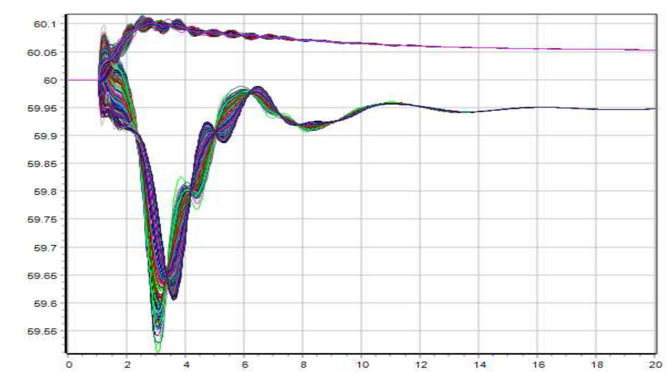

Figure 13. Islanding frequency response with interface flow of -1100 MW.

Using the above data and ERCOT's tolerance for underfrequency load shedding [18], the following criteria were created: The interface flow should not cause islands to reach 0.4 Hz above or below 60 Hz at any time during stabilization, the islands should not reach equilibrium frequencies more than 0.4 Hz apart from each other, and the magnitude of interface flow into the smallest island (MW) should be less than 4% of that island's generation capacity. The 4% metric was created based on the failure of the North island when the flow was slightly above 4%. Based on Figures 10 and 11, this scenario reaches 60.4 Hz at an interface flow of 1815 MW and 59.6 Hz at -1050 MW flow. Therefore, for this scenario on the TSG, the interface study concludes that the net interface flow between the two islands can be no more than 1815 MW into the North island or 1050 MW into the South island. In this case, these constraints are reached before the 4% metric comes into play.

VIII. Conclusion

This paper has presented an example of how large, synthetic electric grids can be used for undergraduate research. In particular, the results of the islanding study on the TSG showed that a system with the approximate size and set-up as the Texas grid can be successfully islanded by following a few key parameters. While stabilizing after separation, the islands' frequencies should not reach 0.4 Hz above or below 60 Hz, and should not finish stabilizing more than 0.4 Hz apart from each other. This can be predicted using the interface flow between the two islands before separation. Also, the magnitude of interface flow into the smallest island should be less than 4% of that island's generation capacity. Priority should be given to opening high-voltage lines over low-voltage lines when implementing islanding. Finally, the islands should be created having common patterns of severe weather in mind. The synthetic grid provides a good testbed for studying system resilience, and this case study shows an islanding strategy can be an effective approach for enhancing system resilience against extreme weather events.

The type of islanding discussed in this paper can be called "predetermined islanding," meaning that in the event of severe weather or natural disaster, the grid is split into islands that have been decided beforehand. That is, the boundaries for the islands are already known along with the amount of load and generation in each. "Adaptive islanding," however, tends to refer to the idea of creating islands in-the-moment based on weather data. Researches have already tested an algorithm on a simplified model of the Great Britain power grid [12, 16]. However, as they mention, there are limitations to this approach such as the computing power needed to find the best scenario, and issues with solutions based on inaccurate weather data. When successful, however, adaptive islanding would be more efficient and less strenuous for the grid than predetermined islanding. Therefore, the next step for the study of islanding the TSG would be to create algorithms and test the benefits and limitations of adaptive islanding.

IX. Acknowledgment

The authors would like to acknowledge that this work was partially supported by the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) under the GRID DATA project.

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