115kV / 34.5kV Solar Power Plant & Substation Distribution Final Report

EE492 Senior Design Project
Team sdmay20-14

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Executive Summary

Engineering Standards and Design Practices

In the scope of this project we adhere to NEC guidelines and practices, specifically with regards to conductor sizing requirements and loading factors. Throughout the design process we followed Black & Veatch standards in regards to safety tolerances, company-specific design tools, and project design flow.

Summary of Requirements

First Semester

- Equipment sizing calculations
- Solar layout drawings
- Solar panel string sizing design
- Electrical layout drawings (substation equipment)
- Protection and Control schematics based on project scope document
- Grounding analysis and ground-grid developed with IEEE 80
- Possibility of additional calculations (DC battery bank, Lightning protection, etc.)

Second Semester

- One line diagram design
- Zones of Protection design and calculation
- Spacing Calculations developed with IEEE 80 standards
- Grounding calculations developed with IEEE 80 standards
- Bus calculations developed with IEEE 80 standards

Applicable Courses from Iowa State University Curriculum

- EE 303
- EE 311
- EE 456
- Engl 314

New Skills/Knowledge acquired that was not taught in courses

First semester

- Solar array layouts
- Array parameter tool calculations and how they are applicable to the process

- Subsystem design
- Voltage drop calculations
- How to set up and run professional meetings
- An understanding of inverter boxes, strings, arrays, and modules involved in creating the solar panel layout.

Second Semester

- Transmission line layouts
- One line diagram and ASCII characters
- Grounding, spacing, battery calculations
- How to set up and run professional meeting
- Staying connected and upto date due to Covid-19

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Module: Also called solar panels, a solar module is a single photovoltaic panel that is an assembly of connected solar cells. The solar cells absorb sunlight as a source of energy to generate electricity.

String: A series-connected set of solar cells or modules.

Inverters: A type of electrical converter which converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or used by a local, off-grid electrical network. This is illustrated below in figure 1.0

Combiner boxes: A device that :combines the output of multiple strings of PV modules for connection to the inverter. This can be seen below in figure 1.1

Array: A group of solar panels arranged into rows with the goal of capturing sunlight to turn into electricity.

And the overlap of the system protects against having holes in the system.

Protective devices: devices that are used throughout the electric power system to detect abnormal and unsafe conditions and initiate corrective action.

One Line Diagram- a model that is a representation of a complicated electrical distribution system into a simplified version using a single line, which represents the conductors, to connect the components. The overall diagram allows the users to see how the components connect and how the power flows through the system.

Zone of Protection- A section of system that protects the system. It is the overlap between different of the system as we have generators, transformers, busses, transmission lines and motors

Solar Modules- Convert sunlight not DC power.

Relays- Switches that open and close circuits; they can measure the current in a line and decide whether to turn off or on a larger current. Relays usually respond to a measured quantity such as current, voltage, heat , pressure, vibraition, etc from one system and switches current in another system for the purpose of protection and control.

Circuit Breaker - A type of switch that gets tripped when there is a fault in the system in order to prevent damage to the circuitry

Current Transformer-- converts alternating currents from one voltage to another; can step down or step up voltage as needed.

Bus- Large inductor that acts as an electrical junction for outgoing and incoming components. If there is a fault in the bus then all the components on the bus will be tripped for a short time to avoid damage.

- <u>Single Bus</u> - simplest but least reliable, small land area needed, potential loss of entire substation, maintenance can be complicated.

- <u>Ring Bus</u> - Flexible , high reliability, allows maintenance on isolations of bus section and circuit breakers, double feed to each circuit, no main buses, economic design. Ring may be split on faults, each circuit has to have its own potential source for relaying, usually limited to 4 circuit positions.

- Breaker-and-a-Half - Flexible, high reliability, more expensive, double feed to each circuit, allows maintenance on main bus and circuit breakers, all switching done with circuit breakers
- Double Breaker-Double Bus - Flexible, most reliable, high cost(2 circuit breakers), double feed to each circuit, allows maintenance on main bus and circuit breakers, all switching done with circuit breakers

Transmission Line- carry electricity over a larger distance with minimal loss; acts as a conductor. Can carry current along a long distance in a manner that doesn't result in loss. They are characterized by a series resistance, inductance, and shunt capacitance per unit length

Disconnect Switches - Switch that allows lines to be energized or de-energized with visual que.

Voltage Transformer -This allows for the voltage to be raised or lowered depending on the type of transformer used; for our design we will be using a step-up transformer that will raise the voltage.

Lighting Arresters -These function to protect the system from surges as it is grounded connected to the earth.

1. Introduction

1.1 Acknowledgement

We would like to thank Black & Veatch for their guidance during this project. They supplied us with the information, suggestions, and support that allowed us to produce the best result possible. We would also like to thank our advisor, Mr. Venkataramana, for taking the time to meet with our team and help us get a deeper understanding in the background theory of our project.

1.2 Problem and Project Statement

Due to the huge changes in the grid energy market that lead to a big change in the electricity system, traditional energy sources such as coal and nuclear are being significantly replaced with renewable energy sources (RES) such as wind and solar. As a team we believe security climate change is a real issue that threatens our globe in many ways and it's our responsibility to take positive actions to reduce its impact.

After intensive research and discussion, we decided if we could design a 60 MW solar power plant and tie it to the general grid that it would be a great contribution to making the grid more flexible by incorporating renewable energy. This project is extremely important in today's climate as renewable energy solutions are becoming increasingly needed for large scale power.

Our focus for the first semester was the solar power plant design including: selecting the budget, location, equipment layout, sizing, array tool parameters, single line diagram, and the control and protection design.

During the second semester we focused on the design of the substation which included the creation of one-line diagrams, CAD models, finding out the zones of protection, and the bus, spacing, and grounding calculations.

1.3 Requirements

The technical requirements that our group will work to achieve is to create a 115kV/34.5kV distribution substation and 60MW solar power plant. This will include the completed design of the solar layout, protection and control design, electrical layout, and associated construction deliverables. We will also be required to perform various calculations required of a typical substation. In addition to these calculations, we will also be tasked with researching the environment in which this substation will be implemented, which includes many factors that we needed to consider.

First Semester

One of the most important criteria that we compared was the different irradiance levels in different possible locations of this substation. Irradiance, or energy per unit area, directly corresponds to the power output of solar panels, so choosing an area with high irradiance is key.

The next important aspect was the cost, which is affected by the community's stance on renewable energy as well as the cost per acre of the specific location. For any end product other than simply a calculation or simulation, it is essential to know the environment in which the end product will be used or to which it is expected to be exposed or experienced. For example, will the end product be exposed to dusty conditions, extreme temperatures, or rain or other weather elements? This information is necessary in order to design an end product that can withstand the hazards that it is expected to encounter.

Second Semester

The most important aspects of the criteria were the calculations necessary for the substation design. Going through the process of figuring out the right zones of protection, spacing, grounding, and bus values was important in order to make the electrical drawings viable.

1.4 Intended Users and Uses

Although this project is through our client, the electricity generated from the solar plant would be sold to local people. This means our primary client is the people buying the electricity. Knowing that the average U.S. household consumes about 1,000 kWh each month, and 12 MWh per year, our 60 MW solar farm would produce enough energy to power close to 10,000 homes.

1.5 Assumptions and Limitations

Assumptions

This project will meet all safety and reliability requirements by NERC for supplying the nominal voltages, frequencies that meet the specifications in order to be connected to the general grid. Second assumption is that the 60MW produced from our solar plant will provide a reliable energy source that can power up to 1000 homes. This project is specifically designed for the United States, for any use outside of the United States, other environmental and economical factors should be taken into consideration.

Limitations

Our energy generation is dependent upon sunlight availability at our location. As a result, the power generated will vary according to the light intensity and irradiance of the area. Moreover the biggest limitation with solar generation is required battery storage within the power plant. The initial cost of installing, purchasing of solar cell panels, combiners, inverters are very high which is considered to be a disadvantage in the solar generation field.

1.6 Expected End Product and Deliverables

Throughout the semesters our team has worked on different PV design tasks to finish the project on time. A list of deliverables will be fulfilled by the end of each semester as determined from our client. Below are all of the required deliverables for the project, it includes all the dates and the sub tasks we will carry out in this project.

For the fall semester, our main goal was to have a fully designed solar farm. This task includes researching and choosing the most efficient location for the project, filling out and analysing the array parameter tool for calculating our component choices, calculating the amount of area that will be required, creating man hour budget deliverables, and calculating the pricing and comparing it with our scheduled budget. We also created a completed schematic, one line diagram, voltage drop calculations, and protection and control schematic.

Below in Figure 1.6.1, you can see how a general solar farm is constructed and connected. This image was provided to us by our client in order to be able to better visualize our project and is strictly for illustrating the individual components that make up the entire system.

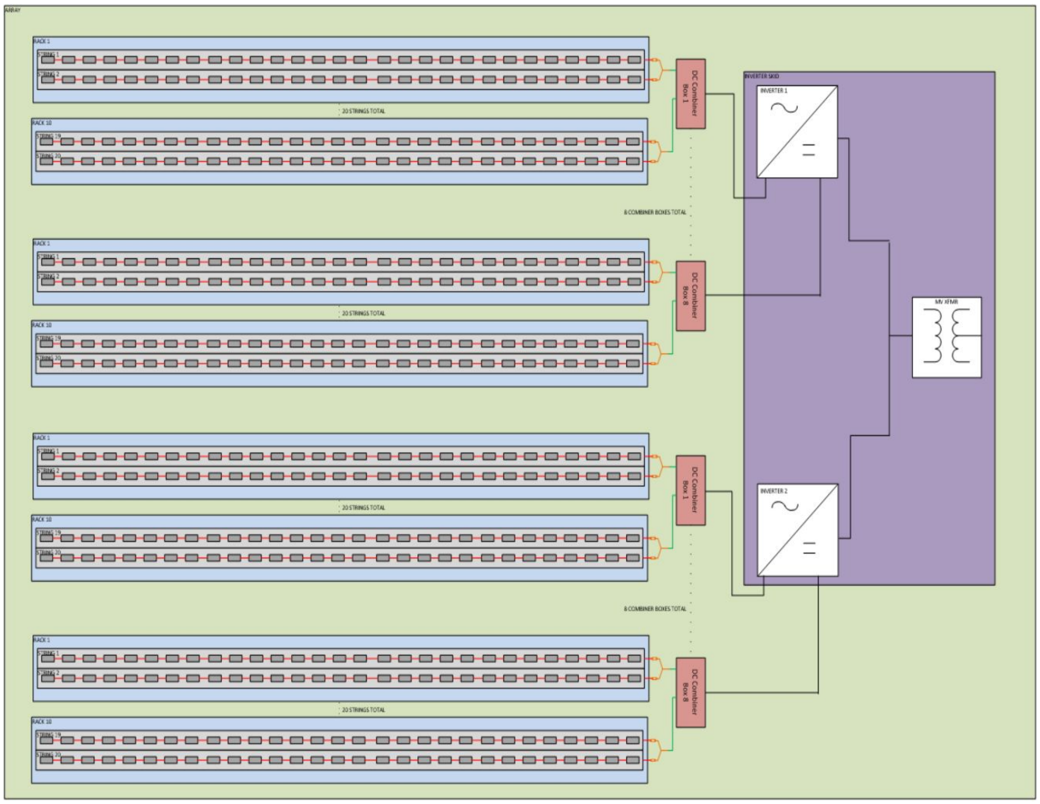

Figure 1.6.1 - General Array Layout

As a part of our first semester deliverable, we produced an accurately scaled layout of the solar plant arrays using AutoCAD. This can be seen in Figure 1.6.2 below.

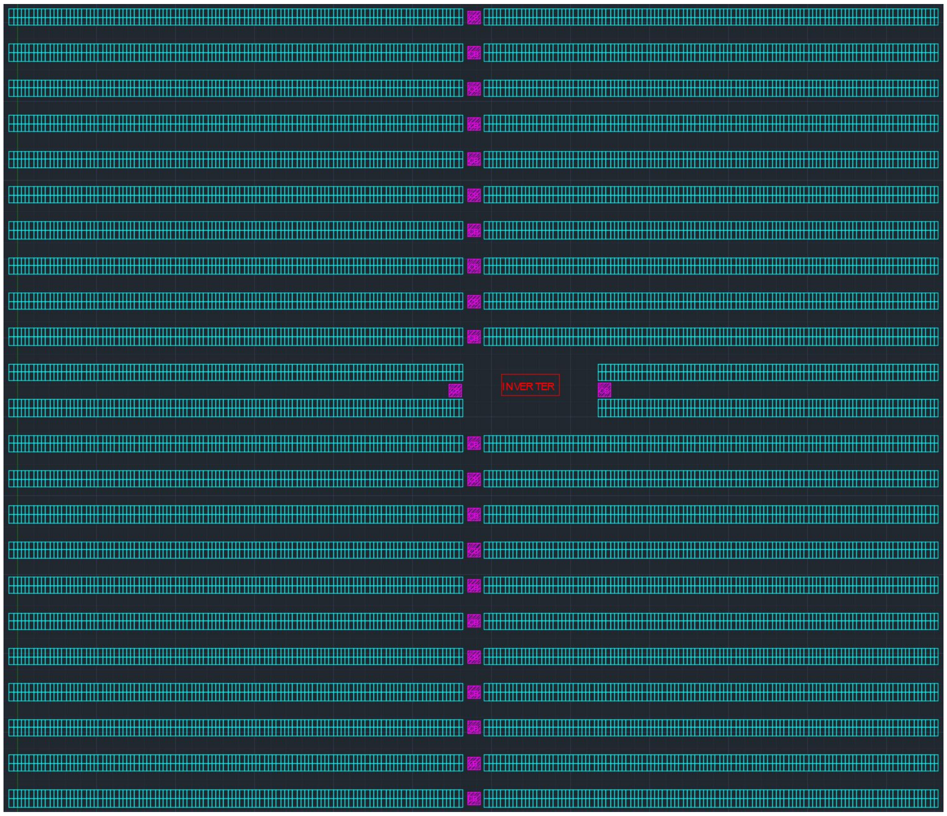

Figure 1.6.2 - Solar Array Layout

In this figure, each individual blue box is a solar panel. These are accurately sized in order to show the scale of the array. The pink boxes represent the combiner boxes and their respective locations. The combiner boxes are not to scale, as they would be too small to see. Lastly, the red box in the center is the inverter for the entire array. This is also not to scale, but is located in the correct position. This location was selected to minimize the maximum run length for any individual conductor. In total, there will be 16 arrays that make up the entire solar plant. These will be arranged in a 4x4 grid to minimize the distance of conductors and to make the most efficient use of space.

In order to achieve our end goal, we had to divide up the process into smaller tasks that we could better manage. In Table 1.6 below we have listed some of these tasks (spread across both semesters), along with how many hours we spent working and also our timeframe.

Task	Deliverable date	Hours taken in the task
Man Hour Budget	9/26/19	14
Protection plan	2/6/20	10
One line diagram voltage drop calculations	12/5/19	48
Protection & control circuit	2/13/20	12
Material list	1/30/20	14
Project Review	11/21/19	16
Presentation document	12/8/19	25

Table 1.6 - A timetable of when our deliverables were met

For the spring semester, our goal was to design a substation. This process involved the creation of a one-line diagram, understanding the zone of protection and their implementation, and calculating the bus, grounding, and spacing for the final design of the substation. In the end of the spring semester we have created a final report, poster, and final presentation that summarizes the work we have done over the past two semesters.

We decided to implement a ring bus configuration in our substation design. The reason we settled on this bus configuration is because it allows us to maintain system operation in the event of an arc fault or circuit breaker failure. As can be seen in the attached Figure 1.6.3 each array input will have two methods of transmission around either direction of the ring bus. The dashed lines show which pieces of equipment are protected within each zone of protection.

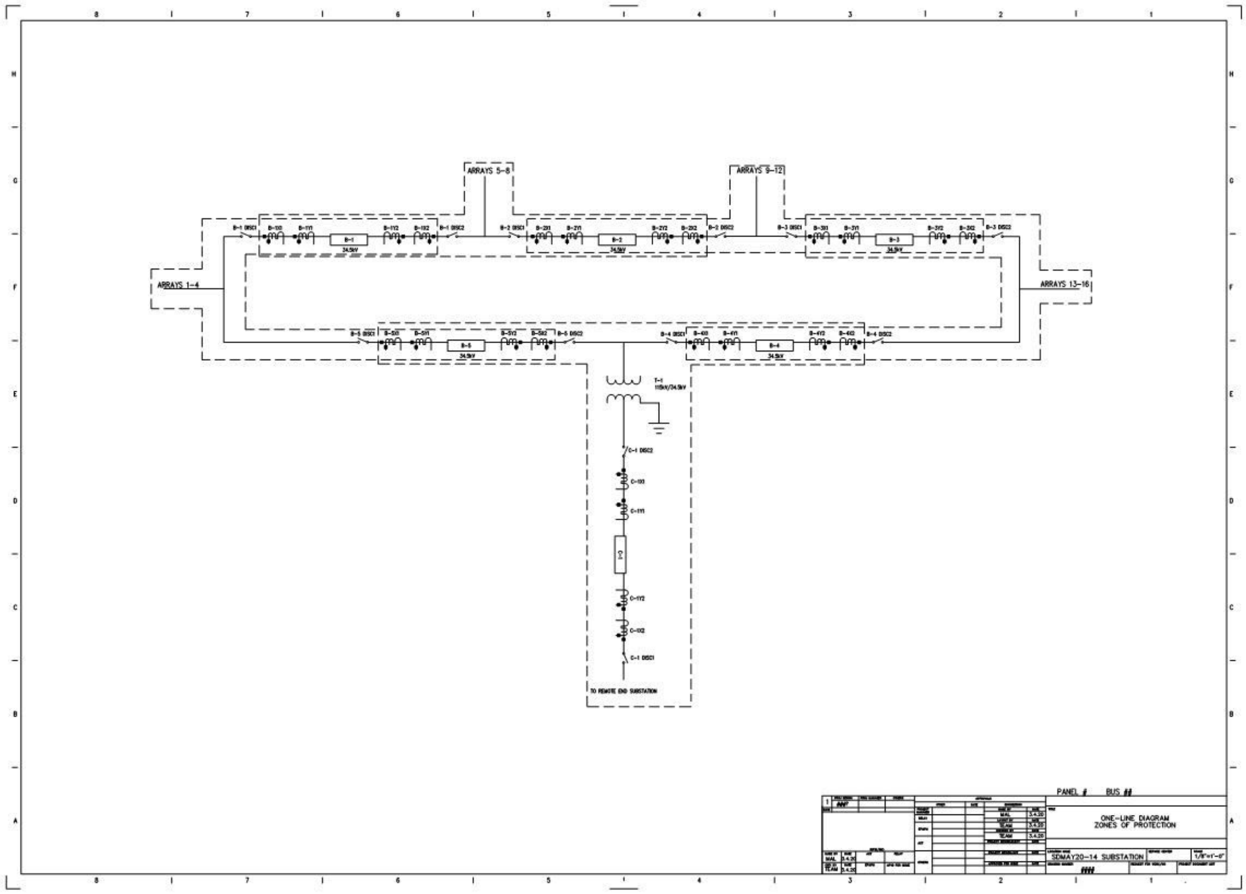

Figure 1.6.3 - One Line Diagram

2. Specifications and Analysis

2.1 Proposed Design

As noted above, our team had a lot of tasks that we worked to accomplish. Some of the work needed to be submitted to our clients at Black & Veatch, the rest will be for our advisor to help guide our progress. The deliverables consists of the layout of the entire project, single line diagrams, land selection, man hourly budget which we did with the support of Black & Veatch, the array parameter tool, voltage drop calculations, protection and the control plan for both the PV and the substation design that ensures reliability for our project. AC, DC schematic, rack layout, panel characteristics and combiner box as well.

Each of the tasks will be checked and approved by Black & Veatch and Dr. Ajjarapu to help with any technical or analysis information required. These tasks will be carried out in the order of design process.

After the first semester, we have completed some of the tasks such as, land requirements and selection, array tool parameters, and voltage drop calculations. The second semester had some similar calculations, but they mainly focused on the substation design. Some of these tasks were the grounding calculations, spacing calculations, and the bus calculations. All of these calculation documents got checked and approved by our client and by our advisor as well.

2.2 Development Process

While Agile is typically used for software development, our group has been following a similar development process in order to efficiently complete our project. We chose to model our development process after Agile because we think that having a lot of interactions within our team, as well as having a lot of collaboration with our customer, will allow us to work efficiently and produce the best solutions to our problems.

2.3 Design Plan

The design plan for our project is mainly divided between the two semesters of the class. The first semester was focused mainly on creating the solar panel design layout. This involved first picking a suitable location for our plant, which depended upon various factors that we had to research. Next we then had to fill out an array parameter tool that was provided to us by our client; this tool allowed us to pick the correct components for our design. After this, we then had to actually design the layout in Autocad. The final design criteria that we had to accomplish the first semester is computing the voltage drop of our design. For the second semester, we focused on the substation aspect of this project. This mainly involved creating a one-line diagram, creating zones of protection. In addition to this, we then had to complete grounding calculations, and bus calculations.

3. Statement of Work

3.1 Previous Work And Literature

Solar panels have existed in the market for a while now; today we know how to maximize the amount of power we utilize from the sun. Using the information gathered from the internet and the Black & Veatch representatives, our team has acquired a solid foundation of what makes a good solar panel layout. We have been given templates from Black & Veatch that previous teams have used in order to gain a deeper understanding of the overall project. Figure 3.1 below shows a portion of one of the templates, the array parameter tool.

A	B	C	D	E	F	G	H	I	J	K	L	
		String Size				Electrical Rack Size				CB capacity		
					Designer		portrait or					
	Location	Min Temp		C	Datasheet	Module width		ft	Datasheet	mod/string Isc		A
					Datasheet	module height		ft	NEC sectic	multiplier	1.25	
	Datasheet	Voc		V						nom Isc	1.25	
	Datasheet	Ref temp		C	Designer	Rack width		modules	Irr.	multiplier	1.25	
					Designer	Rack height		modules		max Isc	1.5625	A
	Datasheet	Temp Coeff of Voc		/C		Modules per rack						
		Temp delta	0			Rack width	0	ft	Designer Choice: 200, 400A etc.	allowed current		A
		temp correction	1.00			Rack height	0	ft				
		V0c corrected	0							strings per CB	0	
										Round down:		
Confirm possible with Panel type chosen		string voltage		V		// ask whther the mechanical characteristics are for the module or the rack						
	Designer Choice: 600, 1000, 1500, 2000V	String size	#DIV/0!			panel module						
		string size	#DIV/0!			rack is the amount of panels						
		Actual String Voltage	#DIV/0!									
						//add price for this panel						
						//solar						
		Input Information =										

Figure 3.1 - Portion of the Array Parameter Tool

While these templates are beneficial in completing many different calculations, we also work with our advisor to make sure that we fully understand what each template is doing. In addition to this, our advisor has given our team some example deliverables from a previous team that was also working on this project. While we feel that these examples are beneficial for gaining a preliminary reference, our team has chosen to complete the project using a different design that we feel will produce an even better result than previous teams, especially considering solar panel technology increases substantially from year to year.

The other main piece of literature we used throughout the project was various IEEE documents. We mainly used IEEE documents that were related to all of the grounding and bus calculations that we completed for our client. These documents were important to use in the understanding of what we were calculating and also as a baseline to make sure that our values were typical in the industry itself.

3.2 Technology Considerations

When creating our design, we initially had to research many different types of hardware components that had the necessary specifications. Considering solar technology has been increasing tremendously in recent years, there were countless components that we had to consider with all different benefits and drawbacks. In the end we chose to use components that worked more efficiently, although costing more. Alternatively, we could have chosen to use more panels that produced less power that cost less per individual solar panel, this however, would have needed a larger land area to lay out the solar array.

3.3 Task Decomposition

As previously stated in our design plan, the overall task of completing the 60MW solar plant is divided into two key smaller tasks between each of the two semesters. The first semester focused on designing the solar panel layout (location, hardware choices, and Autocad layout). The second semester involved researching and designing the substation that connects to our solar plant.

3.4 Possible Risks And Risk Management

During the design phase of our project, because we are only using the software Excel to work on calculations, there really is one possible risk that we could face. This risk is due to using improper values in calculations that would need to be addressed. Fixing these calculations could potentially lead to missing a time deadline.

3.5 Project Proposed Milestones and Evaluation Criteria

There had been three key milestones within the first semester:

1) Fill out the Array Parameter tool and figure out which solar panel to use, JA Solar or the Eagle 72
2) Researching the best place for the substation to be located.
3) Fill out the Voltage Drop Calculation Sheets

4) Complete solar farm design

The milestones for the second semester are as follows:

5) One-line diagrams for substation
6) Zones of protection
7) Substation calculations

3.6 Project Tracking Procedures

Working with a large group on complicated tasks can easily become disorganized throughout the semester so it was very important to our group to make sure we were staying on task. In order to do this, our group created a detailed Gantt chart using Microsoft Project that allowed us to break down tasks and track their progress. In addition to this, our team created weekly reports that summarized our teams progress that week. This allowed us to easily see which tasks we were going to complete on time and also identify tasks that needed more time dedicated to them in order to complete them efficiently.

3.7 Expected Results and Validation

Our desired outcome for part one (fall semester) of this project is to create the most cost effective and highest output solar plant as possible. In order to make sure that the project will be successful, we have different tools such as our array parameter tool, and our voltage drop calculator that allow us to make sure our values are reasonable with real world outcomes. By using these tools, we are able to see how certain parameters change the outputs of each system and therefore can ensure that our project will be successful at the highest ability.

Our desired outcome for part two (spring semester) of this project is to design the corresponding substation that will tie our solar power plant into the power grid. This will be responsible for stepping up our line voltage as well as combing out array outputs from the plant into a single transmission line. It includes grounding protection, as well as circuit breakers in the event of an arc fault. We follow IEEE guidelines in our grounding requirements calculations to design our grounding grid and to size our circuit breakers.

4. Project Timeline, Estimated Resources, and Challenges

4.1 Project Timeline

Early on in our project when we had many tasks coming in at once, it was clear that we needed to make a detailed schedule that our team could follow. In order to accomplish this, our group created a Gantt chart that included important tasks that needed to be completed. This Gantt chart (shown below) helped tremendously when trying to divide up tasks amongst team members, and also to ensure tasks were completed on time. As shown in the images below, the main components of our project are divided up between the two semesters. The first semester is the solar array layout, while the second semester is the substation design. The major benefit of having our design split up into two semesters is that we can got familiarized with the material and processes in the first semester; and the second semester, although covering more challenging material, was easier to approach.

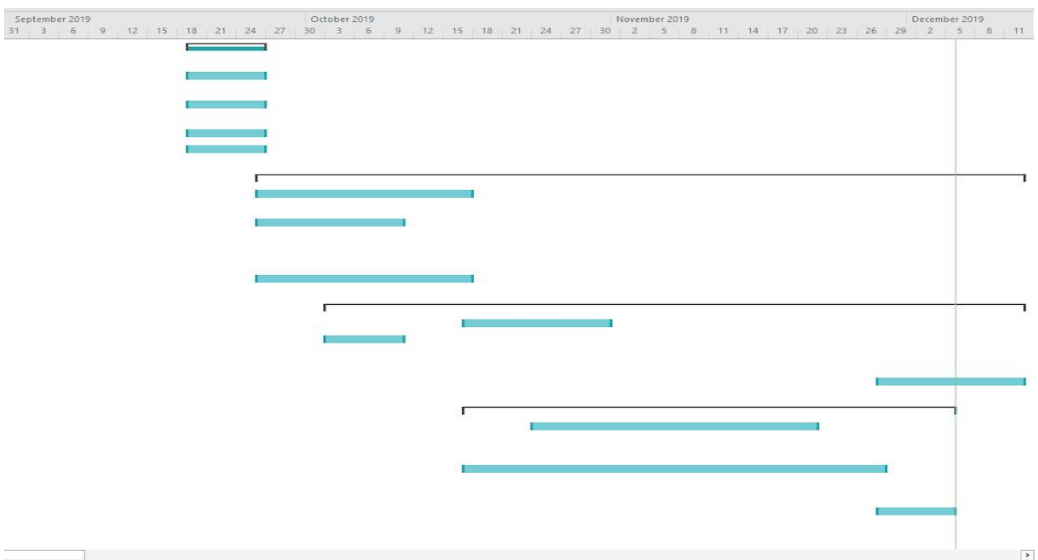

Figure 4.1.1 - A timeline of project schedule

In order to accomplish this, there was initially a lot of research that was needed in order to understand the components we would be designing with, as well as other information crucial for the completion of the project. As shown below, this research was from (9/19/19 - 9/26/19). Once this research was completed, we then had to use the information we gathered in order to make design choices, such as which solar panels would work best in our design. This process was aided by an array parameter tool that was provided by Black & Veatch that we had to fill out with information. Overall, this stage of the project took from (9/26/19 - (12/12/19). After this stage, we then had to complete more research in order to understand how to fill out certain things, such as the voltage drop calculations spreadsheet that was provided by Black & Veatch. This took from (10/3/19 - 12/12/19). This was a large time frame considering it also included research for the substation design that began the following semester. We then moved into the actual design phase which was mainly composed of modeling the array layout in AutoCAD, finishing the voltage drop calculations. This phase took from (10/17/19 - 12/5/19).

TIMELINE

Start Thu 9/19/19	Sep 22, '19	Sep 29, '19	Oct 6, '19	Oct 13, '1

GANTT CHART

	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Preliminary Research**	**6 days**	**Thu 9/19/19**	**Thu 9/26/19**	
2		Research Hardware	6 days	Thu 9/19/19	Thu 9/26/19	
3		Man hour budgets	6 days	Thu 9/19/19	Thu 9/26/19	
4		Software access	6 days	Thu 9/19/19	Thu 9/26/19	
5		Locations for plant	6 days	Thu 9/19/19	Thu 9/26/19	
6		**Design Choices**	**56 days**	**Thu 9/26/19**	**Thu 12/12/1**	
7		Complete array parameter tool	16 days	Thu 9/26/19	Thu 10/17/19	
8		Choose Solar panel, combiner box, and inverter we will use	11 days	Thu 9/26/19	Thu 10/10/19	
9		Choose final location	16 days	Thu 9/26/19	Thu 10/17/19	
10		**Research**	**51 days**	**Thu 10/3/19**	**Thu 12/12/1**	
11		NDA Forms	11 days	Thu 10/17/1	Thu 10/31/1	
12		Research voltage drop calculations	6 days	Thu 10/3/19	Thu 10/10/19	
13		Research substation	11 days	Thu 11/28/19	Thu 12/12/19	
14		**Design**	**36 days**	**Thu 10/17/1**	**Thu 12/5/19**	
15		Model array layout in AutoCAD	21 days	Thu 10/24/19	Thu 11/21/19	
16		Finish voltage drop calculations	31 days	Thu 10/17/19	Thu 11/28/19	
17		Voltage drop revisions	6 days	Thu 11/28/19	Thu 12/5/19	

Figure 4.1.2 - A list of all our scheduled tasks

Considering the tasks that we were presented with for the second semester were just as complicated as the first semester, we also had to implement a gantt chart that allowed us to schedule and break down tasks in order to be properly managed. The first thing that we had to complete for the second semester was a one-line diagram, and this was completed around 1/30/20. After this we then created zones of protection for our one-line that was finished around 2/6/20. We then had to finish our grounding design layout by 2/20/20. Completing this then led us to work on, and complete our grounding calculations by 3/12/20. We then created a comprehensive report for our grounding calculations that was due on 4/2/20. After this, we then created a similar process for our bus calculations, and the report was due on 4/16/20. Finally, we had to complete a battery calculation report that was due on 4/23/20.

4.2 Feasibility Assessment

For this project, we are expecting to design a solar farm and substation that will generate 60MW. While our client didn't give us a budget, it is important for us to keep cost in mind so that our substation will be financially beneficial. While there are many costs we can't accurately account for, such as the construction timeline, degradation of panels, and maintenance, we can do our best to estimate these potential costs. Generally it has been stated that it costs approximately $1/watt for installation, and since our farm is 60 MW, we can assume it will roughly cost $60 million. Given the cost that the electricity can be sold at this project would be economically feasible.

4.3 Personnel Effort Requirements

Tasks	**Requirement to complete task**	**Time taken to accomplish task**
Complete the Array Parameter tool	Understand the equations and how they relate to the future layout of solar panels.	It took roughly 3 weeks to finish, get checked by Black & Veatch, and go back and do corrections.
Choose which Solar Panel to use	Comparing the Eagle 72 and JA Solar array parameter tools and deciding which is better to use	It took about 1 week to make our decision and verify our choice with Black & Veatch.
Research location, layout, and solar panel needs	Finding the right location for solar panels while taking into account the weather, pricing, solar friendly neighborhoods and the land elevation.	Took about 2 weeks to find the right area, which was chosen to be Alburquerque NM, research the land, irradiation levels, and pricing; including making sure Black & Veatch approved of our choice.
Create CAD files for the solar panel layout	Understanding of how to set up the solar panel layout. Need understanding of arrays, modules, strings, inverters, and combiner boxes.	Took about 2 weeks to create a solar farm layout replicating the one we designed. Contains 16 identical arrays.
Fill out the Voltage Drop Calculations	Understanding how the template is used and what value the data should be around. Need an understanding of the Harness and its effects on the other calculations.	This took about 3 weeks to fill out, get it checked by Black & Veatch, and then to go back and do corrections and get final approval.

Research topics regarding substation design	Need to look into substation design and view the information Black & Veatch has recently sent about the desirable for the second part of this project.	We researched these topics over winter break
Create one-line diagram	Understand how to create a full layout which involves the correct labeling, borders, feeder positions, step up transformers, and zones of protection.	This took about 4 weeks to create and update the design to its final layout.
Create zones of protection	Understand what they do for a circuit (the way they protect) and how to correctly implement them into the one diagram.	It took about 2 weeks to create the layout, get it checked by Black and Veatch,and update the final version.
Grounding design layout	Understand the equations that are used to find out the parameters necessary to create a proper grounding design.	It took 4 weeks to properly calculate the values, to design the layout, get it checked and updated.
Grounding calculation report	Understand the equations that are used to find out the parameters necessary to create a proper grounding design.	It took about 4 weeks along with the grounding calculations to finalize the results.
Bus calculation report	Understand the equations that are used to find out the parameters necessary to create a proper bus design.	It took about 2 weeks, along with the grounding calculations, to finalize the results.

Table 4.3 - A breakdown of our completed tasks

4.4 Other Resource Requirements

Since we do not require any financial funding from our clients, the only other resource that we are required to have to complete our project is software that has been made available through Iowa State University. This software we will be using is AutoCad, which will be used for our solar plant layout. In addition to this, Black & Veatch have provided us with all the necessary datasheets to figure out the required calculations.

4.5 Financial Requirements

Currently, our team does not have any financial constraints while working on the project. We will however, consider many different design choices that will affect the overall cost of the project, considering we would like it to be as low as possible without compromising efficiency.

Below, as you can see, Figure 4.5 shows the prices of all the major equipment needed for the solar farm. The price of the panels, combiner boxes, and inverters sums up to a little over $35 million. Given the large scale of our project, this price is going to be fairly high but by choosing high efficiency units, we are able to reduce our quantity needed and therefore, our price. Another aspect that needs to be addressed is the implementation of this project and the cost of the company that will construct this project. We did not include this in the total cost of the power plant because the price will vary depending on which contractor works on the job.

Solar Plant Cost	**Quantity**	**Cost**	**Total**
Panels	163072	$198.68	$32,399,927.71
CBs	368	$900.00	$331,200.00
Inverters	16	$155,000.00	$2,480,000.00
		Total Cost	$35,211,127.71

Figure 4.5 - A breakdown of our solar farm costs

When designing our substation, due to the nature of our confidentiality agreements we were not given access into many of the pricing specs for the equipment used. Under Black and Veatch recommendation, we used standard equipment sizes for our designs that they have used in the past that proved economical, but we do not have actual estimates in overall costs.

5. Testing and Implementation

During the fall semester the “testing” of the project would only be based on completing the provided excel sheets (array parameter tool and voltage drop calculations) and making sure that the values are viable.

During the spring semester we created a design of the substation, which was based on completing calculations in order to create accurate designs for the substation. The team used IEEE formulas and industry parameters to find viable values for the calculations. The ‘testing” aspect was checking our finalized calculations with Black and Veatch.

5.1 Interface Specifications

Considering we are working on a very large-scale project, our team will not work directly with any hardware. Instead, Black & Veatch has provided us with different software solutions that we are able to use for designing and testing. The software that we used was mainly Autocad for the actual layout design, and excel for the calculations and testing to ensure our values would work.

5.2 Hardware and software

As previously stated above, due to the nature of our project we will not be working directly with any hardware. The only interaction we had with "hardware" is during our design phase when we had to research different hardware components that we could use in our design. In terms of software, we have used excel templates to figure out the necessary calculations as well as CAD to create a view of the layout we will use for the solar panels.

Instead of using actual industry hardware for our equipment for the substation, Black and Veatch provided us with standard equipment values based on projects they have completed in the past. We again used AutoCAD to draft our substation design documents and excel to store our calculations.

5.3 Functional Testing

For the fall semester testing can be seen by the math done within the voltage drop calculations and the array parameter tool. Figure 5.3.1 and 5.3.2 below show the excel sheets we commonly use throughout the project:

		String Size		
	Location	Min Temp	-6.6	C
	Datasheet	Voc	48.81	V
	Datasheet	Ref temp	25	C
	Datasheet	Temp Coeff of Voc	-0.003	/C
		Temp delta	-31.6	
		temp correction	1.09	
		V0c corrected	53.43718	
Confirm possible with Panel type chosen	Designer Choice: 600, 1000, 1500, 2000V	string voltage	1500	V
		String size	28.07033	
		string size	28	
		Actual String Voltage	1496.2	
		Input Information =		

	Electrical Rack Size		
Designer		potrait	
Datasheet	Module width	3.2	ft
Datasheet	module height	6.57	ft
Designer	Rack width	28	modules
Designer	Rack height	2	modules
	Modules per rack		
	Rack width	89.6	ft
	Rack height	13.14	ft

	CB capacity		
Datasheet	mod/string Isc	10.03	A
NEC sectio	multiplier	1.25	
	nom Isc	12.5375	
Irr.	multiplier	1.25	
	max Isc	15.67187	A
Designer Choice: 200, 400A etc.	allowed current	275	A
	strings per CB	17.54735	
	Round down:	16	

	Array Design		
Designer	Racks per row	8	
Designer	rows per Array	23	
Designer	Racks removed	2	
	Total Racks/Array	182	
	Total modules	10192	
Datasheet	module capacity	380	W
	dc capacity	3.87296	MW
Designer	inverter capacity	3	MW
			MVA
Provided: Industry standard 1.3	ILR	1.290986	

	Array Size		
Designer	tilt	35	
	table height proj	10.76365	ft
Designer	row spac	15	ft
	pitch	25.76365	ft
	Space for Inverter Maintenance	15	ft
	Array height	592.5641	ft
	Array width	716.8	ft
	Ground Coverage Ratio	0.510020	

Figure 5.3.1 - Excel sheet from the array parameter tool

DCB	Strings per Harness	IMP for Harness	Rack Harness Length	Rack Harness wire size	Rack Harness resistance	Rack Harness resistance	Voltage Drop of Harness	IMP for Jumper	Jumper Length	Jumper wire size	Jumper resistance	Jumper resistance	Voltage Drop of Jumper
DCB#-##	per rack	Amp	feet	AWG	Ohm/kft	Ohm	Volts	Amp	feet	AWG	Ohm/kft	Ohm	Volts
DCB1-01	2	15	89.6	12	1.2600	0.1937	3.38688	30	277	10	1.2900	0.6919055	21.4398
DCB1-02	2	15	89.6	12	1.2600	0.1937	3.38688	30	187	10	1.2900	0.4664314	14.4738
DCB1-03	2	15	89.6	12	1.2600	0.1937	3.38688	30	97	10	1.2900	0.24175	7.5078
DCB1-04	2	15	89.6	12	1.2600	0.1937	3.38688	30	7	10	1.2900	0.018	0.5418
DCB1-05	2	15	89.6	12	1.2600	0.1937	3.38688	30	7	10	1.2900	0.018	0.5418
DCB1-06	2	15	89.6	12	1.2600	0.1937	3.38688	30	97	10	1.2900	0.25	7.5078
DCB1-07	2	15	89.6	12	1.2600	0.1937	3.38688	30	187	10	1.2900	5.061	14.4738
DCB1-08	2	15	89.6	12	1.2600	0.1937	3.38688	30	277	10	1.2900	0.715	21.4398
Combiner Name			panels in string * panel width	IMP x 1.25 AWG size above that	Table 8 NEC						Table 8 NEC		
DCB23-01	2	15	83.2	12	1.2600	0.21	3.38688	30	20.5	10	1.2900	0.0512881	1.5867
DCB23-02	2	15	83.2	12	1.2600	0.21	3.38688	30	20.5	10	1.2900	0.0512881	1.5867
DCB23-03	2	15	83.2	12	1.2600	0.21	3.38688	30	110.1	10	1.2900	0.2748268	8.52174
DCB23-04	2	15	83.2	12	1.2600	0.21	3.38688	30	110.1	10	1.2900	0.2748268	8.52174
DCB23-05	2	15	83.2	12	1.2600	0.21	3.38688	30	199.7	10	1.2900	0.4983655	15.45678
DCB23-06	2	15	83.2	12	1.2600	0.21	3.38688	30	199.7	10	1.2900	0.4983655	15.45678

DCB	No. of Rack Inputs	IMP for DCB circuit	Feeder length	Feeder wire size	Feeder resistance	Feeder resistance			Voltage drop for feeder	Voltage drop for feeder	Voltage drop for circuit	VMP for circuit			Voltage drop for circuit
DCB#-##	#	Amp	feet	kcmil	Ohm/kft	Ohm			Volt	per cent	Volt	Volt			per cent
DCB1	8	240.00	604	600	0.0382	0.0446			11.074944	1.14%	42.032128	1500.00			2.80%
DCB2	8	240.00	575	600	0.0382	0.0425			10.5432	1.08%	41.85488	1500.00			2.79%
DCB3	8	240.00	546	600	0.0382	0.0404			10.011456	1.03%	41.677632	1500.00			2.78%
DCB4	8	240.00	517	600	0.0382	0.0382			9.479712	0.98%	41.500384	1500.00			2.77%
DCB5	8	240.00	488	600	0.0382	0.0361			8.947968	0.92%	41.323136	1500.00			2.75%
DCB6	8	240.00	459	600	0.0382	0.0340			8.416224	0.87%	41.145888	1500.00			2.74%
DCB7	8	240.00	430	600	0.0382	0.0318			7.88448	0.81%	40.96864	1500.00			2.73%
DCB8	8	240.00	401	600	0.0382	0.0296			7.352736	0.76%	40.791392	1500.00			2.72%
DCB9	8	240.00	372	600	0.0382	0.0275			6.820992	0.70%	40.614144	1500.00			2.71%
DCB10	8	240.00	343	600	0.0382	0.0254			6.289248	0.65%	40.436896	1500.00			2.70%
DCB11	8	240.00	314	600	0.0382	0.0232			5.757504	0.59%	40.259648	1500.00			2.68%
DCB12	8	240.00	285	600	0.0382	0.0211			5.22576	0.54%	40.0824	1500.00			2.67%
DCB13	8	240.00	256	600	0.0382	0.0190			4.694016	0.48%	39.905152	1500.00			2.66%
DCB14	8	240.00	227	600	0.0382	0.0167			4.162272	0.43%	39.727904	1500.00			2.65%
DCB15	8	240.00	198	600	0.0382	0.0146			3.630528	0.37%	39.550656	1500.00			2.64%
DCB16	8	240.00	169	600	0.0382	0.0125			3.098784	0.32%	39.373408	1500.00			2.62%
DCB17	8	240.00	140	600	0.0382	0.0104			2.56704	0.26%	39.19616	1500.00			2.61%
DCB18	8	240.00	111	600	0.0382	0.0082			2.035296	0.21%	39.018912	1500.00			2.60%
DCB19	8	240.00	82	600	0.0382	0.0061			1.503552	0.15%	38.841664	1500.00			2.59%
DCB20	8	240.00	53	600	0.0382	0.0039			0.971808	0.01%	38.664416	1500.00			2.58%
DCB21	8	240.00	24	600	0.0382	0.0017			0.440064	0.01%	38.487168	1500.00			2.57%
DCB22	8	240.00	24	600	0.0382	0.0017			0.440064	0.01%	38.487168	1500.00			2.57%
DCB23	7	210.00	36	600	0.0382	0.0027			0.577584	0.01%	24.009768	1500.00			1.60%
													Average of worst-case DCB voltage drop:		2.63%

Figure 5.3.2 - Excel sheet from the voltage drop calculations

As you can see above in figure 5.3.1 and 5.3.2, there are many values that needed to be filled out and just as in any human calculation there were bound to be errors with our initial values. That was why it was so important to constantly be checking our accuracy and legitimacy while filling these out.

For the spring semester testing was done using excel to hold our calculations; this was used for grounding and bus calculations. Figures 5.3.3and 5.3.4 below show our work for the grounding and bus calculations.

Parameters	Calculated Values	Equation Used	Definition	Lx= 153
n	2.890	$n = n_a \cdot n_b \cdot n_c \cdot n_d$	Geometric Factor	Ly=111
na	9.420	$n_a = \frac{2 \cdot L_C}{L_p}$	N/A	
nb	1.006	$n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}}$	N/A	
nc	1.000	$n_c = \left[\frac{L_x \cdot L_y}{A}\right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}}$	N/A	
nd	0.305	$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}}$	N/A	
Lc	757.970	Lc = Lx*9 + Ly*10	Length of Grid	
Lp	160.920	Lp = (Lx+Ly)*2	Periphial length of grid	
Lx	46.630	N/A	Max length of grid x (m)	
Ly	33.830	N/A	Max length of grid y(m)	
A	1577.493	A = Lx * Ly	Area of grid (m^2)	
Dm	17.560	N/A	Max distance between to points in grid	
Ks	1.137	$K_s = \frac{1}{\pi}\left[\frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D}(1 - 0.5^{n-2})\right]$	Spacing Factor for mesh voltage	
Ls	1079.790	$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R$	Effective Length for Step Voltage	
Ki	1.072	$K_i = 0.644 + 0.148 \cdot n$	Irregularity Factor	
Es	952.346	$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_S}$	Step Voltage	
IG	15000.000	N/A	Maximum Grid Current	
p	56.280	$\rho_{a(av1)} = \frac{\rho_{a(1)} + \rho_{a(2)} + \rho_{a(3)} + \cdots + \rho_{a(n)}}{n}$	Soil Resistivity	
LR	601.544	LR = (D * 90) + (D * 59)	Ground rod length (m)	
h	0.150	N/A	SurfaceLayer Thickness	
D	6.096	N/A	Spacing between parallel conductors	
Km	1.226107	$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln \frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{K_{ii}}{K_h} \cdot \ln\left[\frac{8}{\pi(2 \cdot n - 1)}\right]$	Spacing Factor for mesh voltage	
Lm	2415.332	$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] L_R$	Length for mesh voltage	
Estep	2526.351	$E_{step50} = (1000 + 6C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}}$	Step Voltage	
Es	1015.917	Es =(p * Ks *Ki * IG)/Ls	N/A	
Etouch	754.624	$E_{touch50} = (1000 + 1.5C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}}$	Touch Voltage	
Em	489.760	Em = (p*Km*Ki*IG)/Lm	N/A	

Figure 5.3.3 - Grounding Calculations

Variables	Equation	Value	Units	
ΔT	Temperature difference between ambient and conductor size	50	°C	
T2, Tc	Conductor Temperature	90	°C	
Ɛ	Emissivity	0.2	°C	
Ta	Ambient Temperature	40	°C	
Ɛ'	Solar absorption	0.5	°C	
E	Modulus of elasticity for aluminum	6.89E+10	N/m2	
Fg	Gravitational Force	33.7	N/m	
σallowable	Allowable stress of material accounting for welds	120	MPa	
wc	Specific weight of aluminum	26500	N/m3	
wi	Ice weight	0	lbf/in^3	
ri	Equivalent uniform radial ice thickness	0	in	
C	Constant, for metric units	0.613	N/A	
V	Extreme wind velocity	40	m/s (144 km/h)	
Cf	Force coefficient for rigid tubular bus	1	N/M	
Gf	Gust response factor	0.85	N/M	
I	Importance factor	1.15	N/M	
ISC	Short-circuit current	15000	A	for 115kV
Γ	Constant based on type of fault and conductor location	0.866	N/A	
Kf	Mounting structure flexibility factor	1	N/M	
Df	Half cycle decrement factor	0.927	N/A	
η	Allowable deflection as a fraction of span length	0.0067 (1/150)	m	
Ac	$A_c = \frac{\pi}{4} \times \left[(D)^2 - (D - 2\times t)^2\right]$	0.001438153759	m^2	
Dc Resistance	$R = \frac{1.724\times10^{-6}}{C' A_c}\left(1 + \frac{0.00403C'}{61}(T_2 - 20)\right)$	0.00002575545679	ohm	
Lv (Maximum Allowable Span)	$L_V = \sqrt{\frac{16 J \sigma_{allowable}}{F_f D_o}}$	12.93294384	m	
J	$J = \pi \frac{(D_o^4 - D_i^4)}{64}$	0.000001255198736	m^4	
Do	Outside conductor diameter	0.0889	m	
Di	Inside conductor diameter	0.0779272	m	
FW	$F_W = C V^2 D_o C_f K_Z G_f I$	107.3914062	ibf/ft	

Kz	height and exposure factor	1.26		
Fsc	$F_{sc} = \frac{16 \Gamma I_{sc}^2}{10^7 D}$	51.14173228	lbf/ft	
D	conductor spacing	6.096	m	
Fv	Vertical forces	33.7	N/m	
FH	Horizontal forces	158.5331385	N/m	
FT	$F_T = \sqrt{F_V^2 + F_H^2}$	162.0754331	N/m	
I	$I = \sqrt{\frac{q_c + q_r - q_s}{R F}}$	3774.729343	A	
qc	$q_c = 3.906 \times \sqrt{\frac{V}{L}}\, A\, \Delta T$	368.2842272	w/m	
qr	$q_r = 5.6697 \times 10^{-8} \times \varepsilon A \left[(T_C + 273)^4 - (T_a + 273)^4 \right]$	7.827829771	w/m	
qs	$q_S = \varepsilon' Q_S A' K \sin(\theta)$	9.133329028	w/m	
Qs	Solar and sky radiated heat on surface	1028.96		
K	heat multiplying factors for high altitude	1.15		
A'	$A' = \sin \zeta \times A$	0.015437		
theta	$\cos^{-1} [(\cos (H_c) \cos (Z_c - Z_l)]$	90		
Hc	78	78		
Zl	90 for E-W	90		
Zc	the azimuth of sun degrees	180		
F	skin effect coefficient	1		
Rigid Bus Ampacity				
R	0.00003552347204	Ω/m		
Ac	0.00143771964	m^2		
qc	130.9281126	W/m		
qr	61.47963125	W/m		
theta	1.780235837	radians	102	degrees
qs	51.4484733	W/m		
ampacity	1991.999011	A		
D	0.0889	m		
t	0.0054864	m		
C'	40			
A	0.2792875869	m^2/m		
Hc	78	degrees	1.361356817	radians
Zc	180	degrees	3.141592654	radians

Flexible Bus Ampacity

R	DC resistance at operating temperature	0.0000602569938	ohms/m
qc	convective heat loss	70.85288802	W/m
qr	Radiation heat loss	22.09446777	W/m
qs	Solar heat gain	18.49019935	W/m
A	Surface area	0.10037	m^2/m
D	Cylinder diameter	0.03195	m
I	$I = \sqrt{\frac{q_c + q_r - q_s}{RF}}$	1111.602443	A
C'	Conductivity	61	
t	wall thickness	0.0079883	m
Ac	cross-sectional area	0.0006013424541	m^2

Figure 5.3.4 - Bus Calculations

5.4 Non-Functional Testing

Our non-functional testing can be defined as the team sending the values calculated to Black & Veatch and discussing them to make sure that they seem reasonable. If any discrepancies are found during our discussion, we go back and revise them until they are satisfactory.

5.5 Results

Throughout the semesters our results have been positive and approved by Black & Veatch's representatives. We were able to obtain these results after many updates and changes we made. In the first semester the changes were primarily to the array parameter tool and voltage drop calculations, as was seen above.

In the second semester our results from the calculations allowed us to create an acceptable design of a substation which included the final CAD drawings. Using the results from our functional testing, we designed our substation layout as seen in the figure below:

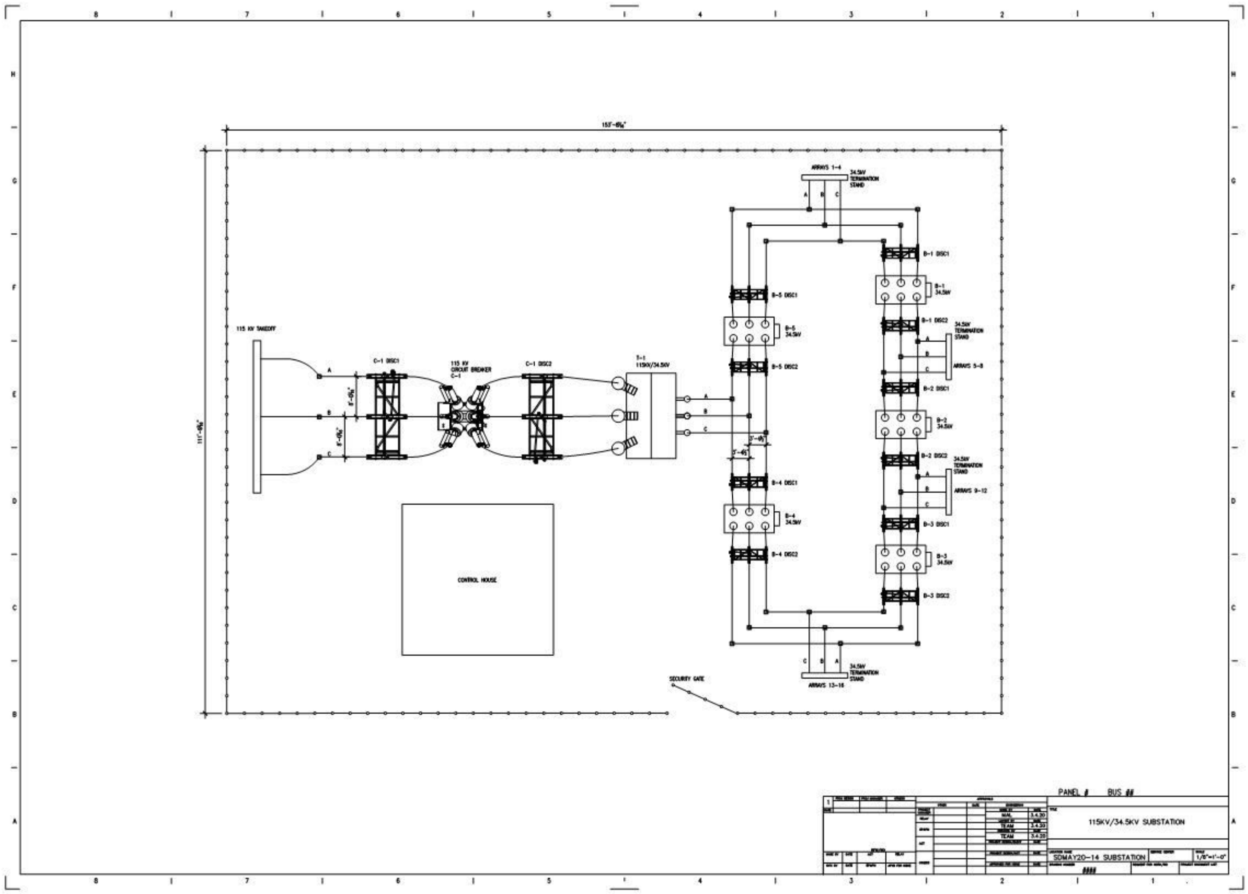

Figure 5.5 - Substation Layout

In this layout, our ring bus is shown on the right side of the substation with our transmission output on the left. It also contains a control house which will be used for daily use and maintenance.

Although we have encountered many challenges and difficulties of understanding various new topics that are necessary for the project, we are able to overcome these obstacles with the help of Black & Veatch, as well as our advisor Dr. AjJarapu.

6. Closing Material

6.1 Conclusion

During the first semester, our design team worked to finalize a 60 Megawatt solar plant. As a team, we have:

- Utilized the provided Array Parameter Tool to determine the quantities of equipment needed.
- Performed voltage drop calculations to determine the size of conductors needed in order to meet NEC guidelines.

- Determine a suitable location for our solar plant with considerations to irradiance, cost of land, and weather patterns.
- Designed a layout in tandem with our voltage drop calculations that minimizes power loss by reducing conductor lengths.

During the spring semester we focused on the design of the substation that will be responsible for integrating our solar plant with the grid. We have provided a final design that adheres to all relevant professional standards and codes. As a team we have:

- Created a one-line diagram for the substation
- Preformed the spacing, grounding, and bus calculations
- Created the CAD drawings for the finalized design
- Write reports for the calculations

The best course of action to reach these goals was to continue our weekly meetings with Black & Veatch. It is through these meetings that we clearly established what professional standards are considered through each phase of design. They also give us key training that we needed in order to utilize the templates they provided for us. We have had the opportunity to ask questions, brainstorm design solutions, and take the next iterative step towards a final design using our abilities as engineers.

Through our time with Black and Veatch has come to an end, we strive to continue using the traits we have learned to be able to maintain an open line of communication in our future employment. We want to thank Black and Veatch for being our mentors and for preparing us for real world problems.

6.2 References

Black & Veatch has provided our group with all necessary files for design work (Array parameter tool, voltage drop calculation spreadsheet, NEC table 3, NEC table 8, substation materials, and other miscellaneous team-based files). In order to use the spreadsheets Black & Veatch provided, we had to find components that fit our design specifications. The datasheets for these components are listed below.

Datasheets For Components:

JA Solar Panel: http://www.wwdfzs.com/uploadfile/2019/0417/20190417043955845.pdf

Eagle Solar Panel:
https://www.jinkosolar.com/ftp/EN%20Eagle%2072PP%20320-340W-V_20.pdf

Bentek PV Harness:

https://www.bentek.com/wp-content/uploads/ds/Bentek-Power-PV-Cable-Harness-DS.pdf

ABB Central Inverter:

https://library.e.abb.com/public/bbbc00f6b0ad4d3f9a703a9a049d53e9/PVS980_central_inverters_flyer_3AXD50000027473_RevJ_EN_lowres.pdf

SolarBOSS Disconnect Combiner:

http://www.solarbos.com/Disconnect-Combiners

Substation Design:

IEEE Guide for Bus Design in Air Insulated Substations:
https://ieeexplore.ieee.org/document/6581801

AFL-Substation-Bus-Conductors:
https://www.aflglobal.com/productionFiles/resources/catalogs/AFL-Substation-Bus-Conductors.aspx

Other Texts Used For Research:

"Photovoltaic Array or Solar Array Uses PV Solar Panels." Alternative Energy Tutorials, www.alternative-energy-tutorials.com/solar-power/pv-array.html.