115kV / 34.5kV Solar Power Plant Substation Design

PROJECT PLAN

Team 26

Client: Black & Veatch

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MW: MegaWatts

kV: KiloVolts

GCR: Ground Coverage Ratio

NEC: National Electrical Code

1 Introductory Material

1.1 Acknowledgement

The senior design team would like to thank Cole Beaulieu and Emily Neumann, employees of Black & Veatch, for their time and willingness to oversee the project and providing the team with the tools necessary to successfully complete the project. The team would also like to thank Dr. Ajjarapu for his time and expertise, serving them as the faculty advisor. This project has been a great learning experience, and the team would like to thank the Department of Electrical and Computer Engineering at Iowa State University for this wonderful opportunity.

1.2 Problem Statement

A steady increase in the use of renewable energy for larger scale power generation has been seen in recent years. Furthermore, the cost of producing renewable energy has decreased over the years and standards pertaining to renewable energy have been improved. As a result, many power companies are expanding into renewable energy and exploring more environmental-friendly energy sources.

General Problem Statement

Black & Veatch has tasked the senior design team with designing a 60 MW solar power plant and a 115 kV/34.5 kV substation. Based on their research, the senior design team has chosen Estancia, New Mexico to be the location of the solar power plant and substation.

General Solution Approach

The senior design team has split the project into two smaller design tasks. The first task is to design the solar power plant. The team will need to do the following to accomplish the first task:

1. Research for a location that receives a high amount of solar radiation.
2. Use the Array Parameter Tool provided by the client to design the solar plant while meeting the specifications desired by the client.
3. Create a layout of the solar power plant.
4. Do voltage drop calculations and conductor sizing.
5. Create a wiring diagram of the solar power plant.

The second task is to design the substation based on the single line diagram that was provided by the client. The team needs to do the following to accomplish the second task:

1. Create the key protection diagram of the substation based on the single line diagram and the project scope document provided by the client.
2. Create AC drawings.
3. Create relay diagrams for protection and control.
4. Create three-line drawings.

1.3 Operating Environment

The power plant is designed to be built in Estancia, New Mexico to maximize sunlight exposure and power generated by the plant. The main concern with placing it in this state is the dusty conditions, which might cause an increase in maintenance to wipe excess dust off the solar panels. There have been other weather concerns, but they are not severe enough to dismiss the location. Both the solar plant and substation are designed to withstand harsh weather conditions, and safety factors concerning employees and the public are also implemented in the design.

1.4 Intended Users and Intended Uses

Because the team is designing a utility-scale solar power plant and a substation for a company and not the end users, who are those that are connected to the opposite end of the grid, the team will utilize all the specifications that have been provided by the client. The team understands that the electrical power generated could be used directly and indirectly. The appropriate way to ensure that the project is successful is by doing extensive research on the subject matter, accurate calculations, and following the specifications set by the client.

1.5 Assumptions And Limitations

Assumptions

- The solar power plant and substation are to be built in the United States of America. Therefore, they are designed based on the national standards and codes. Other countries may have their own codes.
- Locations in other parts of the world have different codes and standards from the ones that are implemented in the design of the power plant and substation.

Limitations

- Since the solar power plant and substation are designed to be built in the United States, the same blueprint or design may not be used in other countries because different countries have their own national codes and standards.
- The client did not provide a budget for the project. Because of this, budgeting and making financial decisions when it comes to choosing solar power plant components and equipment is difficult. However, the team counters this limitation by making cost-effective decisions.

1.6 Expected end product and other deliverables

The project is very complicated as it involves designing two electrical facilities: the solar power plant and the substation. The list below shows the deliverables that need to be completed by the end of the second semester.

- Determine location for solar power plant and substation
- Solar power plant layout
- Solar power plant wiring diagram
- Solar power plant voltage drop calculations
- Solar power plant conductor sizing

- Feeder drawing
- Collector drawing
- Substation key protection diagram
- Substation three-line diagram
- Protection and relays schematics
- Man-hour budget, schedule and cost estimates

In the first semester, the focus of the project is to design the solar power plant and complete the deliverables pertaining to the plant. This includes creating the layouts and doing the voltage drop calculations and conductor sizing. The key protection diagram is also to be completed in the first semester. The focus of the second semester is to create the three-line diagram of the substation and the protection and relays schematics. The team will also optimize and improve the diagrams and schematics made in the first semester.

1.7 Project Description

The team has found a great location in Estancia, New Mexico that receives high amount of solar radiation. The size of the location is about 540 acres, which is more than enough for the solar plant and substation. The remaining unused land will be preserved for possible solar plant or substation expansion in the future.

Solar Plant

The solar plant will be made up of about 117 acres of land. It will be made up of:

- 238,032 solar panels with a rating of 325W per panel
- 36 inverters with a rating of 1666 kW.
- 792 combiner boxes with a rating of 1000 V DC.

The total area of the plant will be approximately 244 acres. The deliverables related to this are:

- AutoCAD designs showing the layout of the panels and other components that will make up the solar plant. The importance of these drawing is that they show the wiring of things and positioning of components. Creating this schematic for our client helps us to perform power flow analysis on our plant and detect possible causes of concern. An estimated delivery date for the AutoCAD drawing relating to the solar plant is October 20, 2018.
- Documents detailing the calculations used to determine currents and voltages in the wires through the plant. These calculations will be used to check the accuracy of the design by checking that the design complies to the National Electric Codes.
- A detailed man-hour budget showing the number of hours spent by the team each week as well as the charge for all hours spent in the first semester. This deliverable is also valid for the second semester.

Substation

The substation design will be made up of:

- The one-line diagram
- The key protection diagram

- The three-line diagram
- Protection and controls schematics

For the first semester, the main task is to create the key protection diagram, which is a simplified notation representing a three-phase power system. It will help us perform power flow studies and determine where electrical elements such as circuit breakers, transformers, and conductors are located. The estimated delivery date for this has been set to be November 29, 2018.

2 Proposed Approach and Statement of Work

2.1 Objective of the Task

The end-product of the senior design project is to design a 60 MW solar power plant and a 115 kV/34.5 kV substation. To successfully conduct this project, a list of goals will need to be accomplished:

- Efficiently manage the scope of the project
- Provide documentation and justification for the design aspect of the project
- Follow the standards set by the NEC for all components of the project, shown in Table 1 below

NEC Code	Description	How to Check	Design Steps
Article 310.10	Discusses the uses of conductors under different conditions	Ensure that we select the right conductors for our conditions	Choose wires that satisfy our conditions and implement them into the design
Article 310.15 and table 310.15	Defines ampacities for different conductors	Using this information in the voltage drop calculations	Applying values from calculations into conductor sizing
Article 300.50 and Table 300.50	Discusses acceptable depth to bury conductors	Using this information during to plan wiring	Design a plant layout that applies this information
Section 310.120	Explains necessary markings for different conductors	Using this information to choose the right type of conductors	Choose wires with the right markings

Table SEQ Table * ARABIC 1: The table shows the NECs used in the design of the project.

2.2 Functional Requirements

For this project, we are required to have knowledge of power systems and solar plants, as this will be the basic information needed for our designs. By utilizing this knowledge and doing further research we will be able to meet the following functional requirements:

- All our design schematics will be created using the CAD drawing tool
- Microsoft Word: Documents and simple diagrams will be drafted in this environment
- Microsoft PowerPoint: This software will be used for weekly presentations to the client/advisor
- Bentley View: This program allows us to view AutoCAD schematics of electrical systems that will be provided by the client
- Array Parameter Tool: A tool provided by the client to help us size the solar plant according to client specifications
- Google Hangout: This will be used to have weekly video conferences with the client

2.3 Constraints Considerations

Seeing that the students on the team have limited exposure to substation design, many things that they will encounter during the course of the project will be foreign to them. The adverse effects of the learning curve will be seen when students use AutoCAD as many of them have no prior knowledge of the program.

All the schematics will be in compliance with the National Electrical Code (NEC) and the Institute of Electrical and Electronics Engineers Power, Switchgear, Substations & Relays Standards Collection.

2.4 Previous Work And Literature

There are several existing projects that are similar to ours, and one of them is the North Star Solar Project, which is a 100 MW solar farm in Saint Paul, Minneapolis integrated by MISO. This solar farm is the largest solar facility in the Midwest and sells its output to Xcel Energy. Even though solar farms have been built in the MISO region before, North Star is the first that can trade its electrical output in the energy market. The following bullet point list more details about the project.

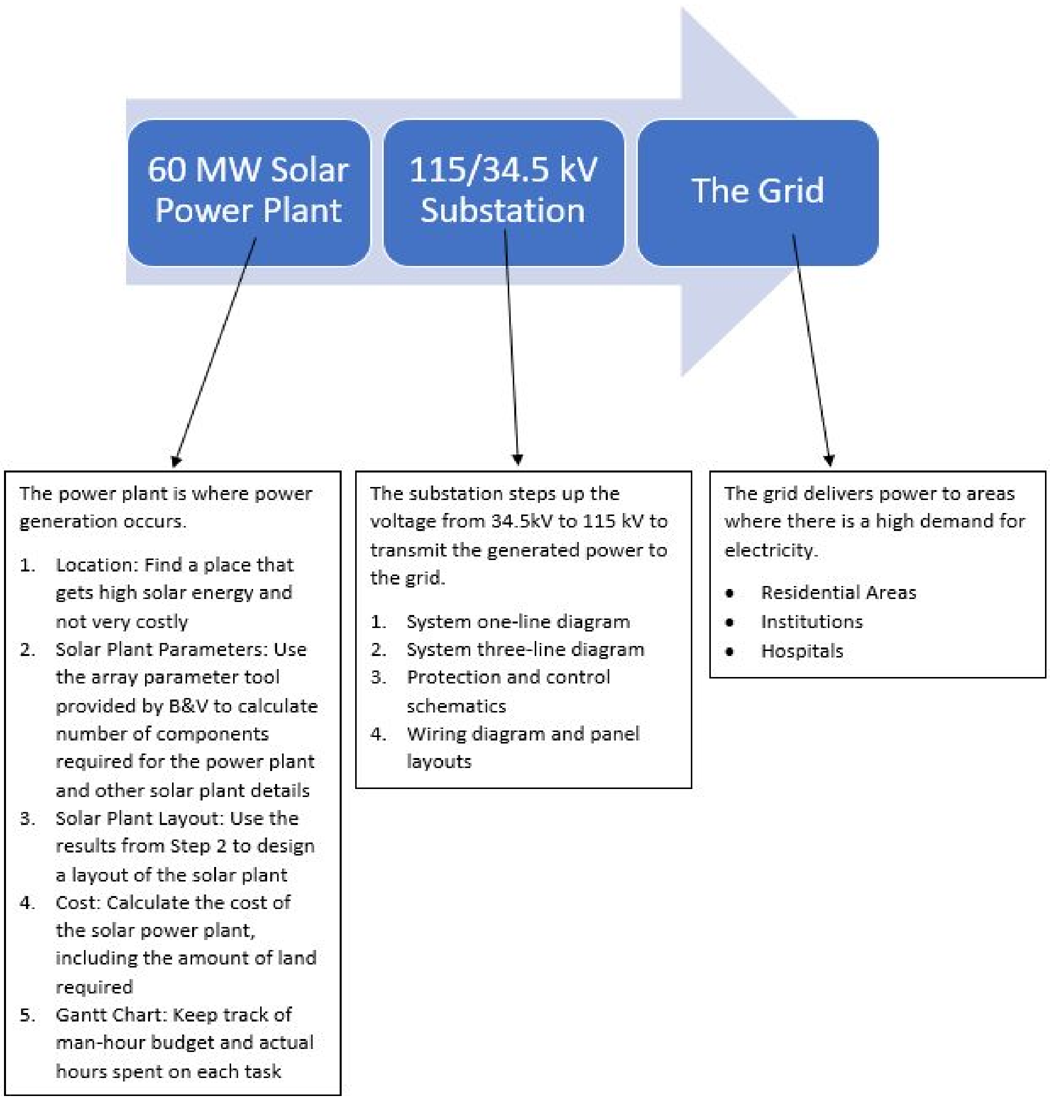
- Located in Saint Paul, MN
- 100 MW of solar PV capacity (440,000 solar panels)
- Approximately 800 acres of agricultural land
- Single axis tracking technology to maximize production
- Grid connection at the Chisago County substation 115kV

Our project is different from MISO's in the location, the amount of power output, the project size, and the rack system. Out of all the differences between our power plant and MISO's, the one that plays the biggest role in the overall output of the plant is the tracking system. MISO uses the single axis tracking system, which means that the solar racks rotate according to the sun, tracking it to maximize production and capture as much solar radiation as possible. This type of rack system is the best in the market as it maximizes production, but it is very expensive and high maintenance. However, MISO decided to use the tracking system instead of a fixed rack system to compensate for the lack of solar radiation there is in the Midwest regions. Our solar plant uses a fixed rack system, which means that the solar racks will face the Sun at a certain tilt angle, depending on the latitude of the location. The fixed rack system is cheaper but does not track the sun. Fortunately, the location that we chose for our power plant receives high solar radiation. Therefore, using the tracking system would be unnecessary and a waste of resources. As a result, we decided to use the fixed rack system.

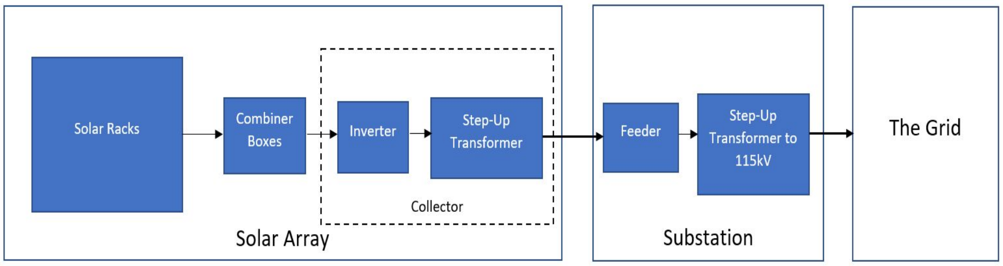
In May 2016, there was a senior design team that did a similar project like ours but had different project parameters, and they did not have to calculate the voltage drop of the entire PV system. Not having to calculate the voltage drop is a disadvantage because in order to meet the specifications set by the National Electrical Code (NEC), the PV system has to have a voltage drop of no more than 5%. Furthermore, the previous senior design team had a string voltage of 1500 VDC while our string voltage is 1000 VDC. An advantage of this is that bigger string voltage allows more panels to be connected in series. This indicates that more panels can be placed on a solar rack, which means that less amount of land would be required to build the solar plant. Another difference in project specifications is the maximum allowed current through a combiner box. The previous senior design team a current of 400 A, while our maximum allowed current is 250 A. An advantage of having a larger allowed current is that a combiner box would be able to take in more current, which means fewer combiner boxes would be needed for the solar plant. Financially, it is always better to need the fewer amount of resources as this would reduce the total cost of the project.

2.5 Proposed Design

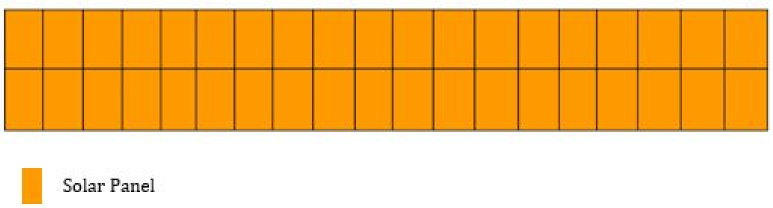
Through our research and by looking at similar projects that have been done previously, we now understand that a solar power plant produces a low voltage and a high current power, which would result in a high amount of power loss during transmission. Therefore, a power substation needs to be connected to the solar power plant before transmission to step the voltage up to a higher voltage level, lowering the current level, which would significantly decrease the power loss during transmission. By following the client's design specifications and requirements, we will be proposing the following design process:

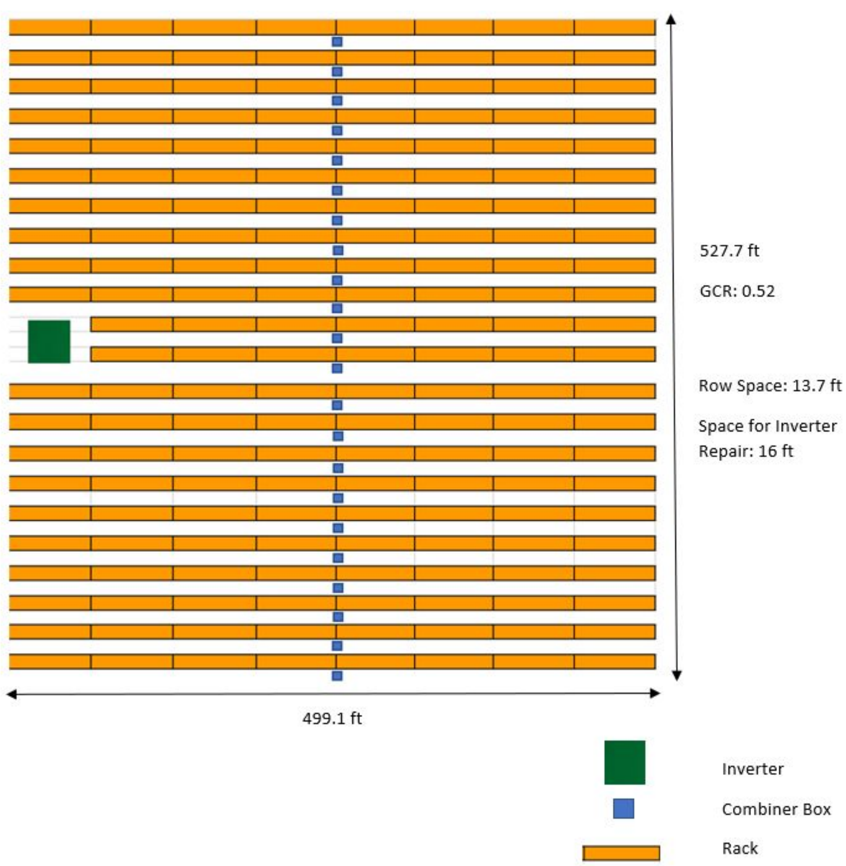


After figuring out more details about the solar plant and substation, we created the block diagram of our project, as shown below, to show the power flow form generation all the way to transmission at 115 kV.

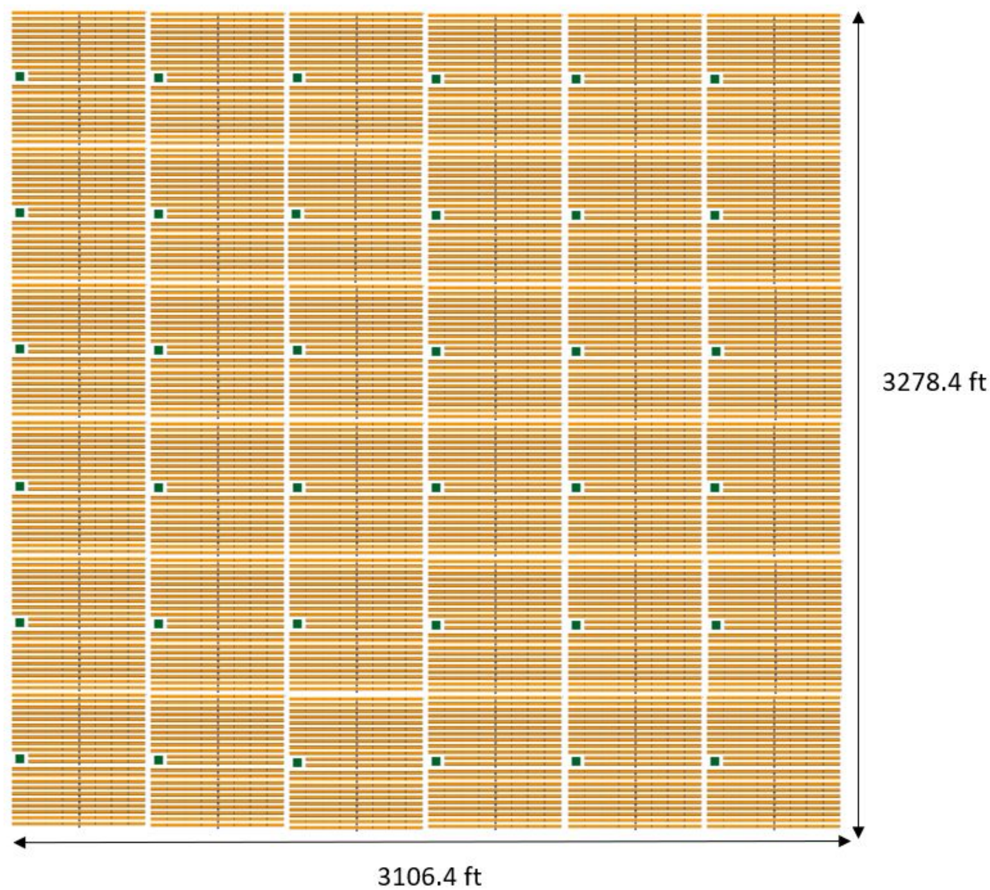


Using the Array Parameter Tool provided by the client and their desired specifications, we created the layouts of a single solar rack and a single solar plant array, as shown below in Figures 3 and 4, respectively.

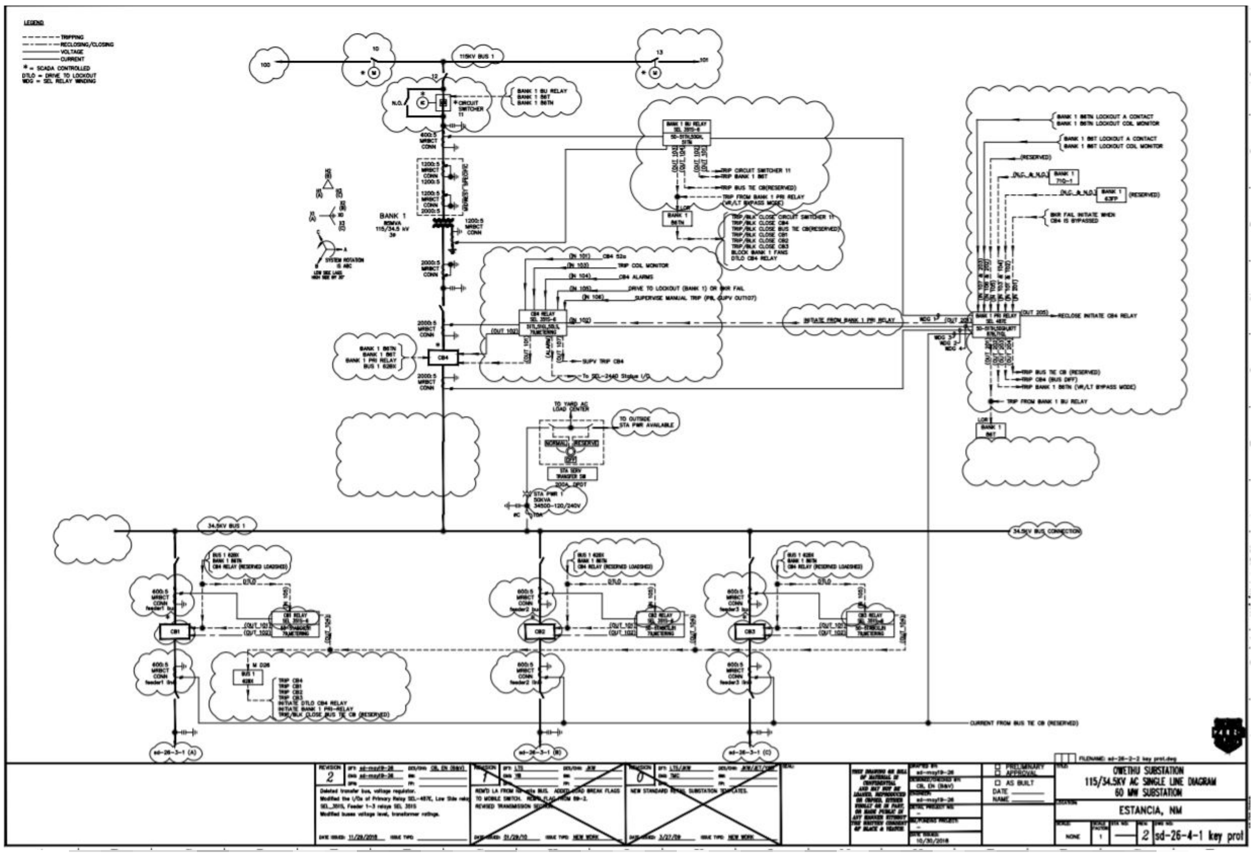




Using the single array design, we created a layout of our power plant, as shown in the figure below. The power plant provides an AC output of about 60 MW after converting the power from DC to AC by running through the power inverters with inverter load ratio (ILR) of 1.3.



After we finished the solar plant aspect of the design, we moved on to the substation aspect by creating the key protection diagram based on the single line diagram provided by the client. The key protection diagram shows the single line diagram of the substation and how the different components, including the relays, circuit breakers, and transformer are connected.



2.6 Technology Considerations

The process of deciding the inverter load ratio (ILR), also known as the DC to AC ratio, that we want to use for our solar power plant design is a trade-off decision between total energy losses versus the design stability.

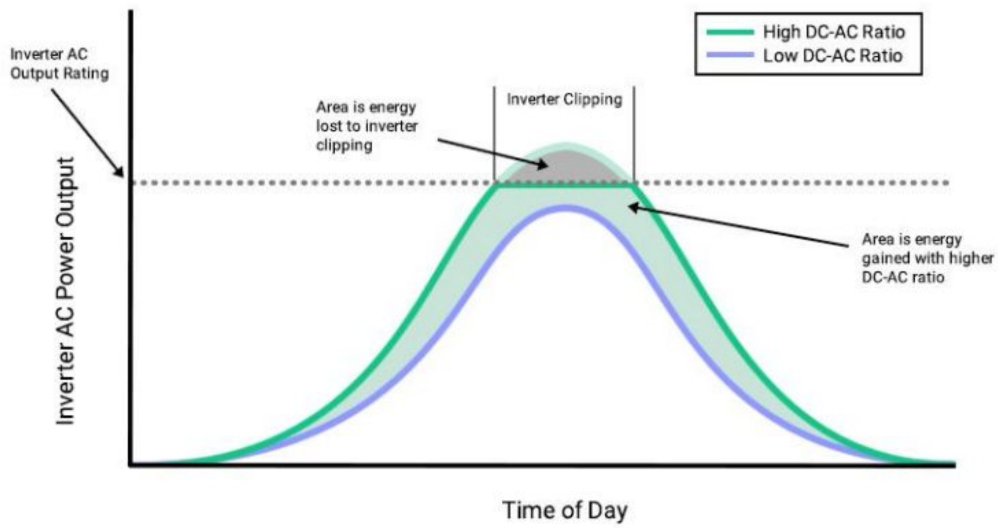


Figure 7: Graph of Energy Production or AC Output vs Tine of Day

Figure 7 indicates the differences between solar power plant that has a lower ILR (or DC-AC ratio) versus power plant that has a higher ILR. A lower ILR has lower power losses because it utilizes most of the power generated by solar panels even under full standard condition while a higher ILR will cause more power losses due to clipping at the inverter AC output rating.

The reason that higher ILR is used is that it is rare that solar power plants work under full standard conditions. With a higher ILR, the solar power plant will provide a more stable and consistent AC power output even when it is not under full standard conditions. Since we are more in favor of designing a solar power plant with a much stable output, we set it to a slightly higher ILR (approximately 1.3) so that the power plant will generate about 60 MW of power under most conditions.

Another technological consideration that we will be taking in the process of designing the solar power plant is the types of solar panel that we should choose. Two common types of solar panels are monocrystalline and polycrystalline. A monocrystalline solar panel has a higher silicon purity and a higher efficiency level because it uses only the purest silicon material in the manufacturing process. On the other hand, a polycrystalline solar panel has a lower silicon purity and a lower efficiency level because it utilizes all silicon materials in the manufacturing process. Despite the fact that the monocrystalline solar panel provides a better efficiency level, it is a lot more expensive as compared to the polycrystalline solar panel (about 50% higher in price) while the efficiency level of polycrystalline solar panel is only about 1-3% lower than the monocrystalline solar panel. Therefore, we have chosen the polycrystalline solar panel in our design.

2.7 Safety Considerations

<u>Danger of Electric Shock</u>

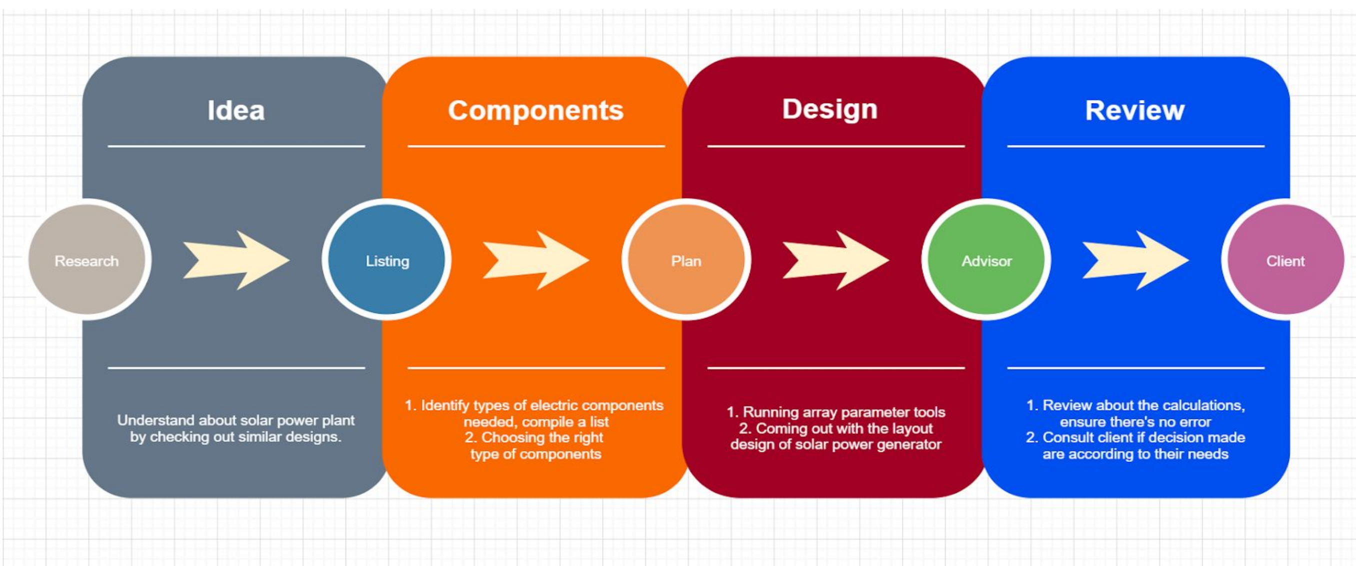
Electric shock is the biggest safety concern when it comes to building power generator and substations because we are dealing with high voltage and high power designs. The lowest voltage that could cause a person's death is only around 60 volts. It is important to know that each solar panel we use has an output voltage of about 46 volts, so just two solar panels could be fatal to a person. Our design consists of hundreds and thousands of solar panels, it could probably kill a person in seconds.

<u>Danger of Fire</u>

Fire usually happens when a connection wire hits an object such as trees or grass. Therefore, it is important to make sure all the connected cables are conductors are insulated and organized well to avoid hitting any object.

2.8 Task Approach

In the process of designing the solar power plant, we will be following the flowchart below:



2.9 Possible Risks And Risk Management

The inverter the client would like us to use has unfortunately been discontinued by the supplier. As such, we had difficulty finding the price of the inverter. To calculate the total cost of the project, we made estimations that we have no way of validating.

We were unsure of whether we would be purchasing the rack system from a supplier or designing one ourselves. If we design it, the project will be delayed since we didn't foresee this at the beginning of the project.

To find a good location for the solar power plant and substation, we need to do research online because we are unable to travel around the United States to find a location. However, using google earth to find a location of at least 244 acres will be difficult as pictures differ from actual view. Besides, we do the project for a year, and the land can change within one year.

2.10 Project Proposed Milestones and Evaluation Criteria

Research:

- Location of solar power plant and substation
- Solar power plant parameters
- Justification of components and designs used
- Study the documents sent by the client

Rough draft of design:

- Look appropriate.
- Approval from the client.
- All members can understand the draft.

Final design:

- Everything is correct base on calculation.
- Approval from the client.
- All members can understand and read information from the design draft.

Finish:

- All design drafts, data, reports, and research are organized.

2.11 Project Tracking Procedures

Using Gantt chart to plan up what we will do every week. Then, using GroupMe and meetings to keep everyone on the same track.

2.12 Expected Results and Validation

Expected results:

- Appropriate final drafts of solar power plant and substation.
- Accuracy parameters in final drafts.
- Accuracy calculations in voltage drop, current in each conductors.
- Suitable conductor for each connection.
- Satisfaction of the client.

Validation:

- All calculations meet the safety standards set by the client and IEEE.
- The handwritten calculations for the solar power plant layout match with the spreadsheet calculations given by Black and Veatch.
- Conductors meet the National Electrical Code (NEC).

2.13 Test Plan

In this project, we need to test the solar power plant layout, voltage drop calculation in each connection, the current calculation in each connection, and conductor for each connection. Therefore, we divide tasks to everyone to test different things in the project.

For the solar power plant, we use array parameter spreadsheet that given by Black and Veatch to test the handwritten calculations about the number of solar panels (also the number of the rack), power from each rack, currents collected from each rack, number of combination boxes needed, Inverter Load Ratio (ILR), the size and the cost of the project.

For voltage drop and current calculations, we use the spreadsheet to test our handwritten voltage drop and current calculations in all conductors.

For choosing conductors, we use the National Electrical Code to choose conductor for each connection, then we use current calculations that are approved by the client to make sure the conductors are appropriate.

1. Functional Test Plan Scope
- Solar power plant layout - Voltage drop calculation - Current calculation - Choosing conductors

2. Functional Test Plan Assumptions and Constraints
- None

3. Functional Test Team Roles and Responsibilities		
Name	**Roles**	**Responsibilities**
Ahmed Sobi	Leader/Tester	- Divide tasks to everyone in the group. - Testing calculation and choosing conductor for the collector.
Katayi Katanga	Tracker/Tester	- Making sure everyone do

		their responsibilities on time. - Testing calculation on voltage drop.
Nur Shuazlan	Tester	- Testing calculation on voltage drop and choosing conductors
Chufu Zhou	Tester	- Testing calculation and choosing conductors for the collector.
Yao Cheah	Tester	- Testing calculation and choosing conductors for the feeder.
Tam Nguyen	Tester	- Testing calculation and choosing conductors for the feeder.
Everyone		- Testing the efficiency of the final layout.

4. Functional Test Criteria	
Scope	**Criteria**
Solar Power Plant Layout	- Least space need - Least cost need - Most power collected - Easy to connect components
Voltage Drop Calculation	- Less than 5% of the original voltage
Current Calculation	- Be agreed by the client
Choosing conductors	- Based on the National Electrical Code (NEC), given by the client

5. Functional Test Cases and Results			
Test Cases	**Pass/Fail**	**Test By**	**Date Tested**
N/A	N/A	N/A	N/A

3 Project Timeline, Estimated Resources, and Challenges

3.1 Project Timeline

The timeline for the entire project is shown in the Gantt Charts below. Throughout the two semesters, the senior design team will track how many hours they spend on each task and keep updating the Gantt Charts.

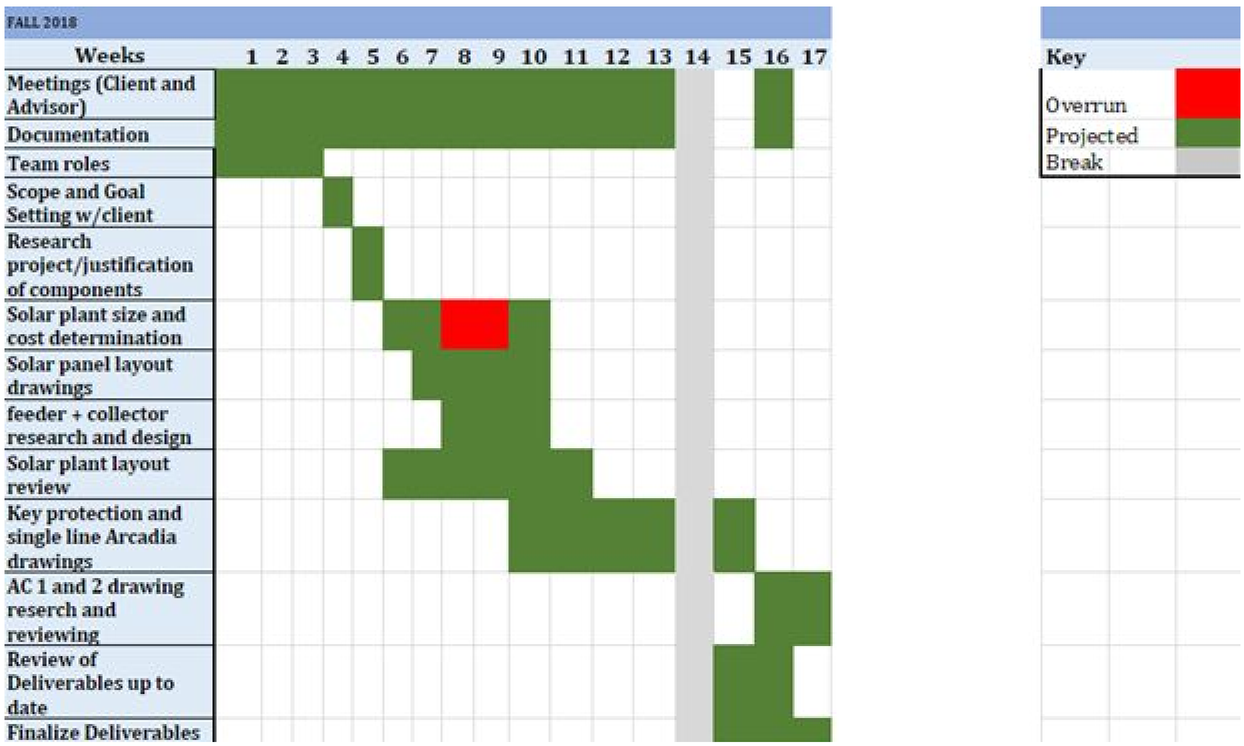


Figure 9: Fall 2018 Gantt Chart

For the first semester of the senior design project, the main focus is to design the 60 MW solar power plant. This includes using the Array Parameter Tool that was provided by the client to generate the parameters of the solar power plant and using the results to create layouts and schematics of the power plant. Then, the team used the voltage drop calculation template provided by the client to determine conductor sizes and to make sure that the total voltage drop of the entire system is less than 5% in compliance with the NEC. After finishing up the solar power plant part of the design, the team will move on to designing the 115 kV/34.5 kV substation based on the specifications set by the Arcadia single line diagram provided by the client. By the end of the semester, the team will have finalized the solar power plant design and wiring.

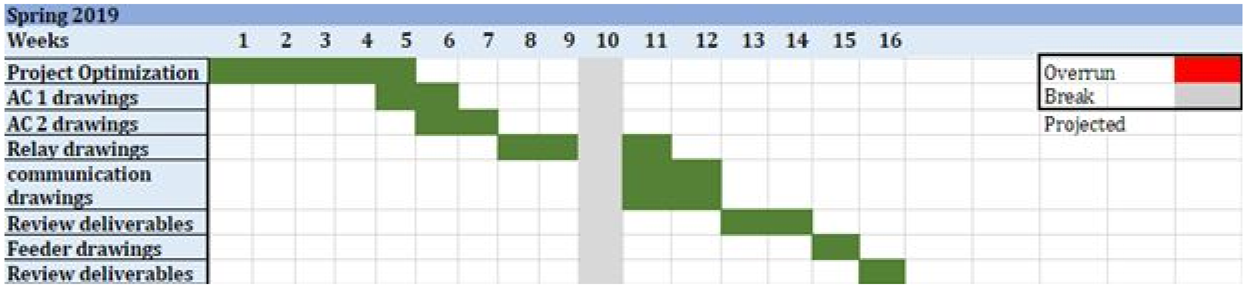


Figure 10: Spring 2019 Gantt Chart

For the second semester of the project, the main focus is to create the three-line diagram of the substation. The team will also keep optimizing and improving the schematics and layouts that were created in Fall 2018. At the end of the semester, the team will have their deliverables finalized and present the final project to the faculty members and Black & Veatch.

3.2 Feasibility Assessment

The feasibility of obtaining funding for a 60 MW solar power plant and a 115 kV/34.5 kV substation in Estancia, New Mexico is likely due to the cheap land and high solar radiation in the location. Even though the project costs over $69 million, the state of New Mexico has one of the best state incentives, which means that it is likely that Black & Veatch could receive funding or loans from the state, reducing the cost of the project. However, it is up to the company whether they want to actually build the power plant and substation or not.

3.3 Personnel Effort Requirements

The tables below show the tasks in Fall 2018 and Spring 2018 as well as the estimation of the total hours that will be spent on each task. Estimations are based on the difficulty of the task and the number of people estimated to take on the task.

Tasks	Description	Estimation of Total Hours
Solar Power Plant Parameters	Calculate the parameters of the power plant to figure out the total cost and size of the power plant	12
Solar Power Plant Layouts	Use the parameters to design layouts of the power plant	9
Voltage Drop Calculations and Conductor Sizing	Determine sizes of conductors and cables	25

	based on the IMP in the cable. Calculate voltage drops across each cable to make sure that the voltage drop percentage of the entire solar plant system is less than 5%	
Solar Power Plant AutoCAD Drawings	Create detailed drawings of the solar plant to show how different components are connected/wired together	5
Collector and Feeder Parameter Calculations	Calculate the parameters, such as currents and voltages, of the collectors and feeders based on the specifications set by the client	20
Collector and Feeder AutoCAD Drawings	Create detailed drawings of the collectors and feeders to show how they are connected to the solar power plant and substation	10
Substation Key Protection Diagram	Create a simplified drawing of the substation layout showing how different components are connected, including the relays and circuit breakers.	20

Table 2: List of Fall 2018 Tasks and Estimation of Total Hours

Tasks	Description	Estimation of Total Hours
Substation Three-Line Diagrams	Create a detailed diagram	20

	showing the actual components that will be used in the substation and the wiring of said components	
Substation Relay Diagrams	Create relay diagrams to show what goes inside of the relays and how they are connected to the rest of the substation.	20
Optimize Diagrams Created in Fall 2018	Improve all the previously made diagrams.	5

Table 3: List of Spring 2019 Tasks and Estimation of Total Hours

3.4 Other Resource Requirements

The resources needed to build the power plant and substation are shown in the tables below.

Components	Number/Amount of Resources
Solar Panel	238,032 units
Inverter	36 units
Combiner Box	792 units
Land	233.8 acres
Step-Up Transformers	37

Table 4: List of Resources for the Project

4 Closure Materials

4.1 Conclusion

Our senior design team will design a 60 MW solar power plant and 115/34.5 kV substation in order to meet the increasing demand for renewable energy and reduce the dependency on non-renewable sources. The team will utilize all the resources have been provided by Black & Veatch to meet the specifications of the project. In the first semester, the team will come up with an optimal location, solar panels parameters, solar layout design, calculate the solar power plant cost, and create a substation one-line diagram. The team will also utilize a Gantt chart in order to keep track of the man-hours and the amount of time spent on tasks. In the second semester, the team will dive deeper into the substation design and utilize AutoCAD to optimize the one-line diagram, three-line diagram and protection, and control schematic.

4.2 References

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4.3 General Information from wikipedia

Substation

https://en.wikipedia.org/wiki/Electrical_substation

Inverter: Eaton 1666kW
https://en.wikipedia.org/wiki/Power_inverter

Single line diagram
https://en.wikipedia.org/wiki/One-line_diagram

4.4 Appendices

Arcadia single-line diagram: