Impact of High Photovoltaic Penetration on Distribution Systems

DESIGN DOCUMENT

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List of Definitions

ANSI: American National Standards Institute

IEEE: Institute of Electrical and Electronics Engineering

GridLAB-D: Open-source, object-oriented software for simulating distribution systems that will often be referred to as GridLab.

MATLAB: Matrix-oriented software used to read and convert spreadsheet data.

PV: Photovoltaic

1 Introduction

1.1   Acknowledgement

We would like to thank our advisor Professor Dr. Ajjarapu, and his research assistants Alok Bharati and Ankit Singhal, for their constant support and guidance. They have helped us in our understanding of distribution systems and solar energy's impact on them, and this has been a great opportunity for all of us to learn and grow as electrical engineers.

1.2   Problem and Project Statement

Problem Statement: Solar energy is making advances very rapidly in today's world. In Iowa, the solar generation and solar power plants are seen as a potential major source of power, to satisfy the needs of people. In this project we are trying to assess the impact of high PV penetration on the distribution feeders and its effect on the power delivered to the consumers.

Project Statement: In order to further understand distribution systems, we are going to simulate them using a power systems software called GridLAB-D. Once we've gotten an understanding of how changing variables such as voltage regulators and load capacitors affect distribution systems, we will begin implementing solar energy into our systems. We will see the effects of

high PV penetration at certain times of the day on our distribution systems, such as opposite direction power flow, and overvoltage. In changing different variables of the distribution system in GridLab, we should be able to find solutions to these problems. We will finally be introduced to an actual distribution system owned by Alliant Energy, and simulate their system to find solutions for how to effectively apply solar power to their distribution system.

1.3   Operational Environment

For our project, we will not be simulating the operating environments, except for the average amount of solar energy output at different times of the year. This will be a given set of information, and our suggestions for the distribution system will all be taken from a simulation.

1.4   Intended Users and Uses

This project is intended to be used by Alliant Energy, with whom we will have signed a non-disclosure agreement. We intend to deliver them suggested solutions to potential problems that may arise in an attempt to incorporate solar energy into their distribution system. It is up to Alliant Energy how they will use these suggestions, which will be meant to better supply power to the general public.

1.5 Assumptions and Limitations

Assumptions:

- The open-source software, GridLAB-D, will be able to effectively simulate the large Alliant Energy distribution system.
- The load values given by Alliant Energy will not change much in the future, nor will any new loads be added.
- The weather for the solar energy system will be typically average for each season that the distribution system is simulated.
- There will be no failures in the distribution system due to extraneous circumstances (extreme load, power line failure, etc.).
- All components of the distribution system will be working at their rated amount.
- Load will not have extreme variances.
- Voltages other than from the power supplied by solar energy will constantly be able to be supplied.

Limitations:

- GridLAB-D runs off code from a text file, and does not have a user-interface that makes alterations to the distribution system as straightforward.
- GridLAB-D is open-source, and is not widely used, so it does not have customer support.

- Alliant Energy uses the expensive software Synergi to model their distribution systems, and cannot provide feedback on our GridLAB-D code.
- Suggestions cannot drastically change existing infrastructure.
- Distribution system will be in Iowa, and will have to account for the less-than-ideal climate throughout the year.

1.6   Goals and Deliverables

We will provide suggestions for how Alliant Energy can implement solar power in one of their distribution systems. Alliant Energy will be supplied with the code for our simulated distribution system that has added solar power. Along with this code, and its results, we will present graphs and data that more clearly demonstrate the value of modeling their future modified distribution system with aspects of our simulated system. These graphs will primarily be voltage profiles comparing the system before we add components such as voltage regulators and capacitors and/or change the position of the solar energy source to get a more favorable impedance. Suggestions for both changes to the current distribution system, and how to best add new infrastructure to the system will be given. These solutions will compare community PV and residential PV generation, and will aim to prevent future problems relating to solar generation on the Alliant Energy system. All of this will be delivered in April 2019.

2 Specifications and Analysis

2.1   Proposed Design

The design will be of a simulation of Alliant Energy's distribution system. Data will be received in the form of spreadsheets from Alliant Energy of their distribution system, and the team will use code that they have written in MATLAB to convert that data into a coding format that can be used by GridLAB-D. These spreadsheets will include distribution system information such as node voltages, conductor specifications, voltage regulator configurations, and distribution lines, and the MATLAB code will read the values in order, and write code that creates the objects used by GridLAB-D. GridLab is an object-based software, and each separate component of the distribution system needs to be defined with values such as nominal voltages and impedance values. An example of the definition of a voltage regulator can be seen below, in figure 1, The distribution system data given will provide the values to be written in GridLab format.

```
127   object load {
128       name load4;
129       phases "ABCN";
130       voltage_A +2400;
131       voltage_B -1200-2078.46j;
132       voltage_C -1200+2078.46j;
133       constant_power_A +1800029.41+871719.07j;
134       constant_power_B +1800029.41+871719.07j;
135       constant_power_C +1800029.41+871719.07j;
136       nominal_voltage 2400;
```

Figure 1: Example of GridLAB-D Format

Once verifying that the distribution system is being simulated correctly with Alliant Energy, the team will begin adding instances of high PV penetration to see the effects. At different nodes, solar energy will be added, and the effects of the voltage profiles on the rest of the system will be observed. Where voltage violations occur, such as overvoltage and reverse power flow, the team will make the necessary adjustments to negate these issues. Many of the methods used will be derived from solutions to IEEE's 34 node test system, that have been verified to work properly. A common solution is adding voltage regulators and capacitors to either boost or lower the voltage in a certain part of the system. Suggestions for where to place the sources of solar energy will also be given based on whether the power flow will function better with a higher or lower impedance due to the distribution lines. The solutions to these problems will be documented, and relevant graphs that show the improvement of the distribution system compared to the original unedited distribution will be provided.

2.2 Design Specification

Functional Requirements:

- Implementation of IEEE distribution systems in GridLAB-D.
  - IEEE has multiple test distribution systems, and relevant systems that we will be implementing are IEEE's 13 node and 34 node test systems. These systems have been thoroughly researched, and will serve as a basis for the verifiability of our findings.
- Implementation of an Alliant Energy distribution system in GridLAB-D.
  - The primary deliverable for our project is suggesting solutions to adding solar energy to one of Alliant Energy's distributions systems. We will need to have a stable simulation of Alliant's distribution system in GridLab in order to find solutions for making changes to the system to account for high PV penetration.
- Code to convert distribution system data into GridLAB-D's format using MATLAB.
  - Alliant Energy uses an expensive software called Synergi to work with their distribution systems. Since we do not have access to this software, we will need to write code that will take their distribution system data in the form of spreadsheets and convert it into code that will work for GridLab.

- Instances of high PV penetration to add to the distribution systems.
  - We will add instances of high PV penetration to the IEEE 34 node test system that we are simulating in GridLAB-D. The changes that we make to the system to account for high PV penetration will serve as a basis for our future solutions.
  - High PV penetration will also be added to the Alliant Energy distribution system that we will be simulating.
- Analyze and adjust the system according to the changes made from adding solar.
  - We will be simulating the Alliant Energy distribution system with multiple levels of PV penetration to see the effects of solar energy on the system.
  - The results of the power flows from these simulations will be compared to the results of the power flow from the distribution system without solar.
  - Will make changes to the system including solar to fix voltage violations, using methods such as adding voltage regulators and capacitors, and changing where the substation from the solar energy source will be placed.
- Determine solutions to adding solar power to Alliant Energy's system.
  - Use data from simulations to conclude how Alliant Energy can best add solar power to their distribution system.
  - Include relevant graphs and voltage profiles to indicate the reasoning behind the suggestions for Alliant Energy.

Non-Functional Requirements:

- Alliant Energy's current infrastructure.
  - Suggestions for how Alliant Energy should add solar energy to their distribution system should avoid making drastic changes to their existing infrastructure, as they would likely not be financially feasible.
- Profitability for Alliant Energy.
  - It would be best to consider solutions that make enough of an enhancement to the stability of Alliant Energy's distribution system that they justify the cost of any changes.

2.3 Design Analysis

So far we have solved the IEEE 4 bus system by hand and gained an understanding of how distribution systems work and power flows are solved. We have also simulated the IEEE 4 and 13 bus systems in GridLAB-D and gotten ourselves comfortable with the GridLab software. We initially had problems working with GridLab, however, as it is a different type of software than we are accustomed to. In GridLab we have been able to observe the effect of various components and the changes they cause on the system. Our aim for the next semester is to see the effect of solar PV being added to our systems. We will be adding the effect of solar PV to the IEEE 34 node test system, which we will have built using code in MATLAB. After understanding the effect and the corresponding results of our 34 bus system our ultimate goal will be to simulate

the Alliant energy system. This will be a challenge, as the Alliant Energy system will be much larger than anything else that we have worked on.

3 Testing and Implementation

3.1   Interface Specifications

There is not a lot of hardware interfacing required for this project as we will not be using any hardware for the project. All measurements and values we obtain will be from GridLAB-D, which we will be putting into excel to analyze. We will also do calculations in MATLAB to ensure that the data we are receiving from GridLab is correct.

3.2   Hardware and software

We will be using GridLAB-D, MATLAB, GitHub, and Excel for testing our project. GridLab will be used to model and test our distribution feeder node. We will be designing the system and running power flow calculations using this software. Excel will be used to store and analyze the data we get from GridLab. GitHub will be used to store code that we will be using in GridLab. Using MATLAB, we will be testing some of the data gathered from GridLab to ensure we are getting the correct values from the software.

3.3 Modelling and Simulation

GridLAB-D is a software in which distribution feeders can be simulated. It is capable of taking the specific line, node, and impedance configurations. We have simulated IEEE 4 and 13 system in GridLAB-D until now. We solved the IEEE 4 bus system by hand to gain a deeper understanding of how power flows work with distribution systems, and then implemented the system in GridLAB-D in order to become accustomed to the software. The IEEE 13 bus system that we implemented We will be simulating the 34 bus system and ultimately the Alliant energy system in GridLab next semester.

3.4   Functional Testing

There are three different tests we will be conducting for our project. First, we will test that we correctly implemented the distribution feeder as it currently is. Next, we will be testing how the system behaves after it is modified with different levels of solar PV penetration and what problems, if any, occur. Lastly, for each level of PV penetration, there will be solutions to whatever voltage violations occur from the different levels of solar penetration.

For Test 1 to be successful we will have implemented all loads, distribution lines, and other items in the distribution system on GridLab. We will be able to determine if the test is successful by comparing our power flow results to what Alliant Energy previously had found to ensure that the numbers are where they should be for the system.

For Test 2 to be successful all of the loads will be correctly modified as they would be with a particular level of solar penetration in the system. Simulations of the distribution system will then be ran to ensure that all of the voltage levels are within acceptable values. Errors in voltage levels and power flow would not be unexpected at this point, as this test is to check for problems rather than solve them.

Test 3 will be designing and implementing a potential solution to any problems that are found during test 2. The first stage of this step will be designing a solution to prevent whatever overvoltage or reverse power flow that occurred during test 2. Next, we will implement the solution in GridLab by making changes to and adding components such as voltage regulators and capacitors to the distribution system. If the solution is successful, the overvoltage and/or reverse power flow will be solved by the implemented solution. If there are still problems in the system, the test fails and we will have to restart the test.

3.4 Non-Functional Testing

As part of non-functional testing, we will compare the results of our solutions to other distribution systems that have successfully implemented solar power. If the improvements to the voltage profiles are comparable, then we will know that our solutions are viable. We will also look at the potential location of the implementation of the solar energy, and see if it is a good choice based on the costs it may take to transmit the power. To verify that our solutions are worthwhile, we will be presenting our solutions to our advisor, Dr. Ajjarapu. We plan to receive feedback on the graphs that we will present the same that we have been receiving feedback from him on our previous work.

3.5 Process

Our learning process started by doing hand calculations of the IEEE 4 bus system. After our hand calculations were in order with the IEEE results, we were introduced to the GridLAB-D software.

Our project plan for smaller bus systems involved doing hand calculations, understanding the concept involved and then simulating the same system in GridLAB-D.

Later in the semester we were asked to simulate IEEE 13 bus system in GridLAB-D. In this system we made different variations (such as adding capacitor to the buses and adding regulators).

Our goal for next semester is going to understand the effect of solar PV on our system. We will be adding the effect of solar in the IEEE 34 bus system.
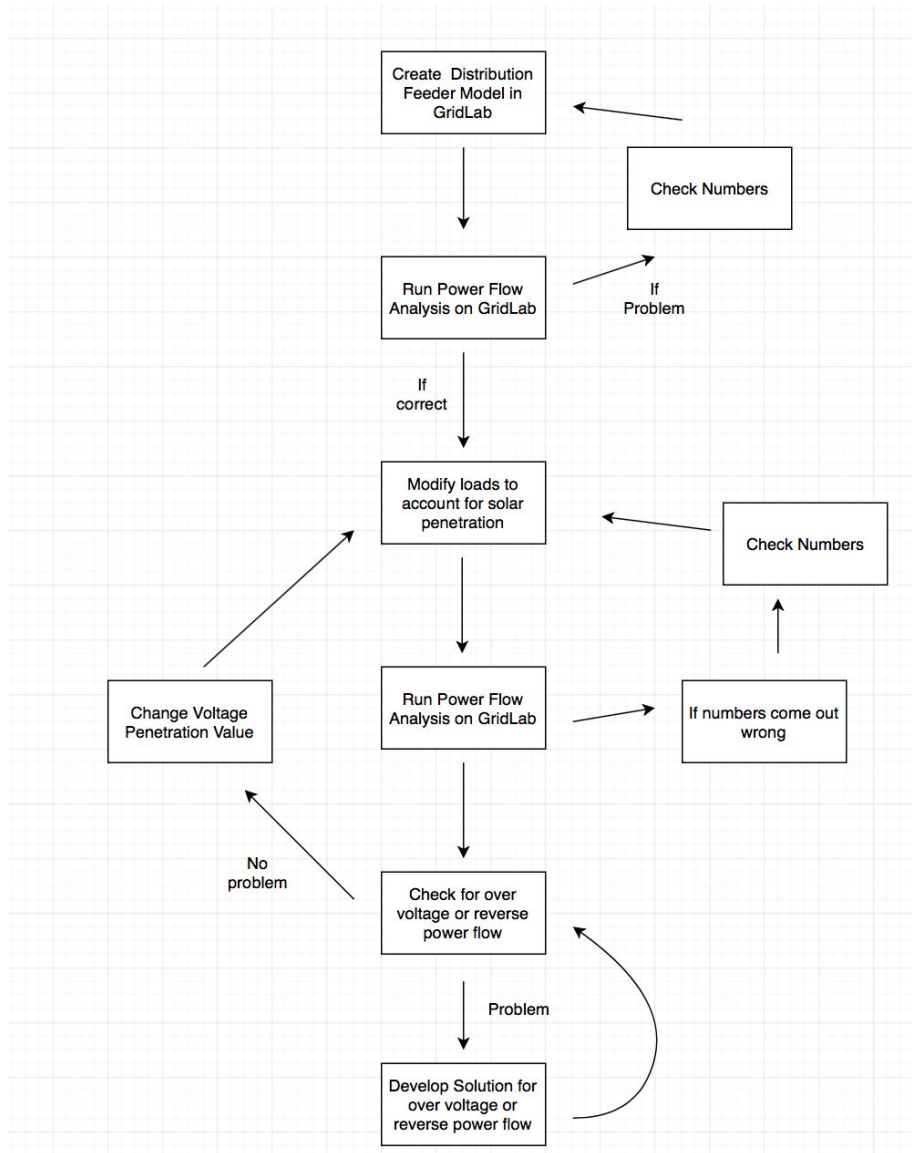

Diagram 1

3.6 Results

IEEE 4 Bus System:

The first major task for this project was to create IEEE's 4 node test system by hand to get accustomed to how distribution systems work. The primary parts of accomplishing this task can be seen in items 1 and 2 in the appendix, as they show the power flow computation by hand, followed by the further power flow iterations in MATLAB. The results of the team's power flow ended being the same as IEEE's solutions, as seen below:

```
V2_final =

  3×1 cell array

    {'7107.065901 < -0.338965'  }
    {'7140.107898 < -120.343857'}
    {'7121.230128 < 119.628481' }


V3_final =

  3×1 cell array

    {'2247.545312 < -3.688820'  }
    {'2268.453357 < -123.472028'}
    {'2255.898927 < 116.399331' }


V4_final =

  3×1 cell array

    {'1918.102614 < -9.063816'  }
    {'2061.022767 < -128.312256'}
    {'1980.865752 < 110.858013' }


I12_final =

  3×1 cell array

    {'347.717404 < -34.893182' }
    {'323.729241 < -154.156423'}
    {'336.745837 < 85.021750'  }


I34_final =

  3×1 cell array

    {'1042.456777 < -34.893182'}
    {'970.540266 < -154.156423'}
    {'1009.564019 < 85.021750' }
```

Connection	Gr Y - Gr Y
Node-2	
V1	7107/-0.3
V2	7140/-120.3
V3	7121/119.6
Node-3	
V1	2247.6/-3.7
V2	2269/-123.5
V3	2256/116.4
Node-4	
V1	1918/-9.1
V2	2061/-128.3
V3	1981/110.9
Current 1-2	
Ia	347.9/-34.9
Ib	323.7/-154.2
Ic	336.8/85.0
Current 3-4	
Ia	1042.8/-34.9
Ib	970.2/-154.2
Ic	1009.6/85.0

Figure 1: IEEE 4 Bus Voltage Profiles

IEEE 13 Bus System:

The IEEE 13 bus test system was done completely in GridLAB-D. Our first attempt to implement this system ended up failing, as the code did not account for the voltage regulator in the system requiring a clock that spanned enough time to allow the voltage regulator to make necessary judgements. Once the clock was working, the voltage profiles were able to be properly calculated. This allowed the team to begin making adjustments to see how capacitors and voltage regulators affected the system. This is relevant because with high PV solar penetration, the major problem is how it can cause voltage violations such as overvoltage and reverse power flow. Capacitors and voltage regulators can be used to adjust the voltages in the system to account for these violations. We saw from our results with removing and adding the capacitors and voltage regulator, that the capacitors were boosting the voltage where it was needed, and the voltage regulator had different impacts on the system, but generally boosted the voltage of the system. We graphed the results of these four different simulations, which can be seen below:
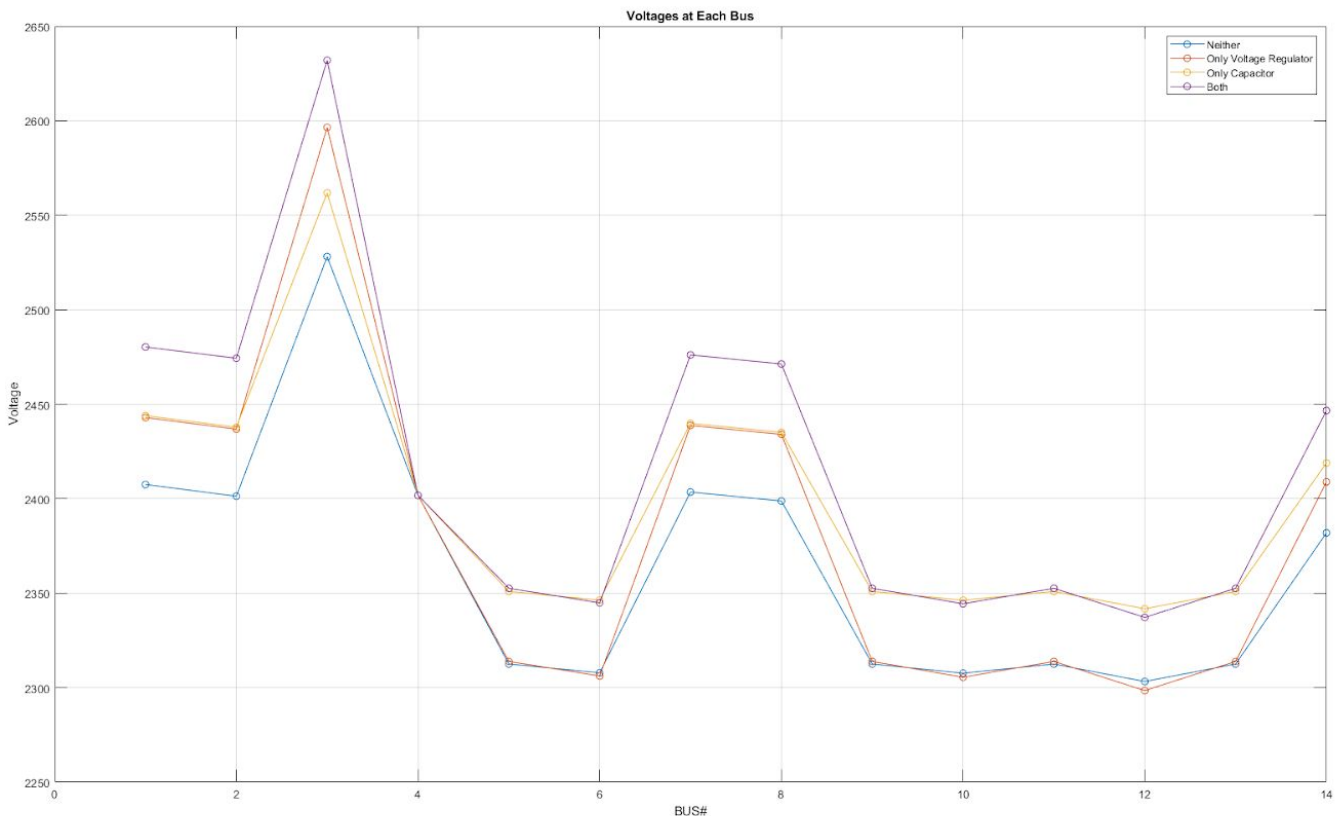
Figure 2: Voltage Profiles of IEEE 13 Bus System with Differing Components

3.7 Implementation Issues and Challenges

GridLAB-D is a new software for all of us. At the beginning of the semester the main implementation issue we faced was learning how to code in GridLab. When we started coding in the software one of the challenges we faced was to identify the right syntax and the right values for a given configuration of a component of the distribution system. We as a team intend to improve our skills on coding in the software over the break. We also have been unable to create a code in MATLAB that successfully writes distribution system data into a format that works for GridLAB-D. With a better understanding of how GridLab works, we should be able to write code that will reliably work in GridLab.

4 Closing Material

4.1 Conclusion

The purpose of this project is analyzing the effects of solar generation on utility distribution systems by using GridLAB-D. We will simulate an Alliant Energy-owned distribution feeder by incorporating a solar generator into the simulation for effect observation, and compare both local PV and residential PV systems to determine the best way to integrate solar energy into their distribution system. From the simulation, we can deduce potential problems of high permeability of solar power in the distribution system and try to seek applicable solutions. From what we have modeled so far, we have been able to make changes to the distribution system to get voltage levels to where they should be. This will be challenging with the variable effects that solar energy can create, but we should be able to find viable solutions to the problem that will be suitable for helping Alliant Energy add solar energy to their system.

4.2 References

W. Kersting, Distribution System Modeling and Analysis. Boca Raton: CRC Press, 2017
   p.141-390

Singhal, Ankit, and Venkataramana Ajjarapu. "Impact Assessment and Sensitivity Analysis of
   Distribution Systems with DG." *2015 North American Power Symposium (NAPS)*, 23
   Nov. 2015, *IEEE*)

5 Appendix

Item 1: IEEE 4 Bus By Hand Calculations


```
%Backward1
I34s = SL./V4;
I34 = conj(I34s);
V3 = V4 + ZL*I34;
I12 = (1/nt)*I34;
V2 = V3*nt + Zt*I12;
V1check = V2 + ZH*I12;
%Forward1
V2b = V1 - ZH*I12;
V3b = (1/nt)*V2b - Zt*I34;
V4b = V3b - ZL*I34;
V4bp = polarPrint(V4b);
```

```
%Backward2
I34bs = SL./V4b;
I34b = conj(I34bs);
V3c = V4b + ZL*I34b;
I12b = (1/nt)*I34b;
V2c = V3c*nt + Zt*I12b;
V1check2 = V2c + ZH*I12b;
%Forward2
V2d = V1 - ZH*I12b;
V3d = (1/nt)*V2d - Zt*I34b;
V4c = V3d - ZL*I34b;
V3cp = polarPrint(V3c);
```

```
%Backward7
I34gs = SL./V4g;
I34g = conj(I34gs);
V3m = V4g + ZL*I34g;
I12g = (1/nt)*I34g;
V2m = V3m*nt + Zt*I12g;
V1check7 = V2m + ZH*I12g;
%Forward7
V2n = V1 - ZH*I12g;
V3n = (1/nt)*V2n - Zt*I34g;
V4h = V3n - ZL*I34g;
V4cp = polarPrint(V4c);
```

Item 2: IEEE 4 Bus MATLAB Code