Substation Design

DESIGN DOCUMENT

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Executive Summary

Development Standards & Practices Used

Software practices used in this project include CAD, specifically Autodesk, for substation circuit design. Engineering Standards which apply include IEEE standard for AC and DC Substation Grounding, IEEE standard for Lead Acid Battery Sizing, and IEEE standard for Lightning Protection.

Summary of Requirements

- Substation One-Line Circuit Diagram:
  - three 138kV gas circuit breakers
  - one 69/138kV transformer
  - two 138kV line positions
  - one 69kV line position
  - one 69kV gas circuit breaker
  - 138kV yard energized in a ring bus configuration with potential for future expansion into a six-position breaker-and-a-half configuration
- Substation Plan View:
  - one plan view document which contains the above hardware components physically connected in precise measurement
  - four section cut views which contain specific locational views of the plan view document physically connected in precise measurement
- Lightning Study to remain in compliance with IEEE standards
- Alternating Current Study to remain in compliance with IEEE standards
- Direct Current Study to remain in compliance with IEEE standards
- Wiring and Schemes to finalize electric connections between hardware components

Applicable Courses from Iowa State University Curriculum

EE 201, EE 230, EE 303, EE 456

New Skills/Knowledge acquired that was not taught in courses

AutoCAD Circuit Design, Large Scale Power System Drawings and Design, Professional Documentation

Table of Contents

List of figures/tables/symbols/definitions

1 Introduction

1.1 Acknowledgment

We would like to acknowledge and thank Burns & McDonnell for their assistance in our project, technical advice, and for providing documentation of which we have used as reference in our design process.

1.2 Problem and Project Statement

General problem statement – The city of Ames, Iowa requires a new 69/138 kV substation to be designed, and later constructed by Burns & McDonnell. It will serve as an interconnection for a new wind generation farm being built outside the city. The substation must be economically viable and laid out in a way to allow for future expansions of equipment and relaying.

General solution approach – Burns & McDonnell have provided scope documents which comprehensively cover all relaying and equipment specifications. With these specifications, it is our team's role to complete the design phase of this substation. The following documents will be included to create a comprehensive substation design: one-line diagram, physical plan of the substation, section cuts extracted from the physical plant, and schematics/wiring diagrams. In conjunction with this, the following studies will be conducted to remain in compliance with IEEE standards: AC study, DC study, and Lightning study. A comprehensive design package is to be finalized once the aforementioned steps have been completed.

1.3 Operational Environment

The Cyclone Substation will be an open-air environment located in Ames, Iowa. It will be exposed to all forms of weather such as thunderstorms and temperatures ranging from extreme heat to extreme cold. The perimeter of the substation will be enclosed with a fence but still may be exposed to certain forms of wildlife such as birds, and rodents. The fencing surrounding the perimeter will also contain roadway access to the site.

1.4 Requirements

Functional Requirements - The comprehensive substation design contains both primary and backup line protection relaying for the Des Moines, Cedar Falls, and Iowa City line exits. The line exits are protected using the electrical relay components provided by Burns & McDonnell. Along with line protection, transformer protection relays are also accounted for. Differential relaying is used to protect both the primary and secondary sides of the 138/69kV transformer. Fiber optic cable is used to communicate between substations for both primary and secondary relays.

Economic Requirements - No specific budget is required for this design process. However, our team has been tasked with physically designing the substation to allow for future expansion and flexibility, as to not take on more of a financial burden in the future.

Environmental Requirements - A perimeter fence in the physical layout of the substation is included so as to prevent both humans and wildlife from entering and causing damage to machinery. The final design also includes fire protection walls on two sides of the transformer to not cause further damage to the environment and substation in the event that the transformer catches fire.

1.5 Intended Users and Uses

The primary end users of the substation are the citizens of Ames who will rely on this design to power their homes and workplaces. Other users include nearby utility companies and power plants that will also be dependent on the functionality of the substation as part of the local power grid.

1.6 Assumptions and Limitations

Assumptions:

- The wind energy farm is rated at 138kV
- The ground on which the substation is to be built has already been leveled
- The equipment and relaying specifications provided by Burns & McDonnell are appropriately rated for the substation we are designing

Limitations:

- The design phase of the project must be completed by May 1st.
- The substation must service incoming lines of 138kV and outgoing lines of 69kV
- Battery bank must be rated at 125V DC and in accordance with IEEE 485
- Lightning protection must be in accordance with IEEE STD 998-2012
- All substation drawings are done using AutoCAD

1.7 Expected End Product and Deliverables

The deliverables for this project are as follows: One-line diagram, physical plans and sections, lightning study, AC/DC Study, and Schematics/Wiring diagrams.

One-Line - Due 10/18/2019

The one-line diagram is the overarching design of the substation. This drawing, as well as all of the others, has been designed using AutoCAD. The drawing includes one transformer, all four breakers and relaying equipment wired together in a three-ring bus configuration on the high-voltage side and single breaker configuration on the low-voltage side. The one-line diagram also shows future equipment and how it will be connected, while signifying that it is not part of our current scope. Additionally, this diagram shows all interconnections in the substation yard as well as the incoming and outgoing lines. It does not show the specifics of the wiring, i.e. port to port contacts, rather it shows which devices and equipment are wired together and where the busses are located.

Physical Plan & Sections - Due 11/22/2019

The physical plan shows precisely where all equipment is laid out in the substation yard. It also shows the substation enclosure, road access, rigid bus, structures, and perimeter fence. An AutoCAD drawing has been submitted to Burns & McDonnell with all relevant and future equipment with adequate descriptions and applicable standards used. The equipment is all properly dimensioned and rounded to the nearest inch. There are also four sections cuts made from the overall plan drawing. The section cuts provide the end user with a side view of certain sections of the substation yard, and when used in conjunction with the plan view, a discernible 3D model of the substation can be interpreted. Elevation section cut drawings include general dimensions and equipment descriptions.

Lightning Study - Due 12/20/2019

The lightning study is conducted in order to evaluate and design lightning protection for comprehensive station protection against direct lightning strikes in accordance with IEEE STD 998-2012 Electro Geometric Model using the empirical curves method. This report contains the following:

- Definitive calculations used in developing the layout of lightning protection
- Summary of the orientation and protection results for each group of shielding electrodes
- A recommended configuration of the shielding electrodes which is to include the maximum effective heights of the lightning masts and shield wires

AC/DC Study - Due 3/13/2020

Similar to the Lightning Study, the AC/DC calculations and subsequent consequences of the calculations have been provided to Burns & McDonnell. The study is predicated on the AC and DC loads in the substation yard and enclosure, and includes a power flow analysis of the substation.

Schematics/Wiring - Due 5/1/2019

Following the development of the AC and DC study, schematics for the 69kV circuit breaker, 138kV circuit breaker, 69kV line relay, and all the transformer protection have been accounted for. In addition to this, panel layouts and schematics for the panel vendor's use have been provided. The wiring diagrams show all interconnections between relays and enclosure equipment.

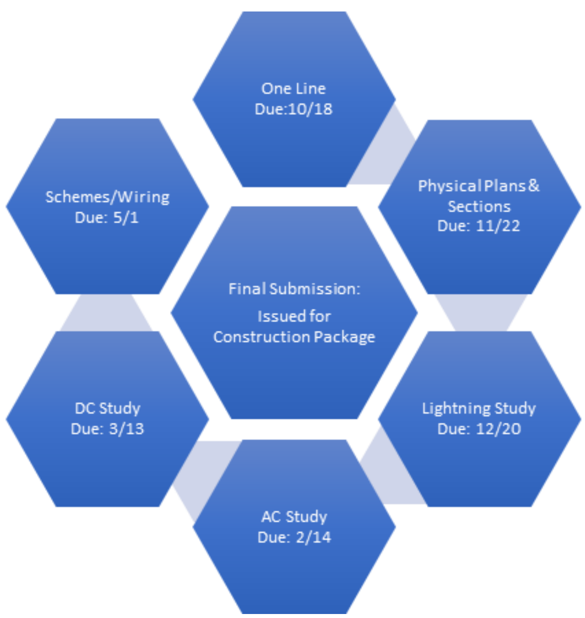

Figure 1-1: Final Construction Package and Constituent Parts

2. Specifications and Analysis

As a group, various skill levels in application to substation design and overall background in energy infrastructure has granted each of our members different learning experiences as this project progresses. Due to our differences in background knowledge, we have used weekly group meetings in conjunction with weekly conference calls with Burns McDonnell to develop questions which mend our differences in skill level and create an environment which welcomes new ideas in our design approach.

2.1 Proposed Design

This section will cover the initial phases of design which resulted in both successes and failures in the creation of our first drawings; these were later revised and corrected with the help of our client and will be further elaborated on in Section 2.2.

2.1.1 Substation Design Layout

Following the schedule in Figure 1-1, the first task was to create an initial one-line layout for the substation. In the given specifications, the system contained the following elements:

1. Install three (3) 138 kV circuit breakers (B1, B2 & B3), to be used for the transformer high-side.
2. Install one (1) 69 kV circuit breaker (B4), to be used for the transformer low-side.
3. Install three (3) Coupling Capacitor Voltage Transformers (CCVT's) (one per phase) on all three of the ring-bus exits.
4. Station surge arrester specification to be determined by substation engineer.
5. All substation equipment and bus should be rated for at least 2000A. All line conductors and equipment should be rated for at least 750A.
6. Install one (1) station service transformer on the 138-kV bus side of the 138/69kVtransformer MOAB to provide AC station service and relaying potentials.
7. New 3-phase 140-72-13.2, 100/134 MVA OA/FOA power transformer with Z1 = 5.6% on 100 MVA base.
8. Install one (1) 138kV motor operated air brake switch (A1).

Furthermore, our system must be in a layout that is initially a ring bus, shown in Figure 2-1, and that can easily be converted into a breaker and a half for future expansion, shown in Figure 2-2.

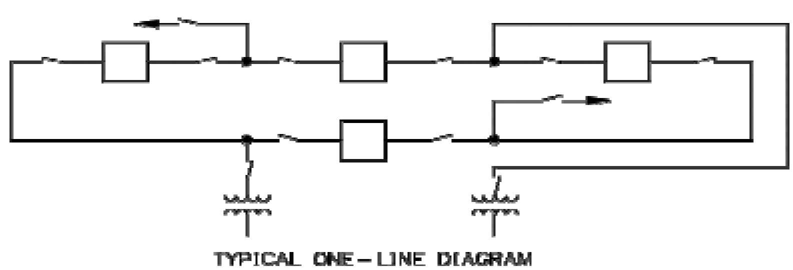

Figure 2-1: Ring Bus Layout

[1]

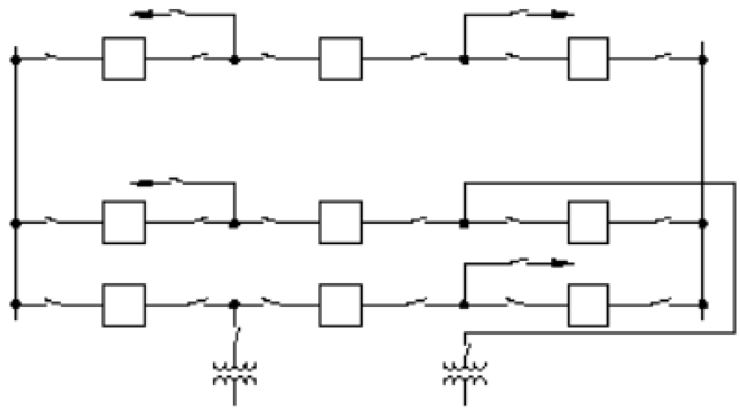

Figure 2-2: Break and a Half Layout

[1]

Starting the design process, our team focused on creating a one-line layout that matched the specifications given Burns & McDonnell, in a ring bus configuration, in the same style shown in Figure 2-1. With this basis, our team began to convert this foundation to include all the necessary information to be included in the final one-line diagram. The initial design is shown in Figure 2-3. All changes made to the initial revision will be covered in Section 2.2.1.

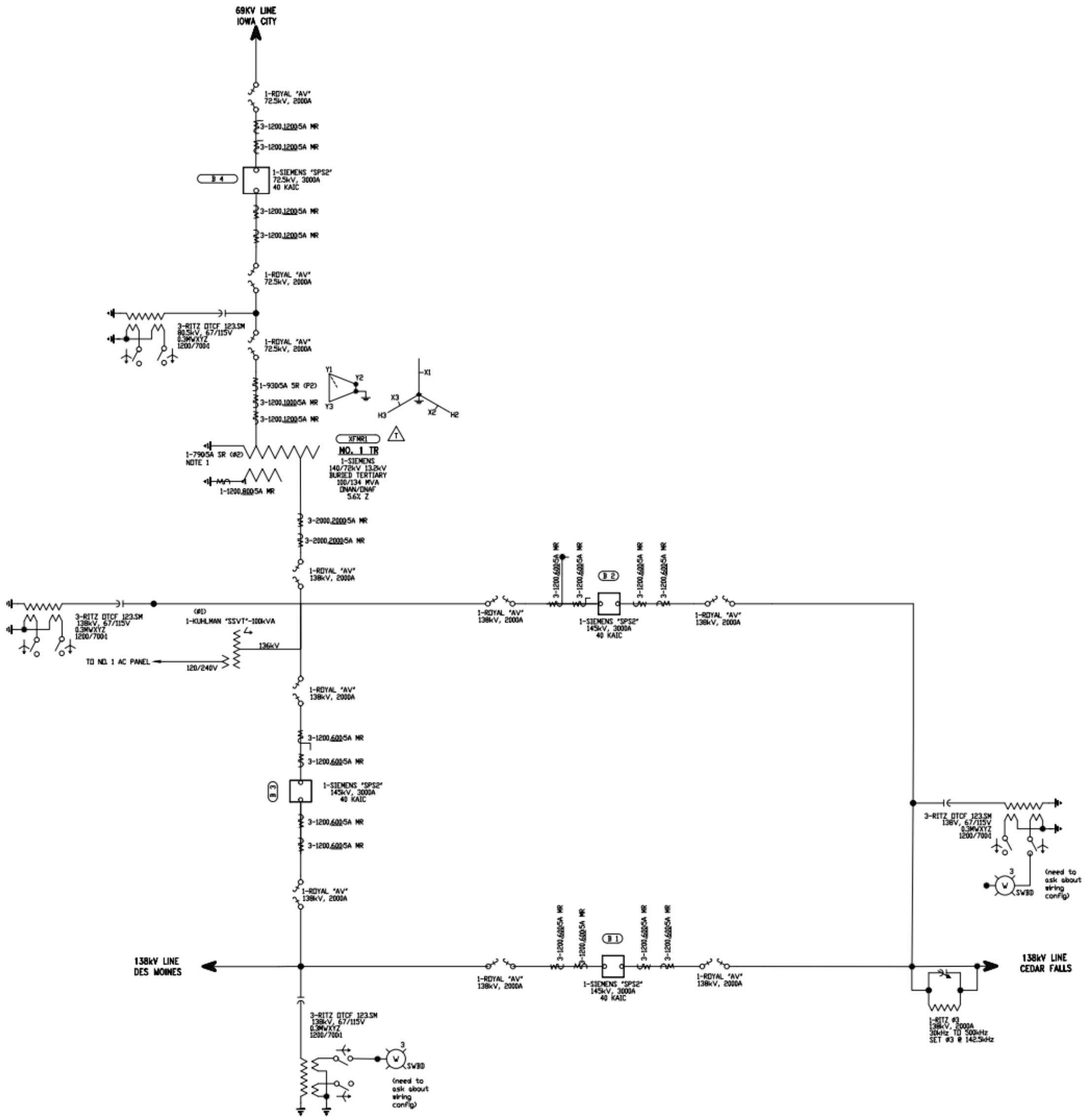

Figure 2-3: Initial One-Line Design

2.1.2 Relay and Protection Design

After the creation of an initial One-Line, details on protection needed to be added. This is also according to the specifications given by the client. The system in total has ten relays wired for different protection schemes and one wave trap utilized for communication; the electrical ratings of these components were given to us directly in the form of AutoCAD cells provided by Burns & McDonnell.

Figures 2-4 and 2-5 describe how the connections between electrical components are defined.

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

Figure 2-4: Example of Relay Connections

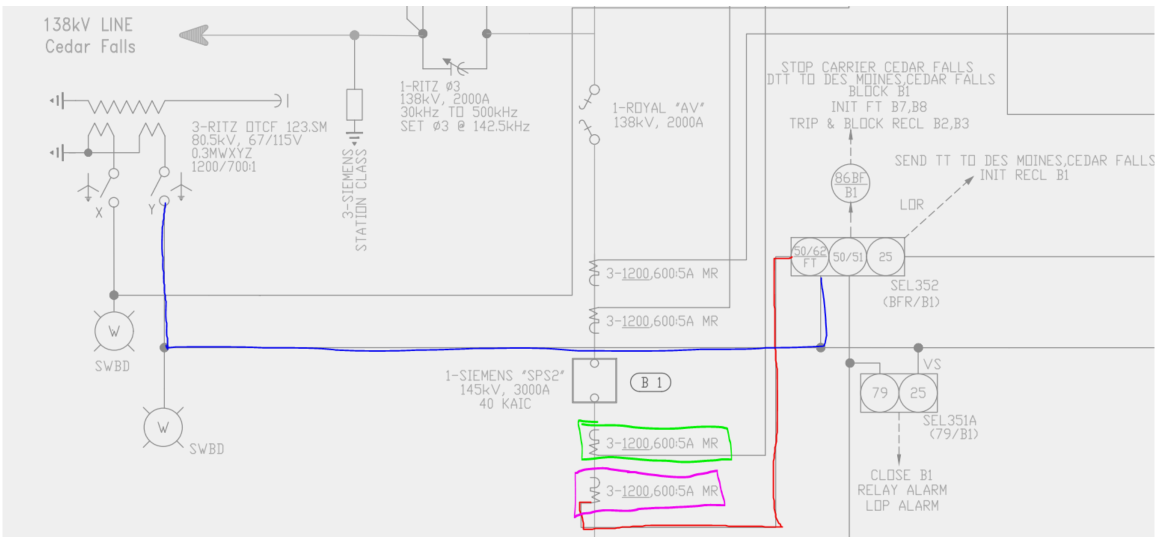

Figure 2-5: Color Coated Wiring Example for Relay Definitions

Using Figure 2-4, CT is defined as a Current Transformer and PT is defined as a Potential or Voltage Transformer. When Connecting a CT to a relay, such as the red line in Figure 2-5, the connection enters either from the left or right side of the relay and exits the opposite side to be used in another relay. When connecting a PT to a relay, nodes can be used to branch the connection from one relay to another and will enter the relays from the bottom, depicted in Figure 2-6 as the blue line. Referenced in Figure 2-4, it was determined that the “top” CT, also called the backup CT, will be connected furthest from the breaker, circled in purple. Likewise, it was determined that the “bottom” CT, also called the primary CT, is the nearest to the breaker and can be seen circled in green in Figure 2-5.

With these features defined, an initial design of the one-line was able to be submitted with the protection schemes included. Results of our team’s one-line design will be analyzed in Section 2.2.

2.1.3 Physical Design

Following the creation of the one-line, as shown in Figure 2-3, there were revisions that will be covered in Section 2.2. These changes to the initial design of our one-line diagram are used as the basis for the physical design, as drafting for the plan view of the substation was not started until the one-line diagram was perfected. This stage of the design is divided into two groups: plan view and section cuts. The team was tasked in submitting a plan view first before working on the section cuts.

The plan view's design is directly extracted from the design of the one-line and is defined as a top down view of the substation which includes all relevant equipment and dimensions that would be needed for construction.

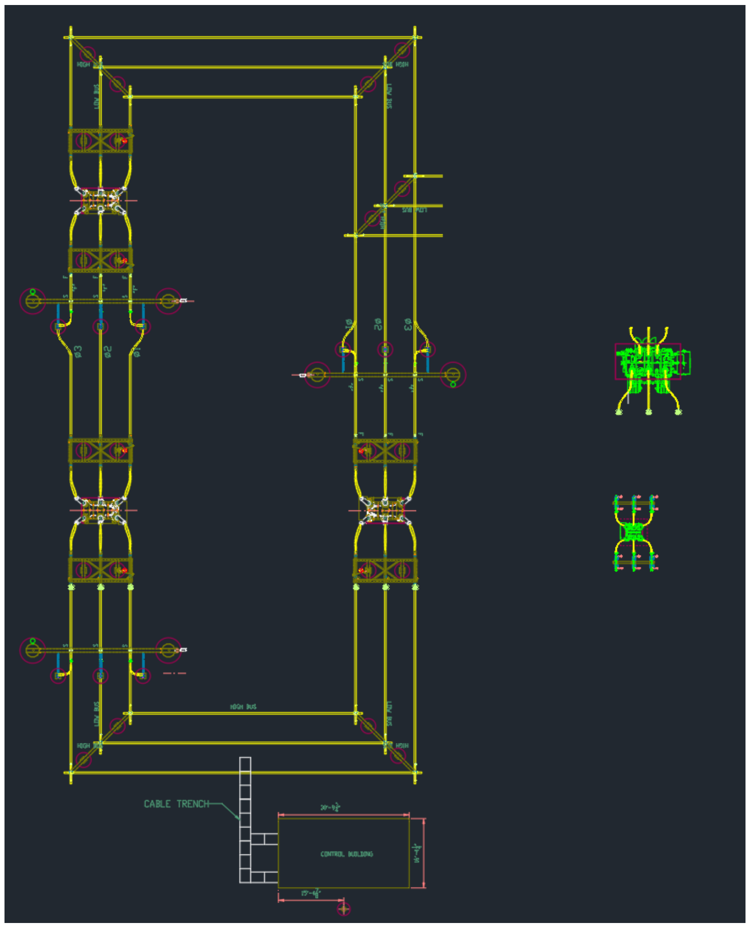

Figure 2-6: AutoCAD Version of Plan View sans Dimensions

Figure 2-6 displays the first draft of our plan view according to the original one-line shown in Figure 2-3. This section required the most knowledge about how a substation was constructed in terms of proper connections and locations, therefore several revisions were conducted before perfecting our design.

After working with advisors from Burns & McDonnell, the group decided to modify the one-line's layout in order to create a consistent design between all drawings which account for our client's revisions, which were directed toward the simplification and organization of our initial design. The new submitted plan view is shown in Figure 2-7.

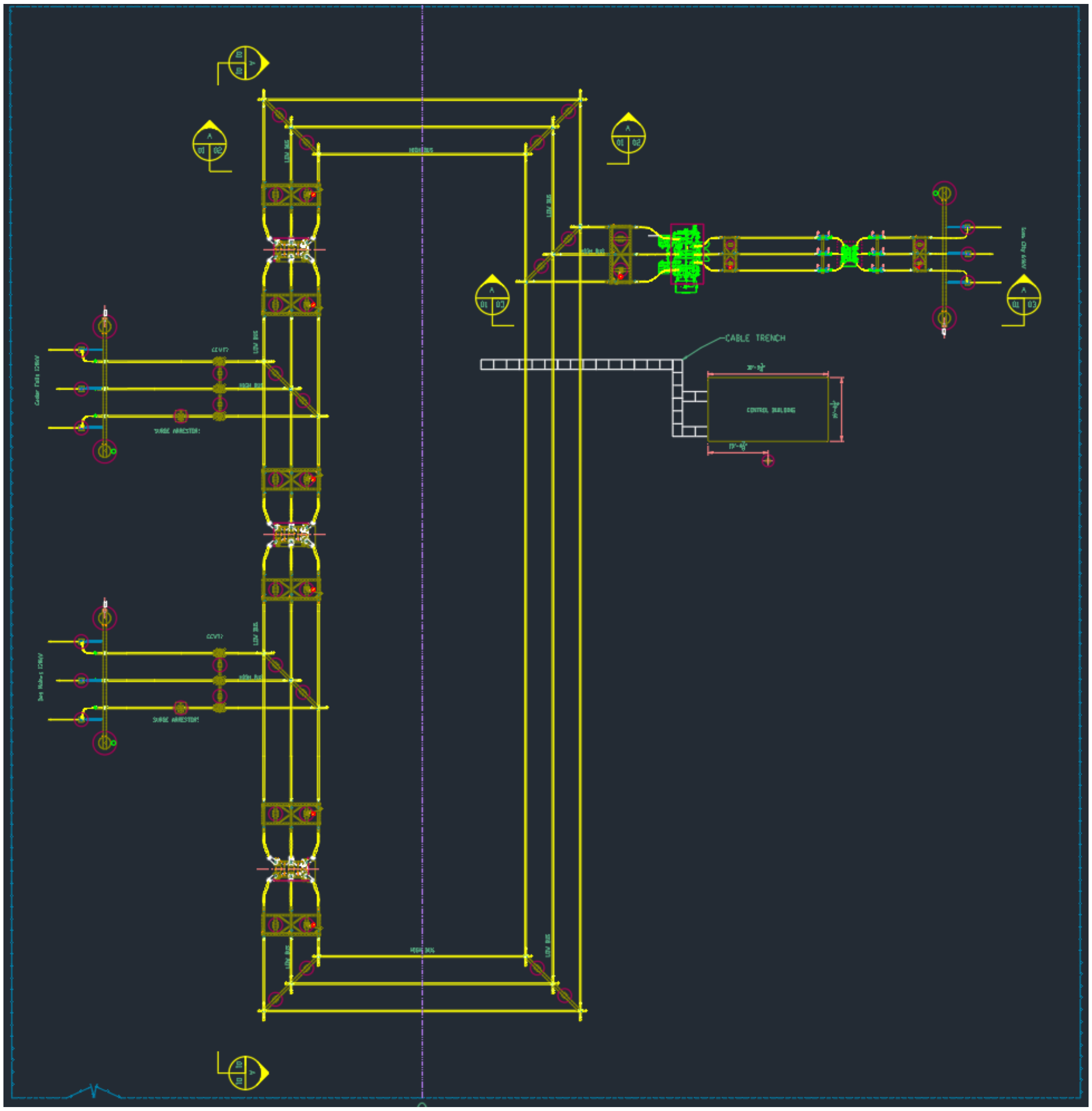

Figure 2-7: Revised Plan View AutoCAD Drawing

Once the plan view was finished, the team focused on the creation of section cut views of the physical design. In Figure 2-7, the direction of the section cut is determined by the yellow circles in correlation to where the arrow is pointed. These section views show equipment heights and details in equipment spacing that is not otherwise shown in the overall plan view.

Using Figure 2-7 as a reference, the first section cut designed was the leftmost bus that travels vertically across the page. The second cut created was the rightmost bus that travels horizontally across the page, and the final cut was the top most cut from left to right. The locations of these cuts can be seen in Figure 2-7. Figure 2-8 shows an example of one of the section cuts in the first revision stage.

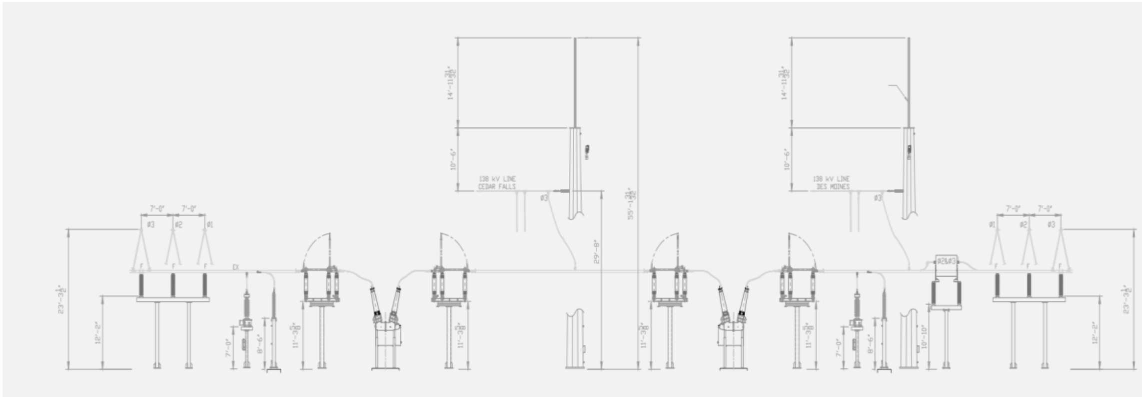

Figure 2-8: Section Cut Dwg# IASTATE-01-02 REV. 0

After all the above was submitted to Burns & McDonnell, the team waited for comments and revisions for each section. These comments will be covered in Section 2.2

2.2 Design Analysis

This section will cover modifications and changes made to the original submissions in Section 2.1.

2.2.1 Substation Design & Relay Wiring Revisions

Though Figure 2-3 was a starting point for the teams one-line drawings, it was not complete enough to function as a true one-line for construction purposes. It had little to no details about the relaying at the substation and in the end many changes to the layout needed to be addressed.

By our second revision, Burns & McDonnell had provided relay wiring examples which could be analyzed and considered in our team's design. Extracting the information displayed in a functional one-line diagram, our team was able to reanalyze our initial errors and apply more solidified knowledge in our next revision. This submission is shown in Figure 2-9.

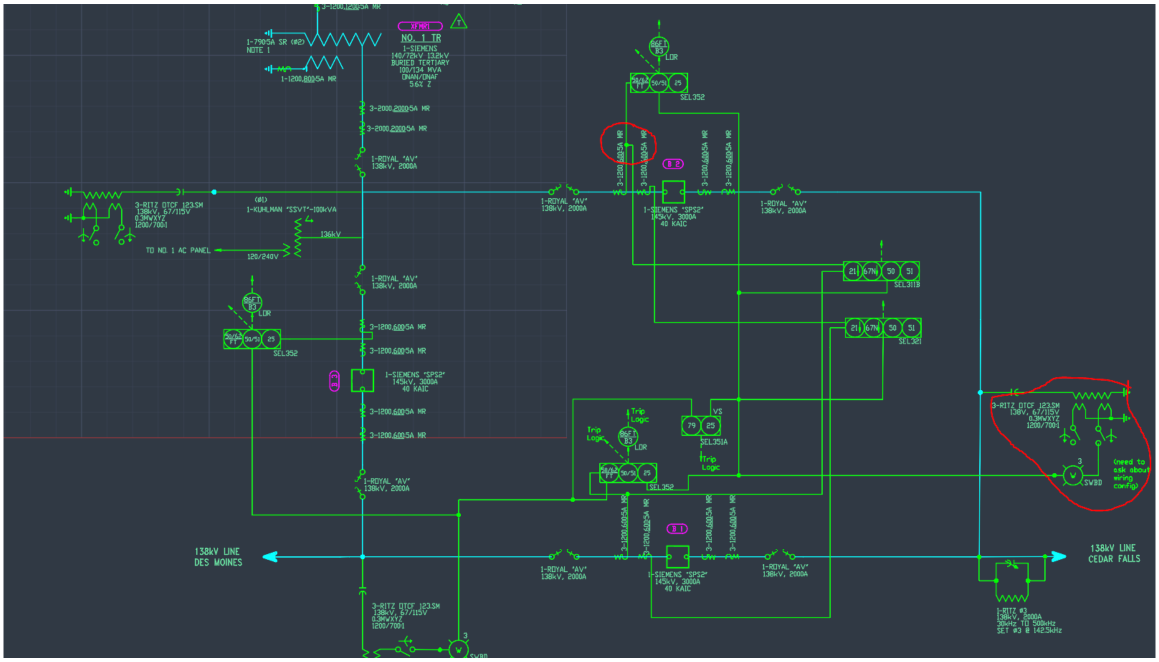

Figure 2-9: One-Line Revision 2

After having revision 2 reviewed, it was determined that this layout meets the ring bus requirement but does not lend itself to be easily modified to create a breaker and a half layout, which is a requirement administered by our client. To change the system, the team altered the location of the breakers to comply with the asked for layout and removed additional breakers.

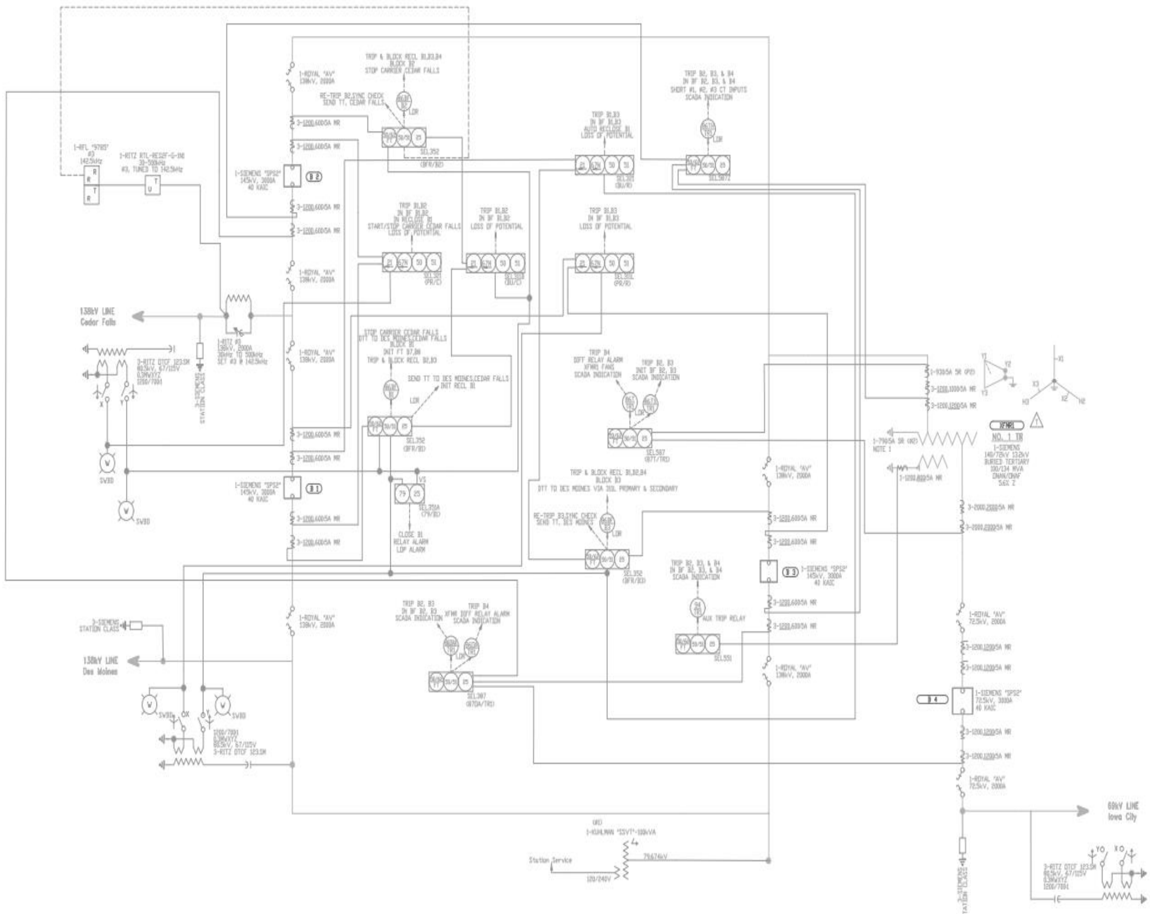

Figure 2-10: One-Line Revision 3

Figure 2-10 depicts the final version of the one-line for the substation. After this was completed, the physical design process began.

2.2.2 Physical Design Revisions

After the submission of the first plan view, our client commented that we should not be fearful of adding too many dimensions. Burns & McDonnell also stated that we should move our line exits to be facing in the same direction of the one-line showed. The next version of what would be submitted is shown in Figure 2-11 with an initial section cut view shown in Figure 2-12.

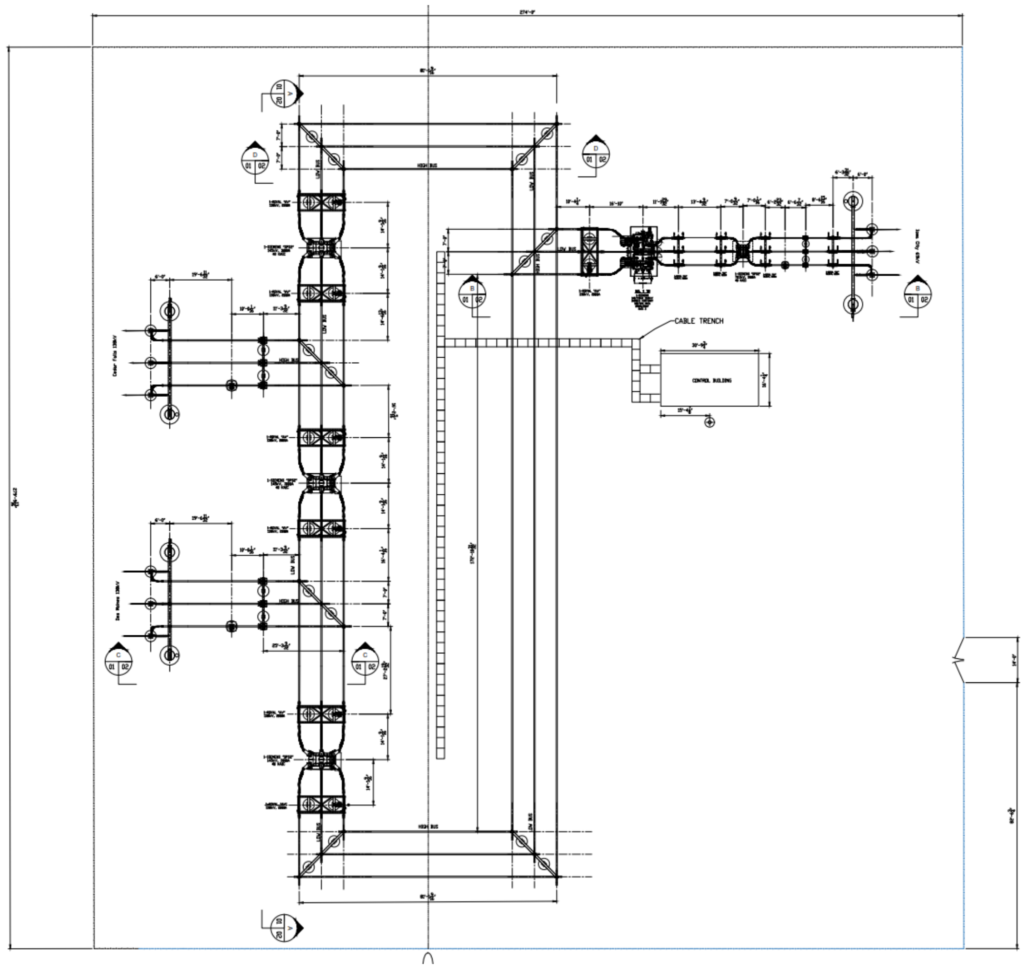

Figure 2-11: Plan View Revision 2

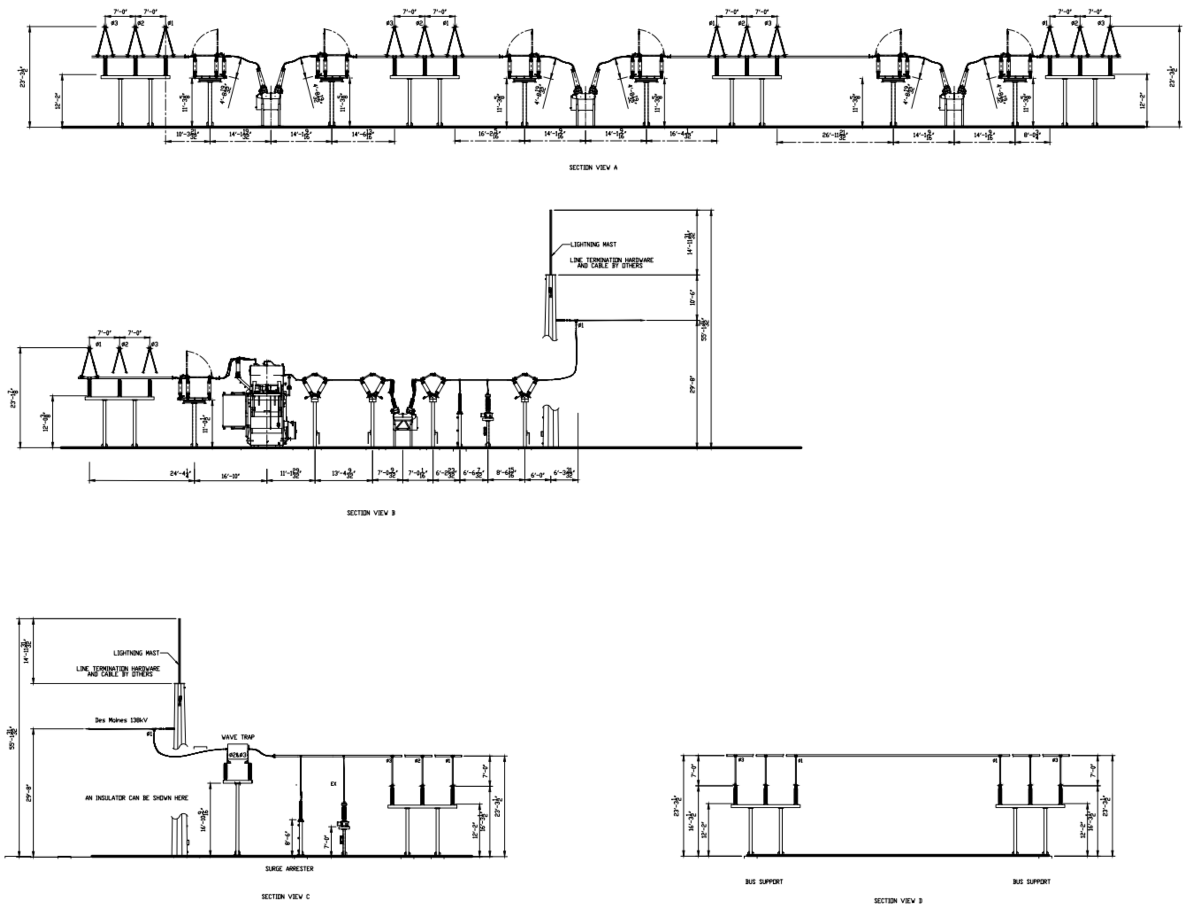

Figure 2-12: Section Cuts Revision 1

After the above revisions were submitted, the team was told to fix the spacing on our section cut B and remove the additional disconnect switches as they were not necessary for the design. According to our client, the design also needed to have all the dimensions adjusted to whole inches as most contractors do not value precise dimensions beyond whole inches.

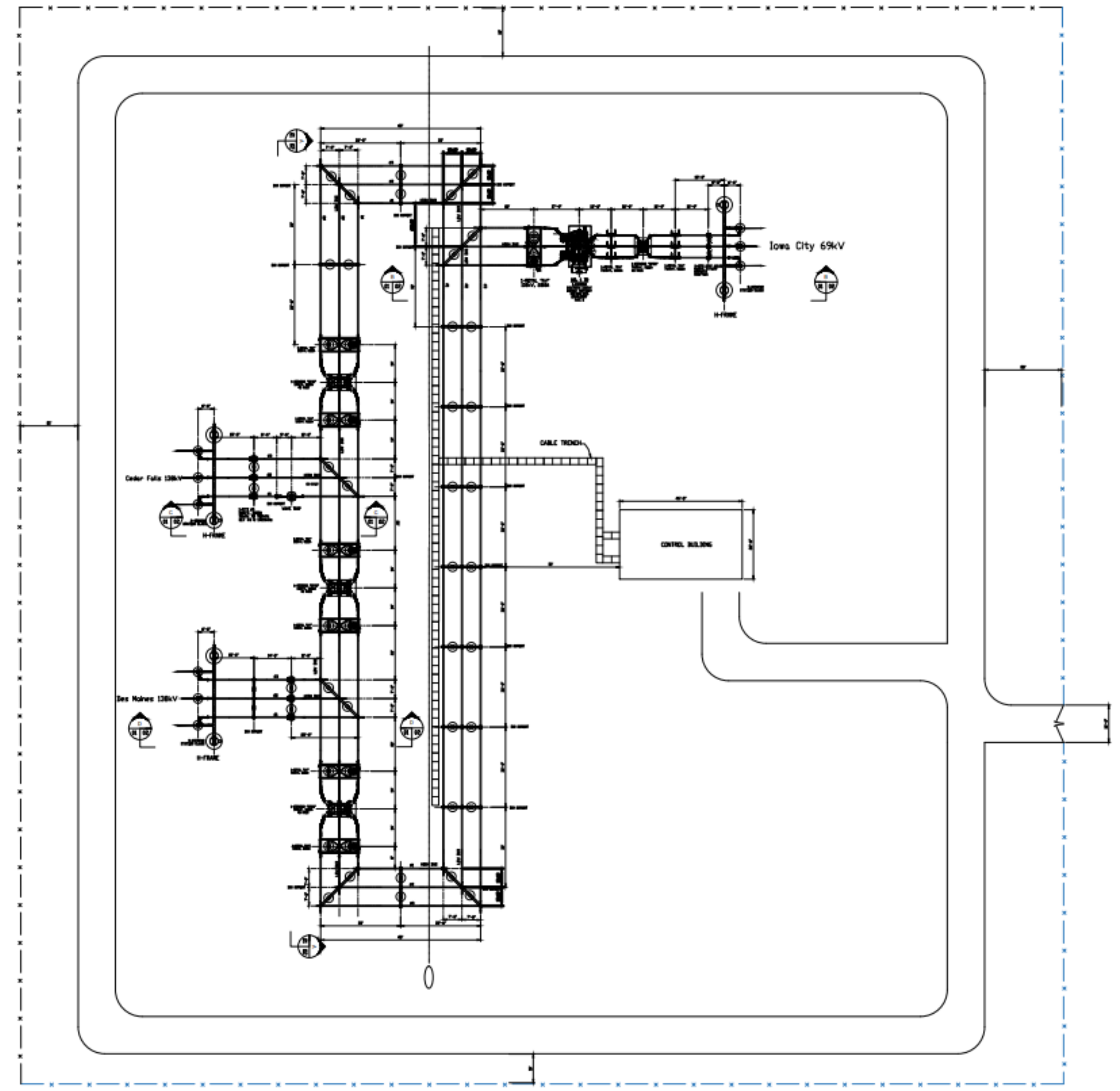

Figure 2-13: Final Plan View Revision

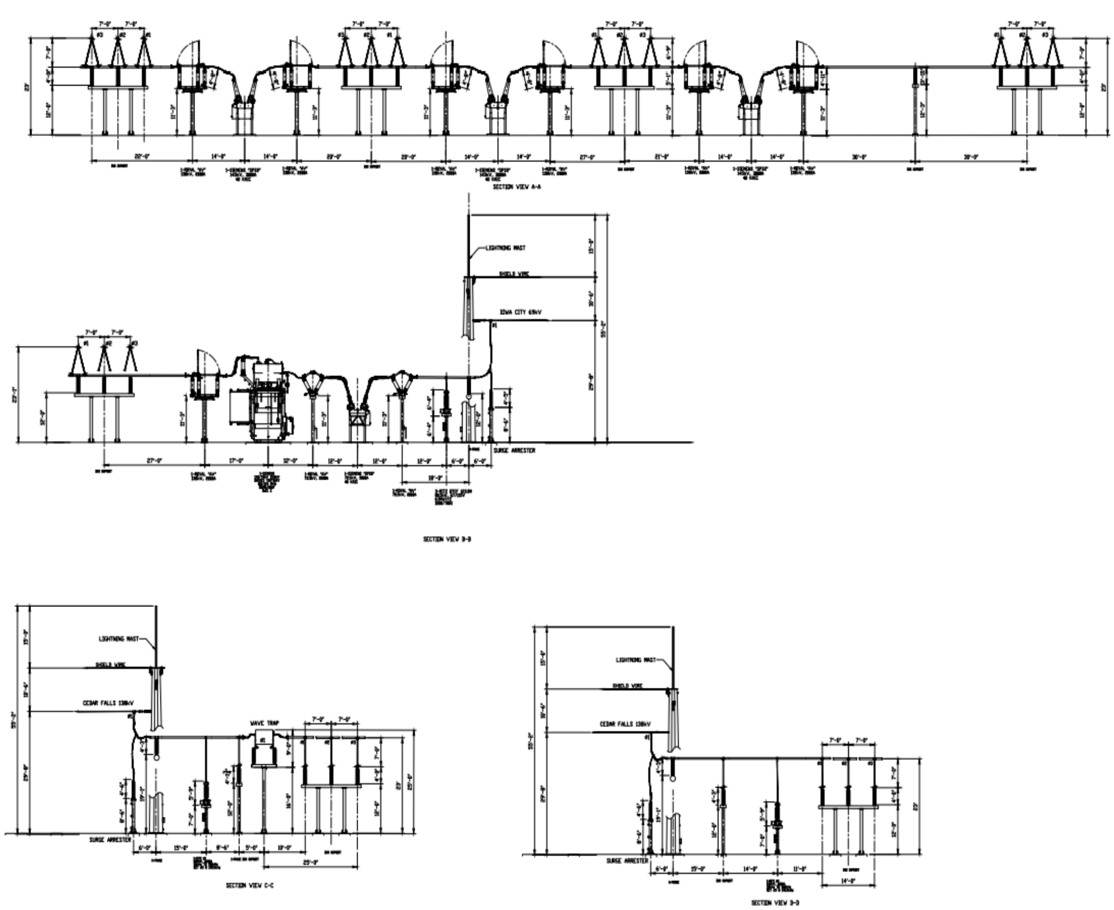

Figure 2-14: Final Section Cut Revision

The above revisions, Figures 2-13 and 2-14, are the last to be submitted until the completion of the lightning study. As we have since concluded this, additional changes to the drawings have been tracked in Section 2.2.3.

2.2.3 Lightning Protection Study

The purpose of the lightning study is to perform calculations based on IEEE standard 998-2012 [2]. The premise is to detail the additional structures necessary to implement proper lightning protection measures and provide a comprehensive protection scheme that will shield the Cyclone Substation from direct lightning strikes.

This study began with identifying components of the substation which are energized and require protection. After assessing the heights of substation equipment against the span of protection given by lightning masts, the level of protection provided by these masts was calculated. The lightning masts required to use in this project stand at 55 feet and calculations relating to the area of coverage these masts provide will be analyzed in this report. The calculations are analyzed from the highest equipment height of the substation to ensure all energized equipment below that height will inherently be protected. All calculations have been derived from the IEEE Standard 998-2012 “IEEE Guide for Direct Lightning Stroke Shielding of Substations” using the method of

Empirical Curves [2]. An exposure rate of 0.1% is utilized per Burns & McDonnell Standard practices.

In order to accurately calculate the parameters of our lightning study, the Empirical Curve Method of lightning protection calculation as defined in IEEE 998 Section 5 was utilized. This method uses a ratio of the equipment's height to distance from a mast required for protection. The ideal coverage ratings based on these ratios are nonlinear and vary based on the protection configuration desired as well as the lighting exposure rate of the region the substation is located.

For the Cyclone Substation a fixed height of 23 feet is used as a conservative estimate for the highest piece of energized equipment to be installed at the upgraded station. This ensures that all energized equipment at a height below the 23-foot mark will also be adequately protected. This is illustrated in Figure 2-15.

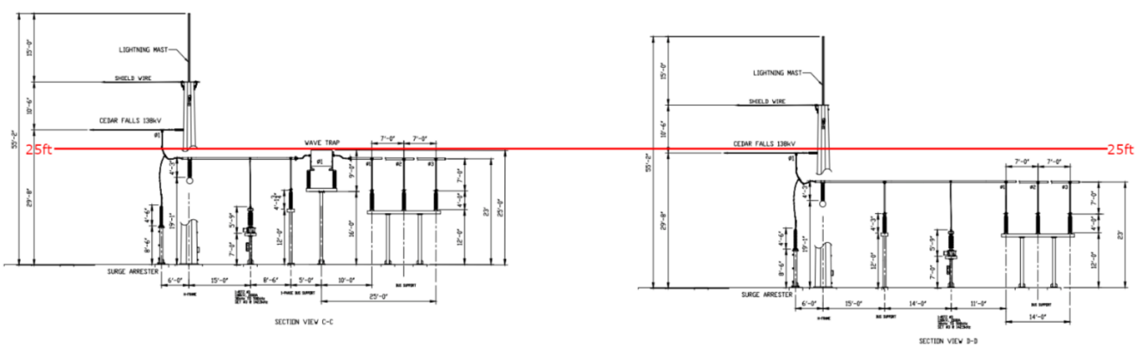

Figure 2-15: Fixed Equipment Heights

Figure 2-16 lists the equipment in the station which requires protection, in addition to relevant parameters which were to be considered in our calculations. Figure 2-17 lists proposed protective equipment heights to achieve the level of lightning protection desired.

Equipment	New/ Existin g	Heigh t (ft)
138kV CCVTs	New	< 25'
69kV CCVTs	New	<25'
138kV Disconnect Switches	New	< 25'
69kV Disconnect Switch	New	< 25'
138kV High Bus	New	< 25'
138kV Low Bus	New	< 25'
138kV Gas Circuit Breaker	New	< 25'
138/69kV Transformer	New	<25'
138kV Arresters	New	< 25'
69kV Arresters	New	< 25'
138/69kV De-Energized Transformer	New	< 25'

Figure 2-16: Station Equipment to be Protected

Designation	New or Existing	Equipment Type
138kV H-Frame	New	Mast at 55'
69kV H-Frame	New	Mast at 55'*

Figure 2-17: Proposed Protective Equipment

It is assumed that the 230kV bus height will not exceed 23 feet (with respect to grade) and that all other energized equipment in the yard will fall below a 23-foot mark, except for the wave trap which sits 25' feet above the ground and directly underneath a lightning mast. We did not use the 25' foot mark because the piece of equipment is already protected by being so close in proximity to a lightning mast.

Figure 2-18 illustrates our first revision of our lightning protection study which was submitted to Burns & McDonnel.

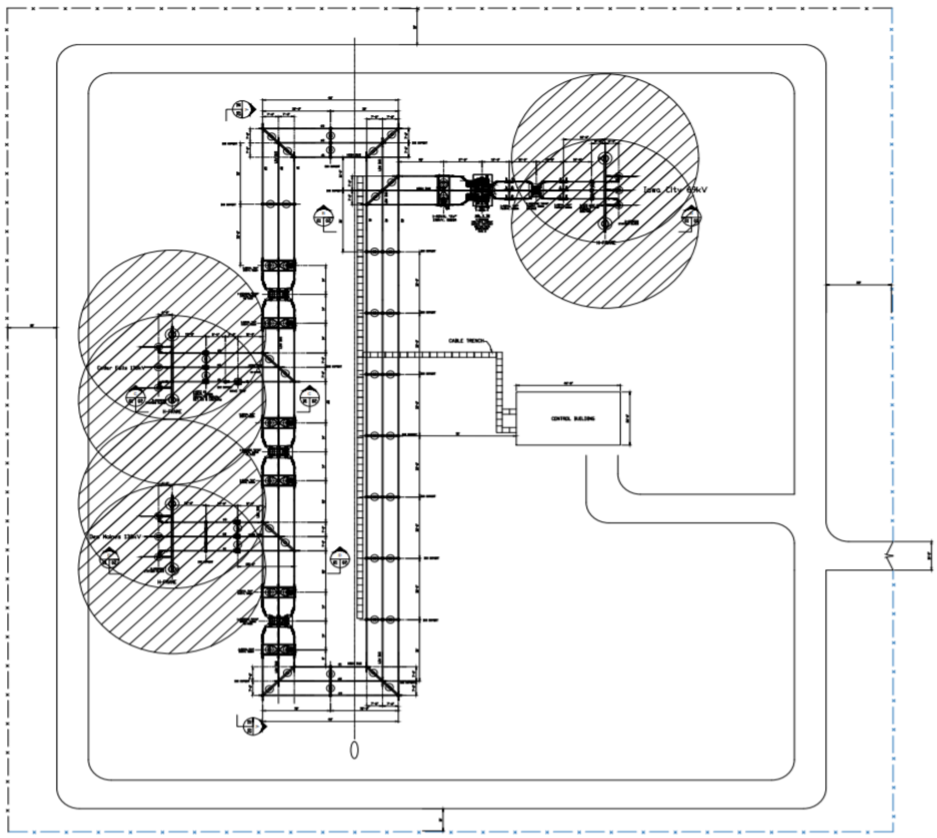

Figure 2-18: Initial Lightning Protection Design

After reviewing our progress with our client, we began finalizing the number of lightning masts necessary to complete full coverage of our substation and found that several more would need to be included in order to fully protect all equipment within the substation. In conclusion, ISU Senior Design has determined that the key plan design contains (9) masts at 55' that sit on top of H-Frames or stand-alone masts.   The final product of our lighting protection study is illustrated in Figure 2-19.

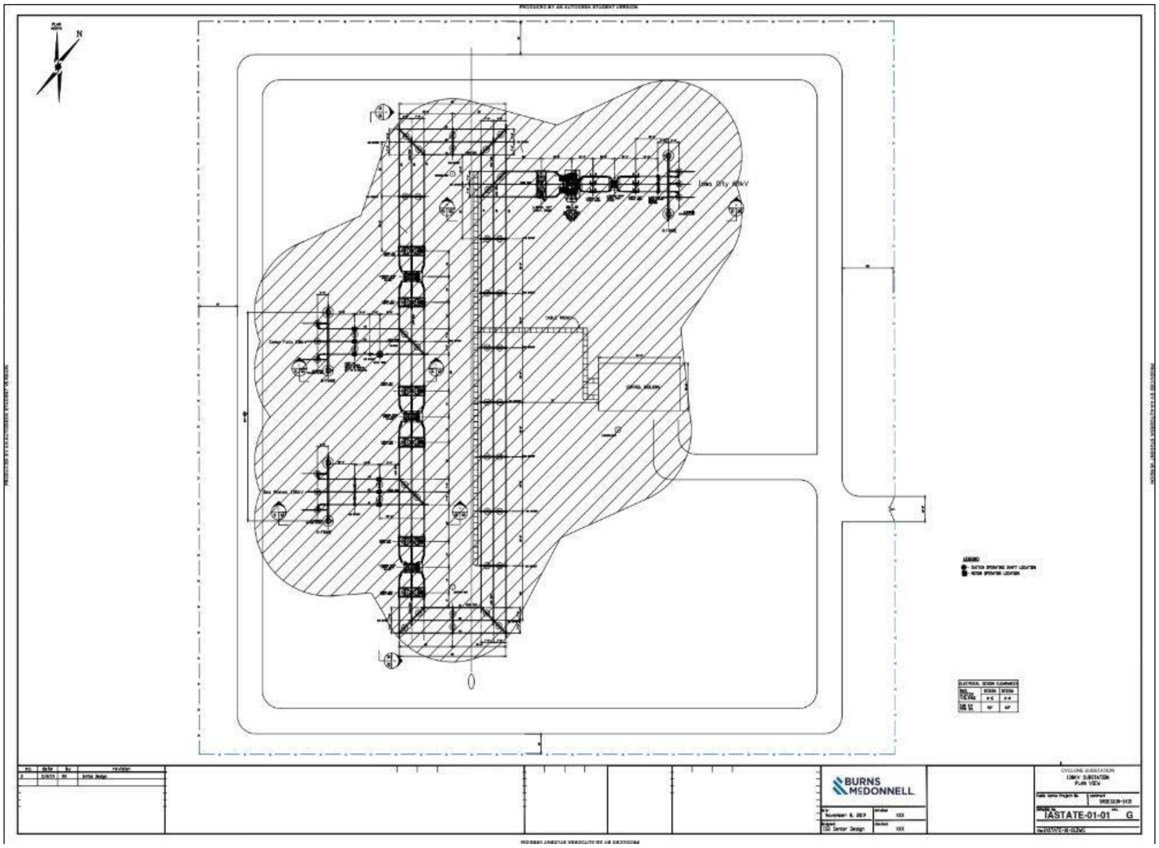

Figure 2-19: Final Revision of Lightning Protection Layout

2.2.4 AC/DC Study

AC Study:

The purpose of the AC study is to determine the appropriate size of the station service transformer (SSVT). The SSVT is used to supply 120/240 V AC power to the devices in the substation that run on AC. These include (but are not necessarily limited to):

- Battery Charger
- Indoor & outdoor lights
- HVAC system in the control house
- Miscellaneous equipment in the control house (smoke detectors, exit signs, exhaust fan, etc.)
- Receptacles in the control house & the yard
- Breaker SF6 tank heaters
- Yard equipment enclosure heaters

The SSVT must be large enough to supply power to all these loads, which was calculated by our team and approved by our client. The diversity factor tells us the estimated percentage of the time that each particular load will be active. For example, the outdoor lights will only be turned on at night, so their diversity factor is 0.5 (i.e. they're turned on half the time).

Diversity factor can be further broken down into summer diversity factor and winter diversity factor. This is because some loads are more likely to be active when the outdoor temperature is either hot or cold. Some examples of these are equipment heaters, transformer cooling fans, and control house HVAC.

We determine the size of the SSVT by multiplying all AC loads by their diversity factor, then summing the total load. We then choose an SSVT of the closest size available above the total. In the example, we calculated a winter load of 144 kVA and a summer load of 113 kVA, so we chose a 167 kVA SSVT (the closest size available above 144 kVA).

Note that the total load we calculated is not necessarily the maximum momentary load. On a cold winter night with electricity at peak demand, the load may go above 144 kVA, or even above the 167 kVA rated capacity of the SSVT. This is okay; the SSVT can operate above its rating for a period of time, and our calculations show that the load will be lower than this on average.

Steps to complete the AC study:

1. Identify all AC loads in the substation
2. Determine the VA rating for each AC load (typically found on the datasheet)
3. Assign a summer and winter diversity factor for each load
4. Multiply each load's VA rating by the summer and winter diversity factors
5. Sum all loads to determine the total load for summer and for winter
6. Choose the larger total load (summer or winter) and size the SSVT above this kVA rating

AC LOADS

Load Description	QTY	Volts Req'd	VA Rating	Winter Diversity Factor (DF)	Summer Diversity Factor (DF)	Total VA	Winter VA	Summer VA
138kV Breaker Bww - Heaters	1	240	3000	1	0.083	3000	3000	250
138kV Breaker Bww - Receptacle	1	120	1920	0.05	0.05	1920	96	96
138kV Breaker Bxx - Heaters	1	240	3000	1	0.083	3000	3000	250
138kV Breaker Bxx - Receptacle	1	120	1920	0.05	0.05	1920	96	96
138kV Breaker Byy - Heaters	1	240	3000	1	0.083	3000	3000	250
138kV Breaker Byy - Receptacle	1	120	1920	0.05	0.05	1920	96	96
69kV Breaker Bzz - Heaters	1	240	500	1	0.083	500	500	41.66666667
69kV Breaker Bzz - Receptacle	1	120	1920	0.05	0.05	1920	96	96
138kV SSVT - Enclosure Heater	1	120	30	1	1	30	30	30
138kV CVT - Enclosure Heater	3	120	30	1	1	90	90	90
69kV CVT - Enclosure Heater	1	120	30	1	1	30	30	30
Exterior Building Lights (26W lights)	2	120	26	0.5	0.5	52	26	26
Interior Building Lights (42W Replacement lights)	20	120	8.5	0.5	0.5	170	85	85
Up Lights (195W Replacement lights)	12	120	25.5	0.5	0.5	306	153	153
HVAC 1	1	240	10000	0.8	0.6	10000	8000	6000
HVAC 2	1	240	5000	0.8	0.6	5000	4000	3000
125VDC Battery Charger	1	240	19440	1	1	19440	19440	19440
120V Building Receptacles	7	120	2400	0.05	0.05	16800	840	840
Exhaust Fan	2	120	250	0.5	0.5	500	250	250
Scada Power Bar	1	120	1800	0.125	0.125	1800	225	225
120V Exterior Receptacles	4	120	2400	0.140	0.140	9600	1344	1344
Smoke Detectors	2	120	9.6	1	1	19.2	19.2	19.2
Wilmore DC/AC Inverter	1	120	250	1	1	250	250	250
Exit Signs	3	120	4.3	1	1	12.9	12.9	12.9
FUTURE EQUIPMENT								
138kV Breaker - Heaters	8	240	3000	1	0.083	24000	24000	2000
138kV Breaker - Receptacle	8	120	1920	0.05	0.05	15360	768	768
CVT - Enclosure Heater	14	120	30	1	1	420	420	420
345/138kV TR (268 MVA)	2	240	25500	0.5	1	51000	25500	51000
138/69kV TR (100 MVA)	2	240	6400	0.5	1	12800	6400	12800
Up Lights (195W Replacement lights)	12	120	25.5	0.5	0.5	306	153	153
MOAB - Heaters	4	120	115.2	1	0	460.8	460.8	0
			TOTAL LOAD (kVA) =			**181**	**99**	**100**

Calculations & Assumptions

1. 69kV Breaker load calculated from Siemens manufacturer drawing 72-481-260-457
   250W x 2 = 500W
2. 138kV Breaker load calculated from Siemens manufacturer drawing 72-481-185-468
   250W x 3 + 375W x 6 = 3000W
4. Exterior building lights assumed in use for winter scenario.
5. Winter scenario assumes night time for coldest part of day, all photocell controlled lights on, all heaters running full load, and building HVAC running 80% load, transformer fans running half load.
6. Battery charger sized in DC Study requires a load of 19,440VA.
7. Summer scenario assumes day time for hottest part of day, low temp. thermostatically controlled heaters off, building HVAC running 60% load
8. MOAB heater load calculated from Typical Southern States manufacturer drawing D-139309
9. Assumptions made for exhaust fan, smoke detectors, exit signs and SCADA from past data.

Conclusion: a 100 kVA SSVT is too close to estimation thus 167kVA SSVT is needed to cover all the current and future loads on the substation.

Figure 2-20: Final Tabulation of AC Loads

DC Study:

The purpose of the DC study is to ensure substation equipment remains energized under all conditions, both planned and unplanned. DC systems provide continuous power for all operating circuit breakers, protective relaying, SCADA system, and all other critical systems. These systems are required to provide continuous power for a minimum of 8 hours after the loss of AC power, provided through station batteries. The DC study is conducted with methods in accordance with IEEE Standard 485 for defining DC load and lead-acid battery sizing.

The worst-case scenario for this substation is a fault on the 138kV Des Moines line exit, followed by a breaker failure of B3. Breaker B1 would initially trip from the fault, and the breaker failure would expose the transformer and breaker B4 and breaker B2 to the fault, resulting in the tripping of all the substation's breakers. The final result is the need to trip (3) 138kV breakers, (1) 69kV breaker and (1) SSVT MOAB.

When sizing a battery, various factors used in the calculations account for the lowest possible temperature, the age, and a design margin; these factors are shown in Figure 2-21.

Correction Factor	Multiplying Factor
Temperature (Assuming 55°F is the lowest)	1.15
Age (Accounts for battery instability 80% of life)	1.25
Design Margin (Accounts for unexpected future loads)	1.10

Figure 2-21: Battery Correction Factors

Figure 2-22 through 2-2 displays all loads that must be taken into consideration. The first minute loads are those which must be energized quickly in a worst-case scenario situation, depicted in Figure 2-22. The continuous load is primarily made up of relay loads and devices to be continuously energized throughout the eight-hour interval, as shown in Figure 2-23. Emergency lighting loads are shown in Figure 2-24 and are only required to operate for the last half of the eight-hour period. Figures 2-25 and 2-26 assume that the transformer fault and failed breaker issues have been resolved and the affected part of the substation can be re-energized. Following the re-energization, it's assumed the station AC service issue is resolved and the eight-hour period concluded.

Quantity	Device	DC Load Current (A)	Total (A)
6	138kV Breaker Trip Coil #1	5.8	34.8
6	138kV Breaker Trip Coil #2	5.8	34.8
1	138kV MOAB	9	9
1	69kV Breaker Trip Coil #1	12	12
1	69kV Breaker Trip Coil #2	12	12
			0
			0
		Total =	102.6 A

Figure 2-22: First Minute Loads (Load L1, Time = 1 minute)

Quantity	Device	DC Load Current (A)	Total (A)
1	Relay Load	20.81	20.81
			0.00
			0.00
			0.00
		Total =	20.8 A

Figure 2-23: Continuous Loads (Load L2, Time = 480 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
5	Emergency Lighting	0.48	2.4
			0
			0
			0
		Total =	2.4 A

Figure 2-24: Non-Continuous Loads (Load L3, Time = 240 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
	Physical switch		0
			0
			0
			0
		Total =	0 A

Figure 2-25: Momentary Loads (Load L4, Time = 1 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
1	Motor Start Current	13	13
			0
			0
			0
		Total =	13

Figure 2-26: Momentary Loads (Load L5, Time = 1 minutes)

To calculate the total number of amp-hours required of the battery, the 480-minute time frame can be divided into periods where each one can be expressed as a function equal to the total amperes consumed in that time frame. The integral of these piecewise functions over the entire time frame yields the total amp-hours; this is shown in Figure 2-27.

T1 = initial load period (minutes)
T2 = continuous load period (minutes)
T3 = non-continuous load period (minutes)
T4 = final load period (minutes)
A1 = total amperes for initial load period (amperes)
A2 = total amperes for continuous load period (amperes)
A3 = total amperes for non-continous load period (amperes)
A4-A6 = total amperes for final load period (amperes)

Total Amp-hours: $$\left[A1*\frac{T1}{60}\right]+\left[A2*\frac{T2}{60}\right]+\left[A3*\frac{T3}{60}\right]+\left[A4*\frac{T4}{60}\right]$$

Period	Loads	Total Amperes	Duration
A1	L1+L2	123.4	1
A2	L2	20.8	239
A3	L2+L3	23.2	238
A4	L2+L3+L4	23.2	1
A5	L2+L3+L5	36.2	1

Total Amp-hours: 178.0

(1) Period	(2) Load (amps)	(3) Change in Load (amps)	(4) Duration of Period (min)	(5) Time to End of Section (min)	(6) Capacity @ T Min. Rate (6A) Amps/Pos (Rt)	(7) Required Section Size (3) / (6A)= Positive Plates
Section 1 - First Period Only - If A2 is greater than A1, go to Section 2. (NO)						
1	A1= 123.4	A1-0= 123.4	M1= 1	T=M1= 1	126.5	0.98
					Sec 1 Total	0.98
Section 2 - First Two Periods Only - If A3 is greater than A2, go to Section 3. (YES)						
1	A1=	A1-0=	M1= 1	T=M1+M2= 240	21.5	0.00
2	A2=	A2-A1= 0.0	M2= 239	T=M2= 239	21.5	0.00
						0.00
Section 3 - First Three Periods Only - If A4 is greater than A3, go to Section 4. (YES)						
1	A1= 123.4	A1-0= 123.4	M1= 1	T=M1+M2+M3= 478	13.5	9.14
2	A2= 20.8	A2-A1= -102.6	M2= 239	T=M2+M3= 477	13.5	-7.60
3	A3= 23.2	A3-A2= 2.4	M3= 238	T=M3= 238	21.5	0.11
					Sec 3 Total	1.65
Section 4 - First Four Periods Only - If A5 is greater than A4, go to Section 5. (YES)						
1	A1=	A1-0=	M1= 1	T=M1+M2+M3+ 479	13.5	0.00
2	A2=	A2-A1= 0.0	M2= 239	T=M2+M3+M4= 478	13.5	0.00
3	A3=	A3-A2= 0.0	M3= 238	T=M3+M4= 239	21.5	0.00
4	A4=	A4-A3= 0.0	M4= 1	T=M4= 1	126.5	0.00
					Sec 4 Total	0.00
Section 5 - First Five Periods Only						
1	A1= 123.4	A1-0= 123.4	M1= 1	T=M1+M2+M3+ 480	13.5	9.14
2	A2= 20.8	A2-A1= -102.6	M2= 239	T=M2+M3+M4+ 479	13.5	-7.60
3	A3= 23.2	A3-A2= 2.4	M3= 238	T=M3+M4+M5= 240	21.5	0.11
4	A4= 23.2	A4-A3= 0.0	M4= 1	T=M4+M5= 2	126.5	0.00
5	A5= 36.2	A5-A4= 13.0	M5= 1	T=M5= 1	126.5	0.10
					Sec 5 Total	1.76
Random Equipment Load Only (if needed)						
R	AR=	AR-0=	MR=	T=MR=		0.00

Maximum Section Size	1.76	Uncorrected Size	1.76
+ Random Section Size (9)	0.00	x Temp. Corr	1.15
= Uncorrected Size	1.76	x Design Margin	1.00
		x Aging Factor	1.25
		= Positive Plates	2.52
		Positive Plates (rounded up)	3.00

Figure 2-27: Total Amp Hours

From the data from Figure 2-27, a duty cycle can be shown as the following Figure 2-28.

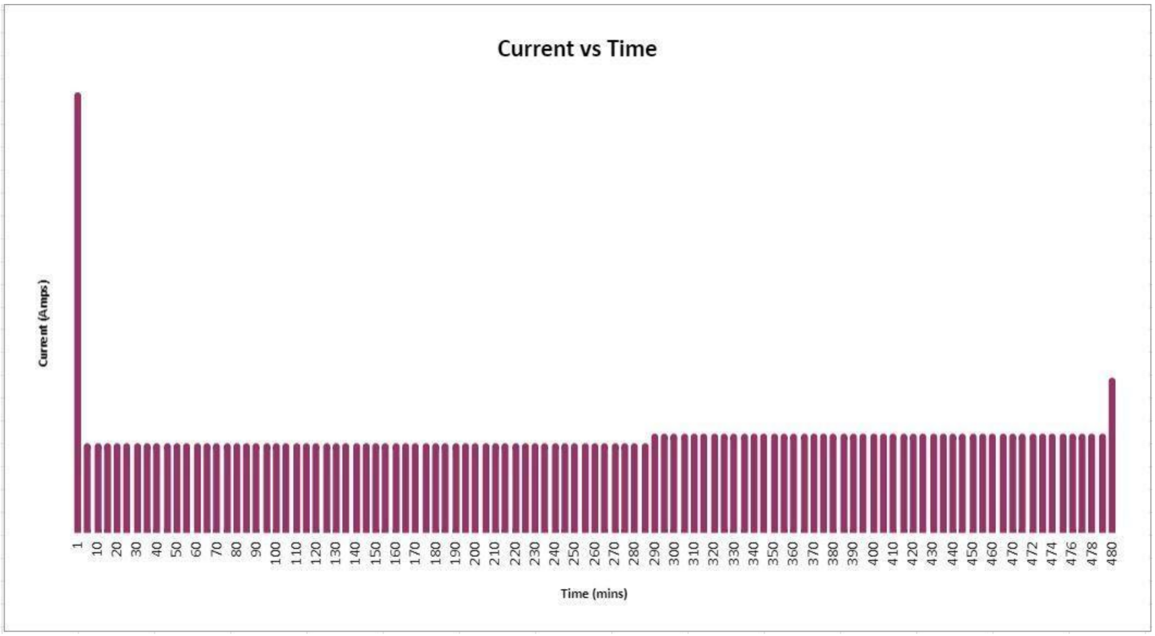

Figure 2-28: Load Profile

IEEE Standard 485 [3] goes into detail on how to calculate the number of positive plates required of the battery. To do this, the load profile shown in Figure 2-27 used in conjunction with the current per positive plate required to bring the batteries' voltage to 2.25 per cell in a specified amount of time are required. The latter is provided by the battery manufacturer and can be referenced in the Appendix.

When sizing the battery charger, the capacity (A) in amps can be found by the following equation where L is the continuous load being 20.8 Amps, C is the ampere hours emergency discharge which is the 290Ah battery rating of the EnerSys EC-7M, H is the number of hours recharge time assumed to be 24 hours, and the 1.1 constant is a factor accounting for the efficiency of lead acid cells.

$$A=L+(1.1*C)H$$

The charger capacity was calculated to be 34.10 Amps, and therefore, the next larger size provided by EnerSys AT10-130-050 power capable of handling 50 Amps will be sufficient for the substation.

In conclusion, the battery sized for the Cyclone Substation can adequately power all major equipment and relays residing in the substation yard and enclosure under emergency conditions. The batteries sized for this substation take into account the possible addition of three (3) 138kV breakers as part of a future breaker-and-a-half expansion. Additional relaying is not included within this document nor the scope of this project, however it is assumed the battery bank will handle all major relaying additions. Currently, the station is rated at nearly 178 Ah while the EnerSys EC-7M is rated at 290 Ah, this difference allows for major future changes to the substation.

2.2.5 Schemes:

To facilitate the readability of the wiring, specific scheme drawings are created for the relays. A set of relays related to a specific breaker or transformer are grouped into a diagram, in which the relays, test switches and fuses are all connected and clearly labeled. These drawings also link to each other to depict the same connections as the one line.

Each scheme drawing, as seen in Figure 2-29, has one to two relays, the basic structure of which is provided by models from Burns & McDonnell for the line relaying diagrams, 2-29 and 2-30, the diagrams have the primary and secondary line relaying relays. Those drawings also contain the X and Y windings from their respective line exit. The breaker relaying diagrams contain the schematics detailing the AC and DC power flow to the breakers, well as the Failure-to-Trip relays, which protect the substation in the instance of a breaker failure or other emergency. There would be one more scheme diagram which would detail the transformer and the 69kV line exit, however Burns & McDonnell asked us not to complete that diagram due to limitations set in place from COVID-19. Figures 2-31 through 2-33 detail the initial revisions submitted to Burns & McDonnell.

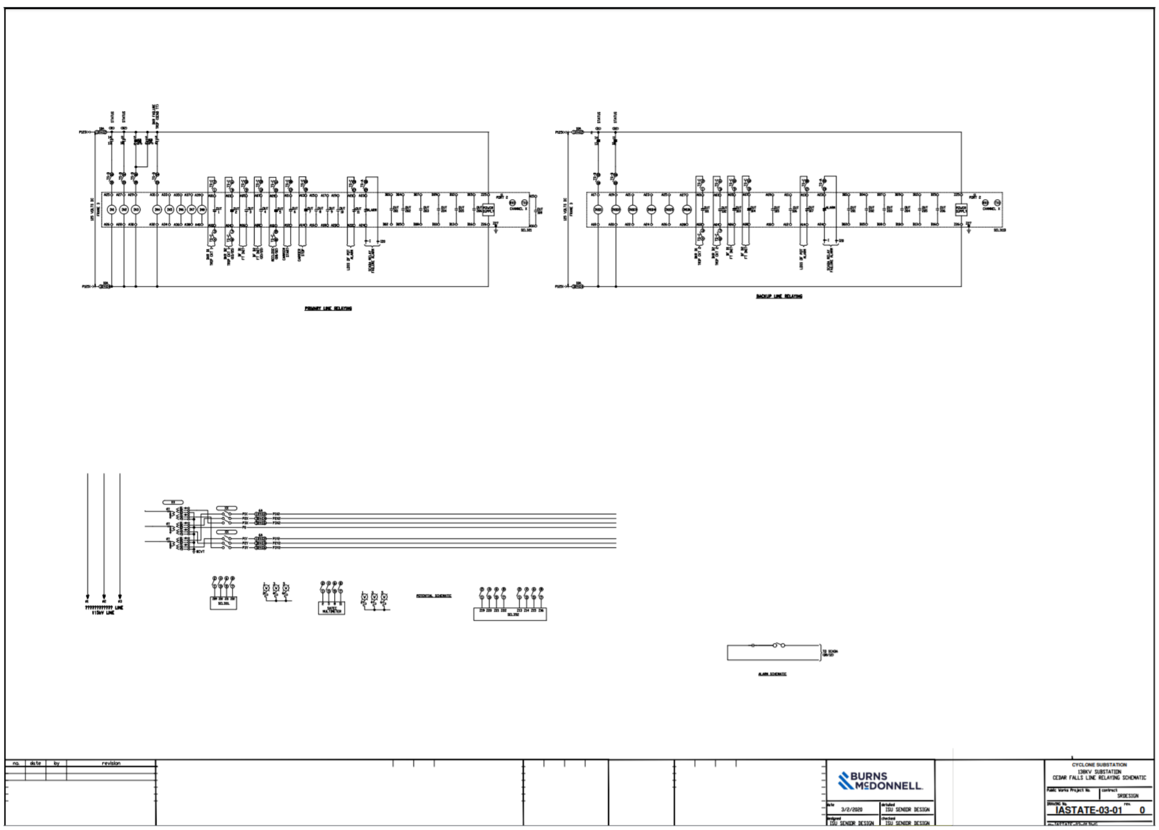

Figure 2-29: Initial Cedar Falls Line Relaying

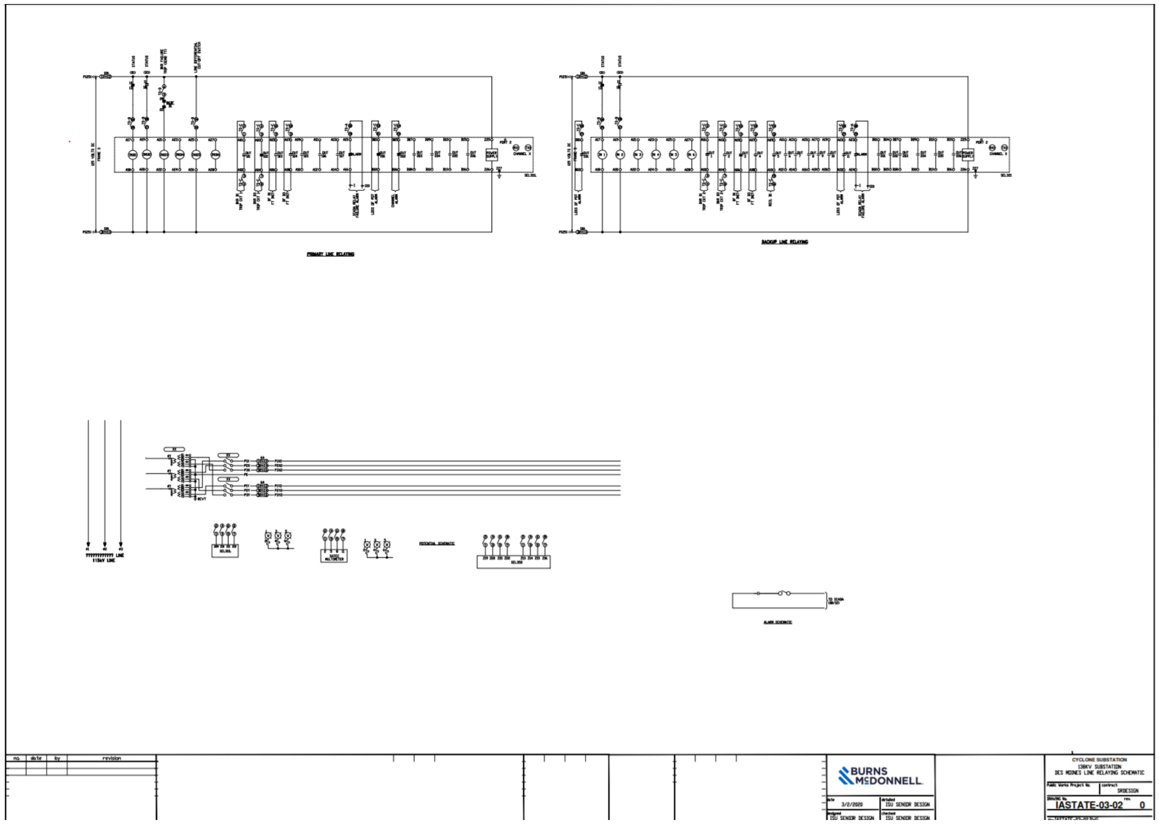

Figure 2-30: Initial Des Moines Line Relaying

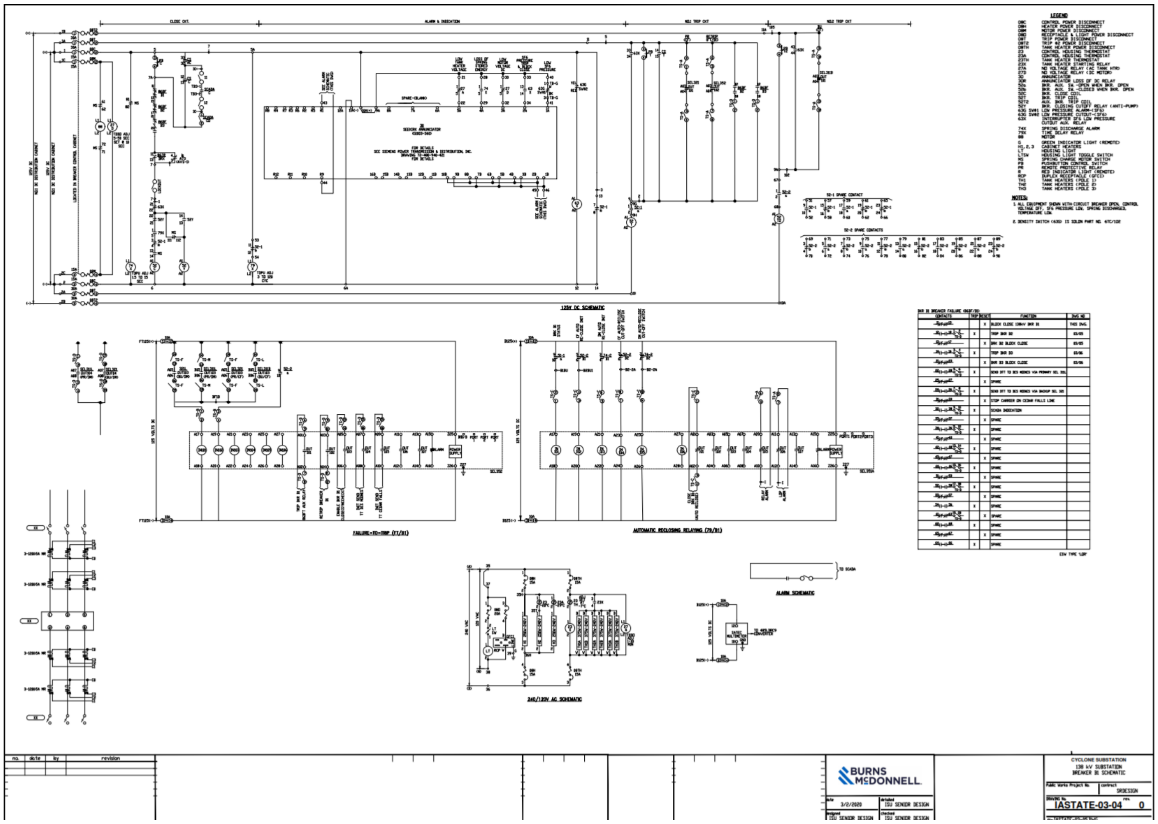

Figure 2-31: Initial B1 Relaying

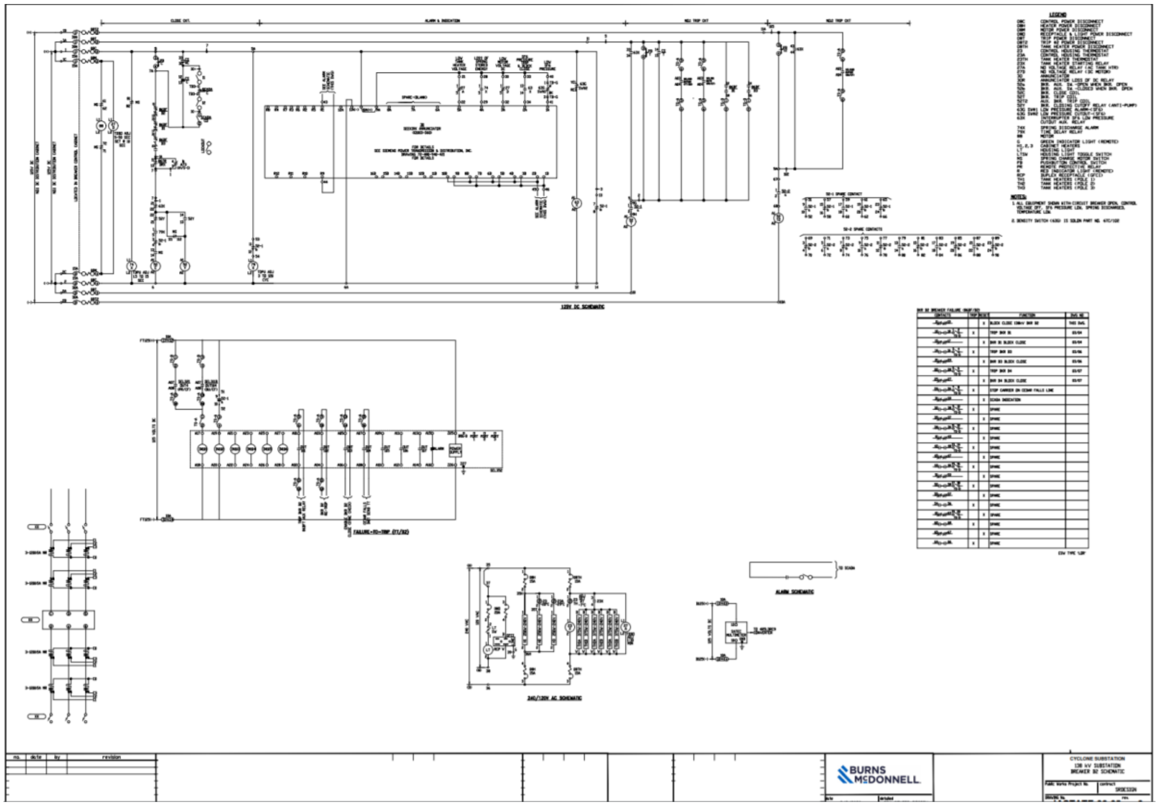

Figure 2-32: Initial B2 Relaying

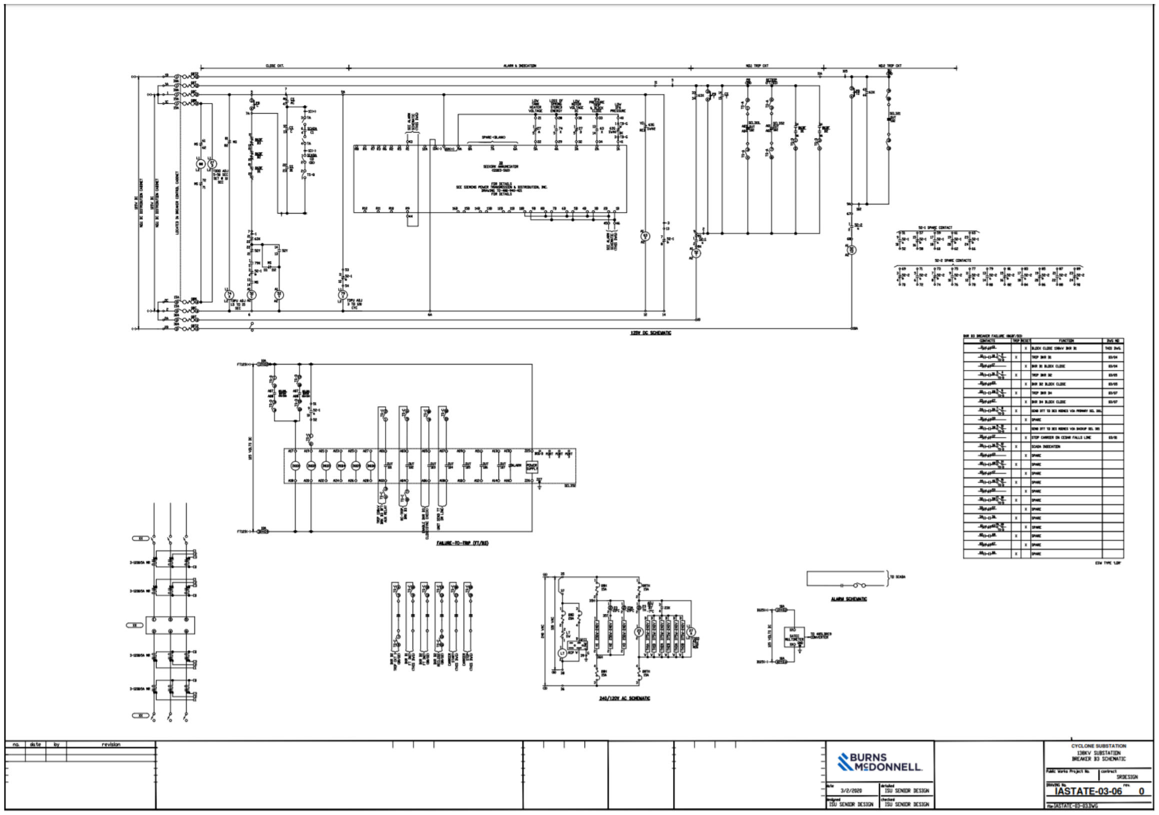

Figure 2-33: Initial B3 Relaying

After creating the initial diagrams, the connections needed to be made. For the line relaying schemes and the breaker relaying drawings, relay blocks needed to be added to the X and Y windings of the line exits. Along with these, warning lights and multimeters were also needed in order to monitor the status of the windings. After this is completed, the connections need to be shown which connect the relays to the other drawings as well as the CTs. These connections are created based on the wiring from the one line as shown in section 2.1.2.

After consultation with Burns and McDonnel, small changes were made with the connections in the diagrams. Firstly, in order to improve clarity, the words “top” and “bottom” were changed to “inner” and “outer” to describe the CTs. Secondly, the naming of the test switches was changed to reflect real connections, as well as keep groupings of test switches correctly together. Thirdly, the schemes were closely looked over to ensure that every connection was traceable on the drawings they were said to go to. By adding these elements, the schemes passed review and could confidently be used to complete the final step of the substation, the wiring diagrams.

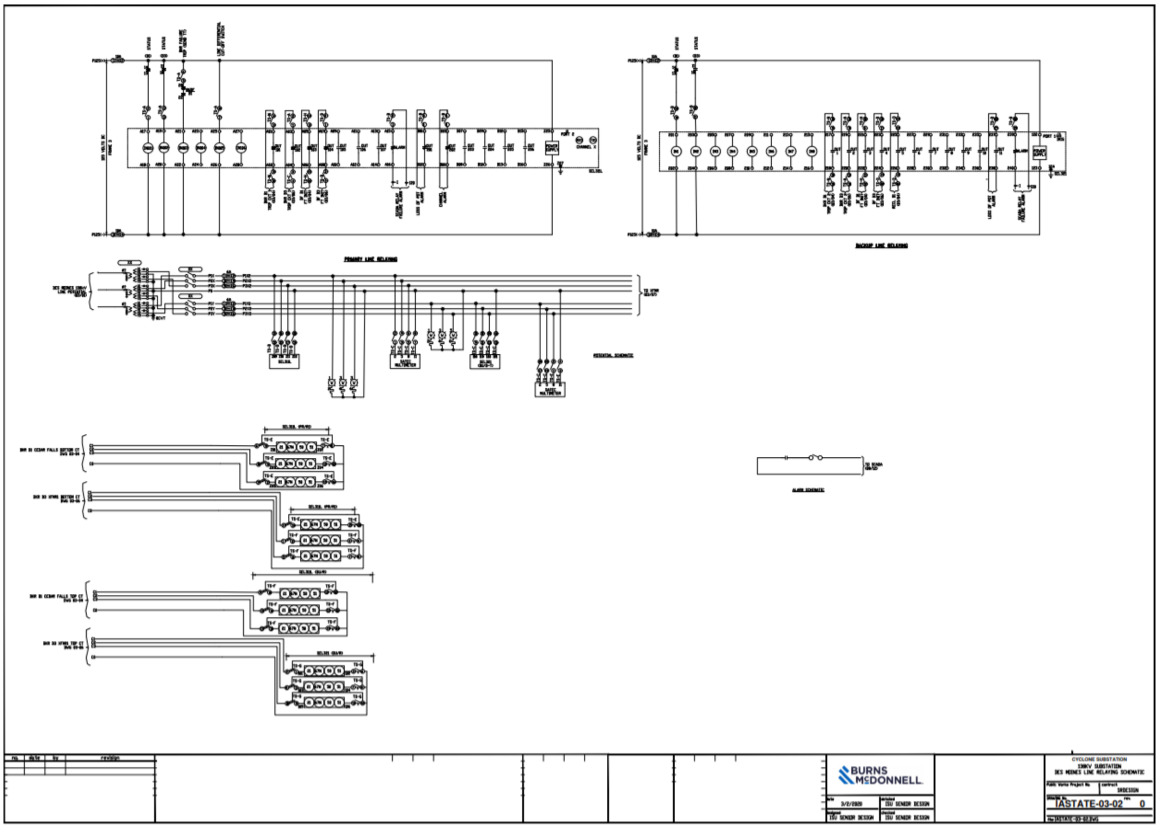

Figure 2-34: Final Des Moines Line Relaying

2.2.6 Wiring:

From the Schemes, we can create the wiring diagrams. These diagrams detail the physical structure of the relay cabinet which contain the equipment needed to test and monitor the relays. These wiring diagrams also show all the physical connections detailed in the scheme drawings, and where they would be linked. This would be used in construction, similar to the plan and section views. Due to this, special care is needed to accommodate the expected use, such as height of commonly used switches, proper spacing and ease of construction.

This was created based on specifications from Burns & McDonnell. The first step was to create the relay cabinet. The basic frame is provided in the form of CAD cells by Burns & McDonnell at the industry standard height of 7'6", or 72 Rack Units (R.U.). A R.U. is a measurement using the standard size of a rack, or 1.25 in. Everything in the cabinet is in terms of rack units, and a 1 R.U. spacer is placed between each major grouping of components.

In this frame, the test switches for the relays related to the specific breaker need to be made easily accessible for the user on the substation. Along with this, relay shutoff electro switches for emergencies or maintenance are added at chest level. This cabinet also includes a multimeter to monitor the relay windings.

The back of this cabinet has the wiring connections. Based on the scheme diagrams, the specific wiring to each test switch, fuse and relays is listed shorthand. Any connections that need to travel to another relay cabinet or another part of the substation are fed through terminal blocks.

Our initial design focused on the initial relay cabinet. This version focused on the switch placement, the test switches needed and the general layout of the cabinet, which can be viewed in Figure 2-35.

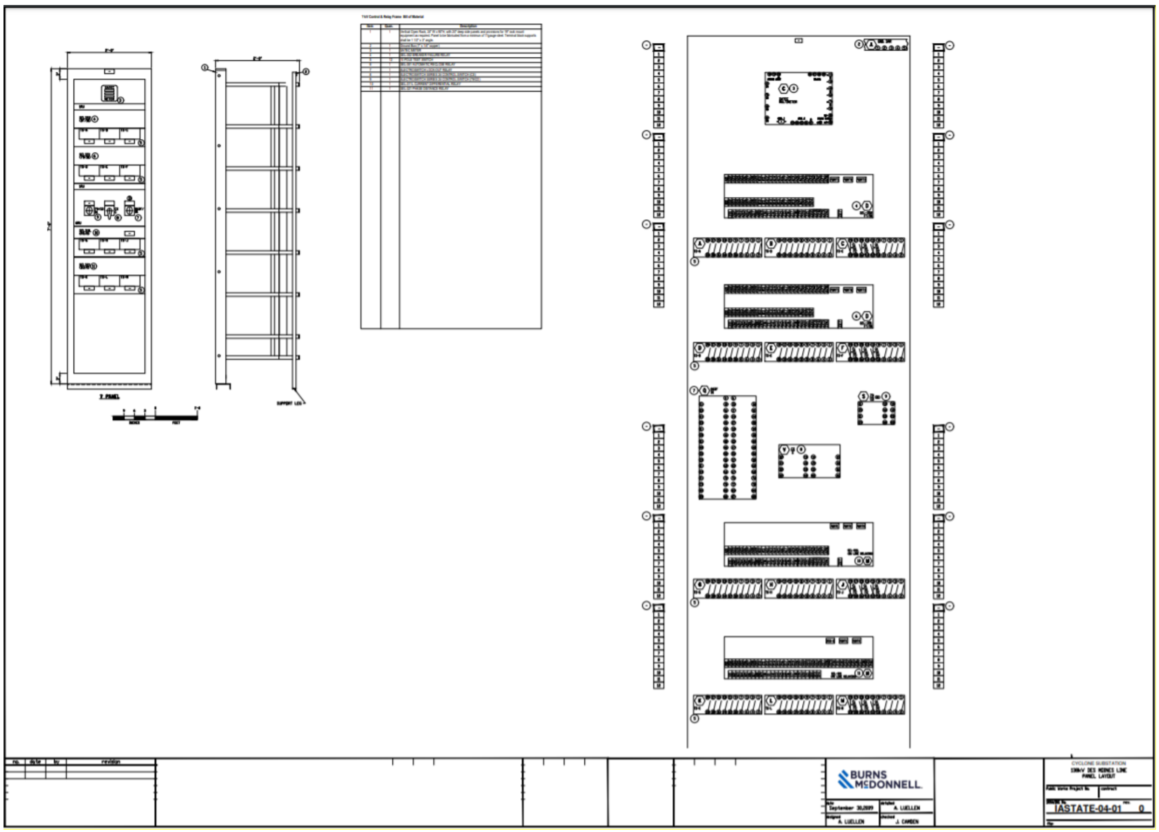

Figure 2-35: Initial Wiring Drawing

After conversing with Burns & McDonnell, several changes were made, and the wiring was completed. The dimensions and nameplates were added to the rack to assist construction workers and substation users, and the wiring was completed. Due to limitations with the coronavirus, as well as Burns & McDonnell's original plan, only one wiring diagram was completed based on scheme drawing 03-02. The substation would have a wiring diagram based on each scheme drawing; however, due to time constraints and the repetitive nature of the work, Burns & McDonnell decided to require only 1 diagram.

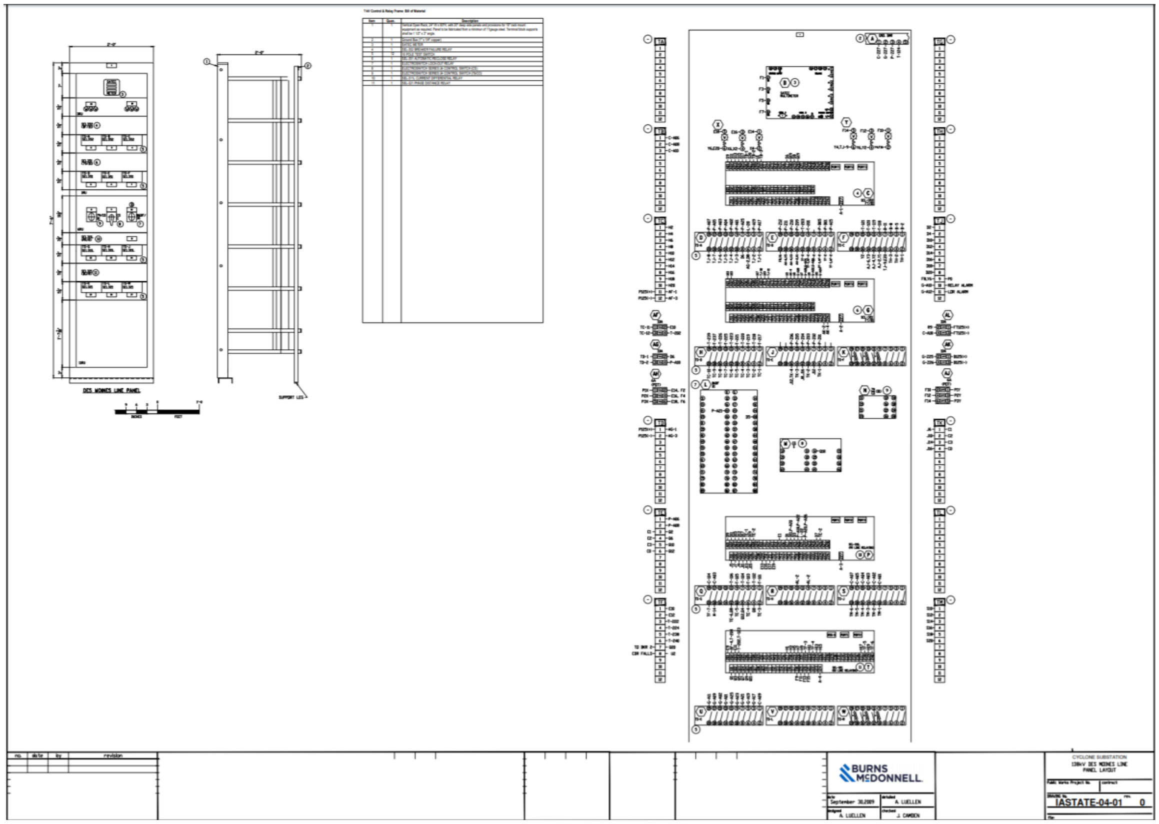

Figure 2-36: Final Wiring Design

3. Statement of Work

3.1 Previous Work and Literature

Created in 1898, Burns & McDonnell has been dedicated to providing engineering solutions and is trusted especially in substation design. The exemplary history of Burns and McDonnell leaves no doubt to the efficacy of their work, documentation, and industry standard.

Our substation project is founded on resources and examples provided by Burns & McDonnell. These resources were specially picked to pertain to our design specifications in order to most help us in providing a high-quality result.

3.2 Technology Considerations

For this project, the substation componentry specified within our scope documents have been provided by Burns and McDonnell as AutoCAD files. While this greatly simplifies the design process, as the components are properly rated and ready for implementation, this also limits some of the freedom available with creating drawings. The CAD files are not easy to modify and creative methods often need to be used to properly integrate all necessary components in accordance with precise measurements and scoping of our project.

3.3 Task Decomposition

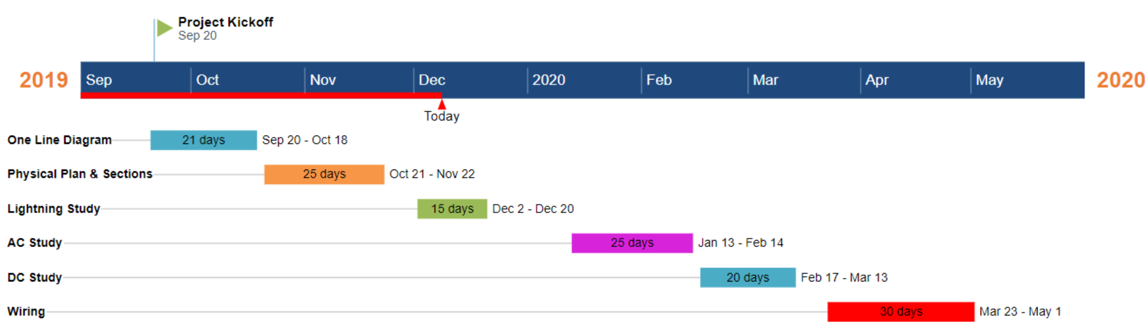

Figure 3-1: Task progression for Substation Design

These tasks follow a linear progression. The initial step, being the one-line diagram, yields a general block diagram layout of the substation. The next step, being the plan view and section cuts, are an elaboration of the one-line diagram, detailing specific dimensions and spacing of components. After the plan is done, 3 studies must be completed to properly provide protection and power to the different components in the substation: the lightning study, the AC study, and the DC study. The lightning study details the protection from lighting strikes and must cover each component in the plan view, while the AC and DC studies focus on the power supplied to run the various high-power components in the substation. Once these are completed, an in-depth wiring scheme is needed to complete the final design. Collectively, these tasks complete the finalization of our substation project.

3.4 Possible Risks And Risk Management

Possible restrictions for this project are mainly related to inexperience and our dependence on contacts at Burns and McDonnel. As this is our group's first experience in power system design, the revision process has proven to be extensive. The time spent between our drafting and our client's revising is unpredictable, changing from task to task.

Elements which may obstruct our intended schedule of work include a lack of understanding which may delay the rate at which our drafts are submitted to our client for review and the rate at which our client is available to review. However, neither of these case scenarios have affected our team's ability to provide exemplary work according to schedule.

3.5 Project Proposed Milestones and Evaluation Criteria

As displayed by the progress tracker in Figure 4-1, there are six major milestones that need to be met throughout the course of the project. We have remained on schedule despite project limitations and delays caused by the development of COVID-19, and have successfully delivered all documentation and designs pertaining to each milestone.

3.6 Project Tracking Procedures

For project tracking, a Google Drive folder is shared between the group and Burns and McDonnell. This folder contains all the reference materials, as well as our deliverables, and each revision made to our documents, detailing our process. It also contains any formal report given to Burns and McDonnel. Our internal weekly reports are included on our team website. This details our individual contributions and progress.

Each time an edit is made to the document, a copy of that revision is saved to the Google Drive folder. This ensures that we can both look back at past work to revert a change, but also illustrates our progression to the Burns and McDonnell representatives.

3.7 Expected Results and Validation

The result is a full set of diagrams detailing the electrical and physical connections, which fulfils all standards, restrictions and regulations. This plan should be "as built", ready for construction. Our final project has been successfully evaluated by representatives at Burns and McDonnel and deemed complete as per our final review. A success in this project is a substation plan that Burns and McDonnell deems fit for construction which has been accomplished.

4. Project Timeline, Estimated Resources, and Challenges

4.1 Project Timeline

PROGRESS TRACKER/SCHEDULE

Assignment	Status	Start date	Due on
One Line		9/20/2019	10/18/2019
Physical Plan & Sections		10/21/2019	11/22/2019
Fall Break (Nov. 25-29)			
Lightning Study		12/2/2019	12/20/2019
AC Study		1/13/2020	2/14/2020
DC Study		2/17/2020	3/13/2020
Spring Break (Mar. 16-20)			
Schemes/Wiring		3/23/2020	5/1/2019
Final Exams (May 4-7)			

Figure 4-1: Progress Tracker/Schedule

The timeline of our project is broken up into the following discrete components: a one-line diagram, a physical plan view, drawing cuts of specific sections extracted from the plan view, a lightning study, AC and DC study, and the wiring and schemes which ultimately finalize the design of our substation.

All deliverables for this project have been completed and submitted to Burns & McDonnell on time, all have been deemed accurate and ready for construction.

4.2 Feasibility Assessment

The final product of this project includes the design phase services necessary to serve as an interconnection for a new wind generation plant being built in the area. We have provided all specified designs, drawings, and protection services to Burns and McDonnell.

4.3 Personnel Effort Requirements

The project was estimated at 400 man-hours and to be completed by the end of the spring semester 2020. With approximately 26 weeks, we have put in about 16 hours of cumulative work a week. Each phase lasted about a month given our deadline, and our work has been allocated appropriately in order to effectively complete our tasks on time.

This breakdown includes two meetings a week, one spent with just our team aimed to organize plans and peer review individual work and one spent with our advisor and client aimed to finalize and perfect work, in conjunction with planning our next steps as a team to ensure we move forward cohesively and effectively.

Beyond these team meetings, our efforts were split between individual and group work. All individual work was peer reviewed by other members of the team to ensure correctness. However, to work most effectively and ensure everyone understands all aspects of the design. While some have a greater proficiency in certain areas and as a team it is in our interest to play to individuals' strengths, we have all contributed to every element of the project, we have aimed to not specialize people to certain types of work exclusively.

Task Description	mean contribution per member (hrs)	Total man-hours (hrs)
Assesment Phase	0.25	1.5
Research Phase	0.5	3
Drafting Phase	0.5	3
Review Phase	0.5	3
Revision phase	0.5	3
External to Design(Conf. Calls, class work.)	1	6
Sum	1.75	10.5
Semester Sum	28	168

Figure 4-2: Resource Hour Allocation

4.4 Other Resource Requirements

All resources for this project have been previously described; documentation and resources utilized in our design process have been provided directly from Burns & McDonnell. Software and other hard materials needed to complete this design have been provided directly from Iowa State University.

4.5 Financial Requirements

There are no significant financial requirements to include with our project.

5. Testing and Implementation (Implementation and Results)

5.1 Interface Specifications

Due to the nature of this project, there will be no hardware or software interface testing of the design work.

5.2 Hardware and software

Due to the nature of this project, there will be no hardware or software testing of the design work.

5.3 Functional Testing

Due to the nature of this project, there will be no functionality testing of the design work.

5.4 Non-Functional Testing

Due to the nature of this project, there will be no testing for non-functional items in the design.

5.5 Process

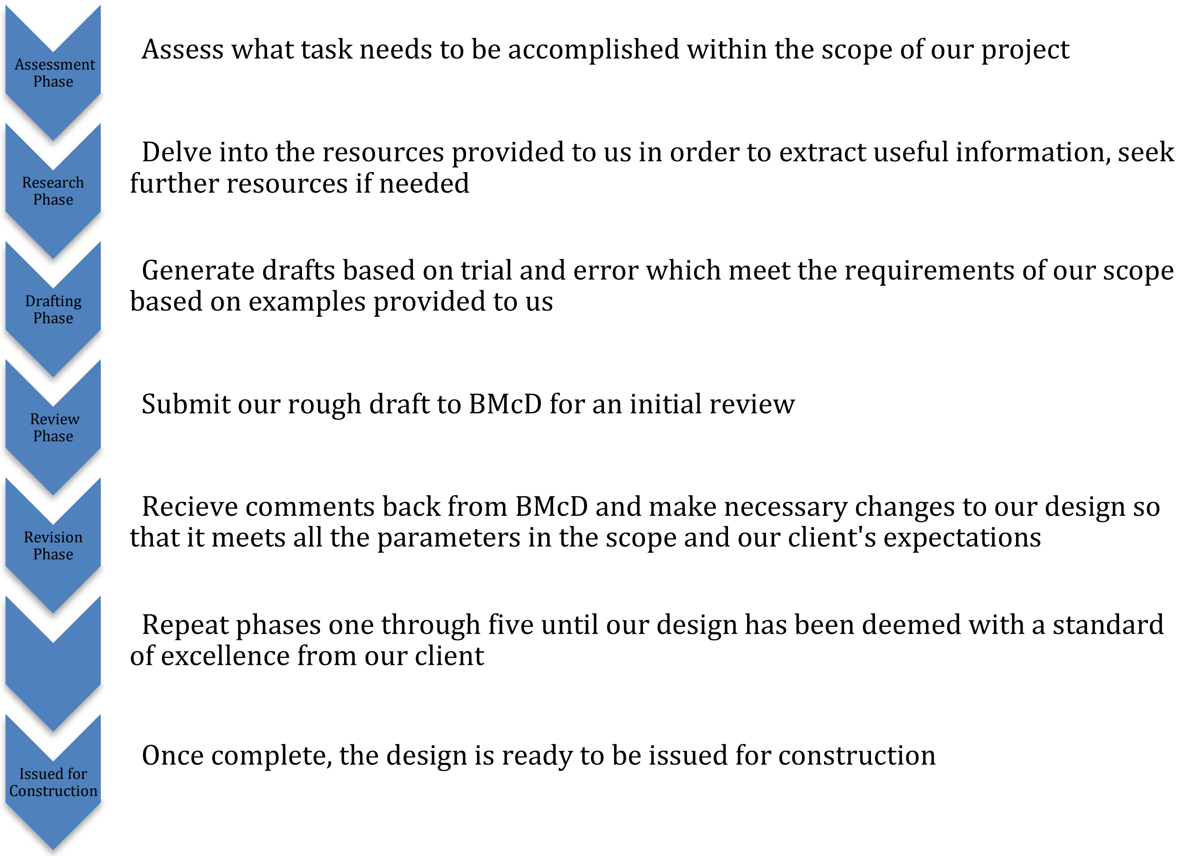

Figure 5-1: Final Design Process Flowchart

Proposed design strengths:

- ➔ Increases communication among team members
- ➔ Efficient
- ➔ Increases accuracy and correctness

Proposed design weaknesses:

- ➔ Time consuming and repetitive

5.6 Results

Following the Design Process depicted in Figure 5-1, Figures 5-2 through 5-5 display the final results of each deliverable which have been finalized and deemed by our client as ready for implementation. As the physical construction of a substation is not within our project scope, these drawing and analyses constitute the final deliverables for our project.

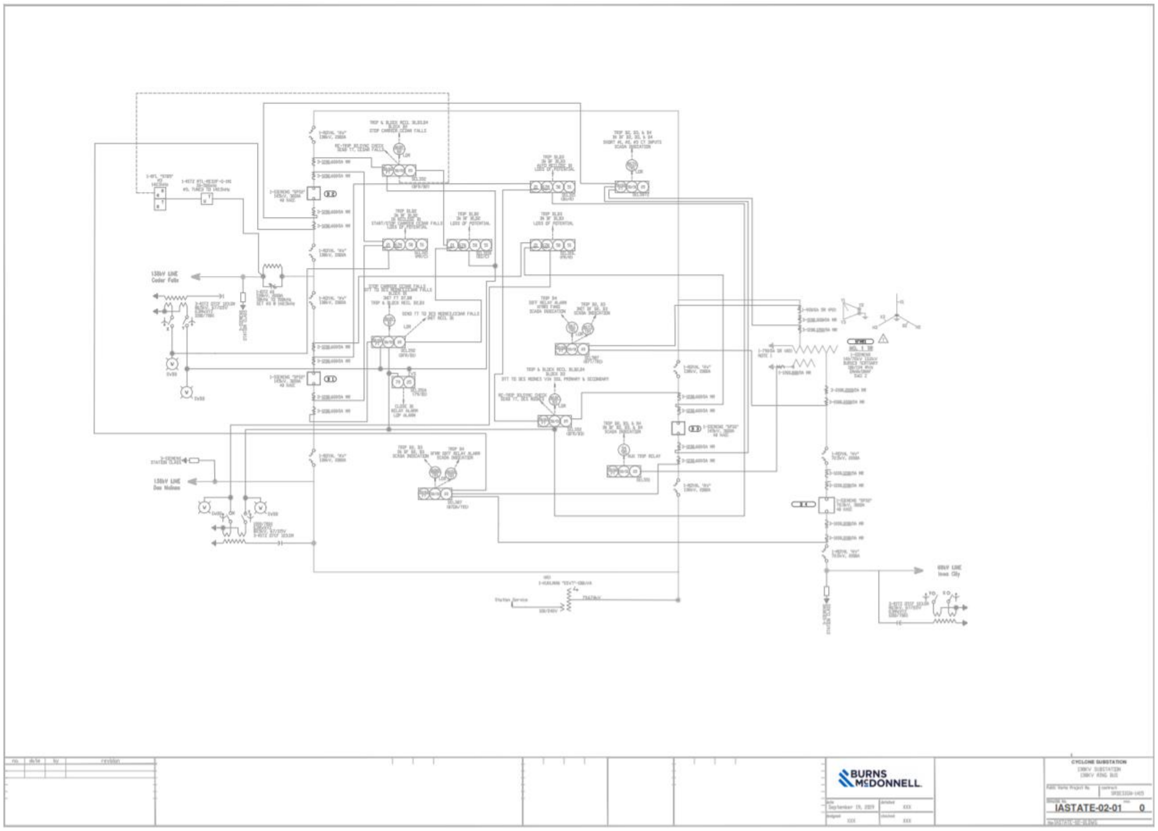

Figure 5-2: Final Submission of One-Line

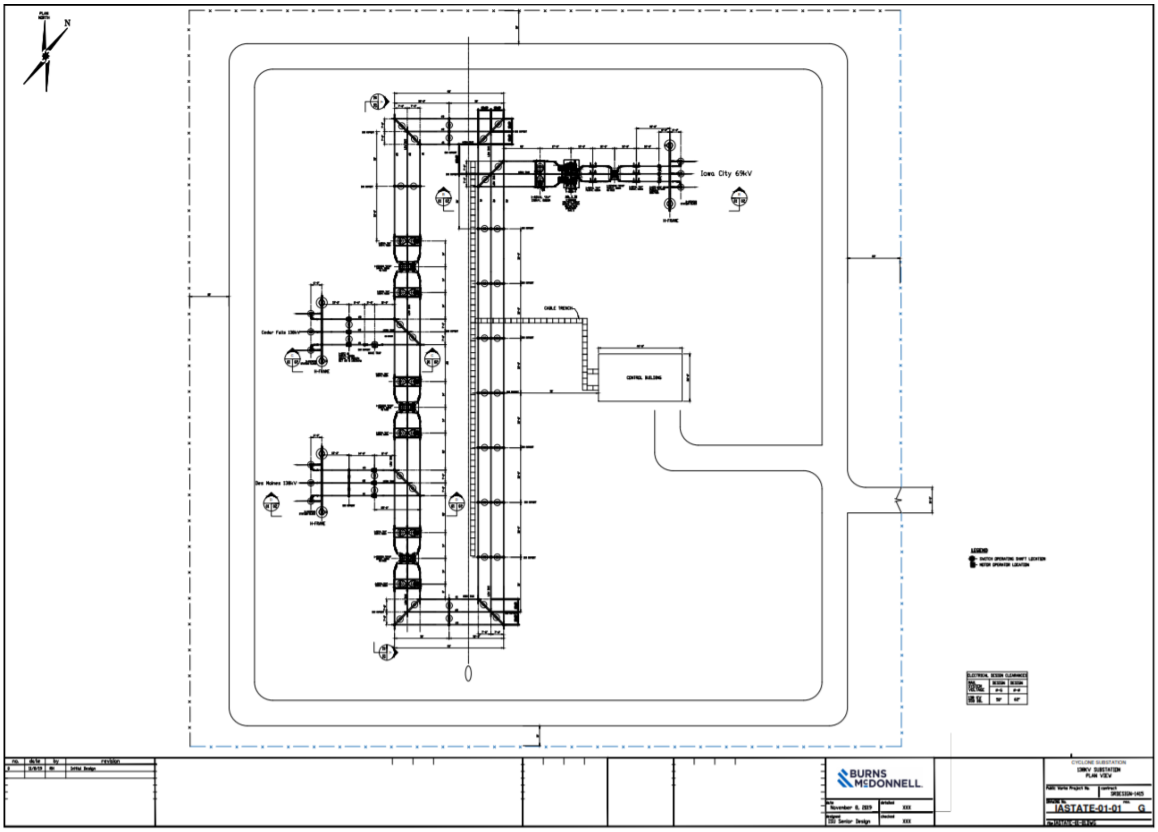

Figure 5-3: Final Submission of Plan View

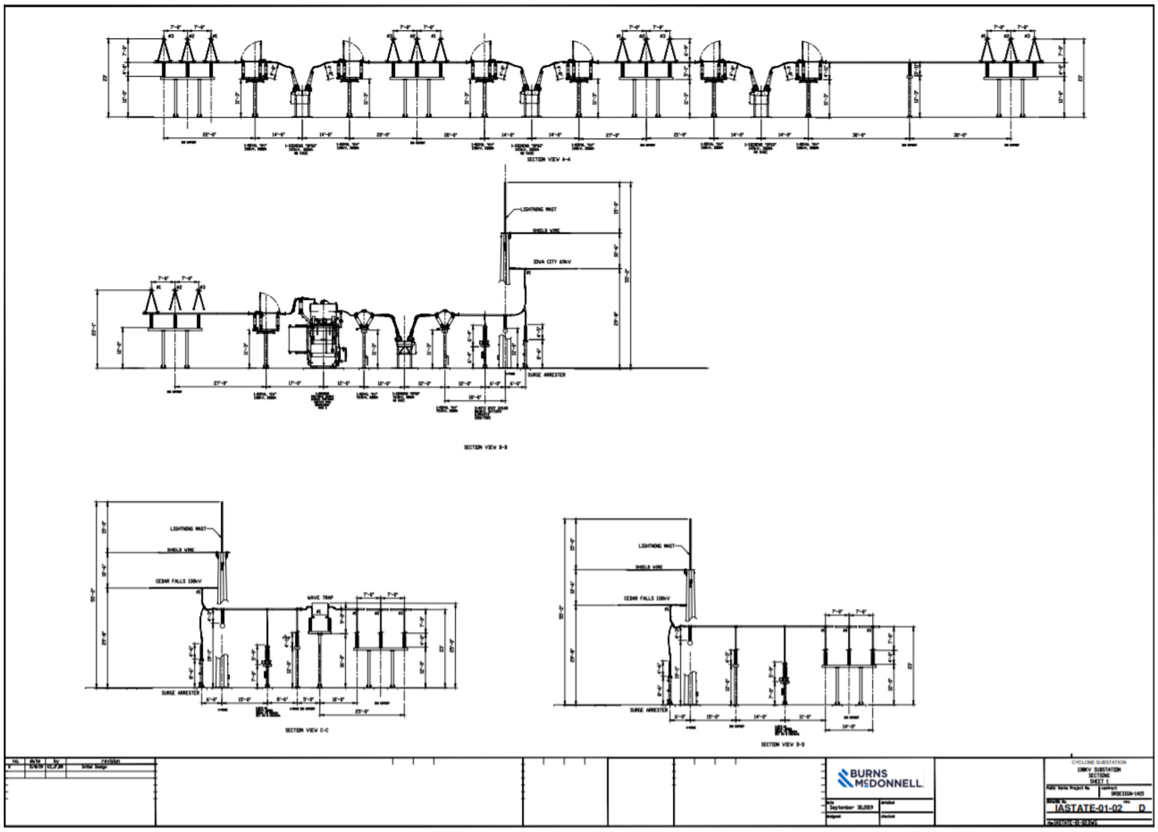

Figure 5-4: Final Submission of Section View

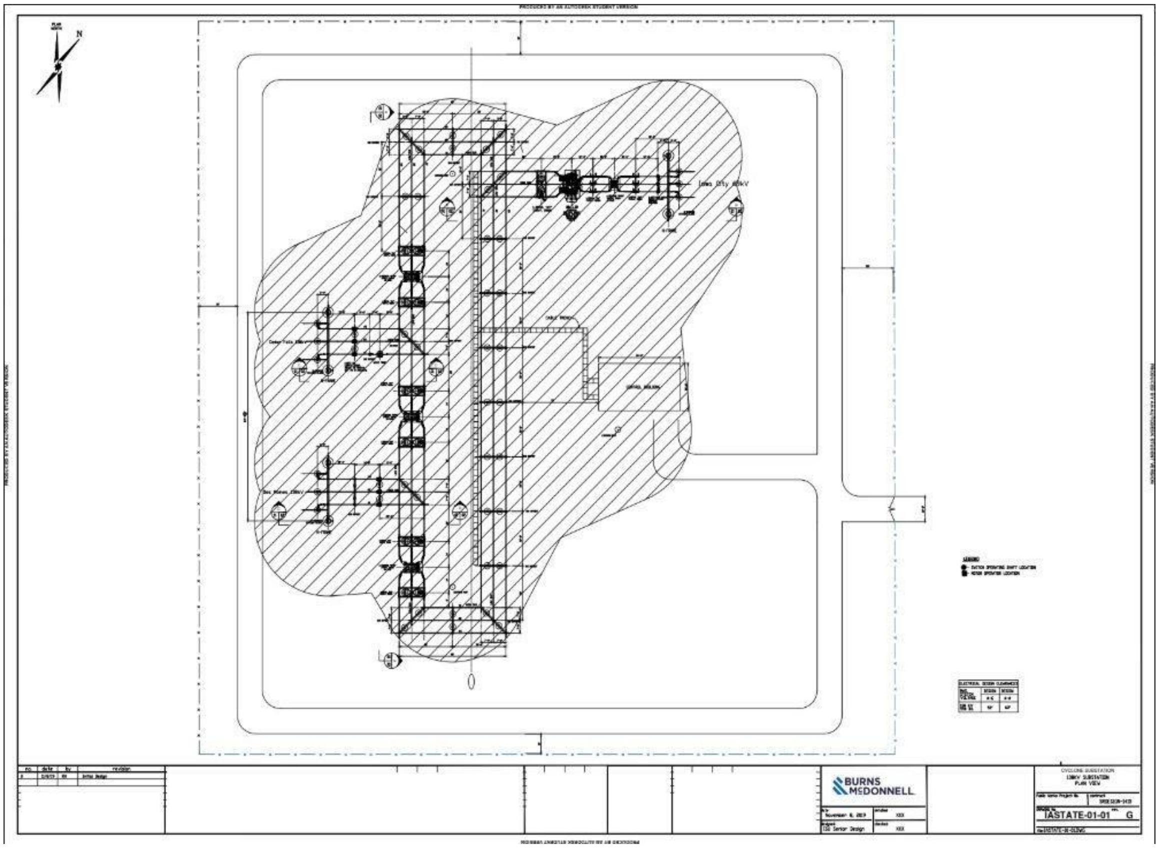

Figure 5-5: Final Results of Lightning Study

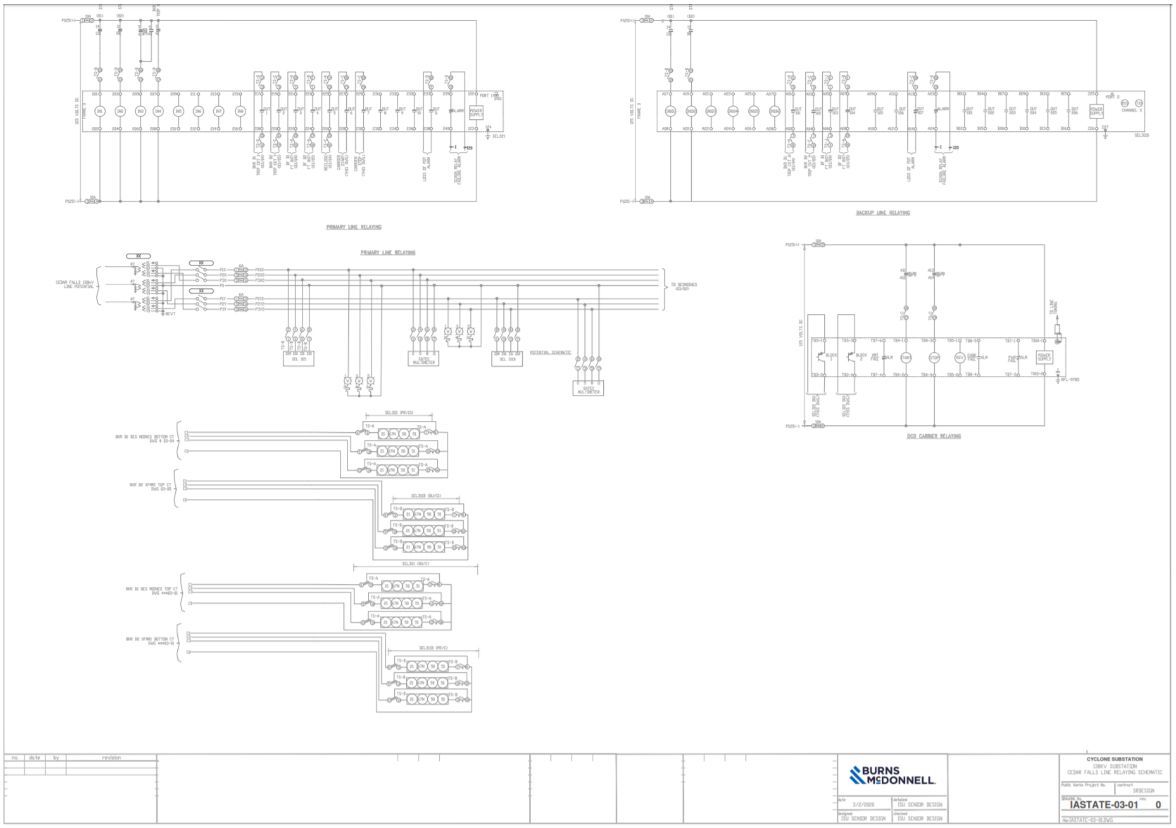

Figure 5-6: Final Cedar Falls Line Relaying

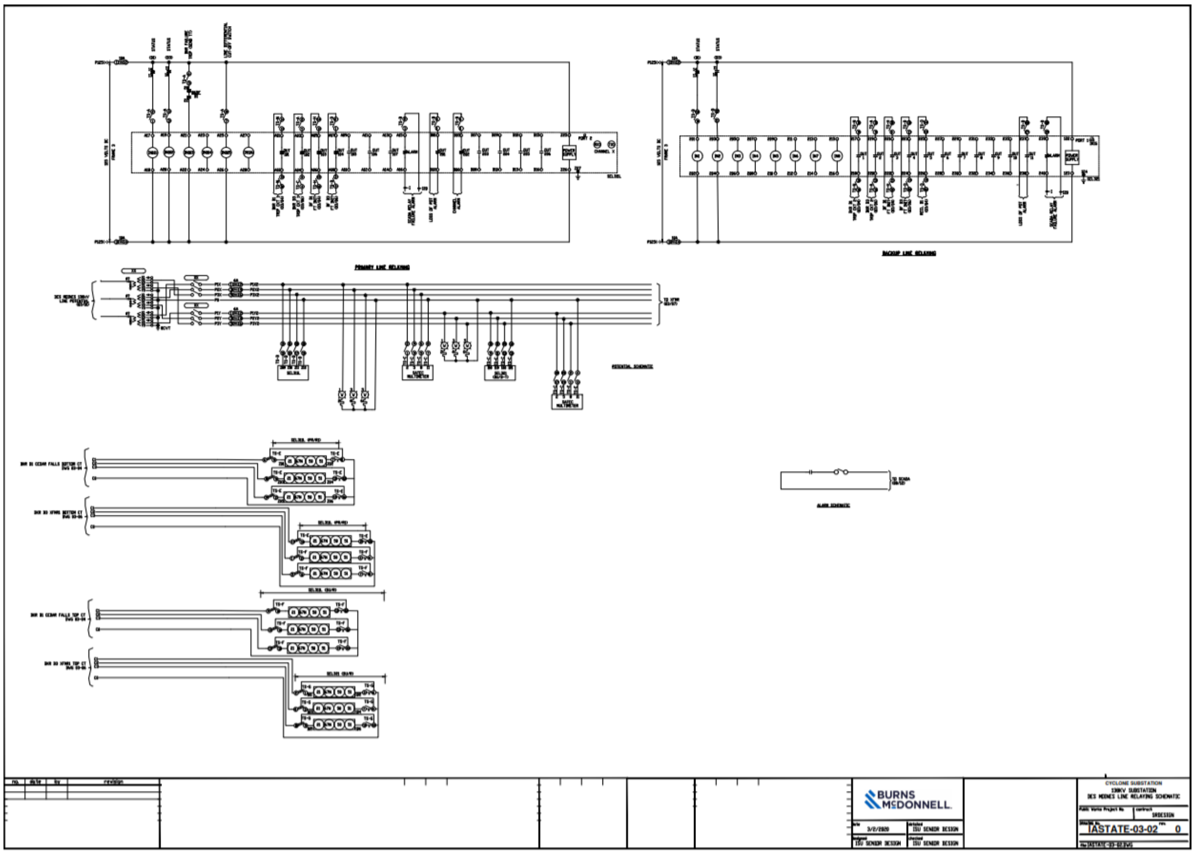

Figure 5-7: Final Des Moines Line Relaying

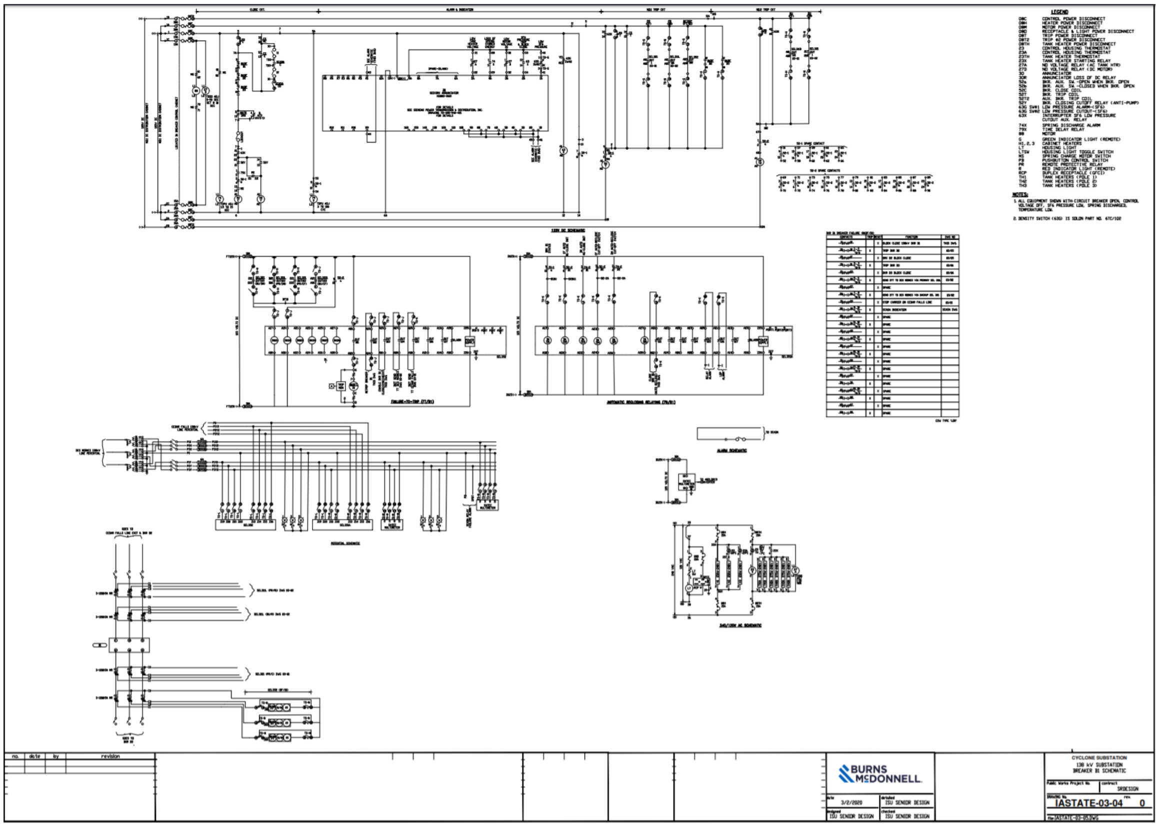

Figure 5-8: Final Breaker B1 Relaying

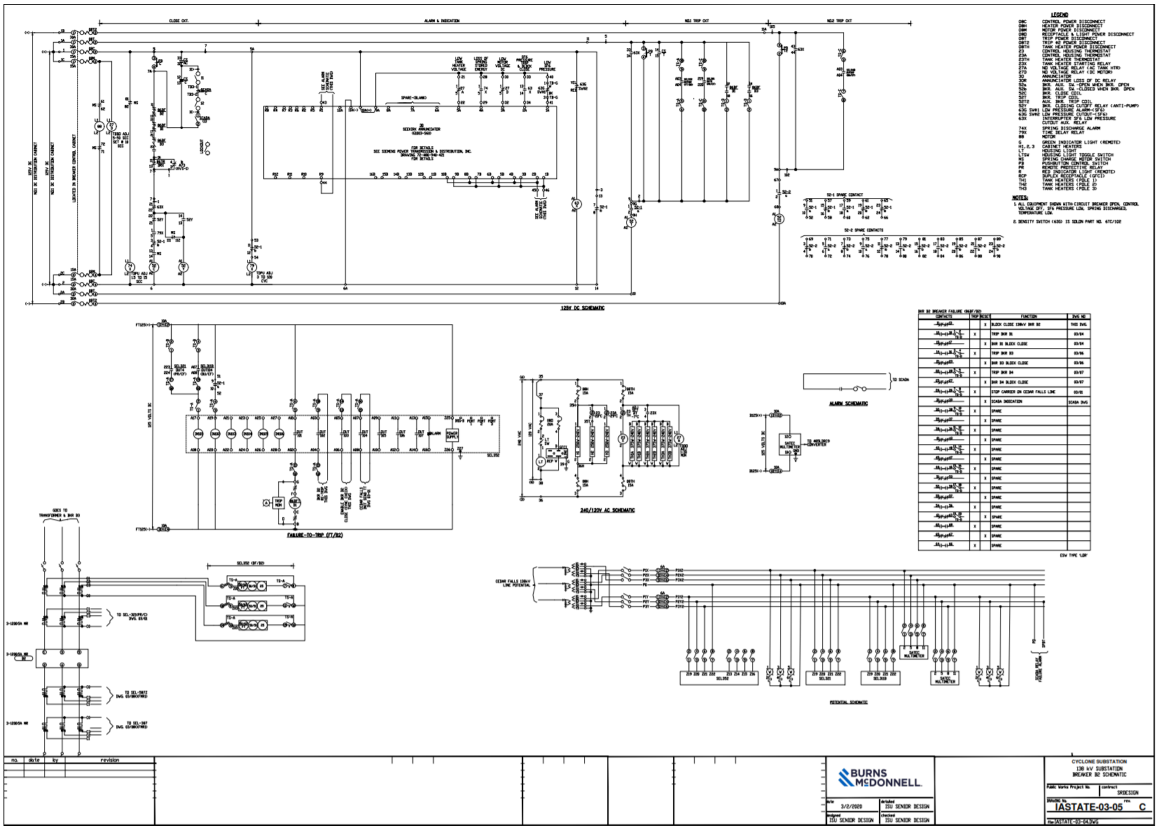

Figure 5-9: Final Breaker B2 Relaying

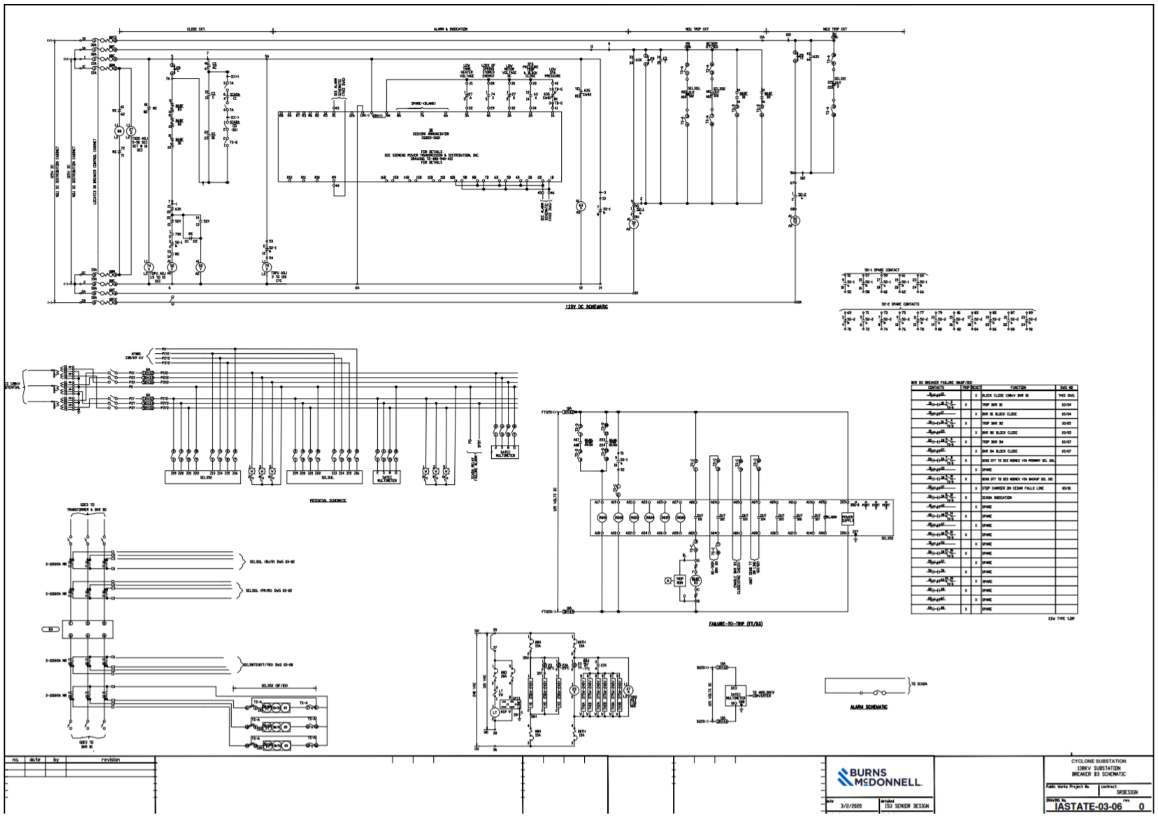

Figure 5-10: Final Breaker B3 Relaying

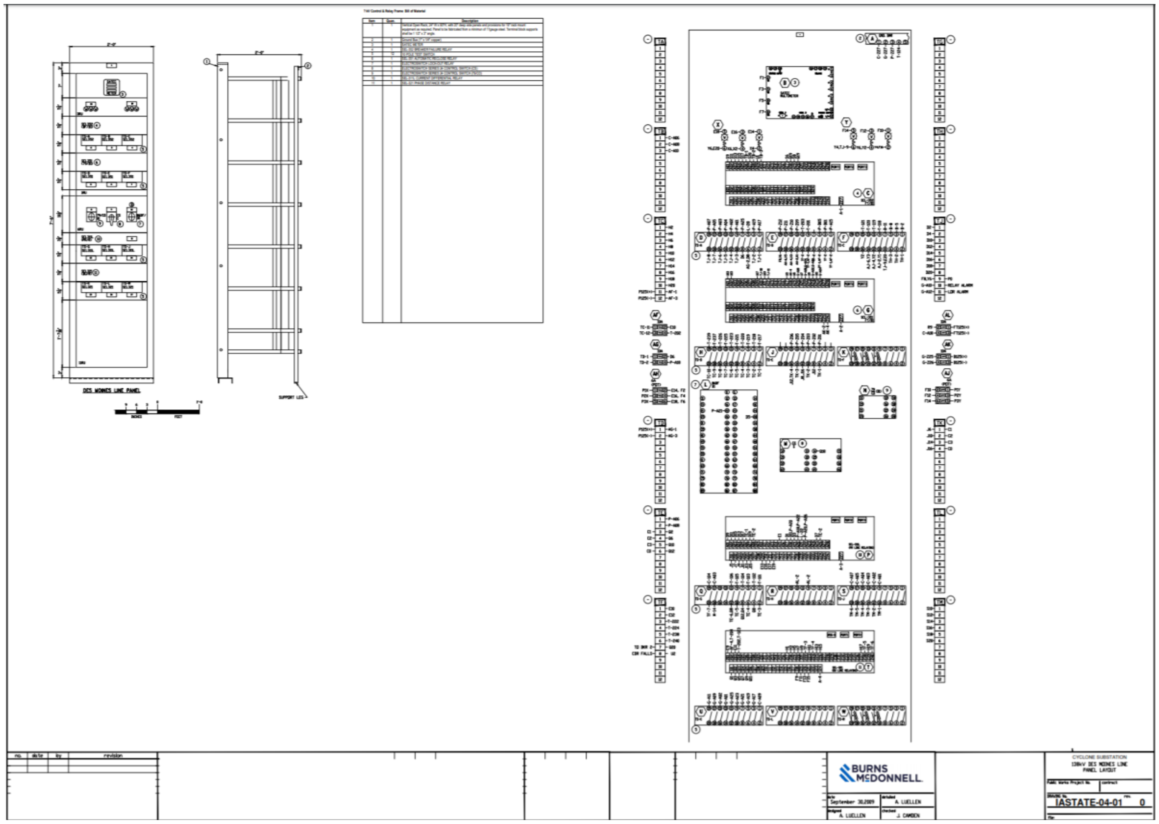

Figure 5-11: Final Panel Wiring

6. Closing Material

6.1 Conclusion

Our team began this project with a goal to create a new substation design which would be used as an interconnection for a wind generation plant near Ames, IA. With the conclusion of this semester, we have successfully accomplished our goal all while providing efficient, reliable, and accurate work to our client. We can proudly say we remained an effective and consistent team, even given the obstacles of computer labs shutting down on campus which limited our ability to gather together in accomplishing each milestone.

We have provided each deliverable described in the sections above, and through vigorous processes of revision and correction, our final product is a perfected and comprehensive substation design ready to begin construction.

6.2 References

[1] Burns & McDonnell (1999) Design guide for rural substations Kansas City, Missouri, Burns & McDonnell.

[2] Ieeexplore.ieee.org. (2019). 998-2012 - IEEE Guide for Direct Lightning Stroke Shielding of Substations - IEEE Standard. [online] Available at: https://standards.ieee.org/standard/998-2012.html# [Accessed 03 Dec. 2019].

[3] Ieeexplore.ieee.org. (2019). 485-1997 - IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications - IEEE Standard. [online] Available at: standards.ieee.org/standard/485-1997.html. [Accessed 23 April. 2020]

6.3 Appendices

Constant Current

Discharge Rates in Amperes** to 1.75Vpc at 25°C (77°F)*

PowerSafe® EC-M cell TYPE*	NOM Ah CAP.*	Minutes 1	15	30	Hours 1	1.5	2	3	4	5	8	12	24	72
EC-5M	215	253	180	140	100	80	67	52	43	37	27	20	12	6
EC-7M	290	364	266	204	144	113	95	72	59	51	36	27	16	7
EC-9M	365	475	351	269	188	147	122	93	76	65	46	33	20	8
EC-11M	470	594	443	340	239	187	155	118	96	82	58	42	25	11
EC-13M	525	694	511	392	274	214	177	134	109	93	65	47	28	11
EC-15M	620	812	596	455	318	249	207	157	128	110	78	56	33	14
EC-17M	670	925	690	525	384	283	233	176	142	120	84	60	34	14
EC-19M	796	981	741	573	406	318	265	202	165	141	100	72	43	18
EC-21M	850	1068	802	625	443	349	290	220	179	152	106	75	45	18

Discharge Rates in Amperes** to 1.81Vpc at 25°C (77°F)*

PowerSafe® EC-M cell TYPE*	Minutes 1	15	30	Hours 1	1.5	2	3	4	5	8	12	24	72
EC-5M	183	150	120	90	73	62	49	41	36	26	20	12	6
EC-7M	264	219	175	128	103	87	68	56	48	35	26	16	7
EC-9M	344	289	229	166	133	112	86	71	61	44	32	19	8
EC-11M	425	364	290	211	169	143	110	91	78	56	41	25	10
EC-13M	497	421	334	242	193	162	125	103	88	62	46	27	11
EC-15M	589	403	380	282	226	190	147	121	104	74	55	33	14
EC-17M	659	567	448	322	256	214	163	134	114	80	58	34	14
EC-19M	707	607	487	357	287	242	188	155	133	95	70	42	18
EC-21M	774	664	534	395	317	267	206	160	145	103	75	44	18

A-1: ENERSYS EC-M BATTERY DISCHARGE CURRENT