115kV/ 34.5kV Solar Power Plant & Substation Design Project

FINAL REPORT

sdmay21-37
sdmay21-37@iastate.edu
https://sdmay21-37.sd.ece.iastate.edu

Client: Black & Veatch
Client Mentors: Patrick Kester, Adam Schroeder
Faculty Advisor: Venkataramana Ajjarapu

Christof Barrier
Logan Hinkle
Keve Hughes
Brian Lemke
Cortland Polfliet
Nolan Rogers
Eric Schultz

Revised: April 25th, 2021 / Final

Executive Summary

Development Standards & Practices Used

This is primarily a design-focused project, so we will be adhering to IEEE standards for reporting and documentation, as well as design layouts. We will also adhere to standard practice when designing with Revu Bluebeam. Additionally, we will need to consider any limitations or requirements associated with construction in specific states, specifically New Mexico. We will also need to specifically follow the substation grounding guidelines of IEEE 80 [12]. We will follow the overcurrent/fault protection rules outlined by the NEC. When dealing with relaying, we will utilize proper ANSI device number nomenclature. We will also strictly adhere to the design standards of Black & Veatch to avoid confusion.

Summary of Requirements

- Design 60 MW Solar Field (Fall 2020)
  - Component Selection
  - Select Location
  - Design Layout of Field
  - Voltage Drop Calculations
  - Economic Analysis
- Design Substation to Harness Output from Solar Field (Spring 2021)
  - One-Line Diagram (Protection and Relaying)
  - Bus Plan Diagram and Calculations
  - Trench Fill Tool
  - Grounding Diagram and Calculations
  - Conduit Sizing and Diagram
  - DC Battery Sizing
  - AC Load Calculations

Applicable Courses from Iowa State University Curriculum

- EE 201: Electric Circuits
- EE 230: Electronic Circuits and Systems
- EE 303: Energy Systems and Power Electronics
- EE 455: Energy Distribution Systems
- EE 456: Power System Analysis I
- EE 457: Power System Analysis II

New Skills/Knowledge acquired that was not taught in courses

- Revu Bluebeam design
- One-line diagrams
- Solar farm layout
- Substation layout
- Functionality of solar farm and substation

Table of Contents

Figures

1 Introduction

1.1 Acknowledgement

We would like to acknowledge Black & Veatch as they guided us as we worked through this project. Additionally, we would also like to thank our faculty advisor Dr. Ajjarapu, our TA Rachel Shannon, and our professors Dr. Daniels and Dr. Tyagi.

1.2 Problem and Project Statement

This project sets out to develop a solar farm to increase the use of renewable energy at Black & Veatch. Additionally, a power substation must be created which will allow for the harnessing and distribution of the solar farm's energy. This project is very important because regulations pushing renewable energy on power companies are rapidly increasing and so Black & Veatch must begin to take the necessary steps towards avoiding penalties from these regulations. It is our hope that with projects like this one, we can help to get one step closer to solving the climate change crises. On the other side of this project, we can find importance through the students who are trying to learn about solar energy and power distribution. Through this project, our team of students gained real world experience of what it would be like to work for a power company using methods outlined in Black & Veatch's internal documents.

The final goal of this project is to design a 60MW Solar Power Plant with an accompanying 115/34.5kV substation. This project was split into two semesters with the first semester being focused toward the creation of the solar plant design and the second semester being focused toward the creation of the substation design. To accomplish this, our team of students collaborated with the mentors completing the following deliverables:

Semester 1

- Equipment Selection
- Solar Array Sizing and Design
- Solar Field Layout
- Voltage-Drop Calculations
- Economic Analysis

Semester 2

- One-Line Diagrams (Relaying and Protection Modeling)
- Bus Plan Diagram and Sizing Calculations
- Grounding Diagram and Analysis
- DC Battery Sizing
- Cable Trench Fill Tool
- Cable and Cable Trench Sizing
- Conduit Plan Diagram and Sizing
- AC Load Calculation
- Updated Economic Analysis

In order to stay on track with all of these deliverables, we were required to develop a detailed engineer man-hour budget and schedule for this project; this was a conclusive way to plan the overall project while allowing us to create consistent meeting times within our team and with our mentors. Through the meetings with the mentors via Microsoft Teams, we shared our work with the Black & Veatch engineers. During these weekly meetings, they assessed the work that we completed and offered ideas about how we could further optimize the realism and accuracy of our design.

General Problem Statement

We were tasked with designing a 60 MW solar farm with an accompanying substation to add clean, renewable energy to the American power grid. This project is a "from scratch" design, and while we used the resources provided to us, the overall design of the final project is of our own creation. The purpose of this project was to create a design that Black & Veatch could possibly use as a template for their own projects. This project is intended to increase their use of renewable energy which in turn will help them to meet new regulation guidelines. These regulations directly impact the complex and important issue of climate change.

General Solution Approach

We designed a 60 MW solar farm and substation by selecting appropriate parts and land, and then decided the most cost-effective way to combine and set up the farm. This consisted of appropriately sizing different arrangements solar panels, combiner boxes, and inverters. We accomplished this by using Excel spreadsheets to see how changing parameters in one area affected other areas. This also allowed us to see expected output values of the plant. Once we had the design of the solar plant completed, we then moved on to the design of our substation. This consisted of detailed adherence to IEEE, NEC, and ANSI regulations while following the general direction provided to us by our mentors. For the substation design, we continued to use Excel for calculations. Additionally, we utilized Revu Bluebeam to virtually build and continuously assess our designs to produce a cohesive final product.

1.3 Operational Environment

This solar farm will operate outside in typically hot, sunny weather but also must be able to withstand temperatures below freezing. It must be resistant to common weather conditions of the area, such as thunderstorms or snow. The substation will operate in the same environment as the solar farm as it will only be 50 feet from the solar field.

1.4 Requirements

Functional

- Must be able to operate in environmental conditions as described in section 1.3.
- Power rating at the solar farm of 60 MW
- Adhere to IEEE, NEC, ANSI standards
- Maintain reliability throughout the lifespan of the project
- Minimize voltage drop across solar plant
- Safely ground the entirety of the substation
- Keep the trench cabling capacity under 40%
- Establish overcurrent protection system
- Calculate overall DC and AC loads

Environmental

- Parcel of land must be flat and continuous (i.e. no hills, creeks, ravines)
- High amount of average sunshine per year
- High irradiance on the land
- Substation should be able to safely provide power to nearby communities
- Efficient use of land

Economic

- Our solar plant must be able to produce enough power per year to recover initial investment and operational costs over 10 years.

1.5 Intended Users and Uses

This substation will service the surrounding areas as a support to current infrastructure. This may include spikes in commercial or residential power usage during the daytime.

1.6 Assumptions and Limitations

Assumptions

- The sun will shine a consistent number of hours per year
- A consistent amount of energy will be generated and sold each year
- Power lost to inefficiencies in equipment/transmission will be constant
- Maintenance will remain within reasonable tolerances
- Price per kWh will remain as calculated or better (adjusting with inflation)
- The equipment will perform like new for majority of life cycle

Limitations

- The plant cannot operate at maximum power rating, as power is lost in wires, equipment, and to indirect sunlight.
- The solar farm must be relatively close to customers as to minimize losses during transmission from the substation to the users.
- Land must be flat and continuous (no creeks/ravines/steep hills).

Engineering / Project Limitations

- No physical testing was possible
- Time to complete project was cut short due to shorter semester
- Background knowledge of this project was limited due to limited experience of the students
- Our economic evaluation was based on estimations for the cost of components

1.7 Expected End Product and Deliverables

There are deliverables for this project that were required from both the mentors with Black & Veatch alongside the mentors/professors from Iowa State. The deliverables that were required for our mentors from Iowa State include:

- Discussion posts covering various topics from the lectures.
- Bi-weekly project reports
- Lighting talks
- Design documents
- Bluebeam Drawings
- Team website
- Final report
- Final presentation

The weekly discussion posts allowed us to learn different processes that our mentors from Iowa State think will help throughout the process of this project. The bi-weekly reports helped our own group along with the mentors to keep track of where we are in the project. This involved us stating current problems and solutions that we are dealing with and current parts of the project that we were finishing and starting. The lightning talks were effective in forcing us to practice talking about our project and giving verbal updates for our ISU mentors. This final report is the last deliverable for our ISU mentors which will serve as an all-in-one project description. The team website is a cohesive way of bringing everything together so that the deliverables can be accessed easily from one place. The final presentation is our team's time to present the hard work and dedication that we put into this project.

With the information given by Black & Veatch, we concluded that we were expected to report the following deliverables:

- Equipment sizing calculations
- Solar layout drawing
- Solar panel string sizing design
- Electrical layout drawings (substation equipment)
- Grounding analysis and ground-grid developed with IEEE-80 [13]
- Bus calculations for substation
- Possibility of additional calculations (DC battery bank, Lightning protection, etc.)
- Creation of solar/substation design-optimizing tool

The equipment sizing calculations are excel documents that Black & Veatch outlined for us. These outlines include built-in formulas that were either given to us or were completed throughout the duration of the first semester of this project as our group put everything together. The 2D model of the solar field that we created in excel provides a visual overview of our farm. The rest of the calculations were completed in the second semester of the project and include DC battery, grounding, bus sizing, and AC load calculations. These calculations were used to determine equipment parameters and limits of our substation design.

All these deliverables helped us to maintain a steady workflow, resulting in a well-documented and complete project by the end of this course. At the end of the project, our clients received a completed (2D) virtual model of the solar farm along with the power substation. This included all deliverables listed above as well as a presentation of the overall progress we made throughout this project.

2 Project Plan

2.1 Task Decomposition

Semester 1 Parts Acquisition

- Select Solar Panels based on price, company, and power rating
- Select Combiner Boxes based on price, number of inputs, Amperage rating, and company
- Select Inverter skids based on capacity, inputs, cost, and company

Semester 1 Design

- Design high-level model to better visualize final design
- Design farm layout within land requirements and accessibility
- Design component connections based on part ratings, cost, and power efficiency

Semester 1 Analysis

- Economic efficiency analysis
- Voltage-drop calculations

Semester 2 Design

- Design one-line diagram of substation
- Design bus plan of substation layout
- Grounding grid layout and calculations
- Create the Trench Fill Tool
- Conduit plan and sizing

Semester 2 Analysis

- Use the Trench Fill Tool to estimate conduit plan
- Bus size calculations
- DC battery calculations
- Assess overcurrent/fault protections
- AC load calculations
- Update economic analysis

2.2 Risks And Risk Management/Mitigation

We will not be physically constructing a prototype for our project, so the risks will relate only to performance targets. We have assumed an ideal plot of land that is perfectly flat at the standard elevation of New Mexico and has enough room for the entire layout of the solar plant and substation. One possible risk is that the minimum temperature of the solar plant's location will affect the solar string voltage. To compensate for this, we set the minimum temperature to -40 degrees Celsius. This ensures a risk factor of zero because New Mexico simply does not get that cold at any point in the year. We have designed the system so that the combiner boxes and inverters will all be of adequate strength to handle all their inputs, even with maximum solar output. The solar plant can also store excess power to keep up production on days with less-than-optimal amounts of sunlight. This means that projected average solar output will not be a risk. The risks presented by the design of our substation were far greater than of our solar plant. There is always a risk of injury associated with improper grounding of a substation. To counter this, we designed many possible grounding grid layouts and chose the design with rated step and touch voltages well below the tolerable step and touch voltage amounts. The only possible risk associated with the grounding is that the tolerable voltages were calculated with a body weight of 50kg or 110lbs. This means that the voltages could be less than tolerable if touched by someone weighing less than 110lbs. Another possible risk is ground or arc faults. We handled this issue by adding relays to our substation. These constantly monitor the system for ground or arc faults and shut off power in the necessary areas if a fault occurs. This almost completely ensures that someone will not be injured by a sudden fault, as the maximum amount of time they could be exposed to a fault is 5 milliseconds. As for the possibility of sudden overcurrent, there are breakers spaced at appropriate intervals along our substation to immediately cut off contact with the circuit if overcurrent is detected. The main risk that we encountered as a team was the possibility of falling behind schedule. This ended up not being a problem. We ended the first semester about one week ahead of schedule and we ended the second semester further than any group to previously attempt this senior design project (according to our mentors). We ensured that we did not fall behind by having a weekly meeting with our mentors and at least two weekly meetings with just our team to work on our assigned tasks.

2.3 Project Proposed Milestones, Metrics, and Evaluation Criteria

Solar Plant Design

- Component Selection
- Array Parameter
- Plant Design/Layout
- Voltage Drop Calculation
- Economic Analysis

Substation Design

- Substation Layout
- Trench Fill Tool
- Grounding Calculations
- Bus Calculations
- DC Battery Calculations
- Overcurrent/Fault Protection
- AC Load Calculations

These milestones were evaluated by percentage complete, as well as by how they affected the projected efficiency of the solar plant and substation system. Whereas the first semester milestones were sequential, most of the second semester milestones were concurrent with at least one other milestone. For example, the substation design was constantly being updated based on whatever set of calculations we had done that week. Overall, setting and constantly evaluating milestones helped us form a conclusive view of our project progression.

2.4 Project Timeline/Schedule

		ISU Senior Design Schedule					
	FALL						
1	September 17th	Array Parameter					
2	September 25th	Array Parameter					
3	October 2nd	Array Parameter (due)			Introduce Trench Fill tool creation		
4	October 9th		Voltage Drop Calc	Design of Array	Trench Fill tool creation		
5	October 16th		Voltage Drop Calc	Design of Array	Trench Fill tool creation		
6	October 23rd		Voltage Drop Calc	Design of Array	Trench Fill tool creation		
7	October 30th		Voltage Drop Calc (due)	Design of Array	Trench Fill tool creation		
8	November 6th			Design of Array (Due)	Trench Fill tool creation		
9	November 13th				Trench Fill tool creation		
10 Last fall week	November 20th	Fall Presentation			Trench Fill tool creation		
11	November 27th						
	SPRING						
1	January 29th	Intro to One Line/Substations					
2	February 5th	Intro to One Line/Substations (due)	Creation of One -line				
3	February 12th		Creation of One -line				
4	February 19th		Creation of One -line (& Zones) (due)	Layout of Substation			
5	February 26th			Layout of Substation	Grounding Calc		
6	March 5th			Layout of Substation (due)	Grounding Calc	Bus Calc	
7	March 12th				Grounding Calc	Bus Calc	DC/AC Battery Calc
8	March 19th				Grounding Calc (initial review)	Bus Calc	DC/AC Battery Calc
9	March 26th				Grounding Calc	Bus Calc (initial review)	DC/AC Battery Calc
10	April 2nd				Grounding Calc (due)	Bus Calc	Battery Calc (initial review)
11	April 9th					Bus Calc (due)	DC/AC Battery Calc
12	April 16th						Battery Calc (due)
13	April 28th	Final Presentation					
14 Last spring wee	April 30th						
15	May 7th						

Figure 1 - Proposed Project Schedule

The figure above (Figure 1) outlines the project schedule that we followed. The creation of the Trench Fill Tool was postponed until after the fall semester had ended, as we felt it would be more relevant to our work with the substation. We began working with this tool over winter break and into the spring semester. The figures below (figure 2 and figure 3) show the Gantt charts that we created, which more accurately depicts our progress and timeline of accomplishments over the course of the fall and spring semesters.

Senior Design Project: GANTT CHART

					Start Date:	17-Aug	24-Aug	31-Aug	7-Sep	14-Sep	21-Sep	28-Sep	5-Oct	12-Oct	19-Oct	26-Oct	2-Nov
TASK NAME	**START DATE**	**END DATE**	**DURATION (WORK DAYS)**	**TEAM MEMBER**	**PERCENT COMPLETE**	**WEEK 1**	**WEEK 2**	**WEEK 3**	**WEEK 4**	**WEEK 5**	**WEEK 6**	**WEEK 7**	**WEEK 8**	**WEEK 9**	**WEEK 10**	**WEEK 11**	**WEEK 12**
Parts Acquistion																	
Solar Panels	8/24	9/7	14	Eric Schultz	100%												
				Christof Barrier													
Combiner Boxes	8/24	9/7	14	Cortland Polfliet													
				Nolan Rogers													
Inverter Skid	8/24	9/7	14	Brian Lemke													
				Keve Hughes													
Location Data	8/24	9/7	14	Logan Hinkle													
Design																	
High Level Model for Visualization	9/7	9/21	14	Eric Schultz	100%												
				Christof Barrier													
Component Attachments	9/7	9/21	14	Logan Hinkle	100%												
				Nolan Rogers													
				Keve Hughes													
Array Parameter Tool	9/14	10/5	21	Eric Schultz	100%												
				Christof Barrier													
				Cortland Polfliet													
				Nolan Rogers													
				Brian Lemke													
				Keve Hughes													
				Logan Hinkle													
Farm Layout	9/28	10/5	7	Eric Schultz	100%												
Calculations																	
Economic Estimates	10/5	10/19	14	Cortland Polfliet	100%												
				Christof Barrier													
				Brian Lemke													
				Nolan Rogers													
				Logan Hinkle													
				Eric Schultz													
				Keve Hughes													
Voltage Drop	10/5	11/2	28	Cortland Polfliet	100%												
				Christof Barrier													
				Brian Lemke													
				Nolan Rogers													
				Logan Hinkle													
				Eric Schultz													
				Keve Hughes													

Figure 2 - Gantt Chart for Fall

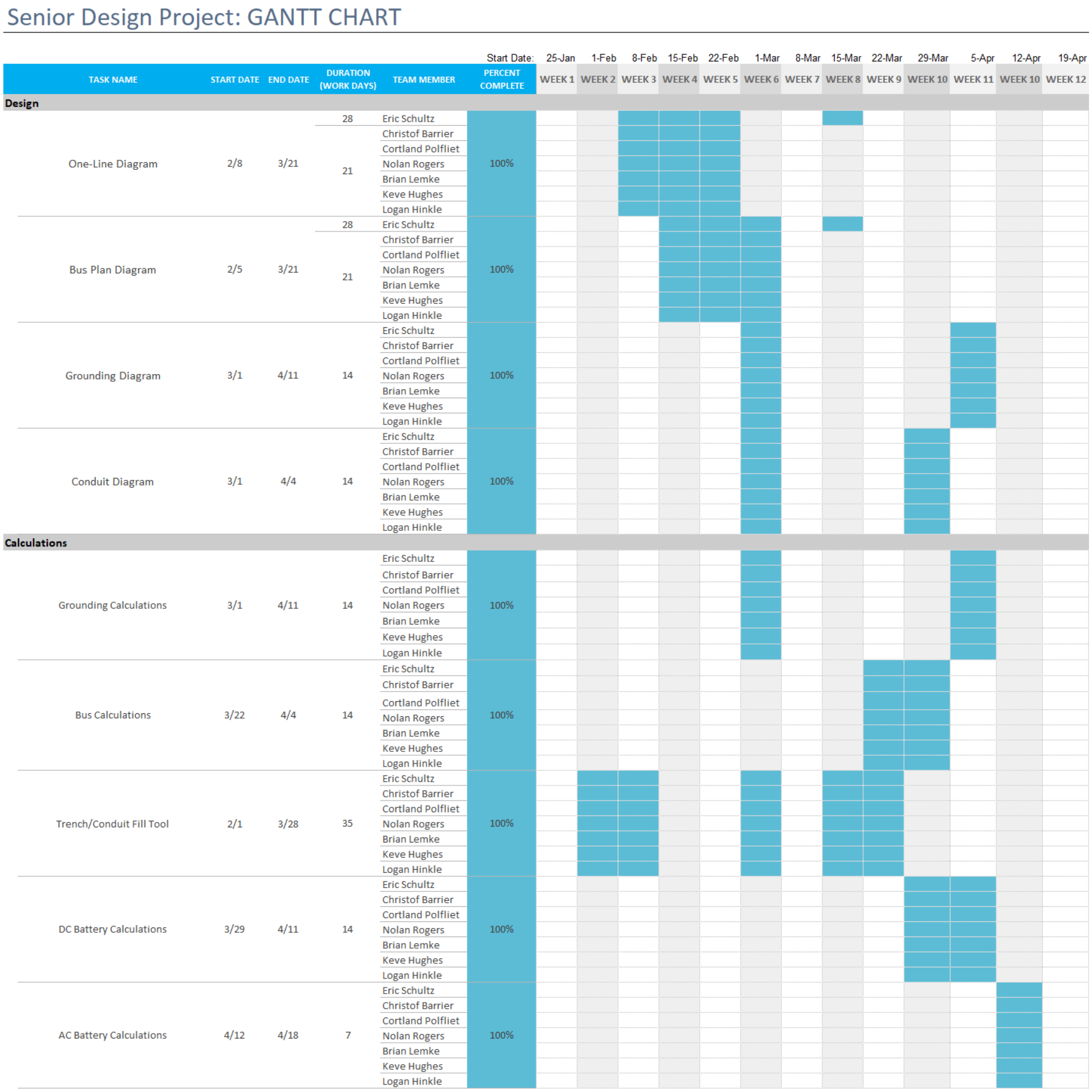


Figure 3 - Gantt Chart for Spring

2.5 Project Tracking Procedures

Our group used Microsoft Teams and Google Drive to communicate and collaborate on all project materials. We met with our mentors every week via Microsoft Teams. In these meetings we presented our weekly progress reports along with any questions from the previous week's workload, and if any issues arose throughout the week we communicated with our mentors via email. We tracked progress by adhering to strict deadlines for the various tasks necessary to complete the project. Additionally, we held team meetings without our mentors at least once per week to discuss progress on tasks and to determine if additional resources needed to be reallocated to the completion of a specific task.

2.6 Personnel Effort Requirements

All tasks have been completed by dividing work amongst team members via our weekly group meetings. The mentors gave the team tasks from the senior design schedule, which were divided amongst the team members during our team meetings.

2.7 Other Resource Requirements

We required access to solar field modeling tools, namely the Array Design Parameter Tool we used to model our initial solar field design. These tools were largely provided by our mentors. We also needed access to software for designing things in the spring semester. We discussed using Revit or AutoCAD but decided on using Revu Bluebeam because some of us have had experience using that software and we could get it for free as students. We also used Microsoft Excel for our trench fill, grounding, bus size, and battery calculations. For battery sizing, we utilized the online EnerSys BSP battery sizing program.

2.8 Financial Requirements

Given that our project is simply designing the solar field and substation there were no actual financial requirements. The software used for design was free to use because we were ISU students. If our project was to completely build the solar plant and substation, the cost would be many millions of dollars. Our Array Parameter Tool had a section for calculating the total cost of our required parts based on an estimated per-unit component cost. Our mentors suggested that we evaluate the 10-year cash flow of the solar plant with and without axis tracking technology. They also said that we were not going to use axis tracking technology because there were many additional factors that come with axis tracking that would complicate our calculations. The first semester economic evaluation is shown below.

No Axis Tracking

$13/kW

Installation Cost	O+M/yr	Inflation Rate	Yearly Revenue
$ 106,020,000.00	$ 780,000.00	3.22%	$ 12,989,088.00

$1767/kW

Cash Flow

Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
$ (106,020,000.00)	$ 12,209,088.00	$ 12,602,220.63	$ 13,008,012.14	$ 13,426,870.13	$ 13,859,215.35	$ 14,305,482.08	$ 14,766,118.60	$ 15,241,587.62	$ 15,732,366.74	$ 16,238,948.95

Present Value

Years	Installation Cost	O+M	Revenue	Profit
10	$ (106,020,000.00)	($6,579,475.14)	$ 141,389,910.25	$ 28,790,435.12

With Axis Tracking

$14/kW

Installation Cost	O+M/yr	Inflation Rate	Yearly Revenue
$ 110,040,000.00	$ 840,000.00	3.22%	$ 16,203,887.28

$1834/kW

Cash Flow

Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
$ (110,040,000.00)	$ 15,363,887.28	$ 15,858,604.45	$ 16,369,251.51	$ 16,896,341.41	$ 17,440,403.61	$ 18,001,984.60	$ 18,581,648.51	$ 19,179,977.59	$ 19,797,572.87	$ 20,435,054.71

Present Value

Years	Installation Cost	O+M	Revenue	Profit
10	$ (110,040,000.00)	($7,085,588.61)	$ 177,924,726.54	$ 60,799,137.93

Figure 4 - Fall Semester Economic Evaluation

Due to the changes made to our project in the spring semester, we figured it would be inaccurate to use the evaluation from the fall semester. We talked with our mentors about price estimates for construction, equipment, and operation/maintenance costs of our substation. We also elected to only evaluate the solar plant without axis-tracking, as that is the design our mentors recommended. Shown below is our economic evaluation to include both our solar plant and our substation.

No Axis Tracking	$13/kW		
Installation Cost	O+M/yr	Inflation Rate	Yearly Revenue
$ 113,020,000.00	$ 1,000,000.00	3.22%	$ 12,989,088.00
$1767/kW			

Cash Flow										
Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
$ (113,020,000.00)	$ 11,989,088.00	$ 12,375,136.63	$ 12,773,616.03	$ 13,184,926.47	$ 13,609,481.10	$ 14,047,706.39	$ 14,500,042.54	$ 14,966,943.91	$ 15,448,879.50	$ 15,946,333.42

Present Value				
Years	Installation Cost	O+M	Revenue	Profit
10	$ (113,020,000.00)	($8,435,224.53)	$ 138,842,154.00	$ 17,386,929.47

Figure 5 - Spring Semester Economic Evaluation

3 Design

3.1 Previous Work And Literature

The design of solar farms and substations has well established practices and methodologies to maximize efficiency. Our mentors at Black & Veatch guided our design process to follow these standard practices. The general layout of a solar array is strings of solar panels connected in parallel, forming racks, which are then linked into combiner boxes. The combiner box outputs are then fed into inverters, which contain the transformer shown in the schematic below. Efficiency has been a constant problem in solar power, as power is lost in equipment, transmission, and due to uncontrollable variables, such as temperature. Some of the advantageous design choices involve strategic placement of combiner boxes and skids to minimize the amount of cable used in the farm. The graphic below shows a sample layout of a traditional solar array.

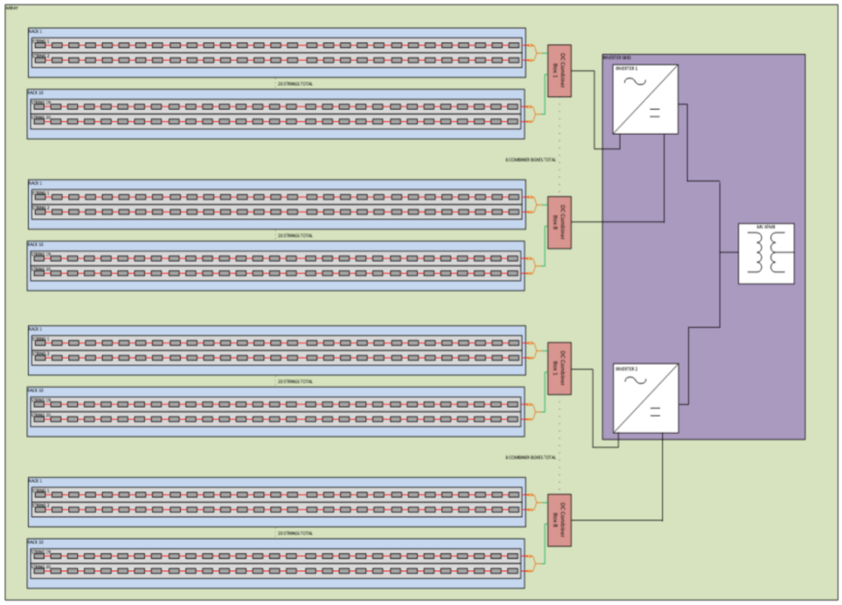


Figure 6 - Sample Solar Array Layout

As for our second semester substation design, Black & Veatch provided us with a toolbox of common substation components for use in our Revu Bluebeam designs. One of our first tasks was to determine what type of bus configuration to use. There are several common configurations and we researched different options in order to find what would work best for our substation. We primarily made use of information on the EEP website as well as recommendations from our industry mentors who have designed similar substations in the past [9]. We chose to use a ring bus layout because of its simplicity, flexibility, and expandability. Additionally, we consulted IEEE [12] documentation to guide our design and calculation process. This documentation gave equations, sample example calculations, and explanations which we consulted for many of our calculations. pictured below is an example ring bus layout which we modified for use in our substation.

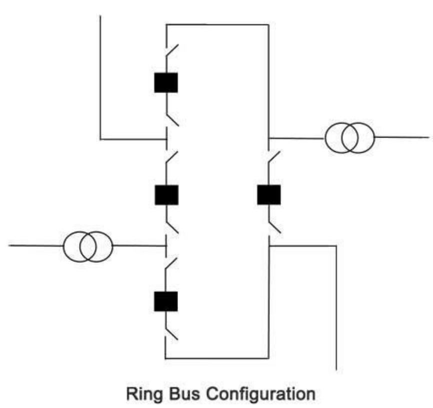


Figure 7 - Sample Ring Bus Layout [9]

3.2 Design Thinking

Much of our design process has been driven by the guidance of our client, Black & Veatch. They provided us with the specifications to meet during different design steps, as well as with advice about common design principles for solar farms and substations.

Some of the important decisions we made about the design of our solar farm were the wattage of the solar panels, the location we would build the solar farm, and the location of the combiner boxes and inverters with respect to the solar panels. We elected to use the 410W solar panels instead of the 340W option to minimize the number of panels needed. As for the location of combiner boxes and inverters, we elected to use a centralized design to minimize overall voltage drop across the circuit. We compared two locations, one in Iowa and one in New Mexico. The property in New Mexico would be significantly better than the property in Iowa. The property in New Mexico has over 100 more sunny days, higher average irradiance each month, much more acreage that can be used to expand the solar farm, and is considerably cheaper than the property in Iowa. The land in New Mexico costs about $750 an acre, and gets approximately 310 sunny days per year.

As for the substation, we utilized the EEP website shown to us by our mentors to narrow down our bus configuration to a ring bus [9] This type of bus provides an optimal amount of safety for maintenance and overcurrent protection, and it is also highly flexible in terms of design. One part of the substation design that was largely left to our discretion was the arrangement of the grounding grid and distribution of grounding rods. We determined that the grid should be divided into smaller squares with grounding rods at the intersections (also sometimes at the middle of the squares) to make efficient use of the given space. We'll talk in greater depth about the design decisions we made for grounding later in this report, as this was a massive portion of our work in the second semester.

3.3 Proposed Design

This project consisted of two separate but related designing processes, divided between the fall and spring semesters. In the fall, our goal was to design a solar farm that produces 60 MW of power. After completing this design, we focused our efforts on designing a substation that can take the power generated from that solar farm and safely prepare it for high-voltage transmission.

3.3.1 Solar Plant Design

We have designed the layout of the panels, combiner boxes, and inverter skids, as well as the components and layout of the substation. The basic idea behind our thinking was to maximize our efficiency on wiring and solar power collection. We made use of the array parameter tool with component choices to guide the layout we created. Below we can see the parameters used in our array parameter tool:

String Size		Electrical Rack Size		Combiner Box Capacity		Array Design		Array Size	
Min. Temp. (location)	-40° C	Module Width (hor.)	3.36 ft	String I_{SC}	10.55 A	Racks per Row	6	Tilt	35°
		Module Length (vert.)	6.64 ft			Rows per Array	34	Adjusted Length	10.88 ft
V_{OC}	49.5 V			NEC Multiplier	1.25	Racks Removed	2		
Reference Temp. (STC)	25° C	Modules per String	25	Nominal I_{SC}	13.19 A			Row Spacing	15 ft
		Strings per Rack	2			Racks per Array	202	Access Road	35 ft
Temp. Coeff. of V_{OC}	-0.26%/°C			Irr. Multiplier	1.25	Modules per Array	10100		
Temp. Delta	-65° C	Modules per Rack	50	Max I_{SC}	16.48 A			Array Width	504 ft
Temp. Correction	1.17					Module Capacity	410 W	Array Length	885 ft
Corrected V_{OC}	57.865 V	Rack Width (hor.)	84 ft	Allowed Current	400 A	DC Capacity	4141 kW	Array Area	446,040 ft^2
		Rack Length (vert.)	13.28 ft	Strings per CB	24.265				10.24 acres
String Voltage	1500 V			(Round Down)	24	Inverter Capacity	3200 kW		
String Size	25.9222			Racks per CB	12			Plant Width	2,520 ft
(Round Down)	25					ILR (must be < 1.3)	1.29406	Plant Length	2,685 ft
Actual String Voltage	1446.6 V			CB per Array	16.833			Plant Area	6,766,200 ft^2
				(Round Up)	17				155.33 acres

Figure 8 - Array Parameter Tool

Using this parameter tool, we determined that there would be 25 solar panels in each string, resulting in 50 solar panels per rack. For the layout of the racks, we settled on 6 racks per row, with 34 rows per array. In each array, there will be 2 racks removed to provide space for the inverter skid, and there will be a 35 ft wide access road running through the middle for maintenance. Based on these calculations, each full array will produce 4.141 MW of power. Since our target power for the entire solar field is 60 MW, we needed approximately 14 full arrays and 1 half-array, resulting in a total system output of 60.024 MW. The layout of a full array as well as the half-array is shown below.

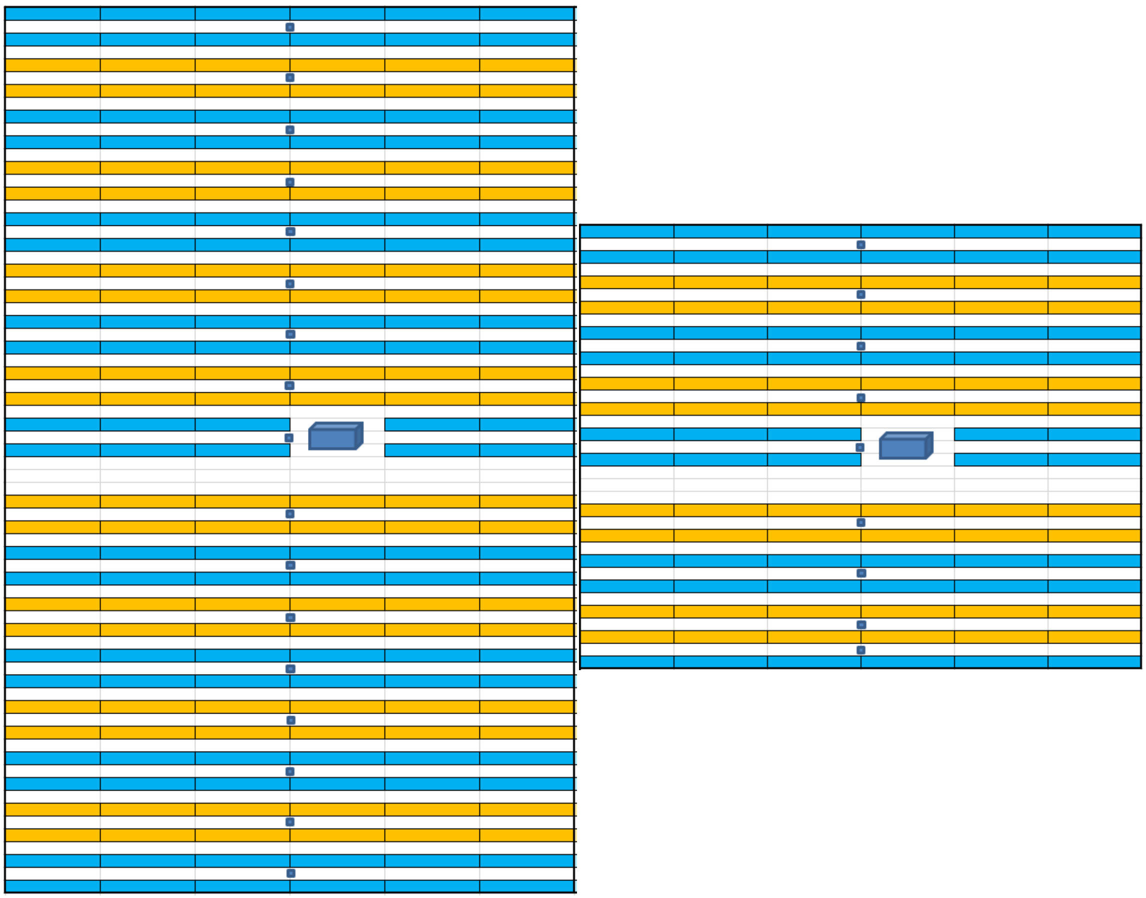


Figure 9 - Full-Array and Half-Array Layouts

Each blue/orange rectangle represents a single rack. The large box in the middle of the array represents the inverter skid, while the smaller dark blue squares represent combiner boxes. Each full array contains 10,100 solar panels, 17 combiner boxes, and one inverter skid.

The full combined layout of the ~14.5 arrays will have a total length of 2,684.59 ft and a total width of 2,520 ft, resulting in a total area of 6,765,168.3 ft, approximately 155.3 acres. The proposed full-sized layout is shown below.

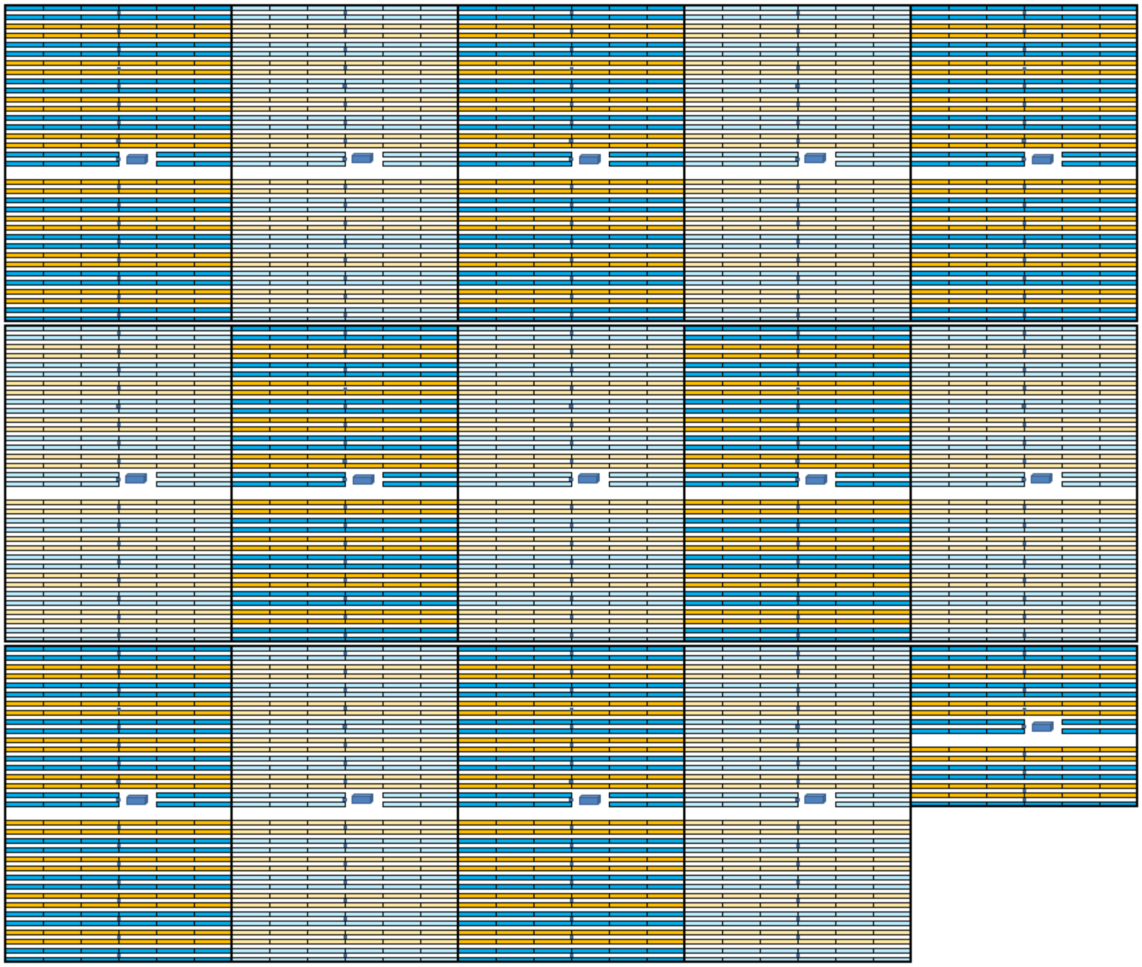


Figure 10 - Multiple Array Layout

Having well-defined information on how to design a solar farm and substation has been very helpful for us. It allows us to focus more on getting this piece of infrastructure built in a timely manner - something important in a renewable energy industry that is continuously innovating and creating more efficient products. However, one downside to having such rigid constraints is removal of creativity in a way - we cannot go out and create something completely original the way an artist might. Efficiency and conformity are rewarded in an industry like this; the most effective plant designs are ones that amalgamate all the best parts of other plans.

We also had to calculate the size of the wires connecting our solar plant. There were many factors to consider, such as outdoor conditions, maximum current flow, and temperature. Using NEC tables (shown in Chapter 6 of this document) we were able to accurately size the wires to minimize voltage drop of the wires to less than 3%, which was our target value. The tables below show a filled-out version of the voltage drop calculation document given to us by Black & Veatch for the 14 full arrays and the 1 half array.

12 Rack Combiner Box:

DCB	Strings per Rack	ISC for String	String Length	String wire size	String Conductor Resistance	String Resistance	Voltage Drop of String	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	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
DCB1-02	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-03	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-04	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-05	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-06	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
DCB1-07	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
DCB1-08	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-09	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-10	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-11	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-12	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
10 Rack Combiner Box:													
DCB9-01	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	0.78	0.279	9.490
DCB9-02	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	0.78	0.152	5.181
DCB9-03	2	16.484	84	12	1.98	0.322	5.483	32.968	17	10	0.78	0.025	0.872
DCB9-04	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	0.78	0.152	5.181
DCB9-05	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	0.78	0.279	9.490
DCB9-06	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	0.78	0.279	9.490
DCB9-07	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	0.78	0.152	5.181
DCB9-08	2	16.484	84	12	1.98	0.322	5.483	32.968	17	10	0.78	0.025	0.872
DCB9-09	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	0.78	0.152	5.181
DCB9-10	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	0.78	0.279	9.490

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	12	395.616	410	600	0.0214	0.01693	6.942	0.71%	44.972	1500	3.00%
DCB2	12	395.616	367	600	0.0214	0.01558	6.214	0.64%	44.729	1500	2.98%
DCB3	12	395.616	324	600	0.0214	0.01345	5.486	0.56%	44.486	1500	2.97%
DCB4	12	395.616	281	600	0.0214	0.01161	4.758	0.49%	44.243	1500	2.95%
DCB5	12	395.616	238	600	0.0214	0.00987	4.030	0.41%	44.001	1500	2.93%
DCB6	12	395.616	195	600	0.0214	0.00803	3.302	0.34%	43.758	1500	2.92%
DCB7	12	395.616	152	600	0.0214	0.00629	2.574	0.26%	43.515	1500	2.90%
DCB8	12	395.616	109	600	0.0214	0.00455	1.846	0.19%	43.273	1500	2.88%
DCB9	10	395.616	38	600	0.0214	0.00155	0.643	0.07%	42.872	1500	2.86%
DCB10	12	395.616	75	600	0.0214	0.00310	1.270	0.13%	43.081	1500	2.87%
DCB11	12	395.616	118	600	0.0214	0.00494	1.998	0.21%	43.323	1500	2.89%
DCB12	12	395.616	161	600	0.0214	0.00668	2.726	0.28%	43.566	1500	2.90%
DCB13	12	395.616	204	600	0.0214	0.00842	3.454	0.36%	43.809	1500	2.92%
DCB14	12	395.616	247	600	0.0214	0.01026	4.182	0.43%	44.052	1500	2.94%
DCB15	12	395.616	290	600	0.0214	0.01200	4.910	0.51%	44.294	1500	2.95%
DCB16	12	395.616	333	600	0.0214	0.01384	5.638	0.58%	44.537	1500	2.97%
DCB17	12	395.616	376	600	0.0214	0.01557	6.367	0.65%	44.780	1500	2.99%
									Average of worst-case DCB voltage drop:		**2.93%**

Temperature correction for resistance:		
α_{cu}	0.00323	/°C
α_{al}	0.00330	/°C
T_a	60	°C
$T_{a'}$	70	°C
KRcu	-0.032	
K_{Ral}	-0.033	

$$V_d = \frac{2LR_2I}{1000}$$

Where: V_d = voltage drop over circuit length (volts)

L = length of circuit (ft)

R_2 = resistance of conductor from Equation (ohm/kft)

I = maximum power current of circuit (amps)

Figure 11 - Full-Array Voltage Drop Calculations

DCB	Strings per Rack	ISC for String	String Length	String wire size	String Conductor Resistance	String Resistance	Voltage Drop of String	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
12 Rack Combiner Box:													
DCB1-01	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
DCB1-02	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-03	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-04	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-05	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-06	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
DCB1-07	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
DCB1-08	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-09	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-10	2	16.484	84	12	1.98	0.322	5.483	32.968	17	8	0.778	0.025	0.872
DCB1-11	2	16.484	84	12	1.98	0.322	5.483	32.968	101	8	0.778	0.152	5.181
DCB1-12	2	16.484	84	12	1.98	0.322	5.483	32.968	185	8	0.778	0.279	9.490
10 Rack Combiner Box:													
DCB5-01	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	1.240	0.444	15.126
DCB5-02	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	1.240	0.242	8.258
DCB5-03	2	16.484	84	12	1.98	0.322	5.483	32.968	17	10	1.240	0.041	1.390
DCB5-04	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	1.240	0.242	8.258
DCB5-05	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	1.240	0.444	15.126
DCB5-06	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	1.240	0.444	15.126
DCB5-07	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	1.240	0.242	8.258
DCB5-08	2	16.484	84	12	1.98	0.322	5.483	32.968	17	10	1.240	0.041	1.390
DCB5-09	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	1.240	0.242	8.258
DCB5-10	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	1.240	0.444	15.126
6 Rack Combiner Box:													
DCB9-01	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	1.240	0.444	15.126
DCB9-02	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	1.240	0.242	8.258
DCB9-03	2	16.484	84	12	1.98	0.322	5.483	32.968	17	10	1.240	0.041	1.390
DCB9-04	2	16.484	84	12	1.98	0.322	5.483	32.968	17	10	1.240	0.041	1.390
DCB9-05	2	16.484	84	12	1.98	0.322	5.483	32.968	101	10	1.240	0.242	8.258
DCB9-06	2	16.484	84	12	1.98	0.322	5.483	32.968	185	10	1.240	0.444	15.126

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	12	395.616	238	600	0.0214	0.00987	4.030	0.41%	44.001	1500	2.93%
DCB2	12	395.616	195	600	0.0214	0.00803	3.302	0.34%	43.758	1500	2.92%
DCB3	12	395.616	152	600	0.0214	0.00629	2.574	0.26%	43.515	1500	2.90%
DCB4	12	395.616	109	600	0.0214	0.00455	1.846	0.19%	43.273	1500	2.88%
DCB5	10	395.616	38	600	0.0214	0.00155	0.643	0.07%	42.872	1500	2.86%
DCB6	12	395.616	75	600	0.0214	0.00310	1.270	0.13%	43.081	1500	2.87%
DCB7	12	395.616	118	600	0.0214	0.00494	1.998	0.21%	43.323	1500	2.89%
DCB8	12	395.616	161	600	0.0214	0.00668	2.726	0.28%	43.566	1500	2.90%
DCB9	6	395.616	204	600	0.0214	0.00842	3.454	0.36%	43.809	1500	2.92%
									Average of worst-case DCB voltage drop:		2.90%

Temperature correction for resistance:		
α_{cu}	0.00323	/°C
α_{al}	0.00330	/°C
T_a	60	°C
$T_{a'}$	70	°C
KRcu	-0.032	
K_{Ral}	-0.033	

$$V_d = \frac{2LR_2I}{1000}$$

Where: V_d = voltage drop over circuit length (volts)
L = length of circuit (ft)
R_2 = resistance of conductor from Equation (ohm/kft)
I = maximum power current of circuit (amps)

Figure 12 - Half-Array Voltage Drop Calculations

3.3.2 Substation Design

The power generated by the solar field is carried along three main feeder lines at a voltage of 34.5 kV each. These feeders serve as inputs to our substation with a total combined load of 1739.83 A. The power then travels through a bus network before reaching a step-up transformer which increases the voltage from 34.5kV to 115kV for long-distance transmission. In terms of bus arrangement, we contemplated between a ring configuration and a breaker-and-a-half configuration. While the breaker-and-a-half configuration would offer more protection and reliability, we elected to go with the ring configuration as it requires less components and streamlines our design process while maintaining sufficient protection. This configuration prevents the entire system from failing due to a fault or overcurrent by isolating the affected components for maintenance while rerouting the power through the other side of the ring.

3.3.2.1 One-Line Diagram

The first step in designing this substation was the creation of our one-line diagram, which establishes the configuration of our ring bus network while modeling fault and overcurrent protection via primary and secondary relaying. The ring bus network that we designed consists of four 34.5 kV breakers and one 115kV breaker, with each breaker being monitored by two primary and two secondary current transformers for use in relay protection. The 115/34.5kV transformer is monitored via four primary and four secondary current transformers, however the four current transformers on the high-voltage (115kV) side of the transformers are unused, and therefore shorted. Regarding relaying, we utilized SEL-411L and SEL-311L relays for the primary and secondary differential protection of each breaker as well as for long-distance fault protection. Additionally, we used SEL-487E relays for the differential protection of the 115/34.5kV transformer and SEL-451 relays for transformer overcurrent protection. The one-line diagram is shown in Appendix II, consisting of two drawings which include the layout of our zones of protection as well as our relaying model.

3.3.2.2 Bus Plan Diagram

After completing the one-line diagram, our next task was to design a three-phase bus plan diagram that accurately portrays the scale and location of each component of the substation as well as the spacing between various elements. To accomplish this, we first needed to determine minimum spacing and clearances for all metal components and cables according to ANSI C37-32 standards [15]. Once proper sizing and spacing was established for each component and structure, we proceeded with the design of the bus plan. This included the addition of a protective fence that extends 15 feet beyond any substation equipment as well as a control structure and accompanying cable trench to house our underground wiring and control systems. The design of this diagram was quite intensive and was often updated throughout the semester as we received more information regarding other calculations, serving as the foundation for the remaining diagrams detailed in 3.3.2.3 and 3.3.2.8. The bus plan diagram is shown in Appendix II.

3.3.2.3 Grounding Calculation and Diagram

The design of the grounding system in a substation is an important aspect that protects personnel and equipment during a fault condition. Grounding systems typically include a "mesh" of bare copper conductor that is placed in the soil beneath the substation equipment. All equipment is then connected to this mesh, which allows for any phase-to-ground faults to travel through the ground conductors and the soil back to its source. It is important that the fault current has multiple paths back to its source in order to protect any nearby personnel from dangerous voltages that exist in the soil and on the equipment within the substation. Our task was to design a grounding grid for our proposed substation area that meets requirements set by IEEE-80 while considering several given parameters, shown below. This calculation process involved calculating a tolerable step and touch voltage which served as a maximum limit that we could not exceed. These calculations are shown in the figure below.

Variable	Description	Value	Units	Soil Measurements: probe spacing (ft)	soil resistivity (Ω-m)
IG	max grid current	32	kA	1	120
IGrms	rms grid current	22.627	kA	2	85
tc	fault duration	1	s	3	65
ts	shock duration	0.5	s	6	48
hs	surface layer thickness	0.15	m	10	32
ps	surface layer resistivity	3000	Ω-m	20	24
Cs	surface layer derating factor	0.8		30	20
w	body weight	50	kg		
T	ambient temp	40	°C		
h	conductor depth	0.15	m		

Variable	Description	Value	Units	Use Value	Units
D	spacing b/w conductors	12	ft	3.657	m
Lc	total length of grid conductor	2340	ft	713.197	m
Lp	peripheral length of grid	456	ft	138.982	m
Lx	max length of grid in x	132	ft	40.232	m
Ly	max length of grid in y	96	ft	29.259	m
Dm	max distance b/w two points	163.218	ft	49.746	m
A	total area enclosed by grid	12672	ft^2	1177.152	m^2
Lr	length of indv. ground rod	20	ft	6.096	m
nr	number of ground rods	278		278	
LR	total length of ground rods	5560	ft	1694.605	m
Cs	surface layer derating factor	0.8		0.8	

Variable	Description	Value	Units
C	material conductivity	100	%
αr	at 20 °C	0.00393	1/°C
Ko	at 0 °C	234	0 °C
Tm	fusing temp	1083	°C
pr	resistivity at 20 °C	1.72	μΩ-cm
TCAP	thermal capacity	3.42	J/(cm^3-°C)

Uniform Soil Resistivity

$$\rho_{a(av1)} = \frac{\rho_{a(1)} + \rho_{a(2)} + \rho_{a(3)} + \dots + \rho_{a(n)}}{n}$$

n is the number of samples

ρa = 56.2857 Ω-m

Minimum Conductor Size

$$I = 5.07 \cdot 10^{-3} A_{kcmil} \sqrt{\left(\frac{TCAP}{t_c \alpha_r \rho_r}\right)} \ln\left(\frac{K_o + T_m}{K_o + T_a}\right)$$

min size = 158.353 kcmil (3/0 AWG - not typically used)

use size= 211.6 kcmil (4/0 AWG - smallest typically used)

d = 0.011684 m

Tolerable Voltages

$$E_{step50} = (1000 + 6C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}}$$

at 50 kg

Estep = 2526.351 V

$$E_{touch50} = (1000 + 1.5C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}}$$

at 50 kg

Etouch = 754.6244 V

Figure 13 - First Half of Grounding Calculations

After calculating our maximum tolerances, we then experimented with various conductor spacings and grounding rod configurations in an attempt to optimize our specific substation step and touch voltages to below those tolerances. After a number of attempts, we ultimately elected to implement a conductor spacing of 12 ft using 4/0 AWG conductors. Our final design included 278 grounding rods that are 20 feet in length, which we understand is a very inconceivable number of grounding rods. After discussing with our mentors at Black & Veatch, we concluded that the reasons for the incredibly large number of grounding rods included the fact that we did not have access to the intensive grounding programs that are readily available and widely used in the field. In our case, we simply followed an IEEE guide that leaves many considerations out of the equation. Another possible reason for the large number of grounding rods is that our soil was input as relatively poor. Our calculations possibly could have been made simpler if we had considered a soil with less uniform soil resistivity.

This was by far the most challenging and confusing aspect of our design process, as it became incredibly tedious to optimize spacing in addition to the amount of ground rods required. Part of the reason for this was that we found inconsistencies with one of the equations given to us. The IEEE grounding guide mandated that a certain geometrical factor "n_d" should be equivalent to 1 for square or rectangular substations. Previous teams who attempted this project had completely overlooked this, instead electing to use a very small fraction rather than 1 for n_d. This perfectly explains why their grounding calculations seemed so optimal with the inclusion of far fewer grounding rods than our team. The image below shows the second half of our finalized grounding calculations.

Maximum Step Voltage

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \qquad n_a = \frac{2 \cdot L_C}{L_p}$$

$$n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}}$$

$n_c = 1$ for square and rectangular grids

$n_d = 1$ for square, rectangular and L-shaped grids

na =	10.2632
nb =	1.0063
nc =	1
nd =	1
n =	10.3281

$$K_s = \frac{1}{\pi}\left[\frac{1}{2 \cdot h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right] \qquad K_i = 0.644 + 0.148 \cdot n \qquad L_s = 0.75 \cdot L_C + 0.85 \cdot L_R$$

Ks = 1.2314 Ki = 2.1726 Ls = 1975.312 m

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_S}$$

Es = 2439.3988 V

Maximum Mesh (Touch) Voltage

$$K_h = \sqrt{1 + \frac{h}{h_o}} \qquad h_o = 1\text{m (grid reference depth)}1$$

Kh = 1.0724

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln\left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{K_{ii}}{K_h} \cdot \ln\left[\frac{8}{\pi(2 \cdot n - 1)}\right]\right]$$

Km = 0.692

$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right]L_R$$

Lm = 3593.168 m

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M}$$

Em = 753.5130 V

Figure 14 - Second Half of Grounding Calculations

3.3.2.4 Bus Calculation

The purpose of high voltage buses in substations is to interconnect the various pieces of equipment to form the desired bus configuration, which in our case was a ring bus configuration. The buses may either provide controlled paths for current to flow between the connected equipment or may maintain the equipment at the same potential. To operate successfully over an extended period, a substation bus must be designed to meet a diverse variety of criteria. The basic task of a substation bus designer is to select the bus conductor, components, and arrangement to meet each of the criteria at the least possible expense to the owner. For the purposes of this project, our group calculated only a few of the necessary calculations needed to complete a full bus calculation. Black

& Veatch provided us with a large list of variables relating to the material properties of the conductors or insulators, some of which we converted to different units for ease of use. The image below shows these given values.

Variable	Description	Value	Units		
ΔT	temp diff b/w ambient and conductor surface	50	Deg. Celsius		
T2,Tc	conductor temp	90	Deg. Celsius		
Ɛ	emissivity for new aluminium	0.2			
Ɛ	emissivity for weathered aluminum	0.5			
Ta	ambient temp	40	Deg. Celsius		
Ɛ'	solar absorption	0.5			
E	modulus of elasticity for aluminum	6.89E+10	N/m^2		
Fg	gravitational force	3.37E+01	N/m^2		
σ	allowable stress of material accounting for welds	120	MPa	120000000	Pa
Wc	specific weight of aluminum	26500	N/m^3		
Wi	ice weight	8820	N/m^3		
Ri	equivalent uniform radial ice thickness	0.00635	mPa		
C	constant, for metric units	0.613			
V	extreme wind velocity	40	m/s		
Cf	force coefficient for rigid tubular bus	1			
Gf	gust response factor	0.85			
I	importance factor	1.15			
Isc	short-circuit current	15	kA	15000	A
Γ	constant based on type of fault and conductor location	0.866			
Kf	mounting structure flexibility factor	1			
Df	half cycle decrement factor	0.927			
η	allowable deflection as a fraction of span length	0.0067			
D rigid	outside diameter	3.5	in	0.088900178	m
t rigid	wall thickness	0.216	in	0.005486411	m
D flex	diameter	1.258	in	0.031953264	m
C'	conductivitiy at 20 Deg. Celsius in % of IACS	55			
Hc	Altitude of sun for latitude of 30°N at noon time	83	deg		
Zc	Azimuth of sun for latitude of 30°N at noon time	180	deg		
Zl	Azimuth of conductor line for a north– south orientatior	0	deg		
Qs	for latitude of 30°N at noon, Hc = 83 and Zc=180.	1032.6	W/m		
F	skin effect coefficient	1			
K	Heat multiplying factor based on elevation of 336 m, int	1.036			
C' Flex		61			
Kz	Height and exposure factor	0.57			

Figure 15 – Given Values for Bus Calculation

Our substation consists of rigid buses that form the skeleton of our bus configuration along with flexible buses that connect each major piece of equipment to the rigid bus. Although we have two voltage classes, 115kV and 34.5kV, we will be using the same size rigid and flexible bus for both classes. We conducted the following calculations with an assumed 15kA fault current, representing the worst-case scenario for the substation. Based on our feeder load current of 1739.83 A, we established our rigid bus to be a 3-inch nominal 6061-T6 schedule 40 pipe, and our flexible bus to be 1113-45/7 Bluejay ACSR. Our first task in this calculation was to verify that our feeder load current would not exceed the maximum allowable current capacity of our selected bus conductors, adhering to the guidelines of IEEE 605. This calculation is shown in the figure below.

Ampacity

$$R = \frac{1.724\times10^{-6}}{C' A_c}\left(1+\frac{0.00403C'}{61}(T_2-20)\right) \quad A_c = \frac{\pi}{4}\times\left[(D)^2-(D-2\times t)^2\right]$$

$$A = \pi D l \quad q_c = 3.561\, D^{-0.4}\, A\, \Delta T \quad q_s = \varepsilon' Q_s A' K \sin(\theta) \quad \theta = \cos^{-1}\left[\cos H_c \cos(Z_c - Z_1)\right]$$

$$q_r = 5.6697\times10^{-8}\,\varepsilon\, A\left[(T_c+273)^4-(T_a+273)^4\right] \quad I = \sqrt{\frac{q_c+q_r-q_s}{RF}}$$

Rigid	Ac =	0.001437725	m^2	(calculated using equation above)
	R =	2.73475E-05	Ohms/m	
	A =	0.279288145	m^2	
	qc =	130.9282697	W/m	
	qr =	24.59190168	W/m	
	θ =	97	degrees	
	qs =	47.19708972	W/m	
	I =	**1990.221419**	**A**	
Flexible	Ac =	0.000563965	m^2	(converted from 1113 kcmil)
	R =	6.42506E-05	Ohms/m	
	A =	0.100384139	m^2	
	qc =	70.85997365	W/m	
	qr =	8.839032091	W/m	
	θ =	97	degrees	
	qs =	16.96398253	W/m	
	I =	**988.135368**	**A**	

Figure 16 - Bus Calculation (Ampacity)

According to these calculations, the maximum allowable current of our rigid conductor is 1990.22 A. In our configuration, two flexible buses branch from the rigid conductor to each major component, resulting in a combined maximum ampacity of 2 x 988.135 A = 1976.27 A. This confirms that both of our selected bus conductors can handle the load of 1739.83 A coming into our substation.

Our next step was to calculate the forces acting upon our rigid bus, specifically the weight of the conductor, F_c, the wind load, F_w, the force of a short circuit, $F_{sc\_corrected}$, and the total gravitational force, F_G. This calculation is shown below (Figure 16).

Forces

$$F_c = \pi w_c t_c (D_o - t_c) \quad F_G = F_c$$

$$F_{sc\_corrected} = D_f^2 K_f F_{sc} = D_f^2 K_f \left(\frac{16\,\Gamma\, I_{sc}^2}{10^7 D}\right)$$

$$F_w = C V^2 D_o C_f K_Z G_f I$$

Rigid	**Fc =**	**38.100**	**N/m**
	Fw =	**48.582**	**N/m**
	Fsc.corr. =	**292.984**	**N/m**
	Fg =	**38.100**	**N/m**
	Ft1 =	343.684	N/m

Figure 17 - Bus Calculation (Forces)

The final step of this bus calculation was to determine the maximum distance that our rigid bus can span without requiring additional bus supports. We performed this calculation twice, first based on the deflection limit and second based on fiber stress, and chose the fewer of the two to be our maximum span.

Span

$$L_V = \left(\frac{384 E J \eta}{5 F_G}\right)^{\frac{1}{3}} \qquad J = \pi \frac{\left(D_o^4 - D_i^4\right)}{64} \qquad L_S = \sqrt{\frac{16 J \sigma_{\text{allowable}}}{F_T D_o}}$$

Rigid	J =	1.25585E-06	m^4	
	Lv =	10.53310807	m	
	Ls =	**8.883573211**	**m**	(this would be what we choose)

Figure 18 - Bus Calculation (Span)

3.3.2.5 DC Battery Sizing Calculation

Battery Sizing

Number of Cells = $\dfrac{\text{Maximum Battery Voltage}}{\text{Recharge Volts/Cell}}$

= $\dfrac{\text{140 Volts}}{\text{2.33 Volts/Cell}}$

= 60.09 Cells (60 cells are required)

End of Discharge Voltage = $\dfrac{\text{Minimum Battery Voltage}}{\text{Number of Cells}}$

= $\dfrac{\text{105 Volts}}{\text{60 Cells}}$

= 1.75 Volts/Cell

Determination of Loads for Duty Cycle

<u>*Continuous Loads*</u>

SEL-411L	5 @ 0.28 *A*	=	1.4 *A*
SEL-311L	5 @ 0.2 *A*	=	1 *A*
SEL-487E	2 @ 0.28 *A*	=	0.56 *A*
SEL-451	2 @ 0.28 *A*	=	0.56 *A*
Battery Monitoring Equipment		=	0.024 *A*
DC Ammeter		=	0.048 *A*
DC Voltmeter		=	0.048 *A*
SACO Annunciator (L8)	6 @ 0.12 *A*	=	0.72 *A*
Edwards Bell		=	0.012 *A*
Indicating LEDs	8 @ 0.017 *A*	=	0.136 *A*
		=	4.508 *A*

Continuous Load = 4.508 *amps* (*use* 5.0 *amps for continuous loads to be conservative*)

<u>Momentary Loads</u>

34.5 *kV Breakers:*	*Tripping Current* = 3.3 *A*	*Closing Current* = 2.6 *A*
115 *kV Breakers:*	*Tripping Current* = 6.6 *A*	*Closing Current* = 3.6 *A*

Determination of Duty Cycle

A) 115 *kV bus fault:* 1 - 115 *kV breaker would trip; if that breaker failed,* 2 - 34.5 *kV breakers would also trip.*

1 - 115 *kV breaker with a trip coil current inrush of* 6.6 *A*. 1 x 6.6 *A* = 6.6 *A*

2 - 34.5 *kV breakers with a trip coil current inrush of* 3.3 *A each.* 2 x 3.3 *A* = 6.6 *A*

Total current inrush = <u>13.2 *A*</u>

B) 115/34.5 *kV transformer fault:* 1 - 115 *kV breaker would trip, and* 2 - 34.5 *kV breakers would trip; if either* 34.5 *kV breaker failed,* 1 *additional* 34.5 *kV breaker would also trip.*

1 - 115 *kV breaker with a trip coil current inrush of* 6.6 *A*. 1 x 6.6 *A* = 6.6 *A*

3 - 34.5 *kV breakers with a trip coil current inrush of* 3.3 *A each.* 3 x 3.3 *A* = 9.9 *A*

Total current inrush = <u>16.5 *A*</u>

Situation (B) provides the worst-case dc load for a fault condition with 16.5 *amps.*

@ Time T = 0 *min,*

Trip the 115 *kV breaker with a trip coil current inrush of* 6.6 *A, and* 3 - 34.5 *kV breakers with a trip coil current inrush of* 3.3 *A each. Include continuous load current.*

Trip Load	*6.6 A + 3(3.3 A)*	=	16.5 *A*
Continuous Load		=	5.0 *A*
	Total Load	=	<u>21.5 *A*</u>

@ T = 1 *min,*

Continuous load for 239 *minutes.*

Continuous Load		=	5.0 *A*
	Total Load	=	<u>5.0 *A*</u>

@ T = 240 *min,*

Close the 115 kV breaker with a close coil current inrush of 3.6 A, then the 3 - 34.5 kV breakers one at a time with a close coil current inrush of 2.6 A each. Include continuous load current.

$$\text{Close Load} \qquad 3.6\,A + 3(2.6\,A) = 11.4\,A$$

$$\text{Continuous Load} \qquad = 5.0\,A$$

$$\text{Total Load} \qquad = \underline{16.4\,A}$$

Based on the data gathered from this calculation, we generated a sizing report using the IEEE-485 method via EnerSys. According to that report, we would need one string of (20) CA-03M rated at 50 AH with a margin of 11%.

3.3.2.6 AC Load Calculation

The goal of the AC load calculations was to determine the AC current draw on our system. This involved adding up the individual AC loads of all substation components, which were calculated by dividing the rated wattage by the rated voltage and multiplying by the number of specific components. The image below shows our method of calculating these loads.

Assumptions

1. 180VA load per Outlet assumed as worst case
2. The worst case scenario will be as follows:
   a) Time of day: Day (no lights on).
   b) Temperature: 90 deg F (all Transformer fans on).
   c) Battery: Deep discharge (charger on full).
3. Worst case tripping conditions shall be as follows:
   a) 115/34.5 kV transformer fault
      - (1) 115 kV breaker will trip
      - (2) 34.5 kV breakers will trip

[i] - Ratings estimated.

Calculations

The continuous 120/240VAC single phase loads are as follows:

Assumed Values:

Breaker Motor 720W at 240V
Feeder Motor 720W at 240V
Breaker Recepticle and Lights 210W at 120V
Transformer Fans 24,000W, 100A at 240V
Transformer Sump Pump 2000W at 240V
Control House Lighting 20 Qty at 36W each running at 120V
Yard Lights 55W at 120V
HVAC System 10,000W at 240V
Fire Detection Equipment 150W at 120V
Exhaust Fan 132W at 120V

		Quantity	Load/Unit(W)	Amps (ea)	Voltage(V)	Total(W)	Amps Total
AC Panel - Control Building	All Transformer Fans	1	24,000	100.00	240	24,000	100.00
	Transformer Sump Pump	1	2,000	8.33	240	2,000	8.33
	Control House Llghting	20	36	0.30	120	720	6.00
	Breaker Recepticle and Lights	5	210	1.75	120	1,050	8.75
	Yard Lights (Daytime)	0	55	0.46	120	0	0.00
	HVAC System	1	10,000	41.67	240	10,000	41.67
	Fire Detection Equipment	1	150	1.25	120	150	1.25
	Exhaust Fan	1	132	1.10	120	132	1.10
	Power Outlets (One for each piece of equipment)	6	180	1.50	120	1,080	9.00
	AC Battery Charger	1	3,360	14.00	240	3,360	14.00
		0	0	0.00	120	0	0.00
		0	0	0.00	120	0	0.00
		0	0	0.00	120	0	0.00
	Worst Case Tripping:						
	High Side Breaker Motor	1	720	3.00	240	720	3.00
	Low Side Breaker Motor	2	720	3.00	240	1,440	6.00
	Total Worse Case AC Panel Load					43,212	199.10

Total Worst Case Load (+10 %)	**47,533**	**219.01**

Sizing Recommendations:
Station Service - 50kVA
MTS, Safety Switch - 225A

Figure 19 - AC Load Calculation

Based on the total worst-case load of 47663 W, we decided to size our station service at 50 kVA. We sized the safety switch based on the total current load of the system, sizing up from 219.01 to 225 A.

We also had to size the battery charger for our substation battery. We ended up with a value of 8.25 but rounded up to the minimum size supplied which is 25. The image below shows how we sized that battery charger for our substation.

Battery Charger Sizing

$$A = L + \frac{AHR * K}{T}$$

AHR (Ah)	21	
K	1.15	
L	7.5	(from DC battery calc, continuous load)
T (h)	32	
A	8.25	
A	25	(round up to be conservative)

Figure 20 – Battery Charger Sizing

3.3.2.7 Trench Fill Tool

At the start of the semester, our mentors challenged us to create a trench fill tool that helps size substation cable trenches. The cable trench and corresponding conduit route auxiliary power and control cables from the control house out to main pieces of equipment like the transformer and circuit breakers. The central focus of the calculation was to minimize the trench size while still meeting the standard fill capacity of 40% as outlined by IEEE standard 525-2007 [18]. This tool helped us design our substation and will be utilized in the future by B&V. Our calculation used standard cable and sizes for substation equipment. The total cross-sectional area of cable running through our trench came out to 119 in^2 and adhering to the 40% fill constraint corresponds to a minimum cable trench area of 297 in^2. Of course, cable trenches from Trenwa/Old Castle come in standard sizes so we need to select the next closest size up, 300 in^2 for Trenwa trench.

Component	Number of Components	Component Area (in²)	Total Area (in²)
Transfomers	1	15.64	15.64
Breakers	5	16.42	82.12
Lighting	8	2.62	20.99
Component Total			118.76
Minimum Allowable Trench Area			296.89
		Trenwa Trench Area	300
		Oldcastle Trench Area	430

Figure 21 – Trench Fill Tool Inputs

Equipment		Cable Quantity	# of Conductors	Cable Size	Gauge area (in²)	Area (in²)	AWG
Transformer							
	AC Power	4	4	9	0.317	1.268	3/C#8W/#10GND
		1	4	6	0.407	0.407	3/C#6W/#8GND
	AC Test	1	4	9	0.317	0.317	3/C#8W/#10GND
	DC Power	1	1	2/C#1	7.069	7.069	2/C#1
		1	4	9	0.656	0.656	T-401
	Control	2	9	14	0.656	1.312	T-401
		2	4	9	0.656	1.312	T-401
		6	4	14	0.105	0.63	4/C#14
	Fiber Optic	1	12	MMF	0.049	0.049	12 COUNT MM
	CT	3	4	9	0.656	1.968	T-401
	Sump Pump	1	4	9	0.656	0.656	T-401
Transfomer Total						**15.64**	
Breakers							
	Control	5	9	9	1.202	6.01	T-901
		2	4	9	0.656	1.312	T-401
		4	9	14	0.656	2.624	T-914
		6	4	14	0.38	2.28	T-414
	AC Power	2	4	9	0.407	0.814	3/C#6W/#8GND
	PT	2	4	14	0.38	0.76	T-414
	CT	4	4	9	0.656	2.624	T-401
Breaker Total						**16.42**	
Lighting							
		4	4	9	0.656	2.624	T-401

Figure 22 – Trench Fill Tool Calculations

3.3.2.8 Conduit Plan Diagram

Using the trench fill tool that we created, our final task was to properly size and model the PVC pipe conduits which house the cables that connect various pieces of equipment into the cable trench, and subsequently to the control structure. Typically, in practice, a maximum of 5-inch nominal PVC pipe is used for conduit planning, which we adhered to in our substation design. Utilizing the same 40% fill constraint as before, we calculated the cross-sectional area of the cables for each piece major piece of equipment and distributed them amongst different sizes of PVC pipes accordingly while considering our constraints. The diagram of this conduit plan is shown in Appendix II.

Component	Conduit Area Needed (per piece of equipment)	40% PVC Pipe Area
Transformer	15.64	19.8157
Circuit Breaker	16.42	19.8157
Lighting	2.624	2.9072

Figure 23 – Conduit PVC Sizing

3.4 Technology Considerations

Solar panel technology is evolving, and as a result, large amounts of equipment with vastly different specifications is available. Higher wattage solar panels produce more energy in less space but are more expensive and require equipment that can handle the larger load. Copper cables are more efficient than aluminum cables, however they are significantly more expensive at the gauge required to transfer utility scale power. Sun tracking technology increases efficiency of the solar panels and generates more power but involves more maintenance and higher installation costs. The trade-off in equipment is usually power/efficiency for cost. After careful research, economic evaluation, and discussion with our mentors, we concluded that using axis-tracking technology was unneeded. The benefit of producing more power is outweighed by the added installation and maintenance costs and because we already are producing enough power due to the sheer number of solar panels. As for the specific tilt angle of our panels, multiple sources claimed that an angle between 30 and 40 degrees is optimal for an area like New Mexico. Given that we did not adjust the angle of our panels throughout the year, it makes more sense to go with the angle that provides the best year-round results. Winter has a lower sunshine output, so optimizing our tilt angle to maximize power in winter is the way to go. This gives us an angle of 35 degrees, which will compensate for the lower sunlight levels in the New Mexico winter. This careful design is the only way to minimize the impact of the tradeoffs.

The technological considerations for the substation mostly revolve around protections and monitoring systems. Most of the other components are a set standard and we did not have many options to choose from in that regard. The DC system in the substation was designed based on constraints given to us by Black & Veatch to meet their desired specifications. The battery which gives power to relaying and tripping devices needed to be sized in accordance with a "worst-case" fault scenario in which three circuit breakers trip. Another technological consideration that we encountered during the substation design was proper relay placement. There are multiple ways to set up relays depending on which bus type you choose, so we talked with our mentors about the optimal relay arrangement for our specific design. We ended up having to add a few grounded current transformers after the 34.5/115kV transformer to allow for more rigorous relaying setup. The relay and protection devices in our design came from SEL due to their high quality and dependability [14]. Detailed data pulled from cutsheets on the SEL website helped us complete the

DC battery sizing for the substation. Substation design is a well-established industry practice and there are many less technological considerations to deal with compared to designing a solar farm.

3.5 Design Analysis

Our solar array design works well. We completed all necessary documents on time and successfully met the technical requirements outlined for us by Black & Veatch. The 410 W panels generate the 60 MW required using the least amount of space, while not overloading the equipment and keeping the costs as low as we can. Our design iterations have involved tweaking the number of panels in the arrays as well as trying out different types of cable in our design to minimize voltage drop.

The final substation design also turned out wonderfully. Completion and review of all design tools along with comparisons to the projects of past groups demonstrated that we successfully met guiding requirements established at the beginning of the semester. The ring bus layout connected the solar plant and substation perfectly and the 12x12 foot grounding grid matched up evenly with the overall dimensions of the substation. All equipment is well protected from harmful overcurrents and fault events thanks to our rigorous protection network of circuit breakers and relays.

3.6 Development Process

We have adopted a Waterfall development process for this project. This method makes sense for us as our requirements have been laid out specifically for us by Black & Veatch and following with a high-level design to detailed design is the most straightforward way to getting to a final product.

3.7 Design Plan

Our design did take into consideration intended users and use cases from section 1.5, however, they were not as important as other technical aspects of our design. For example, we researched potential locations and completed an economic evaluation of the project; factors which are usually very important considerations for a project like this. However, our solar plant will not actually be constructed so these considerations just gave us a better conceptual understanding of our design and did not significantly affect its technical aspects. The vast majority of our design plan focused on meeting the technical requirements for the solar plant and substation such as component choice, physical layout, and generating capacity because they were most pertinent to the overall design. These requirements were laid out by our Black & Veatch mentors who pushed us to design our solar plant to meet the constraints as closely as we could.

The figure below shows a high-level overview of how Black & Veatch and our intended users informed our design requirements. Our design process was centered around meeting these requirements. Component selection includes the panels, inverters, combiner boxes, and cables for the solar plant. Substation components include current transformers, disconnect switches, circuit breakers, relay and protection equipment, DC batteries, and the power transformer. The solar array layout encompasses string/rack sizes, array size and layout, panel tilt, and row spacing. Substation layout includes bus breaker scheme, trench routing, grounding grid, and control enclosure placement.

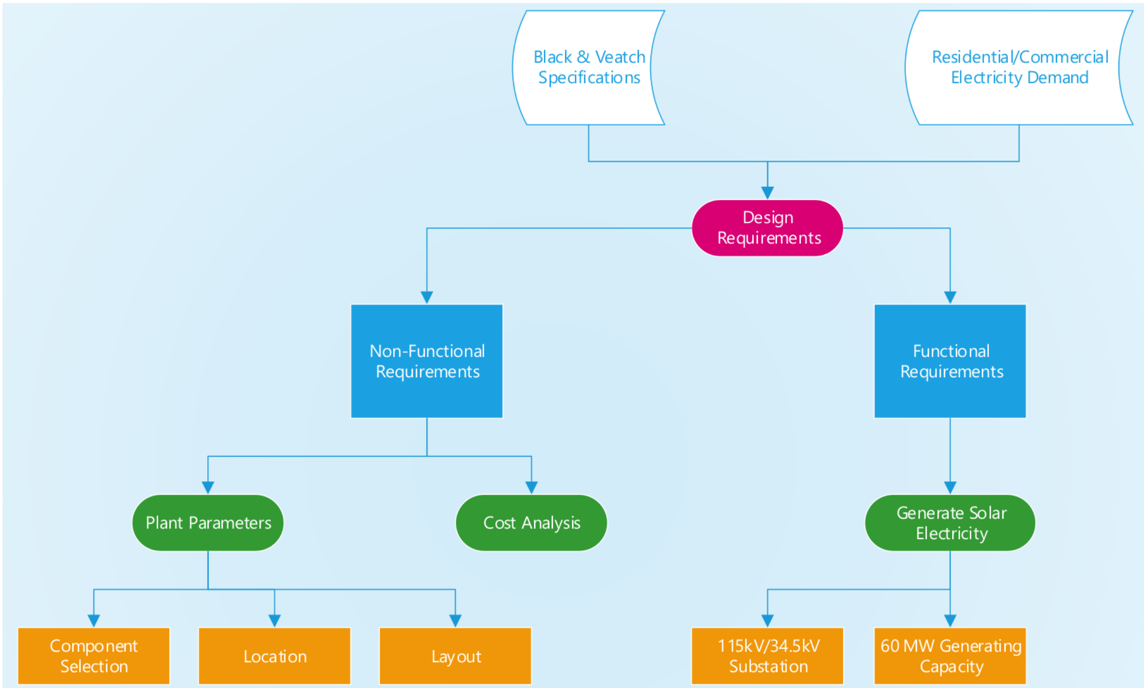


Figure 24 - Plant Design Flowchart

4 Testing

Within our project, individual unit testing is not directly related to the desired outcome. The type of testing we did is based more on iterative calculations that met predetermined constraints such as in the array parameter tool and the voltage drop calculation for the solar array portion of the project. Similarly, the grounding calculation, bus load calculation, and battery sizing test were all iterative calculation tests that guided our design for the substation. Furthermore, we did cost analysis on the project to see what our return on investment would be. Again, because we are not physically building this project, no real-world tests were conducted. Despite this, we gained an understanding of what kind of challenges arise when designing and building a utility scale solar farm and step-up substation in industry practice.

One of the challenges we encountered while testing the array parameter tool was confusion of the terminology used because it is proprietary to Black & Veatch. We were able to clear this up by asking our mentors questions and researching other plant designs. When we moved into the second semester, we also had challenges with testing the grounding grid. We discovered errors in some parameter assumptions which were given to us by our industry mentors. We raised these concerns to our mentors, and they agreed that previous groups had failed to recognize these errors. One way industry clients avoid this type of error is by using a dedicated program to complete the grounding calculation. Due to financial constraints, we did not have access to this type of software.

4.1 Unit Testing

Under the category of unit testing, we worked on the solar farm and substation design as separate entities. Within the solar farm design, we have a few different topics that we spent multiple weeks testing and refining (array parameter tool, voltage drop calculator, and economic analysis). A very similar process carried us through the second semester where we focused on the substation design and analysis. Documents and calculations we tested include the grounding grid, trench fill tool, DC battery calculation, and bus load calculation. For the purposes of our project, each of these were treated as individual units and were continually tested and improved as they are not physical designs but rather conceptual units.

4.2 Interface Testing

Interface testing was not utilized in our first semester while we were designing the solar panel array field, but it did come into play while we designed the corresponding substation. When selecting which substation bus configuration to use, we had to consider the size and layout of our solar array to ensure the substation protection scheme was appropriately set up. Synthesizing our solar farm with the substation ensures the designs fit together seamlessly to squeeze the most power possible out of the panels. This consideration led us to select a ring bus which is simple, effective, and easily expandable in case the solar field is expanded in the future.

4.3 Acceptance Testing

To show that we met the design requirements, we presented our findings, testing, and designs with our peer mentors in our weekly meetings. There, we received feedback and criticisms to ensure that we were moving in the right direction. Over the course of the week, we would tweak and optimize our designs to better match the expectations of our mentors.

4.4 Results

In our iterative testing of the array parameter tool, we encountered two main obstacles. First, we needed to get familiar with all the terminology and background information and second, we needed an understanding of how the array parameter tool worked. We were successful in this endeavor and were able to design a 60MW solar farm consisting of modules split into 14.5 arrays of panels. This requires 1 inverter per array, for a total of 18 inverters, and 247 combiner boxes.

The next aspect of our project, the substation, also had some obstacles. The first was understanding how to use Bluebeam software in order to build our diagrams. The second was designing tools to help us determine the sizing of certain components of the substation. We utilized Excel to do this and were successful in creating a substation design within the constraints provided to us. This is a ring bus configuration with 4 low-side breakers and 1 high-side breaker, a 34.5kV/115kV 20MVA step-up transformer. We also created a grounding grid consisting of a 12ft x 12ft conductor mesh which reduces ground potentials caused by high voltage equipment. The relay control houses a 60 cell DC battery capable of delivering 24 A to breakers and protection equipment under the worst-case fault scenario.

Our cost analysis shows that we will turn a ten-year profit of about $17.4 million. Government subsidies and bonuses for solar applications may mean it is possible that the solar plant could make even more of a profit. This is very promising as the life of these solar panels is 25 years, meaning there will be 15 more years of high profitability. The voltage-drop calculations helped us determine how to efficiently wire our solar farm to minimize losses across wires, which means there will be less wear and tear on the system and help ensure the 25-year lifespan.

5 Implementation

We will not be directly involved with the implementation of this project. Our two semesters involved two separate, yet intertwined, design projects, and as such, we will not have time to see a fully built solar farm or substation of our design. Any and all implementation will be handled by Black & Veatch.

6 Closing Material

6.1 Conclusion

In the first semester we completed selection and sizing of solar farm components, and analyzed voltage drop and layout options. We have also done cost analysis for return on investment over the course of 10 years and it looks promising. In the second semester we amended the economic analysis to include substation equipment, construction, and operation costs. Although the added cost of the substation reduces overall profits of the project, it will still generate a positive return on investment after 10 years. Design of the substation included one-line diagrams for bus configuration, grounding, and overall substation design including breakers, lighting, and a transformer. These design specifications were all selected based on calculations for safe and efficient operation of the solar farm. We believe this farm is a solid investment for anyone wanting to provide more renewable energy to the US power grid.

6.2 References

[1] C. R. Landau, *Optimum Tilt of Solar Panels*, 18-Mar-2017. [Online]. Available: https://solarpaneltilt.com/

[2] J. Marsh, "Best Solar Panel Angle by Zip Code in 2020: EnergySage," *Solar News*, 15-Jul-2020. [Online]. Available: https://news.energysage.com/whats-the-best-angle-for-my-solar-panels/

[3] J. Sandhu, "Best solar panel angle: How do you find it - and does it matter?" *Solar Reviews*, 22-Oct-2020. [Online]. Available: https://www.solarreviews.com/blog/best-solar-panel-angle

[4] "NeON 2: NeON: Products: Solar: Business," *LG Global Business Solutions*, 2019-2020. [Online]. Available: https://www.lg.com/global/business/neon-2

[5] "Wire Gauge and Current Limits Including Skin Depth and Strength," *PowerStream* , 18-Oct-2019. [Online]. Available: https://www.powerstream.com/Wire_Size.htm

[6] "LG410N2W-V5 Cut Sheet," *LG Solar*, 2019. [Online]. Available: https://www.lg.com/us/business/download/resources/CT00002151/LG410N2W-V5_AUS_FinalVer_083019[20200306_084005].pdf

[7] "Disconnect Combiners," SolarBOS Disconnect Combiners. [Online]. Available: https://d3g1qce46u5dao.cloudfront.net/data_sheet/solarbos_disconnect_combiners__1_.pd f

[8] "Solar inverter PVS980-CS-US Compact Skid for US Market," *FIMER*, 2020. [Online]. Available: https://www.fimer.com/sites/default/files/FIMER_PVS980-CS_US-CompaktskidforUSmarket_US_Rev_A.PDF

[9] "6 common bus configurations in substations up to 345 kV," Electrical Engineering Portal, 2019. [Online]. Available: https://electrical-engineering-portal.com/bus-configurations-substations-345-kv

[10] "NEC Table 8 Conductor Properties," [Online]. Available: http://necaibewelectricians.com/wp-content/uploads/2013/11/Table_8-Conductor-Propertie s-.pdf.

[11] "Conductor Ampacity Based on the 2011 National Electrical Code," *manualzz.com*. [Online]. Available: https://manualzz.com/doc/11130693/nec-tables.

[12] "IEEE guide for safety in AC substation grounding - IEEE Std 80-2000." [Online]. Available: http://www.dee.ufrj.br/~acsl/grad/equipamentos/IEEE-std80.pdf.

[13] "POWERING THE FUTURE," *EnerSys BSP. BatterySizingProgram*. [Online]. Available: https://bsp.enersys.com/bsp/index.do.

[14] “SEL Home,” *selinc* [Online]. Available: https://selinc.com/.

[15] "American National Standard for High Voltage Switches, Bus Supports, and Accessories Schedules of Preferred Ratings, Construction Guidelines, and Specifications," in IEEE Std C37.32-2002 , vol., no., pp.1-42 doi: 10.1109/IEEESTD.2003.7116714. [Online], Available: https://ieeexplore.ieee.org/document/7116714

[16] "IEEE Guide for Bus Design in Air Insulated Substations," in *IEEE Std 605-2008 (Revision of IEEE Std 605-1998 / Incorporates IEEE Std 605a-2010)* , vol., no., pp.1-247, 14 May 2010, doi: 10.1109/IEEESTD.2010.658180 [Online], Available: https://ieeexplore.ieee.org/document/6581801

[17] “AT30 Battery Charger,” *mdspower.com*. [Online]. Available: https://www.mdspower.com/img/product/description/HindlePower/AT30-Battery-Charger-Specs.pdf.

[18] “ IEEE 525-2007,” *ewh.ieee.org*. [Online]. Available: https://ewh.ieee.org/cmte/substations/scdo/wgd2/IEEE 525 - standard/IEEE 525-2007_accepted.pdf.

[19] “One Piece Multi-Duty Trench,” *Trenwa*. [Online]. Available: https://www.trenwa.com/trench-products/one-piece-mp-trench/.

[20] “Trench,” *Oldcastle Infrastructure*. [Online]. Available: https://oldcastleinfrastructure.com/product/trench/.

[21] “PVC Piping Dimension Chart for Sch 40 & Sch 80,” *Commercial Industrial Supply Product Specs, Industry Knowledge & More*. [Online]. Available: https://www.commercial-industrial-supply.com/resource-center/pvc-pipe-and-fittings-dimensions/.

[22] “AFL-Substation-Bus-Conductors,” aflglobal. [Online]. Available: https://www.aflglobal.com/productionFiles/resources/catalogs/AFL-Substation-Bus-Conductors.aspx.

[23] “Aluminum Conductor. Steel Reinforced . Bare.,” ACSR. [Online]. Available: https://assets.southwire.com/ImConvServlet/imconv/6e40b948ad8bbb2c69490138659678cbf373c912/origin?assetDescr=ACSR-Dec-2020.

6.3 Appendices

Appendix I: Pertinent Tables

Table 8 Conductor Properties

			Conductors							Direct-Current Resistance at 75°C (167°F)					
			Stranding			Overall				Copper					
Size (AWG or kcmil)	Area			Diameter		Diameter		Area		Uncoated		Coated		Aluminum	
	mm²	Circular mils	Quantity	mm	in.	mm	in.	mm²	in.²	ohm/km	ohm/kFT	ohm/km	ohm/kFT	ohm/km	ohm/kFT
18	0.823	1620	1	—	—	1.02	0.040	0.823	0.001	25.5	7.77	26.5	8.08	42.0	12.8
18	0.823	1620	7	0.39	0.015	1.16	0.046	1.06	0.002	26.1	7.95	27.7	8.45	42.8	13.1
16	1.31	2580	1	—	—	1.29	0.051	1.31	0.002	16.0	4.89	16.7	5.08	26.4	8.05
16	1.31	2580	7	0.49	0.019	1.46	0.058	1.68	0.003	16.4	4.99	17.3	5.29	26.9	8.21
14	2.08	4110	1	—	—	1.63	0.064	2.08	0.003	10.1	3.07	10.4	3.19	16.6	5.06
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004	10.3	3.14	10.7	3.26	16.9	5.17
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005	6.34	1.93	6.57	2.01	10.45	3.18
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006	6.50	1.98	6.73	2.05	10.69	3.25
10	5.261	10380	1	—	—	2.588	0.102	5.26	0.008	3.984	1.21	4.148	1.26	6.561	2.00
10	5.261	10380	7	0.98	0.038	2.95	0.116	6.76	0.011	4.070	1.24	4.226	1.29	6.679	2.04
8	8.367	16510	1	—	—	3.264	0.128	8.37	0.013	2.506	0.764	2.579	0.786	4.125	1.26
8	8.367	16510	7	1.23	0.049	3.71	0.146	10.76	0.017	2.551	0.778	2.653	0.809	4.204	1.28
6	13.30	26240	7	1.56	0.061	4.67	0.184	17.09	0.027	1.608	0.491	1.671	0.510	2.652	0.808
4	21.15	41740	7	1.96	0.077	5.89	0.232	27.19	0.042	1.010	0.308	1.053	0.321	1.666	0.508
3	26.67	52620	7	2.20	0.087	6.60	0.260	34.28	0.053	0.802	0.245	0.833	0.254	1.320	0.403
2	33.62	66360	7	2.47	0.097	7.42	0.292	43.23	0.067	0.634	0.194	0.661	0.201	1.045	0.319
1	42.41	83690	19	1.69	0.066	8.43	0.332	55.80	0.087	0.505	0.154	0.524	0.160	0.829	0.253
1/0	53.49	105600	19	1.89	0.074	9.45	0.372	70.41	0.109	0.399	0.122	0.415	0.127	0.660	0.201
2/0	67.43	133100	19	2.13	0.084	10.62	0.418	88.74	0.137	0.3170	0.0967	0.329	0.101	0.523	0.159
3/0	85.01	167800	19	2.39	0.094	11.94	0.470	111.9	0.173	0.2512	0.0766	0.2610	0.0797	0.413	0.126
4/0	107.2	211600	19	2.68	0.106	13.41	0.528	141.1	0.219	0.1996	0.0608	0.2050	0.0626	0.328	0.100
250	127	—	37	2.09	0.082	14.61	0.575	168	0.260	0.1687	0.0515	0.1753	0.0535	0.2778	0.0847
300	152	—	37	2.29	0.090	16.00	0.630	201	0.312	0.1409	0.0429	0.1463	0.0446	0.2318	0.0707
350	177	—	37	2.47	0.097	17.30	0.681	235	0.364	0.1205	0.0367	0.1252	0.0382	0.1984	0.0605
400	203	—	37	2.64	0.104	18.49	0.728	268	0.416	0.1053	0.0321	0.1084	0.0331	0.1737	0.0529
500	253	—	37	2.95	0.116	20.65	0.813	336	0.519	0.0845	0.0258	0.0869	0.0265	0.1391	0.0424
600	304	—	61	2.52	0.099	22.68	0.893	404	0.626	0.0704	0.0214	0.0732	0.0223	0.1159	0.0353
700	355	—	61	2.72	0.107	24.49	0.964	471	0.730	0.0603	0.0184	0.0622	0.0189	0.0994	0.0303
750	380	—	61	2.82	0.111	25.35	0.998	505	0.782	0.0563	0.0171	0.0579	0.0176	0.0927	0.0282
800	405	—	61	2.91	0.114	26.16	1.030	538	0.834	0.0528	0.0161	0.0544	0.0166	0.0868	0.0265
900	456	—	61	3.09	0.122	27.79	1.094	606	0.940	0.0470	0.0143	0.0481	0.0147	0.0770	0.0235
1000	507	—	61	3.25	0.128	29.26	1.152	673	1.042	0.0423	0.0129	0.0434	0.0132	0.0695	0.0212
1250	633	—	91	2.98	0.117	32.74	1.289	842	1.305	0.0338	0.0103	0.0347	0.0106	0.0554	0.0169
1500	760	—	91	3.26	0.128	35.86	1.412	1011	1.566	0.02814	0.00858	0.02814	0.00883	0.0464	0.0141
1750	887	—	127	2.98	0.117	38.76	1.526	1180	1.829	0.02410	0.00735	0.02410	0.00756	0.0397	0.0121
2000	1013	—	127	3.19	0.126	41.45	1.632	1349	2.092	0.02109	0.00643	0.02109	0.00662	0.0348	0.0106

Notes:

1. These resistance values are valid **only** for the parameters as given. Using conductors having coated strands, different stranding type, and, especially, other temperatures changes the resistance.
2. Equation for temperature change: $R_2 = R_1\,[1 + \alpha\,(T_2 - 75)]$ where $\alpha_{cu} = 0.00323$, $\alpha_{AL} = 0.00330$ at 75°C.
3. Conductors with compact and compressed stranding have about 9 percent and 3 percent, respectively, smaller bare conductor diameters than those shown. See Table 5A for actual compact cable dimensions.
4. The IACS conductivities used: bare copper = 100%, aluminum = 61%.
5. Class B stranding is listed as well as solid for some sizes. Its overall diameter and area is that of its circumscribing circle.

Figure 25 - NEC Table 8: Conductor Properties [10]

Conductor Ampacity Based on the 2011 National Electrical Code®

Ampacity based on NEC Table 310.15(B)(16) (Formerly Table 310.16) – Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60° Through 90°C (140° Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)*

For conduit fill see 2011 NEC Annex C.

For Information on Temperature Ratings of Terminations to Equipment See NEC 110.14(C).

Size	Temperature Rating of Conductor. [See Table 310.104(A).]						Size
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RH, RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	AWG or kcmil
	Copper			Aluminum or Copper-Clad Aluminum			
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	350	420	475	285	340	385	600
700	385	460	520	315	375	425	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	445	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	525	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	555	665	750	470	560	630	2000

* Refer to 310.15(B)(2)(a) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F).
** See Section 240.4 (D) for conductor overcurrent protection limitations.

Figure 26 - NEC AWG Chart [11]

ANSI C37.32-2002

Phase spacing and ground clearance for station class outdoor air switches and bus supports

Line	Rated maximum voltage	Rated lightning withstand voltage[1]	Minimum metal-to-metal distance disconnecting switches, bus supports and rigid conductors[2]		Ground clearance[3]				Centerline-to-centerline phase spacing[4]					
					Recommended		Minimum		Vertical break disconnecting switches and bus supports		Side break (horizontal break) disconnecting switches		All horn gap Switches (vertical and side break)	
	kV rms	kV Peak	mm	(inches)	mm	(inches)	mm	(inches)	mm	(inches)	mm	(inches)	mm	(inches)
Number	(1)	(2)	(3)		(4)		(5)		(6)		(7)		(8)	
1	8.3	95	178	(7)	191	(7.5)	152	(6)	457	(18)	762	(30)	914	(36)
2	15.5	110	305	(12)	254	(10)	178	(7)	610	(24)	762	(30)	914	(36)
3	27	150	381	(15)	305	(12)	254	(10)	762	(30)	914	(36)	1220	(48)
4	38	200	457	(18)	381	(15)	330	(13)	914	(36)	1220	(48)	1520	(60)
5	48.3	250	533	(21)	457	(18)	432	(17)	1220	(48)	1520	(60)	1830	(72)
6	72.5	250	533	(21)	457	(18)	432	(17)	1220	(48)	1520	(60)	1830	(72)
7		**350**	787	(31)	737	(29)	635	(25)	1520	(60)	1830	(72)	2130	(84)
8	123	350	787	(31)	737	(29)	635	(25)	1520	(60)	1830	(72)	2130	(84)
9		450	1120	(44)	991	(39)	846	(34)	1830	(72)	2310	(91)	2620	(103)
10		**550**	1350	(53)	1190	(47)	1070	(42)	2130	(84)	2740	(108)	3050	(120)
11	145	350	787	(31)	737	(29)	635	(25)	1520	(60)	1830	(72)	2130	(84)
12		450	1120	(44)	991	(39)	846	(34)	1830	(72)	2310	(91)	2620	(103)
13		550	1350	(53)	1190	(47)	1070	(42)	2130	(84)	2740	(108)	3050	(120)
14		**650**	1600	(63)	1330	(52.5)	1270	(50)	2440	(96)	3350	(132)	3660	(144)
15	170	450	1120	(44)	991	(39)	846	(34)	1830	(72)	2310	(91)	2620	(103)
16		550	1350	(53)	1190	(47)	1070	(42)	2130	(84)	2740	(108)	3050	(120)
17		650	1600	(63)	1330	(52.5)	1270	(50)	2440	(96)	3350	(132)	3660	(144)
18		**750**	1830	(72)	1560	(61.5)	1470	(58)	2740	(108)	3960	(156)	4270	(168)
19	245	550	1350	(53)	1190	(47)	1070	(42)	2130	(84)	2740	(108)	3050	(120)
20		650	1600	(63)	1330	(52.5)	1270	(50)	2440	(96)	3350	(132)	3660	(144)
21		750	1830	(72)	1560	(61.5)	1470	(58)	2740	(108)	3960	(156)	4270	(168)
22		**900**	2260	(89)	1930	(76)	1800	(71)	3350	(132)	4870	(192)	4870	(192)
23		1050	2670	(105)	2300	(90.5)	2110	(83)	3960	(156)	5500	(216)	5500	(216)
24	362	1050	2670	(105)	2300	(90.5)	2130	(84)	3960	(156)	5500	(216)	5500	(216)
25		**1300**	3020	(119)	2690	(106)	2640	(104)	4430	(174)	Note 5		6100	(240)
26	550	1550	Note 5		Note 5		3150	(124)	Note 5		Note 5		7620	(300)
27		**1800**	Note 5		Note 5		3660	(144)	7620	(300)	Note 5		8230	(324)
28	800	2050	Note 5		Note 5		4220	(166)	Note 5		Note 5		15240	(600)

NOTES –

1 Close lightning arrester coordination may allow lower lightning impulse values. Traditional values shown in bold font.

2 Minimum metal-to-metal distance may be modified providing proof of performance is substantiated by dielectric tests.

3 Ground clearances for switches with voltages 362 kV and above are based on switching surge voltage levels. Refer to bibliography, Annex C.

4 The phase spacings in columns 6, 7, and 8 are recommended values. Overall width of switch and bus support energized parts, angle of opening of side break switches, etc., may allow a reduction in phase spacing dependent upon voltage concentration on sharp projections. Resultant metal-to-metal distances between phase energized parts should not be less than that shown in column 3.

5 Values not yet established.

Figure 27 - IEEE ANSI Phase Spacing [16]

Physical & Electrical Properties of Aluminum

Standard Pipe-Size Conductors at Typical Conductivities

Nominal Size in	A	B	Area sq in	Weight lbs/ft	Inductive reactance 1 ft spacing 60 Hz microhm/ft	6063-T6				6061-T6			
	Outside Diameter of Tube in	Wall Thickness in				DC Resistance at 20°C microhms/ft	60 Hz Rac/RDC at 70°C	AC Resistance at 70°C 60 Hz microhms/ft	Current Ratings Amp at 60 Hz (1) (2) (3) (4) Outdoor	DC Resistance at 20°C microhms/ft	60 Hz Rac/RDC at 70°C	AC Resistance at 70°C 60 Hz microhms/ft	Current Ratings Amp at 60 Hz (1) (2) (3) (4) Outdoor
Schedule 40 Pipe													
1	1.315	0.133	0.494	0.581	68.24	31.120	1.00039	36.580	681	38.360	1.00032	43.820	622
1 1/4	1.660	0.140	0.669	0.786	62.68	22.990	1.00050	27.030	859	28.340	1.00039	32.370	705
1 1/2	1.900	0.145	0.800	0.940	59.45	19.220	1.00064	22.600	984	23.690	1.00046	27.070	900
2	2.375	0.154	1.075	1.264	54.15	14.300	1.00082	16.820	1234	17.630	1.00055	20.140	1128
2 1/2	2.875	0.203	1.704	2.004	49.85	9.019	1.00220	10.620	1663	11.170	1.00150	12.710	1520
3	3.500	0.216	2.228	2.621	45.19	6.897	1.00300	8.126	2040	8.500	1.00180	9.725	1865
3 1/2	4.000	0.226	2.680	3.151	42.05	5.736	1.00380	6.761	2347	7.070	1.00220	8.091	2145
4	4.500	0.237	3.174	3.733	39.28	4.842	1.00470	5.712	2664	5.968	1.00270	6.834	2436
4 1/2	5.001	0.247	3.688	4.337	36.81	4.167	1.00570	4.920	2984	5.136	1.00330	5.885	2728
5	5.563	0.258	4.300	5.057	34.31	3.574	1.00680	4.224	3348	4.406	1.00400	5.051	3063
6	6.625	0.280	5.581	6.564	30.23	2.754	1.00950	3.263	4064	3.394	1.00540	3.897	3719

Figure 28 – AFL Rigid Bus Conductor Properties [22]

ACSR

Code Word	Size (AWG or kcmil)	Stranding (Al/Stl)	Diameter (ins.)				Weight Per 1000 ft. (lbs.)			Content (%)		Rated Strength (lbs.)	Resistance OHMS/1000 ft.		Allowable Ampacity+ (Amps)
			Individual Wires Al	Individual Wires Stl	Steel Core	Complete Cable	Al	Stl	Total	Al	Stl		DC @ 20°C	AC @ 75°C	
Canary	900	54/7	.1291	.1291	.3873	1.162	848	310	1158	73.22	26.78	31900	.0190	.0241	961
Rail	954	45/7	.1456	.0971	.2912	1.165	899	175	1074	83.67	16.33	25900	.0180	.0225	993
Cardinal	954	54/7	.1329	.1329	.3987	1.196	899	329	1227	73.21	26.79	33800	.0179	.0228	996
Ortolan	1033.5	45/7	.1515	.101	.3031	1.212	973	190	1163	83.67	16.33	27700	.0167	.0209	1043
Curlew	1033.5	54/7	.1383	.1383	.415	1.245	973	356	1330	73.21	26.79	36600	.0165	.0211	1047
Bluejay	1113	45/7	.1573	.1048	.3145	1.258	1048	205	1253	83.67	16.33	29800	.0155	.0194	1092
Finch	1113	54/19	.1436	.0861	.4307	1.292	1053	375	1429	73.72	26.28	39100	.0154	.0197	1093
Bunting	1192.5	45/7	.1628	.1085	.3256	1.302	1123	219	1343	83.67	16.33	32000	.0144	.0182	1139
Grackle	1192.5	54/19	.1486	.0892	.4458	1.337	1129	402	1531	73.72	26.28	41900	.0144	.0184	1140
Bittern	1272	45/7	.1681	.1121	.3362	1.345	1198	234	1432	83.67	16.33	34100	.0135	.0171	1184
Pheasant	1272	54/19	.1535	.0921	.4605	1.381	1204	429	1633	73.71	26.29	43600	.0135	.0173	1187

Figure 29 – ACSR Flexible Bus Conductor Properties [23]

	DC Output Rating		AC Input Ampere Rating Based on maximum rms value of the input current delivered to the charger under all operating conditions within manufacturer's specifications							
	Volts	Amps	208 VAC	220 VAC	240 VAC	380 VAC	416 VAC	440 VAC	480 VAC	600 VAC
(130Vdc) Float Adjust 110.0-141.0Vdc	130Vdc	25	17	16	14	10	9	9	8	7
		30	20	20	18	12	11	10	9	8
		40	26	23	22	14	13	12	12	10
		50	33	30	28	18	16	15	15	12
		75	48	44	43	26	25	24	22	18
		100	64	60	57	35	32	30	29	24
		125	80	75	69	44	40	42	38	33
		150	93	87	80	52	46	46	42	37
		200	125	120	110	70	62	60	55	48
		250	158	150	137	79	72	68	68	59
(130Vdc) Equalize Adjust 117.0-143.0Vdc		300	180	170	160	93	85	80	80	72
		400	255	235	220	127	116	110	110	96
		500	320	300	280	160	148	140	140	120
		600	378	354	331	200	180	177	169	145
		800	503	473	439	266	241	233	224	194
		1000	628	590	547	330	300	291	279	240

Figure 30 – Battery Charger Sizing [17]

Trench Type	Depth (in)	Width (in)	Cross-Sectional Area (in^2)	Available Area (in^2)
12x10	12	10	120	48
12x20	12	20	240	96
12x24	12	24	288	115.2
12x30	12	30	360	144
12x40	12	40	480	192
12x48	12	48	576	230.4
15x10	15	10	150	60
15x20	15	20	300	120
15x24	15	24	360	144
15x30	15	30	450	180
15x40	15	40	600	240
15x48	15	48	720	288
24x10	24	10	240	96
24x20	24	20	480	192
24x24	24	24	576	230.4
24x30	24	30	720	288
24x40	24	40	960	384
24x48	24	48	1152	460.8

Figure 31 – Trenwa Trench Information [19]

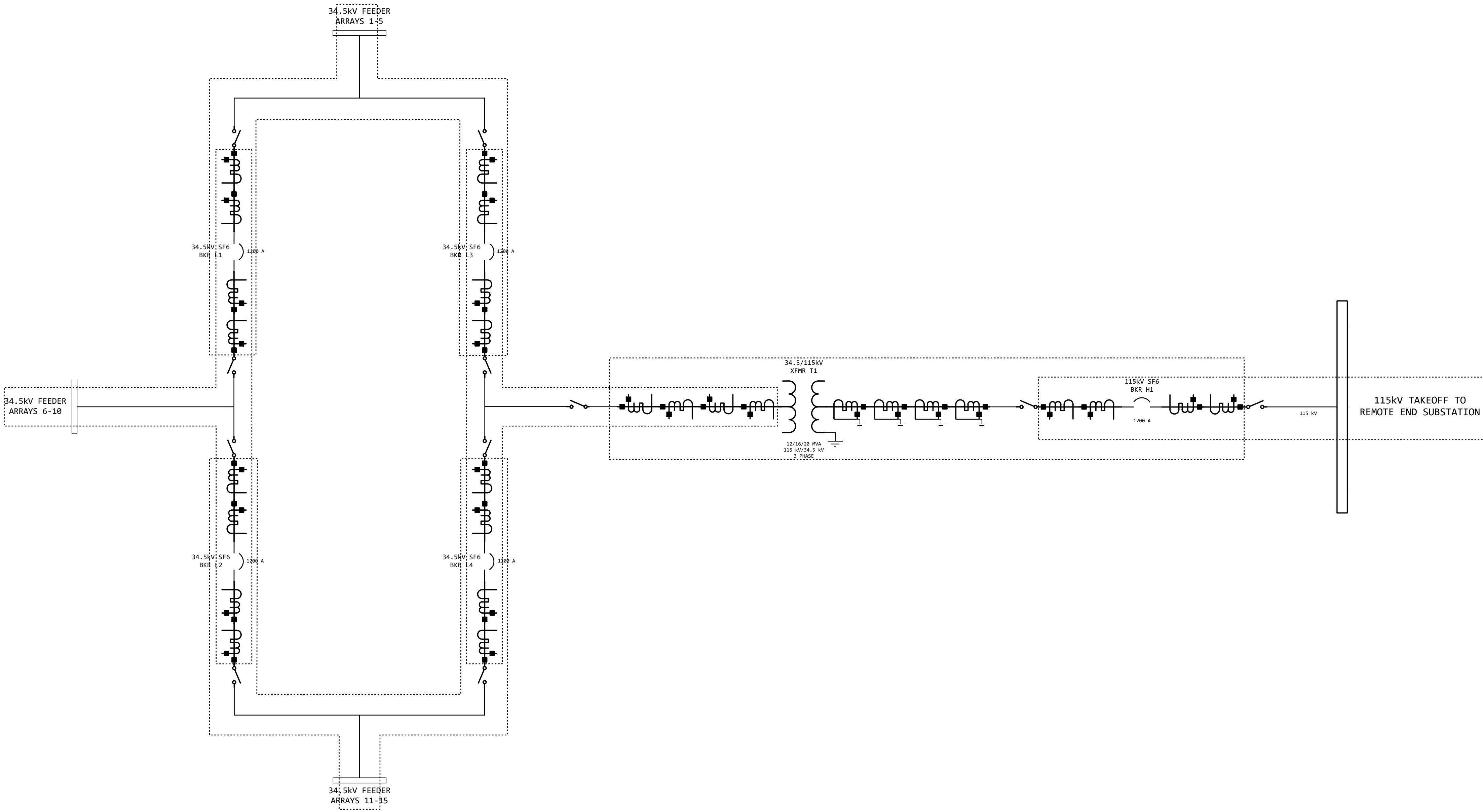
Trench Type	Depth (in)	Trench Width (in)	Cross-Sectional Area (in^2)	Available Area (in^2)
2110	14	21	294	117.6
2636	34	27	918	367.2
440	40	40	1600	640
4048	48	40	1920	768
4510	10	43	430	172
5648	49	45	2205	882
5672	72	45	3240	1296
4860	62	49	3038	1215.2
558	20	52	1040	416
5076	90	63	5670	2268
6070	86	75	6450	2580
8056	66	97	6402	2560.8
1050	60	122	7320	2928

Figure 32 – Old Castle Trench Information [20]

Nominal Pipe Size	OD (inches)	ID (inches)	40% fill area
1/8"	0.405	0.249	0.0195
1/4"	0.54	0.344	0.0372
3/8"	0.675	0.473	0.0703
1/2"	0.84	0.602	0.1139
3/4"	1.05	0.804	0.2031
1"	1.315	1.029	0.3326
1-1/4"	1.66	1.36	0.5811
1-1/2"	1.9	1.59	0.7942
2"	2.375	2.047	1.3164
2-1/2"	2.875	2.445	1.8781
3"	3.5	3.042	2.9072
3-1/2"	4	3.521	3.8948
4"	4.5	3.998	5.0215
5"	5.563	5.016	7.9043
6"	6.625	6.031	11.4269
8"	8.625	7.942	19.8157
10"	10.75	9.976	31.2653
12"	12.75	11.889	44.4059
14"	14	13.073	53.6909
16"	16	14.94	70.1215
18"	18	16.809	88.7633
20"	20	18.743	110.3642
24"	24	22.544	159.6658

Figure 33 – PVC Piping Sizing Chart [21]

Appendix II: Bluebeam Diagrams



PANEL # BUS ##

3	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/25/21		

- Created a separate version of the diagram to model zones of protection
- Removed various labels to reduce clutter
- Added 2 CTs to each side of XFMR T1 (4 total) and shorted the 4 unused CTs on 115kV side
- Changed color of entire document to black and increased the size of the diagram

MADE BY	DATE	ACT	RELAY
ES	4/25		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

2	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/6/21		

- Began to include relays on the 34.5kV side
- Reduced space between each component after consulting B&V
- Changed colors of certain elements for clarity

MADE BY	DATE	ACT	RELAY
ES	4/6		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

1	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	3/15/21		

- Turned layout sideways to match plan view
- Added space between each component to prepare for relaying
- Renamed/labeled numerous components
- Removed unnecessary disconnect switch by transformer

MADE BY	DATE	ACT	RELAY
ES	3/15		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

APPROVALS

	OTHER	DATE
PROJECT MANAGER		
RELAY		
EP&PM		
ACT		
OTHERS		

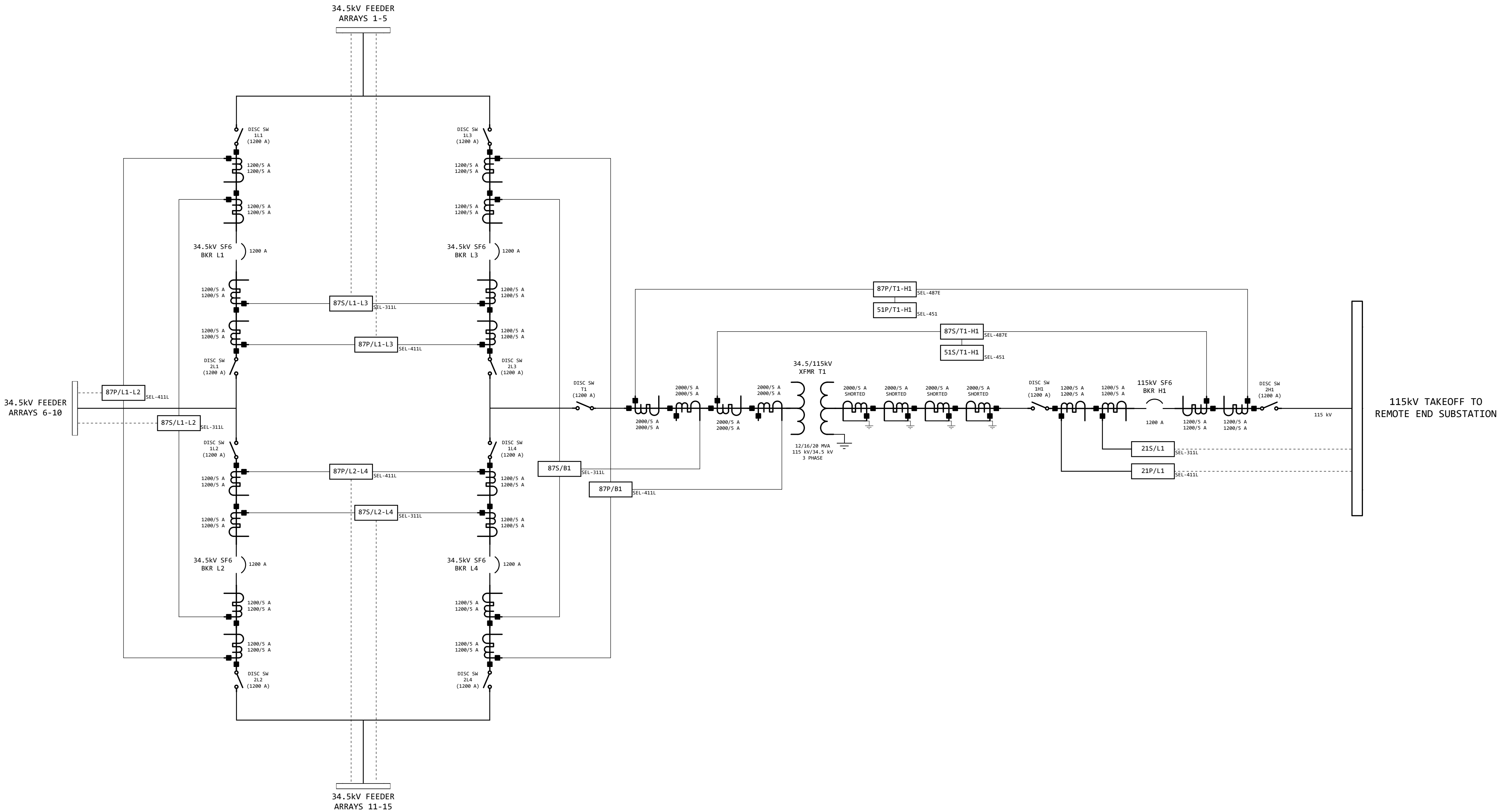
ENGINEERING	
MADE BY	DATE
Eric Schultz	2/25/21
LAYOUT BY	DATE
CHECKED BY	DATE
PROJECT DESIGN/ELECT	DATE
PROJECT DESIGN/ACT	DATE
APPROVED FOR ISSUE	DATE

TITLE

ONE-LINE DIAGRAM
ZONES OF PROTECTION

LOCATION NAME	SERVICE CENTER	SCALE
SDMay21-37 SUBSTATION FOR SOLAR POWER PLANT		NONE

DRAWING NUMBER	REQUEST FOR WORK/WO	PROJECT DOCUMENT LIST



PANEL # BUS ##

3	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/22/21		

- Finalized relaying based on B&V recommendations
- Included labels for relays, both ANSI and SEL
- Added 2 CTs to each side of XFMR T1 (4 total) and shorted the 4 unused CTs on 115kV side, updated CT ratings
- Changed color of entire document to black and increased the size of the diagram

MADE BY	DATE	ACT	RELAY
ES	4/22		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

2	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/6/21		

- Began to include relays on the 34.5kV side
- Reduced space between each component after consulting B&V
- Changed colors of certain elements for clarity

MADE BY	DATE	ACT	RELAY
ES	4/6		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

1	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	3/15/21		

- Turned layout sideways to match plan view
- Added space between each component to prepare for relaying
- Renamed/labeled numerous components
- Removed unnecessary disconnect switch by transformer

MADE BY	DATE	ACT	RELAY
ES	3/15		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

APPROVALS

OTHER		DATE
PROJECT MANAGER		
RELAY		
EP&PM		
ACT		
OTHERS		

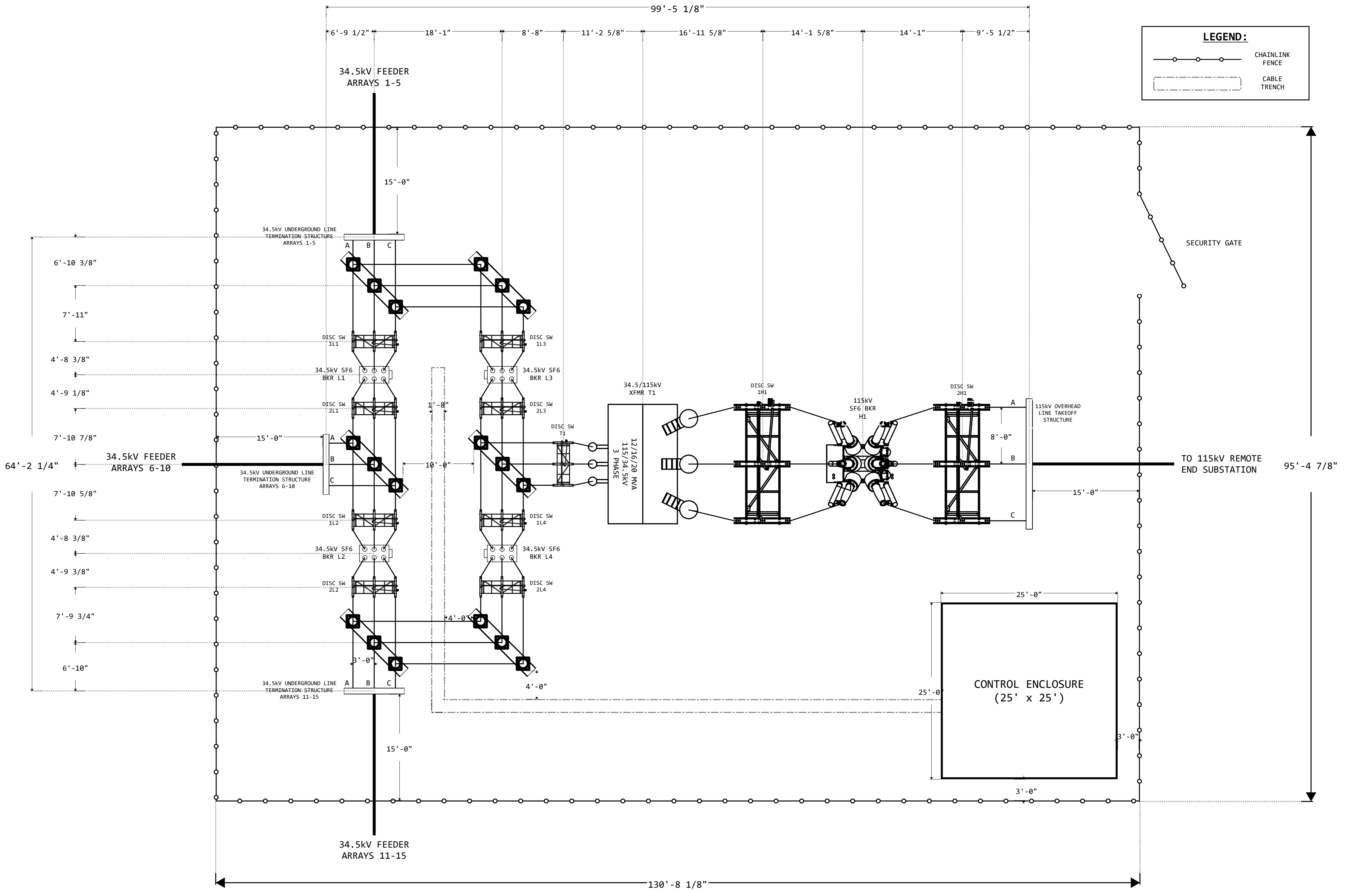
ENGINEERING	
MADE BY	DATE
Eric Schultz	2/25/21
LAYOUT BY	DATE
CHECKED BY	DATE
PROJECT DESIGN/ELECT	DATE
PROJECT DESIGN/ACT	DATE
APPROVED FOR ISSUE	DATE

TITLE

ONE-LINE DIAGRAM RELAY MODEL

LOCATION NAME	SERVICE CENTER	SCALE
SDMay21-37 SUBSTATION FOR SOLAR POWER PLANT		NONE

DRAWING NUMBER	REQUEST FOR WORK/WO	PROJECT DOCUMENT LIST



PANEL # BUS ##

3	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/22/21		

- Updated trench sizing and color, removed conduits, save for conduit plan
- Updated font and added security gate
- Changed color of entire document to black, added additional measurements
- Increased size of diagram

MADE BY	DATE	ACT	RELAY
ES	4/22		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

2	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	3/16/21		

- Turned layout sideways for better viewing
- Changed spacing of fence (10 -> 15 ft)
- Changed color of cables to black, added new measurements, condensed text and measurements
- Updated termination structure descriptions
- Re-routed trench and added conduits

MADE BY	DATE	ACT	RELAY
ES	3/16		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

1	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	3/9/21		

- Re-dimensioned and properly spaced entire substation, included numerous measurements
- Added takeoff structures, fence, cable trench, and control enclosure
- Renamed/labeled numerous components
- Removed unnecessary disconnect switch by transformer

MADE BY	DATE	ACT	RELAY
ES	3/9		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

APPROVALS

	OTHER	DATE
PROJECT MANAGER		
RELAY		
EP&PM		
ACT		
OTHERS		

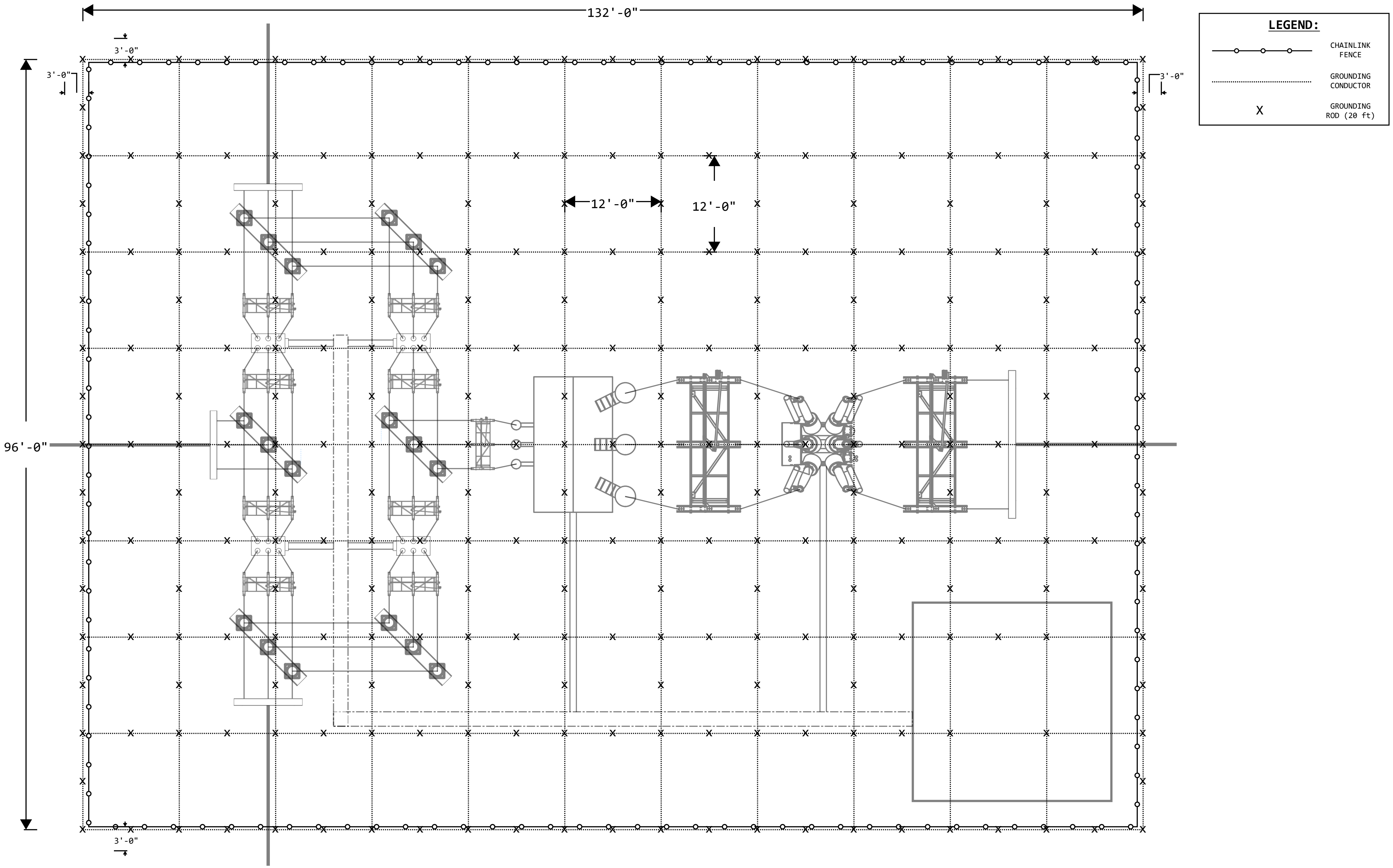
ENGINEERING	
MADE BY	DATE
Eric Schultz	2/25/21
LAYOUT BY	DATE
CHECKED BY	DATE
PROJECT DESIGN/ELECT	DATE
PROJECT DESIGN/ACT	DATE
APPROVED FOR ISSUE	DATE

TITLE

BUS PLAN DIAGRAM

LOCATION NAME	SERVICE CENTER	SCALE
SDMay21-37 SUBSTATION FOR SOLAR POWER PLANT		

DRAWING NUMBER	REQUEST FOR WORK/WO	PROJECT DOCUMENT LIST



PANEL # BUS ##

3	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/25/21		

- Finalized conductor spacing of 12 ft
- Reduced ground rod length from 50 to 20 ft
- Added many more grounding rods and adjusted their position
- Increased the size of the diagram

MADE BY	DATE	ACT	RELAY
ES	4/25		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

2	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/22/21		

- Decreased conductor spacing from 15 to 12 ft, still experimenting with various spacings
- Increased ground rod length from 10 to 50 ft
- Changed location of many grounding rods
- Changed color of entire document to black

MADE BY	DATE	ACT	RELAY
ES	4/22		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

1	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/19/2021		

- Decreased conductor spacing from 20 to 15 ft
- Reduced opacity of substation to allow for better viewing of the grounding grid
- Included symbols for grounding rods and placed them appropriately
- Included various measurements

MADE BY	DATE	ACT	RELAY
ES	4/19		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

APPROVALS

OTHER		DATE
PROJECT MANAGER		
RELAY		
EP&PM		
ACT		
OTHERS		

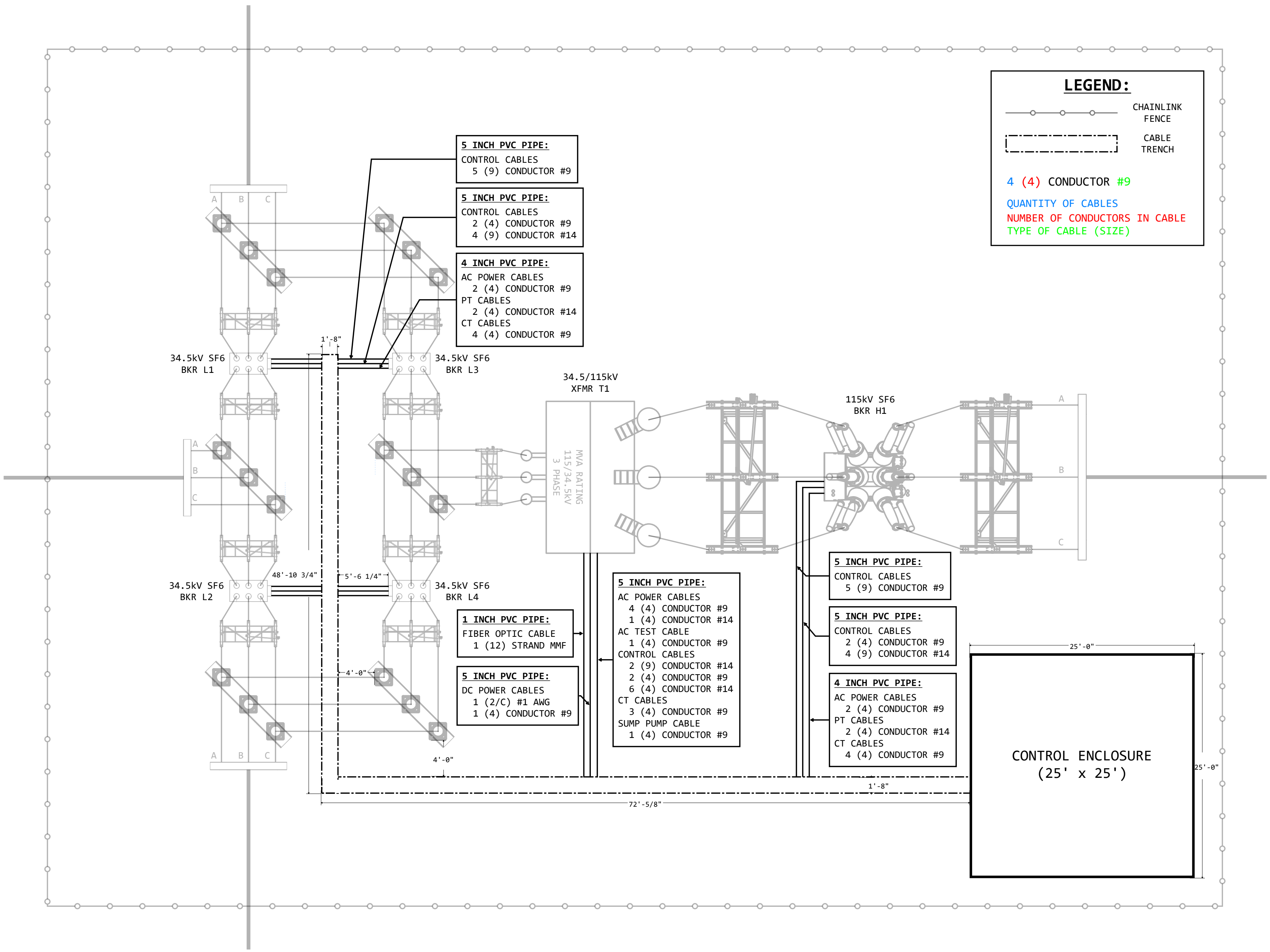
ENGINEERING	
MADE BY	DATE
Eric Schultz	3/19/21
LAYOUT BY	DATE
CHECKED BY	DATE
PROJECT DESIGN/ELECT	DATE
PROJECT DESIGN/ACT	DATE
APPROVED FOR ISSUE	DATE

TITLE

GROUNDING DIAGRAM

LOCATION NAME	SERVICE CENTER	SCALE
SDMay21-37 SUBSTATION FOR SOLAR POWER PLANT		

DRAWING NUMBER	REQUEST FOR WORK/WO	PROJECT DOCUMENT LIST



PANEL # BUS ##

3	PROJ DESIGN	PROJ MANAGER	OTHERS
DATE			
MADE BY	DATE	ACT	RELAY
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

2	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/25/21		

- Removed various labels to reduce clutter
- Altered color of key to highlight conductor key
- Increased size of diagram
- Included various measurements

MADE BY	DATE	ACT	RELAY
ES	4/25		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

1	PROJ DESIGN	PROJ MANAGER	OTHERS
	Eric Schultz		
DATE	4/22/21		

- Updated conduits to be single lines
- Included size of PVC pipe for each conduit
- Included list of conductors per conduit
- Edited legend to include key for understanding list of condutors

MADE BY	DATE	ACT	RELAY
ES	3/15		
CH'K BY	DATE	EP&PM	APVD FOR ISSUE

APPROVALS

OTHER		DATE	ENGINEERING	DATE
PROJECT MANAGER			MADE BY	DATE
			Eric Schultz	4/19/21
RELAY			LAYOUT BY	DATE
EP&PM			CHECKED BY	DATE
ACT			PROJECT DESIGN/ELECT	DATE
			PROJECT DESIGN/ACT	DATE
OTHERS			APPROVED FOR ISSUE	DATE

TITLE

CONDUIT PLAN DIAGRAM

LOCATION NAME SDMay21-37 SUBSTATION FOR SOLAR POWER PLANT	SERVICE CENTER	SCALE
DRAWING NUMBER	REQUEST FOR WORK/WO	PROJECT DOCUMENT LIST