



# Impact of High Photo-Voltaic Penetration on Distribution Systems

*Senior Design Final Document*

DEC-1614

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## Introduction

Solar Photovoltaic generation is gaining popularity across the nation, including Iowa. Because of its volatility nature, when generation exceeds certain limits, it introduces undesirable stability issues such as transients, high voltage levels, and reverse power flow.

As a senior design project, our team is collaborating with Alliant Energy to develop a preventive plan to tackle these instability issues as more photovoltaic generation is added to their Washington distribution feeder



*Figure 1 Google Map of Washington Area*

## Purpose

Our team is focused on making sure that Alliant Energy's Washington distribution system will have the capabilities of handling higher Photovoltaic penetration. For this purpose, we used OpenDSS to run simulated tests for various generation levels located in three main strategic areas. As result, we Identified generation levels that will contribute to stability problems and their locations. Based on our analytical simulations, we drew some conclusions that will help in creating preventive measures to keep their distribution system running in a stable fashion. Stability is key factor in making solar Photovoltaic generation attractive to Alliant Energy and to their customers.

## Goals

Our group's goals consist of:

- Develop a working model of a real world feeder with high PV penetration.
- Discover what locations are points of interest, then connect solar in multiple configurations (community and residential).
- Use findings to determine some guidelines that would benefit Alliant Energy to prevent future problems related to high solar PV penetration.

## Deliverables

As an outcome of this project, we came up with recommendations regarding the level of photovoltaic penetration that would create voltage level violations as well as reversed power flow. We focused our study on the worst case scenario according to the period of the year which has the lowest load value. We added these solar sites and the end of each region as a point of interest. These solar sites were added as a single site and in a distributed configuration. We will go in more depth in the "Testing" section.

# Design

To achieve the project's goals, we divided the Project followed the flow chart below:

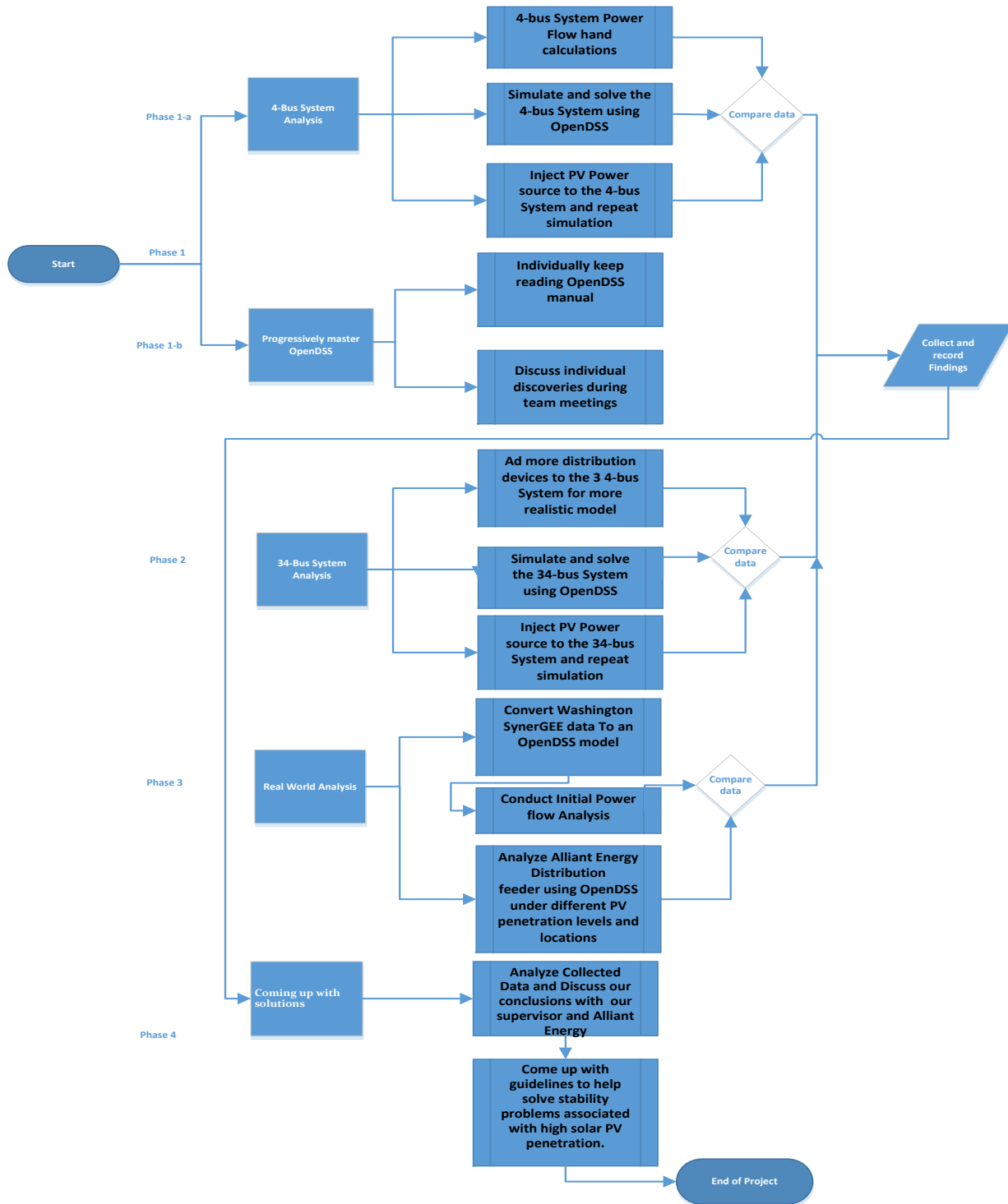


Figure 2 Project Flow Chart

# System Specifications

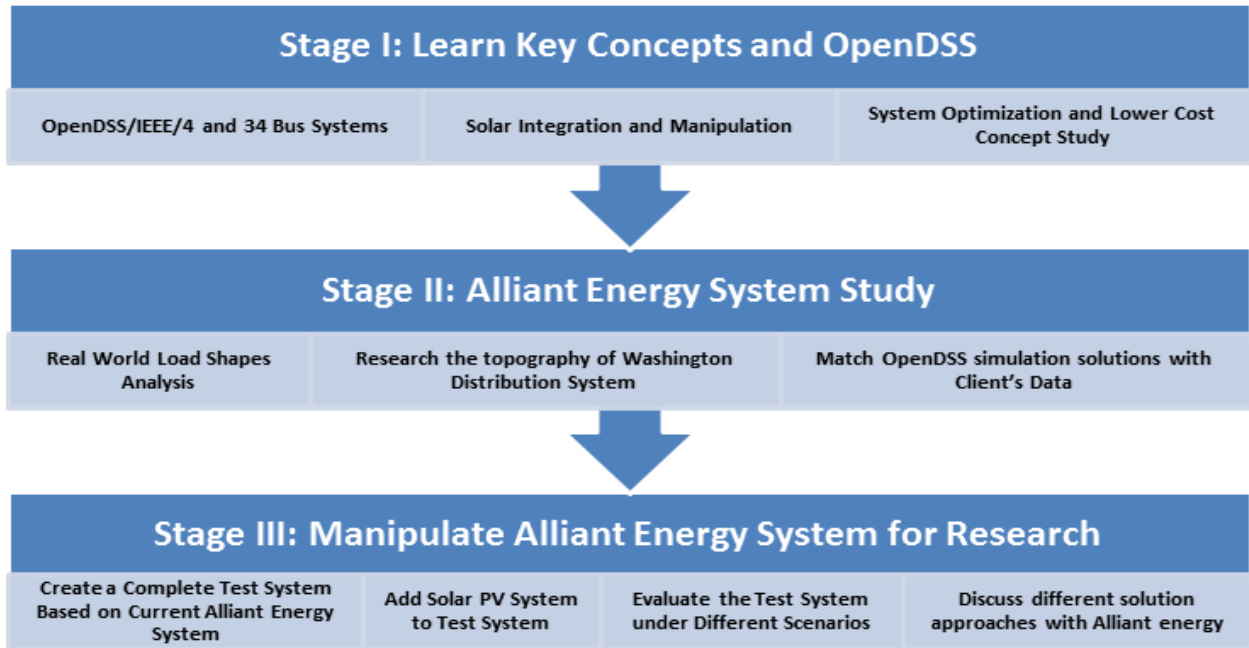


Figure 3 Stages

## Stage I: Learn Key Concepts and OpenDSS

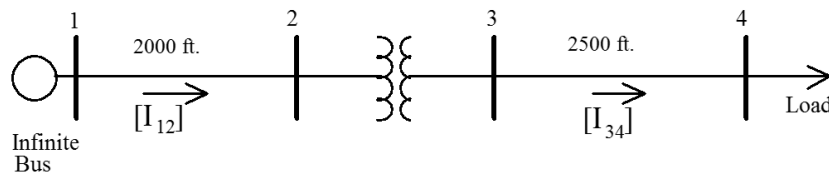
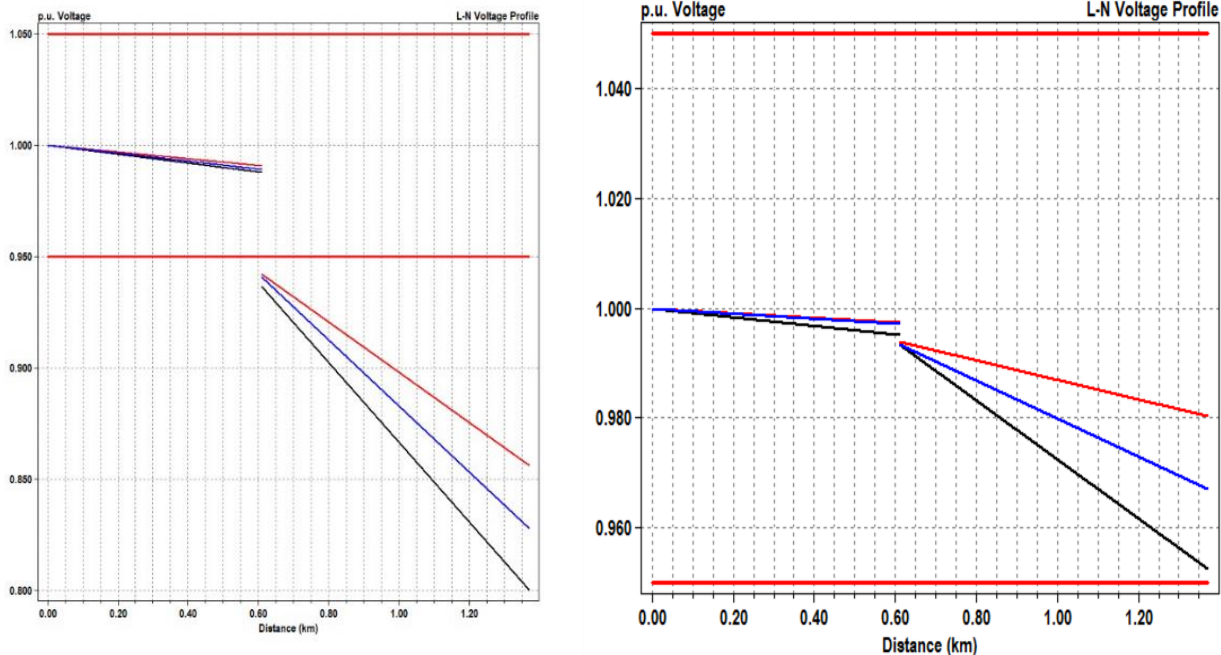


Figure 4 IEEE 4-bus System

Our team spent multiple weeks reviewing the fundamentals of power analysis. We first performed two power flow iterations of a 4-bus System by hand. This task was time consuming; however, it offered us a good revision for different technics that we previously learned in different power classes. To verify our hand calculations, we simulated the 4-bus system then ran power flow analysis using OpenDSS. OpenDSS is an electric power Distribution System Simulator (DSS) for supporting distributed resource integration and grid modernization efforts. The team was pleased since current and voltage levels we obtained by hands indeed matched the OpenDSS results. In addition, we repeated this process with the load adjusted with a factor of plus and minus thirty percent.



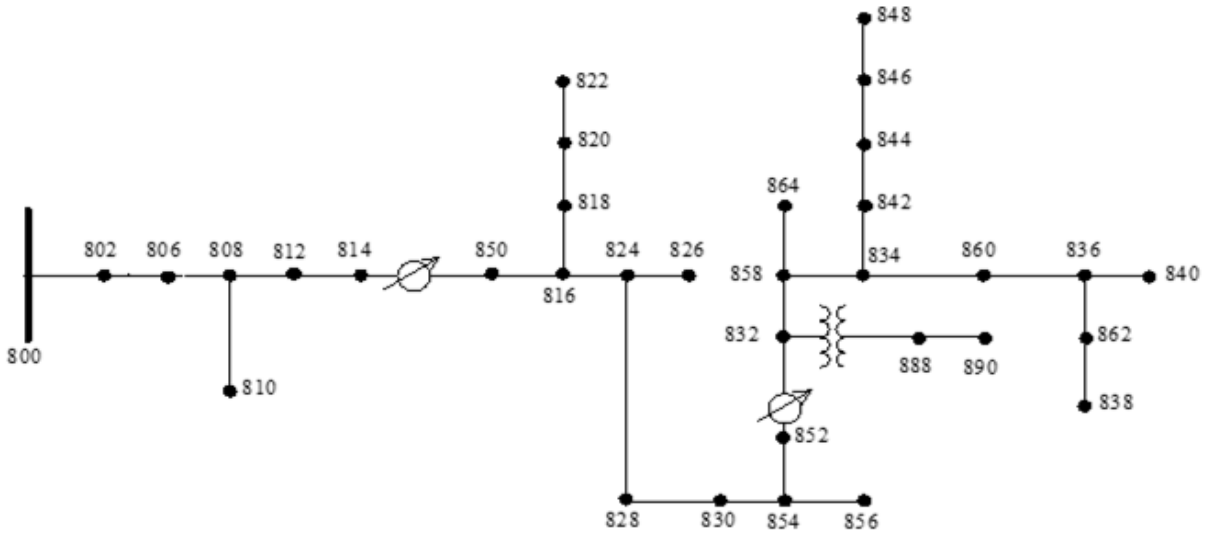
*Figure 5 Per Unit Voltage Profiles*

Black line: Phase A  
 Red line: Phase B  
 Blue line: Phase C

**Fix Voltage P.U. with Capacitors**

Node 4 Phase A = 4538 kVAR  
 Node 4 Phase B = 4178 kVAR  
 Node 4 Phase C = 4178 kVAR

After discussing our findings among the team members as well as drawing conclusions with the help of our advisor, we added distributed PV generation to the system. We modeled the PV as a power sources injected in various buses. Once more, we ran simulations and analyzed the modified 4-bus system. With PV integrated into the system, our team noticed some voltage level violations (above graph on the left) and discussed these issues with Dr. Ajjarapu. In the attempt to bring voltages to an acceptable range, we added capacitor banks in various locations. This solution indeed resolved the voltage levels concern as it can be seen above in the right graph. This process pushed us to start exploring different possible approaches to such voltage level problems. Moving on to the next phase, we felt that through this simpler model, we started recognizing how electric systems performance changes under different distributed generation conditions. We also learned the significance of capacitor banks in distributions systems.



*Figure 6 IEEE 34-Bus System*

## Test Plan

1. Fix Voltage p.u. With Capacitors
2. Manipulate Setting in Voltage Regulators
3. 24-hour Load Profile
4. 24 hour Solar PV Penetration
5. Observe Tap Changes, Losses, and Violations with different Solar PV locations and penetration



PV	Location of PV	Peak Losses	# of Tap Changes	Violations
0%	808	273.5kW (15.42%)	30	814 Phase A, 4 hours (14-17) below 0.95
0%	814	273.5kW (15.42%)	30	814 Phase A, 4 hours (14-17) below 0.95
0%	830	273.5kW (15.42%)	30	814 Phase A, 4 hours (14-17) below 0.95
0%	852	273.5kW (15.42%)	30	814 Phase A, 4 hours (14-17) below 0.95
0%	848	273.5kW (15.42%)	30	814 Phase A, 4 hours (14-17) below 0.95
0%	840	273.5kW (15.42%)	30	814 Phase A, 4 hours (14-17) below 0.95
20%	808	257.1kW (14.51%)	27	0
20%	814	225.9kW (12.75%)	33	0
20%	830	207.2kW (11.69%)	27	0
20%	852	184.2kW (10.39%)	30	0
20%	848	181.0kW (10.19%)	32	0
20%	840	181.0kW (10.19%)	31	0
40%	808	243.6kW (13.76%)	29	0
40%	814	190.0kW (10.73%)	31	0
40%	830	158.2kW (8.91%)	28	0
40%	852	121.9kW (6.86%)	33	0
40%	848	115.9kW (6.55%)	34	0
40%	840	116.1kW (6.56%)	33	0
60%	808	234.0kW (13.21%)	33	808 Phase C, 6 hours (1-5,24) above 1.05
60%	814	165.0kW (9.30%)	32	808 Phase C, 8 hours (1-6,23-24) above 1.05
				814 Phase B, 6 hours (1-5, 24) above 1.05
				814 Phase C, 8 hours (1-6, 23-24) above 1.05
60%	830	124.5kW (7.01%)	27	808 Phase B, 3 hours (2-4) above 1.05
				808 Phase C, 8 hours (1-6, 23-24) above 1.05
				814 Phase B, 7 hours (1-5, 23-24) above 1.05
				814 Phase C, 8 hours (1-6, 23-24) above 1.05
60%	852	81.3kW (4.58%)	29	808 Phase B, 5 hours (1-4, 24) above 1.05
				808 Phase C, 8 hours (1-6, 23-24) above 1.05
				814 Phase B, 8 hours (1-6, 23-24) above 1.05
				814 Phase C, 8 hours (1-6, 23-24) above 1.05
60%	848	77.5kW (4.37%)	31	808 Phase B, 5 hours (1-4, 24) above 1.05
				808 Phase C, 8 hours (1-6, 23-24) above 1.05
				814 Phase B, 8 hours (1-6, 23-24) above 1.05
				814 Phase C, 8 hours (1-6, 23-24) above 1.05
60%	840	77.7kW (4.38%)	31	808 Phase B, 5 hours (1-4, 24) above 1.05
				808 Phase C, 8 hours (1-6, 23-24) above 1.05
				814 Phase B, 8 hours (1-6, 23-24) above 1.05
				814 Phase C, 8 hours (1-6, 23-24) above 1.05

## Results

1. PV Penetration 0%-100%
2. 6 different locations for Solar
3. Losses
4. Number of tap changes
5. Number of Violations

We moved to a more realistic 34-bus model that incorporates transformers, voltage regulators, and capacitor banks. To help understand the implications of voltage regulators, we used OpenDSS to simulate and analyze the 34-bus system when load is varied with a factor of plus and minus thirty percent. Additionally, we deactivated each voltage regulator at the time, observing its impact on the voltages and currents in each node. Finally, we added PV generations in six locations varying injection from zero to hundred percent. The losses and tap changes under

each situation is shown on the spread sheet above. Our team was able to understand how to record and manage high levels of PV penetration with these IEEE 34-Bus system results. We discovered by bringing PV penetration level above 40% of maximum load, the system began to run into problems. With these finding we predict that this range to begin problem for Alliant Energy's system in Washington, IA.

## **Stage II: Alliant Energy System Study (Washington 1329-bus system)**

For this stage we worked a real world system and located points of interest according to our client's recommendations. We matched the output data in OpenDSS with the data provided by Darin, and we Added solar at points of interest while varying penetration levels. We then developed a guideline to the amount of penetration possible on the feeder which will be discussed in "Results" section.

## **Stage III: Manipulating Alliant Energy System for Research**

During this stage, we divided our test system is in North, South, and Residential Regions. We varied solar injection from 0 to 100 percent in single site and distributed fashion. We recorded the number of buses in violation of the ANSI standard ( $1 \pm 0.5$  per unit), maximum voltage, minimum voltage, and total losses of the system.

## **Testing**

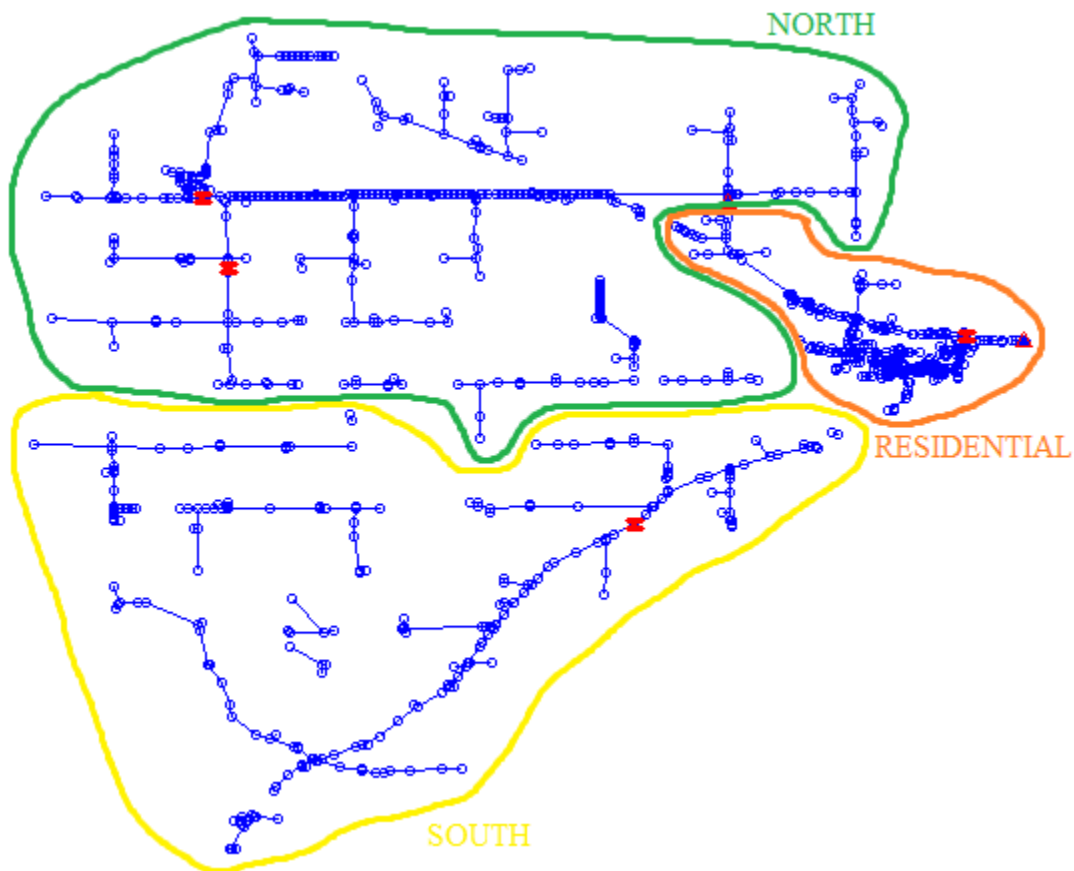
Our team and Alliant Energy came to understanding that the best way to analyze the Washington, IA area our team will have to discover where the points of interest are, then connect solar in multiple configurations (single site and distributed). After analysis of these points of interest the team will give limits of how much penetration and recommendation on the placement of solar sites. The team was provided with a full year of loadshapes and decided that choosing the time with the lowest load value would be the most beneficial. This is because when the load decreases the voltage increase and when solar is added to the system the voltage will also rise. Therefore, our team analyzed the Washington system's worst case scenario, lowest load and high PV penetration. Our team varied the PV penetration levels for 0-100% of the max load to observe when the voltage breaks the ASCII standard of 1.05 per unit. The solar site will operate at unity power factor without a smart inverter.

The Washington, IA system was separated into three different regions, North, South, and Residential areas. Figure 7 shows the Washington, IA system split into the three regions. The North region, green, was between the voltage regulator and the end of the system. The South region, yellow, was split between the densely load area in town and the end of the system. The Residential region, orange, begins at the substation and spread to the beginning of the voltage regulator and the edges of the town. The reason our team split the system into these regions is because the voltage regulator only affects the North region, the South region has the longest

conductors and is independent of the north, and the residential region contains the most loads with the shortest conductors.

Our team chose to add the solar site at the end of the system at each region because the end of the system is a point of interest. This is because if the solar site was added to the beginning of the system the substation can correct for add generation. Once the site is at the end of the system the substation struggles to correct for this generation. If the solar site exceeds the load of the feeder it is connected to, then the system will begin to experience reverse power flow. After the single site was added, our team added five solar sites within each region and evenly distributed the solar generation. Our team would run the same process and see if there is any significant difference in the amount of PV penetration allowed.

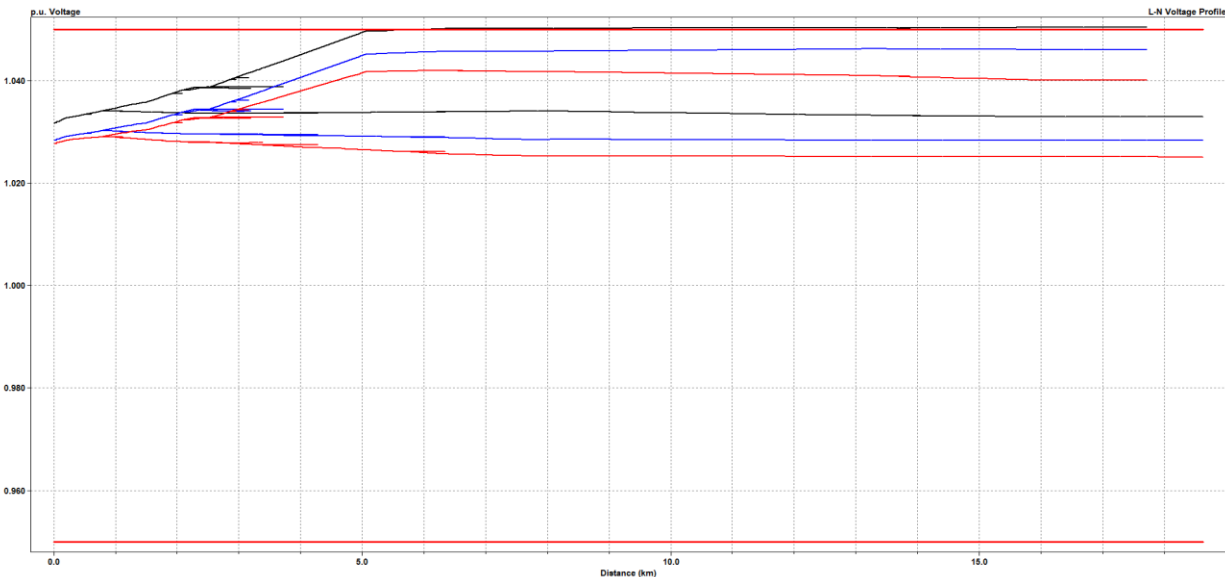
Once our team was ready to begin the analysis, we had to discuss what information collected would benefit Alliant Energy the most. Therefore, after multiple discussions, our decided to record number of buses in violation of the ASCII standard, maximum voltage, minimum voltage, and the total losses of the system. Our team wanted to collect the number of lines experiencing reverse power flow. However, in order to record that, there needs to be a monitor placed at each bus. Therefore, due to time constraints, our team was unable to add 1329 monitors and analyze the power flow.



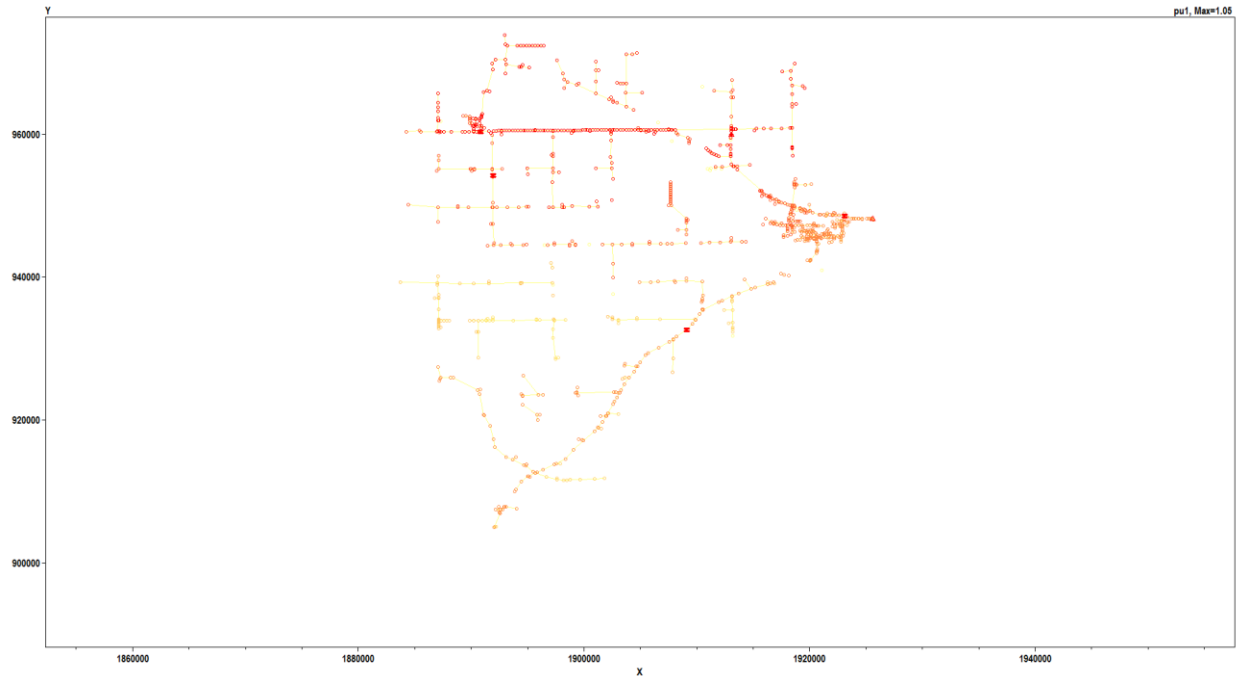
*Figure 7 Three Region*

## Results

Due to the NDA form signed between our team and Alliant Energy, we are not permitted to release any numerical data. However, our team can explain the trends for the recording and findings. Our team noticed as the PV penetration increased so did the total losses of the system. As our team expected the Residential region was able to support the most PV penetration before the system violated the ANSI standard. This region was able to exceed 100% of the maximum load in PV penetration. This is most likely due to the high amount of load in a small region and how relatively close the region is to the substation. However, the voltage may have not violated the ANSI standard, the system will experience reverse power flow throughout the entire region. Most protective electronics can only handle a little amount of reverse power flow. Therefore, the Residential region should be studied with the observation of reverse power flow. Figure 8 shows the voltage per unit value for the system and figure 9 shows the per unit violations, red represents a voltage violation and orange represents the lowest per unit value.

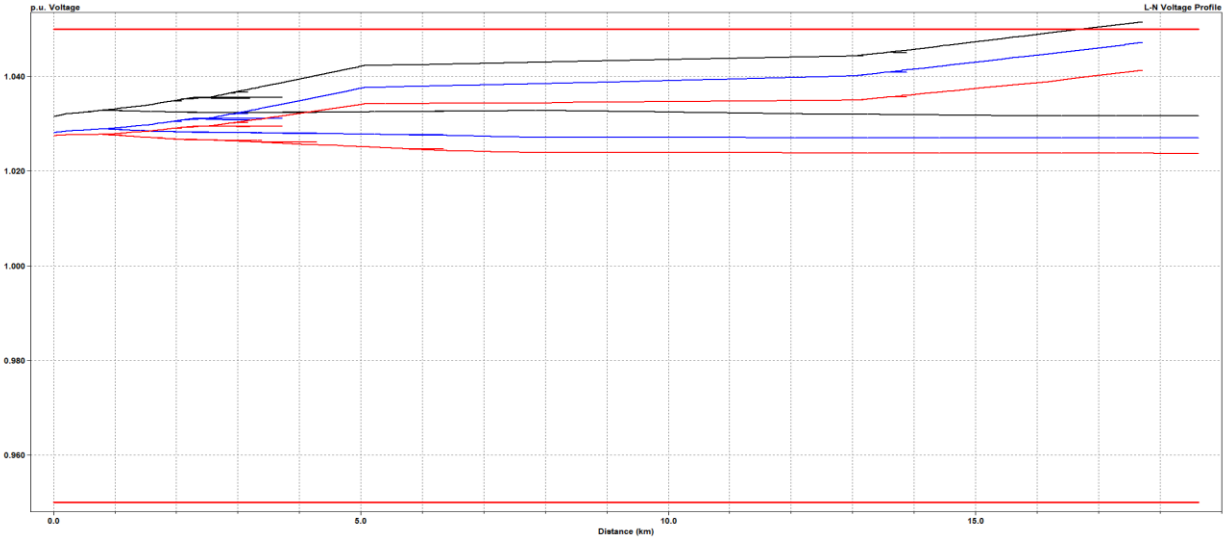


*Figure 8 Residential Voltage Profile*

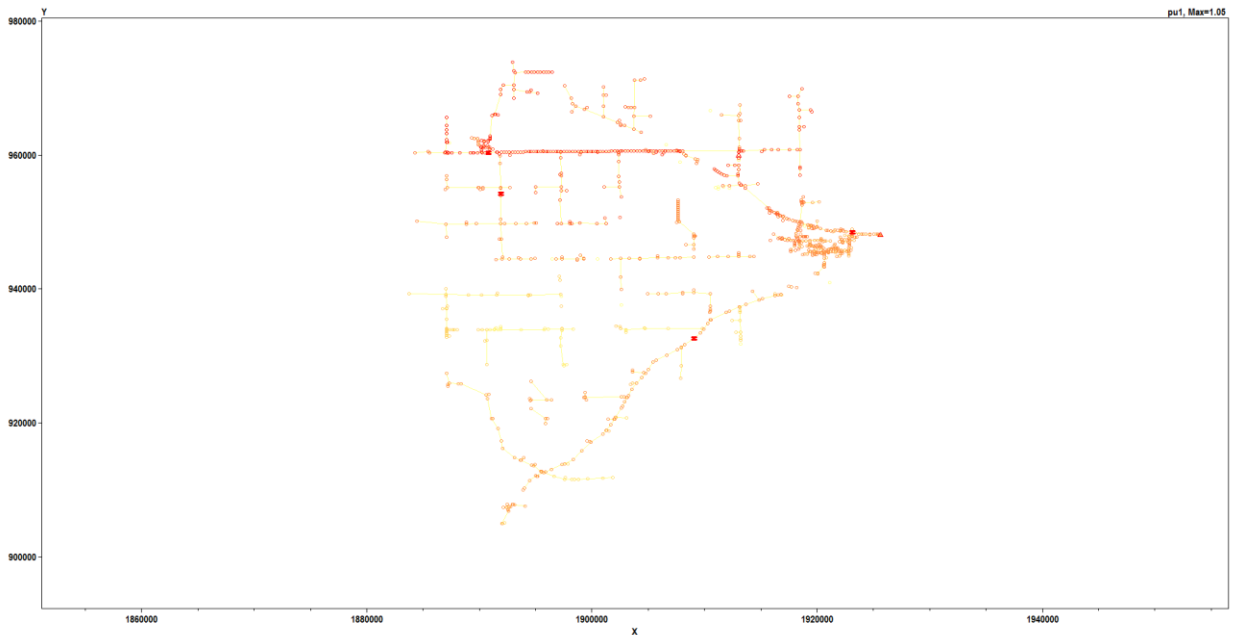


*Figure 9 Per Unit Map*

The North region was the second region to support the highest amount of PV penetration. The North region reached 70% of maximum load in PV penetration before the system violated the ANSI standard. The reason this region performed better than the South region is because the region has slightly shorter conductors and has a voltage regulator to help lower the voltage by changing the taps. However, the North region did worse than the Residential region because the loads in the North region are spread out by longer conductors; which gives the system more of an opportunity to drop in voltage. Figure 10 shows the voltage per unit value for the system and figure 11 shows the per unit violations, red represents a voltage violation and orange represents the lowest per unit value

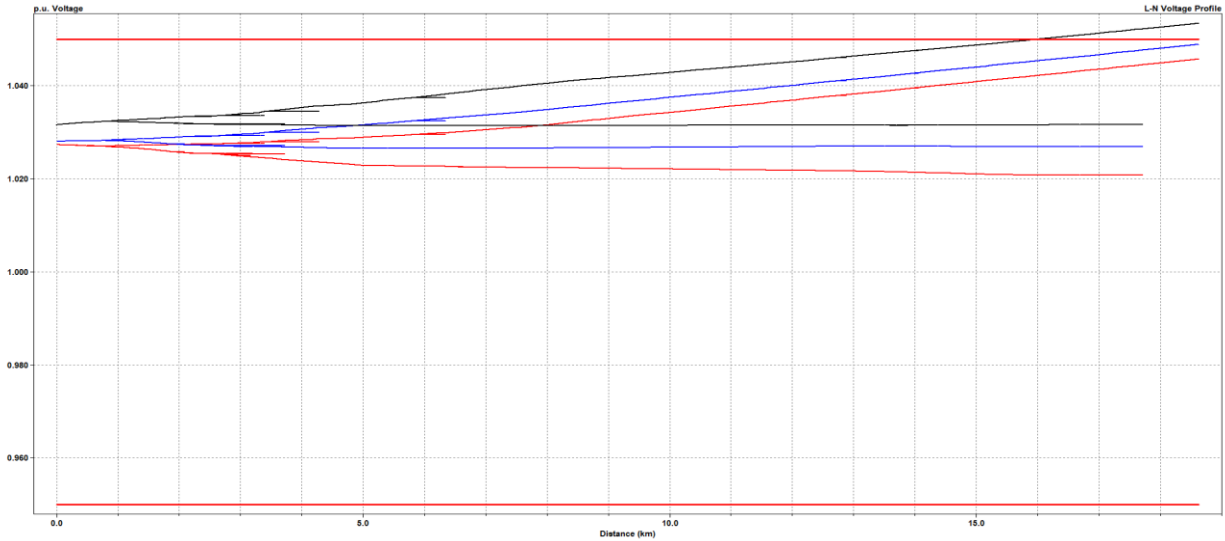


*Figure 10 North Voltage Profile*



*Figure 11 Per Unit Map*

The South region performed the worst and was only able to support 50% of the maximum load in PV penetration before violating the ANSI standard. This is because the South region has the longest conductors for the substation and the substation cannot correct for the level of PV penetration. The team also ran these simulations again with multiple solar sites rather than one and observed that the amount of allowed penetration rose. Figure 12 shows the voltage per unit value for the system and figure 13 shows the per unit violations, red represents a voltage violation and orange represents the lowest per unit value



*Figure 12 South Voltage Profile*



*Figure 13 Per Unit Map*

After our team observed the results of the simulations, our team has come to the conclusion that if Alliant Energy wants to increase their solar penetration, they should place the solar panels in the Residential region and place them in a distributed manner. However, if local farmers want to add solar panels to their hog barns, these additions would most likely be in the North and South regions. Therefore, just because the North and South regions did not perform as well as the Residential region, it does not mean Alliant Energy should not take that opportunity. There will just have to be lower PV penetration level than available in the Residential region.

## Conclusion

After one year of analyzing all of our project simulations and test and results, we have made great progress in this project with Dr. Ajarapu and Alliant Energy. In the first half period, we successfully simulated and understood the concept of 4-bus and 34-bus system in the OpenDSS. In the 4-bus system, we observed the changes in per unit voltages when changing the load, adding capacitors, and injecting solar PV in to feeder 4. In the 34-bus system, we observed the changes in per unit voltages with the slow removal of voltage regulators. In our second half period, we were using the technology that we learned in OpenDSS to simulate and test our final scenario – Washington area solar PV distribution system. We simulated the worst case scenario for the addition of PV penetration. We tested solar PV injection in 3 different regions in Washington – north, south and residential region. We had the most important result that solar PV installed in Residential region with distributed configuration would be the most efficient way to increase Alliant Energy’s solar growth.



## Appendix I: Operation Manual

This section will provide step-by-step instructions on how to run OpenDSS and obtain the desired exported data.

How to Properly Run the Code:

1. Open OpenDSS
2. Open FinalCode.dss
3. Verify that the correct files, provided by Alliant Energy, are being “Redirected”
  - a. Line Codes
  - b. Lines
  - c. Loads
  - d. Bus Coordinates
4. Verify that the correct files, created by our team, are being “Redirected”
  - a. PV System
  - b. Loadshape
5. Verify that all Energy Meters and Monitors are set to the desired locations
6. Verify that the Exports and Plots are what data is desired
7. Open PV\_System.dss
8. Verify that the solar sites are connected to the desired locations
9. After kVA=, type the desired kVA value for the solar site and make sure it is the same value at Pmpp= (for our analysis)
10. Save PV\_System.dss
11. Return to FinalCode.dss
12. Press ctrl + a (Select All)
13. Press ctrl + d (Do Selected)
14. Repeat from step 7 for different penetration levels
15. Repeat from step 7 for different penetration locations

This section will provide step-by-step instructions on how to take the outputted Excel files into more organized data.

Organize the output Excel files

1. Open Results.xlsx
2. Verify the “find Maximum value” function: =MAX(K3:K2000) for phase A, B, C, and 3-phase
3. Verify the “find Minimum value” function: =SMALL(K3:K2000,COUNTIF(\$K\$3:\$K\$2000,0)+1) for phase A, B, C, and 3-phase
4. Verify the “find total number of Violations” function: =COUNTIF(K3:K2000, ">=8000") for phase A, B, C, and 3-phase
5. Open Wash1304\_EXP\_VOLTAGES.csv
6. Copy all the data
7. Return to Result.xlsx
8. Paste the data copied into the correct column, K

- Put the data provided by all of the function into the correct cell in the table in Results.xlsx

## **Appendix II: Versions of Design**

During the project design procedure, our team met series of problems and issues because of software, schedule, and distributing researches. And that is why the versions of our problem were gradually changed and updated. As it is mentioned above, the final goal and deliverables of Senior Design Project have been decided to find the most suitable spots to install solar PV and observe the system have voltage violations or reverse power flow at what penetration level. Here are how our design versions evolved.

### **Initial Version of Design**

When our team first join the project, the initial expected deliverables are as following:

- A working simulation model of a real world feeder with high PV penetration;
- Comparison between impact of residential PV and community solar PV;
- At least one solution or guideline to prevent problems with solar PV.

And the approach of our project design to work on the simulation via selected software, OpenDSS. With a working simulation combined with setting and data from real world feeder that is located in Washington area, the design project should be fine in the end. Then our team started to learn and manipulate OpenDSS, and we first began with IEEE 4 bus system. After we were familiar with OpenDSS and its common commands, we researched and modified the 34 bus system. In both systems, we deliberately add generator, capacitor, and solar PV to observe how systems were affected by additional elements. Finally, we started to work with the simulation that is directly from our client, the Washington area feeder.

However, problems showed up during this period of time. Since our client uses a different commercial software, the feeder generated from their system is never complete. That is to say, the system we shall run in OpenDSS is not as same as the real system. To fix the problem, we spent about two weeks on combining incomplete systems and creating our own test system. In the end of this version, we had a fully functional test system, and it is better and closer to real system. Before the second version of design, we had two conference calls with our client and advisor. First, we reported our progress on the project and design. Second, we were assigned different goals of design because of time issue.

### **Updated Version of Design**

As mentioned above, our design goals have been changed and updated because we run out of time. But the first deliverable was fulfilled already in this stage. The change happened in this version of design is that we will focus on the test system and explore more about the location issues and penetration levels. So our targets are now as following:

- Discover some suitable spots to add solar PV in the test system

- Discover impacts to the system of installing solar PV at different penetration levels
- Analysis the limit of PV penetration
- Potential problems under worst scenario

These new targets can all be discovered in our test system, and what we did is to dig deeper on the test system and collect data. By running the systems with different settings for hundreds of times, we finally collected all the necessary data and analyzed how system would react with solar PV. This version of design might be our final design version because we saw goals and deliverables were fulfilled one by one, and we felt confident with our progress as well.

### **Deeper Explored Version of Design**

Additionally, in this version of design, our team went deeper with the system and simulations under Dr. Ajjarapu's advices. The system was separated into three regions, North, South, and Residential. And we installed both community solar PV and distributed PV (Individual) with different power levels. Although we did not have time to compare results from systems with different types of PV, we came up with a conclusion and some suggestions with installing solar PV at least. It could be called as a breakthrough.

## **Appendix III: Other considerations**

### **Multiple Solar PV injection**

In our project, we design a solar PV injection simulation model for the Washington area. We test 3 different area of locations of the solar PV injection. The system is divided in North, South and East (Residential Regions). We test 5 locations in each area and the solar PV range is from 10-100% of maximum load. Each time we add power generators as our source to simulate the system. For the interest, our team would like to test multiple solar PV injection at multiple locations. This is interesting because it is closer to the real world situation however it is hard and complex for us to simulate this situation at this point.

### **Cost**

The interesting thing for the project is that we can have multiple options for achieving the goals, and each of them costs differently even though we do not work on or worry about the cost of the project. Generally, we have two options:

- Install smart inverters – cost less but more difficult to satisfy new problems in the future.
- Add capacitor banks – costly but less functional due to set capacitor values.

### **Land**

The Residential region may have had the best results for the addition of solar but is limited on the space to add solar panels. The North and South regions will have the most opportunity to add land because these areas are made up of mostly farmland.

## References

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*“High Penetration Photo-voltaic Case Study Report”*

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*“Distribution System Modeling and Analysis”*

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*“Reference Guide The Open Distribution System Simulator”*

by Roger C. Dugan

*“Distribution Test Feeders”*

By IEEE PES