Impact of High Photo-Voltaic Penetration on Distribution Systems

FINAL DOCUMENT

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1 Introduction

1.1 PROJECT STATEMENT

The amount of solar generation is increasing rapidly in Iowa, and the current systems are having problems (over-voltage, opposite direction power flow, the possibility of islanding, etc.) keeping up with all the additions. In this project, we are trying to assess the impact of high penetration solar power generation on distribution feeders and its effects on the power quality delivered to the consumer.

1.2 PURPOSE

The purpose of this project is to use computer-modeling systems to analyze the impacts of solar generation in the utility's distribution systems. This will be beneficial to society because we will be able to find the adverse effects of high penetration solar generation before the implementation of the generation, so the customers never see the problems. Also, this project will allow for more solar power on distribution systems while limiting the problems seen.

1.3 GOALS

We have several goals that we would like to achieve. Our goals are shown below.

- Simulate an Alliant-owned distribution feeder while incorporating solar PV generation into the simulation to observe the effects
- Compare community PV generation and residential PV generation to determine the best way to incorporate solar power into distribution systems
- Find solutions that will prevent future problems relating to solar PV generation on the Alliant Energy Systems

2 Deliverables

The deliverables necessary in this project are listed below.

- Voltage profiles and/or other necessary plots from simulations
- Comparison of residential and community solar PV generation
- Results of simulation with solar PV in certain areas
- Possible solutions for modifications to distribution system

Throughout the past two semesters, our project has been split into three parts: IEEE 4 bus test system, IEEE 34 bus test system, and the Alliant Energy system. In our first semester, our team worked with the IEEE 4 bus system and the IEEE 34 bus system, while the second semester was spent working on the Alliant Energy distribution system. During our work, we have observed the effects of different components (i.e. Voltage regulators, capacitors, etc.) within distribution systems, as well as the effects of PV penetration at different locations and different amounts.

3 Design

3.1 SYSTEM SPECIFICATIONS

3.1.1 Non-Functional

- Can the current Alliant system support high solar penetration as it exists now?
    - What modifications will the system need?
- How much would modifications cost to the current system?
    - We are looking for the best solution with the lowest cost

3.1.2 Functional

- Analyze IEEE distribution systems.
    - Load profiles
    - Voltage magnitudes and angles
    - Voltage violations at busses
- Add Solar PV to the distribution models
    - Compare the load profiles to those from the base case
    - Compare the power flows to the base case
- Analyze the Alliant Energy bus system provided
    - Load profiles
    - Compare those when solar is added
- Determine what modifications need to be made to the current Alliant system for it to be feasible to add residential and community solar PV

3.2 INTERFACE SPECIFICATIONS

During our first meeting with our adviser, he explained which software we would be using for the entire project, which in our case is OpenDSS. We have worked with the software a lot over the course of the past two semesters. It is the same software that we used to load in the Alliant Energy distribution system.

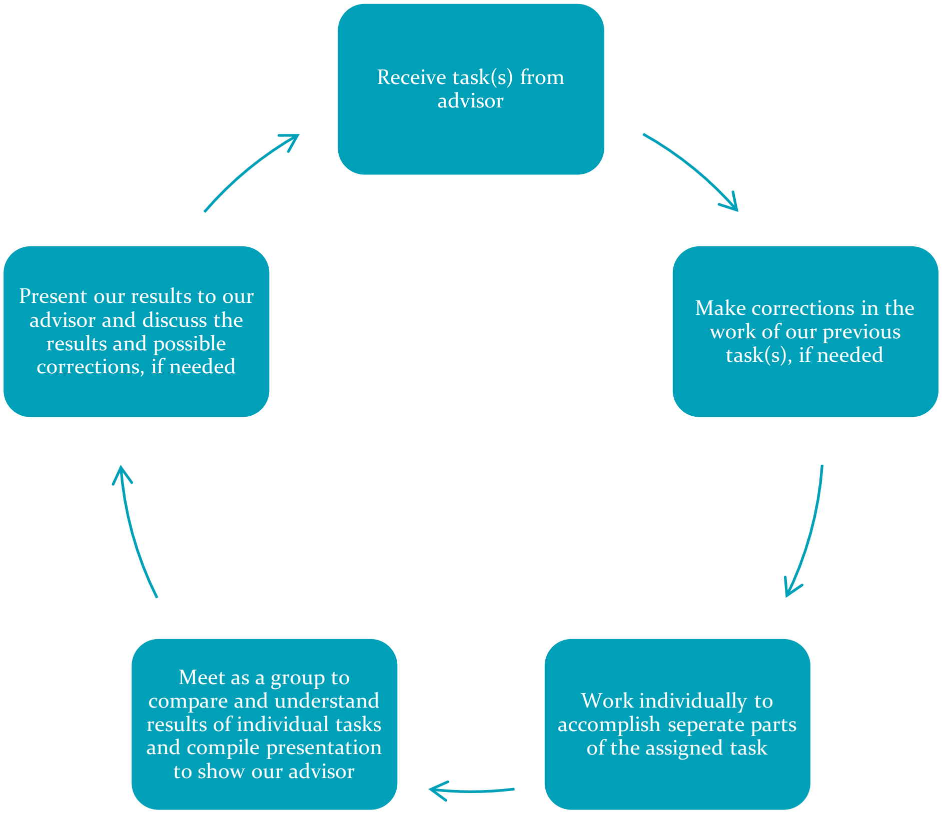
3.3 HARDWARE/SOFTWARE

We have been using OpenDSS for the entirety of the project. It is the leading software that is used to simulate our scenarios for the IEEE 34Bus system. We also used the Alliant Energy distribution system with our simulation and used OpenDSS to run it.

We use Excel to export data into organized files. This way, we can plot the data in graphs to explain what happened during the simulation clearly.

3.4 PROCESS

Shown below is our flow diagram for how we handled our work:


Receive task(s) from advisor
Make corrections in the work of our previous task(s), if needed
Work individually to accomplish seperate parts of the assigned task
Meet as a group to compare and understand results of individual tasks and compile presentation to show our advisor
Present our results to our advisor and discuss the results and possible corrections, if needed

3.5 SEMESTER 1 – IEEE 4 BUS & 34 BUS SYSTEMS

To start our project, we worked on the IEEE 4 bus test system which is shown in the figure below.

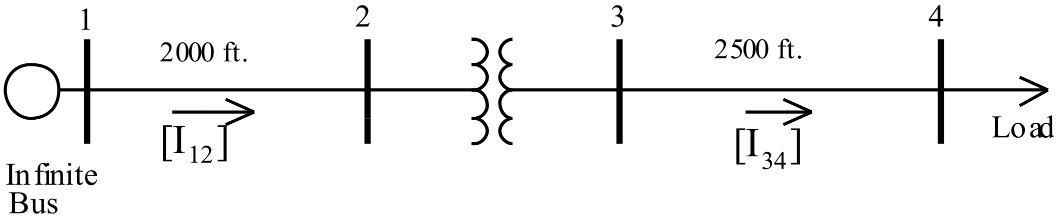


Figure 1: IEEE 4 Bus Test System
www.ewh.ieee.org/soc/pes/dsacom/testfeeders/feeder4.zip

Using this test feeder, we calculated the voltages at each bus and the currents in the lines of the feeder. Our team did this hand calculation and compared it to the results that we found by running the 4 bus system in OpenDSS. We did this as our first step in our project so we could obtain a base understanding of how OpenDSS solves for values in distribution systems using an iterative process. Our team's hand calculation is shown in Appendix IV.

After we finished working with the 4 bus system, our team moved on to a slightly larger system, the IEEE 34 bus test system, to gain a better understanding of how we can use OpenDSS to analyze distribution systems. We analyzed different components of the 34 bus system using different load shapes to study the system over a period of 24 hours. The IEEE 34 Bus Test System is shown in the figure below. In this figure, we can see two voltage regulators—the circles with the arrows through them—and the transformer between bus 832 and bus 888.

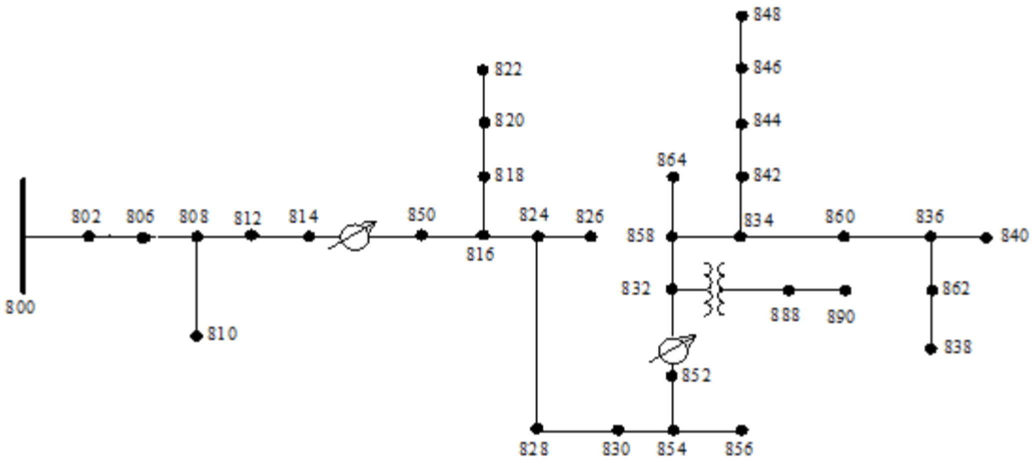


Figure 2: IEEE 34 Bus Test System
www.ewh.ieee.org/soc/pes/dsacom/testfeeders/feeder34.zip

After running simulations with the 34 bus system, we observed the effects of capacitors and voltage regulators. We also analyzed the impact of PV penetration at different penetration levels and at different locations. The results of our analysis are shown in the rest of this section.

Each group member had to analyze load profiles for different loads and see how capacitors and regulators affect the system. There were four cases that we analyzed of capacitors switched on and off and same for regulators. We did the same thing for three more cases. We looked for voltage violations shown by the red lines on top and bottom. The load voltage plots are shown in the figure below. The upper left plot shows the load voltage with both capacitors and regulators on. The upper right plot shows the load voltage with regulators on and capacitors off. The lower left plot shows the load voltage with capacitors on and regulators off. The lower right image shows the load voltage with both capacitors and regulators off.

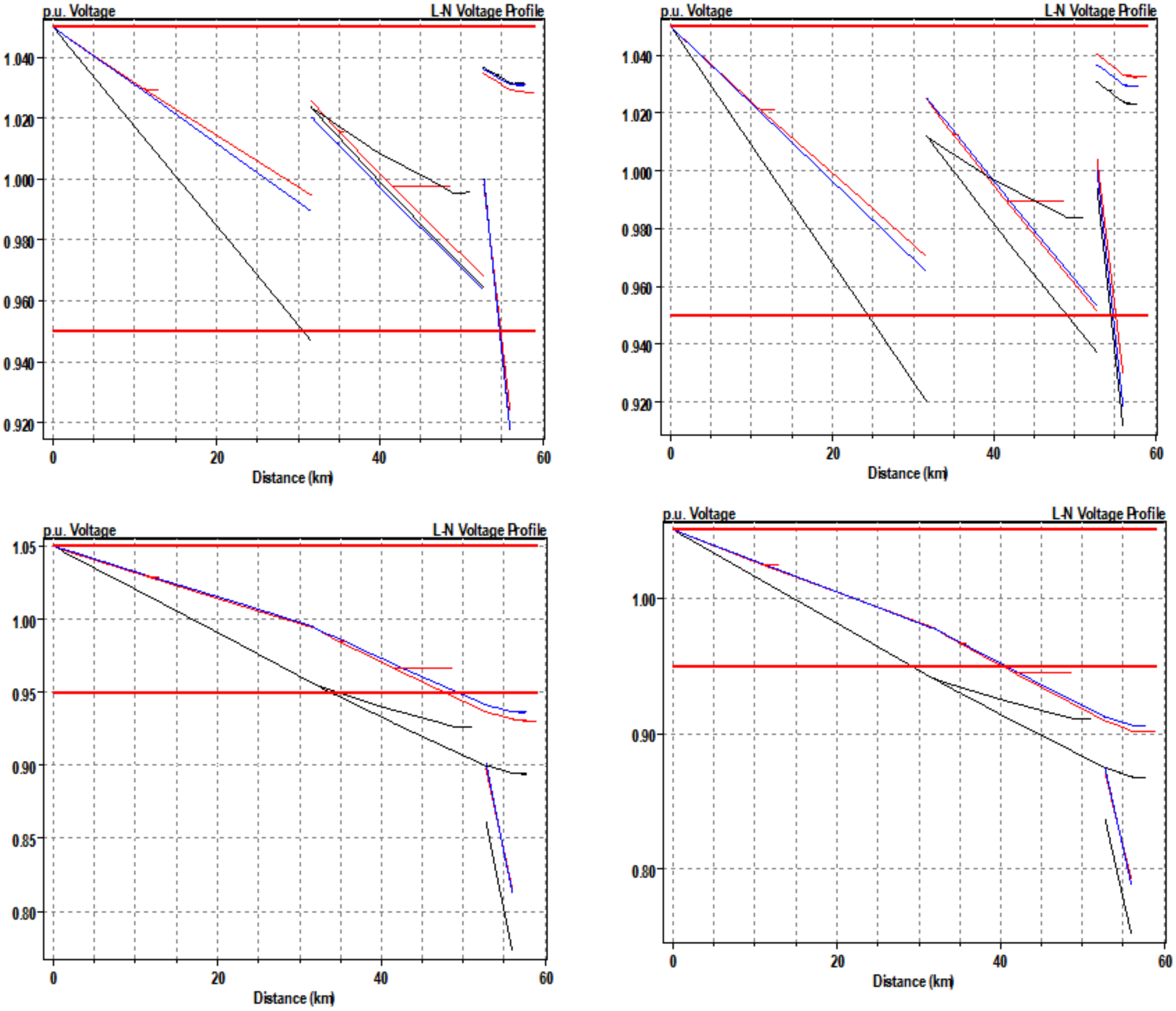


Figure 3: Load Voltage Plots

From the plots it can be seen that even though both voltage regulators and capacitors are needed for keeping the voltage within the .95 to 1.05 per unit range, the voltage regulators are more effective at stabilizing voltages since they are more variable than capacitors.

The figure below is an example of time series plots with an addition of capacitors. First, we had to calculate what capacitance value is required by the system to eliminate violations. Each member analyzed a different month of the year. We did see that December had the highest number of violations and June had the highest standard deviation.

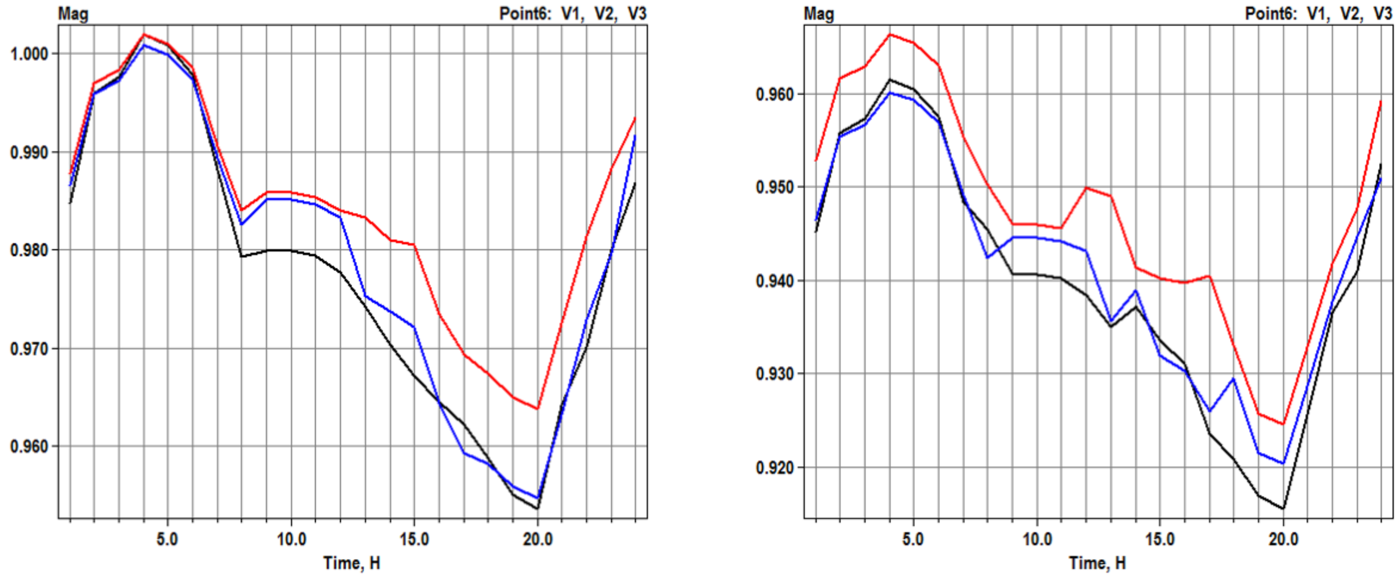


Figure 4: Time Series Plot with capacitors on the left and without Capacitors on the right (June Loadshape)

The figure below describes how regulator taps change over a period of 24 hours for the month of June. We analyzed for December as well and noticed how the regulator was reacting to different loads at different times.

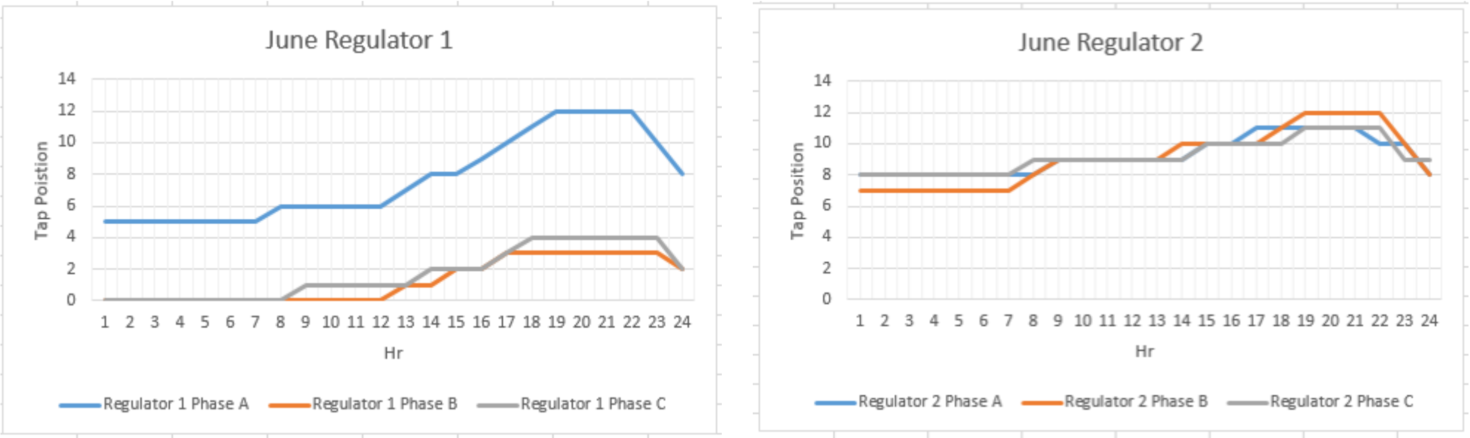


Figure 5: Regulator Tap Positions over 24 Hours (June Loadshape)

When adding solar PV at different locations along the system we looked at the load losses as a function of the solar source, voltage violations, and regulator changes. We analyzed this at 10 different buses with individual generation (community solar), and then again with a solar cell at each load on the system (residential or distributed solar). We also analyzed each one of these situations at different penetration levels of 20%, 40%, 60%, 80%, and 100%.

The impact of solar on the voltage violations at regulator changes at 80% for all the different scenarios is shown in the figure below.

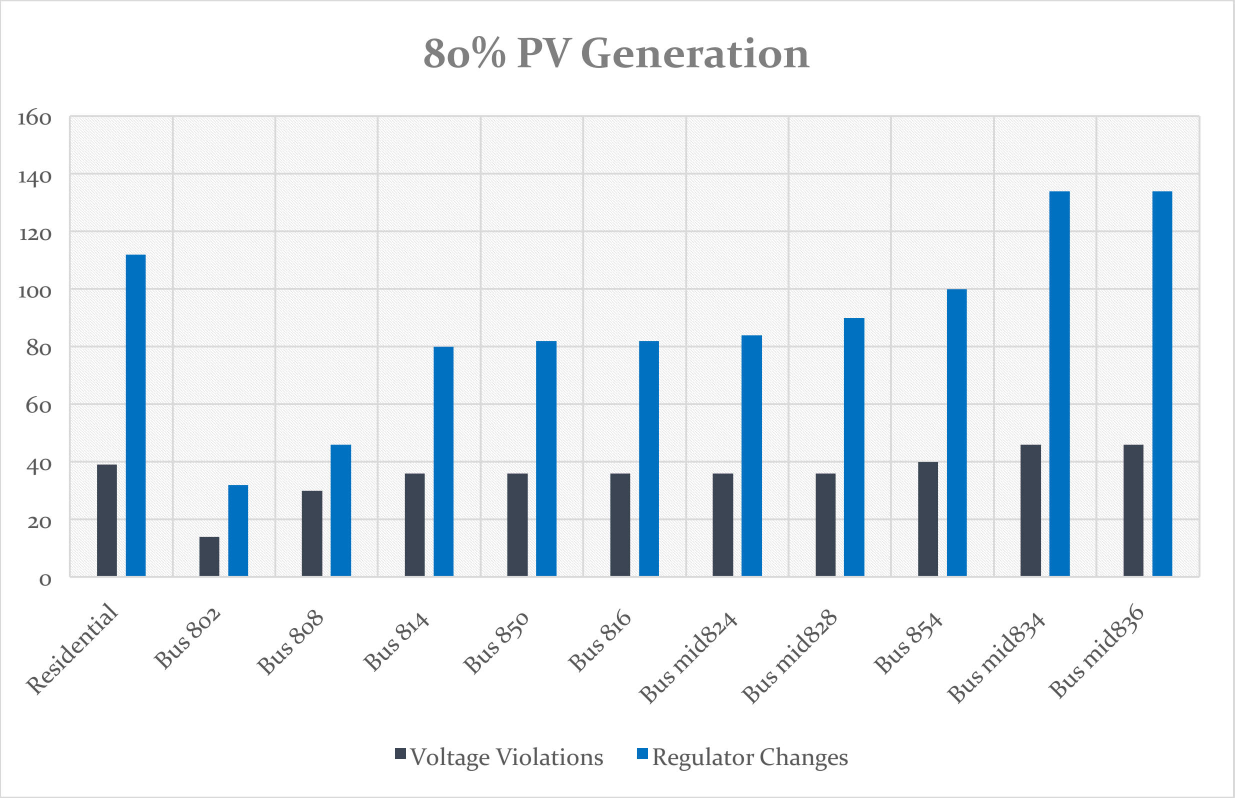


Figure 6: Voltage Violations and Regulator Tap Changes at 80% PV Penetration

This figure shows that voltage violations and the number of tap changes as the solar location moves away from the substation, with the residential solar case falling somewhere in the middle.

After observing the voltage violations and the regulator changes, we ran an analysis to see what the line losses looked like for all the different scenarios we described above. The figure below shows the losses as a function of PV penetration level (from 0% to 100% of the maximum load).

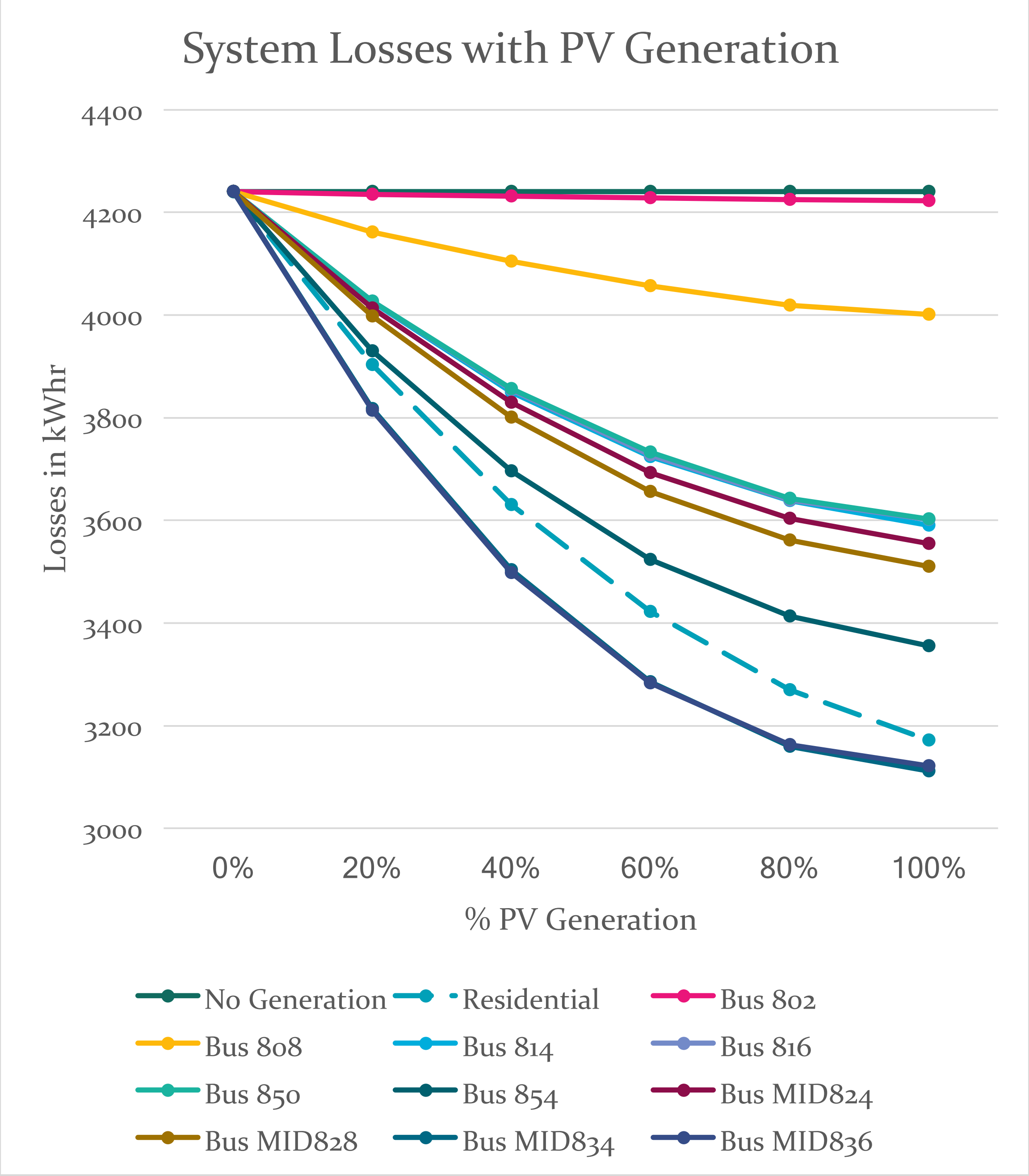


Figure 7: Line Losses vs PV Penetration Level (All Scenarios)

In the figure, as you move from the pink line, bus 802, down to the solid dark blue line, bus mid836, it can be seen that losses decrease as the solar location moves away from the substation and as the penetration level increases. The residential solar case is closer to smallest amount of losses as the penetration level increases.

The bar chart in the figure below shows how much penetration is possible at each bus (assuming no other solar is present elsewhere on the system) before there will be voltage violations within the system.

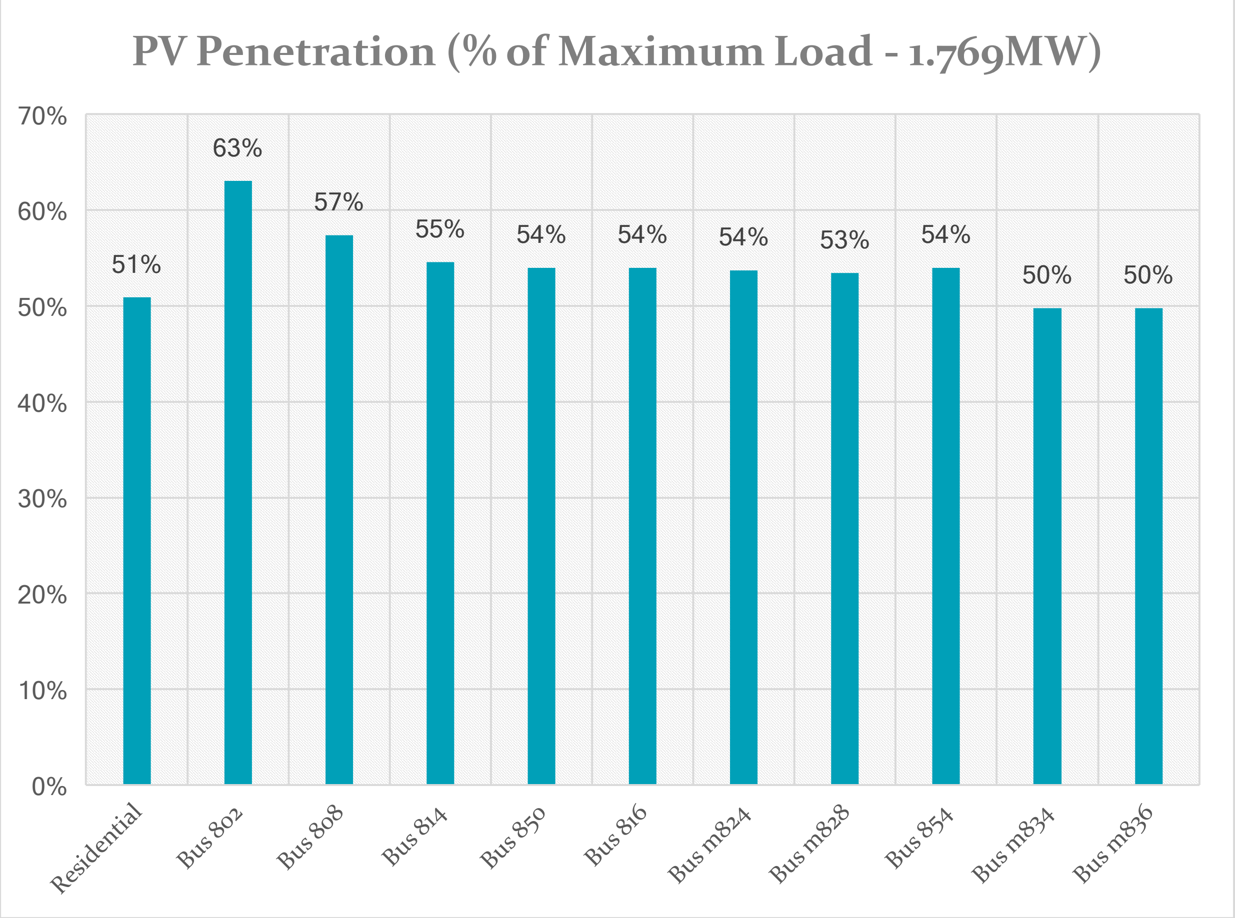


Figure 8: PV Penetration Level Possible before Voltage Violations Occur

The bar graph shows that as the solar site is closer to the substation, more PV penetration can be handled without seeing voltage violations. The residential (distributed) solar scenario falls towards the least amount of solar that can be seen before voltage violations occur.

From our findings on the 34 bus system, we could apply the knowledge of the trends we found to our analysis of the Alliant Energy distribution system and to aid in our design project.

4 Testing

For the second semester of our project, our team worked together to decide that the goal of our project was to design a solar generation system within the Alliant Energy distribution system that could handle cloud coverage and the maximum amount of PV penetration (varying between 0% and 100% of the maximum load) without violating ANSI standards, which means the voltages of all the buses in the system must stay between .95 and 1.05 per unit. We decided to design our solution for the worst case scenario in order to provide a solution that would work in any situation.

With the system split up, our team decided that we would do our design in the south region. This would provide the worst case scenario since the south could handle the smallest amount of PV penetration before seeing voltage violations. Within the south region, our team chose to add the PV penetration at the end of the feeder. With the PV at the end of the feeder, the substation cannot adjust for the additional generation, which could possibly result in reverse power flow if the generation amount is too large. Our team was also provided load shapes for each month of the year, which allowed us to determine peak and minimum load values for the system.

In order to simulate cloud coverage on the system, our team designed load shapes for the solar elements, similar to that shown below in Figure 1, that would be able to simulate the effects of clouds covering the solar sites by varying between minimal and maximum power output over a 24 hour period. In the figure, the blue dotted line represents a normal solar curve and the solid red line represents a solar curve with cloud coverage throughout the day, resulting in values deviating from the normal curve.

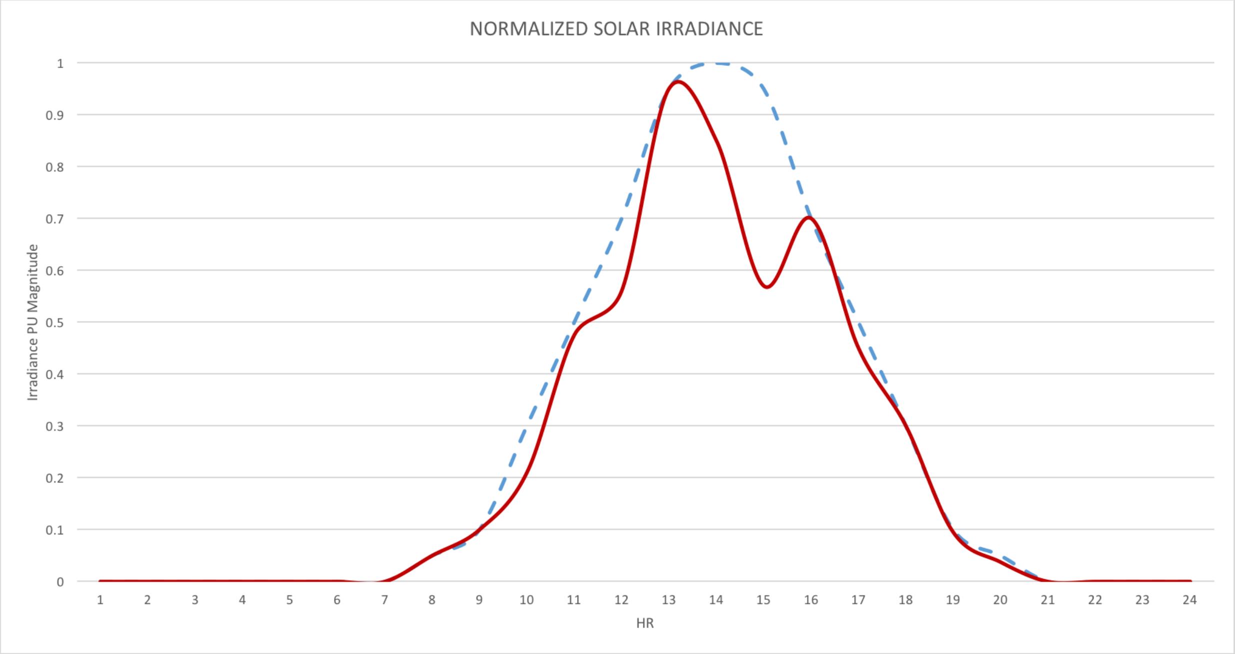


Figure 9: Sample Cloud Coverage Loadshape

Our team chose to analyze multiple cases for each potential design solution. To make sure the system did not cause violations before the cloud coverage was added, we simulated the system with the solar addition at the minimum load value found from the load shapes given to us. This was done because the voltages of the buses would be largest at minimum load, so we wanted to make sure the additional generation did not cause any voltage violations above 1.05 per unit. If the solution did incur violations, the PV level was changed. If the solution did not incur any voltage violations, then we would simulate the system with the cloud coverage load shape applied to the solar sites at peak and minimum load and analyze the resulting data. If violations were found during the cloud coverage simulation, we applied smart inverters to see if the violations could be corrected by the use of one or both of these elements. From there, our team would see if the design would be a viable solution, or we would decide to proceed with a different design.

5 Results

Due to our NDA with Alliant Energy, we are not able to release any specific numerical data. However, we are able to describe our findings and the trends that we were able to see. Using our process, we started by testing a single solar site at the end of the feeder in the south region, which is shown below marked as a red dot at the bottom of Figure 2.

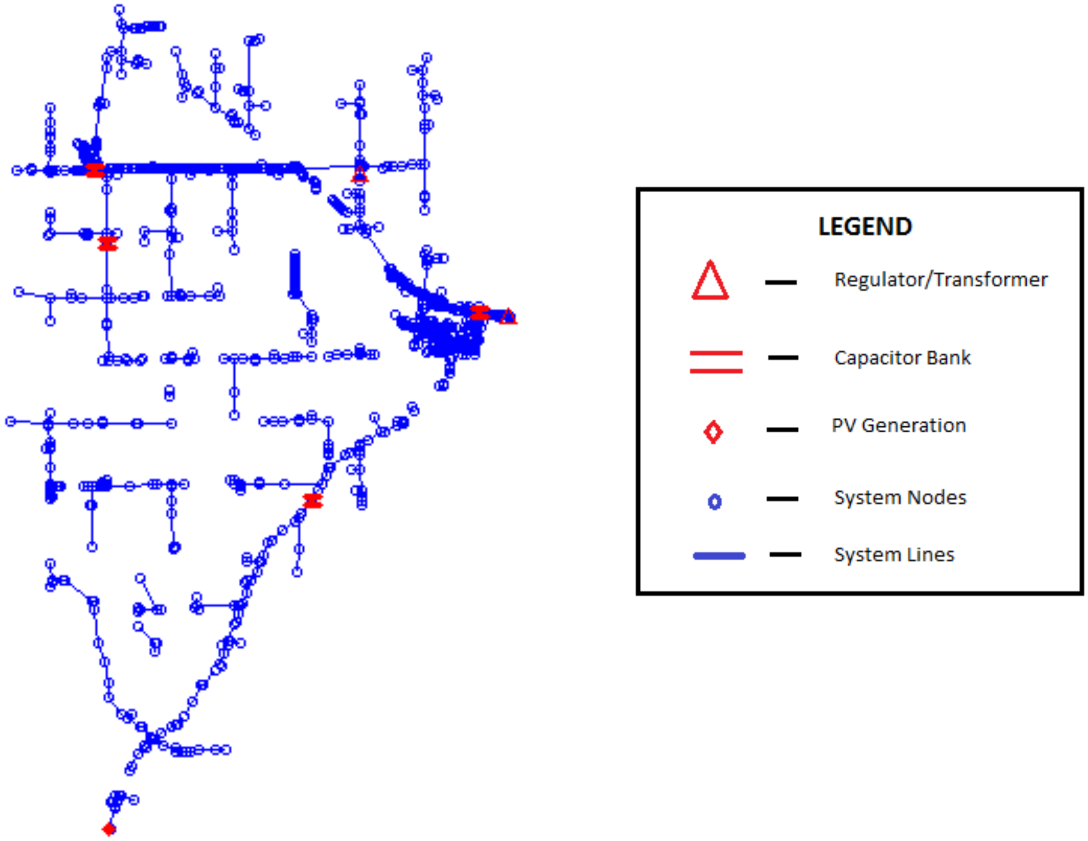


Figure 10: Map of System with Single Solar Site

From our testing of this system, our team found that the single solar site had voltage violations with cloud coverage at a PV penetration level of 50% of the maximum load. Our team attempted to correct these problems with a smart inverter at the solar site, but the smart inverter was not able to fix the present problems in the system. Since the smart inverter did not fix the problem, we decided to move on to a different design to see if the problem could be corrected by equally distributing the generation to ten locations within the south region near the ends of the feeder, to obtain the worst case scenario, which is shown below in Figure 3.

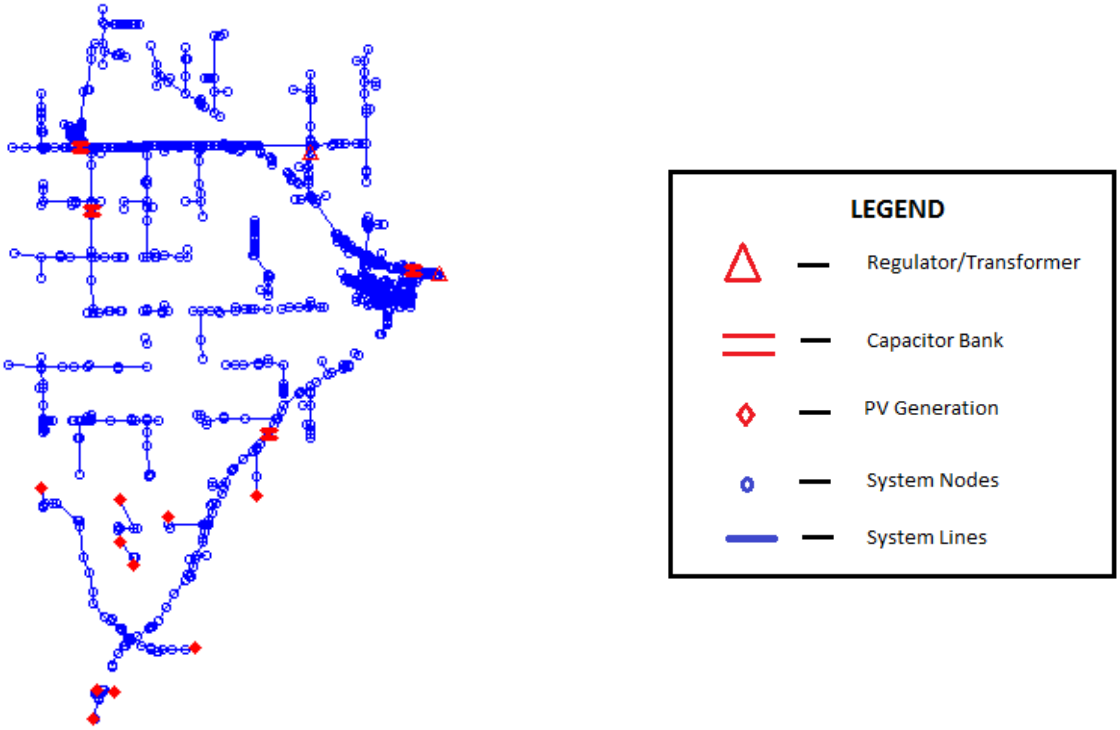


Figure 11: Map of System with Distributed Solar Sites

When our team analyzed the distributed solar site system, we found that even with cloud coverage, the system did not see any voltage violations at a PV penetration level of 50% of the maximum load. Since there were no violations with the cloud coverage, it was not necessary to add smart inverters to distributed solar sites. However, our team still ran a simulation with smart inverters added to see their impact, and we found that the smart inverters were somewhat effective in improving the voltage quality, which means the average voltage of all of the buses was brought closer to 1 per unit, since that was our voltage setting on our smart inverter element. Also, the system was not able to handle a PV penetration level of 60% without cloud coverage at the minimum load without seeing voltage violations. We were able to see that even though smart inverters were not necessary to meet our goals, they were helpful in increasing the voltage quality in the system. With these results, our team concluded that our design to accomplish our goal is to distribute the generation within the region with the possibility of adding smart inverters.

6 Conclusions

During our project, we have worked with several different distribution systems using OpenDSS. While doing the voltage and current calculations by hand for the IEEE 4 bus system, we were able to see the iterative process that OpenDSS uses to solve for values in different systems. On the IEEE 34 bus system, we were able to learn about the different trends involving solar generation, as well as the impact of capacitors and voltage regulators. For our second semester, we explored the Alliant Energy system to design a PV system that can support the largest value of generation while being able to withstand cloud coverage without incurring voltage violations.

For our design, we found that Alliant should distribute the generation within the region to be able to handle the most PV penetration while also being able to meet ANSI standards with cloud coverage on the system. However, if Alliant would want to put even more generation within their system, some changes will need to be made to our design.

If a single solar site is desired for the Alliant system with a generation value closer to 100% of the maximum load, then the solar site will need to be placed closer to the substation so it can correct for the additional generation. If distributed solar sites are desired for the Alliant system with a total generation value closer to 100% of the maximum load, then Alliant will need to cap the generation limits at each of the locations, depending on the amount of load in that area. Also, other elements (i.e. smart inverters at the solar sites, voltage regulators, etc.) might need to be added to the system to withstand up to 100% PV penetration.

7 Appendix I - Operation Manual

7.1 OPERATION MANUAL

In this part of the document, instructions will be provided to demonstrate how to use OpenDSS to simulate the distribution system and retrieve the desired data. The instructions are shown below.

1. Open OpenDSS
2. Open pvcode1.dss
3. Confirm the needed files/elements, given to us by Alliant Energy, are being properly implemented in the code
    a. Substation Transformer
    b. Line Codes
    c. Line Data
    d. Capacitors
    e. Load Data
    f. Voltage Regulator
4. Open solar_addition.dss
5. Set the loadshape of the solar generation to the desired waveform
6. Confirm the desired location of the solar site(s)
7. Set the kVA of the solar site(s) to the desired amount
8. Set the Pmpp value equal to the kVA value for each solar site
9. Save the changes to solar_addition.dss (if any)
10. Switch back to pvcode1.dss
11. Set the loadshape to the desired file
12. Confirm the monitors are in the desired locations
13. Choose which plots are wanted for analysis
14. Save the changes to pvcode1.dss (if any)
15. Select all of the code in pvcode1.dss (ctrl + a)
16. Right click and select Do Selected (ctrl + d)
17. Save the produced plots to a preferred location
18. Find the output excel files in the folder where the .dss files are located and save the desired output excel files to a different folder for each simulation (the files in the original folder will be overwritten every time the pvcode1 is ran)
19. Repeat steps 5-18 for different conditions (i.e. cloud coverage, different solar locations, etc.)

7.2 ANALYZING THE DATA

1. Determine which simulation scenario is going to be analyzed
2. Locate folder with output data from the simulation
3. Open the excel files
4. Use the following functions in excel to analyze the data
    a. MAX
    b. MIN
    c. AVERAGE
    d. COUNTIF
5. Compare the values to the base case values
6. Document the differences to understand what is happening
7. Repeat steps 1-6 for each simulation

8 Appendix II - Design Iterations

8.1 34-BUS SYSTEM

The initial conditions for the 34 bus system were such that there were many problems with low voltages across the system. To rectify this problem, we went through a series of changes to the system that included adding capacitors and regulators to increase the voltage across the line. Once this was accomplished, we were then able add solar PV generation throughout the system to test the voltage response as well as the number of tap changes our regulators would be performing with this new localized generation. We went through different iterations- putting solar in centralized locations, distributing it across the system, and putting it at the end of the line. We were looking for which one of these scenarios would bring us the most benefit as well as what problems arise. Using these different designs, we could make educated predictions as to how the placement of solar sites would affect the Alliant system.

8.2- ALLIANT SYSTEM

There were 3 different variations of the Alliant system that we designed. The first was made based on the data given to us from Alliant. It was the current state of the system-meaning there were very few customers using solar PV generation. From there, we created 2 more designs; one of which had a centralized solar site, and the other which had solar distributed across the system. From here we looked to see how much solar power could be generated from these areas without creating voltage violations. Once we completed this initial test, we added simulated cloud intermittency to our model. This allowed us to further test the limits of our design by having fluctuations in the amount of sun the panels were getting on a minute-by-minute basis. Using the base model, single site solar, and distributed solar models, we determined the capabilities of each one of the models and which one would work as the best case solution.

9 Appendix III - Other Considerations

While working on this project, we considered several other ideas for possible system simulations and the different scenarios that we could analyze.

9.1 ENTIRE SYSTEM SOLAR ADDITION

For our project, we split up the system into three regions and analyzed the South region with different PV penetration at different levels and locations within the South region. Since we only looked at one of the regions, another idea that we considered was being able to analyze the entire system with PV penetration located throughout all three regions. Being able to do this would be very beneficial since the system will most likely have PV penetration in each of the regions.

9.2 COST OF DIFFERENT POTENTIAL SOLUTIONS

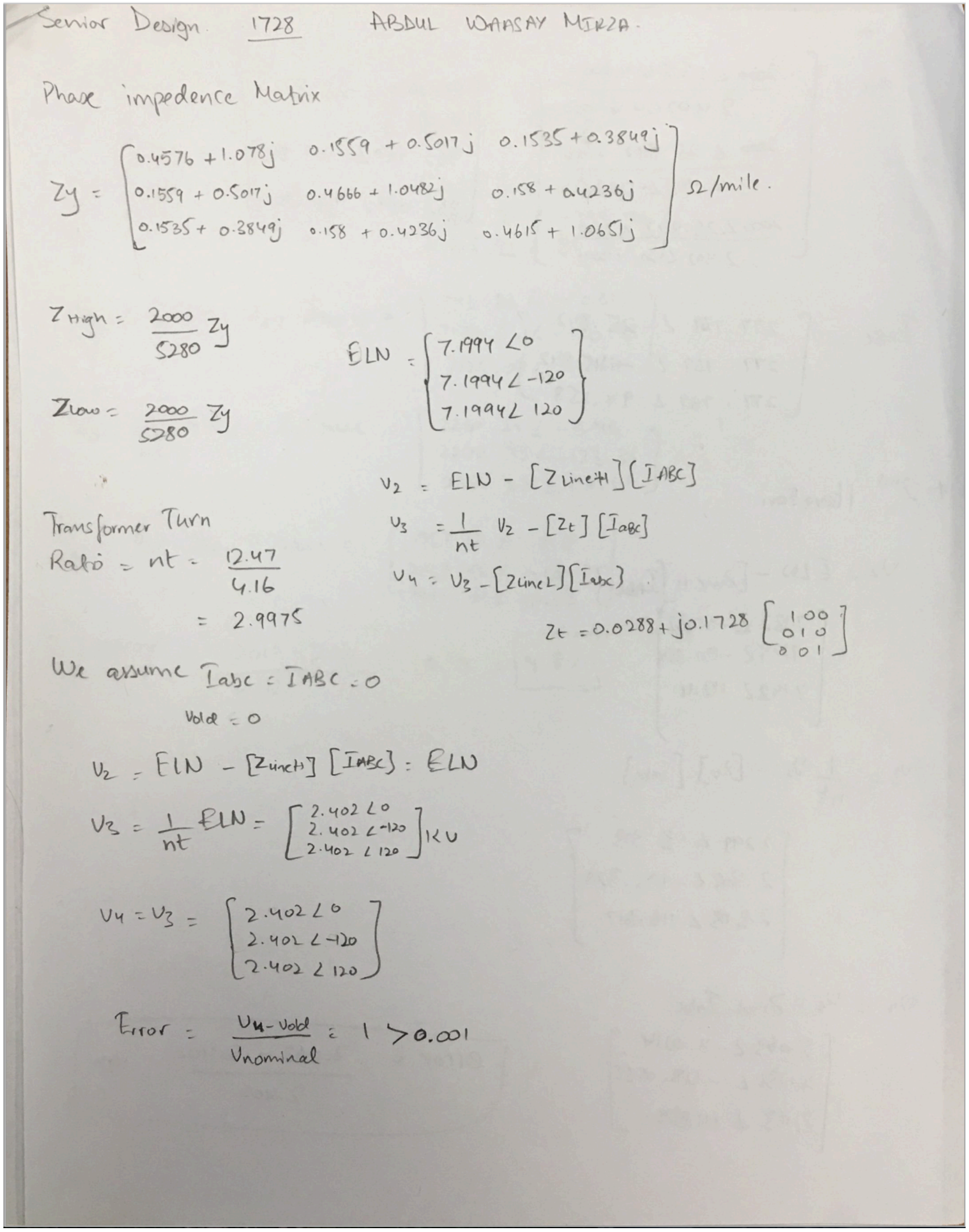
In our findings, we found that distributing the generation would be the best solution for withstanding weather conditions. However, our team looked into the possibility of adding smart inverters and capacitors into the system as possible solutions. Even though they are not needed, both smart inverters and capacitors can be used in certain locations to improve the voltage quality of the system. Smart inverters tend to cost less and capacitors tend to be on the more expensive side compared to the smart inverters. Both of these elements have their perks, so cost analysis will be needed in the future if one or both of these elements will be used to correct future problems.

9.3 DIFFERENT SOFTWARE

Since there was some uncertainty with the data received from Alliant Energy from the export function in the program that Alliant uses, Synergi, we talked within our group about the possibility of trying to use the same software. However, there was limited information that we could find about the program. It would have been interesting to see if we could achieve the same results by using both programs.

10 Appendix IV – IEEE 4 Bus Hand Calculation

4-bus system hand calculations:



Senior Design 1728 ABDUL WAASAY MIRZA.

Phase impedence Matrix

$$Z_y = \begin{bmatrix} 0.4576 + 1.078j & 0.1559 + 0.5017j & 0.1535 + 0.3849j \\ 0.1559 + 0.5017j & 0.4666 + 1.0482j & 0.158 + 0.4236j \\ 0.1535 + 0.3849j & 0.158 + 0.4236j & 0.4615 + 1.0651j \end{bmatrix} \Omega/\text{mile}.$$

$$Z_{High} = \frac{2000}{5280} Z_y$$

$$Z_{low} = \frac{2000}{5280} Z_y$$

$$ELN = \begin{bmatrix} 7.1994 \angle 0 \\ 7.1994 \angle -120 \\ 7.1994 \angle 120 \end{bmatrix}$$

$$V_2 = ELN - [Z_{lineH}][I_{ABC}]$$

$$V_3 = \frac{1}{nt} V_2 - [Z_t][I_{abc}]$$

$$V_4 = V_3 - [Z_{lineL}][I_{abc}]$$

Transformer Turn Ratio $= nt = \frac{12.47}{4.16}$

$$= 2.9975$$

$$Z_t = 0.0288 + j0.1728 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

We assume $I_{abc} = I_{ABC} = 0$

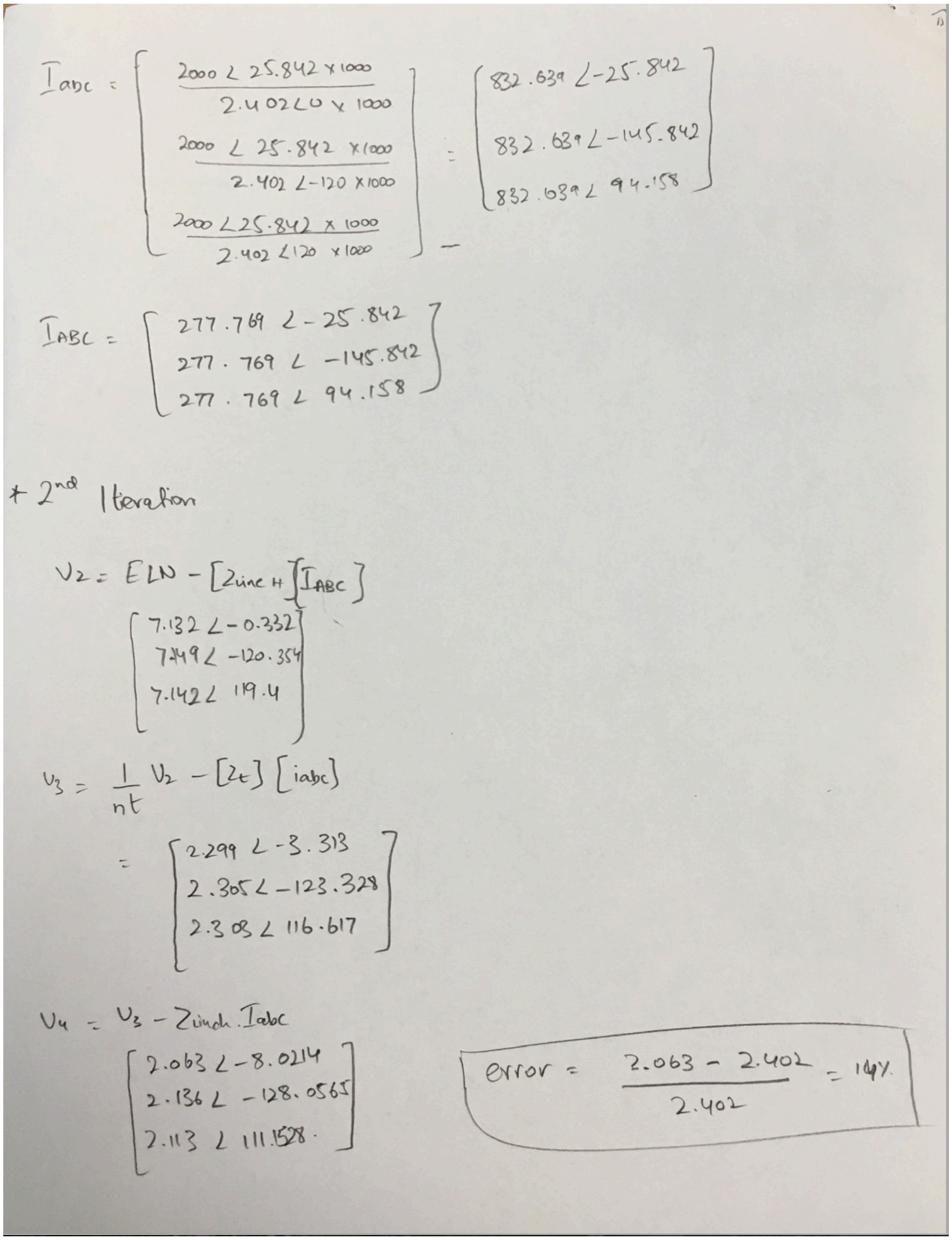
$V_{old} = 0$

$$V_2 = ELN - [Z_{lineH}][I_{ABC}] = ELN$$

$$V_3 = \frac{1}{nt} ELN = \begin{bmatrix} 2.402 \angle 0 \\ 2.402 \angle -120 \\ 2.402 \angle 120 \end{bmatrix} \text{KV}$$

$$V_4 = V_3 = \begin{bmatrix} 2.402 \angle 0 \\ 2.402 \angle -120 \\ 2.402 \angle 120 \end{bmatrix}$$

$$\text{Error} = \frac{V_4 - V_{old}}{V_{nominal}} = 1 > 0.001$$



$$I_{abc} = \begin{bmatrix} \frac{2000 \angle 25.842 \times 1000}{2.402 \angle 0 \times 1000} \\ \frac{2000 \angle 25.842 \times 1000}{2.402 \angle -120 \times 1000} \\ \frac{2000 \angle 25.842 \times 1000}{2.402 \angle 120 \times 1000} \end{bmatrix} = \begin{bmatrix} 832.639 \angle -25.842 \\ 832.639 \angle -145.842 \\ 832.639 \angle 94.158 \end{bmatrix}$$

$$I_{ABC} = \begin{bmatrix} 277.769 \angle -25.842 \\ 277.769 \angle -145.842 \\ 277.769 \angle 94.158 \end{bmatrix}$$

* 2nd Iteration

$$V_2 = ELN - [Z_{line\,H}][I_{ABC}]$$

$$\begin{bmatrix} 7.132 \angle -0.332 \\ 7.149 \angle -120.354 \\ 7.142 \angle 119.4 \end{bmatrix}$$

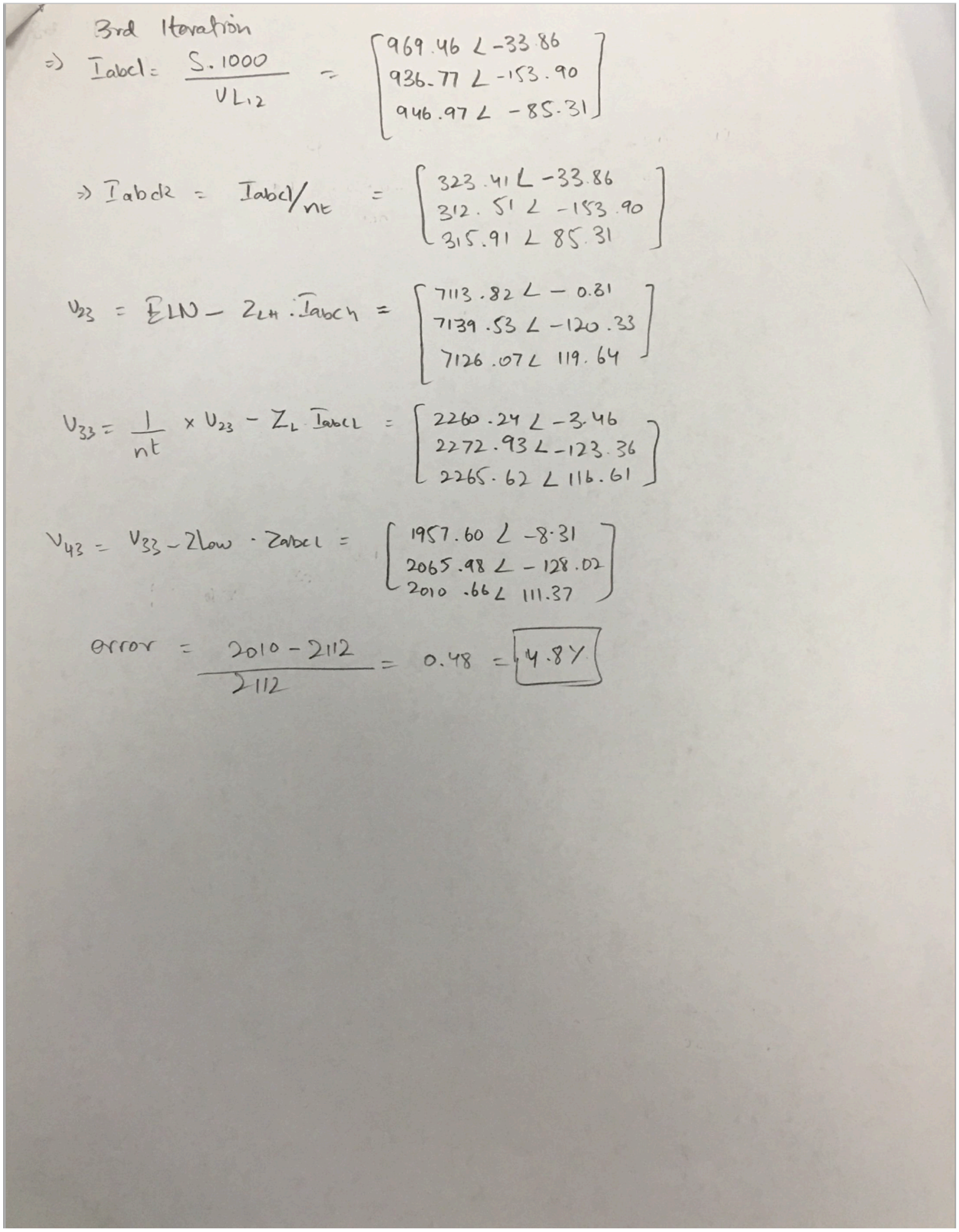
$$V_3 = \frac{1}{nt} V_2 - [Z_t][i_{abc}]$$

$$= \begin{bmatrix} 2.299 \angle -3.313 \\ 2.305 \angle -123.328 \\ 2.308 \angle 116.617 \end{bmatrix}$$

$$V_4 = V_3 - Z_{linch} \cdot I_{abc}$$

$$\begin{bmatrix} 2.063 \angle -8.0214 \\ 2.136 \angle -128.0565 \\ 2.113 \angle 111.528 \end{bmatrix}$$

$$\text{error} = \frac{2.063 - 2.402}{2.402} = 14\%$$



3rd Iteration

$$\Rightarrow I_{abc1} = \frac{S \cdot 1000}{V_{L12}} = \begin{bmatrix} 969.46 \angle -33.86 \\ 936.77 \angle -153.90 \\ 946.97 \angle -85.31 \end{bmatrix}$$

$$\Rightarrow I_{abc2} = I_{abc1}/n_t = \begin{bmatrix} 323.41 \angle -33.86 \\ 312.51 \angle -153.90 \\ 315.91 \angle 85.31 \end{bmatrix}$$

$$V_{23} = ELN - Z_{LH} \cdot I_{abcH} = \begin{bmatrix} 7113.82 \angle -0.81 \\ 7139.53 \angle -120.33 \\ 7126.07 \angle 119.64 \end{bmatrix}$$

$$V_{33} = \frac{1}{n_t} \times V_{23} - Z_L \cdot I_{abcL} = \begin{bmatrix} 2260.24 \angle -3.46 \\ 2272.93 \angle -123.36 \\ 2265.62 \angle 116.61 \end{bmatrix}$$

$$V_{43} = V_{33} - Z_{Low} \cdot Z_{abcL} = \begin{bmatrix} 1957.60 \angle -8.31 \\ 2065.98 \angle -128.02 \\ 2010.66 \angle 111.37 \end{bmatrix}$$

$$\text{error} = \frac{2010 - 2112}{2112} = 0.48 = \boxed{4.8\%}$$