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

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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 has 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 will 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 will contain both primary and backup line protection relaying for the Des Moines, Cedar Falls, and Iowa City line exits. The line exits will be protected using the electrical relay components provided by Burns & McDonnell. Along with line protection, transformer protection relays will also be accounted for. Differential relaying will be used to protect both the primary and secondary sides of the 138/69kV transformer. Fiber optic cable will be 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 will be included so as to prevent both humans and wildlife from entering and causing damage to machinery. The final design will also include 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 will be 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, will be designed using AutoCAD. The drawing will include 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 will also show future equipment and how it will be connected, while signifying that it is not part of our current scope. Additionally, this diagram will show all interconnections in the substation yard as well as the incoming and outgoing lines. It will not show the specifics of the wiring, i.e. port to port contacts, rather it will show which devices and equipment are wired together and where the busses will be located.

Physical Plan & Sections - Due 11/22/2019

The physical plan shows precisely where all equipment is laid out in the substation yard. It will also show 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 3-d 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 will be 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 will contain 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 will be provided to Burns & McDonnell. The study will be predicated on the AC and DC loads in the substation yard and enclosure and will require 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 will be accounted for. In addition to this, panel layouts and schematics for the panel vendor's use will be provided. The wiring diagrams will show all interconnections between relays and enclosure equipment.

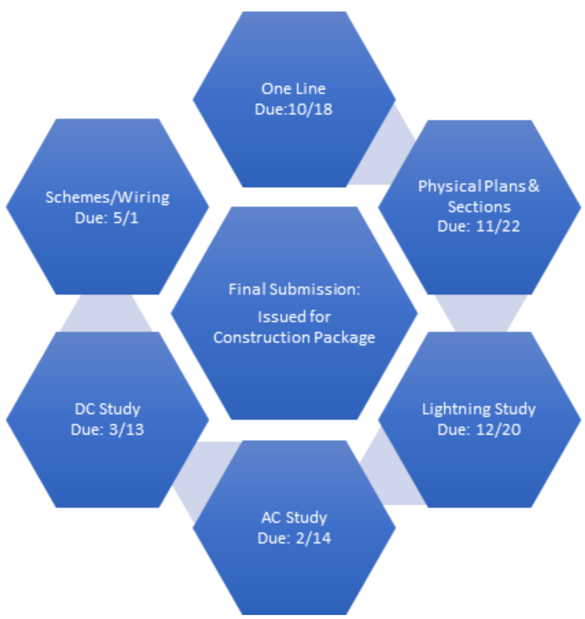

Figure 1-1: Final Construction Package and Constituent Parts

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 conductor 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 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.

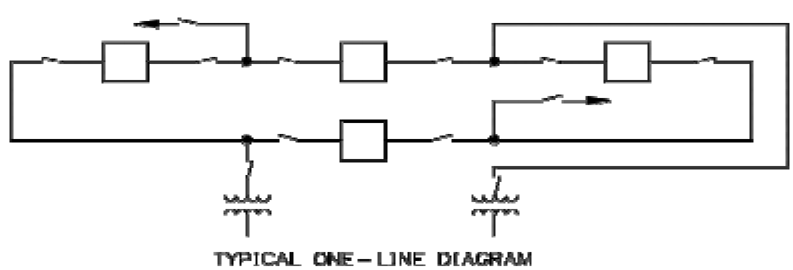

Figure 2-1: Ring Bus Layout

[1]

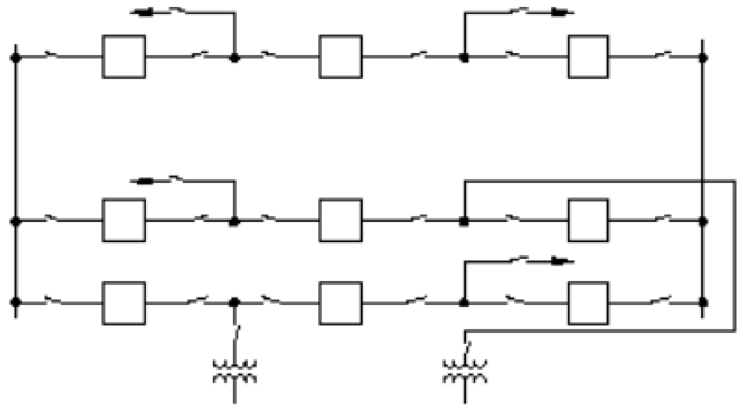

Figure 2-2: Break and a Half Layout

[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. Any changes made to the initial revision will be covered in Section 2.2.1.

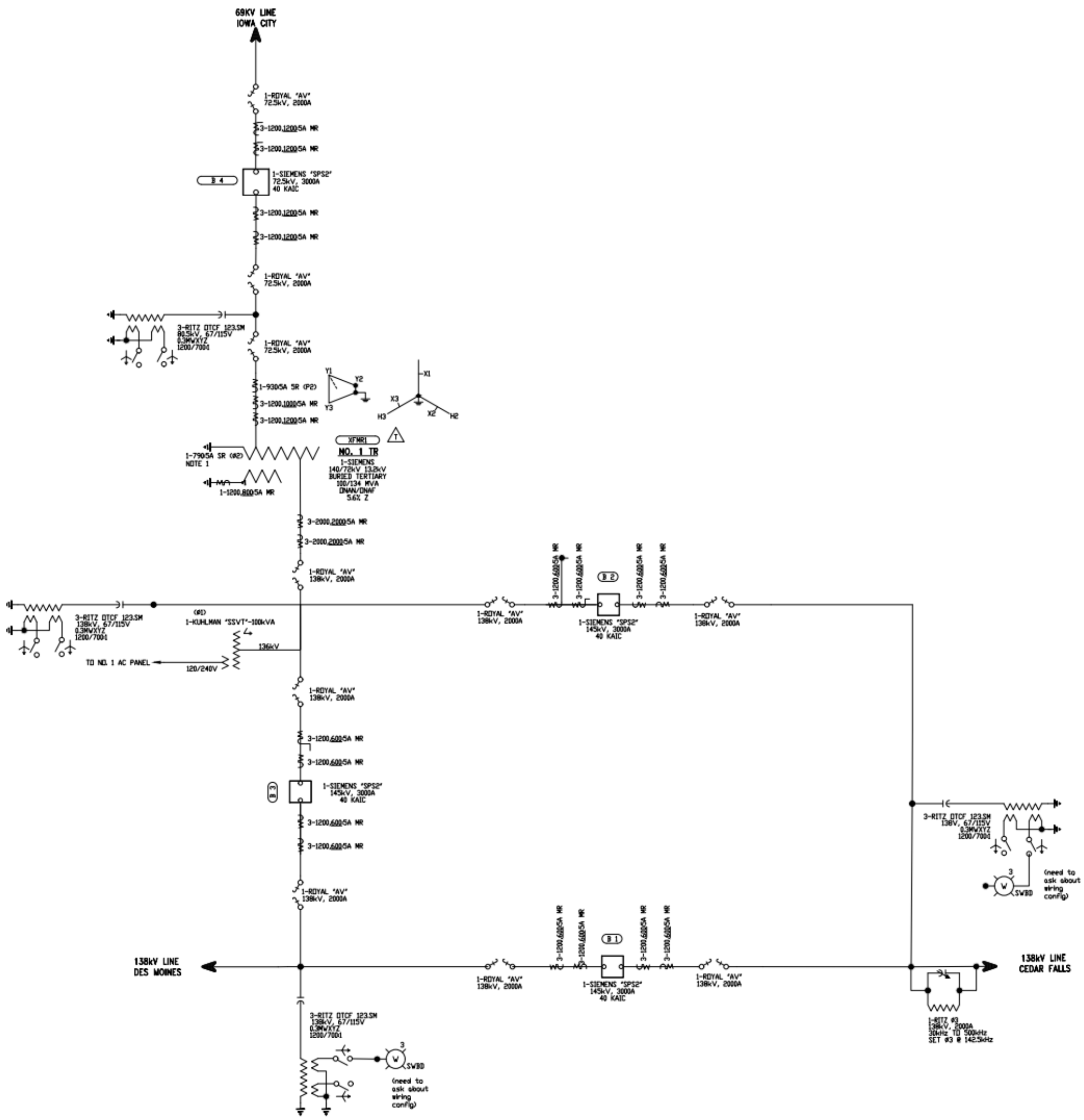

Figure 2-3: Initial One-Line Design

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

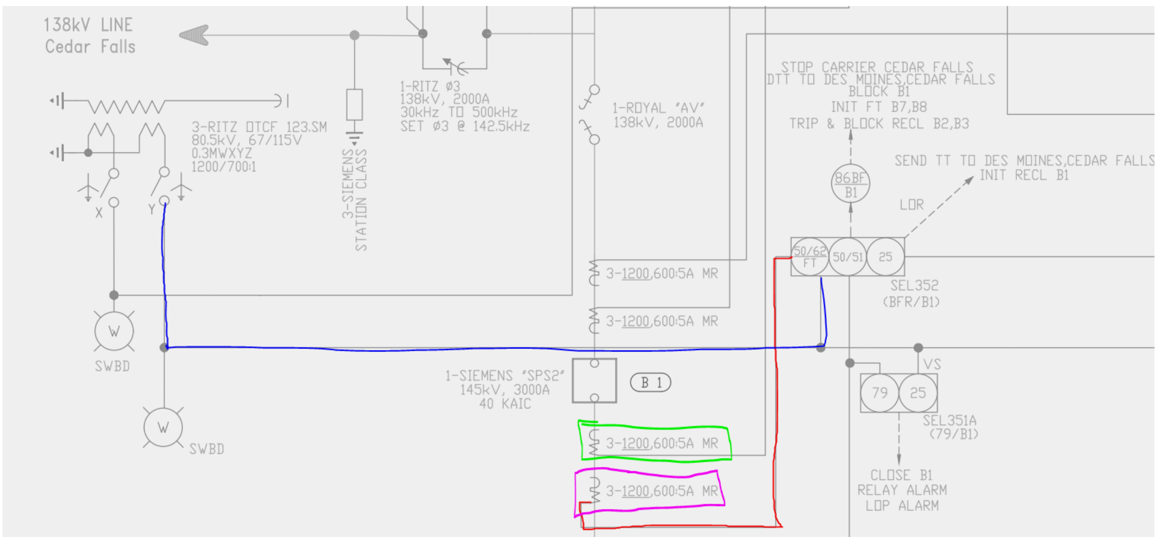

Figure 2-5: Color Coated Wiring Example for Relay Definitions

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.

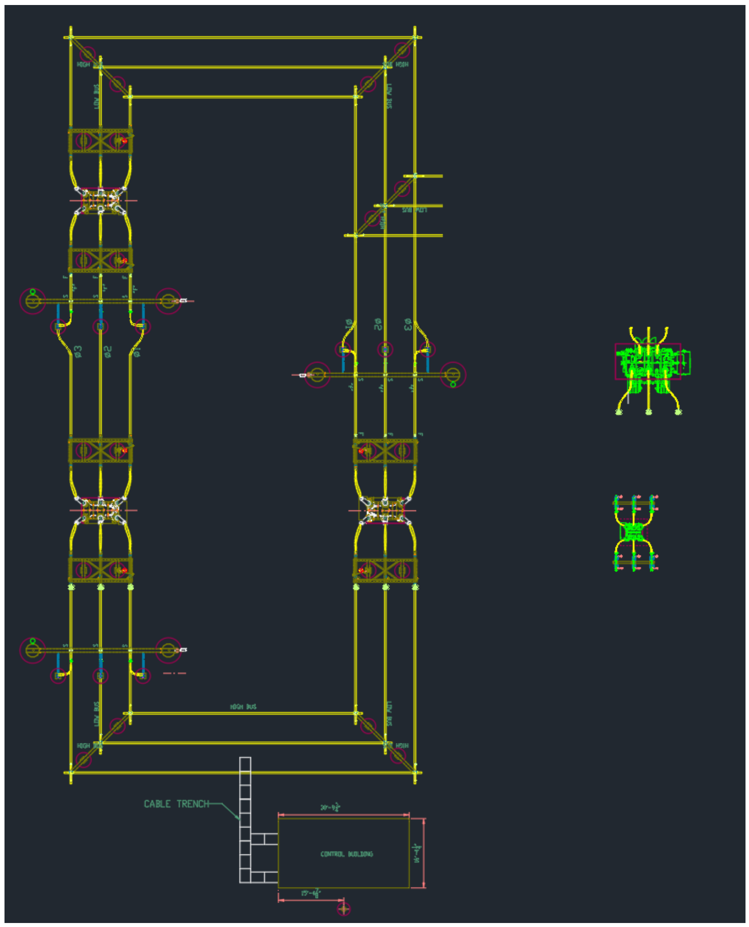

Figure 2-6: AutoCAD Version of Plan View sans Dimensions

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.

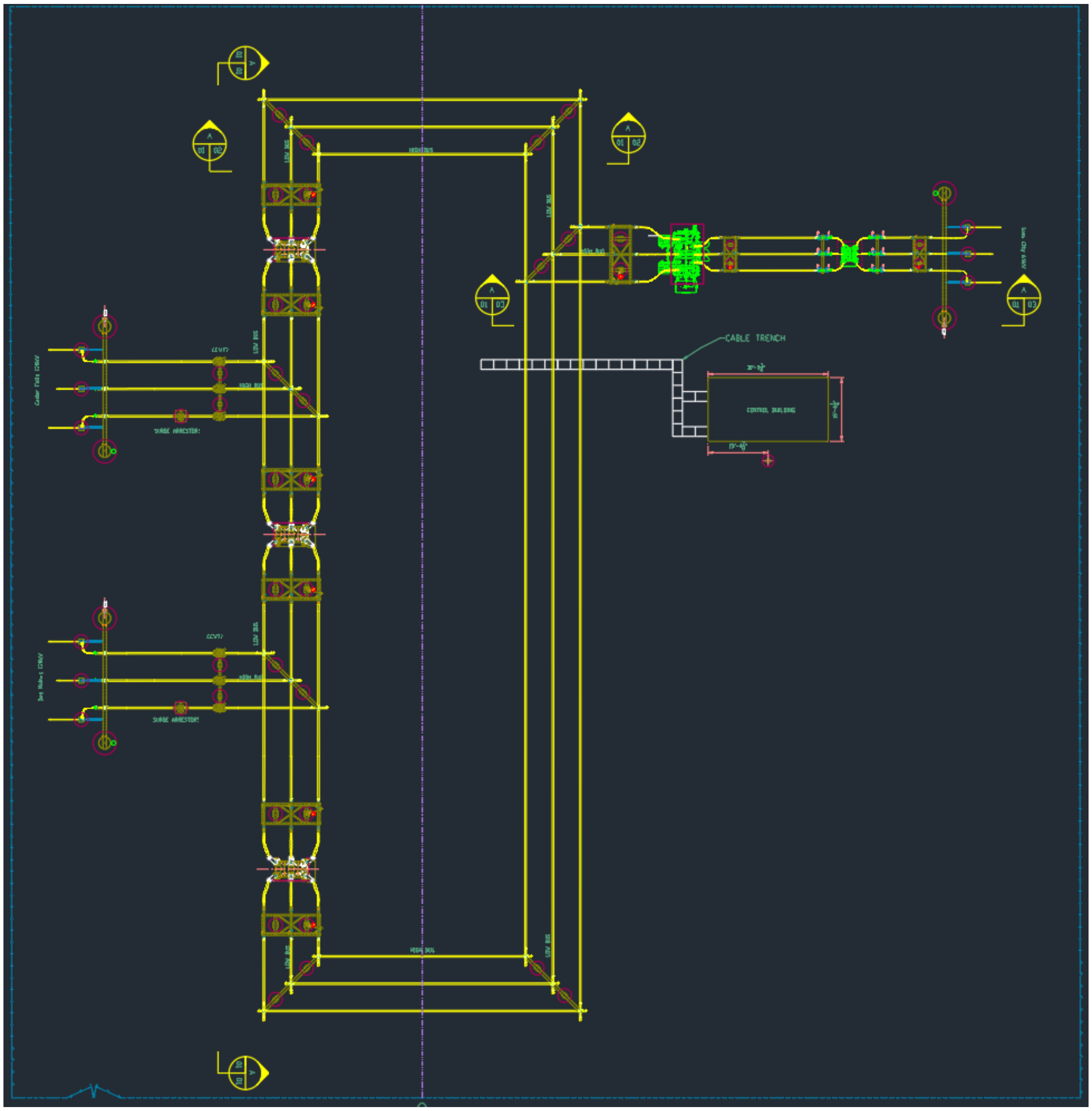

Figure 2-7: Revised Plan View AutoCAD Drawing

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.

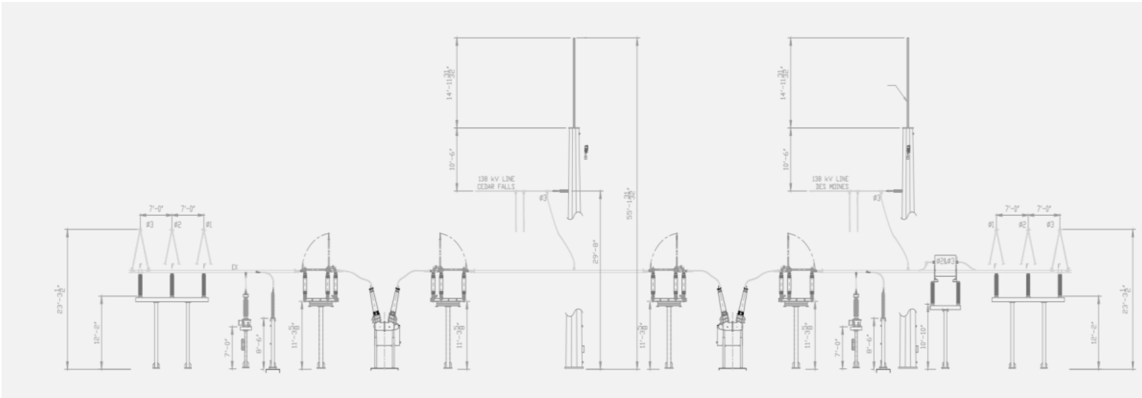

Figure 2-8: Section Cut Dwg# IASTATE-01-02 REV. 0

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.

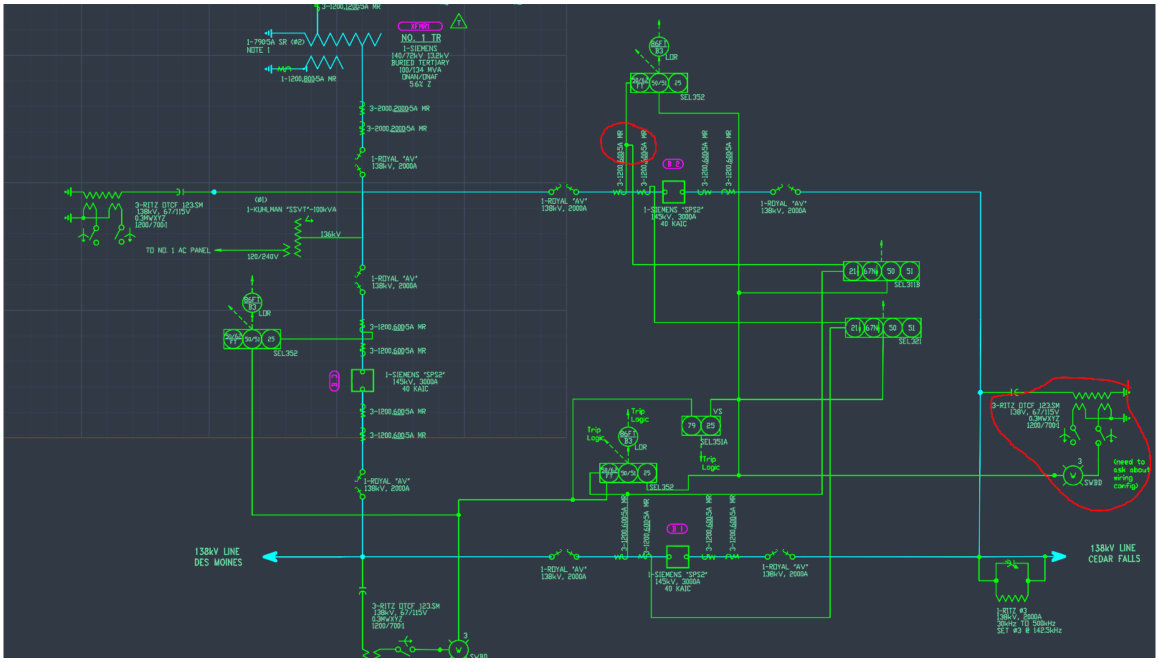

Figure 2-9: One-Line Revision 2

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.

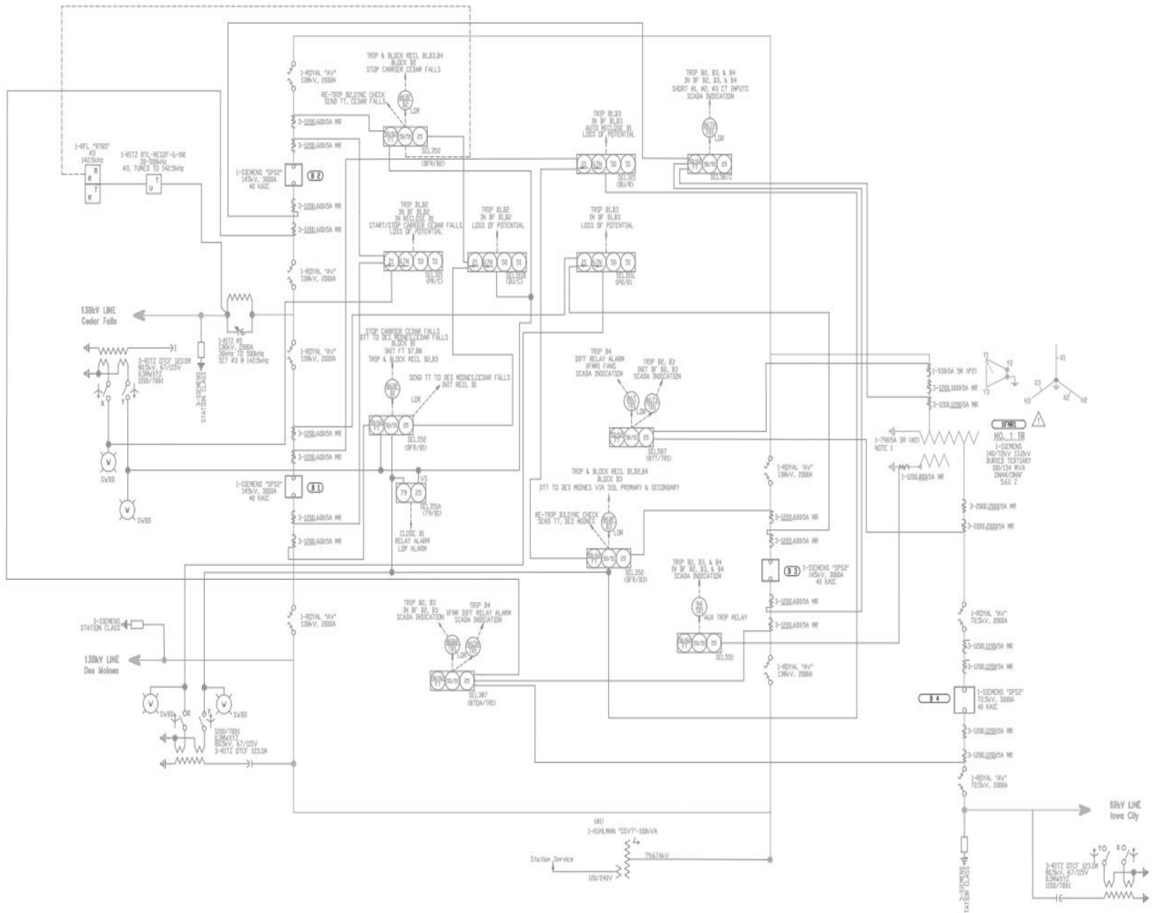

Figure 2-10: One-Line Revision 3

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.

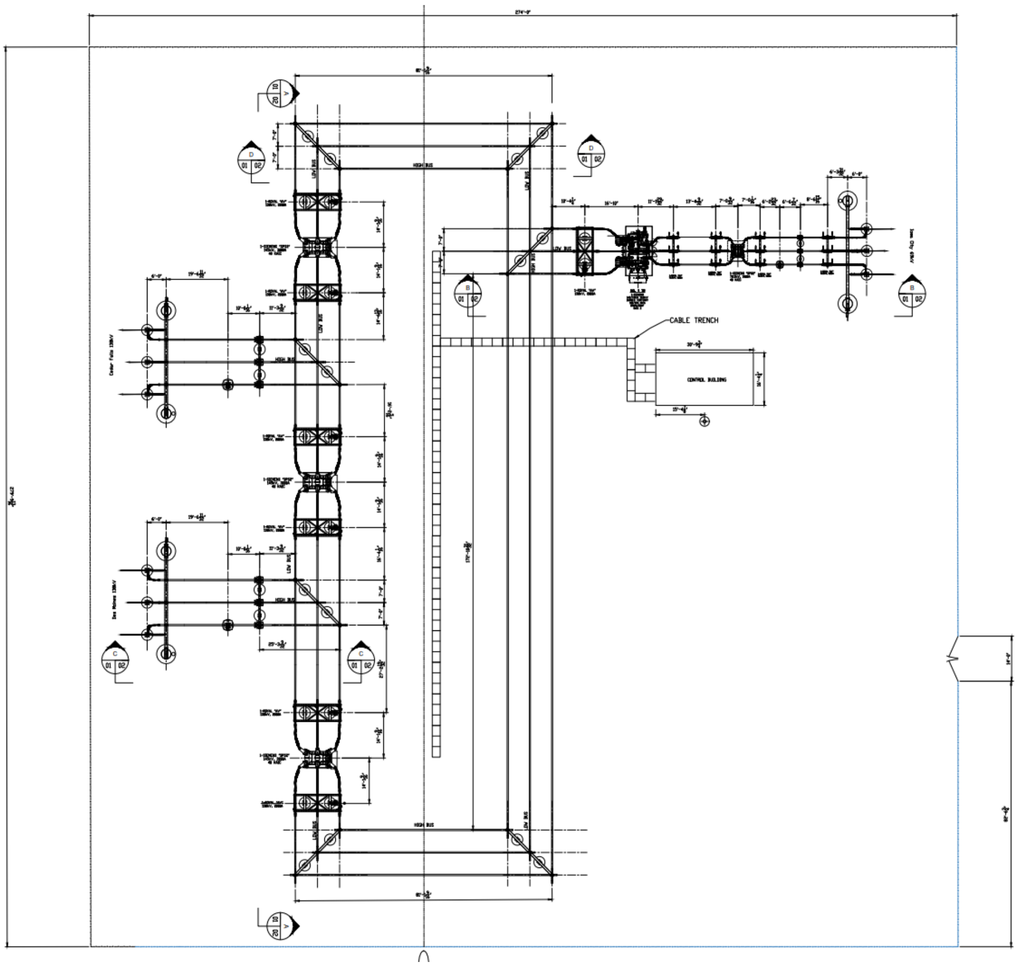

Figure 2-11: Plan View Revision 2

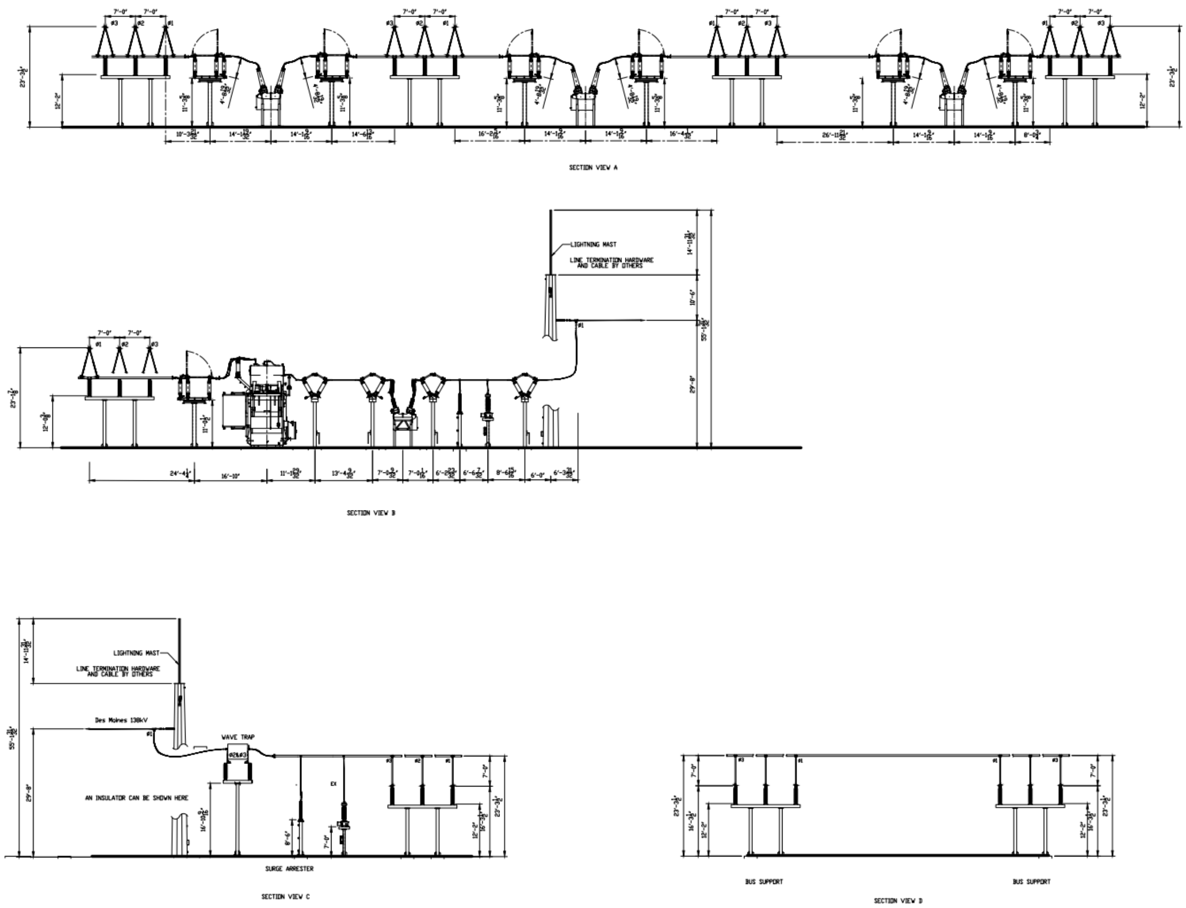

Figure 2-12: Section Cuts Revision 1

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.

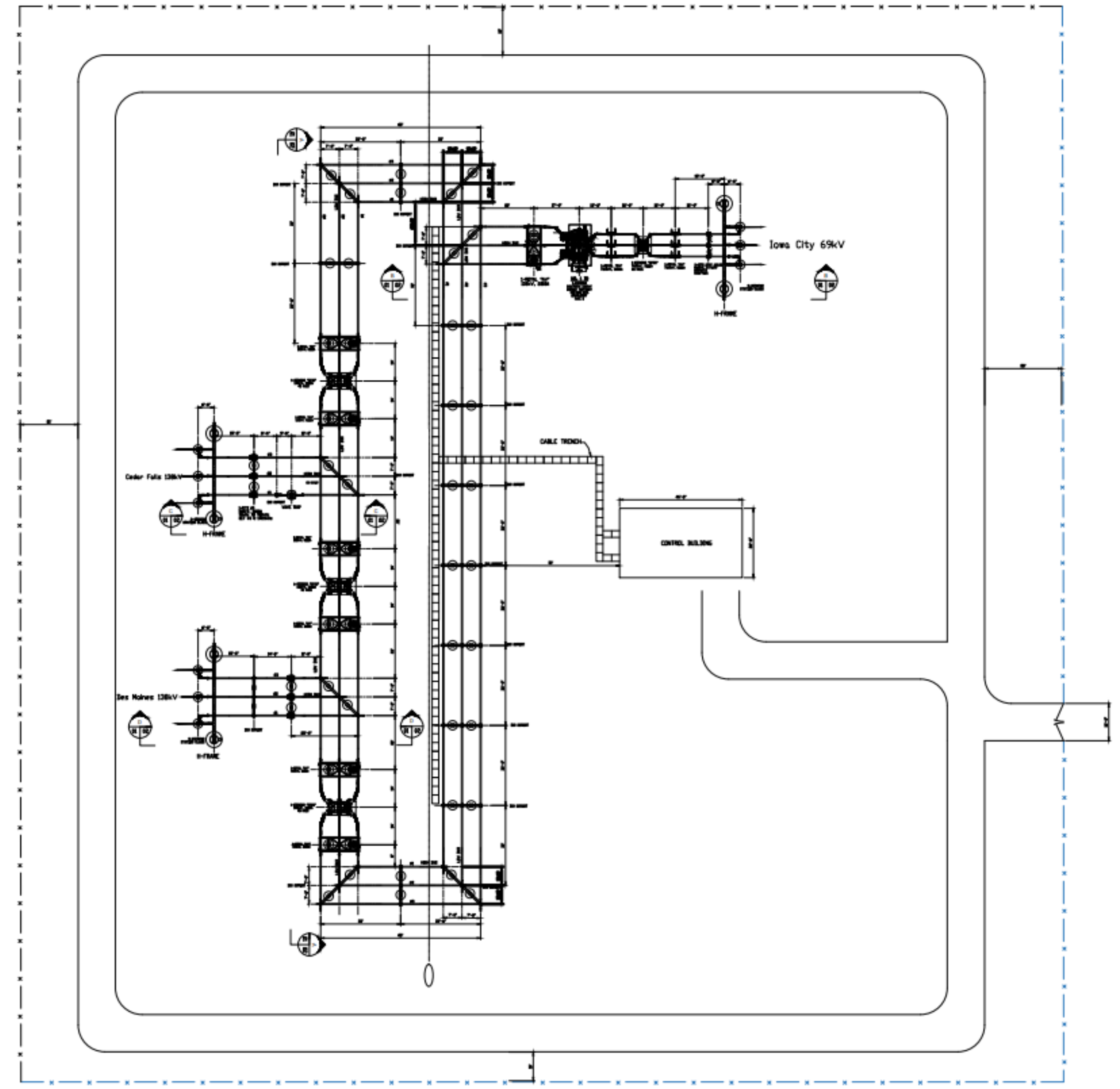

Figure 2-13: Final Plan View Revision

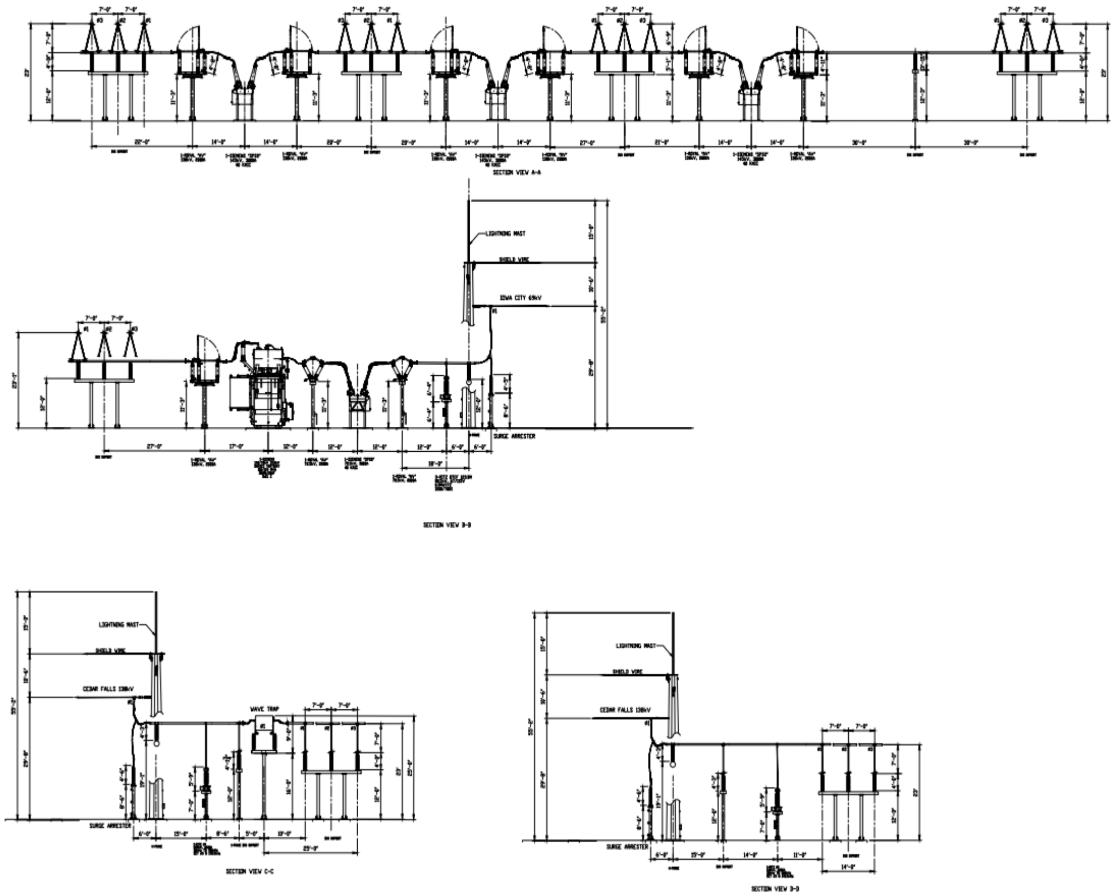

Figure 2-14: Final Section Cut Revision

The above revisions, Figures 2-13 and 2-14, are the last to be submitted until the completion of the lightning study. Once that study has concluded, additional changes to the drawings will be tracked in Section 2.3.1.

2.3.1 Lightning Protection Study

The purpose of the lightning study is to perform calculations based on IEEE standard 998-2012 [2]. This standard and the results of the study are still being performed at the submission point of this paper.

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

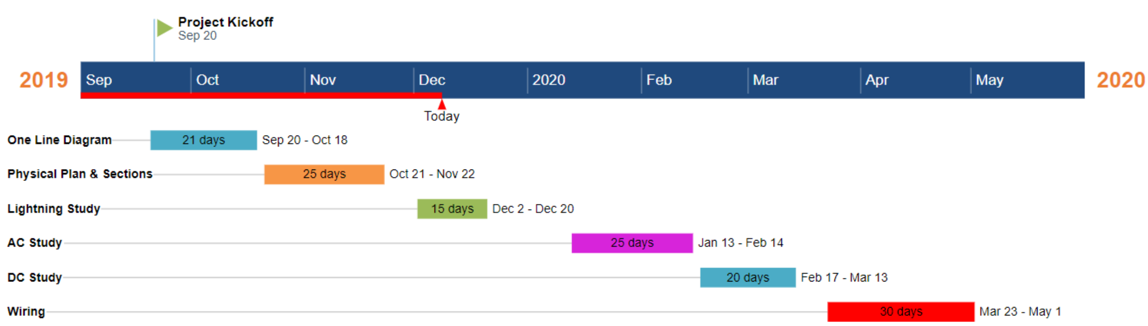

Figure 3-1: Task progression for Substation Design

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 will 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 are on track to meet each deadline, and to deliver 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 will be included in our team website. This will detail our individual contributions and progress, though the overall progress and major developments will be included in the Google Drive folder.

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 desired 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 will be evaluated by a final presentation to Burns and McDonnel, and the final review. A success in this project is a substation plan that Burns and McDonnell deems fit for construction.

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 will ultimately finalize the design of our substation.

The one-line diagram for the substation has been reviewed, approved, and finalized on schedule. The plan view and four section cuts have also been completed on schedule.

The current task is the lightning study, a figure showing the first revision of the lightning study can be seen in Figure 5-4. After the lightning study has been finalized, we will be starting the next two studies for AC and DC systems in the substation before completing our project with Schemes and Wiring.

4.2 Feasibility Assessment

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

4.3 Personnel Effort Requirements

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

This will include two meetings a week, one which will be spent with just our team aimed to organize plans and peer review individual work and one which will be 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 will be split between individual and group work. All individual work will be 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 will all contribute to every element of the project, we will not be specializing 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

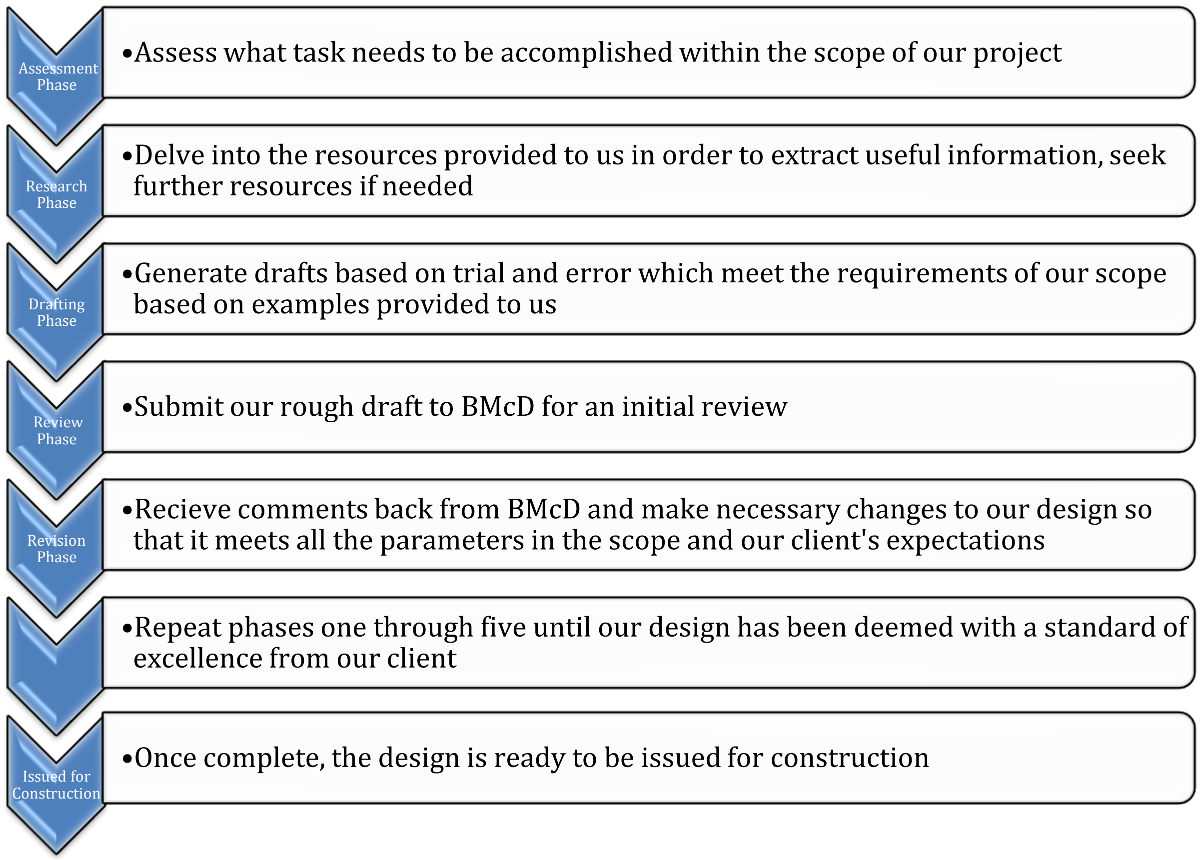

Figure 5-1: Final Design Process Flowchart

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.

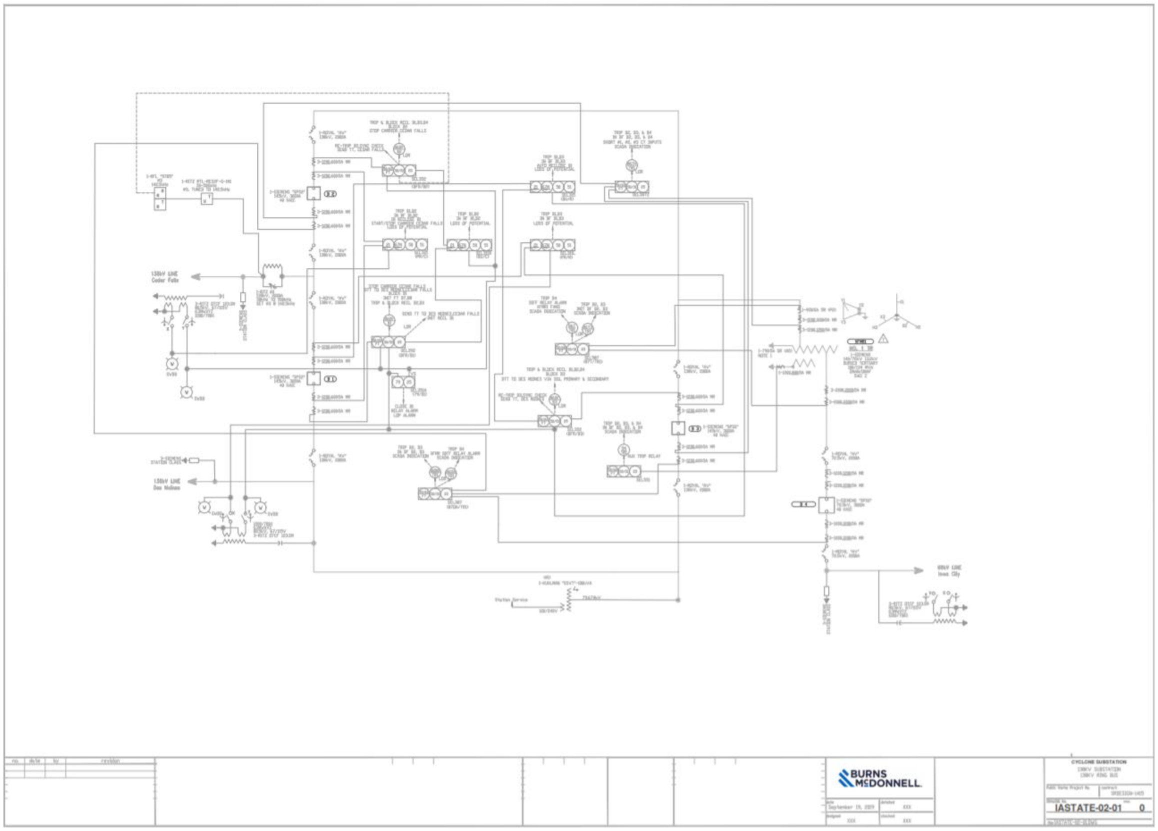

Figure 5-2: Final Submission of One-Line

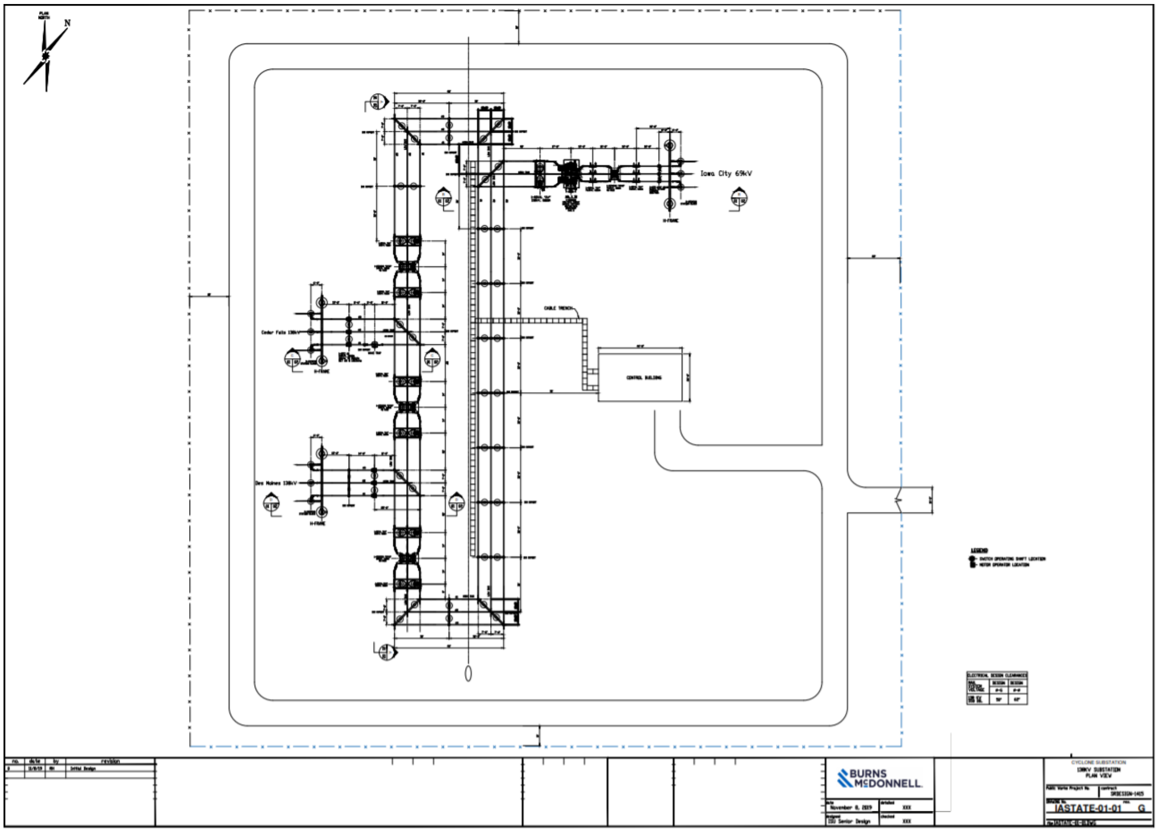

Figure 5-3: Final Submission of Plan View

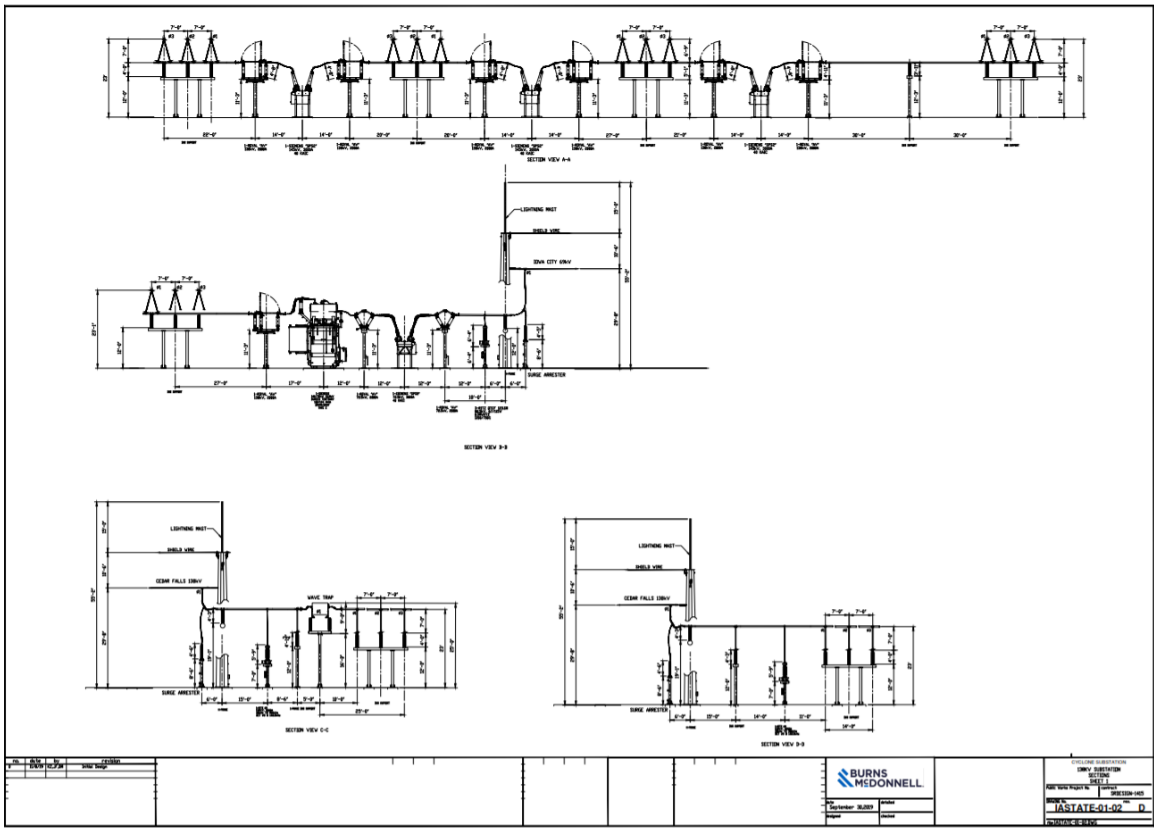

Figure 5-4: Final Submission of Section View

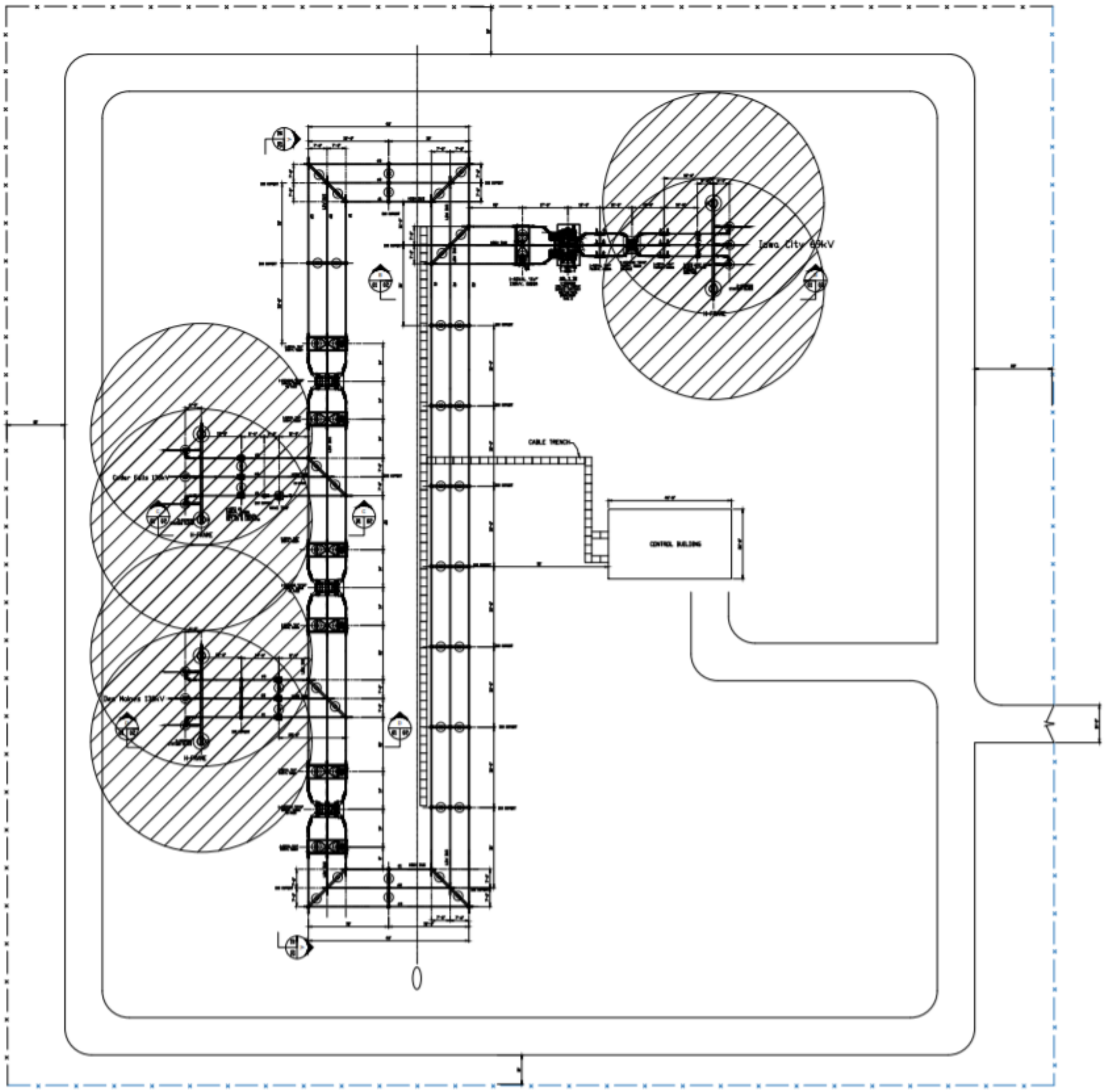

Figure 5-5: Initial Results of Lightning Study

6. Closing Material

6.1 Conclusion

To date, we have completed our final drafts of a one-line diagram, the physical plan view drawings, as well as 4 section-cut drawings; this is in accordance with our expected timeline. From here, we will begin work on a lightning study, AC study, DC study, and schemes/wiring as requested by Burns & McDonnell. Ultimately, it is our goal to create a new substation design which will be used as an interconnection for a wind generation plant near Ames, IA.

We will continue to work within our specified timeline in order to ensure efficient, reliable, and consistent work is done within our group. We will also remain consistent in this plan so as to allow Burns & McDonnell sufficient time to evaluate our work and provide feedback; with this plan, by the end of Spring semester 2020, we will have our substation design perfected.

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].

6.3 Appendices

There is no additional information to be included at the moment.