Impact of High Photovoltaic Penetration on Distribution Systems

PROJECT PLAN

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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 Introductory Material

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 Statement

Solar energy is making advances very rapidly in today's world due to lowering costs and increased demand for renewable energy. In Iowa, solar generation is seen as a potential source for power, to satisfy the needs of people. Adding solar energy can cause problems since the highest levels of PV penetration, which provides more power, occur at the middle of the day, when the load demand is not at its highest. The high amounts of power can cause voltage violations, such as overvoltage and reverse power flow. Alliant Energy is looking to add solar energy to one of their distribution systems, and they will need solutions to these problems in order to effectively implement solar energy into their system.

In this project, we will model an Alliant Energy distribution system using GridLAB-D, and will simulate the addition of solar energy to the system. We are going to analyze the impact of high PV penetration on Alliant's system and its effect on the efficiency of the power being delivered. In GridLAB-D, we will add different levels of solar generation to the system, and when overvoltage and reverse power flow occurs, we will implement a solution by making changes to the distribution system. The voltage profiles of the distribution system before adding solar, after adding solar, and after implementing our solutions will be shown in graphs to show the effectiveness of our solutions.

1.3 Intended Users and Intended 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.

1.4 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.

1.5 Expected End Product

The expected results of our project are listed below and are expected to be completed before the end of the second semester.

- Simulate an Alliant Energy-owned distribution feeder while incorporating solar PV generation into the simulation to observe the effects.
- Identify voltage violations due to high PV penetration.
- Compare community PV generation and residential PV generation to determine where to best incorporate solar power into the distribution system.
- Find solutions that will prevent future problems relating to solar PV generation on the Alliant Energy system.
- The voltages of the loads need to be between 0.95 and 1.05 per unit, and our solutions need to provide voltage profiles that meet those standards.

2 Proposed Approach and Statement of Work

2.1 Objective of the Task

Our task is to simulate an Alliant Energy system, and determine methods of averting the problems that come with high PV penetration from solar energy. Some of the main complications that can arise due to high PV penetration are reverse power flow, and overvoltage. In researching its impact on distribution systems, we can find potential solutions to these problems. We will present these solutions to Alliant Energy, along with relevant graphs that display the effectiveness of our changes to the distribution system.

2.2 Functional Requirements

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 for 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.

2.3 Constraints Considerations

- Profitability - The team's recommendations for implementing solar energy into an Alliant Energy distribution system have to be financially justifiable. The application of the solutions has to mitigate enough energy loss to validate creating the infrastructure necessary for them.
- Current Infrastructure - The team's solutions for adding solar energy to an Alliant Energy distribution system has to account for the infrastructure that is already in place. Unless the findings are significant enough to rationalize rebuilding components of the distribution system that are already in place, the recommendations have to account for infrastructure already in place.
- Climate - In Iowa, the climate isn't ideal for solar energy. The team's findings have to be accountable for all of the seasons.
- Application - The team will be looking into solar energy at both the community and residential levels. The solutions for applying solar energy to an Alliant Energy system has to show the benefits/disadvantages at both levels for each recommendation.

- Standards - For this project we will be following ANSI and IEEE standards. The ANSI standard is that the voltage levels need to be between 0.95 and 1.05 per unit. We will also be following IEEE ethics standards. The primary points in IEEE's code of ethics are number 2, which states, "to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist," and number 3, which states, "to be honest and realistic in stating claims or estimates based on available data" (IEEE). The team needs to provide data for Alliant Energy that is honest and effective, as it will affect the general public. We also need to keep in mind all of their code of ethics, as they are a strong basis of how we should approach our work as engineers.

2.4 Previous Work And Literature

As problems with adding solar energy are widespread, there has been a lot of documentation on this issue. The California Duck Curve is a widely used concept in solar energy that shows how overvoltage can occur around midday due to the difference between load and high amounts of PV penetration. The sentence in the article by the Department of Energy, "Another challenge with high solar adoption is the potential for PV to produce more energy than can be used at one time, called over-generation," does well to summarize the problem we are facing (Confronting). For understanding the workings of distribution systems, the team will make use of the textbook Distribution System Modeling and Analysis by Kersting. At this level of research, this textbook will be able to supply the basis of the different aspects of distribution systems. A previous team has also done the same project, and their conclusions will be a good starting point for considering solutions to problems that occur from solar generation, as mentioned previously.

2.5 Proposed Design

There are two main components to this project. The first is designing the distribution feeder as it currently is using GridLAB-D. The second component is analysing what happens to the system when different percentages of solar PV penetration are added to the system. The first component involves entering every node, distribution line, transformer, and any other parts of the distribution system into GridLab exactly as it appears today. This will be done using some MATLAB coding to convert the distribution data from spreadsheets to GridLab. We will research instances where distribution system data has been converted into a coding format, and potentially use an alternative coding language such as C or Python if they are more useful. The second component involves adding different amounts of solar penetration at different parts of the system. The team will identify instances where voltage violations have occurred and make alterations such as adding voltage regulators and capacitors to adjust the voltages to a more ideal level. We will be experimenting with both community and residential solar generation, and seeing what happens when the sources of solar power are in different locations. Using the results we find from these experiments, we will implement solutions to the problems that arise from the solar generation being added to the system. We will also create general guidelines for future additions of solar energy according to the most common solutions used.

2.6 Technology Considerations

Before starting this project we had to decide what software to model the distribution system on. The two main options that were considered by the research assistants for this project were GridLab and OpenDDS. Both programs were open source and free, however, it was decided that GridLab would be easier to model the distribution system and was easier to use with MATLAB. GridLab also has a much better technical support wiki, which makes it easier to learn.

2.7 Safety Considerations

There are very few safety concerns for this project. All of the project will be conducted using either the group's personal laptops or Iowa State's computers. This has no human safety issues. There is the possibility of getting viruses when downloading GridLab software but it is a very low risk and we will be taking precautions to prevent it.

2.8 Task Approach

We will be following the path below while working on this project. It gives us a good way to come up with solutions to design problems that we will face.

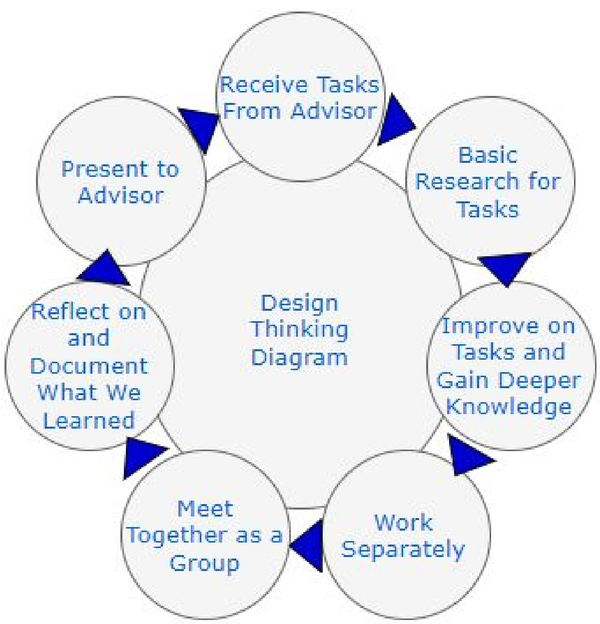

Figure 1: Task Approach

2.9 Possible Risks And Risk Management

One risk that we have to deal with is our lack of experience dealing with solar generation in a distribution system. We are learning about this topic as we go along but lack the practical experience associated with this. We also only have one member attending EE 455, which is the introduction to power distribution course, which means much of what we learn is out of a textbook. We have also never used GridLab previously, which could slow down how fast we are able to implement the distribution system. It may also take time to come up with solutions to cases where voltage violations occur, as designing a solution to this is not something we have experience with.

2.10 Project Proposed Milestones and Evaluation Criteria

Our first project milestone is solving the IEEE 4 node system by hand. This is important so that we can understand when our GridLab simulation is having problems. We have the expected results from IEEE to check our work. We will then implement the IEEE 13 node test system in GridLab to get more familiar with the software and get a better understanding of how voltage regulators and capacitors impact a system with more buses. Our third milestone will be to implement the distribution system in GridLab, using a combination of our own code and spreadsheet data from Alliant. We will test this by simulating the system and getting the actual values at all of the nodes. Our last milestone will be adding increasing amounts of solar generation to the system, analyzing the results, and designing solutions when problems occur.

2.11 Project Tracking Procedures

We will be using GitLab to keep track of our coding for the distribution system model. We will also be meeting as a group once or twice a week, as well as meeting with Professor Ajjarapu once a week.

2.12 Expected Results and Validation

The desired outcome of this project is to have a modeled distribution system in GridLab that we can use to simulate the effects of solar generation on the system. We also expect to come up with solutions that can solve problems from solar generation as outlined in section 2.1. We will know if our solutions work by implementing them into our test system and seeing if it works as we expect. We can also check if our solution is acceptable by making sure there are no voltage violations in the system. The voltage level will also be between 0.95 to 1.05 per unit, which is the ANSI standard.

2.13 Test Plan

All of our testing will be done using GridLab and MATLAB. We will be making sure all voltages are within ANSI standards. For each test we will first need to find the voltage profiles of all the loads in the system, as well as all transformer, line, and other values in the system.

Test Case 1: The first test we will be doing is to see if the distribution system is modeled correctly. We will be creating this system with a combination of our own GridLab code and transferring data from an Alliant spreadsheet using MATLAB. We will be measuring voltage levels and if it matches the values of the actual system we will know we have modeled it correctly. Once we have done this we can then add instances of solar energy to the system.

Test Case 2: We will be adding solar power to the system and measuring the voltage at each node by running a power flow solution. If the voltage levels are within ANSI standards and there is no reverse power flow we know that the system as is can handle that amount of solar generation. The voltage level will be between 0.95 to 1.05 per unit, which is the ANSI standard. If there are any problems we will then design a solution and run the power flow solution with it implemented.

Test Case 3: Here we will be testing the solutions 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 Project Timeline, Estimated Resources, and Challenges

3.1 Project Timeline

Semester 1 - 8/29/2018 - 1/16/2019

Task	Task Title	Start	End	8/29	9/5	9/12	9/19	9/26	10/3	10/10
1	Study Distribution Systems and Solar Power	8/29	9/5							
2	Solve 4 Node Distribution System by Hand	9/5	9/26							
3	Integrate Voltage Regulator in 4 Node System	9/26	10/17							
4	Implement 4 Node System in GridLAB-D	9/26	10/17							

Task	Task Title	Start	End	10/17	10/24	10/31	11/7	11/14	11/28	12/5
5	Implement 13 Node System in GridLAB-D	10/17	11/7							
6	Summarize Research and Present Findings	11/7	11/14							
7	Write MATLAB code to convert data	11/14	1/16							
8	Prepare for next semester	12/5	1/16							

Figure 2: Semester 1 Gantt Chart

The basis of the project for the first semester will be research into distribution systems while getting an idea of how high PV penetration impacts a distribution system. Figure 2 shows the general schedule of the tasks for the first semester. The team studied concepts pertaining to distribution systems, and solved some relevant examples including the power flow of IEEE's 4 node test system. After becoming comfortable with how distribution systems work, the team will implement distribution systems using GridLab, starting with the original 4 node system. The team will then move on to working on more complex distribution systems in GridLab. This will start with solving the power flow for the IEEE's 13 node system in GridLab, which will introduce the team to working with voltage regulators and capacitors in a distribution system. To show how far the team has come in their understanding of distribution systems, a presentation will be given to the advisor. In order to construct larger distribution systems, the team will begin working more in MATLAB to write code that will take distribution system data and write it to a text file in GridLAB-D's format.

Semester 2 - 1/16/2019 - 5/1/2019

Task	Task Title	Start	End	1/16	1/23	1/30	2/6	2/13	2/20	2/27
1	Implement IEEE 34 Node System in GridLAB-D	1/16	1/30							
2	Add Solar Energy to IEEE 34 Node System	1/23	2/6							
3	Build Alliant Energy Distribution System	1/30	2/20							
4	Add Solar Energy to Alliant Energy System	2/20	3/6							
Task	**Task Title**	**Start**	**End**	**3/6**	**3/13**	**3/27**	**4/3**	**4/10**	**4/17**	**4/24**
5	Document High PV Penetration Effects	3/6	3/13							
6	Adjust Alliant System and Document Solutions	3/13	4/3							
7	Analyze Solutions	4/3	4/24							
8	Compile and Present Solutions	4/24	5/1							

Figure 3: Semester 2 Gantt Chart

For the second semester, the team will be working with Alliant Energy to simulate one of their distribution systems. The first few weeks of the semester, the team will build the IEEE's 34 node test system using IEEE's system data and MATLAB to verify that the MATLAB code is able to effectively convert the distribution system data into GridLAB-D's format. Once the system is modeled in GridLab, the team will begin adding solar power at different parts of the system. Where voltage violations occur, the team will find solutions to make the IEEE 34 node system stable. Upon finding acceptable solutions for the IEEE 34 node system, the team will build the Alliant Energy distribution system. Similarly to the 34 node system, the team will add solar energy to the Alliant Energy system and identify the effects from the addition of high PV penetration. The team will adjust variables like substation positions, voltage regulator and capacitor placements, and voltage levels. We will analyze our solutions, and make certain that all of the solutions found are optimal. We will compile all of the solutions together, and make presentable graphs that display the effects that our changes have made to the system for Alliant Energy.

3.2 Feasibility Assessment

For the first part of the project, the team will be doing research on solar power and distribution systems, and getting comfortable with understanding distribution systems in using GridLab. During this time there will not be many challenges as the team is solving problems that already have solutions, and will receive guidance from the team's advisor. When the team begins research into how high PV penetration impacts the distribution systems, there will be more challenges. The team will have to have become adept at understanding all that effects distribution systems, and separate outlying factors from how the excess solar energy is affecting the system. In finding methods to avert the impact of high PV penetration, the team will be trying to fix problems that have been difficult for the world's engineers to find an answer to. The known solutions to handling the excess energy, however, will help make the work more manageable by being able to apply them to our own distribution systems.

There are some specific problems we may run into regarding Alliant's distribution system. The first challenge will be converting Alliant's distribution system from Synergi to GridLab. Synergi is a high-end power system software that is outside of the team's price range. Data will have to be received in Synergi's format, and then converted into the text format of GridLab. To do this the team will have to write code to remodel all of the data without error. This is because there will be thousands of lines of GridLab format code, which will have to be broken into different notepad files, as text files can only hold 10,000 lines. Once the system is modeled in GridLab, the team will have to go through those thousands of lines to make adjustments to the distribution system, which will be challenging for a four-person team.

We believe we will be able to complete this project before the end of the semester. The most difficult parts of this project will be initially implementing the system in GridLab and then learning how to best implement solutions to problems that occur when solar is added to the system. Our stretch goals are to test the system at different times of the year rather than just the worst case scenario, as well as looking into the profitability of any of our proposed solutions.

3.3 Personnel Effort Requirements

The table below shows all of the tasks that need to be completed in order to do the project. We will be spending most of our time using GridLab working on the Alliant Energy distribution feeder.

Task	Description	Time(hours)
General Research	Research duck curve, distribution systems, and residential and community solar generation.	20

4 Node System	Solve by hand IEEE 4 node system with and without voltage regulator, shunt capacitor, and in per unit.	60
Learn GridLab	Using GridLab, solve IEEE 4 node system, IEEE 13 node system, and IEEE 34 node system.	100
Implement Distribution Feeder in GridLab	Using GridLab, model Alliant Energy distribution feeder.	80
Research High Solar Penetration	Using distribution feeder modeled in GridLab, research what happens when high amounts of solar PV generation is added to the system. Research for both residential and community solar cases.	100
Identify Solutions	Based on the research on high solar penetration in the distribution system, identify guidelines or solutions to prevent problems that occur with high solar penetration	100
Prepare Presentations	Throughout the class we will be preparing presentations for Professor Ajjarapu	30

Table: Primary Tasks

3.4 Other Resource Requirements

As of now, there are not many resources required for the project. All of the team member's are in possession of the textbook *Distribution System Modeling and Analysis* by Kersting, which is relevant to the distribution systems we will be working with. The work will primarily be done in using the software GridLab and MATLAB.

3.5 Financial Requirements

This project uses a number of open source software programs to model the system. All of the programs we are using are free of charge or covered by using a student license. We are using GridLab and MATLAB for this project.

4 Closure Materials

4.1 Conclusion

In this project, we have done the voltage and current calculations by hand for the IEEE 4 node system in order to understand basic principles of power flow. On this basis, our team is going to assess the impact of high penetration solar power generation on distribution feeders and the power supply to consumers. High penetration solar power energy can cause problems such as reverse power flow and over-voltage in the distribution process. Our mission is to simulate an Alliant Energy system and determine how to avoid problems caused by high PV penetration. In examining the impact on distribution systems, we can find solutions for those potential problems. We will use open-source GridLab software to simulate the effectiveness of integrating high PV penetration impacts into the distribution system, and determine the most appropriate changes to make to the system to account for any voltages. From various attempts and mistakes, we will find the most reliable way to supply energy.

4.2 References

"Confronting the Duck Curve: How to Address over-Generation of Solar Energy." *Office of Energy Efficiency and Renewable Energy*, www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy.

IEEE. (n.d.). IEEE Code of Ethics. Retrieved November 28, 2018, from https://www.ieee.org/about/corporate/governance/p7-8.html

Summit, Nathaniel, et al. *Impact of High Photo-Voltaic Penetration on Distribution Systems*. pp. 1–25, *Impact of High Photo-Voltaic Penetration on Distribution Systems*.