Cyclone Substation Design

FINAL REPORT

Senior Design Team 04

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Executive Summary

Development Standards & Practices Utilized

For this project, the following IEEE standards were considered:

- IEEE Standard 80 – Pertaining to substation grounding
- IEEE Standards 450,484,485,1187,1188 – Pertaining to battery sizing
- IEEE Standard 998 – Pertaining to lightning protection

The team also implemented formatting standards across all deliverables using client-standard symbols to represent substation equipment.

Summary of Requirements

The following requirements for the project were specified by Burns & McDonnell:

- The voltage produced by the Cyclone Generation Wind facility located from Ames, IA is to be increased from 69 kV to 138 kV and transmitted over 138 kV transmission lines to Cedar Falls, IA, and Des Moines, IA
- The substation is to include the following equipment at a minimum:
  - (1) 72 kV to 141 kV power transformer
  - (1) 69 kV breaker
  - (3) 138 kV breakers in ring-bus configuration
  - (3) Capacitively coupled voltage transformers
  - (1) Station service voltage transformer
  - (1) Wave trap
  - (1) Motor operated air breaker switch
  - Relaying equipment is called out in the relay specification.
- Lightning, grounding, and AC/DC studies must be performed.
- Plan for future expansion to a six-position breaker-and-a-half configuration

Applicable Courses from Iowa State University Curriculum

- EE 201 - Electrical Circuits
- EE 230 - Electrical Circuits and Systems
- EE 303 - Energy Systems and Power Electronics

New Skills/Knowledge Acquired Through Project Work

- AutoCAD
- Control schematic/ wiring design

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List of figures/tables/symbols/equations

1. Introduction

1.1 Acknowledgment

Tom Kelly and Riley O'Donnell, both substation engineers at Burns & McDonnell, provided technical support for this project. The design team appreciates their time and thoughtful answers to our questions during the design process. Their assistance made this senior design project's goal obtainable.

1.2 Problem and Project Statement

The city of Ames, IA is in need of a new transmission substation to increase the voltage level from a newly installed wind power facility. The purpose of a transmission substation is to increase the input voltage and transmit the power long distances. The voltage coming from the wind power facility is to be increased from 69 kV to 138 kV. The increase in voltage is to improve the efficiency of long-distance power delivery. Large transmission voltages reduce transmission line losses via a decrease in line current. The substation will feed two transmission lines: one going to Cedar Falls, IA, and the other going to Des Moines, IA. The primary objective of this project is to produce a set of deliverables detailing the equipment layout, electrical connections, and design specifications to meet the needs of the cities using the station.

Burns & McDonnell selected the senior design team at Iowa State to complete the substation design. The engineers have been provided with guidelines on the arrangement of the equipment, specifications of protections/controls equipment, and vendor prints detailing the major equipment to be used.

To complete the design of the substation, the design team will work in phases to complete the different deliverables of the design and send them to Burns & McDonnell for review. Upon completion of the review by Burns & McDonnell, the engineers will make changes to the design according to the received comments. The specific deliverables for this project are outlined in § 1.7 of this document. At the completion of the project, the entire set of drawings can be issued to construct the substation.

1.3 Operational Environment with Emphasis on Safety and Security

The majority of the substation, excluding the protections/ controls equipment, will not be enclosed by any sort of shelter. Thus, the substation will be susceptible to weather, animal encounters, and unwanted intrusion by people. To keep wildlife and unwanted onlookers out of the substation, a fence will be erected enclosing the entirety of the substation. The fence not only keeps people and terrestrial animals out of the substation to protect assets but also prevents people from getting seriously injured due to inadequate knowledge of how to interact with substation equipment. The failure to operate equipment properly could result in fatality.

Another safety concern is the impact that a lightning strike could have on the station. Lightning strikes have currents in excess of 30 kA compared to 200 A from a common welder. This means that if lightning strikes the substation, it could do some serious damage to the equipment and render the substation inoperable. To counteract the effects of lightning, we will conduct a study to determine how best to protect the substation using lightning mitigation technologies.

In addition to the aforementioned physical threats, there are also less obvious threats. For example, our substation is entirely dependent on having AC power to operate. Specifically, AC power is used to charge batteries within the substation which in turn power protective relays. If power is lost to these relays, then the station becomes inoperable. To counteract the loss of AC power, A DC study shall be conducted to elucidate the capacity of the batteries required to keep the substation operational for at least 8 hours.

Because the substation is planned to be located within the bulk power grid, we need to ensure that faults can be isolated within the substation and on the line exits we serve. This is necessary to improve the reliability of the power grid and prevent a large-scale blackout. To this end we need to have two different systems in place: (i) a protective relay system that monitors system conditions and isolates the substation or line exits if a fault is detected and (ii) communication with other substations. To this end, an extensive control strategy shall be implemented that has been specified for our substation by Burns & McDonnell. This strategy is laid out in the relay specification document provided to our team. Communicating with other substations will be through two means of communication: (i) for the distribution substation located in Cedar Falls there will be a modulated communication signal over the power line; this technique is known as power-line carrier communication and (ii) communications with a distribution substation in Des Moines substation will be via fiber optic cables. Communication is key to isolating long sections of transmission lines from the power system to ensure that large-scale blackouts do not occur.

The hope is that the design efforts will limit the damage done to the substation through erecting a fence, designing a lighting protection system, providing sufficient battery backup power, implementing a complex control strategy, and communicating with other substations will be successful. In real-world substation design, these methods are commonly used and are, in general, successful security techniques.

1.4 Requirements

The substation is to include the following equipment at a minimum:

- (1) 72kV to 141 kV power transformer with current transformers
- (1) 69 kV breaker with current transformers
- (3) 138 kV breakers with current transformers
- (3) Capacitively coupled voltage transformers
- (1) Station service voltage transformer
- (1) Motor operated air breaker switch
- (1) Wave trap
- Relaying equipment specified in the relay specification document.

Redundancy in power systems is essential to ensure a continuous supply of electricity to customers. As a result, careful consideration is taken into account when determining the breaker arrangement such that any breaker may be disconnected from the substation and allow it to continue to operate. In the first phase of construction, the 138kV breakers are to be placed in a ring-bus configuration. The ring-bus configuration can be seen in Figure 1:

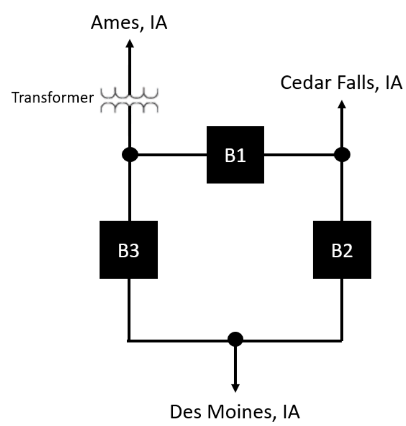


Figure 1 - Ring-Bus Configuration

In the ring-bus configuration, any breaker can be disconnected, and the substation will continue to supply the desired voltage level to both outbound lines. The ring bus is able to effectively isolate transmission lines also. Our design must allow for future expansion into a six-position breaker-and-a-half configuration as seen in Figure 2:

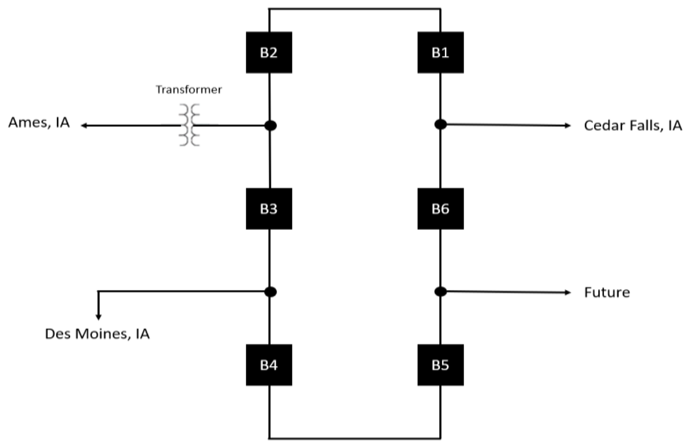


Figure 2 - Six-Position Breaker-and-a-Half Configuration

In the six-position breaker-and-a-half configuration, the convenience of maintenance remains where any breaker can be taken out of service without affecting the operation of the substation. But here, the substation is able to have both a line fault and a breaker fault and remain largely unaffected.

The design must use standards for reliability and safety purposes. For example, lightning protection and grounding layout at this site is required and will be planned according to IEEE standards 998 and 80 respectively. Additionally, adequate DC and AC supply to the control house must be ensured per IEEE standards 450, 484, 485, 1187, and 1188.

The last requirement of the design is that the protections/ controls equipment is connected to perform the relaying functions per the ISU Senior Design Protection Requirements 2020-2021 document provided by Burns & McDonnell.

1.5 Intended Users and Uses

The initial user of the substation design will be construction crews who will rely on the designs provided to arrange equipment in the substation yard and wire the panels per the protections and controls drawings that we produce. The deliverables will also serve as a starting point for the next round of engineering once it is decided that it is time for the future expansion to take place. The utilities within the three cities will work together to maintain the substation upon construction. Daily users of the substation include the general public as they connect to the grid and consume power that has flowed through our substation. Our design will be deemed a success if the customers experience constant uninterrupted power to all of their devices.

1.6 Assumptions and Design Limitations

The design constructed makes the following assumptions:

- The transformers and breakers selected by Burns & McDonnell are sufficient for the application.
- The protections and control specifications provided for the design are adequate.
- The operating frequency of the power system is 60 Hz.
- A site will be located to meet the requirements of the completed design.
- The wiring design will only be completed if time permits.

The following are the design limitations:

- Breakers are to be arranged in a ring-bus configuration.
- Design must allow for future expansion into a six-position breaker-and-a-half arrangement.
- The incoming voltage level is 69 kV.

- ❖ The outgoing voltage is 138 kV.

1.7 Expected End Product and Deliverables

As per the problem statement in § 1.2 of this document, the completed design shall be an issuance of the following deliverables. The dates provided in this section are the dates that the deliverables are sent to Burns & McDonnell.

- ❖ One-Line Diagram (10/09/2020)
  The one-line diagram shows the interconnection of the major equipment in the substation as well as the associated protections/controls associated with each piece of equipment. The purpose of this document is to provide an overview of the substation with the abstraction of representing three phases as a single line. This document allows a substation engineer to understand the function of the substation and the associated relay at a glance.

- ❖ Plan-view (10/23/2020)

  The plan-view depicts a physical representation of the major equipment inside the substation yard. Also, the plan-view shows the control building location, fence perimeter, and the associated roadway access to the site. The plan-view is synonymous with the expected satellite view of the substation if it were to be seen via satellite mode in Google Maps.

- ❖ Elevation View (11/06/2020)

  During the construction of the substation, it is helpful for the field engineers and construction crews to visualize their work. As such, an elevation view is produced, the view depicts section cuts of the plan-view as though a person were standing on the ground looking at the completed structure. The elevation view also calls out a specific bill of material items such that the proper type of bus connectors can be established and used in their appropriate application.

- ❖ Foundation Layout (11/06/2020)

  After the land has been cleared for the substation to be erected, the first task is to pour the appropriate foundations for the various pieces of equipment. The location of these foundations must be clearly specified to avoid design conflicts. The foundation layout serves to provide this level of clarity by accurately depicting the position and type of foundation to be poured.

- ❖ Conduit/ Raceway Plan (11/06/2020)

  Connecting the equipment to the control house for monitoring is done through the use of cable trenches and conduits underground. To place these correctly a plan is created showing the proper run of the cable trench and conduits to each piece of equipment.

- ❖ Lightning Study (02/19/2021)

  As stated in § 1.3 of this report, lightning strikes are of grave concern to the substation designers. Thus, a lightning study is conducted to determine the zones of protection for the station. This study is conducted through the practice of empirical curves in conjunction with the IEEE standard 998. The zones of protection are then indicated on the plan-view created earlier.

- ❖ Grounding Plan (03/17/2021)

  To protect the equipment, but more importantly people, from the live voltage on the metal casing of the equipment it must all be grounded. Thus, a study will be conducted through the use of the CDEGS (Current Distribution, Electromagnetic interference, Grounding, and Soil structure analysis) software in conjunction with the IEEE standard 80 to study the effective size of the grounding grid required for the station. Once the study has been conducted, a drawing will be created indicating the appropriate grounding for the substation.

- AC / DC Study (02/19/2021)

  Under normal operating conditions, the substation will use AC to provide electricity to relays, lights, equipment heaters, battery chargers, and HVAC systems. The AC study focuses on sizing a breaker cabinet for the station which can handle the load that the substation demands during operation. In the event that the incoming power to the station is lost then batteries are used to provide short-term power to the essential items. The DC study focuses on sizing the battery bank to serve the station long enough to bring it back online. The battery sizing is done through the use of IEEE standards 450, 484, 485, 1187, and 1188.

- Schematic Diagrams (04/16/21)

  Drawings are created which are based on the protection specifications which show how the relaying connects to the equipment in the substation. The schematic representation does not show point-to-point wiring, but instead shows the relaying connections in more of a block-diagram manner. Schematics will be created for the transformer, breakers, and line relaying.

- Panel Layouts (04/23/2021)

  The relaying equipment resides within the control house in housings similar to conventional server racks. The placement of the devices in these racks must be carefully thought out to ensure the easy operation of the equipment by field personnel. Thus, panel layouts are generated which show the physical arrangement of the relays.

- Wiring Diagrams (05/07/2021)

  To connect the relays to the equipment the schematics are used to generate point-to-point wiring diagrams. These diagrams can be used to have a company wire the relay panels and then allow the field to connect the fully wired panels to the equipment in the substation yard. These diagrams also assist the field personnel in troubleshooting should something go wrong (i.e., a fire in the back of a relaying panel).

2. Analysis and Development

2.1 Previous Work and Literature

Substations are integral in any bulk power distribution system; they are built on either side of transmission lines to reduce power losses from generation to the end-user. At the source of generation, a transmission substation is used to increase voltage. A transmission substation can also be used to connect transmission lines of different voltage classes. At the load end of the transmission line, a distribution substation is employed to reduce the voltage. As of December 31, 2018, there were 9,719 power plants within the United States [1]. It follows that there are tens of thousands of substations within the United States.

Power systems planners, such as local utility companies and independent system operators, determine when a new substation is required. Having substations distributed across the generation and distribution space limits the probability of a large-scale blackout in the event of a catastrophic event such as a lightning strike, storm, or maintenance caused faults. Renewable energy generation is expected to become the largest source of energy by 2045 as can be seen in Figure 3 [2]. Due to the increase in renewable energy generation and other generation resources, there will be a need for the construction of more substations.

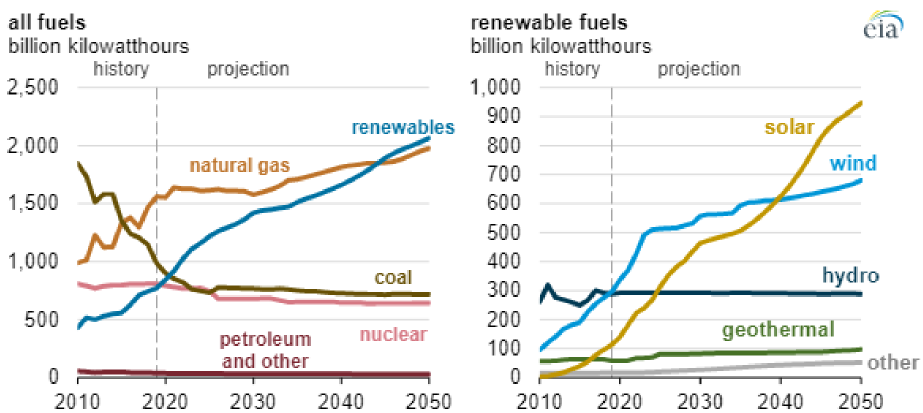


Figure 3 - Increase of Renewable Contributions

Because substations are integral to efficient power transmission and distribution, they are heavily monitored and protected. The protection of substations is done via protective relaying [3]. The primary goal of protective relaying is to monitor system voltages and currents through the use of voltage and current transformers to detect when values are out of range. Relays use the currents and voltages to trip breakers to protect station equipment which can be costly or difficult to replace due to manufacturing time constraints.

Remote monitoring for a substation is done via a Supervisory Control and Data Acquisition (SCADA) [4] system. Remote monitoring allows system operators to determine what relays have been activated and which breakers are tripped. Monitoring allows for better control and automation of the power system.

Several companies design substations such as Burns & McDonnell, Black & Veatch, Olsson, POWER Engineers, RUE, and many more. However, the work done by these companies is dependent upon client standards. Oftentimes specific client standards enforce uniformity across all stations and are rarely updated and thus do not necessarily involve current industry practices. The work done by the design team aims to incorporate all required IEEE standards as stated in § 1.4 of this report. The uniqueness of the design will result from limited client standards which will allow the team to innovate. Because the design team is working with Burns & McDonnell and not a utility company there exist no strict client standards. Additionally, the team has full flexibility in terms of site conditions.

2.2 DESIGN THINKING

During design thinking, it is crucial to clearly define the problem statement. The problem statement is typically given by a client through a list of requirements and constraints. But the problem is better understood upon conversations with the client and understanding the scope of the project.

Problem definition: A new substation needs to be constructed to increase the voltage level coming from the Cyclone Generation facility from 69 kV to 138 kV to reduce transmission losses. Drawings and studies need to be created to aid in the construction of the new substation. The design must incorporate all major equipment and relaying devices as specified in the protections document provided by Burns & McDonnell. The new substation will benefit the communities around Des Moines and Cedar Falls as the new substation is to have line exits to these two cities. The requirements are specified throughout § 1 of this report.

After the problem has been identified, the ideation phase begins. During the ideation phase, the team explores different avenues to fulfill the requirements. The team brainstormed about what the physical arrangement of major equipment within the substation will look like. Two possibilities were identified to meet the requirements of the project.

The first design considered allowed for two future line expansions with the following system diagram:

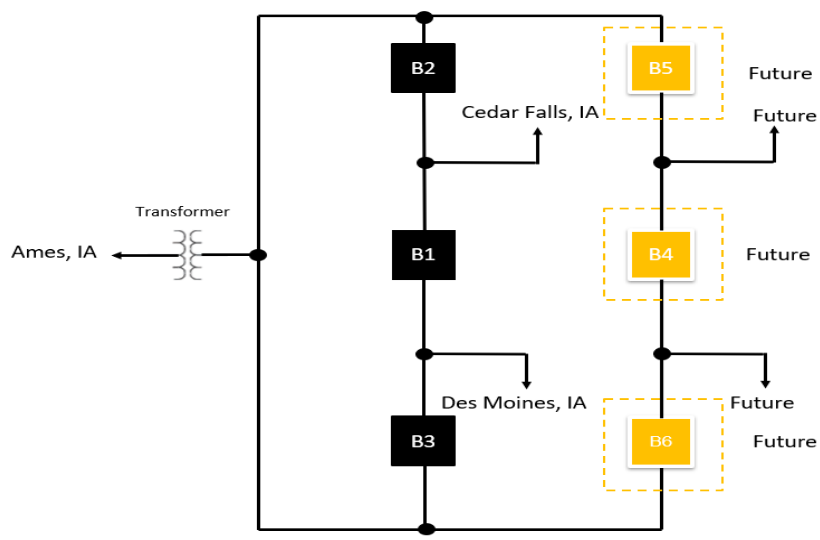


Figure 4 - Design #1

The second design considered allowed for one future line expansion with the following system diagram:

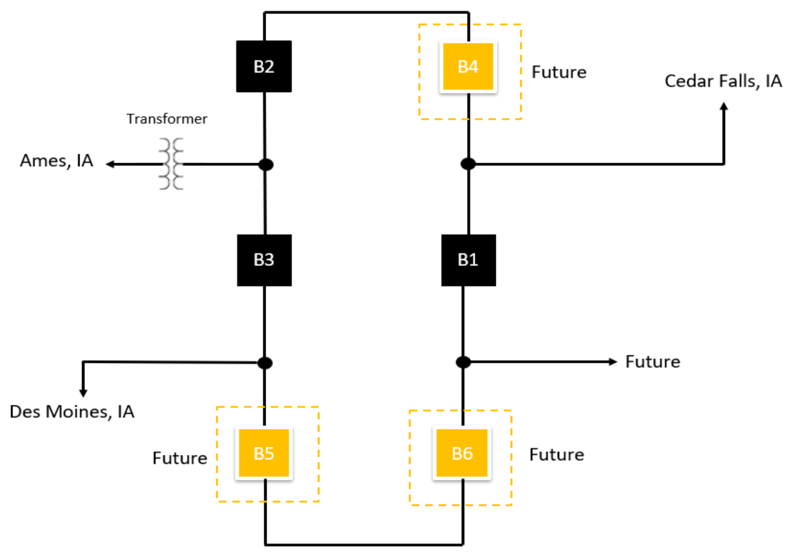


Figure 5 - Design #2

Both designs feature the ability to expand from ring-bus to six-position breaker-and-a-half. The primary difference is the number of future line exits available.

2.3 Proposed Design

Of the two system diagrams proposed in § 2.2 of this report, the design team moved forward with the design which has one possible future line expansion. This design was chosen based on the feedback provided by Burns & McDonnell when the team presented them with the options. The reason for their selection had to do with the substation with only one line exit would require less bus runs to construct. In the event of future construction, the system can be easily modified to become a six-position breaker-and-a-half configuration. The one-line shows, in more detail, the exact system diagram with all of the other equipment and relaying as specified in § 1.4 and the protection requirements provided by Burns and McDonnell. The one-line diagram can be found on the team website.

The proposed design meets the requirements for the project as it fully incorporates all of the major equipment and relaying that the client specified. The plan-view we created has ample room for maintenance personnel to drive their truck around and service any part of the facility. This was a design feature we wanted to add on top of what Burns and McDonnell requested. The completed plan-view drawing can be found on the team website.

2.4 Technology Considerations

For this project, the main technical considerations the team made was selecting electrical components that fulfill the requirements set forth by Burns & McDonnell. Some equipment, such as the breakers and transformer is already specified by Burns & McDonnell. The current transformers are directly coupled to the breakers and transformers. Additionally, the specific relays being used are specified by the client in the protection specification.

The design team has specified the following items: capacitively coupled voltage transformers, bus conductors, a wave trap, and a service station voltage transformer.

- Capacitive Coupled Voltage Transformer (CCVT): The voltage transformers reduce the voltages in the substation to a voltage that can be used by the protection relays. The CCVTs are to be rated at 80.5, 500 volts phase-to-neutral. And have secondary voltages of 115/67 volts. The team selected to use Artech DDB-145 CCVTs as they fit the design requirements. There are several manufacturers which produce CCVTs, but the documentation for the Artech model is easily available.

- ❖ Bus Conductor: The bus conductor connects the major pieces of equipment in the substation. It is commonplace to use aluminum tubing for bus conductors in a substation. The requirements specify that the bus conductors are rated for 2000 amps of current. The design team selected to use AFL global seamless bus pipe. Specifically, the team opted for the use of a 3-inch schedule 80 pipes as it is the lowest diameter that meets design requirements. The other option considered was a 4-inch schedule 80. The advantage of the 4-inch pipe is that it would not require as many buses supports as the 3-inch. However, the 4-inch pipe would be more expensive than the 3-inch so it was ultimately decided that the 3-inch would be better.

- ❖ Wave Trap: The wave trap decouples communication frequencies from the 60-hertz carrier frequency. The requirements for the project specify that the wave trap is to be tuned to 142.5 kHz and rated for 2000 amp continuous current. The design team opted to use Trench wave traps as they meet the design requirements and documentation is widely available.

- ❖ Station Service Voltage Transformer (SSVT): The SSVT transforms voltages from the substation down to typical voltages used in residential buildings (120/240 volts). This voltage is used to supply power to the control building and substation lights. The voltage is also used in some of the control enclosures for the other equipment in the yard to power heaters. The design team opted to use ABB Kuhlman SSVTs because they are reputable and widely used in the industry. There are other SSVTs manufacturers, but the ABB device meets the design requirements for the project.

2.5 Design Analysis

The design proposed in § 2.3 coupled with the selected components in § 2.4 meets all of the requirements set forth by the client. More specifically, the one-line shows how the relaying requirements specified in protection specification are met. The team continues to evaluate and modify previous documentation, such as the one-line, as the team discovers more details about the project. As our project evolved, we went back and added to the drawings created to make sure that our design was up-to-date, and all of the drawings reflected the most current configuration.

2.6 Development Process

For any project, it is important to develop a process that sets the pace for how the design will be created. For this project, the design team opted to use the waterfall development model. The waterfall development process is linear and is depicted as in Figure 6 [5]. The objective with waterfall development is to progress on one item at a time until it is working as expected. This is naturally extrapolated to our project because we can consider each deliverable as part of our project. Hence, we work through the entire design process for each deliverable and make sure that it is meeting requirements throughout the entire project.

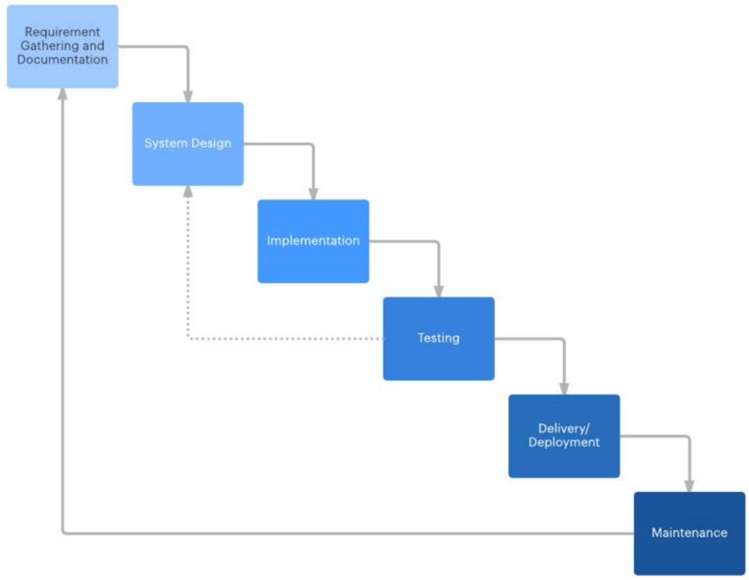


Figure 6 - Waterfall Development Process

It was determined that the waterfall process is best as it enforces that requirements are enforced at the early stages of the design and carried throughout the remainder of the project. Because of all of the interdependence of deliverables, this development process also enables the team to work in an efficient and well-defined manner. It is also easy to track progress and plan ahead as the workflow is linear. Furthermore, because the project is well-defined and the requirements are relatively strict, this method works better than the agile development process for this project.

2.7 Design Plan

During the design phase of the project, the team reflects back on the use cases and the requirements specified for the project because the substation will need to be maintained. It is important to design the substation such that maintenance can be performed easily. Furthermore, the substation needs to be designed such that minimal service interruptions occur.

Figure 7 shows a flowchart showing how the design of the substation is split up. Upon completion of each major drawing/study, the team ensures that the project fulfills the use cases and the requirements of the project. In Figure 9, the peach and green colored blocks represent the different design periods for the deliverables and are also points in which the deliverables are evaluated against the use cases and requirements. As the last step, the entire package will be examined to ensure that the design lives up to the use cases and the client requirements. This being said, the client requirements are viewed as minimal expectations. The design team's goal is to innovate beyond the requirements ensuring that the client is satisfied, but that new and creative designs are being generated.

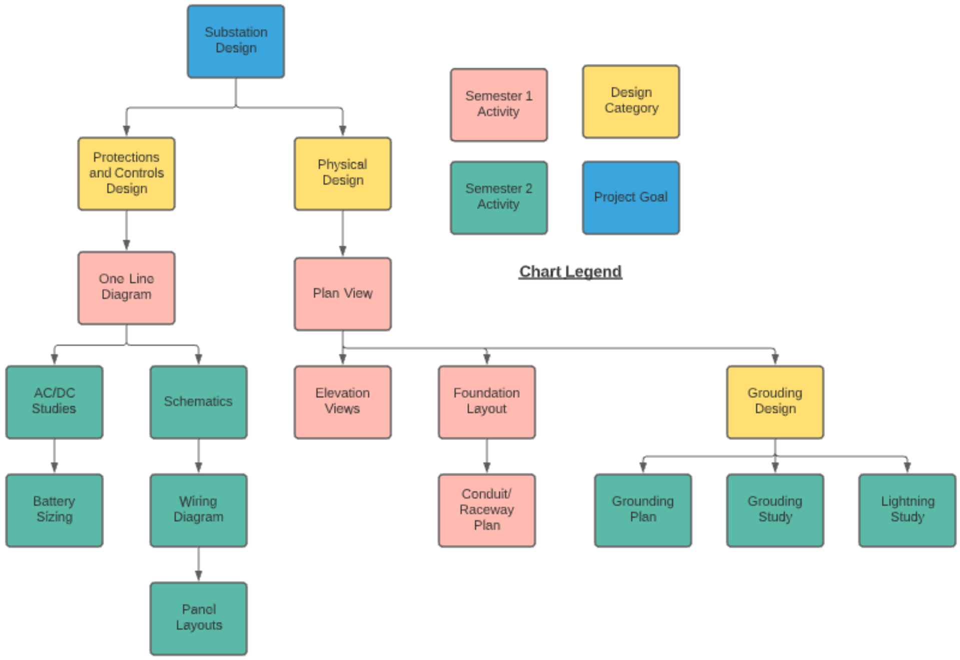


Figure 7 - Conceptual Design Diagram

3 Design

This portion of the report indicates the general procedure followed to create each of the deliverables for the project. During the first semester of the project, we focused on the physical design aspects of the susbtation. This included deliverables such as the one-line, plan-view, elevation views, foundation layout, and the conduit/raceway layout. During the second semester, the work shifted heavily into the studies and protections and controls aspects of the project such as the: AC/DC study, lightning study, grounding study, schematic design, panel layouts, and wiring diagrams. The project was split up between semesters like this to provide a good stopping point at the end of the first semester which is indicated in this section.

3.1 One-Line

The one-line diagram is the first step in designing a substation because it also doubles as a block diagram of the substation. In particular, a one-line diagram gives a high-level illustration of the substation configuration and purpose. From this drawing, an engineer can also determine how the system is protected from various fault conditions. This is because the one-line diagram, in addition to showing the general site layout, also depicts the relaying equipment. The relaying equipment is used to detect and isolate faults within the substation or on the lines exiting the substation. Upon detection of a fault, the relays activate their outputs to trip breakers to de-energize certain line exits.

The one-line diagram was created by first drawing a simple block diagram which consisted of only the major pieces of equipment (excluding relaying) q.v. Figure 12. To determine the major equipment within our substation, we consulted the protection specification provided to us by the client. The protection specification is a valuable resource as it laid out what equipment the substation must have in it. The project description was also referenced which added details do not present in the protection specification such as the specific configuration that the breakers needed to be in. Once we identified the major pieces of equipment and the constraints associated with each, we drew a simple diagram showing the interconnection of all components.

With this sketch in hand, we noticed that we did not have all of the information required for the project. Specifically, we needed to identify more information about some of the components we would use within our substation. This included components such as the capacitively coupled voltage transformers, disconnect switches, the motor-operated air break switch, and the station service voltage transformer. This information is used on the diagram to accurately call out the equipment, on this see Figure 8. To solve this issue, we used the protection specification and Google to research which components would best meet the needs of our site. We decided to choose the components which had the most publicly available documentation to lessen the burden we would endure trying to contact the vendors directly for drawings. We refer the reader to section § 2.4 for the component selection.

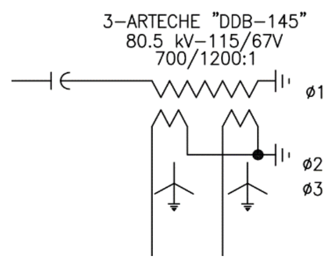


Figure 8 - CCVT Specification

After selecting the components, we moved our drawing into AutoCAD where we made a formal sketch of our substation. This sketch still only included the major equipment because we wanted to save the relaying for last. By designing in this way, we were able to maintain full flexibility without having to move the relaying equipment around too much. Once we were satisfied with our sketch, we went ahead and added in the future breakers. We added the future breakers as a placeholder so that way we would maintain our alertness of them throughout the project q.v. Figure 9. Once this was done, we were able to move onto the relaying.

To add in the relaying, we first had to consider the function of each relay. The relay functions are displayed in two ways on the drawing. The first way is to directly say what the various outputs of the relay perform. For example, in Figure 11 the main relay (represented by the rectangle) has outputs to trip breaker 3, send a transfer trip command to Des Moines, do a synchronism check with breaker 3, and then also trip a lockout relay which has its own set of outputs. The second manner of description resorts to using the American National Science Institute (ANSI) equipment ID numbers. These are enclosed by the circles in Figure 10. For example, 25 means synchronism check, 50 is an instantaneous overcurrent relay, 51 is an AC time overcurrent relay, 62 is the time delay, and 86 is a lock-out relay. We were able to display the data in both ways by carefully reading and interpreting the protection specification.

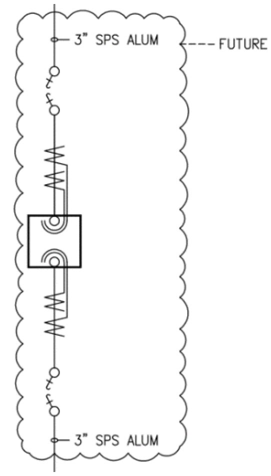


Figure 9 - Future Breaker

Once we populated our relays with their ANSI numbers and outputs, we began to focus on the current and voltage inputs. On the one-line diagram, we are more concerned with the currents inputs to the relay coming from a current transformer (CT) and the voltage inputs coming from a capacitively coupled voltage transformer (CCVT). Again, we consult the protection specification which outlines what CT and CCVT each relay needs to use. We were told by the client to show the CT inputs coming into the sides of the relays and the CCVT inputs should go into the top of the relay. This convention improves the readability of the one-line diagram because an engineer can choose to look for only the current inputs or only the voltage inputs if need be. A complication that arose during our design was that some relays had multiple current inputs but only had physical spots for one current input. We were initially unaware of this because we assumed that all of the relays could accommodate the number of inputs specified in the protection specification. Upon sending the one-line to the client for review they caught our mistake and let us know how to correct it, as seen in Figure 10. The CT inputs were also complicated because if multiple relays needed to use the same CT, they had to be connected to it in series to avoid current splitting. This was problematic mainly for formatting reasons on the drawing.

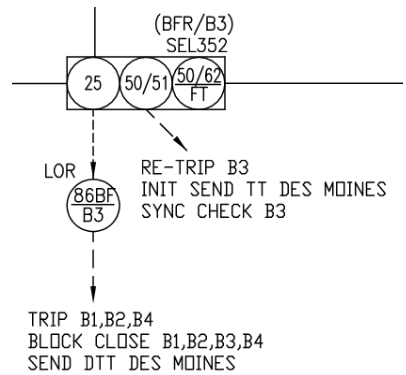


Figure 11 - One Line Representation of BFR/B3

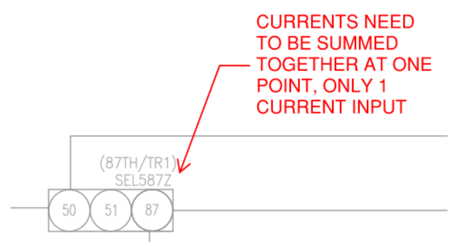


Figure 10 - Comment Pertaining to CT Inputs

Once the relaying was completed we followed our testing procedure to make sure that the drawing met client specifications and requirements. Once it passed the review, it was sent to the client for feedback. Please see the testing section of the report and the one-line diagram on the website for the results of the one-line design process.

3.2 Plan View

The plan view of a substation is one of the most important drawings because it lays out the components such as the transformer and breakers onto a physical design that then serves as a baseline for several other drawings such as the elevation views, foundation layout, and conduit/raceway plans. The way this drawing was created was very simple once the one-line and block diagrams were completed. The block diagram found in Figure 12 was created from the need for a ring bus, one incoming line, and two outgoing lines.

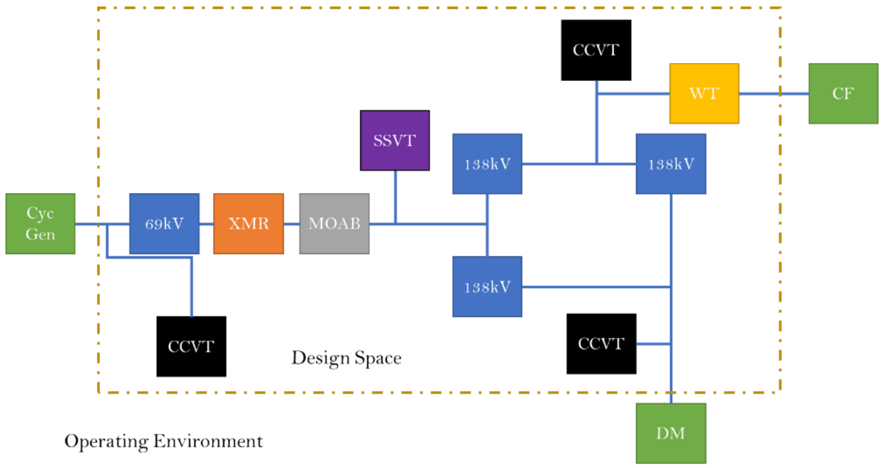


Figure 12 - Conceptual Block Diagram

Using the block diagram, all that was needed to create the plan view was to transfer the location of each component into AutoCAD and to add room for future expansion into a six-position ring bus. The largest design-related consideration in creating the plan view was the spacing of the various components. The spacing between the transformer and each circuit breaker was determined based on the knowledge that the equipment would likely need to undergo maintenance by field personnel who would likely drive service vehicles to the equipment. Another spacing consideration was the spacing between the bus phases. The spacing between the bus phases was determined by the maximum allowable line current. For our substation, this quantity is two thousand amperes (specified in the protection document). In the design guide provided by Burns & McDonnell, a table was provided that displayed the spacing requirement of seven feet between each phase. The next spacing requirement dealt with the supports that we needed to prevent sagging of the aluminum bus as it ran throughout the substation. The design guide also laid the specifications and equations necessary to solve this spacing. Using the equations provided, we determined that bus support would be required around every sixty feet of continuous bus run. With these spacing considerations, the components were placed into the drawing.

The next step was to create a road leading into the substation and to the control building. As there was no specification for this, we designed the road to fit two pickup trucks side by side in the entryway as this way the road can handle incoming and outgoing traffic. The final step was to place a fence around the substation. Due to the high voltages within the substation, the requirement in the design guide called for the fence to be at least twenty feet away from any bus or wire.

The plan view design then went into the testing process. After feedback from the team, fixes were issued, and the final design was sent to Burns & McDonnell for review.

3.3 Elevation View

The elevation view is derived directly from the plan view and is crucial for the physical construction of the substation. Field engineers and construction crews need to be able to visualize their work and have access to very accurate measurements. In the elevation view, these accurate measurements are provided from the perspective of looking at a substation from the ground view. Our elevation view was split up into three different sections of the substation. One of the sections was along the transformer branch, as shown in Figure 13 and Figure 14. The other two elevation views of the substations were of the two-line exits: Cedar Falls and Des Moines.

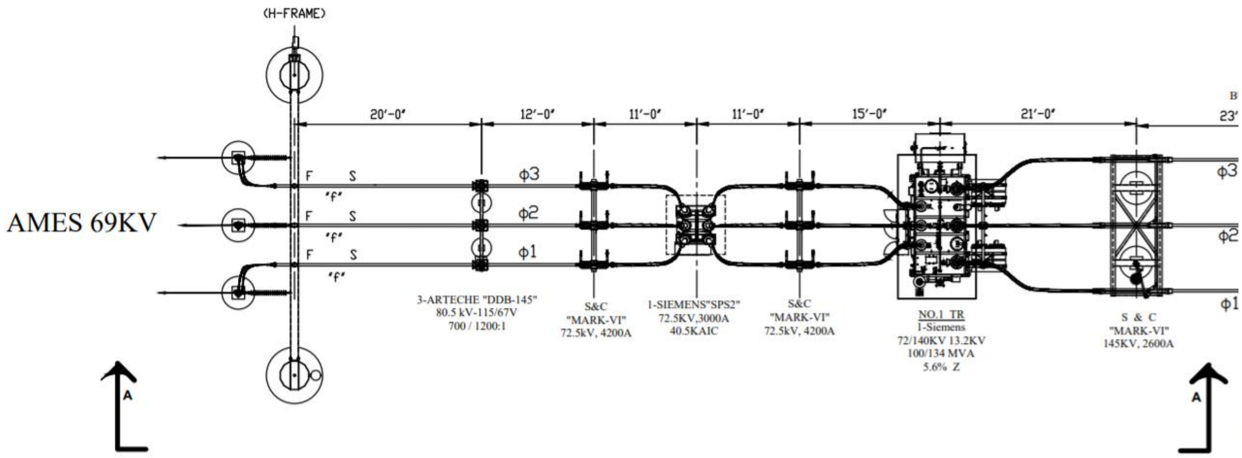


Figure 13 - Plan view of the transformer section A-A

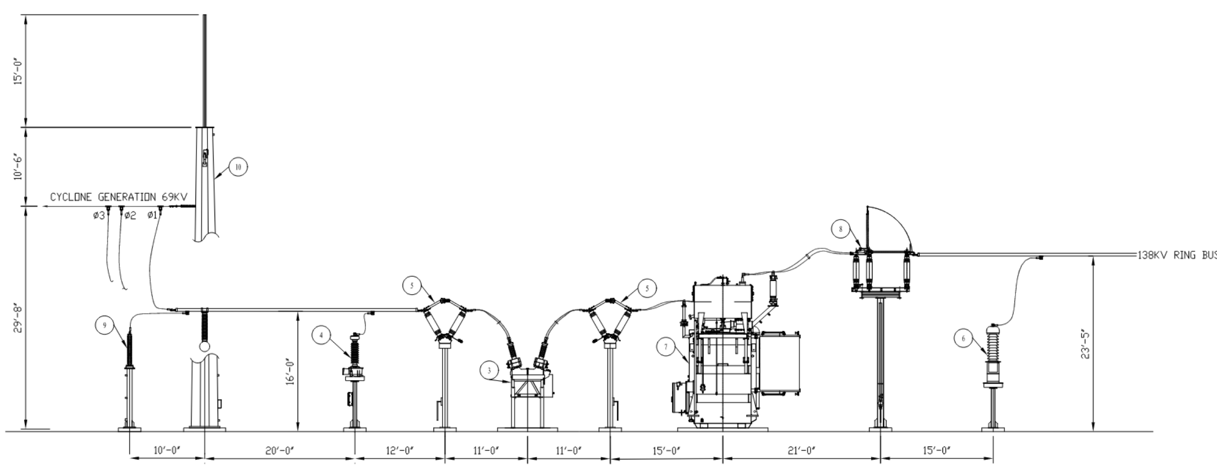


Figure 14 - Elevation view of the transformer section A-A above

As shown in the figures above, field engineers and construction crews will consult with the elevation view to determine the height of each component in addition to the horizontal spacing between all of the components. In addition to the added dimension of measurements, the elevation views also provide field engineers and construction crews with the bill of material labels. The bill of materials provides the proper type of bus connectors to be used while constructing the substation.

To design the elevation views, the team placed the components per the horizontal spacing dimensions listed in the plan view. Once the components were placed and spaced horizontally, it was time to dimension the vertical heights of the equipment. The visualization of equipment height of the equipment is the biggest difference between the elevation and plan-view. The plan-view calls out only the horizontal spacing between equipment, whereas the elevation view calls out both horizontal and vertical spacing.

Once we dimensioned the drawing, it was sent to the design team and Burns & McDonnell for the testing phase of our project.

3.4 Foundation Layout

With any large-scale piece of equipment, certain precautions are put in place to ensure that it can withstand the test of time. One such consideration is the proper design of a concrete foundation. The foundation, similar to a foundation found in a home, is there to keep the equipment from sinking into the ground and maintain its elevation as much as possible. Designing the foundation itself is out of the scope of our work because this is typically left to civil engineers. However, we are able to place the foundations that they deem appropriate within our substation. We consider in our design two main classes of foundations: (i) poured pad foundation (Figure 15 [7]) – typically used to support circuit breakers and transformers and (ii) drilled shaft foundations (Figure 16 [8]) – for most other equipment in the substation yard.

Figure 15 - Pad type foundation

The design process of the foundation layout is relatively straightforward for this project. To get started, we looked at the AutoCAD drawing of the plan-view and noticed an interesting occurrence. It turns out that the plan-view already contains the general location of the foundations as can be seen by the magenta lines in Figure 17. Thus, we simply remove all of the instances which are not colored magenta to get down to the foundations.

Figure 17 - Drilled shaft foundation

Once we have removed the artifacts from the plan view drawing to obtain a clean look at the foundations, we can better begin to dimension the foundations. To dimension the drawing, we chose to work from the bottom left corner of the drawing. We chose to do this because it would be easier for the construction crews to refer to a common point inside the substation as they prepare to lay out and pour the concrete foundations. For all of the foundations, we provided dimensions to the center of the foundation, this was mainly because for the construction of the drilled shaft foundations it would be simplest to place the drill at the center. Additionally, for the poured pad foundation it is easy to dimension out the rest of the pad based on the center point. Once the drawing was fully dimensioned, this phase of the project was complete.

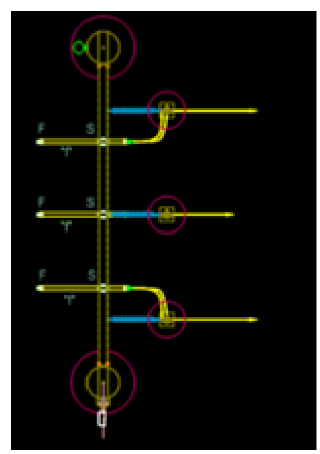


Figure 16 - Termination tower with foundations colored in magenta

It was interesting to get a look into what goes on in civil drawings because often as electrical engineers we tend to focus only on our trade. However, it is helpful to explore other trades because in the actual design of a substation we would have to coordinate schedules with the civil engineers to make sure the project goes off without a hitch. Being able to at least do the foundation layout gives us an idea of the amount of time and expertise that goes into properly designing a foundation system. We sent this drawing to Burns & McDonnell for review and received no comments or requests for changes to be made.

3.5 Conduit/ Raceway Plan (End of Semester 1)

The conduit and raceway plan was relatively simple to design as the conduit and raceway size were provided to us. To design the plan, future expansion was taken into consideration as it is less expensive to dig more raceway trench when the substation is initially being constructed than at the time of future construction. The raceway starts from the relays and terminal blocks inside of the control building and takes a short path to reach the transformer and each circuit breaker (including the future breakers). Conduit is then run into each piece of equipment from the raceway. The conduit and raceway system ensures that the cable is protected from the time it leaves the control building all the way until it is landed on the contacts within the equipment. The number of cables for each piece of equipment was determined from the specification documents provided. From the provided number of cables, the number of conduits runs to each piece of equipment can also be determined.

Once we completed this drawing, it entered the testing phase of the project. After it passed the team review it was sent to Burns & McDonnell for acceptance testing.

3.6 AC / DC Study (Beginning of Semester 2)

The Alternating Current (AC) study was created so that the utility company knows what amount of power is needed to be supplied to the substation during construction and during normal operation. The main difference between these two loads is that during construction, loads such as future breakers and receptacles are not included since they will not exist while the substation is being constructed. This design was created by looking at all the components that require AC power in the substation and forming them into a list. Each component's specification sheet on the list is then inspected to determine the AC power requirements.

After the power requirements had been recorded, a diversity factor was determined for each item based on its usage during the summer and winter months. An example of this is the heaters in the transformer and circuit breakers. During the winter, these heaters can be assumed to run all the time to keep the equipment from freezing over so the diversity factor is 1 during the winter while in the summer it can be assumed that the heaters will only run at nighttime when the temperature drops below a certain point, so the diversity factor is 0.5.

The power rating on the equipment is then multiplied by the diversity factor to determine the power requirements for each component in the winter and the summer. The list of the power requirements is then totaled to determine the maximum load for the substation during construction and normal operation.

The Direct Current (DC) study's purpose is to find the DC load that is required to adequately size the battery for both normal operations and emergency outages. To perform the DC study for our project our team followed IEEE 485 in-depth to analyze every DC load over eight hours. This eight-hour period would simulate the amount of time needed to provide current to electrical components while the problem that caused the outage was fixed. The DC load consists of electrical components such as breaker trip coils, emergency lighting, and all the relays. Every component is determined to be active and thus requiring current for specific periods during the eight-hour period.

After calculating the current draw for each of the DC load requirements, the battery and charger can be adequately sized. The battery itself is a bank of smaller DC battery cells configured to handle the load over eight hours. The worst-case emergency scenario is when the AC power is lost, the output of the battery charger is interrupted, and the load on the DC system is greater than the maximum output of the battery charger. This study sizes the DC battery system to be able to power to the substation under such conditions.

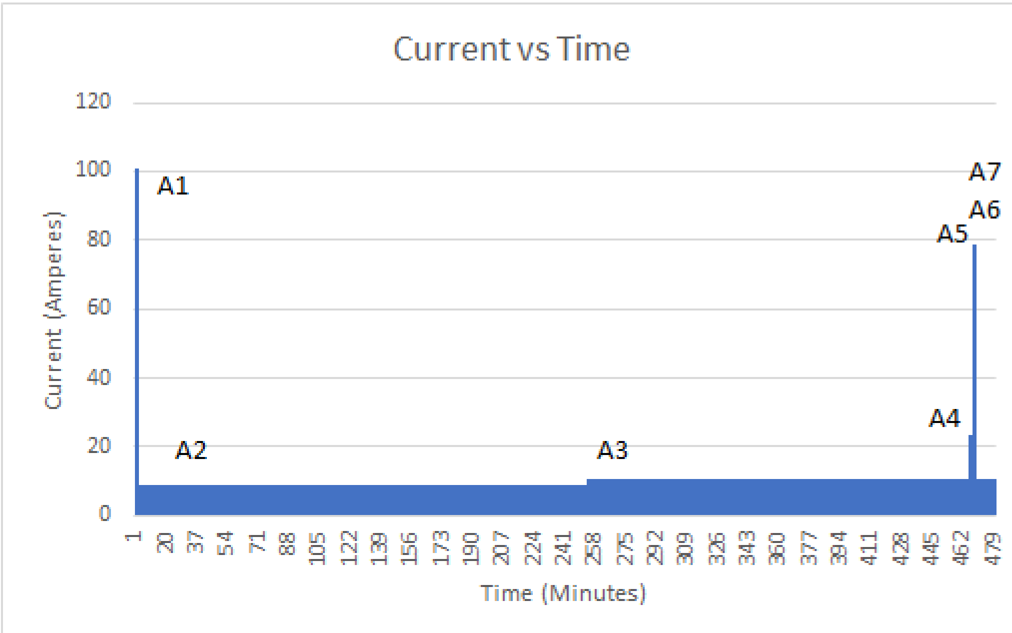


Figure 18 - The DC current required by the substation during an emergency operation

Figure 18 shows the 480 minutes (8 hours) where different DC loads will be pulling power from the battery in an emergency situation.

After the studies were conducted, formalized reports were drawn up and reviewed by the team in the testing process. After the team was satisfied with the reports, they were sent to Burns & McDonnell for acceptance testing.

3.7 Lightning Study

The purpose of the lightning study is to develop a drawing which depicts how the substation is protected from lightning strikes. An uncontrolled lightning strike can cause damage to major electrical components and relaying devices due to the high electrical current the strike carries with it. There are two main results of the lightning study: (i) a formal report indicating relevant calculations and (ii) a set of drawings showing the zones of protection provided by various different lightning strike mitigation technologies. The development of the lightning study relies heavily on IEEE standard 998 – IEEE Guide for Direct Lightning Stroke Shielding of Substations. This standard describes three main methods for shielding a substation from lighting: the fixed angle method, empirical curves, and the rolling sphere method. In our study, we were instructed by the client to use the empirical curves method.

The empirical curves method uses a set of experimentally developed charts to determine if a piece of equipment will be protected with 99.9% certainty. We consider two main classes of protection technology for this study: (i) a single lightning mast protecting a single object, and (ii) two lightning masts protecting a single object without overlap. We also note that in our study we consider two types of lightning masts (i) lightning masts affixed atop termination towers and (ii) standalone lightning masts.

To begin the design, we first examined the existing protection provided by the termination towers. Two important parameters determine the amount of protection provided by the termination tower: (i) the overall mast height and (ii) the height of the objects being protected. Both of these parameters are extracted from the elevation views where the overall heights of both the equipment and lightning masts are called out. For the example shown in Figure 14, it can be determined that the height of the mast is $h(m) = 55.7'$ and the height of the objects are $d = 20'$. (Note that the height of the object, $d \in \{20', 30', 40', 50'\}$). To determine the radius of protection, we consider the difference between the height of the mast and the height of the equipment to be $y = h(m) - d = 35.7'$. With this information, we are able to turn to Figure 20 [9] to calculate the radius of protection.

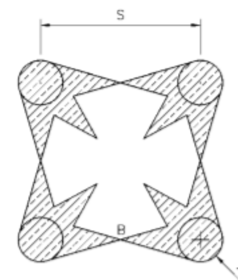


Figure 19 - Protection provided by multiple masts without overlap

We indicate in Figure 20 the calculation carried out using dashed lines. From these lines, it is possible to see that the radius of protection provided by this particular termination tower is $x = 52'$. With the radius of protection, we can then find the maximum amount of spacing between two lighting masts which fully protects equipment in the direct line of sight between two masts as seen in Figure 19 [9]. We use Figure 22 [9] to determine the tolerable separation distance, again we display the calculation with dashed lines. (Note that we are considering $y = 25.7'$ because the tallest piece of equipment in the entire substation is $d = 30'$. We are doing this so that we can use a common separation distance for the entire substation.) We can see that the separation distance $s = 185'$.

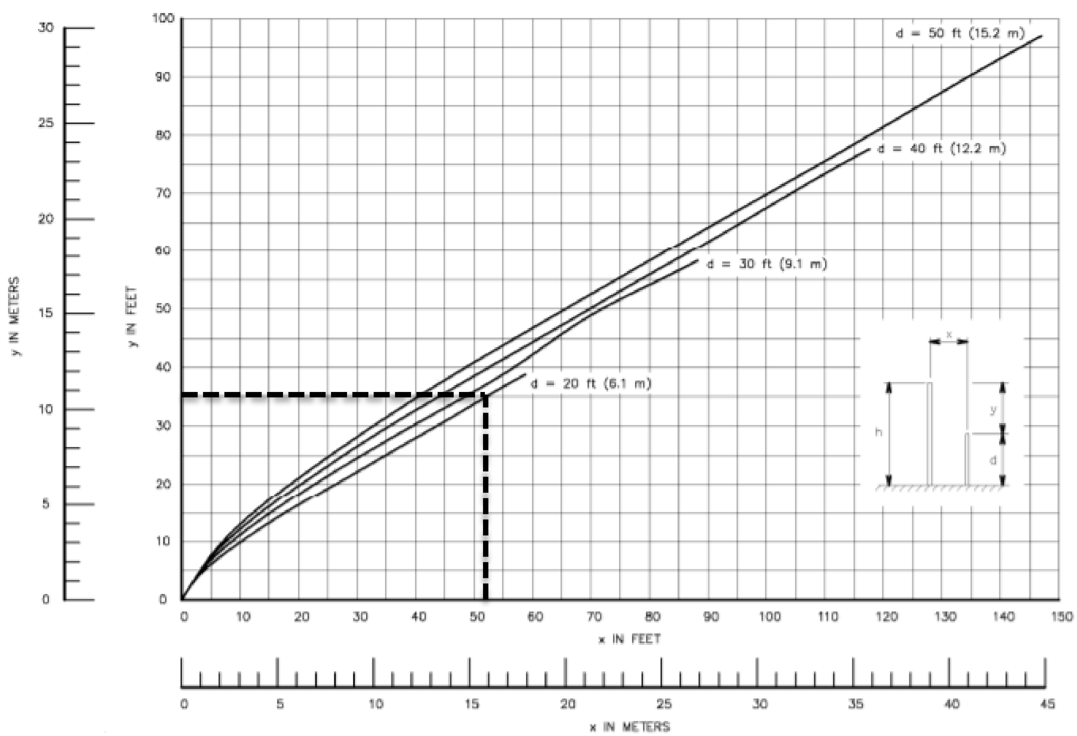


Figure 20 - Chart from IEEE 998 showing the radius of protection provided by a single lightning mast

This separation distance is used to draw the triangular shapes shown in Figure 19. Such triangular regions are important because of the tip of the triangle points in the direction of the adjacent lightning mast. If there are N lightning masts within the substation, then each lighting mast will have $N - 1$ lighting mast associations. If two masts are closer than the distance, S then their zones of protection are allowed to overlap as can be seen in Figure 21 [9]. If two masts are further apart than the distance, S then the triangular region still points at the other mast as can be seen along the diagonals of Figure 19. To develop the zones of protection provided by each mast, the triangular shapes are placed at the location of each mast and rotated to point at all other lightning masts in the system.

As stated before, we began with the lightning masts affixed atop the termination towers to see how much of the substation was protected by them alone. We created a drawing showing these zones of protection, this can be found on the website under the drawing name “Lighting Protection Report - Towers Zone of Protection Drawing”. We discovered that these termination tower structures do not provide adequate coverage for our substation and that more lightning masts would need to be added to fully protect the site. To correct this, we added lightning masts at strategic locations to account for the holes in the protection. The location of these masts and the additional protection added by them can be seen in the drawing on the website titled “Lighting Protection Report - Rods Zone of Protection Drawing”.

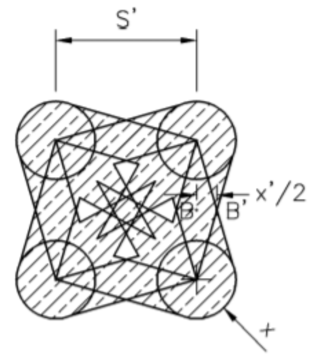


Figure 21 - Overlapping zones of protection provided by multiple lightning masts

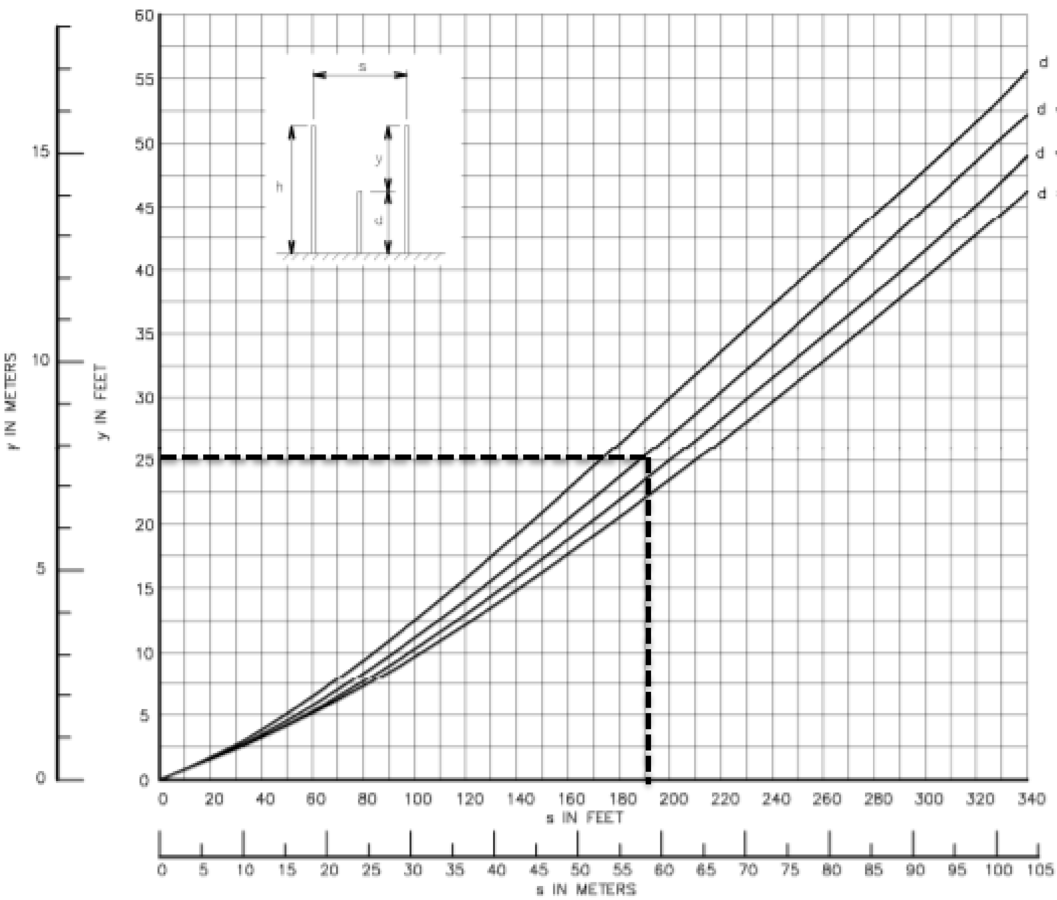


Figure 22 - Chart from IEEE 998 used to calculate the maximum protection provided by two masts

Once we showed the relationships between the new lightning masts, we connected them to the existing masts to create a depiction of the overall zones of protection. This complete zone of protection can be seen in Figure 23. As one can see, the entire substation is protected from a lightning strike with 99.9% certainty.

After creating this drawing, we formalized the report and drawings and sent them to the client to review. The client stated that the deliverable was completed properly and that our substation would be protected from lightning strikes.

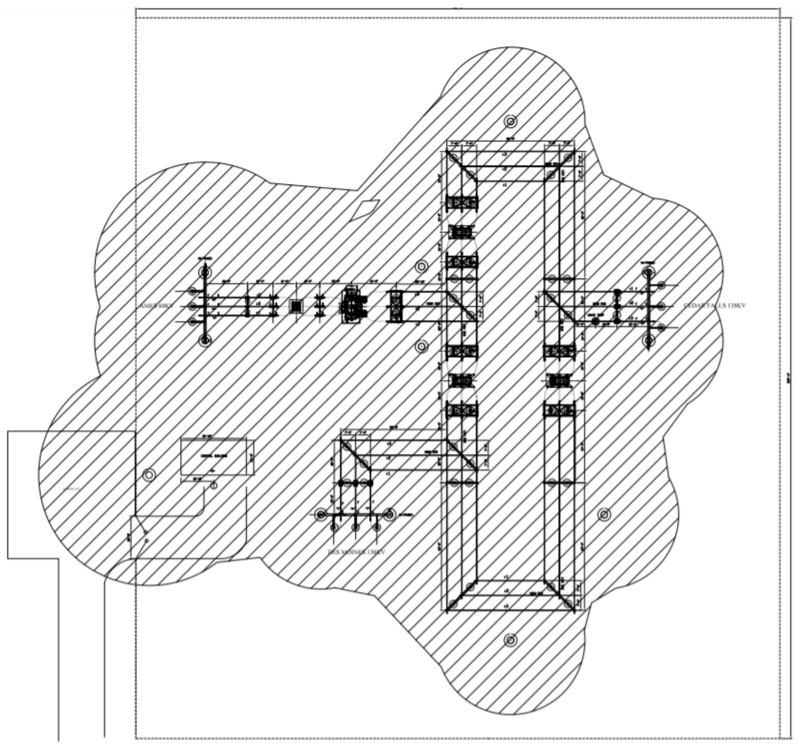


Figure 23 - Total lightning protection at the substation

3.8 GROUNDING PLAN

To ensure that the substation is safe, we designed a grounding system to protect the field crew and major electrical devices from stray currents. This design is dependent on IEEE standard 80 in addition to requirements specified by Burns and McDonnell. The premise of the grounding study is to ensure that the step and touch voltages experienced within the substation are below the minimum threshold.

We define here the parameters used in calculating the ground safety grid:

CDEGS: Current Distribution, Electromagnetic Interference, Grounding, and Soil Structure Analysis

Ground Potential Rise (GPR): The maximum electrical potential that a ground electrode may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage is equal to the maximum grid current multiplied by the grid resistance.

Touch voltage: The potential difference between any equipment chassis and GPR. To find the touch voltage, we would use the CDEGS software with the requirements provided by Burns and McDonnell. Figure 24 [10] shows an example of touch voltage.

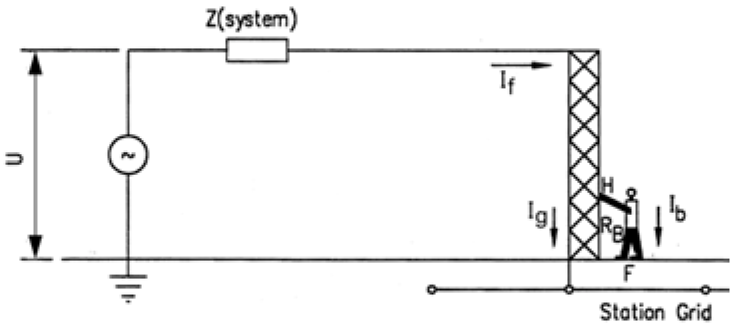


Figure 24 - Touch Voltage

Step voltage: is the voltage measured between the feet of a person standing near an energized, but grounded, piece of equipment. It is yet another one of the hazards considered when designing a grounding system. To find the step voltage, we will use the CDEGS software with the requirements provided by Burns and McDonnell. We note that the actual step voltage of the grid layout should have a value less than the value calculated using the following equations to be safe. Step voltage is depicted in Figure 25 [10].

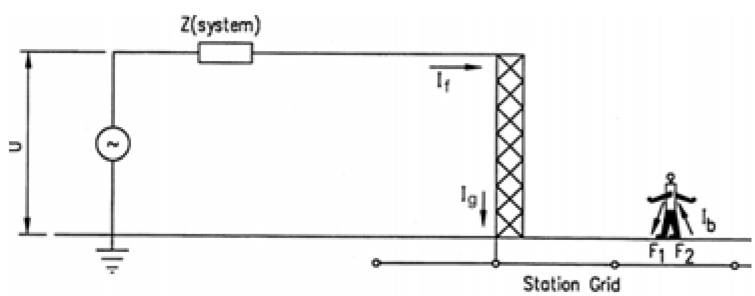


Figure 25 - Step Voltage

Equation 1 - Step Voltage

$$E_s = \frac{\rho K_s K_i I_G}{L_s}$$

Here, $\rho$is the soil resistivity measured in Ω-m, $K_s$is the spacing factor for step voltage, $K_i$is the correction factor for grid geometry, $I_G$is the maximum grid current that flows between ground grid and surrounding earth measured in Amperes, and L_s is the effective length of the ground conductor measured in meters.

The maximum step voltage is assumed to occur over a distance of 1 m as this is the distance between a person's feet. For the standard conductor burial depth of 0.25 m < h < 2.5 m, $K_s$is determined via:

Equation 2 - Spacing Factor

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{n-2})\right]$$

Here, h is the depth of ground grid conductors measured in meters, $D$is the spacing between parallel conductors measured in meters, and n is a geometric factor composed of factors $n_a, n_b, n_c,$and n_d.

Up to this point, we have covered the general definitions that will be key to understanding how our grounding study was conducted. To begin our grounding design, we first calculated the soil resistivity. For the Cyclone substation, we used the Wenner four-pin method to ascertain values for soil resistivity. This method uses four equally spaced probes at varying depths to obtain estimates on soil resistivity as can be seen in Figure 26 [10]. Once we have these measurements, Equation 3 is used to calculate the soil resistivity based on the Wenner four-pin measurement method.

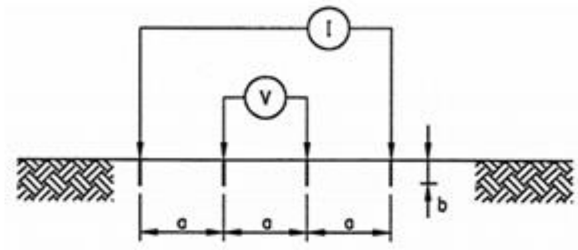


Figure 26 - Wenner four-pin measurement method

Equation 3 - Soil Resistivity

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

Here, R is the resistance obtained through the Wenner four-pin measurement method measured in ohms, a is the spacing between adjacent electrodes in meters and $b$is the depth of the electrode.

Based on our soil resistivity measurements, we determined we needed to add a layer of surface material on top of the soil at a thickness between three and six inches deep. Adding this layer of material is done to ensure that any person in the substation is not exposed to electrical currents. We use the resistance of the human body, 3000 ohms, to determine a material with sufficient resistivity at this depth to properly protect a human. We chose to use crushed rock as our insulating material because at a thickness of three to six inches it would have an impedance similar to that of the human body.

Next, we determined the resistance of our grounding grid and its associated GPR. Ground potential rise occurs when a large amount of electricity passes to the ground. Such conditions occur as the result of a lightning strike or a high voltage fault. We calculate the GPR using the following equation:

Equation 4 - Ground Potential Rise

$$GPR = I_{g\,x}\, R_g$$

Here, GPR is the ground potential rise in volts (V), I_g is the grid current in amperes (A), and R_g is the ground grid resistance in ohms (Ω). GPR is a key factor in determining the step and touch voltages that could be experienced within the substation. To calculate the GPR, we had to determine what conductor the ground grid and grounding rods would be made out of. This is an important factor because it will help us to determine the resistance of the ground grid. For this, we referred to the Burns & McDonnell standard titled “Inside Plant Construction Standard”. Here it specified that the ground grid conductor size is 350 MCM tinned copper, and the standard ground rod is a 20ft rod with a 1-inch diameter. We followed this standard because it was Burns & McDonnell’s industry practice. We also consider how deep the ground grid will be buried. This depth should be 12 to 18 in based on IEEE standard 80. From here we were able to determine how much condor and ground rod would be required for the substation. For the cyclone substation with an area of 303’-2” x 339’-4” with 20’x 20’ spacing, the calculation is carried out below:

Total length = (18x303’-2”) + (16x339’-4”) = 10888 feet

Total rod length = the number of the ground rod times the length of the rod = 20’ x 100 = 2000 feet

With this information, we would be able to enter the design into CDEGS to determine what the GPR, step, and touch voltages would look like in our substation. However, due to the inability to access the CDEGS software, we were unable to run any tests. An example of the output that would be obtained from CDEGS is shown in Figure 27.

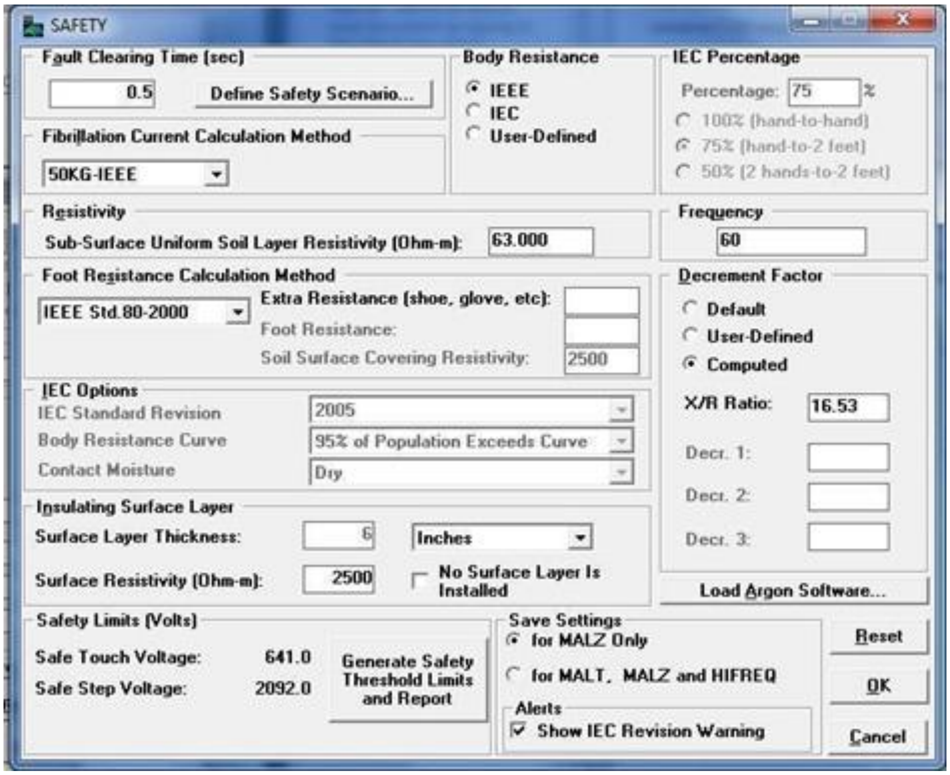


Figure 27 - CDEGS example

For more details regarding how CDEGS could be used please refer to the document titled” Grounding study report” on the team website.

We show the final design parameters for the grounding study in Table 1.

Table 1 - Ground Grid Physical Parameters

Physical Parameter	Description
Crushed rock layer	3” to 6” thick layer of limestone rock having a wet resistivity of at least 2500 ohmmeter
Conductor type	350MCM BTN Copper
Conductor burial depth	18 inches below the top of the soil
Grounding conductor connection method	Exothermic weld
Copper-Clad Ground rods	20 feet long with a diameter of 1 inch
Number of ground rods	100
Copper grid dimensions	Approximately 303’-2” x 339’-4”
Total Copper/350KCM Conductor length	10888 feet
Total 1” Copper Clad Rod Length	2000 feet
Average Grid Spacing	20’x20’

To ensure the safety of the field personnel and the equipment inside the substation, we must provide a passage to earth for fault currents. For this reason, we design the grounding grid safety system to ensure the current will follow a path without causing any damage. We determine the soil resistivity based on the soil type and measurement method. Having this information, we can determine the GPR. The relationship between the grounding resistance and the protection provided varies depending on where the substation is constructed. The location of the site determines the type of materials available at the time of construction. Thus, the safety criteria based on IEEE standard 80 have to be followed. Having all of the details mentioned above, we can determine the step & touch voltage through the grid sizing obtained by the CDEGS software and evaluate the effectiveness of the grounding system. Our calculations follow IEEE standard 80 to determine the safety for a person weighing 50 kg (110 lb) walking around within the substation.

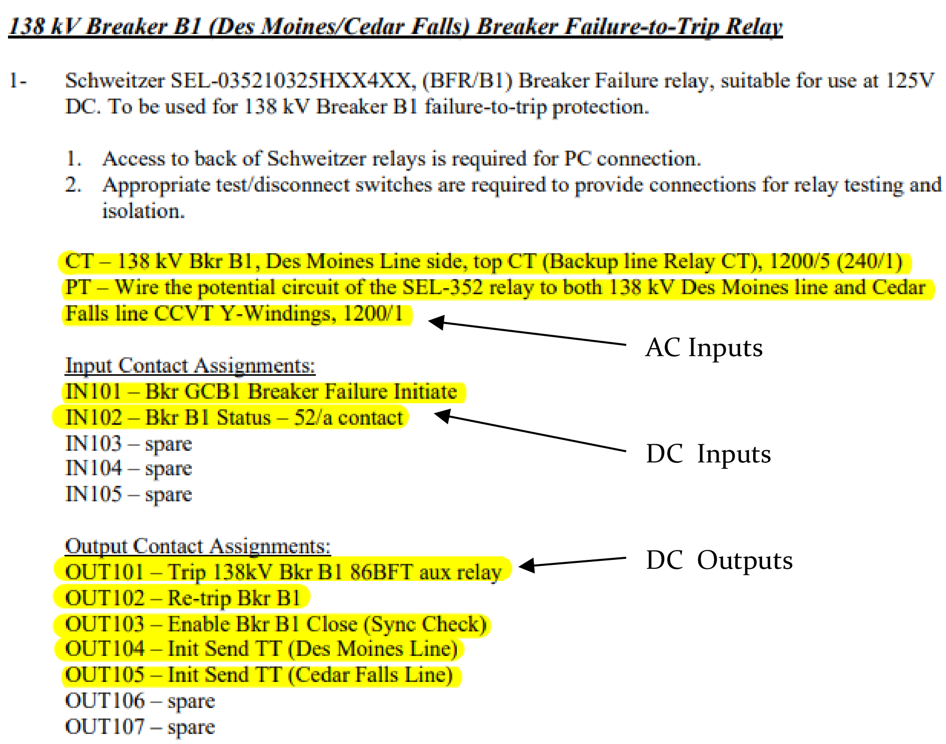
Upon the completion of the grounding study, we put it through the testing process and sent it to Burns & McDonnel for their review as well.

3.9 Schematic Diagrams

Schematic diagrams depict how the relaying equipment is connected to perform the functions specified in the protection's specification. A schematic diagram is different from a wiring diagram because the schematic diagram is an abstract representation. Particularly, the schematic diagram depicts where continuity should exist, but does not indicate how to physically connect the relays. When we refer to relays in this report, we are referring to rack-mounted relays such as the one shown in Figure 28 [11].

Figure 28 - SEL311L Relay

In the portion of the schematic of the project, we create drawings that show both the AC and DC interconnections from the relays to CTs, CCVTs, transformers, and breakers. To find the required function for all contact assignments, we referred to the protection specifications provided by Burns and McDonnell. A sample page of this document is shown in Figure 29:


138 kV Breaker B1 (Des Moines/Cedar Falls) Breaker Failure-to-Trip Relay

1- Schweitzer SEL-035210325HXX4XX, (BFR/B1) Breaker Failure relay, suitable for use at 125V DC. To be used for 138 kV Breaker B1 failure-to-trip protection.

1. Access to back of Schweitzer relays is required for PC connection.
2. Appropriate test/disconnect switches are required to provide connections for relay testing and isolation.

CT – 138 kV Bkr B1, Des Moines Line side, top CT (Backup line Relay CT), 1200/5 (240/1)
PT – Wire the potential circuit of the SEL-352 relay to both 138 kV Des Moines line and Cedar Falls line CCVT Y-Windings, 1200/1

Input Contact Assignments:
IN101 – Bkr GCB1 Breaker Failure Initiate
IN102 – Bkr B1 Status – 52/a contact
IN103 – spare
IN104 – spare
IN105 – spare

Output Contact Assignments:
OUT101 – Trip 138kV Bkr B1 86BFT aux relay
OUT102 – Re-trip Bkr B1
OUT103 – Enable Bkr B1 Close (Sync Check)
OUT104 – Init Send TT (Des Moines Line)
OUT105 – Init Send TT (Cedar Falls Line)
OUT106 – spare
OUT107 – spare

Figure 29 - 138 kV Breaker B1 (Des Moines/Cedar Falls) Breaker Failure-to-Trip Relay assignment

For the creation of any schematic, we start by focusing on the AC inputs in what is known as the AC schematic. The AC schematic shows the inputs to relays that come from current transformers (CTs) and the capacitively coupled voltage transformers (CCVTs). On the breaker and transformer schematic drawings, we depict the CTs. And on the line relaying schematics, we display the CCVT relay connections. We do it in this way because the CTs are directly coupled to the transformers and breakers, whereas the CCVTs are associated with each line exiting the substation. For each relay, the specifications for how CT and CCVT inputs should be made are specified in the protection specification requirements provided by Burns and McDonnell as is seen in Figure 29. A sample AC schematic can be seen in Figure 30 for breaker 1.

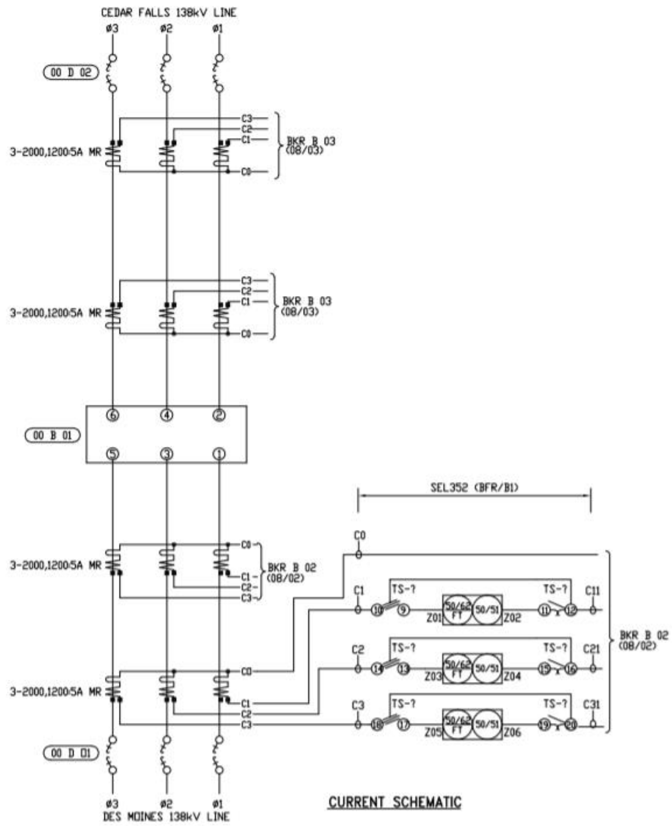


Figure 30 - 138 kV Breaker B1 (Des Moines/Cedar Falls) AC Schematic

After we have completed the AC schematic, we begin work on the DC schematic. The DC schematic focuses more on what specific output functions the relay will perform. In addition, the DC schematic will also depict DC inputs to the relay, for example, it may show breaker statuses as a DC input to the relay. To begin work on the DC schematics, we again resort to the protection specification. The protection specification outlines the DC inputs and outputs for each relay. Some of the vendor drawings for the breakers and transformers may need to also be altered based on the function the relays are performing. For example, a DC output to trip a breaker requires that the normally open relay contacts are added to the trip circuit of the breaker. Seeing how the vendor prints are altered to accomplish relay functions can be seen on the drawings uploaded to the website. A completed DC schematic for the relay for breaker 1 can be seen in Figure 31.

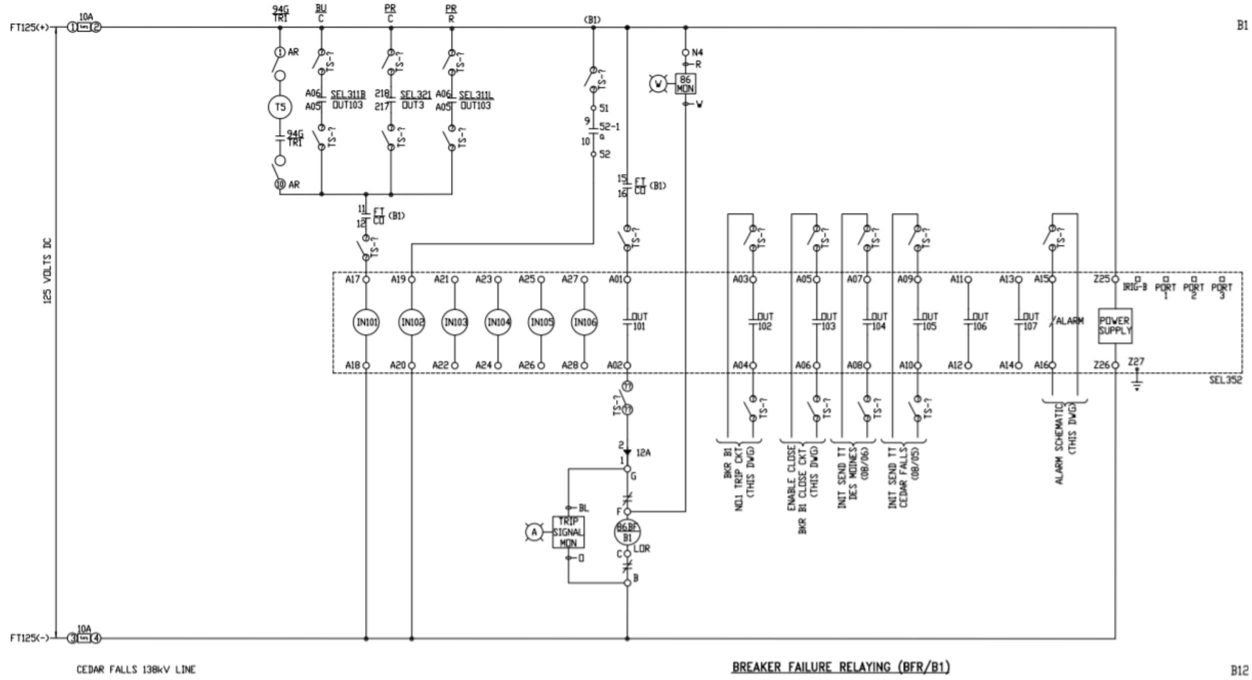


Figure 31 - Breaker Failure Relaying (BFR/B1) DC Schematic

The general process for creating a schematic follows a particular sequence of events:

1. Determine the AC inputs
    a. Create the AC schematic for the CT inputs on the appropriate drawing.
    b. Create the AC schematic for the CCVT inputs on the appropriate drawing.
2. Display the inputs and outputs on the relay.
3. Show the outputs of the relay on the correct drawings i.e., if the relay is meant to trip a breaker, then its contact should appear in the breaker trip circuit.

We applied this process to every relay within the protection specification. After we completed all of the schematics, they entered the team's testing procedure and were subsequently submitted to Burns and McDonnell to receive their feedback as they undergo acceptance testing.

3.10 Panel Layouts

Figure 32 - Relay panel

The panel layouts serve to depict the major relaying equipment on the panels within the substation control room. The racks used have the same general dimensions as networking racks commonly found in commercial applications. The majority of the Schweitzer Engineering Laboratory Incorporated (SEL) relays and ABB Flexiest test switch assemblies are able to be mounted directly to these racks. However, some components such as the lockout relays, control switches, and indication lights need to be mounted onto a steel plate. For both personal safety and aesthetic purposes, the entire front of the relay panel must be covered with steel plates. This prevents field personnel from accidentally coming in contact with stray wires. Figure 32 shows examples of relay panels in a substation control building.

There are a few design considerations taken into account when it comes to drawing plans for a panel layout. The first consideration would be making sure that operators are able to easily read and interact with the equipment. This means trying to concentrate as much of the equipment in the middle of the panel as possible to avoid having to crane one's neck or crouch down to read a meter or relay status. Another consideration is that in our particular application, there are plans for future expansion. Thus, we must leave room for additional equipment on all of the panels. A final consideration is that we need to focus on keeping the same types of equipment in the same general location from panel to panel. This makes it easier for the operators when it comes to diagnosing problems and also allows them to quickly know where to go on the panel in the event of an emergency too, for example, disable a circuit breaker by flipping its lockout relay.

We had three main types of panels to design: (i) 138 kV circuit breaker panels, (ii) line relaying panels, and (iii) the transformer panel. We are not designing a panel for the 69 kV panel at the request of the client because insufficient relaying data was provided to us. To begin the design process, we first went through the entire protection specification and the schematics to identify the types and quantities of all equipment required for a particular panel. An example of this, the list is shown below for the breaker 3 panel:

Table 2 - Breaker 3 Equipment

Relaying Equipment		
Relay	**Current Test Switch Pairs**	**Potential Test Switch**
SEL 352 (BFR/B3)	3	15
LOR (86BF/B3)	0	10
FT/ CO	0	0
CS/ B3	0	0
Extra Equipment		
Device	**Quantity**	
SCADA CO	1	
Indication Lights	5	
Fuse holder	1	
10 A fuse	2	

Once we determined what equipment the particular panel needed to have, we placed the equipment on the back of the panel. We started with the back of the panel because it allowed for the most flexibility of movement. For example, if a relay was placed in the incorrect spot, it could be easily moved without having to adjust the dimensions that appear on the front of the relay panel. The back of the panel also doubles as the location where the wiring will take place. Due to the size of the drawings, we recommend the reader refer to the website for examples of our panel layout drawings.

After we were satisfied with the layout of the equipment on the back of the panel, we laid it out neatly on the front of the panel by doing a mirror image. We had to do a mirror image because when you look at the front of the panel, the equipment that was on the right-hand side when viewing the panel from behind would now be on the left-hand side looking at it from the front. A sample panel is depicted in Figure 33 for reference. The front of the panel gives the best indication of where the equipment will be located. As mentioned before, careful attention is paid to improve the readability of equipment status by placing it in the center of the panel as much as possible. In designing the front of the panel, we also determined the spacing between all of the major equipment. Again, we tried to leave enough room for future expansion, but also so that the client could affix nameplates to the panel in the future if this is something they wanted to do.

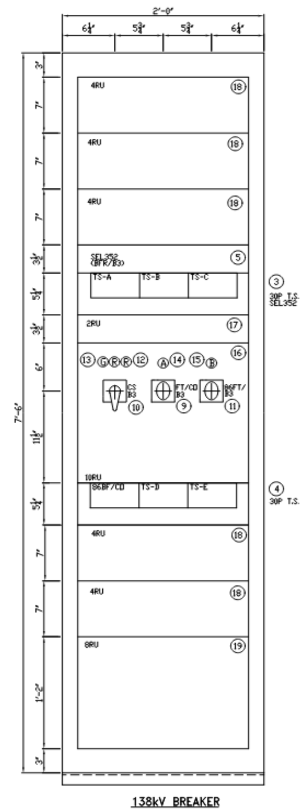


Figure 33 - Sample panel layout for breaker 3

Once we completed the panel front, we moved onto developing the bill of materials. The bill of materials for this drawing specifies what the equipment is. Call-outs to the bill of materials are done using a number enclosed by a circle. To create the bill of materials, we focused our efforts on describing the specific piece of equipment in as much detail as possible. Furthermore, we also provided part numbers so that the client could easily search the part on the vendor's website. An example of the bill of materials can be seen in the following image:

3	1	ABB Flexitest switch assembly, type FT-19RX, for 19 inch rack mounting with one 10.5" extended case FT-1 switche, 3 rack units, switches low, gray, Cat. No. FSXG119001001NX10.

Figure 34 - Sample bill of materials callout for a test switch

Here we are specifying how the top-most bank of test switches in Figure 33 is configured. Once the bill of materials is completed, the design of the panel layout is also completed. We were unable to receive comments from the client regarding this deliverable because it was towards the end of the project.

3.11 Wiring Diagrams

A wiring diagram depicts the physical interconnection of equipment terminals. Specifically, the wiring developed in this project shows how the equipment in the relaying panels is connected to one another. The creation of wiring diagrams is dependent on two other deliverables being completed: (i) schematics, and (ii) panel layouts. The schematics are important because they depict the function of what the wiring will end up needing to meet. For example, the schematic diagram depicts the inputs and outputs of all of the relays, thus when the wiring diagram is created it needs to make the physical connections on the relays to perform the functions shown on the schematics. The panel layouts are integral to the creation of the wiring diagrams because the panel layout drawing shows the back of the panel which is where all of the wirings take place. For example, see Figure 35 which shows the back of a breaker failure relay (SEL352) both in the physical world and the representation of it shown on the panel layout.

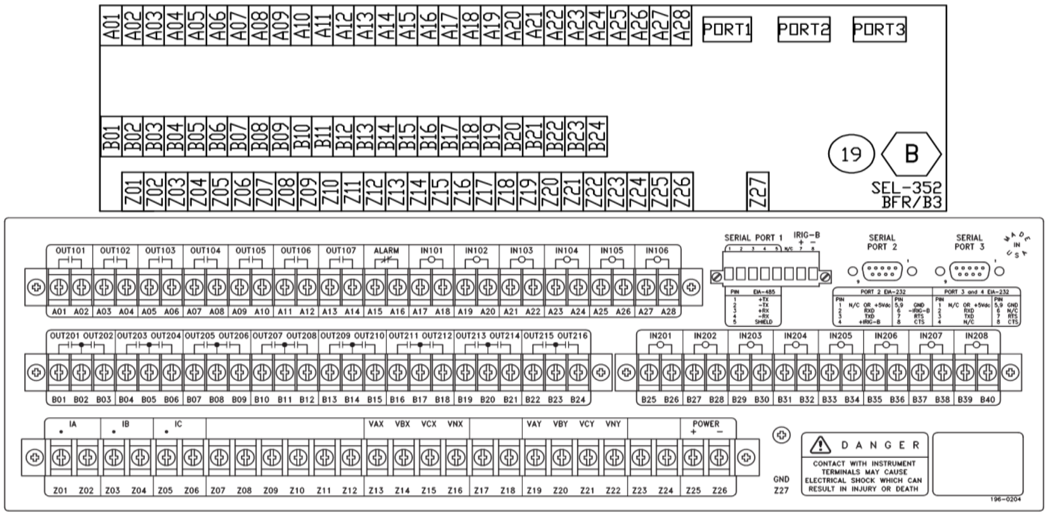


Figure 35 - Back of an SEL 352 relay as shown on the panel layouts (top) and as shown in the SEL documentation (bottom)

From this depiction, one can see that the panel layout representation is very similar to the actual piece of equipment that the field personnel would be interacting with. Hence, the wiring is done entirely on the section of the panel layout depicting the rear of the rack.

To begin the wiring process, we first consider the AC inputs to the relay. This includes signals from the CTs on the breakers or transformers and the CCVTs tapping off the Des Moines and Cedar Falls exit. Let's consider that we are wiring the SEL352 relay for breaker B3 depicted above. Using the schematic diagrams, we completed earlier, we would find where the relay exists within the AC schemes:

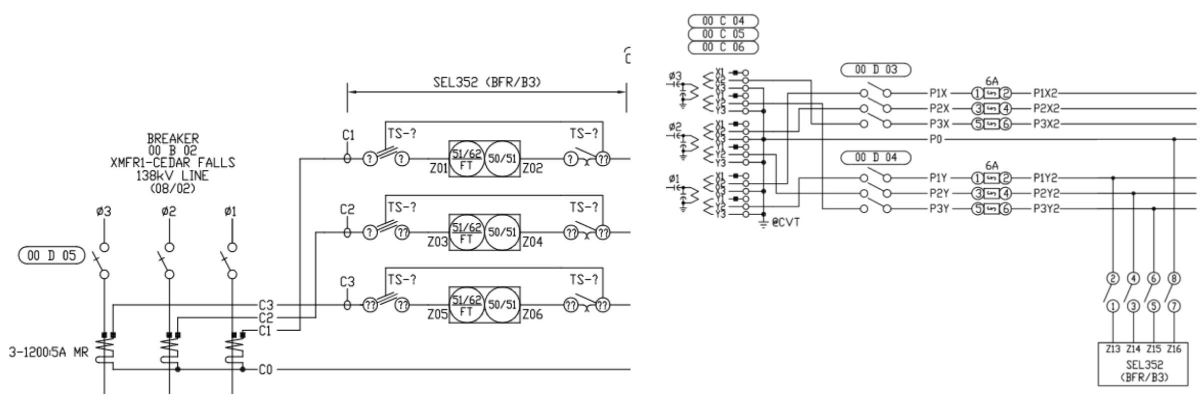


Figure 36 - AC schematics showing how the SEL 352 relay for breaker 3 gets its current and voltage inputs from the CTs and CCVTs

We see from these AC schematics that there is only one set of inputs from CTs at breaker 3 and one set of voltages from the CCVTs coming from the Des Moines line exit. We wire these inputs through their respective switches as shown in Figure 37. One can see that the top side of the switch corresponds to the Z## designation shown by the relay in the drawing. The bottom side of the test switch has the designation T## to represent that the switch is connected to a terminal block. The terminal block is used to distribute outgoing wires to other panels or equipment located in the yard of the substation.

Once we have wired up the inputs from the CTs and CCVTs it is time to begin wiring the relay per the depiction shown in the schematics. To this end, we have to reference the DC schematic shown on the breaker panel for the relay; this drawing is listed on the website. From here on, it is easiest to reference the example drawing depicting the wiring for the relay which is located on the team website because the drawing encompasses quite a bit of detail. The general process for wiring the DC scheme looked as follows:

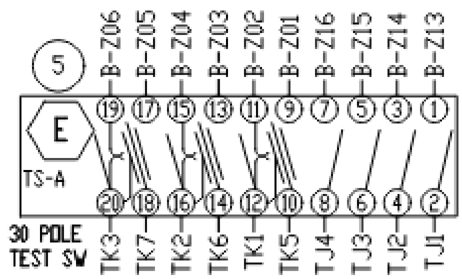


Figure 37 - Sample test switch used to send voltage and current signals to the relays

1. Connect the positive and negative 125-volt rail to the fuses on the panel and the power supply of the relay.
2. Daisy chain the negative 125-volt rail to all of the other points along with the relay which requires it.
3. Connect the input contacts of the relay to either the test switches or the terminal blocks going to relay statuses.
4. Connect the outputs of the relay to their respective test switches.
5. Connect the alarm output of the relay to its own test switch.
6. Wire the other sides of the test switches to terminal blocks to exit the panel and connect to other equipment.

We followed this six-step process whenever wiring the SEL relays and in general, the same procedure can be followed for wiring all of the other equipment on the panel. Due to the time constraints on our project, we were unable to complete the wiring of an entire panel, but we were able to get at least one relay wired, which gives us a sense of what the wiring process looks like.

3.12 Applicable Design Standards

In working on the aforementioned deliverables, we found it necessary to consult a subset of IEEE standards:

- IEEE 998 - IEEE Guide for Direct Lightning Stroke Shielding of Substations
- IEEE 80 - IEEE Guide for Safety in AC Substation Grounding
- IEEE 485 - IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

The focus of the standards is twofold: (i) ensure that the completed substation design is able to perform its function to the expectation set forth by IEEE and (ii) ensure the reliability and safety of the substation operation. In this section of the report, we connect the design process with its relevant standards.

To begin, consider the lighting study that was conducted. To assist in our design, we needed to employ a tested method for determining the amount of protection provided by the various lighting masts within our substation. To this end, we employed the empirical curves method that was specified in IEEE 998. The IEEE 998 standard provided the charts that we used to determine the radius of protection of the masts and the maximum amount of protection provided by two lightning masts. This standard also considers other methods to determine the protection provided such as the fixed angle and rolling sphere methods, the latter of which requires extensive computer modeling to pull off.

In the grounding study, we considered IEEE 80 which deals with the development of a grounding grid within a substation. The first step of completing the grounding study is to determine the resistivity of the soil, to this end, we employed the Wenner four-pin method described in IEEE 80. Once the soil resistivity is determined we need to determine the step and touch voltages experienced within the substation. Step voltages are the voltages seen as an individual walks around the substation. Touch voltages are the potential difference between a person and the chassis of a piece of equipment within the substation. The calculation methods for these quantities are clearly specified in the standard. The actual computations are carried out using a computer program to reduce the computation time.

In our final study, the DC study - which focused on determining the size of the batteries required for the substation, we enlisted IEEE 485. This standard, while not being directly developed for use within substation design is still applicable. This standard is still applicable because a substation is a stationary application, hence the methods described in the standard are easily extendable to the substation application. This standard clearly explains the process of splitting the loads in the substation into continuous and discontinuous loads. Once we got these loads determined we were able to refer to the standard for methods to calculate the total capacity of batteries to keep the substation operational for 8 hours after the loss of AC power (AC power is used to power the battery charger).

From this, one can see that the standards were integral to the development of the various studies completed for the design of the substation. Standards in general, ensure that a developed design is reliable and safe for human interaction. We need to ensure reliability because the substation is operating within a power grid where a mis-operation could lead to death or loss of revenue.

3.13 Design Summary

The final design is a compilation of all of the deliverables as described in sections 3.1 – 3.12. The design incorporates all of project requirements and follows the limitations described in section 1.6 of this report. Additionally, the standards described in section 3.12 are used to aid in the design process. The objective with this project is to provide a construction crew with a set of drawings that would enable them to fully construct a substation. To this end, we have described the design process for both physical and protections/control drawings. Section 1.7 of this report clearly details how all of these deliverables fit together to accomplish the larger goal. The design that the team presents as a solution to the problem statement would be all of the deliverables found on the team website. The purpose of this section of the report was to describe the considerations taken into account as each of the deliverables was created, so that the reader could see the thought process behind the design.

Final set of deliverables: https://sdmay21-04.sd.ece.iastate.edu/docs.html

4. Testing

In a design project, a testing plan provides a method for engineers to ensure that their work will meet client specifications and relevant industry standards. To this end, three main tests must be carried out: (i) unit testing, (ii) interface testing, and (iii) acceptance testing. These testing categories provide a sample framework for our project. The guiding principle for our testing is a quality assurance/ quality control (QA/QC) process. During the QA/QC process, each drawing is checked over itself to ensure that the entire drawing is correct. The unit testing phase ensures that the drawing is technically correct with respect to the information on that drawing. In this section of the report, we define how we approached each testing section and also the results of the testing process.

4.1 Unit Testing (Step 1)

This project does not require the testing of any hardware/software, instead, the electrical components are connected to one another via drawings in AutoCAD. In our unit testing procedure, we examine the deliverable against itself. Namely, we make sure that the deliverable is depicting what it needs to show and that it is technically accurate. Additionally, we check that the drawing conforms to industry and client specifications. We define this as unit testing because, in our project, each drawing/deliverable corresponds to a subtask of the larger goal of the design of a substation.

4.2 Interface Testing (Step 2)

Each drawing in this project typically has dependencies and calls on other drawings. For example, the one-line diagram acts as a detailed system sketch showing the configuration of the electrical components within the substation. Thus, when the plan-view is analyzed, it is checked in isolation first (unit testing as discussed in § 4.1) then it is compared against the one-line to make sure that the two drawings make logical sense and are accurate when viewed together. Each deliverable goes through interface testing with the deliverables issued before it. See § 1.7 for a list of deliverables in sequential order. § 2.7 also provides a logical flow chart of the deliverables showing their interdependence. As the design progresses, these checks will continue until the entire substation package is checked. When the whole package is complete, it will be confirmed that all drawings make logical connections to others and are technically accurate.

4.3 Acceptance Testing (Step 3)

The focus of acceptance testing is to ensure that the deliverable conforms to industry standards and client expectations. Acceptance testing involves three different groups of people (i) the original creators of the drawing (ii) the entire design team, and (iii) the client. The first two entities ensure that the drawing is as correct as possible based on their knowledge. These entities should also focus on checking the deliverable against the design requirements. The client, Burns & McDonnell, will then review the deliverable provided by the team to check for accuracy and application of the necessary standards/requirements. Hence, the final acceptance testing is the responsibility of Burns & McDonnell who provides comments on the success or pitfalls of our designs.

4.4 Results

While checking the documentation through the testing procedures in § 4.1 -4.3, the team has discovered a few errors that were corrected through the testing process. Once errors are identified they are immediately corrected, and the entire document is again reviewed to ensure that no more errors were created in updating the drawing.

- One-Line Diagram: Once the one-line diagram was completed, it entered the testing phase. The team found that some of the information given to us by the client was different throughout the protection specification. This caused some confusion as part of the one-line was created using the information in one place and the other was created using information from another place. After discovering this error, the team met with the client and was able to clear up the confusion by determining which information was correct. The client informed us of some mistakes we made while they were conducting acceptance testing. Their comments pertained to how we were showing the currents going into the relays. Some of the relays only allow for one current input, however, we were showing multiple current inputs. This was subsequently solved by summing the currents before sending them into the relay. Another comment they made was that we needed to put the relays in series to avoid current splitting when connecting multiple relays to the same CT.

- ❖ Plan-View: The plan-view went through various reviews once it was completed. Unit testing was completed by the plan-view sub-team. In this review, the basic layout was reviewed for errors and it was found that the design did not meet the bus support length requirements on a few bus sections. The team was able to fix this issue by adding four bus supports on the longer bus sections. Interface testing was conducted with the whole design team. In this review, it was found that the team needed to fix the labels on a few pieces of equipment as they were inaccurately labeled compared to the information on the one-line diagram. There have been other small changes corrected throughout the review process such as changing font sizes and capitalization to maintain consistent formatting practices.
- ❖ Conduit/Raceway: This deliverable had two reviews by the team before sending to the client for review. During the second of these two reviews, it was suggested by a team member that since the future raceway was being added to the drawing that the future foundations for circuit breakers should be added and clouded out as to not have confusion as to why there is extra raceway added. This change was made before submitting it to the client.
- ❖ Foundation Layout: During the unit testing process for this particular drawing, few errors were discovered. In the internal team review, we discovered that there were a few formatting errors in the title block and throughout the drawing. In the interface testing of this drawing, we checked to make sure it matched the plan-view drawing with respect to the layout of components. We determined that the deliverable passed the interface testing because it maintained the placement of components. After sending the drawing to Burns and McDonnell for acceptance testing, we received no comments indicating that we had completed the design properly and to client satisfaction.
- ❖ Elevation View: After the review of this deliverable, it was found that there were only minor details that needed to be fixed. These details included the layout of each section of the drawing on the paper and the consistency between dimensioning and labeling of the three different views. After these changes were made, the diagram was sent to the client for review. The client reported no issues with the drawing.
- ❖ Lightning Study: Because of the nature of this particular deliverable, it only underwent unit and acceptance testing. It did not need to undergo interface testing because it does not make any calls to any other drawings and no other deliverables are dependent on it. In the unit testing phase, it was determined that we could improve the wording of how we were describing the design process we went through in the report. Additionally, we noticed that we needed to make the formatting more consistent with the other studies we had sent to the client. When we sent the lightning study to Burns and McDonnell for review, we got all clear. We were told that we met their expectations and that we could move onto the next phases of the project.
- ❖ Grounding Study: The testing of the grounding study resulted in the detection of some formatting issues. Mainly, we needed to make sure that the report produced followed similar guidelines we had established with the lightning and AC/DC studies. We could not perform a rigorous test of our grounding grid due to the inability to access the CDEGS software, hence the emphasis of the testing phase was centered around the proper formatting of the report. We are still awaiting feedback from the client regarding their acceptance testing of this deliverable.
- ❖ Schematic Diagrams: During the unit testing phase, we were able to detect errors such as inconsistent labeling of the relays. Additionally, we checked in the unit testing phase that the relay had the inputs and outputs specified in the protection specification. A few relays were missing

inputs and outputs, or they were incorrectly configured. In the interface testing process, we noticed that some of the drawings were not calling each other properly. We also noticed some inconsistencies with formatting from drawing to drawing that needed to be sorted out. We are still awaiting the results from acceptance testing with Burns & McDonnell regarding this particular deliverable.

- Panel Layouts: We are still working to complete all of the panel layouts and plan to get them completed by April 30, 2021. Hence, these items will be undergoing review during the same week as the Industry Review Panel. We at this time cannot make comments regarding the results of testing for this particular deliverable.
- Wiring: We were unable to complete all of the wiring diagrams because of time constraints associated with the project. However, we were able to at least complete one wiring diagram which taught us the general process. We do not plan on completing these drawings by the end of the semester and hence will not be able to put them through the testing process.

5. Implementation

Our project presents a unique challenge in terms of implementation. The challenge comes in that we are not the ones who would take the designs we produced and implement them. The following flowchart shows the general transition of control for a substation project:

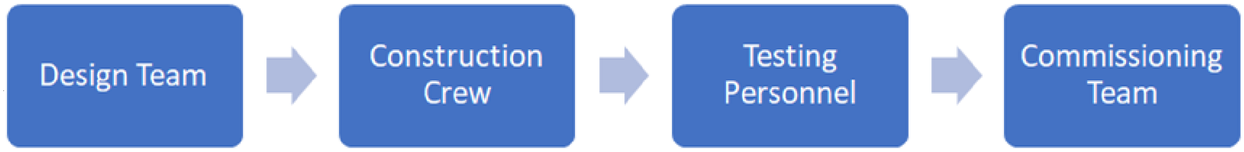


Figure 38 - Flow of responsibility

commissioning the substation. The information provided here is meant only to provide insight, but not exact workflow processes (i.e., describe each step of the construction). The amount of work that goes into designing and building a single substation is immense, and it is only one part of a complex electric grid that connects generation facilities such as the Cyclone Generation to the end-users like residents and companies in Cedar Falls and Des Moines. Figure 39 puts into perspective just how complex the electric power grid actually is, we have only designed the boxed component in this project.

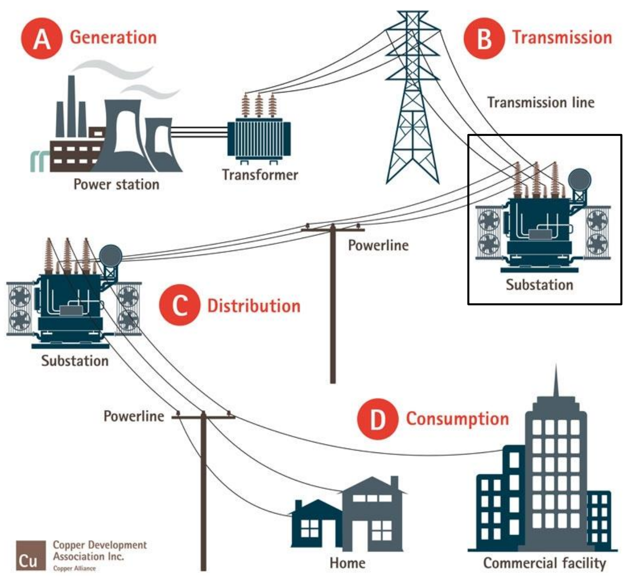


Figure 39 - Our substation in the context of the power grid

We have decided to break the implementation section into three main parts following the responsibility flow chart in Figure 39 [12]. Hence, we will discuss the general steps that should be taken to construct the substation, the procedure often followed to test the substation protection and controls, and the commissioning process.

5.1 Construction

The construction of this type of substation could take as little as six months to complete after all of the parts are ordered and received. This is because our substation is relatively simple and does not require many custom components to be manufactured. The first order of business for the construction phase of the project would be to order materials. Some of the electrical components within the substation can have a long lead time, such as the transformer which could take up to a year to manufacture. So, the construction team will need to make sure all of the components are ordered ahead of the planned start date for construction. Once the parts begin to arrive at the site of the substation, the construction work can begin. In general, the construction of a substation will likely take the following steps:

1. Bring the substation to grade based on specifications provided by civil engineers.
2. Pour concrete foundations for the equipment based on the foundation layout produced by the design team.
3. Lay the copper ground grid per the ground grid design.
4. Install the conduit and raceway per the conduit/raceway plan.
5. Mount the major equipment to their foundations and install the control building.
6. Run the major bus sections to connect the major pieces of equipment together using the plan view as a guide.
7. Pull cables through the conduit and raceway to interconnect the control building to the components in the yard that the protective relays will control.
8. Install relaying equipment into the racks inside the control building.
9. Wire the relaying equipment per the wiring and schematic drawings provided by the design team.

This is simply a rough outline of the general path to the construction of the substation. These are some of the broader categories of the work that a construction crew would need to do to implement the designs that we created in our project. After the construction crew has everything roughed in the way that they think it should be, they hand the keys over to the testing personnel to make sure that everything is wired correctly such that the substation can be fully operational.

5.2 Testing

The testing phase of a substation is rigorous and complex. This is because the substation is soon to be connected to a power grid that demands reliability. Field personnel who do the testing of a substation are highly trained and skilled individuals. Some of the fundamental tests conducted within a substation are [6]:

- Protective Relay Calibration / Testing - Ensuring that the relays perform their intended functions.
- Low and High Voltage Circuit Breakers - Making certain that the breakers operate.
- High Potential Testing - Checks to make sure that equipment insulation can withstand high voltage.
- Power Factor Testing - Checking the input and output power factor of the substation.
- SCADA Integration - Checks that the communication between the substation and the control building is functioning properly.
- CTs and CCVTs Testing - Confirm that the CTs and CCVTs are operating correctly.
- Transformer Testing - Tests to make sure that the transformer is behaving correctly.
- Ground Grid Testing - Make sure that the ground grid is configured correctly.
- Battery Rack Testing - Ensure that the batteries are functioning properly.

With the complexity of the testing procedures, it is not feasible for us to delineate how to conduct the tests, but rather cite which tests are commonly performed to ensure that the substation is ready to be energized and connected to the bulk power system. Once the testing personnel is satisfied with the operation of the substation, they are able to turn the project over to the commissioning team.

5.3 Commissioning

After the testing process is complete, a substation is ready to be brought online. Before this can happen, it must be approved to be energized. The commissioning of a substation often resorts to doing a final system check to make sure that the substation is going to operate properly. This could include manually tripping relays to ensure they function properly, manually tripping breakers, and providing load to current transformers so that they can operate correctly. After the substation has passed this final inspection, it is ready to be brought online. At this point, field operators should be in contact with grid operators to allow them to connect and control the substation to bring it online. The commissioning of the substation marks the end of the complete design and build process.

6. Limitations and Future Work

The primary limitation of our project is that we focused only on the design aspect of substation construction. This was an appropriate focus as this is what is commonly done in the consulting industry through companies such as Burns and McDonnell. Additionally, the six-member team would have had trouble getting together sufficient funding and permitting to physically construct the substation. On the broader scale, design is only one part of the project. From here, the project would be turned over to construction managers to determine the proper sequence of events to procure materials and construct the substation. At request, companies like Burns and McDonnell can also do this type of work in what is known as an Engineering, Procurement, and Construction (EPC) project. Such projects are often high risk but could yield a high reward. The EPC designation was not applied to this project at the time it was scoped.

Another limitation is that our design could not be rigorously tested due to the inability to access substation testing laboratories where relay functions can be monitored to determine the proper configuration of relaying equipment. Often in the consulting business, engineers rely on the wealth of accumulated knowledge regarding substation design to be assured that their design will work. We relied on the knowledge of two industry representatives for this project, but our team did not have sufficient substation design experience to say that the protections and controls design will work right away. Instead, confirming the protection system is left to future work. Possible ways of confirming proper protection operations on the budget of most senior design projects would be to take the designs created in this project and simulate the relays in a computer-simulated environment such as PLECS. The idea being that the relays could be modeled using C-programming blocks and the substation equipment could be modeled using pre-defined PLECS libraries. The substation system could then be subjected to numerous fault conditions and the current and voltage waveforms as well as relay operations could be examined.

This future work would also involve getting ingrained into programming relays, which again is something we did not dive into because we do not have a testbench for these components. This future work could serve as a unique opportunity to bring together software, computer, and electrical engineers together on a senior design project in the power engineering sector. Alternatively, this could provide a great launch for a research publication. A fully functional computer-based substation model could provide valuable insight into voltage and current profiles during different faulting conditions, relay performance, and the effect that substation configuration has on substation reliability.

7. Closing Material

7.1 Conclusion

The objective of our project was to design a substation that would increase the voltage level from the Cyclone Generation Wind Farm (69 kV) located in Ames, IA; to a higher voltage level (138 kV) which would be transmitted to the communities of Cedar Falls, IA and Des Moines, IA. We accomplished this task, with the exception of providing a full set of wiring diagrams for the substation. Even without the wiring diagrams, we can say that our design was successful because we provided a design which encapsulated the requirements specified in § 1.4 of this report. Additionally, we were able to verify that the protections and controls system design was acceptable because it fully implemented the relay functionality described in the protection specification provided to us by Burns & McDonnell.

Through the course of this project, our team learned a variety of professional and technical skills such as:

- The importance of communication early in workflows
- Creating a design through a design thinking process
- Identifying project requirements and engineering constraints
- Establishing clearly defined project goals
- Building relationships within a team
- Asking technical questions
- Implementing details listed in standards.
- Carrying out testing procedures
- Becoming detail-oriented

All of these project outcomes have allowed each member of the team to grow in some way throughout the project. Our team rose to the challenge that COVID presented in the way of not being able to meet in person to work on the project. We are pleased with the work and effort put into this project and feel that it was a success.

8. References

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Appendix I - Operation Manual

There are two primary users for the drawings produced in this project: (i) substation engineers that need to make modifications and/or upgrades to the substation, and (ii) construction personnel that are tasked with creating the substation in the physical world. This operation manual aims to serve both audiences by providing a clear-cut way of accessing, modifying, and requesting modifications for the drawings. Going from design to end-product is left to the implementation portion of the report.

Accessing Drawings and Studies

In this project, several deliverables were created to take the green-field site from dirt to a substation. To cope with the relatively large number of deliverables created, we decided to place them on the team website page at the following URL: https://sdmay21-04.sd.ece.iastate.edu/docs.html. The drawing names are made to be as specific as possible such that the deliverables can be accessed with relative ease. The drawings at the provided URL represent the most up-to-date copies, any request for modifications is to be sent to the Iowa State Senior Design Team 04 at the following email: sdmay21-04@iastate.edu.

Drawing Modification Process (Engineers Only)

A drawing shall be modified if it contains information which is inaccurate, misleading, or contains an out-of-date practice. Additionally, the scope of work at the original time of drawing publication cited that there may be a need for future expansion work to take place at the substation. To this end, it will be necessary to modify some, if not all, of the drawings. All changes to the drawings must be sealed by a licensed professional engineer before re-issuing any part of the design. The following drawing modification procedure shall be followed in any of the aforementioned cases:

1. Download the most recent version(s) of the document(s) to be edited.
2. Request AutoCAD drawings and/or Microsoft Word documents from the original design team via the aforementioned email. AutoCAD and Microsoft Word documents are not made public on the website for document control purposes.
3. Modify the document(s) and its dependencies per the change to be made.
4. Cloud (AutoCAD-based drawing) or bold (Microsoft Word-based document) the revision to be made.
5. Update document control information:
    a. AutoCAD drawings:
        i. Initials of engineer
        ii. Initials of the approver (must be a licensed professional engineer)
        iii. Date to be issued.
        iv. Type of issue (For Review, construction, record)
        v. Description of a revision made (must be clear enough to be fully understood by anyone)
        vi. Revision count
    b. Microsoft Word files:
        i. Add to the first page the name of the engineer altering the report.
        ii. Increment the version count.
        iii. Change the date.
6. Review document(s) to ensure that all of the steps thus far have been followed.
7. Seal with a stamp by a licensed professional engineer
8. Send both the updated AutoCAD and/or Microsoft Word files and the updated PDF to the aforementioned email address. In this email, clearly state the overall scope of work performed and list the affected drawings.

Request for Drawing Modification Process (Construction Use)

In the construction phase of the substation, it is likely that modifications to the original drawings will be necessary. This may be the result of unexpected field conditions, engineering oversight, or miscommunication between engineers and field crews. In this event, a review of what caused the deviation from the construction plans will be required. Hence, the construction crew should create a set of red-line documents. A red-line drawing refers to a drawing which is marked in pen to show how a specific part of the project was implemented that is different from what was shown in the original plans. The following pen-color convention is used to recommend changes:

> Red - additions to the drawing, green - removals from the drawings, and blue - general comments

To request changes the following sequence of steps must be followed:

1. On a printed copy of the drawing, mark the changes to be made using the pen color assignments listed above.
2. Circle the change in blue to draw attention.
3. Send the drawing to the Iowa State Senior Design team at the aforementioned email address.
    a. Include a scanned copy of the drawing marked in pen.
    b. Include a written statement including a description of the problem and a statement pertaining to what lead to the change.

The following is to be completed by the Iowa State Senior Design team:

1. Review the changes to be made that were submitted by the field.
2. The team member that created the deliverable should read the reason behind the change and make a note of why it occurred for future projects.
3. Follow the procedure titled “Drawing Modification Process” to update the drawings per the field marks with the exception that the type of issue would be “As-Built”.

The steps listed here are common industry steps for the as-built process. In industry, an as-built refers to picking up changes to a construction package upon the completion of the construction phase.

Review of Operation Manual

Two main procedures are described in this process which directly impacts the products of the design process performed by Iowa State Senior Design team 04. This manual outlines the general procedure that engineers and construction personnel must follow to update drawings. Having drawings which are up to date is important for two main reasons: (i) future projects make the assumption that the current drawing reflects what is actually constructed in the substation, and (ii) field crews who must work quickly to diagnose problems rely on the drawings to be correct. The field relying on the drawings also means that they are basing life and death control decisions on the drawings being updated. For example, if the drawing shows that flipping a certain breaker will de-energize a section of the substation, but the drawing is out of date then there is the possibility that the substation is still energized. Following these document control procedures will make sure that we have up-to-date drawings.