Topological Impacts of Renewables and Storage on Operational Costs and Phase Stability of a Power System

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Abstract

This project investigates the impact of where 30% renewable penetrations and storage is interconnected into a IEEE 24 bus test power system. Its inspiration comes from a previous project I completed that needed a more realistic and applied investigation, which this provides. Given data from a 2017 Texas load profile, one week from each season is simulated to test the phase angle stability of each node in the power system and the overall operational cost. The optimal topology for the addition of renewable generation to the power system was found to be in a scattered, non-centralized arrangement of renewables. Storage proved to improve stability in testing situations of peak load, and a clustered, centralized configuration of storage emerged as the best implementation strategy. This project serves as a basis for many potential, influential future projects on power system topology that would be impactful in a world with growing renewable penetrations and storage dependence.

1 Introduction

United States power systems, and power grids around the world, are expected to transform dramatically with surging implementation of renewable generation. The National Renewable Energy Lab and many other research institutions are outputting plenty of publications addressing the integration of renewables and storage into a power system. One topic that will be crucial when small energy companies and even individual families start adding renewable penetration to the power grid is exactly where these renewables and storage are connected to in the power system network. This is called network topology.

In a network dynamics applied mathematics course I took last semester, I did a project on the dynamics of a 2000 bus power system (Fig. 1) investigating how the addition of 200 intermittent and asynchronous renewable nodes can impact the stability of the overall system. The project had interesting results, but had many approximations and assumptions about a real operating power system that distanced some of its conclusions from the reality of a power grid.

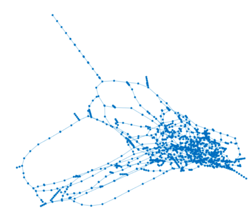

Figure 1: Chinese-like power system.

This project will serve as the next step in my investigations towards the impacts of renewable generation topology on power system dynamics and stability. Specifically, the purpose of this project is to use General Algebraic Modeling System (GAMS) to investigate the following research questions:

- What is the best way to convert a power system to high renewable penetration while retaining stability and minimizing operating cost?
- How should storage be coupled with renewables to make their implementation more stable and cost effective?

Many other student in this class will be investigating the impact of high renewable penetration and storage n on a power system. At some point in building their networks, they will have to make the decision of where to place renewables and storage in their power systems. The affects of that decision is what this project gives a closer look.

2 Project Model

Simulation and modelling for these research questions is done on the IEEE 24 bus test power system to insure realistic power system parameters and topology. The power system shown in Figure 4b will be used in all simulations in this project, while unit type in Figure 2a will vary as different generators are replaced with curtailable solar generation.

Unit Type	*Unit(s)*
Nuclear	18 21
Coal/Stream	1 2 15 16 23a
Coal/3 Stream	23b
Oil/Stream	7 13 15
Hydro	22

(a) Generator type of base case. (No Renewables)

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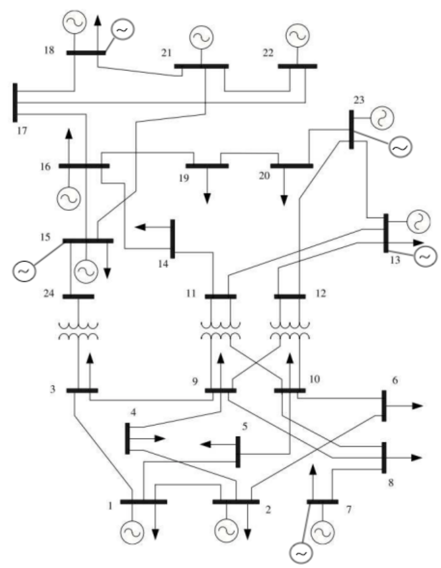


(b) IEEE 24 Bus Test Power System [1]

Figure 2: Along with the topology and generator type, IEEE provides values for generation data, operating costs, load distributions, and transmission line parameters for accurate simulation

To allow for cross comparison, every simulation will be ran with the same four weeks of a 2017 load demand time series from Texas. Each of these four weeks will represent a different season of the year. The week representing summer surrounds the peak hour of load demand for the entire year.

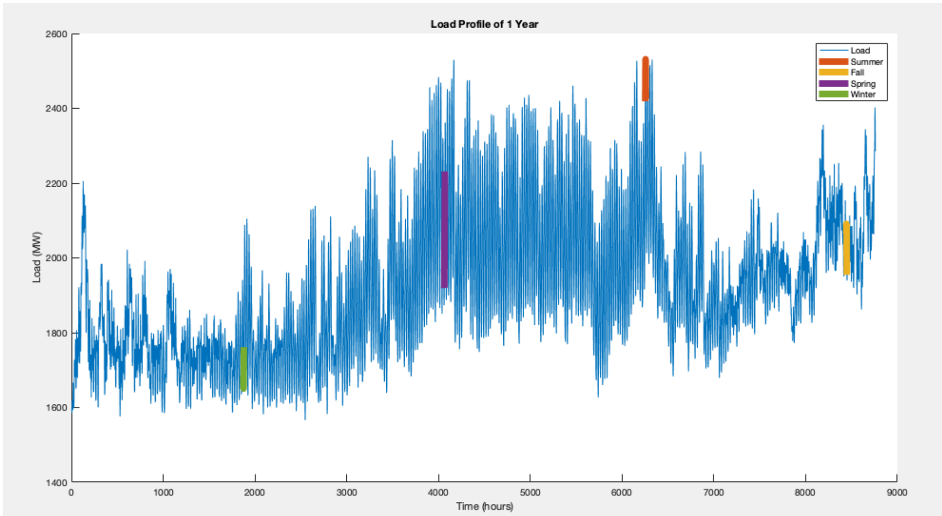


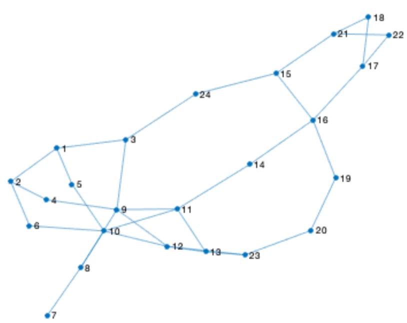
Figure 3: Load Demand Profile for Texas 2017. Weeks of all four seasons that were used in simulations are highlighted in orange, yellow, purple, and green.

2.1 Assumptions

- This IEEE test power system is an accurate model of a real system by using the common DC approximation for an AC power system, which linearizes the power flow dynamics across the grid.
- DC Power Flow Assumption 1: The transmission lines in our DC OPF IEEE 24 bus power system have negligible resistance. This means the only impedance and form of congestion on the lines is reactance.
- DC Power Flow Assumption 2: Evenly distributed voltage profile across the power system.
- DC Power Flow Assumption 3: Voltage angle differences *between* neighboring nodes are small.
- Curtailable solar is a strong generalization of renewable generation being added to the system.
- Replacing an asynchronous generator with a renewable generator (curtailable solar) is a relevant operation that represents renewables being integrated to the grid in the future. I chose to do this in order to keep the accurate topology system parameters of the accredited IEEE 24 bus test power system.
- All solar forecasting is entirely accurate allowing for dispatching of solar based on real time solar availability data.

2.2 Network Topology

The topology of an undirected network is built by a binary N×N matrix called the incidence matrix (also known as an adjacency matrix) where a 1 indicates that the associated nodes of the row and column indices are directly connected with a transmission line. A zero indicates that they are not.



(a) Matlab representation of the 24 node network with corresponding topology

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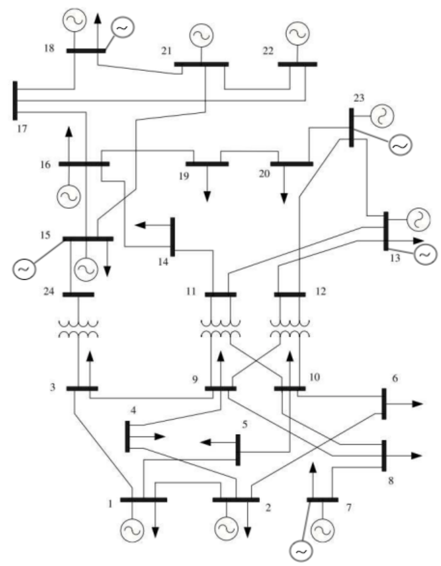


(b) IEEE 24 Bus Test Power System [1]

Figure 4: IEEE 24 bus test power system from the eyes of the computer from the incidence matrix. All generation, load, and line reactance information is stored in a data structure at each node.

In Figure 4 it becomes clear how this project covers topics similar to my previous project in Figure 1 while adding a much higher level of accuracy and application.

One of the most important definitions of network theory that apply to this study is the concept of centrality. Centraility is a measurement of how connected and influential a single node is to the whole power system. Using Figure 4a as an example we can see that node 9 is extremely centralized as it is connected to five other nodes and therefore has dynamical influence on their behaviors. Node 7 is extremely uncentralized because it only directly influences one node (node 8).

2.3 Constraints of Optimal Power Flow Simulation

GAMS was an extremely useful tool in the modelling of the dynamic power system. It allows more mathematical and computationally intensive calculations (like modelling Equation 4) to be replaced by entering a series of linear constraint equations and pressing "run". From there GAMS takes on the tough numerical computation itself to find an optimal solution where all constraints are met.

After constructing the necessary power system network in GAMS and defining all necessary coefficients and parameters, I added constraints to calculate the total cost, regulate generation vs load consumption equilibrium, power flow, generator up and down ramping towards synchronous frequencies, generation reserve, turning generators on and off, storage capacity and equilibrium, and phase angles. Many of these constraints simply required adding a maximum or minimum value, but it is important to visualize the cost, equilibrium, and power flow equations as they are integral to the implementations of my simulation.

The objective function given for GAMS to optimize through minimization was the cost function. Conceptually, this economic dispatch was implemented as follows where n represents one specific node in the network and t is time in hours.

$$\text{Cost} = \sum_{t=1}^{168}\sum_{n=1}^{24}(\text{O\&M Costs})_n + \sum_{t=1}^{168}\sum_{n=1}^{24}(\text{Fuel Costs})_n + \sum_{t=1}^{168}\sum_{n=1}^{24}(\text{Start Up Costs})_n \tag{1}$$

An additional value is added to the cost objective function for any imbalance in generation and load. This value is implemented to avoid infeasible solutions, but is given an enormous coefficient to deter GAMS from considering this as a valid solution. The constraint that generation must equal load in the power system at all times is defined by the equilibrium equation below. This equation is also given the same high cost, relief value for unserved or dumped energy when actually implemented into the code (to relieve from impossible solutions).

$$\sum_{t=1}^{168}\sum_{n=1}^{24}(\text{Generation})_n + \sum_{t=1}^{168}\sum_{n=1}^{24}(\text{Stored Energy})_n = \sum_{t=1}^{168}\sum_{n=1}^{24}(\text{Load})_n + \sum_{t=1}^{168}\sum_{n=1}^{24}(\text{Line Congestion})_n \tag{2}$$

2.4 Dynamics & Phase Stability

One of the primary challenges of adding renewable generation to a power system is the inherent instability that results from their indeterminacy and asynchronous behaviors. In a power system, instability can be detected by large and chaotic oscillations in the phase angles of each node. Phase angle can be defined by $\delta_n - \delta_x$ in the DC active power flow equation

$$P_n = \sum_{x=1} B(\delta_n - \delta_x) \tag{3}$$

for all neighboring nodes x and the coefficient B which is derived from voltage and reactance values. You will see similar structure in dynamic swing equations like the Kuramoto model that I used in my previous project.

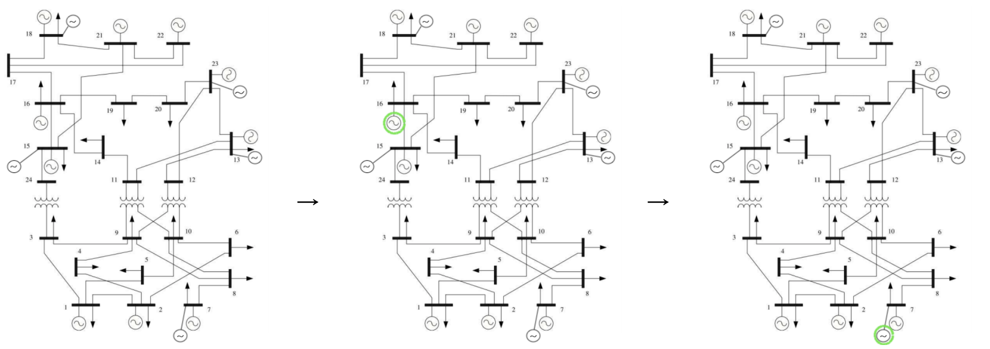
$$\frac{d\omega_n}{dt} = P_n - \alpha_n\omega_n + \sum_{m=1}^{N} K_{nm} sin(\theta_m - \theta_n) \tag{4}$$

There also exists plenty of stability metrics to give numerical value to the stability state of a system. For this project, I decided not to dive deep into the mathematics of stability and to instead show the immediate output of the new cool program that we are learning: GAMS. Since, I did implement a stability metric in my previous (more math focused) project, this would be a useful future work idea if I choose to continue my projects in this area. In this project, I will be generally determining stability based on the "chaoticness" of the angle swing plots, which still allows me to come to strong general conclusions.

3 RQ 1: Optimal Topology for Renewable Generators

3.1 Approach

In the investigation of my first research question, I will be running 7 cases through my GAMS code, which is interfaced in MATLAB. I first will run the base case scenario which is the 24 bus power system with all original, synchronous generation units. I will then run two more cases converting one central then one uncentral node to curtailable solar. I do this by keeping the potential energy output of the generator constant, yet eliminating all ramping and downtime constraints and replacing them with real time solar availability data. In both cases, the generator converted to renewable is of similar energy capacity.



(a) Origional non-Renewable Base System

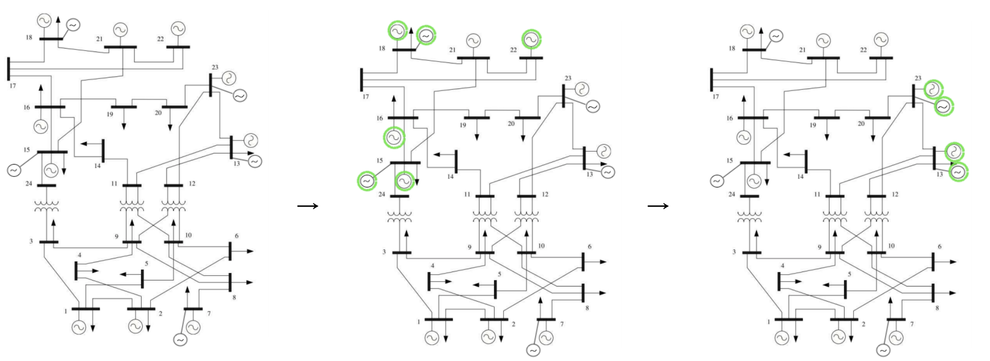
(b) Central node is converted to Renewable

(c) Uncentral node is converted to Renewable

Figure 5: Conversion of single generator to renewable.

The cases will provide a good foundation into this renewable topology investigation, but for substantial results we will then add multiple renewable generators to the test power system. In all cases of the addition of multiple generators, we will be adding approximately 30% renewable penetration.

First we will run two cases on the addition of renewables in a centralized, clustered fashion, meaning all renewable generators are either directly adjacent or share the same neighbors.



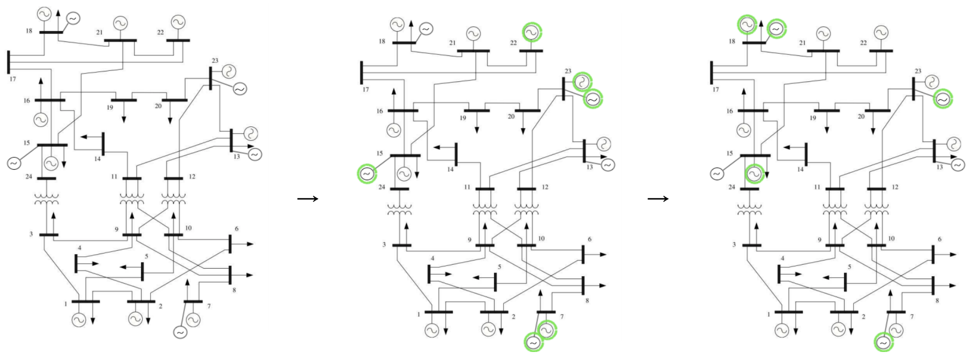
(a) Origional non-Renewable Base System

(b) Case 1 of clustered renewables

(c) Case 2 of clustered renewables

Figure 6: Approach for examining response to clustered renewable generation

Finally, we will compare our results of clustering renewable generation to those of scattering renewables. The scattered renewable generation again retains approximately 30% of renewable penetration.



(a) Origional non-Renewable Base System

(b) Case 1 of scattered renewables

(c) Case 2 of scattered renewables

Figure 7: Approach for examining response to scattered renewable generation

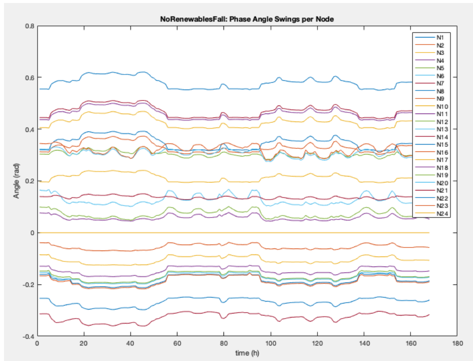
These seven cases will each run through 4 weeks, representing all 4 seasons, resulting in 28 different scenarios.

3.2 Results & Discussion

With the results from these cases we should have a clear understanding towards which renewable node addition technique is healthier for the stability and operational costs of the power system.

3.2.1 Phase Stability

There are 56 different result plots from these simulations. In this section I will be displaying results that summarize the data and discussion points well, which I have chosen to be data from the Fall season.



(a) Original non-Renewable Base Stability

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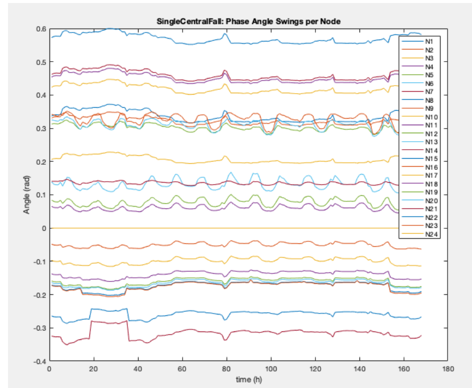

(b) Single Central Renewable case stability

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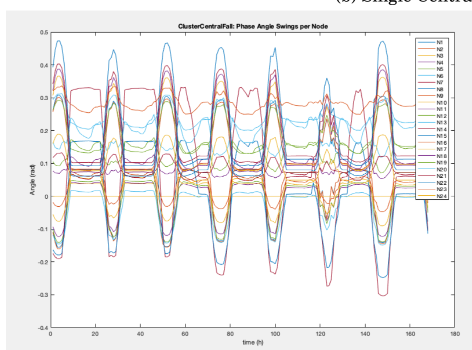
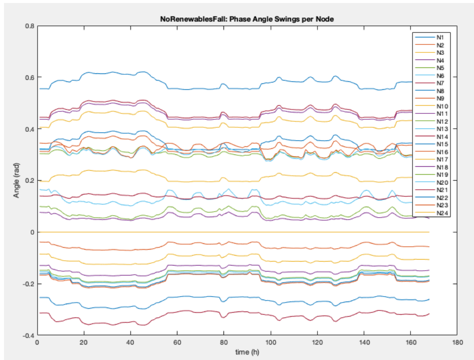


(c) Case 1 of clustered renewables stability

Figure 8: Results of Fall stability of **centralized** renewable generation vs base case

Figure 8a displays the phase angle of every node in the non-renewable base case 24 bus power system over time. What we observe here is relatively constant phase angles from all nodes throughout the entire week. When compared to Figure 8b, we can begin to notice the renewable generator caused slight increase in chaos fin the system-wide phase angle oscillations, but we can generally deem this case nearly as stable as the Figure 8a. On the other hand, Figure 8c, which is the first clustered generation case depicted in Figure 6b shows behavior of an extremely unstable power system. The large swings of phase angles is a characteristic of power systems that are struggling to restabalize. Although GAMS was able to simulate the power system dynamics on this case, the a power system with this large of phase swings would potentially collapse. As we will see in the operation cost results, the summer week for this case was infeasible (required relief variables dumping and unserved) because instability was so high that the power system would have needed to exceed the power flow capacity constraints to restabalize.

Using the same week in the Fall of 2017, the results for scattered, uncentralized renewable generation was much more promising.



(a) Original non-Renewable Base Stability

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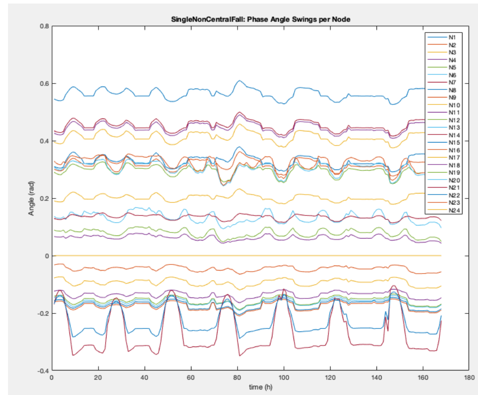

(b) Single Non-Central Renewable case stability

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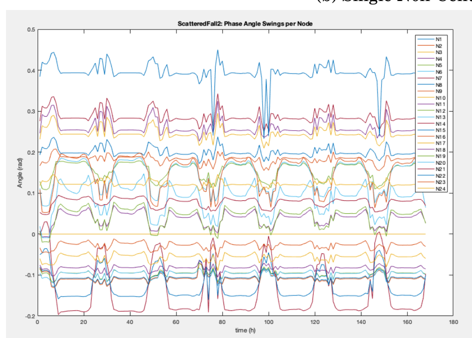


(c) Case 2 of scattered renewables stability

Figure 9: Results of Fall stability of **scattered** renewable generation vs base case

Again, adding a singular renewable generator (Figure 9b), this time in a non-centralized node, allows the system to remain nearly as stable as in the base case, yet one node does cause a slight increase in instability of neighboring nodes as shown in the bottom two node plots in the figure. The substantial finding for this research question is shown in Figure 9c. Here we can see more instability than in the base case, but still relatively low swings in phase angle and quick returns to flat line stability. If the physical parameters of the IEEE system are a strong approximation of a real power system, this scattering of renewable generation shows a much more stable and functional power system.

3.2.2 Operational Cost

The results of operational costs appear to be closely tied to the stability trends of this simulation. Compared to the base case with no renewables, the clustering renewable generation technique is resulting in higher costs. Although renewables are inherently cheaper because they have no fuel or start up costs, and low maintenance, the system is more expensive to keep operational because of how much all the non-renewable generators are having to over compensate for instability from renewables. Specifically, this means start up costs are increasing from the chaotic dispatching of fuel consuming generators. In the far more stable case of scattered renewable generation, the cost of operating the power system was significantly lower than the base case and clustered renewable test cases. With renewable generation scattering, our

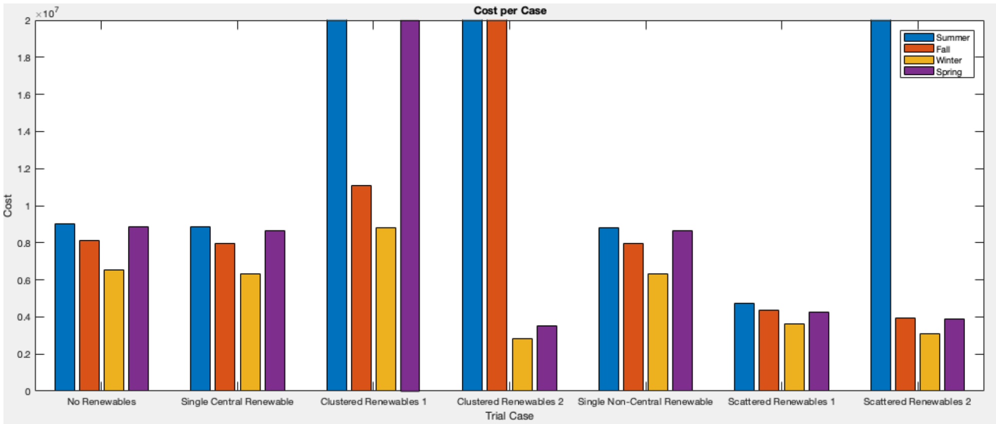


Figure 10: Operational costs for 24 bus power system in all seasons for all scenarios

power system is benefiting from the low cost of renewable generation.

With this obvious visualization of grid performance and failures, Figure 10 also illustrates major physical issues with clustering renewable generation at 30% penetration. You may notice that in five cases, operational costs seem to be through the roof. These are the places where there was no feasible solution in the simulation for generation to stay equal to load consumption, so these high costs are a result of the extremely high penalty set in the code to prevent actual errors. There is also one failure in the renewable scattering simulation, which is supposed to be the "success story" of these simulations according to all of our other results thus far. These instances where any real solution to the power flow of the grid cannot be found are exactly why experts say storage will be crucial for the implementation of high renewable generation. In the storage investigation portion of this project (research question 2), we will be looking at how storage can "save" the simulations of Clustered Renewables 1 and Scattered Renewables 2.

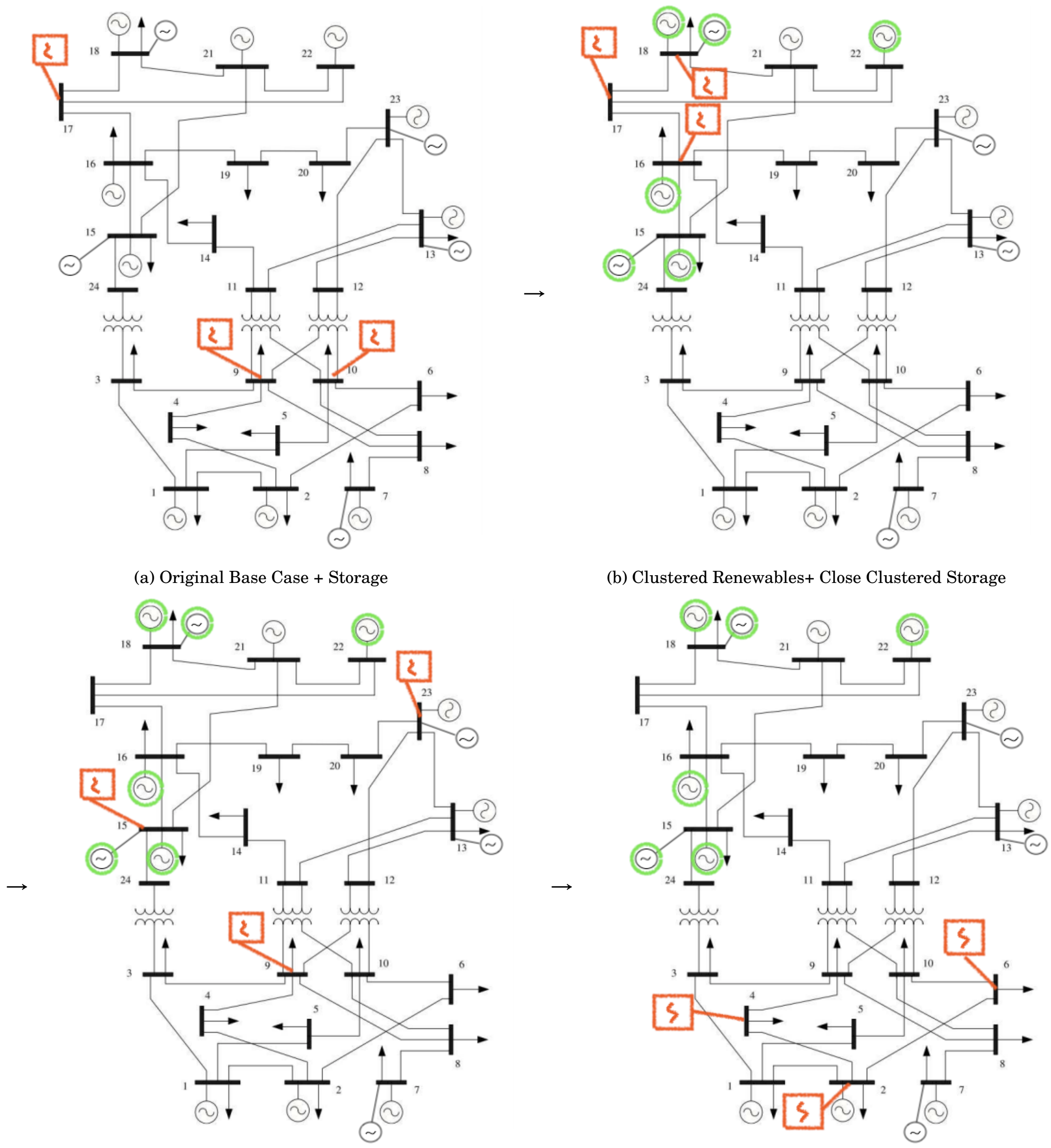
4 RQ 2: Improving Renewable Integration with Storage Topology

As done when investigating the impacts of renewable topology on a power system network, this storage topology study will have 28 total *new* simulations being tested against the same 4 weeks of the same year. Although all cases in this study are completely new simulations, there will be a significant amount of information to be gained from cross comparison to some results from part 1. In the results of this section we will be focusing on the the peak demand summer case of these simulations because these were the "system failure" cases in part 1.

4.1 Approach

In this part of our project we want to learn the best ways to apply storage to a power system to improve stability and operational costs. The base case for this series of simulations is the original non-renewable generation with implemented storage. In these simulations, the storage capacity will be equivalent to 40% of peak system energy, and will begin each simulation at 50% capacity.

We will then compare three different storage typologies to cases Clusetered Renewables 1 (Figure 8b).



(a) Original Base Case + Storage

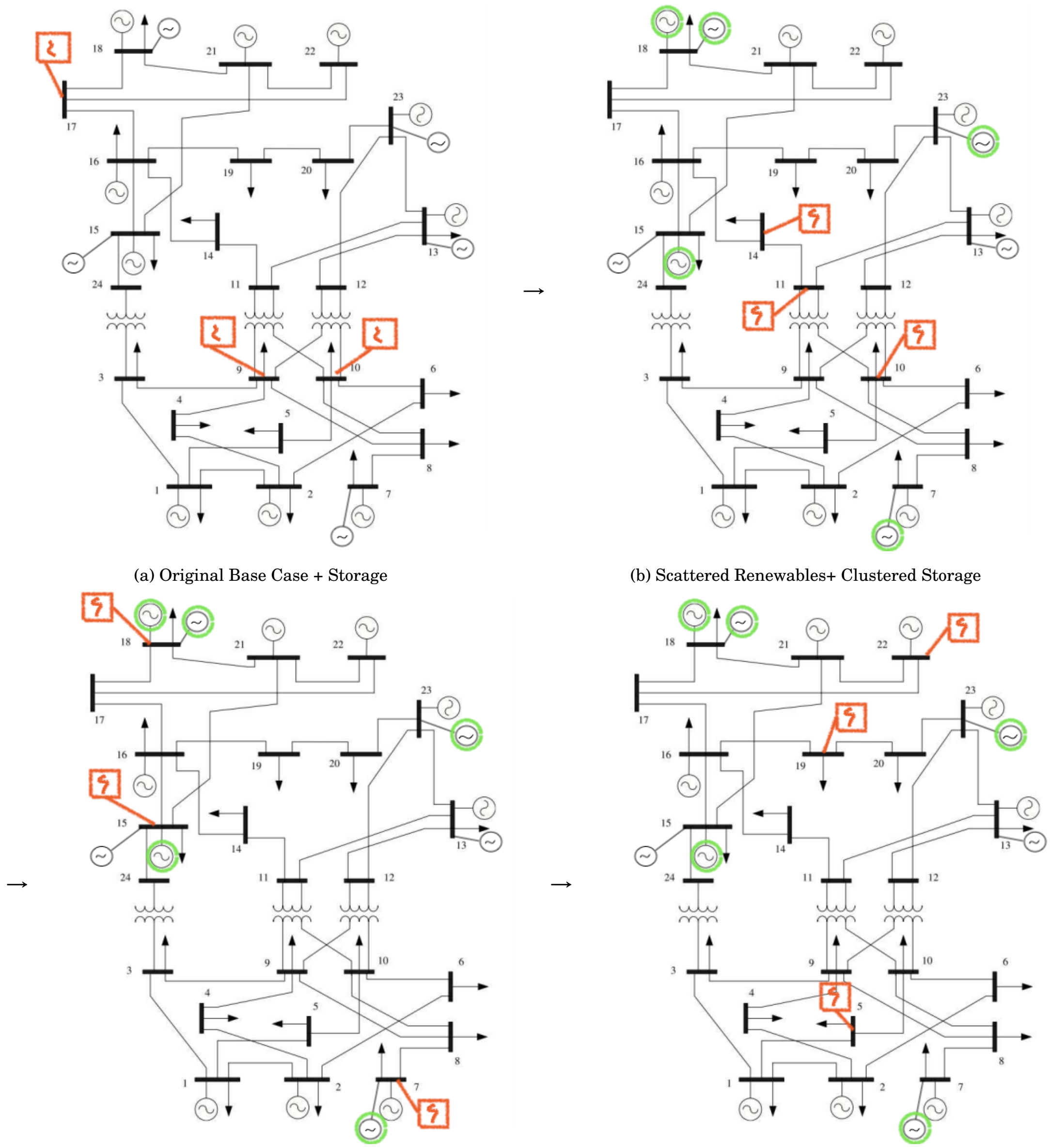
(b) Clustered Renewables+ Close Clustered Storage

(c) Clustered Renewables+ Distributed Storage

(d) Clustered Renewables+ Far Clustered Storage

Figure 11: Storage Topology with Clustered Renewables Trial Cases

Secondly, we will be looking at three topology configurations on the scattering renewables case 2 from part 1 (Figure 16c).



(a) Original Base Case + Storage

(b) Scattered Renewables+ Clustered Storage

(c) Scattered Renewables+ Adjacent Storage

(d) Scattered Renewables+ Scattered Storage

Figure 12: Storage Topology with Scattered Renewables Trial Cases

4.2 Results & Discussion

4.2.1 Operational Costs

We will start by looking at operational costs to immediately compare if our system is still paying for unserved or dumped energy that resulted from system wide failure.

From Figure 13 we can see that the spring system failure of the clustered renewables case

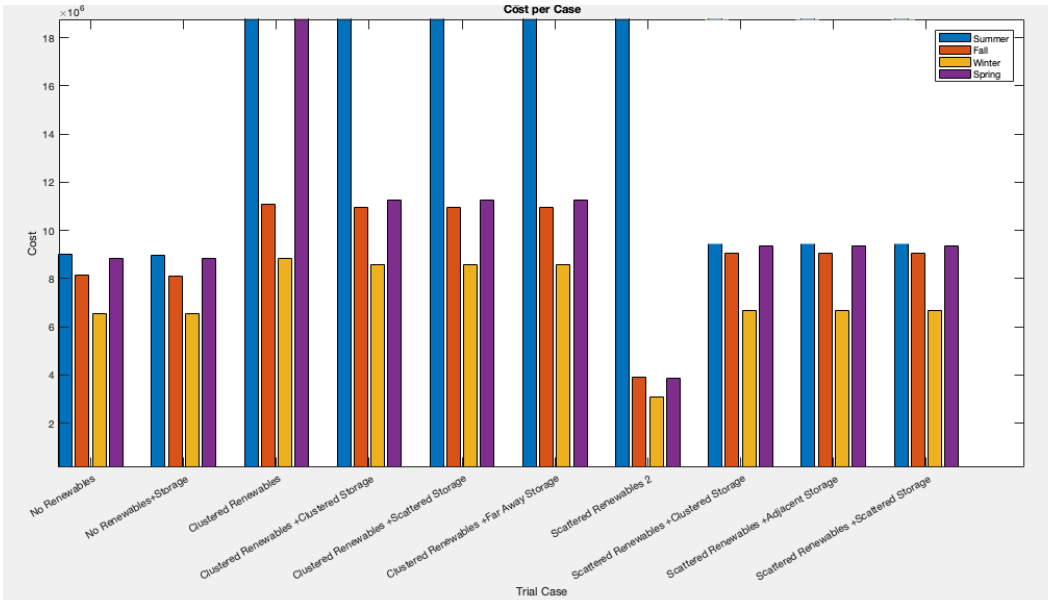
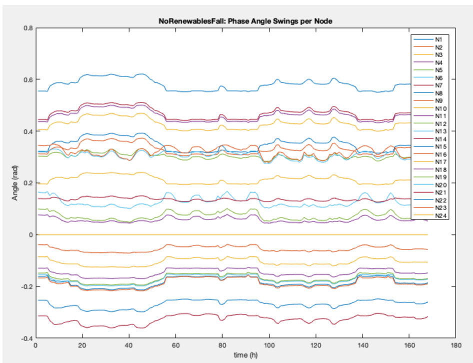


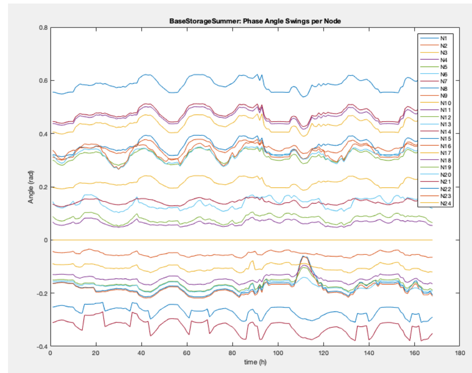
Figure 13: Operational Costs of Power System With Storage vs Previous Cases without Storage

and the summer failure of the scattered renewables case have been resolved in all cases of storage implementation! This is a great result, but apparently at a reasonable operational cost increase. This is a very curious result and would require me to run further simulations and studies to distinguish whether or not this is some sort of oversight in constraint equations, or if this would indeed be the result of implementing renewable generation and storage. My initial hypothesis is that renewables and storage should not have higher operating cost in the scattered cases because my cost function did not include installation costs or maintenance costs of storage.

4.2.2 Phase Stability



(a) Original Base Case Stability

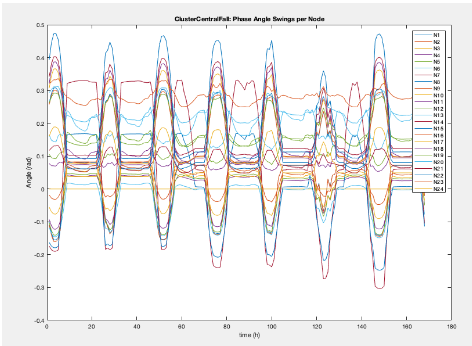


(b) Original Base Case+ Storage

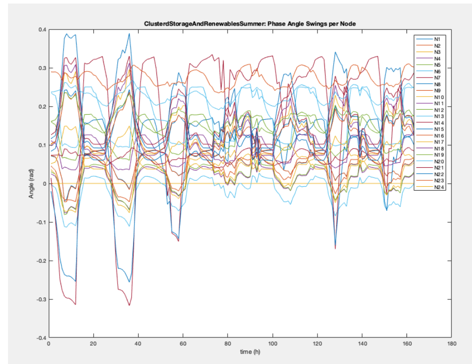
Figure 14: Both base case stabilities

Curiously, the base case test system appears to get slightly less stable with the addition of storage. This would be an interesting result to confirm with a numerical stability metric. Regardless Figure 14b still shoes clear signs of a stable power system and serves well as a base case.

Because the base case + storage is displayed right above in Figure 14b, I will include the stability results from Clustered Renewables 1 in part 1 of this project. Keep in mind that graph will be of Fall instead of Summer, but will provide more information than the Summer Clustered Renewables 1 case because as seen in the cost rests, the summer result was an impossible solution and may not show accurate stability. Also,the summer load data contains peak demand and thus if storage improves stability compared to a fall stability case it will be more impressive.



(a) Clustered Renewables+ No Storage



(b) Clustered Renewables+ Clustered Storage Stability

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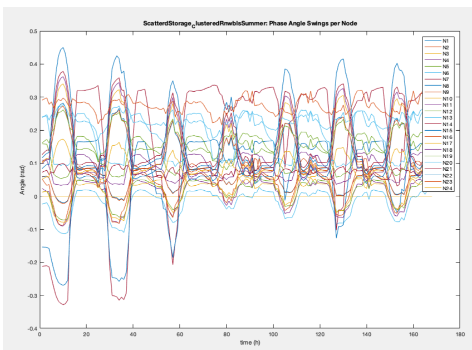

(c) Clustered Renewables+ Scattered Storage Stability

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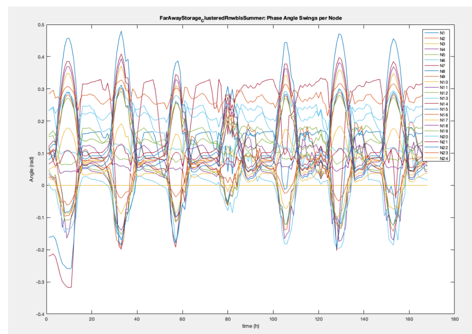
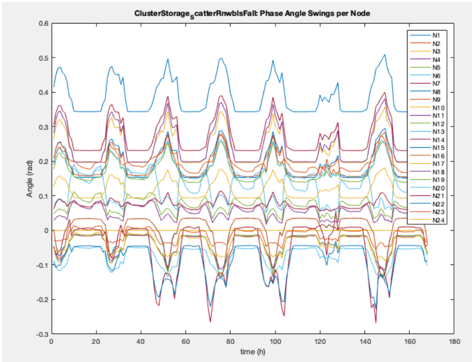


(d) Clustered Renewables+ Clustered Away Storage

Figure 15: Storage Topology with Clustered Renewables Stability

Figure 15a and Figure 15b show clear improvement in minimizing large phase swings for most nodes throughout the summer week, and 15d appears to improve slightly. In this situation it would be useful to numerically computer these stabilities to distinguish which storage topology is superior. From visual inspection it appears that clustered renewables and clustered storage is more stable.

To confirm that clustered storage is the best topological configuration in this clustered renewables case, below compares the Fall case of clustered storage, scattered storage, and no storage all with clustered renewables.



(a) Clustered Renewables + Clustered Storage Fall

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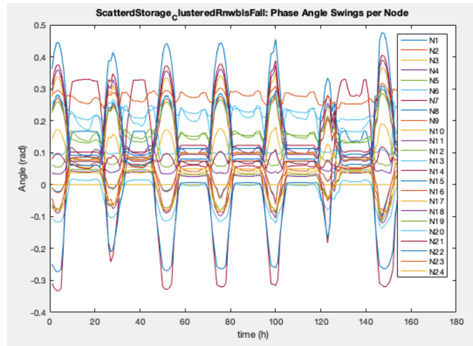

(b) Clustered Renewables + Scattered Storage Fall

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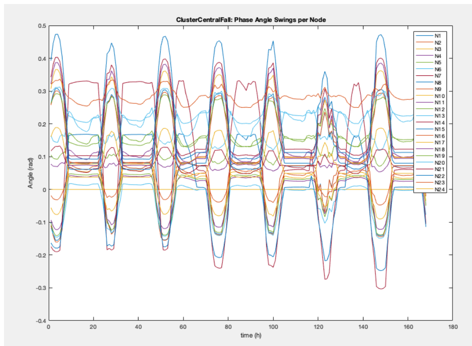
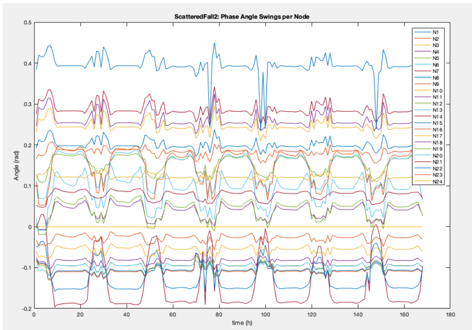


(c) Clustered Renewables + No Storage Fall

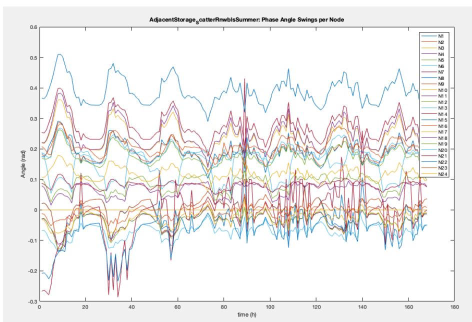
Figure 16: Fall Stability for Clustered Renewables

In Figure 16 it is far more visually evident that clustered storage is the optimal topology for stability of a clustered renewable power system.

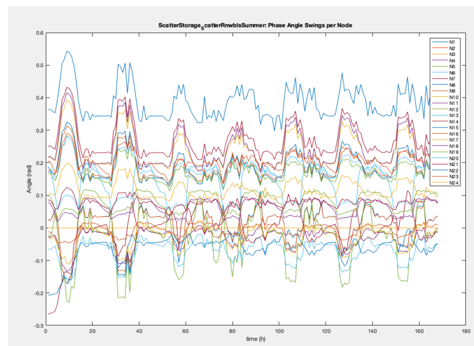


(a) Scattered Renewables+ No Storage

(b) Scattered Renewables+ Clustered Storage Stability

→ 

(c) Scattered Renewables+ Adjacent Storage Stability

→ 

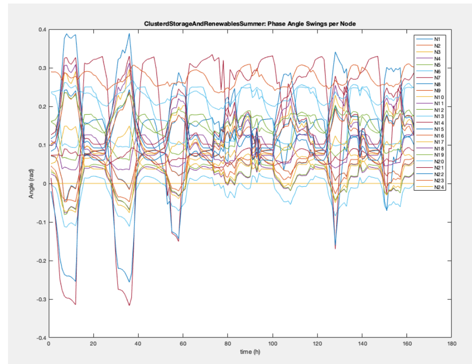
(d) Scattered Renewables+ Scattered Storage Stability

Figure 17: Storage Topology with Clustered Renewables Stability

Again we find that clustered storage is the most stable storage topology. Although, one may be tempted to believe that scattered renewables without storage is more stable than scattered renewables *with* storage, keep in mind that the summer case of scattered renewables with no storage was unsolvable. I have chosen to display the summer cases for these storage stability plots to point out how storage is making these cases solvable (without need of unserved or dumped energy).

From this topological storage data, we are starting to learn that the most stable configuration to introduce renewable generation into a power system is scattered renewables with centralized clustered storage. Figure 18 shows the most stable Summer cases of clustered renewables + storage and scattered renewables + storage. Both have turned out to be clustered storage.

(a) Scattered Renewables+ Clustered Storage Stability



(b) Clustered Renewables+ Clustered Storage Stability

Figure 18: Best Storage topologies for Scattered vs. Clustered 30% Renewable Penetration Cases

5 Future Directions

Although 56 different simulations and stability plots came out of this project, it serves as a fundamental investigation into topological impacts of renewable generation and storage on a power system. Some may even say that some of the results were "predictable", but the relevance of this project was to at least confirm expected results and establish the computation and software required to solve these problems.

It is very possible I build off of this project in future class projects, research, or graduate thesis work. If I do, here are some future work ideas I believe would "amp up" the impact of this study:

- Implement and compute numerical values from a widely accepted network stability metric to give exact results of how topology is impacting the grid.
- Instead of choosing one or two cases that fit certain topological profile types like "clustered renewables", run a recursive algorithm (very computationally expensive with GAMS) to consider all topological combinations for the *real* optimal configuration.
- Consider different renewable generation types. Specifically, if I were doing many more cases, I could have compared all of my results to non-curtailable solar and wind.
- Expand the entire project and potentially any of these future work ideas to a larger test power system. I have seen 128 node systems, or in my internship at NREL I even had real data of the United States Western Interconnection.
- Create an interactive software that reads in input data and can spit out results like this for any realistic power system.

6 Conclusion

Power system topology is extremely influential to power system phase stability and operational costs. In this project we set out to find evidence towards the best topological configurations to add 30% renewable penetration and coupled storage. The results suggest that the most stable and cost effective way to implement renewable generation is by placing renewables at scattered and non-centralized nodes of the network. Storage on the other hand proved to improve stability most from a centralized and clustered topology. Overall, this project was a strong basis for research that will seemingly be crucial in the future as renewable generation and storage begin their major additions to the grid.

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