Impact of High Photo-Voltaic Penetration on Distribution Systems

Design Document

DEC1614

Alliant Energy

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Contents

1 Introduction

1.1 Project statement

Our senior design project is about observing and analyzing new trends in distributions systems as solar Photo-Voltaic generation is increasing in Washington, Iowa. We will collaborate to develop a solution that can handle extreme instability trends such as over-voltage and reverse power.

1.2 Purpose

Our team is focused on making sure that Alliant Energy's distribution system will have the capabilities of handling an increasing PV generation. These tests will help develop a steady system that will keep their distribution system running in a stable fashion. Stability will be able to keep Alliant Energy's solar Photo-Voltaic generation attractive to their customers. Alliant Energy and our team are looking forward to helping the energy grid become more eco-friendly.

1.3 Goals

Our team will familiarize ourselves with OpenDSS to achieve these goals. Our group's goals consist of:

- Simulating a real world distribution feeder owned by Alliant Energy with high solar PV penetration.
- Assessing the impact of high PV penetration on voltage profile of the feeder for the worst case scenarios such as high generation, low demand etc.
- Analyzing and comparing the impact of residential PV and community solar PV generation.
- Developing some solutions or guidelines that would benefit Alliant Energy to prevent future problems associated with high solar PV penetration.

2 Deliverables

Our deliverables will be better achieved by partnering with Alliant Energy. They own the distribution feeder that allows us to simulate high solar PV penetration. This feeder will be the key to our analysis.

One of our project deliverables is to perform a simulation of a real world distribution feeder with high solar PV penetration that will be finished by the end of the project design. Additionally, our team will conduct an evaluation and assessment for the worst case scenario. Finally, the output of the project will consist of concrete solutions and guidelines for the previously stated provisioned problems.

3 Design

To achieve the most possible practicable solutions to come up with a stable distribution system with high Photovoltaic penetration. Our Team has created the following road map:

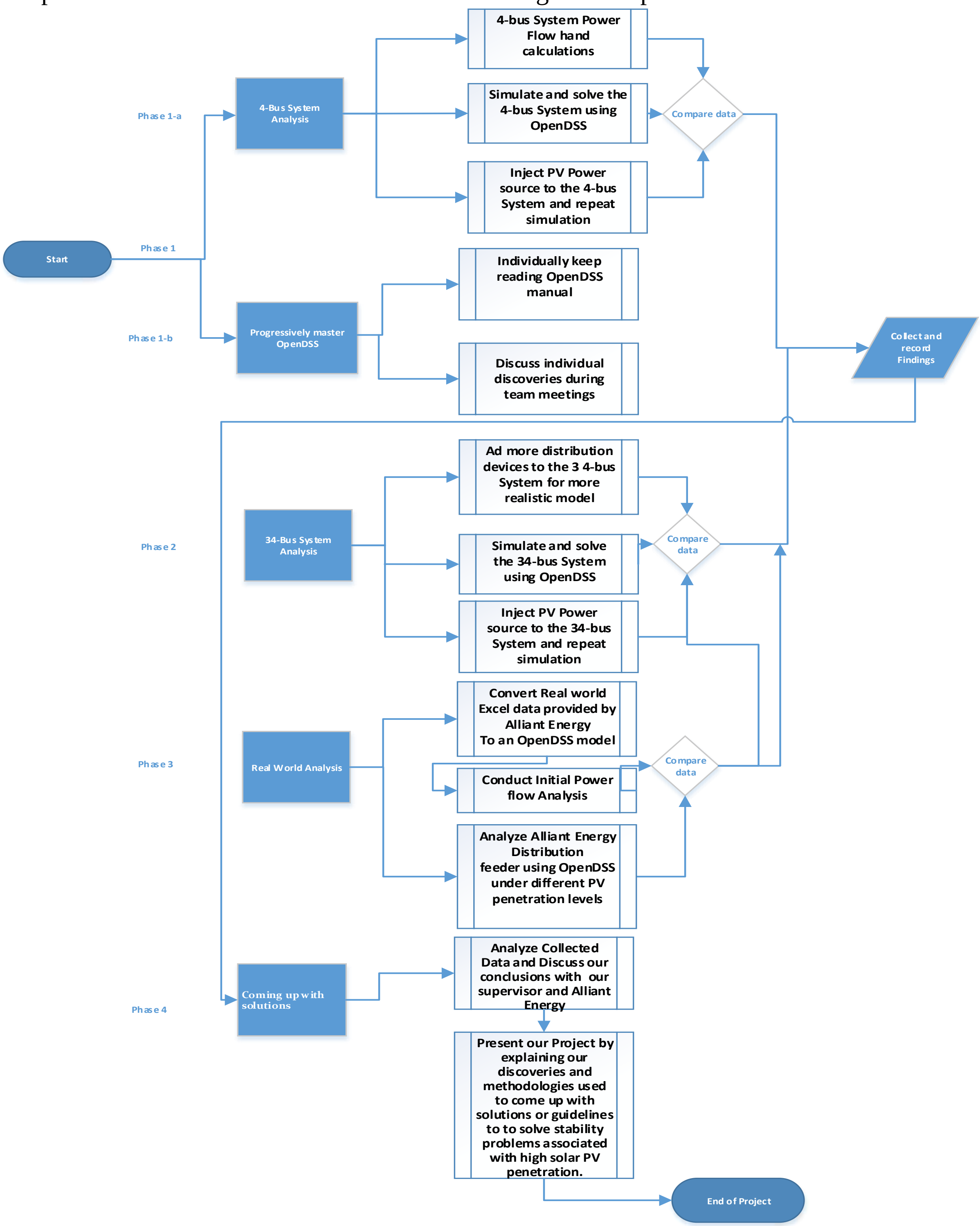


Figure 1 Project Roadmap

3.1 System specifications

Presently, we are almost done with all the components of phase two of the road map. Once we processed administrative forms and started familiarizing ourselves with OpenDSS, we were ready to start working on the first phases of the project. The following few paragraphs demonstrates what we have accomplished so far:

Phase 1

Our Team spent multiple hours 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. 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.

After discussing our findings among the team members as well as drawing conclusions with the help of our advisor, we introduced distributed PV generation to the system. We modeled the PV impact 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 has noticed some voltage level violations and discussed these issues with Dr. Ajjarapu. In the attempt to bring voltages to an acceptable range, we added capacitor banks in various locations. These solutions indeed resolved the voltage levels concern and pushed us to start exploring different possible approaches to such problems. Moving on to the next phase, we felt that through this simpler model, we started recognizing how electric systems perform under specific conditions creating many performance issues.

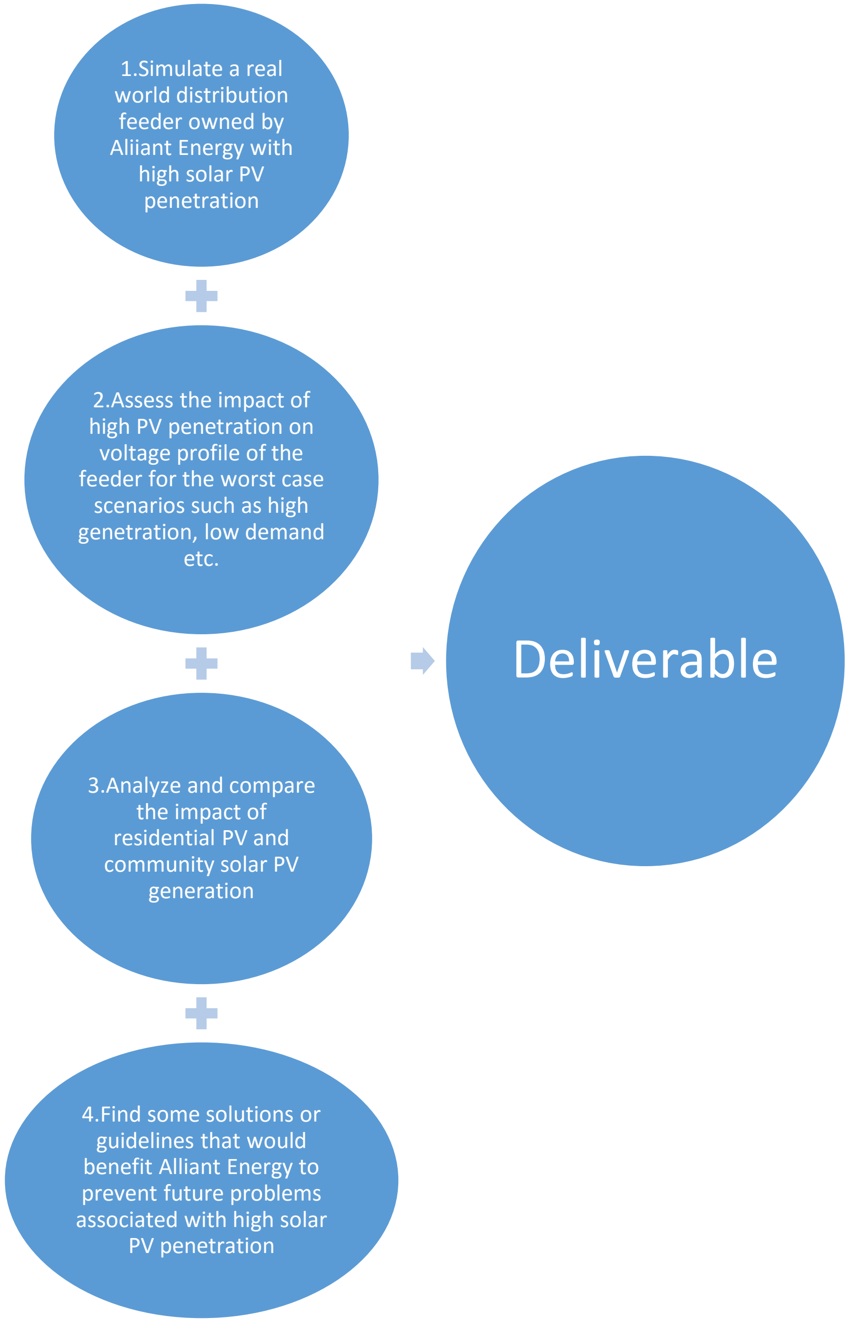
Phase 2

With voltage level problems found in phase 1, Dr. Ajjarapu decided that we should move to a more realistic 34-bus model that incorporates transformers and voltage regulators. To help understand the implications of voltage regulators, we used OpenDSS to simulate and analyze the 34-bus System when Load is varied the load by the same factors as phase 1. Additionally we deactivated each voltage regulator at the time, observing its impact on the voltages and currents in each node. Finally we discussed our findings as usual.

After the break, we will finish phase 2 by attending PV sources, and look for any stability issues. Any problems found will be discussed with our advisor and we will find possible solutions wrapping up phase 2.

3.1.1 Non-functional

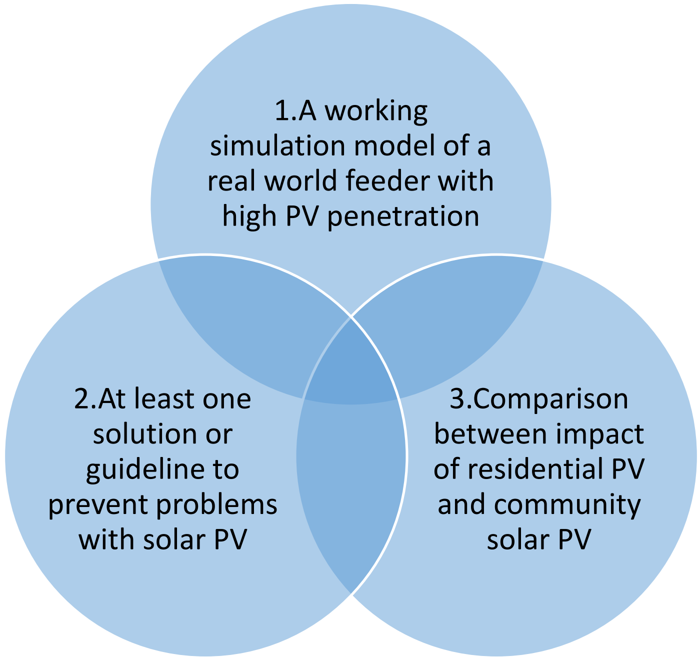
Our project has the resulting four non-functional requirements and deliverables



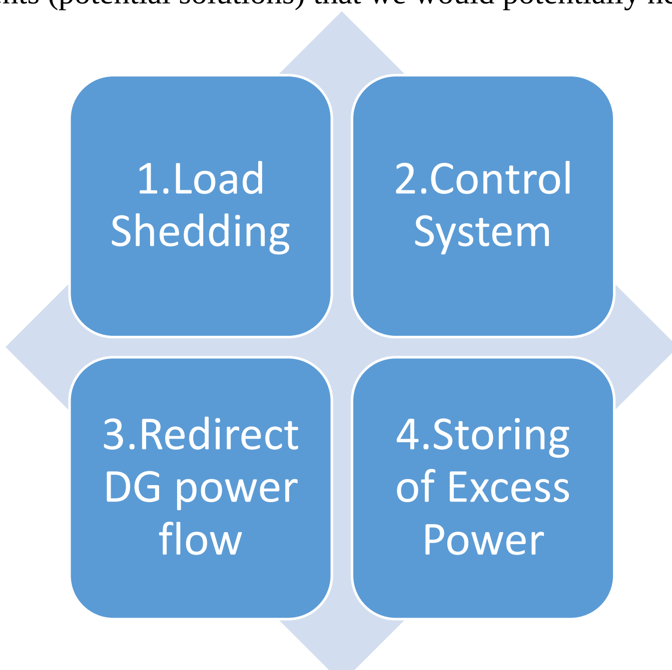
3.1.2 Functional

Project functional requirements:

There are three fundamental functional requirements for our project:



In order to deal with the requirements more specifically, we did some research and we found four possible specific requirements (potential solutions) that we would potentially need to solve in our project:



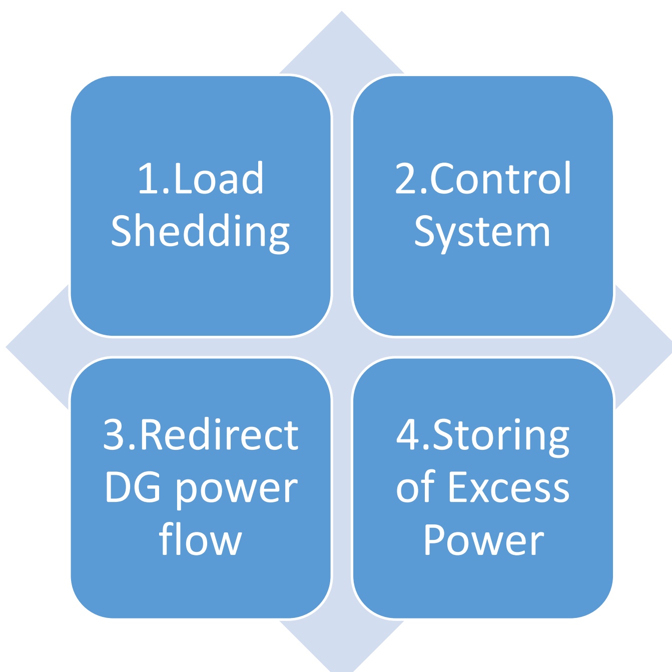
1. **Distribution Load Shedding**
   Load shedding is a controlled way to prevent the unplanned events to the electricity power system from blackout. In other words, based on our project—in Washington, Iowa, consumers could use their own green generation power (solar PV) to feed themselves while the energy they are generating is sufficient

and that would lead them to be disengaged from the grid temporarily. Once the power that they are generating is not sufficient, the system could draw them back to the grid by a sensor. Load shedding can dramatically increase the efficiency of the power usage of the grid in Washington area and it would effectively lead the power not excess the maximum limit of the entire system.

2. **Control System**
The control system would possibly introduce a sensing mechanism that will detect the feedback power and voltages into the distribution loads/feeders and reroute the energy into a capacitor bank. The system can operate reversely to allow the energy back to the grid when the system is at a lower stage of usage.

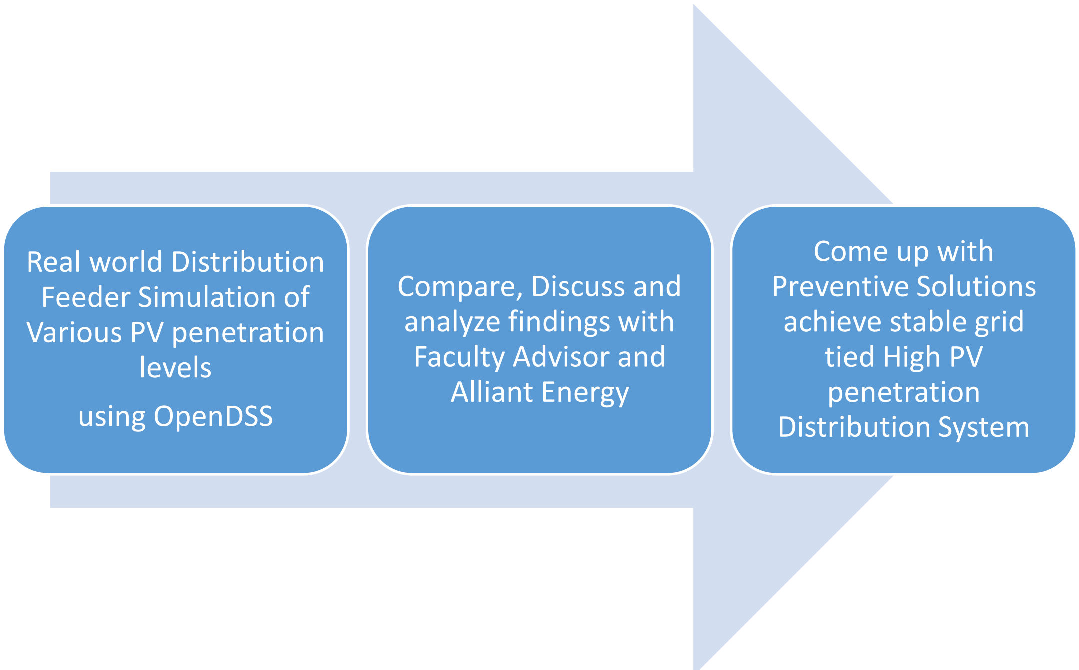
3. **Redirect DG Power Flow**
Modify the connection lines to the home—allow the excess of the power that generated by each individual home to transfer to the nearest substation and have it redistributed to the entire grid of the power system.

4. **Storing of Excess Power**
Each individual customer may generate additional DC power by the solar PV and it will be stored in their own batteries. Once the demand of a load is in some specific scenario it could convert the excess power to an AC form and be transferred to the distribution grid in case to compensate the additional demand on utility lines especially in some high peak periods (hot summer & cold winter).



3.2 PROPOSED DESIGN/METHOD

Our team will be processing the project by dividing it into 3 main stages as follow:



Through OpenDSS we will be able to inject PV generation to various buses varying the level of PV penetration. During each case we will observe and compare how the distribution feeder responds to each scenario. Data will be collected in the form of voltages, currents, and power values at all buses. By analyzing each case, our team will define the proportion to where such PV integration starts causing problems to Alliant Energy's distribution system. Knowing the exact percentage will allow us to conduct more realistic simulations which would be more applicable to our client. Finally, we have to come with preventive plan to solve problems such as voltage level variations due the cycle nature of solar energy (day versus night), and reverse power flow.

3.3 DESIGN ANALYSIS

After discussing our progress with Dr. Ajjarapu, our group believes that the project is developing according to road map. As stated formerly, we are currently working on analyzing the 34-bus system with distributed PV generation. This step is going to move us one step closer towards working on our client's distribution system. We had made some coding mistakes which caused some unpredicted voltage output in certain phases. These mistakes were identified and corrected with the help of our advisor. We believe that making mistakes is part of the learning process and we are going to work harder moving forward.

4 Testing/Development

4.1 INTERFACE SPECIFICATIONS

Impact of High Photo-Voltaic Penetration on Distribution Systems is a project based on computer simulation and real world data collected from real distribution feeder owned by Alliant Energy with high solar PV penetration. We will study about solar PV distribution before solving real world data analysis and problems on computer via software. For meeting all the goals and deliverables, OpenDSS and MATLAB software will be used for the simulation and analysis. At the end of the project, we should be able to find some solutions or guidelines by combining the simulations and real world distribution collections, assess the impact of high PV penetration on voltage profile for the worst cases.

4.2 HARDWARE/SOFTWARE

OpenDSS and MATLAB software will be used for the simulation and analysis. OpenDSS is an open source platform and can easily grasped, which is the most important topic for the project team to study at the beginning.

On the one hand, in order to have a better understanding of distribution systems before inserting complex database from real world feeder, OpenDSS can help us preview and build up sample circuits to simulate ideal distribution systems. Besides, OpenDSS is more readable to us to study and analyze the power factor, power flow, and voltage profile.

On the other hand, we will face thousands sets of data from customers residential solar PV feeder that are collected by Alliant Energy. MATLAB is the best way to deal with the large database for students at Iowa State University. In the undergraduate period, we are familiar with MATLAB and able to make full use of MATLAB on data analysis, matrix calculation and further distribution system simulation.

4.3 PROCESS

As the first step, project team will study OpenDSS and work on distribution system simulation, calculations and analysis. Through OpenDSS, we will be capable to inject PV generation to various buses varying the level of PV penetration. The challenge will be if Alliant Energy's system can or cannot be simulated on OpenDSS correctly and get relating simulation results by comparing voltages, currents, and power values at all buses.

Secondly, team will also import all the data into MATLAB, both simulation and real world collection, and compare the two. The way to test the comparison is to detect errors among most sets of data, and try to clear all the simulating and design problems. Finally, team shall develop a solution or guideline for Alliant Energy and also mention all the potential problems that collected or predicted from worst case simulation.

Below, is a flow diagram shows how the project will be proceed and how the team will apply the OpenDSS and MATLAB while study and design the project:

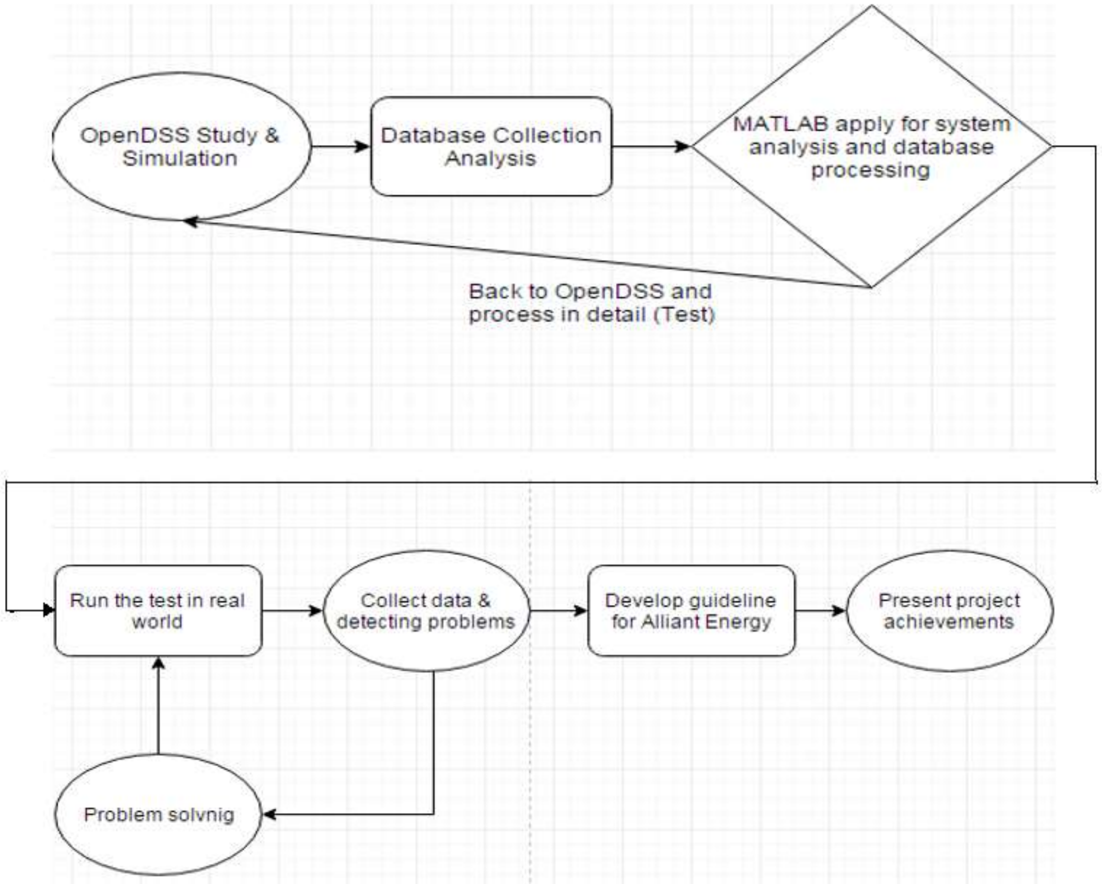


Figure 1- Our team's process in a flow diagram

5 Results

Our group is currently working on the 4-bus and 34-bus distribution feeders in OpenDSS from IEEE data. We are looking for the details and obtaining a deeper understanding of these cases of a distribution system. Our final project goal is to simulate a real world distribution feeder system with the arbitrary amount of solar PV injected in Washington area which is around a 300-bus distribution system. Therefore, understanding the fundamental feeder system is important and necessary for our group.

Our team has successfully simulated and understood both the 4-bus and 34-bus systems. Furthermore, in order to look forward to a broader understanding of the basic distribution system, we not only did the simulation through OpenDSS but we also the hand calculation of its first and second iteration to check our understanding of the concept. For now, our team understands what we need to do and we are ready to move forward to a more real world situation case--123 bus feeder system with solar PV injected.

At this point, our team had two major results:

1. 4-bus distribution system OpenDSS simulation result and hand calculation comparison work.

2. 34-bus distribution system OpenDSS simulation result (Without solar PV injected).

Result: 4-bus system OpenDSS simulations (Original/without regulators):

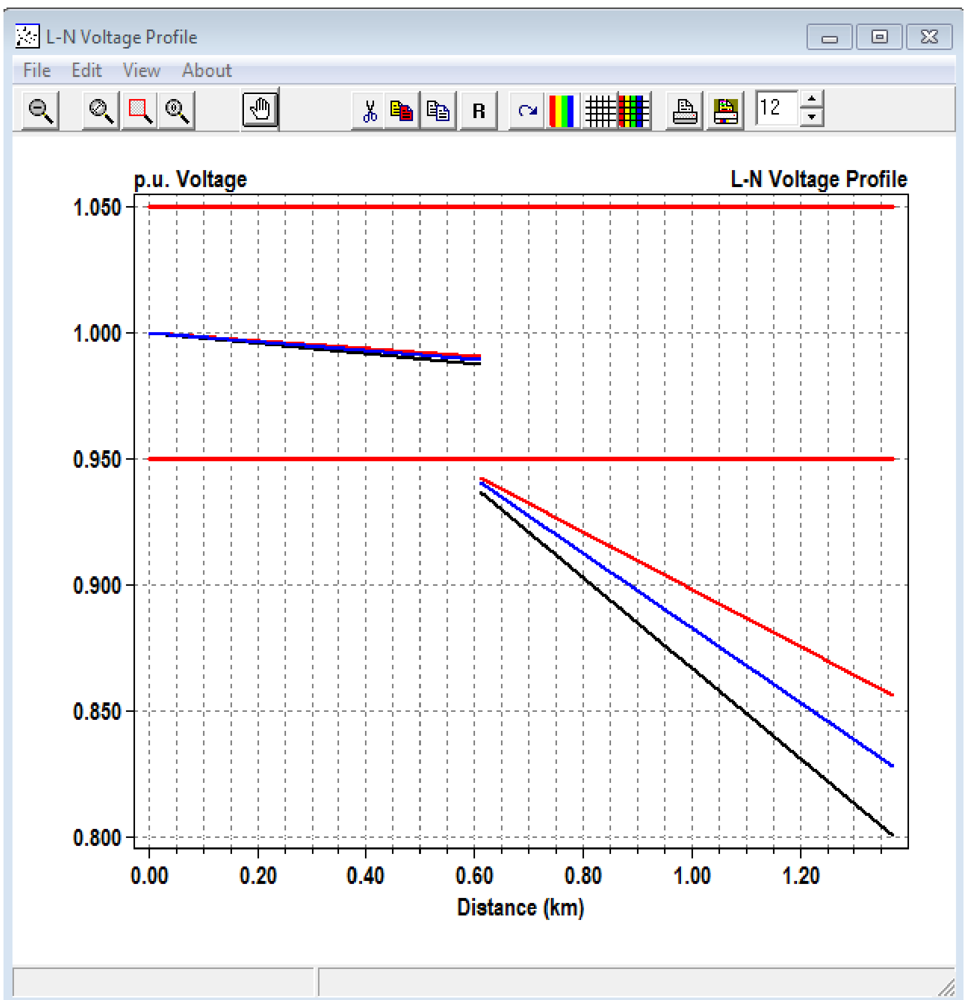


Figure 1-Original 4-bus system

From figure 1, we could easily see that the voltages at node 3 and node 4(which represents the right corner lines) are under the acceptable desired per unit voltage range.
In comparison, we did the hand calculations for obtaining the per unit voltages at each node as shown in the Appendices. Next, we added a capacitor at node 4 in each phase, and we found the best simulated result with the specific value of capacitance, the results are shown in below.

Result: 4-bus System Hand Calculation comparison:

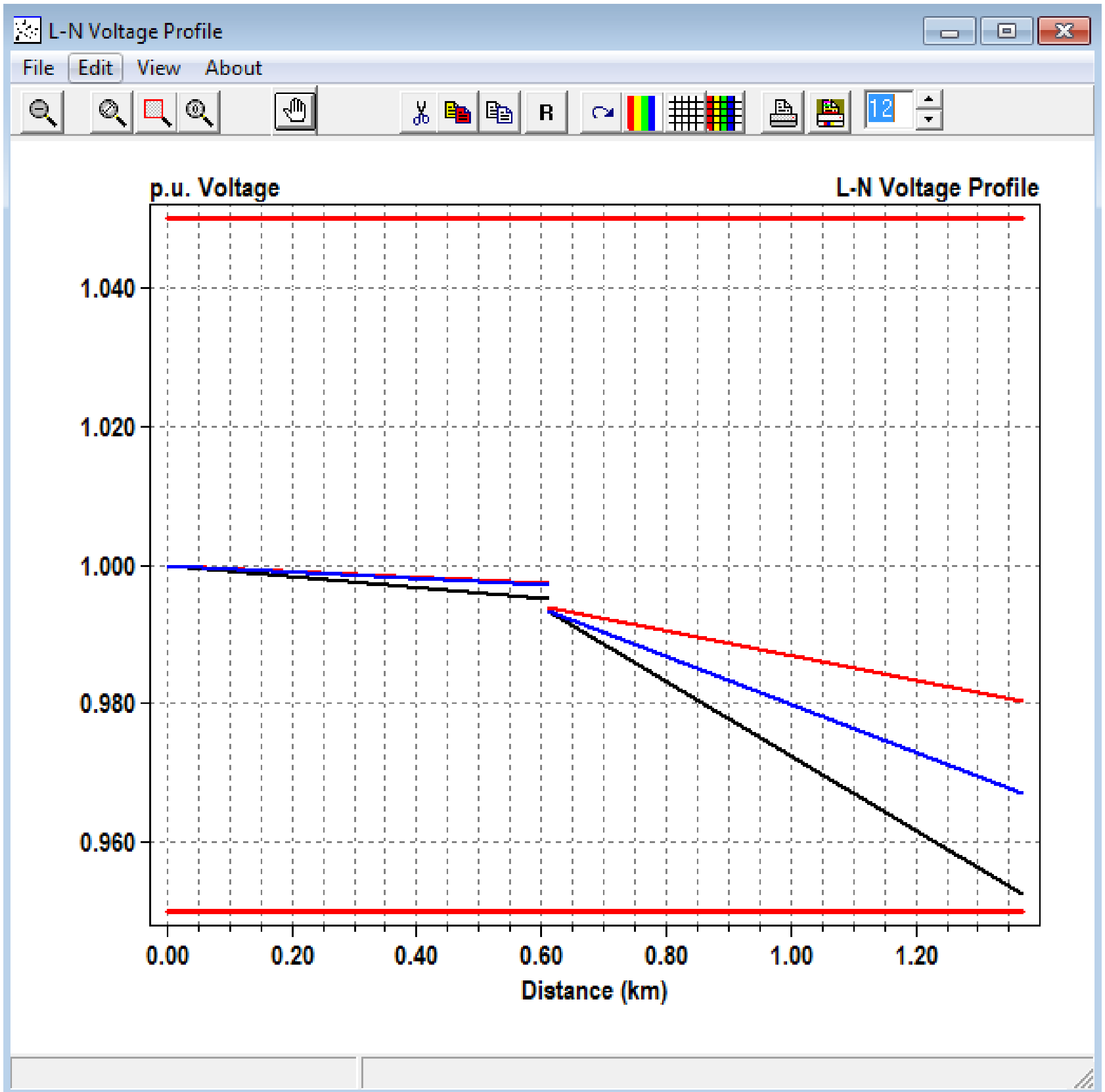


Figure 2- 4-bus system with Capacitors

Figure 2 shows all voltages at all nodes at all phases are under the desirable per-unit voltage range (0.95-1.05). Since our final goal is to simulate the real world distribution feeder system with solar PV injection, we also did a modification which we added the solar load to the basic 4-bus system to learn the fundamental concept of the consequence of solar injection to the system.

Result: 4-Bus system simulation (With solar):
The left one is the original one and the right one includes the solar load at node 4(the most right side of the image).

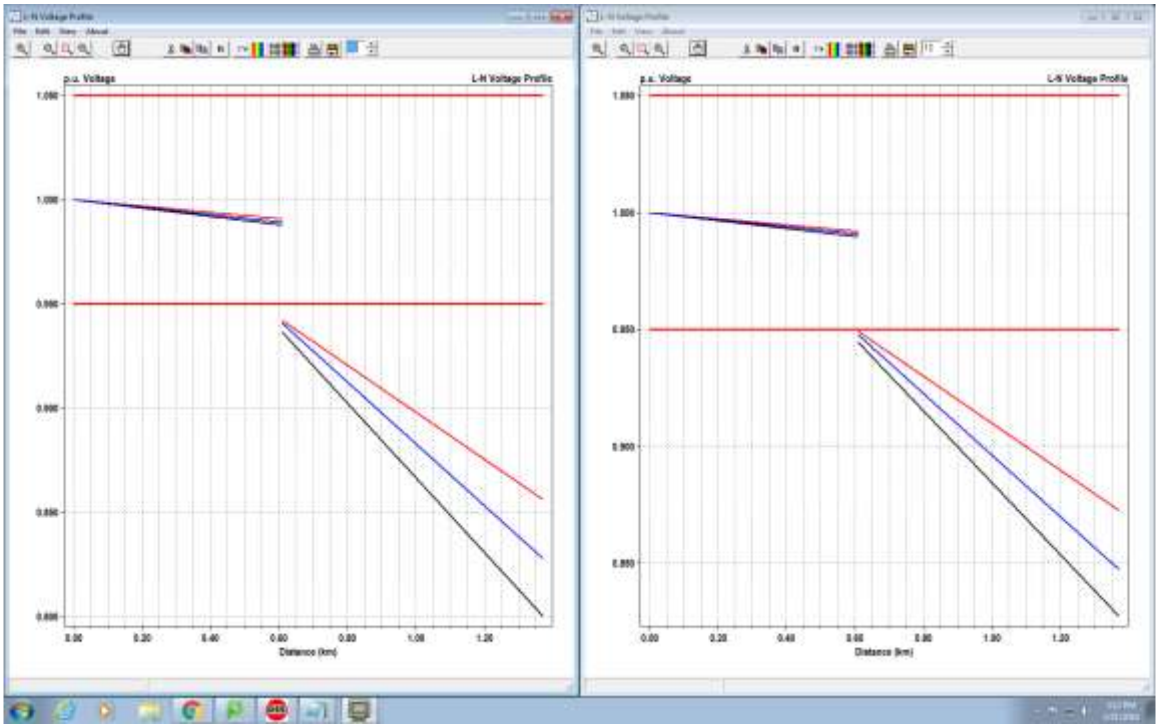


Figure 3- 4-bus system with solar PV penetration

From our view, the solar load effects the total voltage variation only a little bit, we can add voltage regulators or capacitors to avoid this undesirable effects as well as we did before.

Results from 34-bus system:
The schematic view of the 34-bus system is shown as below:

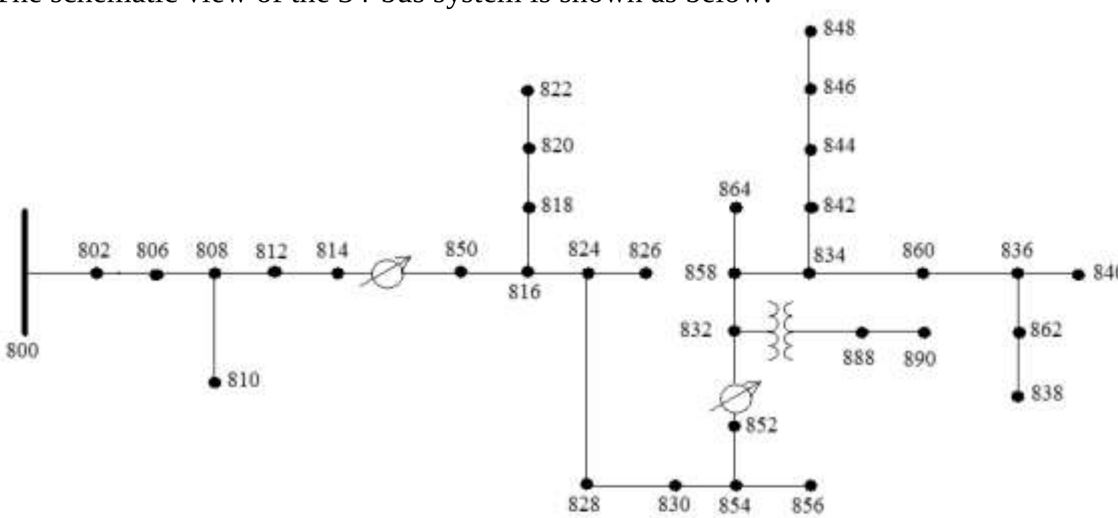


Figure 4- 34-bus system schematic

Result: 34-Bus system voltage feeder Simulation (Original)

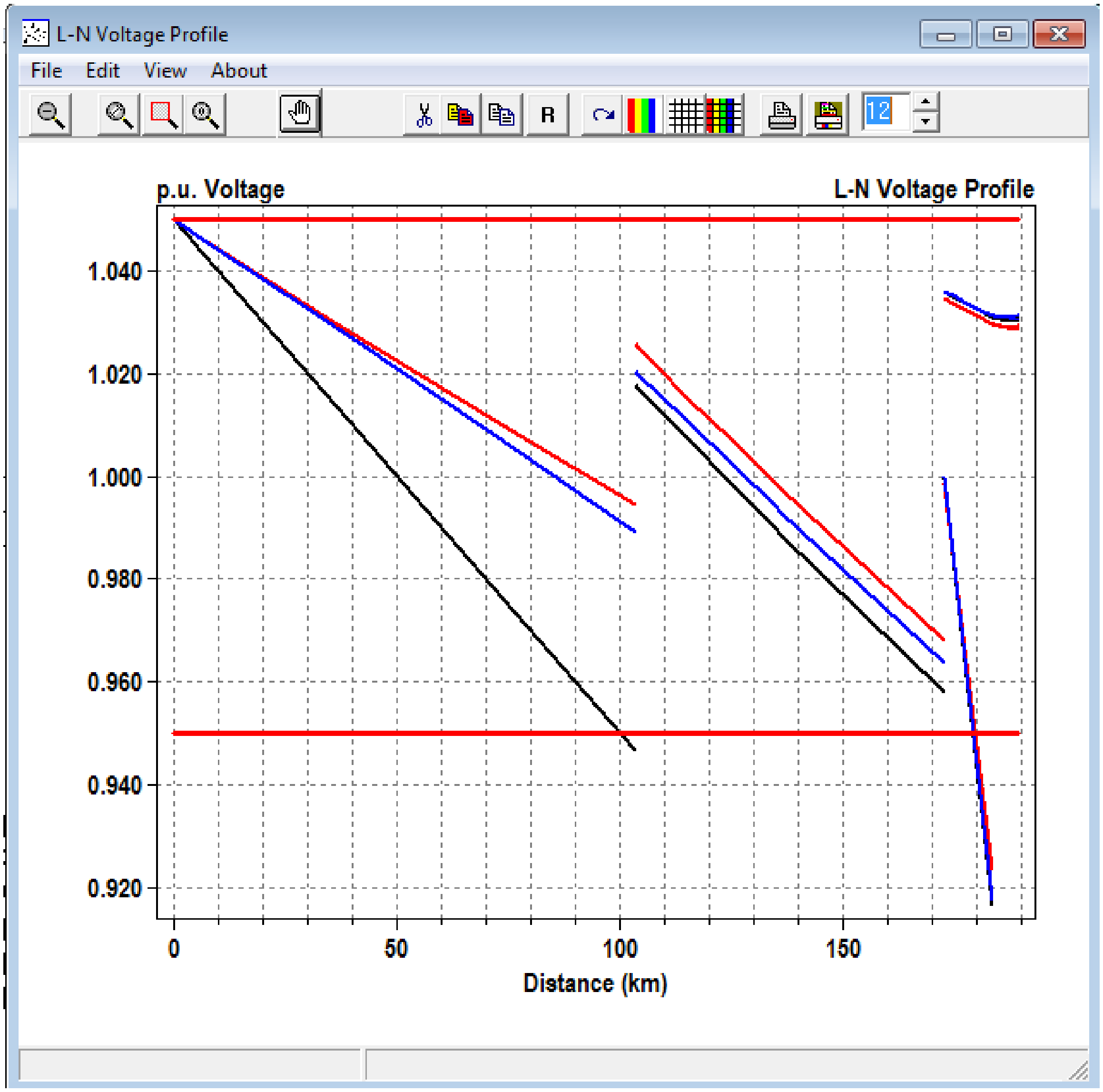


Figure 5-Original 34-bus system

As you can see, this simulation is more complex. It has 34 feeders and it has a total of 200 km of transmission lines. The nodes from 834 to 848 and nodes from 888 to 890 are under the per unit voltage range. We are currently working on the optimization of the feeders by adding voltage regulators to the 34-bus distribution system to make all the per unit voltages at all phases within the required voltage range.

6 Conclusions

After analyzing all of our project tests and results, we are thrilled to be making progress with Dr. Ajjarapu and Alliant Energy. As a team, we have successfully simulated the 4-bus and 34-bus system in OpenDSS. We have been able to manipulate both systems in 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. Our goals for this senior design project are as follow: to simulate a real world distribution feeder owned by Alliant energy with high solar PV penetration, assess its impact for different cases, analyze and compare the impact of residential and community solar PV generation, and find solution or guideline to their existing problems. Our team will be able to achieve all the goals and deliver all the results to Dr. Ajjarapu and Alliant Energy by the end 2016 fall semester. For the first semester of project, residential solar PV generation effects will be fully understood and simulated via OpenDSS. This will help understand the effects with the simple addition and removal of different equipment. Once we all understand this on a smaller scale, we will be able to move onto Alliant Energy's larger system. The fall semester will be spent on understanding these effects and forming a solution. A formal SOP will be edited as a part of expected deliverable as well. At the end of each semester, our team will conduct presentations to show our progress and end results.

7 References

"Project Abstract"

by Department of Electrical and Computer Engineering

"High Penetration PV Handbook"

by Rich Seguin, Jeremy Woyak, David Costyk, Josh Hambrick, Barry Mather

"High Penetration Photo-voltaic Case Study Report"

by J. Bank, B. Mather, J. Keller, M. Coddington

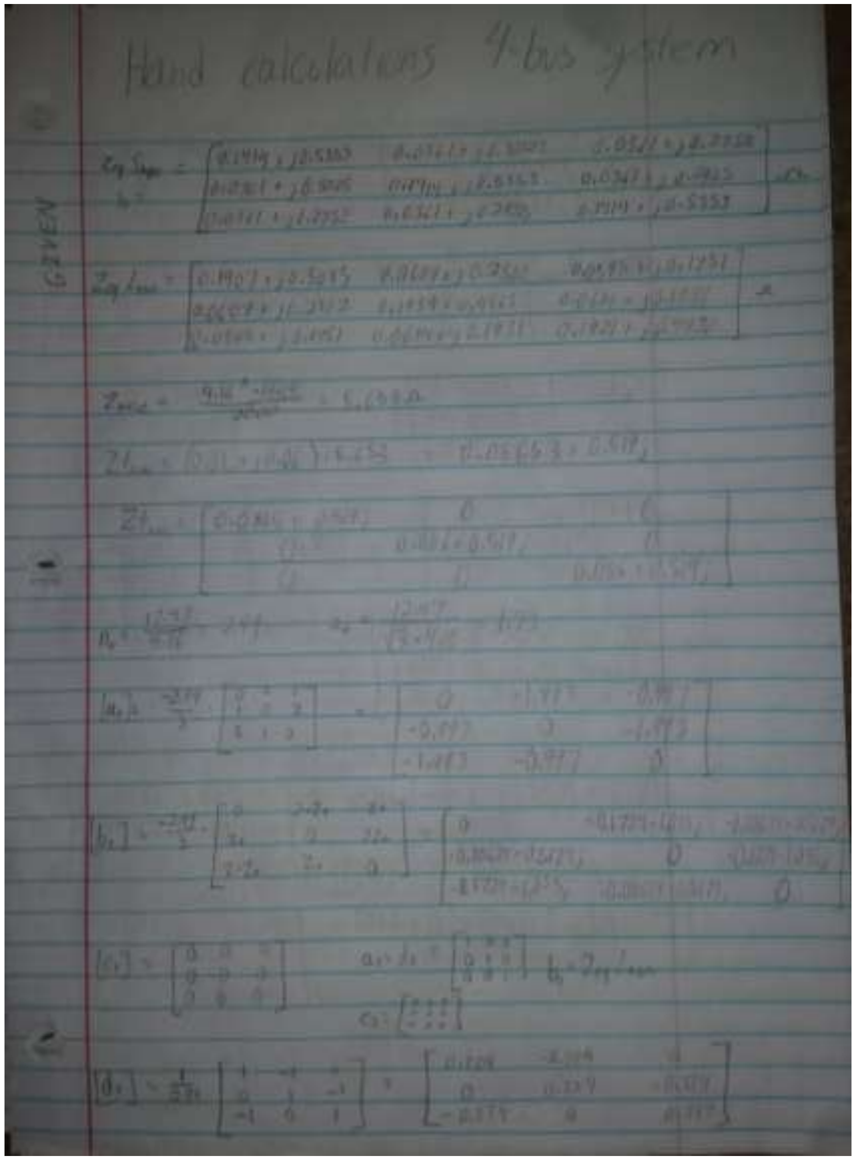
"Distribution System Modeling and Analysis"

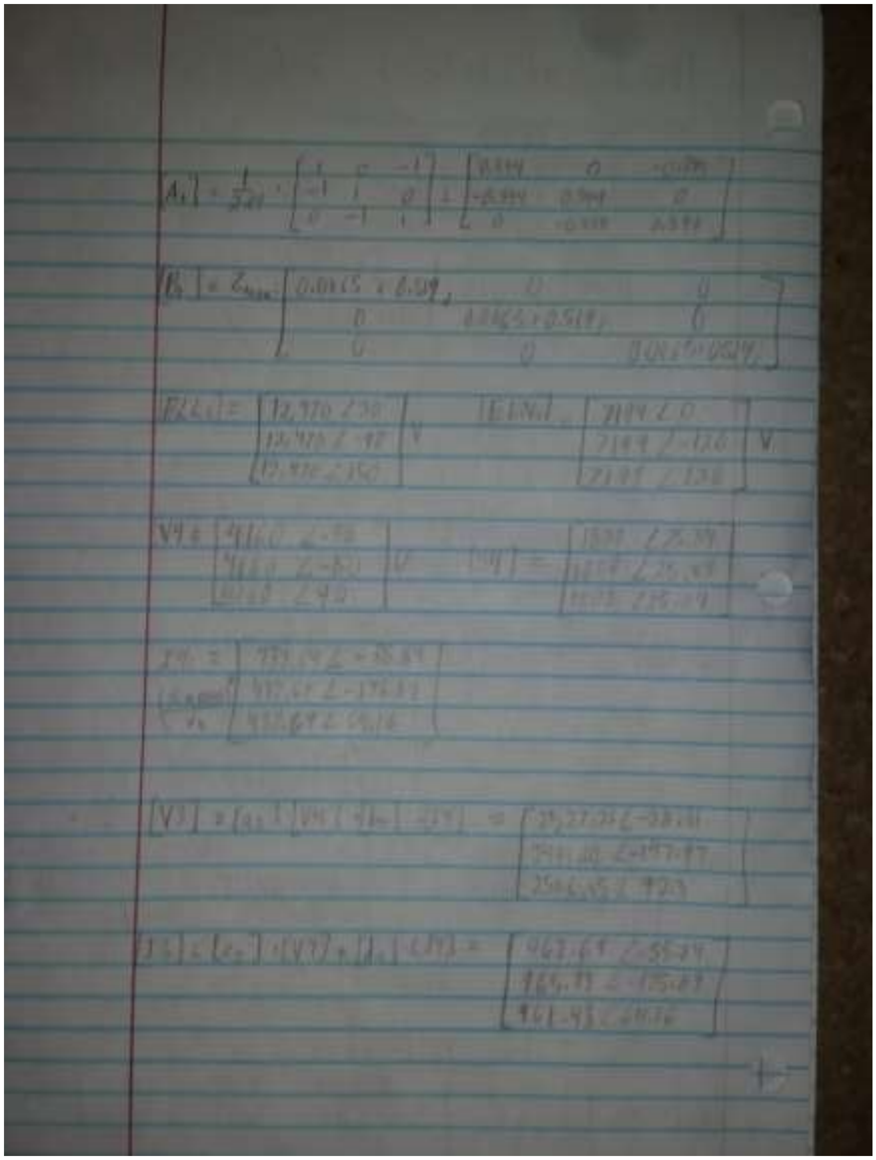
by William H. Kersting

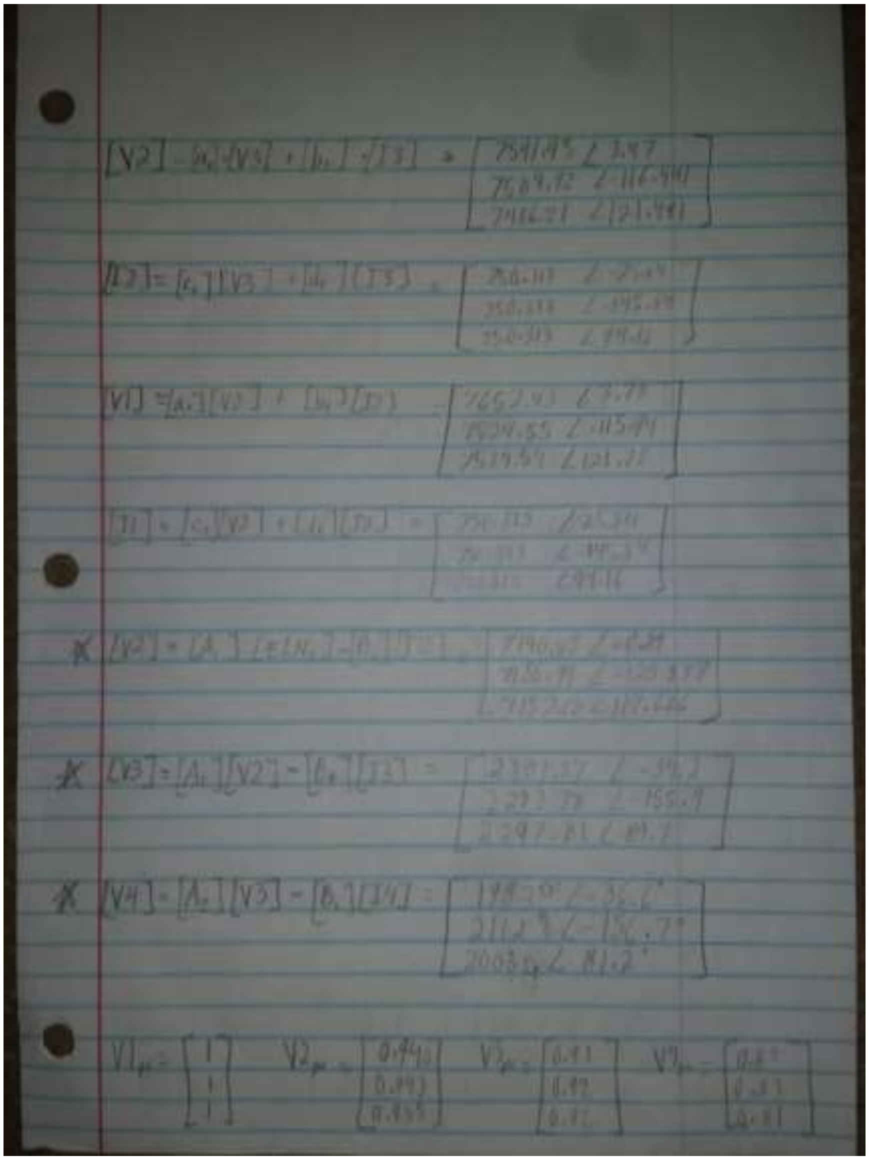
"Reference Guide The Open Distribution System Simulator"

by Roger C. Dugan

8 Appendices







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[V1] = [a1][V2] + [b1][I2] = [2652.43 ∠ 3.77; 2624.55 ∠ -115.49; 2519.54 ∠ 121.72]

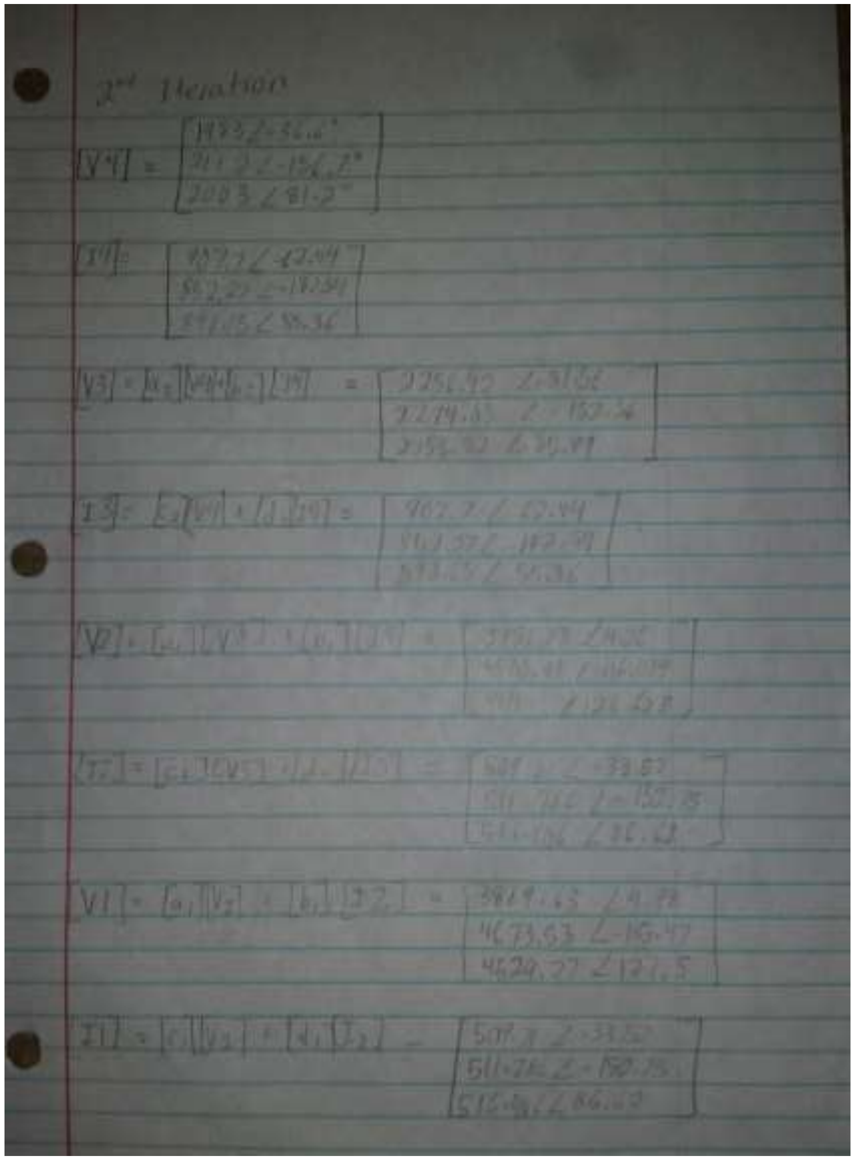
[I1] = [c1][V2] + [d1][I2] = [250.113 ∠ 25.34; 250.113 ∠ -145.3; [illegible] ∠ 99.16]

[V2] = [A1][...] − [B1][I1] = [2190.[illegible] ∠ -0.[illegible]; [illegible] ∠ -120.377; 2152.[illegible] ∠ 119.[illegible]]

[V3] = [A2][V2] − [B2][I2] = [2301.37 ∠ -34.2; 2293.[illegible] ∠ -155.9; 2297.81 ∠ 83.7]

[V4] = [A3][V3] − [B3][I3] = [1983.[illegible] ∠ -36.[illegible]; 2112.[illegible] ∠ -156.7°; 2003.[illegible] ∠ 81.2°]

$V1_{pu}$ = [1; 1; 1] $V2_{pu}$ = [0.995; 0.993; 0.985] $V3_{pu}$ = [0.91; 0.92; 0.92] $V4_{pu}$ = [0.8[illegible]; 0.83; 0.81]


2nd Iteration

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[I3] = [C2][V4] + [D2][I4] = [987.3 ∠ 42.94 ; 961.57 ∠ 182.59 ; 593.15 ∠ 56.36]

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[I1] = [C1][V2] + [D1][I2] = [507.3 ∠ -33.52 ; 511.78 ∠ -150.75 ; 515.[illegible] ∠ 86.42]

$$[V2] = [A_1][ELN_s] - [B_1][I2] = \begin{bmatrix} 7381.71 \angle 3.06 \\ 7101.4 \angle -120.604 \\ 7098.56 \angle 119.33 \end{bmatrix}$$

$$[V3] = [A_1][V2] - [B_1][I3] = \begin{bmatrix} 2154.16 \angle -36.13 \\ 2167.98 \angle -150.426 \\ 2304.76 \angle 86.9 \end{bmatrix}$$

$$[V4] = [A_2][V3] - [B_2][I4] = \begin{bmatrix} 1984.79 \angle -36.44 \\ 2105.82 \angle -156.74 \\ 1971.91 \angle 80.7 \end{bmatrix}$$

$$V1_{pu} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad V2_{pu} = \begin{bmatrix} 0.97 \\ 0.97 \\ 0.94 \end{bmatrix} \quad V3_{pu} = \begin{bmatrix} 0.91 \\ 0.91 \\ 0.93 \end{bmatrix} \quad V4_{pu} = \begin{bmatrix} 0.84 \\ 0.81 \\ 0.82 \end{bmatrix}$$