Substation Design

Design Document

Team Number
SDMAY19-17

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Burns & McDonnell

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IEEE: Institute of Electrical and Electronics Engineers
AC: Alternating Current
DC: Direct Current
SCADA: Supervisory Control and Data Acquisition
RTU: Remote Terminal Unit
NIA: Networks, Integration, and Automation

1 Introduction

1.1 Acknowledgement

The Substation Design team would like to thank Grant Herrman, Abeer Hamzah, Thanh Nguyen, Zach Porter, and Brian Obermeier, employees of Burns & McDonnell, for their willingness to oversee this project and for serving the team as technical advisors. The Substation Design team would also like to Craig Rupp, the faculty advisor for this project, for serving the team as a technical and professional advisor.

1.2 Problem and Project Statement

While electric power transmitted a long distance has a high voltage which reduces power losses as electricity flows from one location to another, it is unsafe to distribute electricity at such a voltage directly to consumers. Similarly, though the production capabilities of electric power generators vary, electric power generators are incapable of generating electric power at voltages necessary to transmit that electric power long distances.

General Purpose
For this reason, substations are necessary throughout power grids. The primary function of a substation is to raise or lower the voltage of the electric power flowing into the substation. The main piece of equipment located at a substation is a power transformer. The transformer is an electromagnetic apparatus capable of raising or lowering an input voltage. The power supply voltage is scaled and then transmitted long distances or distributed to power consumers.

Substations also help to ensure the reliability of the power grid. Two other pieces of equipment located at substations are circuit breakers and disconnect switches. This protective equipment allows utilities to isolate electrical equipment from the rest of the power circuit/power grid in the event of a fault.

General Problem Statement
Burns & McDonnell has tasked the Substation Design team with designing a new, 138/69 kilovolt (kV) substation that will not be built, but that could theoretically “be used as an interconnection for a new wind generation plant near Ames, IA.”

General Solution Approach
The Substation Design team will need to do the following to complete this project:

1. Specifications:

    Relay Panels – The Iowa State Senior Design team will create all relay panels including protective relays.

2. Substation Layout:

    The Iowa State Senior Design team will submit a substation layout—including substation equipment, the control building, rigid bus, structures, and perimeter fence—based on the most economical option, which allows for future expansion with maximum flexibility.

3. Bus and Insulator Sizing Design

    The Iowa State Senior Design team will perform calculations using predicted fault levels and weather criteria to establish the mechanical forces resulting at each of the substation buses.

4. Ground grid

    The Iowa State Senior Design team will utilize software provided by Burns & McDonnell to design and analyze the grounding system. The grounding design will be consistent with IEEE 80 techniques, using a combination of ground mat and rods for arriving at acceptable step and touch potential limits and resistance to remote earth.

5. Raceway

    The Iowa State Senior Design team will design a conduit plan using a combination of surface trenches, subsurface conduits, and equipment riser conduits.

6. Control Building

    The Iowa State Senior Design team will prepare control building equipment layout drawings for the substation. The control building will be sized to accommodate the 125V DC battery and charger, AC & DC panels, SCADA RTU and all protective relay panels required for the initial installation.

7. 125V DC Station Battery Design

    The Iowa State Senior Design team will develop a battery design for the substation using IEEE 485 techniques. Loads will be sized, including future loads, for the sizing of batteries, chargers, and panels used in the 125V DC system. The time period for a station service outage will be considered when arriving at the required battery size.

    The Iowa State Senior Design team will submit a report which:

    i. Clearly summarizes the design requirements
    ii. Defines the calculations used
    iii. Summarizes the results and recommended battery design

8. Relaying and Controls

The Iowa State Senior Design team will generate a one-line diagram, one 69kV circuit breaker schematic, one 138kV circuit breaker schematic, one-line relay schematic, and the transformer schematics.

9. Lightning Protection

The Iowa State Senior Design team will evaluate and design lightning protection for complete station protection against direct lightning strikes in accordance with IEEE STD 998-2012 Electro Geometric Model (EGM) using the empirical curves method.

The Iowa State Senior Design team will submit a report which:

i. Defines the calculations used in developing the layout of the lightning Protection
ii. Clearly summarizes the orientation and protection results for each grouping(s) of shielding electrodes
iii. Summarizes the failure rate of the substation
iv. Provides a recommended configuration of the shielding electrodes which includes the maximum effective heights of the lightning masts and shield wires.

10. Communications

The Iowa State Senior Design team will do the following:

i. Create a communications block diagram and design the substation communications network using a combination of serial and ethernet network equipment.
ii. Design microwave radio system for communications transport. This will include frequency selection, tower sizing and placement.
iii. Provide equipment quotes and engineering cost estimate.
iv. Generate a SCADA points list from a provided template.
v. Configure the RTU and protective relays, as specified by the points list and comm block diagram, to provide SCADA information to a remote master station.
vi. Program a local HMI in the RTU to show an animated one line with real-time values and an alarm annunciator.
vii. Program a remote EMS master using Kepware on Windows

1.3 Operational Environment

When engineers are designing a new substation that will be built, they must design it so that, once built, it will remain functional when exposed to regional extreme temperatures and regional extreme weather. Though the substation designed by the Substation Design team will not be built, Burns & McDonnell still expects the Substation Design team to design a substation that would remain functional if exposed to regional extreme temperatures and regional extreme weather.

1.4 Intended Users and Uses

If the substation designed by the Substation Design team were to be built, the intended use of the substation would be to raise the voltage of the electric power generated by wind turbines so that that electric power could be injected into the power grid and distributed to electricity consumers.

The intended user of the substation would be whichever utility owned it, as that utility would use the substation to distribute more electric power to its customers. Electricity consumers would benefit from the operation of the substation, though they would not technically be using it.

1.5 Assumptions and Limitations

Assumptions:

- A new substation in or near Ames, IA is needed
- A 138/69 kV power transformer should be located at the new substation
- The new substation should have a ring bus configuration

Limitations:

- The new substation would be built in or near Ames, IA
- The new substation must be designed such that it complies with relevant client and industry standards
- The only major pieces of equipment to be located at the new substation are three 138 kV circuit breakers, one 138/69 kV transformer, and one 69 kV circuit breaker
- The new substation should have a ring bus configuration

1.6 Expected End Product and Deliverables

The majority of the deliverables for this project will be in the form of documents and drawings given as a final package to the client. Along with the documents and drawings, our team will also be providing studies that are the basis for our design package decisions. In addition, our team will be providing a 3D model of the completed substation, with the major equipment being displayed in an easy to view manner.

The first deliverable to the client is the grounding and lightning studies. This deliverable shall be turned over to the client by November 2nd, 2018. The grounding study utilizes software provided by the client to assist in the design and analysis of the grounding grid. The grounding design will be reliant on this study and with this study, we will be able to appropriately design a ground grid that is consistent with IEEE 80 standards and ensures the step and step potential limits and resistance to remote earth are all within acceptable parameters. The lightning study is an important piece for designing a substation's lightning protection in accordance with IEEE Standard 998-2012. The lightning study will define our calculations used in developing the layout of the lightning protection, clearly summarize the orientation and protection results for each grouping of shielding electrodes, summarize the failure rate of the substation, and provide a recommended configuration of the shielding electrodes which includes the maximum effective heights of the lightning masts and shield wires.

Our second deliverable to the client is the physical design of the substation, which shall be turned over by November 30th, 2018. The physical design of the substation will include drawings which show the layout of the whole substation. The physical design will be shown on a plan view drawing which will include the locations of the following: the substation equipment, control building, rigid bus, structures, and the perimeter fence. This deliverable will also include section cuts from the overall plan view, which will show the elevation view of the substation and also include the Bill of Material call-outs for major equipment shown in the drawing. This deliverable will be designed based on the most economical option, which allows for future expansion and with the client preferences in mind. The grounding and lightning studies will also be taken into account and the physical design will be shaped by their specifications.

Our third deliverable is the AC/DC studies, which shall be turned over to the client by March 1st, 2019. The AC/DC study will specify the battery sizing that will be needed to power the station during a station service outage. The study will take into account all of the equipment on the site and will need to follow the standards laid out in IEEE 485. Our study report will need to include a summary of the design requirements, definitions of the calculations used, and a summary of the results and our recommendation for the battery design.

Our fourth and final deliverable is the Controls and the Networks, Integration, and Automation (NIA) design package, which shall be turned over to the client on April 12th, 2019. These packages will include the final design of the substation's controls and communications equipment. The controls package will include several drawings which represent the complete controls for the substation. These drawings will include a one-line diagram, a 69kV circuit breaker schematic, a 138kV circuit breaker schematic, a line relay schematic, and the transformer schematics. Along with these drawings, the package will include the relay panel layouts for an outside panel vendor to manufacture. The NIA design package will include a layout for the communications system used at the substation. The package will include: a communications block diagram and the design of the substation communications equipment using combinations of serial and Ethernet network equipment, the design of the transport via fiber to a neighboring substation, quotes for the equipment, an engineering cost estimate, and a simulation of the network topology using CISCO Packet Tracer.

2. Specifications and Analysis

2.1 Proposed Design

2.1.1 Grounding Design

The first task our team completed was the grounding study and design of the site's grounding grid. Several factors were considered during this process. The sections we completed are as follows:

- Soil Resistivity measurements
- Area of the ground grid
- Ground fault currents
- Ground conductor
- Safety considerations
- Tolerable touch and step voltages
- Design of substation ground system

Soil Resistivity Measurements

Before designing a grounding grid, soil resistivity of a site must be measured. There are various types of methods that can be used when testing soil resistivity. A Wenner 4-Point Method was used to determine the resistivity of the soil for this grounding study. The Wenner 4-Point Method involves placing 4 equally-spaced and in-line electrodes into the ground as shown in Figure 1 below. The two outer electrodes inject current into the soil and the two inner electrodes measure voltage which is used to measure the soil resistance. The resistivity can then be calculated based on the soil resistance, the electrode spacing, and the depth of the electrodes based on Equation 1 below. These parameters were supplied to us by Burns & McDonnell and can be found in Table 1 below.

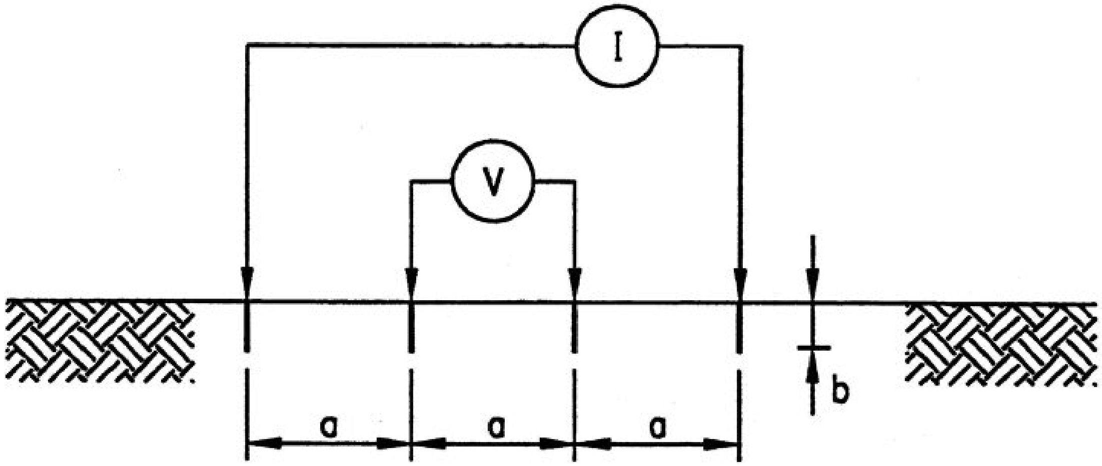

Figure 1: Probe locations for Wenner 4-Point Method

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

where

ρ_a	is the apparent resistivity of the soil in Ω-m
R	is the measured resistance in Ω
a	is the distance between adjacent electrodes in m
b	is the depth of the electrodes in m

Equation 1: Calculating Resistance using Wenner 4-Point Method

Probe Spacing	Resistivity (ohms-m)
(feet)	1 Data Set
1	124.9
1.5	93.5
2	76.6
3	47
5	31.7
7.5	25.3
10	25.9
15	27.7
20	32.9
30	39
45	41.9
60	45.8

Table 1: List of resistivity values for Cyclone Substation

The various resistivity values were then input into RESAP, a tool in CDEGS, to determine a model for the soil where the substation will be located. This soil model was three layers deep, having resistivities and thicknesses outlined in Figure 2 and Figure 3 below. Figure 2 shows the model while Figure 3 shows the output report of the model build. The soil composition, temperature, and moisture content are all important characteristics that need to be noted during testing. It was assumed that extreme conditions were considered when the Wenner 4-Point Method was conducted and the resistivity values reflect those extreme conditions.

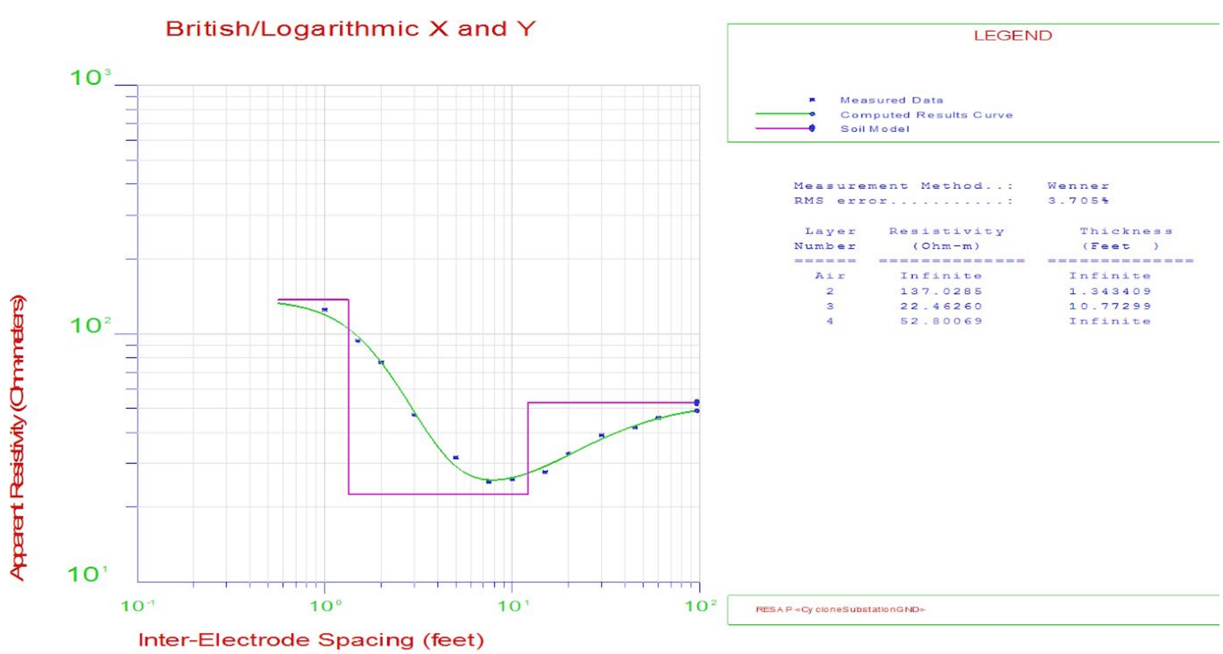

Figure 2: RESAP Model for Cyclone Substation

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Report #1:

=========< R E S I S T I V I T Y  ( SYSTEM INFORMATION SUMMARY ) >=========

Run ID.....................................: CycloneSubstationGND
System of Units ...........................: British
Soil Type Selected.........................: Multi-Layer Horizontal
RMS error between measured and calculated...:   3.70454    in percent
resistivities (Note RMS=SQRT(average(Di**2)).


        <--- LAYER CHARACTERISTICS -->  Reflection    Resistivity
 Layer   Resistivity       Thickness     Coefficient    Contrast
Number     (ohm-m)         ( Feet )        (p.u.)         Ratio
======  ==============  ==============  ============  ============
   1      Infinite        Infinite         0.0           1.0
   2      137.0285        1.343409       -1.0000       0.13703E-17
   3      22.46260        10.77299      -0.71832       0.16393
   4      52.80069        Infinite       0.40309        2.3506


**WARNING** MORE THAN ONE SOIL MODEL CAN PRODUCE SIMILAR APPARENT RESISTIVITY
            MEASUREMENT CURVES. IF YOU USE THE DEFAULT STEEPEST-DESCENT METHOD,
            THEN YOU WILL MOST OFTEN OBTAIN DECENT AGREEMENT BETWEEN MEASURED
            VALUES AND THE COMPUTED CURVE, WITH A REALISTIC SOIL MODEL; HOWEVER,
            THE FIT MAY OCCASIONALLY BE SUB-OPTIMAL. IN SUCH CASES, THE MARQUARDT
            METHOD WILL USUALLY YIELD AN EXCELLENT FIT, BUT MAY SOMETIMES SUGGEST
            EXTREME RESISTIVITY VALUES. NOTE THAT DIFFERENT SOIL MODELS WILL USUALLY
            YIELD SIMILAR RESULTS FOR YOUR GROUNDING SYSTEM MODELS (I.E., GPR, TOUCH &
            STEP VOLTAGES), PROVIDED THAT THE GROUNDING SYSTEM IS LOCATED CLOSE TO
            THE EARTH SURFACE. IF IN DOUBT, CHECK YOUR RESULTS WITH BOTH SOIL MODELS.


End of Report #1
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Figure 3: Layer Characteristics of Soil Model for Cyclone Substation

In Figure 3 above, we can see the different layers of soil and how the resistivity and thickness differs in each. The soil model is created using the data collected during soil resistivity testing in the field. The model is used to determine at what level the soil has the least resistance. This is important because multiple design factors come from this model, including te depth of the grid and length of ground rods. The path in which current travels is that of least resistance to ground which can be seen in Figure 4 below. Ground is referred to as a zero potential point, in a lot of cases, the Earth. We use the soil model to decide which layer of soil we want to direct the fault current to. In this case, we can see that layer 2 has the smallest resistance. In our design then, we placed the ground grid 1.5 feet below the surface and used 10 foot ground rods, placed vertically from the grid, to reach a depth of 11.5 feet, ending within the limits of layer 2. This approach works in the following order: a fault current enters the substation through a tall mast, the fault current takes the path of least resistance to a zero potential-running down the mast, into the ground grid, and through the ground rods. Once the current flows through the ground grid and reaches the soil, it travels through the Earth eventually dissipating.

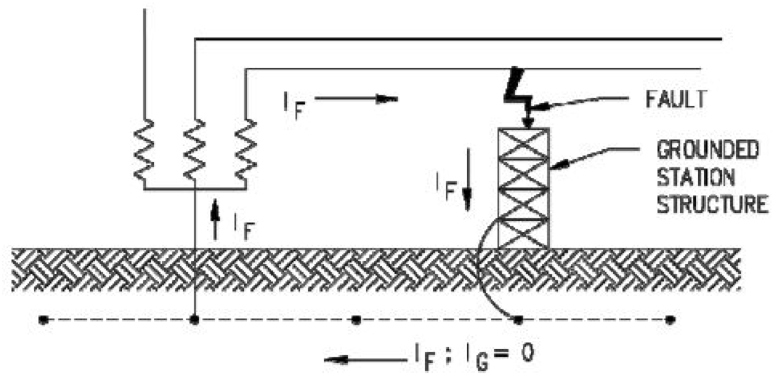


FIGURE 9.2: Fault Within Local Substation, Local Neutral Grounded. Ref. IEEE Std. 80, Draft 13, June 19, 1998, Figure 15-1.

Figure 4: Path of Least Resistance in a Substation

Area of the ground grid

It is generally advisable to design the area of the ground grid to be as large as possible to ensure personnel at or near the substation is safe; however, cost optimizations must be considered. Our site is rectangular in shape with outer dimensions of 400 ft. x 400 ft. This size was given to us in our design specifications to ensure that all equipment will fit and there will be room for future expansion. To determine the grid spacing, we performed an iterative process where we started with 30 foot spacings of copper, as recommended by our client to get a baseline for our design, running horizontally and vertically inside the perimeter of the grid and increased the spacing of the grid by 10 feet each time until we found the largest spacing that still maintained safe touch and step potentials. We found the largest spacing while maintaining safe touch and step potential was 70 feet in both the horizontal and vertical directions. The larger spacings require less copper runs and rods to be used in the implementation of the design. This lessens the amount of equipment in the bill of materials, ultimately decreasing the cost of the package.

Ground fault currents

When determining the ground fault current that will be used in the design, worst case scenario is always assumed to ensure that no matter what personnel will always remain safe. In the case of a substation the worst fault current that could occur is if there was a fault directly applied to the transformer. Based on typical industry values and from Burns and McDonnell experience, the maximum single phase grid current during fault conditions has been determined to be 21kA.

Ground conductor

In designing a grounding system, the minimum conductor sizing must be calculated to ensure the conductor will be able to withstand the maximum fault current. This minimum conductor size was found using Equation 2 below found in IEEE 80-2013. The value for K can be found in Table 2 below. We will be using copper, annealed soft-drawn material and therefore the value for K is assumed to be 7. The fault current I and clearing time have been given to us by Burns and McDonnell to be 21kA and 0.5 seconds, respectively. When this calculation is performed, a value of 103.945 is obtained. While remaining extremely conservative, we chose to use 4/0 conductor sizing based on this calculation to ensure the conductor could withstand the maximum fault current.

$$A_{kcmil} = I \times K_f \sqrt{t_c}$$

where

A_{kcmil} is the area of conductor in kcmil

I is the rms fault current in kA

t_c is the current duration in s

K_f is the constant from Table 2 for the material at various values of T_m (fusing temperature or limited conductor temperature based on 11.3.3) and using ambient temperature (T_a) of 40 °C.

Equation 2: Calculation for determining size of grounding conductors

Material	Conductivity (%)	T_m [a] (^oC)	K_f
Copper, annealed soft-drawn	100.0	1083	7.00
Copper, commercial hard-drawn	97.0	1084	7.06
Copper, commercial hard-drawn	97.0	250	11.78
Copper-clad steel wire	40.0	1084	10.45
Copper-clad steel wire	30.0	1084	12.06
Copper-clad steel rod	17.0	1084	14.64
Aluminum-clad steel wire	20.3	657	17.26
Steel 1020	10.8	1510	18.39
Stainless-clad steel rod	9.8	1400	14.72
Zinc-coated steel rod	8.6	419	28.96
Stainless steel 304	2.4	1400	30.05

Table 2: Constants for the material at various values of fusing temperature

Safety considerations

The purpose of a ground grid is to protect anyone in the vicinity of the substation from electric shock and to reduce possible overvoltages that can cause damage to substation equipment. IEEE Standard 80 outlines the specific permissible levels for step and touch potential voltages. These safety requirements are based off of multiple characteristics provided by the client, including the maximum fault current, maximum fault clearing time, average body mass, and surface layer thickness and resistivity.

When fault current flows through above-ground equipment at a substation, a ground grid provides a path to ground so that the fault current dissipates into the earth rather than continuously flowing through the above-ground equipment, exposing everyone in the vicinity of the substation to the risk of electric shock and potentially damaging that substation equipment. Some considerations need to be taken into account when developing a ground grid design, including the substation size and equipment layout. All major substation equipment as well as the fence surrounding the substation are tied to the grounding system.

Figure 5 below outlines the maximum step and touch voltages that are considered safe in the Cyclone Substation. From this figure we see the safe touch voltage to be 672 volts and the safe step voltage to be 2219.9 volts. These values are based on the amount of current, the fault clearing time and the surface layer added. We added a surface layer of 4 inches with 3000 ohm-m resistivity which is the resistivity value for that of crushed rock.

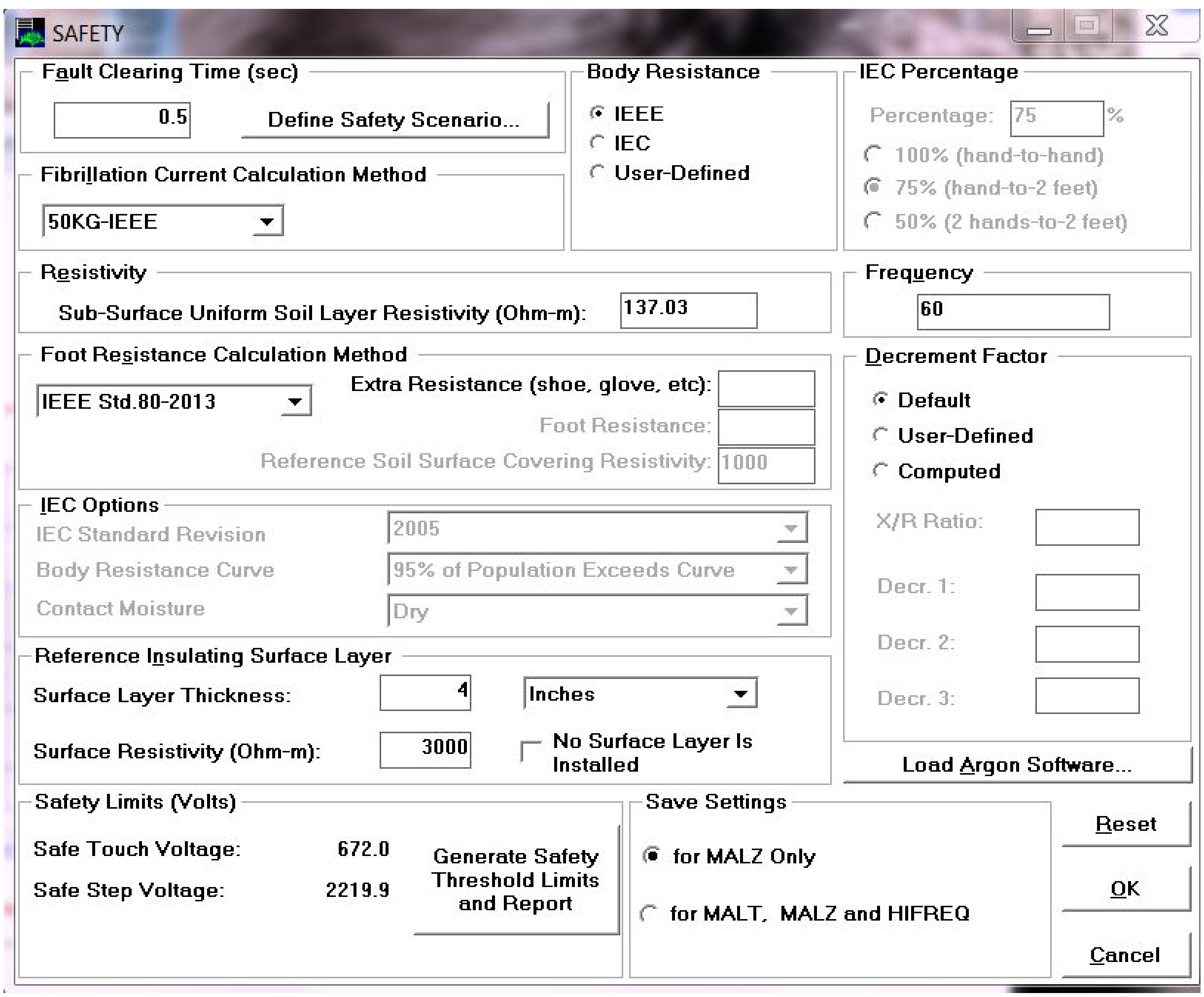


Figure 5: Safety Thresholds for Cyclone Substation

Design of substation ground system

After all the data is collected, the soil model is created, and all the client's specifications have been made, the grounding system can be designed. The client provided us with various constraints to take into account when designing the grid. Burns & McDonnell provided us with a Substation Design Guide to follow in order to adhere to their standard procedure in ground grid design. This design included 16 steps to produce a functional design. Although this design guide would lead the user to produce a functional design, it does not guarantee the design meets all safety criteria and site specific constraints.

Specifications that were provided to use by Burns & McDonnell to take into account when designing the grounding system include the following:

- The site shall be 400 ft. by 400 ft.
- The ground grid should be set 18 inches below the surface of the ground
- The grounding system shall use 4/0 stranded copper offset by 3 feet outside the parameter of the fence.
- Conductor sizing based on calculation
- Optimize the grounding system to use the least amount of material while still guaranteeing a safe environment.

2.1.2 Physical Design

The second task our team completed was the design of the layout and elevation views of our yard. The sections we completed are as follows.

I. Development of the plan-view
II. Elevation A-A
III. Elevation B-B
IV. Lightning protection

Development of the plan-view
There were many factors that played into the design of the plan-view. They are as follows:

i. Bus sizing
ii. Placement of all major equipment
iii. Termination tower placement for 138/69 kV yards
iv. Orientation of the substation
v. Future expansion of the 138 kV yard

Bus sizing

To begin the design, we needed to understand the different bus sizing of the high and low side of the yard. Industry standard indicates that the 138 kV high-side of the yard requires rigid bus of 4" Schedule 80. Industry standard also indicates that the 69 kV low-side of the yard requires rigid bus of 3” Schedule 40. Our client provided us with CAD drawings of each major component we will be using for our design, with the bus sizing complete, we were able to modify the spacing between each phase of each piece of equipment to reflect industry standard. This affected our design by ensuring that we had the correct conductor size and that we minimized the amount of bus that we used, because with less bus, the cost of the project decreases.

Placement of all major equipment

In our Project Scope document provided to us by our client, the client highlighted that this substation will be a 138 kV three-breaker ring bus with a 138/69 kV transformer (XFMR1) and a single 69 kV line exit with breaker. We will also be designing this substation for future expansion to a breaker-and-a-half arrangement. This section had the biggest impact on our overall design. We were required to place the transformer in a centralized location with the breakers on either side of it. We had to ensure that the high side breakers were allocated much more space than the low-side breaker, because of the general design of a ring bus. The equipment all had to be spaced out with respect to industry clearances and fall within IEEE standards. For example, on the high side, the phases were required to be 8 feet apart and 6 feet apart on the low side.

Another significant consideration was the placement of the control building. We needed to keep the control building mainly centralized, as all of the equipment has cable runs that need to connect to the control building and having it centralized reduces the amount of wire that needs to be run and in turn reduces the cost. The control building was required to be a minimum of 60 feet from the Transformer, though, because the transformer can cause the most damage if it fails and the control building needs to stay operational, even when the transformer fails.

In accordance with the location of the control building and the cable runs, all of the major equipment that have cable runs back to the control building should be oriented so that the electrical boxes on the equipment are on the side that is closest to the cable run through which goes to the control house. Typically this cable trough is designed so that the control building is connected to all of the major equipment in the yard in the most optimal way.

Most of our design for the placement of major equipment was based off of examples provided by Burns and McDonnell and from their comments on our preliminary designs. These examples were from previous projects that were successfully built and designed by Burns and McDonnell. These examples gave us a better understanding for the work required to be done by our team.

Termination Tower Placement for the 138/69 kV Yards

In our design, we had to account for the termination tower placement. The termination towers are the structures that receive the outside transmission lines into the substation and transfer the lines into the buses in the substation. The two termination towers on both the

138 kV and the 69 kV are H-Frames, which can be seen below in Figure 6. The devices are also the location for where our lightning masts are located. The H-Frames need to be located so that the outside lines can easily be routed to them. These H-Frames are very big and need significantly sized foundations to bear the load of being dead end structures. That means that there needs to be significant space surrounding the H-Frame, so that the foundations can be constructed and they don't affect the place of other equipment. We decided to place the H-Frames close to the fences so that the outside lines are not going overtop of any major equipment and so the outside lines don't have to be rerouted very far.

Figure 6: Termination Towers with H-Frames

Orientation of the Substation

Along with the placement of the H-Frames, the orientation of the substation needs to be considered. The substation should be oriented so the lines to Des-Moines comes out of the the low side breaker and the lines to Cedar Falls comes out of the high side breaker. This will affect where the H-frames are located and which side of the substation will be the low side and which side will be the high side. For our design, we decided that the best way to design this would be to place the low side breaker near the south end of the substation and place the high side breaker near the north end of the substation.

Future expansion of the 138 kV yard

We had to keep in mind that we were also allocating space for an expansion to the ring bus to make it into a breaker-and-a-half arrangement, which essentially adds another bay of 3 breakers and will take up a significant amount of space. These breakers will be added in a future expansion but will need to be accounted for in our current design. To do this, we just added the bay of breakers, but had them dashed so that our client knows that they are not part of the current design and will be implemented at a later date.

2.1.3 Lightning Protection Design

The empirical curves method was employed in order to determine the suggested lightning protection design for Cyclone Substation. Though there are other methods of determining the lightning protection design for a substation, Burns and McDonnell instructed our team to employ the empirical curves method.

The primary goal was to determine the least amount of lightning protection equipment that could be configured such that all critical substation equipment would be within some zone of protection, shielding that substation equipment from lightning strokes and providing the substation with adequate lightning protection per IEEE standards.

First, the circular zones of protection associated with the shielding masts—both existing masts and masts that should be installed to protect the equipment outside of the zones of protection associated with existing masts—were determined. Then, the interactions between those zones were modeled; this zones-of-protection-interactions modeling slightly reduced the total number of lightning masts needed to ensure that all critical substation equipment would be within some zone of protection.

The circular zones of protection associated with the shielding masts were calculated based on data from IEEE Standard 998-2012. First, a *d/h* ratio was determined for each mast. *d* represents the height of the tallest equipment that needed to be protected by any given mast. *h* represents the height of a given lightning mast. The heights of the lightning masts on top of the H-frame termination towers were known based on the elevation drawings. *h* values for the new lightning masts were estimated and adjusted as needed.

As shown in Figure 7, based on the .1% exposure curve, an *x/h* ratio could be determined based on the associated *d/h* ratio. Once this *x/h* ratio was known, the known *h* value could be substituted into the denominator of *x/h* and that could be set equal to the ratio value in order to solve for *x*, the radius of the zone of protection for a given lightning mast.

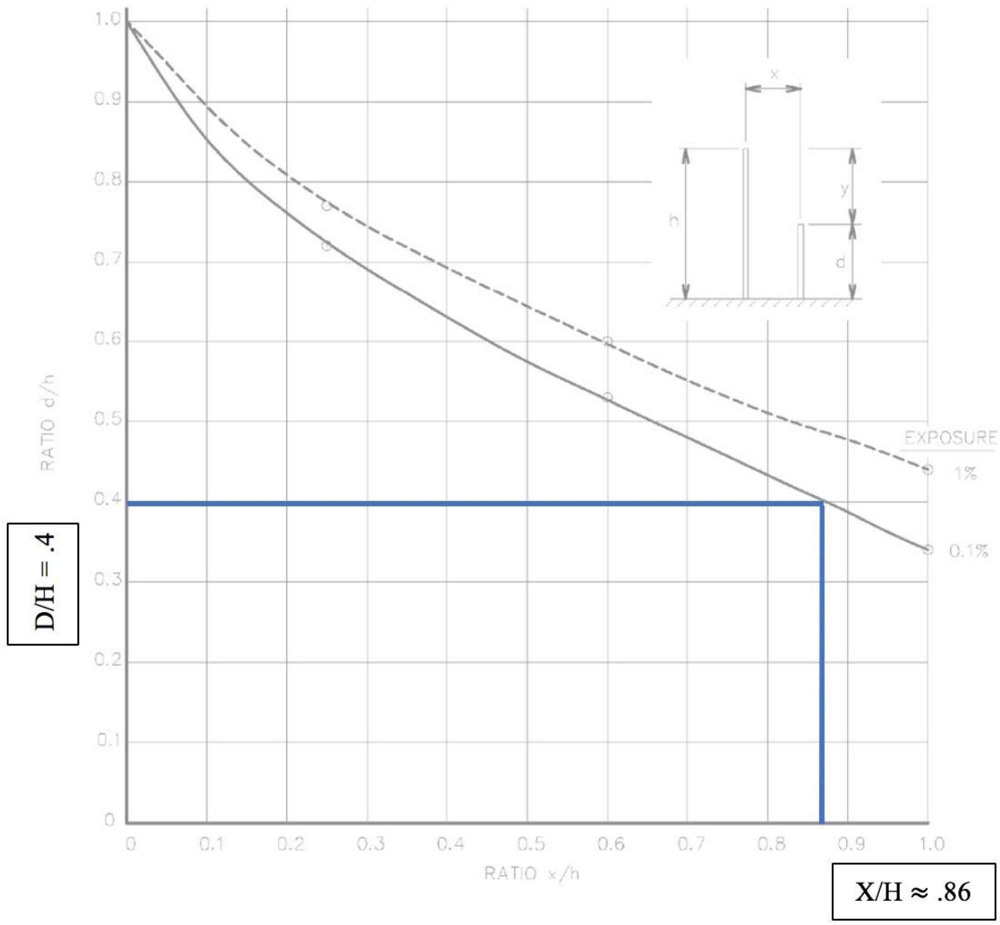


Figure 7: Exposure Curve to Determine X/H

Once *x* values for each mast were determined and zones of protection could be estimated, the lightning protection design could be drafted in AutoCAD. The initial lightning protection design is shown below.

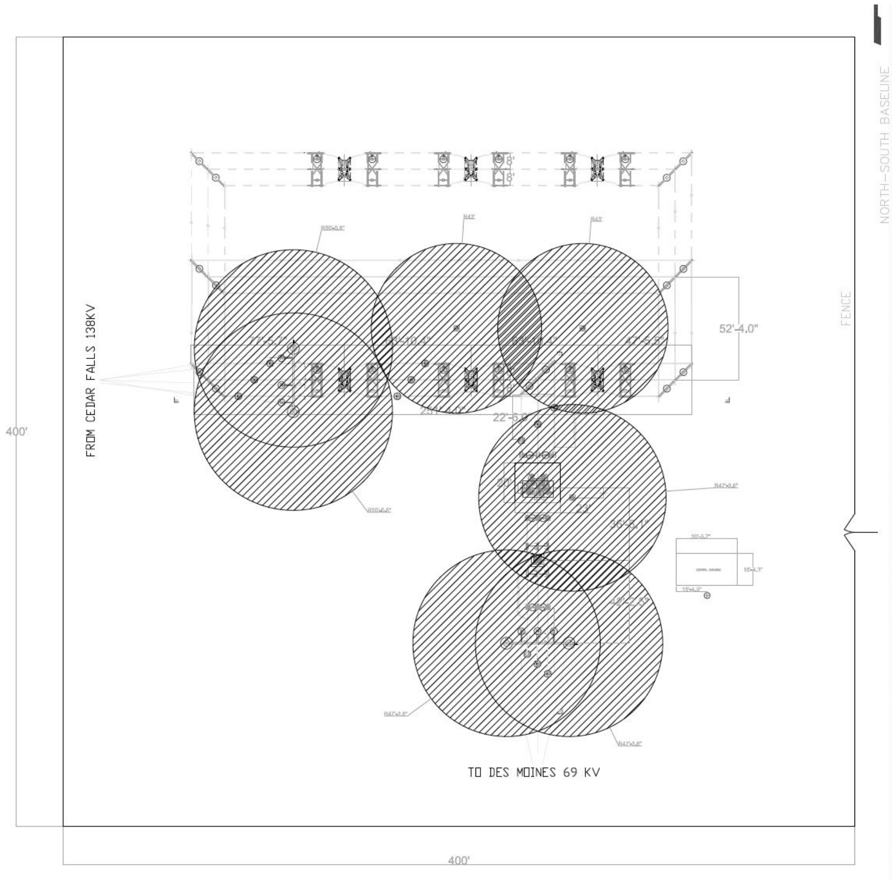


Figure 8: Initial Lightning Protection Design

However, accounting for the interactions between zones of protection made it possible to eliminate one lightning mast while still protecting all critical substation equipment.

If zones of protection are certain distances away from each other, there is no interaction between them. These distances can be calculated based on data from IEEE Standard 998-2012. Based on the *d/h* ratio of a given lightning mast and the .1% exposure curve, an *s/h* ratio could be determined based on the associated *d/h* ratio. Once this *s/h* ratio was known, the known *h* value could be substituted into the denominator of *s/h* and that could be set equal to the ratio value in order to solve for *s*, the furthest apart two zones of protection can be while still interacting with each other.

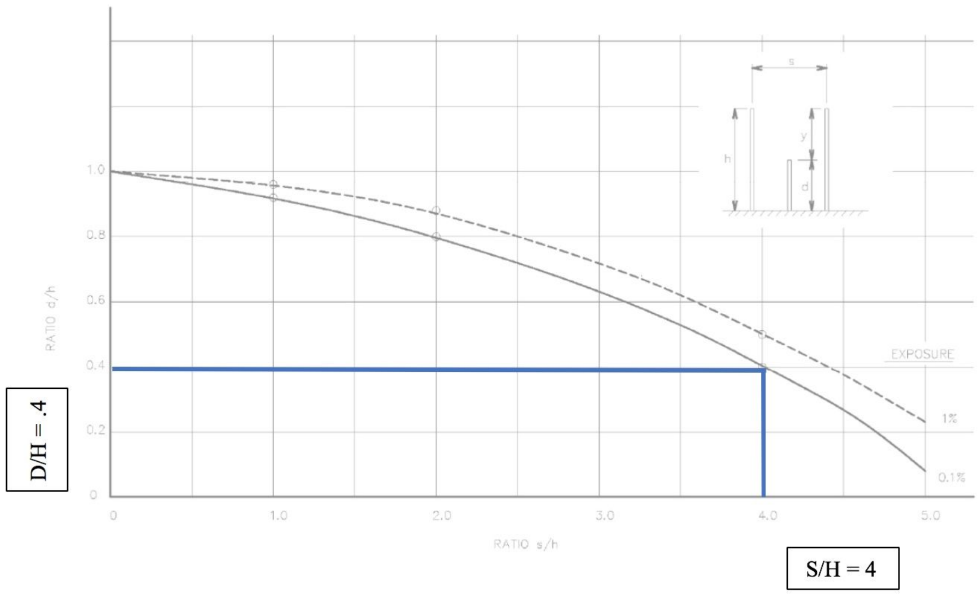


Figure 9: Exposure Curve to Determine S/H

After accounting for the interactions between zones of protection and eliminating one lightning mast the optimized lightning protection design shown below could be drafted in AutoCAD.

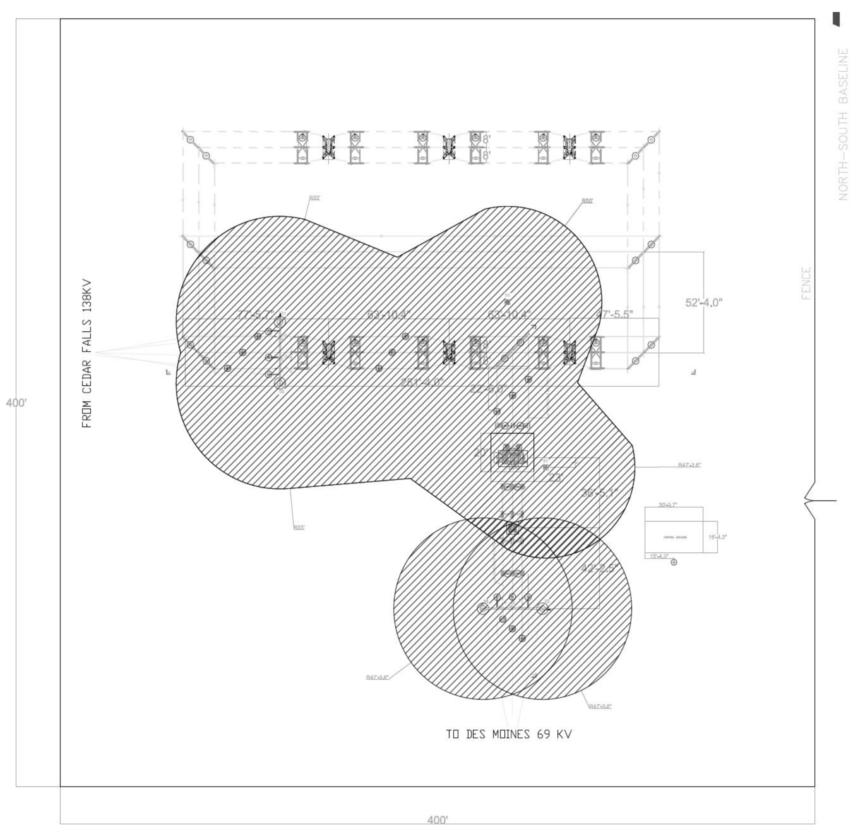


Figure 10: Optimized Lightning Protection Design

2.2 Design Analysis

2.2.1 Grounding Design

The process of designing a grounding system is an iterative process. With each step, you either accept the outcome, or make adjustments to better fit the needs of the client. We want to ensure that our design is created with the highest level of accuracy as well as optimize our design to keep the cost down for our client. The initial design created will accommodated all the criteria set by the client and passed all necessary tests. Because this design is created conservatively to ensure it surpasses the required level for safety. Following, we will to go back to the design process and use fewer materials and copper rods. This process will be repeated until a grid design that meets all the criteria, safety requirements, and a decreased cost for our client is reached.

This optimization process takes an increased amount of time; however, the trade offs are satisfying to the client. Below, we list the trade offs to our grounding design process and what it means for our client.

Proposed design strengths:

- Cost efficient
- Considered future additions
- Ensures the safety of individuals in the event of a fault

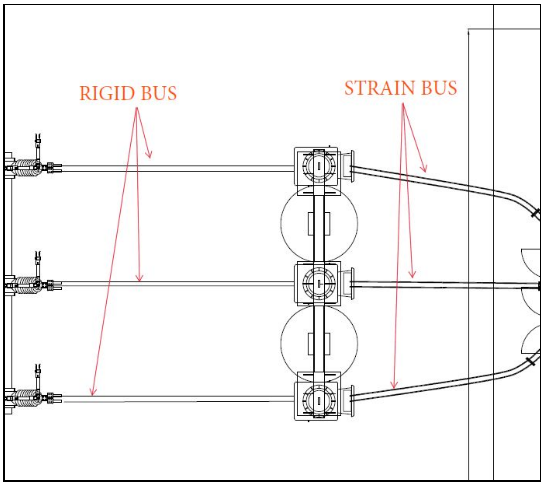
Proposed design weaknesses:

- Trial and error process
- More time consuming

2.2.2 Physical Design

The process of designing the physical layout of the yard requires the designer to complete an initial draft of the yard and submit the drawing to another member of a team to review the work. Then after the review was complete and the necessary changes had been made, we then submit the drawing to the client. During this process, our client acted as another member of our team, giving us comments regarding what we needed to change. This process is essential for the success of designing a substation because all other subsequent drawings will be based off of the layout.

After we had been given the approval from our client, we were then allowed to start drafting the elevation view's A-A and B-B. Again, the process of drafting was exactly the same as before, except coordinating between different drawings. These elevation views show a profile of a major part of our substation. These drawings require precise placement of each major piece of equipment. Once the placement had been made, then we were able to work on the heights of each bus section, whether it be strain bus, or rigid bus. Below are two screenshots highlighting the difference between a strain bus and a rigid bus from our layout and our elevation drawings.



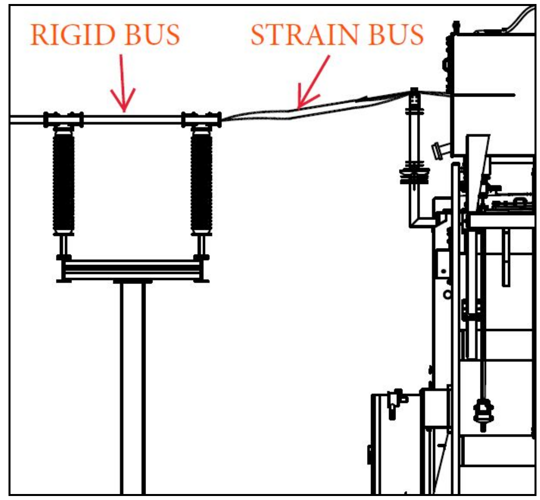


Figure 11 & Figure 12: Plan View and Elevation View of Rigid and Strain Bus

The left image is from our plan-view and the right is from elevation view A-A. The difference between a strain bus and a rigid bus is the strain bus is a bus structure comprised of flexible conductors, and a rigid bus is a non-flexible bus structure.

Once we had approval of our elevation views, we were then able to draft the lightning protection overlay of the substations plan-view. The lightning protection overlay comes last in our drafting process because we need to have all dimensions between each major equipment final. The overlay position is decided on the location of lighting masts. Lightning masts are provided on each H-Frame termination structure which is seen exiting both the 138 kV and the 69 kV yard. To save money on the cost of each lightning mast, we determined we would place two additional lightning masts, one next to the 138/69 kV transformer, and the other between two of the 138 kV breakers on the ring bus. After we had covered all necessary equipment, we needed to show how each lighting mast would react with the other lighting masts to create a zone of protection for our equipment.

Proposed design strengths:

- Accounting for future expansion of the yard
- Protecting all necessary equipment from lighting strikes
- Protecting all necessary equipment from current surges and arcs
- Accounting for spacing of each phase and each piece of equipment to allow any repairs to be completed with the safety of the worker in mind
- Cost efficient

Proposed design weaknesses:

- Time consuming
- Inability for additional members to work on drawings simultaneously

3 Testing and Implementation

3.1 Interface Specifications

Our project will primarily have physical components that do not require coding or software provided by our team. One component of our project that will require hardware and software interfacing is the design of the communications systems. The communications systems will run via Remote Terminal Units (RTUs) and Real-time Automation Controllers (RTACs) and an MPLS network. The RTU will need to be configured in order to run properly, but the configurations is not within our scope and therefore will be provided by our client.

There will be several relays that will be installed during our project and those relays will need to be routed back to the RTACs, where the data is aggregated. These RTACs have serial ports on the units and will use serial connections to the relays to gather the needed information about the system. The RTACs will then be connected to the RTU. The RTU will be the human interface system with the system. This RTU will send data to other substations surrounding it and to control centers via a router that is connected to the MPLS network via ethernet cables. This RTU unit has the ability to trip the breakers and will need to be programmed with the SCADA point list, which is provided by our client.

The RTU will have the ability to be both remotely accessed and assessed on site. The RTU will be programmed to work with the client’s current network and all the programming and code needed will be provided and uploaded by the client. There will be several security measures on the devices to ensure that the devices cannot be accessed by unregistered and unwanted users. Again, these security measures will be programmed by the client.

3.2 Hardware and software

Throughout the design of a substation, multiple software programs are used to calculate critical values to remain in agreement with IEEE standards. For our project, we will be performing multiple studies. These studies require handwritten calculations to be made, and design criteria will be based off of these calculated values. After the handwritten calculations are done, the values can be entered into software that determines specifications of equipment and regulates if the proposed design aligns with the written standards.

3.2.1 Grounding Design

CDEGS is the software the design team will use in the grounding system design process. CDEGS is a grounding and electromagnetic analysis software package. The acronym stands for Current Distribution, Electromagnetic interference, Grounding and Soil structure analysis. This integrated set of software tools is designed to accurately analyze electric networks for industry. IEEE standard values and calculations are pre programmed into the software, and data values that are site-specific are entered into the program by the user.

The data collected during soil resistivity testing is entered into the RESAP program. Correctly interpreted soil structures are essential for the analysis of grounding systems. RESAP is used to compare field data collected to the resistivities produced in different soil models. This program automatically determines the soil structure of the site, providing accurate representation of the soil and electric surface response values.

The program used to test an initial ground grid design is MALZ. A ground grid design is imported into the program and a test plot is set over the grounding system. MALZ analyzes the frequency domain performance of the buried conductor network and outputs multiple values that are then compared to IEEE standards and safety considerations to determine is the grounding system provides a safe environment.

3.2.2 Physical Design

The design of our substation will be done using AutoCAD. AutoCAD is a computer aided design software that allows the user to draft engineering drawings. All drafting will be done using AutoCAD, while each review of each draft will be completed using Adobe Acrobat. Adobe is a PDF software that allows the user to create, edit and comment on the document.

One important feature of AutoCAD that will be imperative in our drafting process is the ability to insert a title block and the feature of clouding different parts of the drawing. The title block feature is important because it allows the user to track the each revision of the drawing along with allowing the drafter to comment on what they have changed. The clouding feature is perhaps the most important feature because it will created a cloud around a user defined region allowing the individual reviewing the drawing to view exactly what was changed. It limits confusion and time while reviewing the work.

3.2.3 Lightning Protection Design

Another important study that our project requires is a lightning study. Like the grounding study, the lightning study observes the substation layout in regards to ensuring the safety of the substation equipment. The empirical curves method was used as the approach in our study. Next semester, Burns and McDonnell will supply us with an intra-company-developed Microsoft Excel program that is used by their employees to confirm the results found through by-hand calculations. A simple explanation of the program's main task is to ensure that there are enough masts and/or shielding wires in place to ensure that if lightning strikes the substation, the strike will hit the highest point/s within the substation, absorbing the shock and dissipating it into the earth, as opposed to the lightning striking the expensive equipment.

3.3 Functional Testing

3.3.1 Grounding Design

An initial ground grid is designed prior to soil testing and running any tests in CDEGS. This initial design is based off of client templates and imported into the MALZ tool in CDEGS. After soil resistivity testing is done and data is entered into the RESAP tool in CDEGS to build a soil model, MALZ uses the data from the soil model and partners it with the initial design. Various calculations are run inside the program and multiple tests to ensure a safe environment for those who find themselves within the vicinity of the substation.

This program takes the soil model and partners it with the ground grid design and runs various tests to ensure a safe environment for those who find themselves within the area of a substation. The main objective of a grounding study is to design a ground grid that efficiently absorbs the highest possible fault current in the substation into the Earth, to ensure no person inside, or three feet surrounding, the substation is in harm's way. The MALZ tool outputs a safety report, showing the areas in which more copper needs to be added to the ground grid to absorb the fault current, and which areas are sufficiently accounted for. The passing rates in MALZ are based upon IEEE standards and once a ground grid is modified to meet these standards, the test passes and the grid design is accepted into use.

3.3.2 Physical Design

Functional testing for the physical design of the yard requires coordinating between each drawing simultaneously. This is necessary due to the number of checks associated with the progression from the draft, to the final product. The client provided us with a major equipment list that is to be used in the design of the substation. Both our client and a team member uses this equipment list when reviewing the drawing to account for all equipment used in the drafting process and to ensure that no necessary equipment is added.

Additional testing was done by performing peer quality review checks. We would have a group member that was not working on the physical design look over and ensure that all of the equipment needed is included and that the comments from the clients were all resolved. The reviewer would then bring up any results that did not conform to standards provided in IEEE standards and standards that the client provided. After the comments were reviewed by both the peer reviewer and original drafter, then the final version was sent to the client and any final comments from the client were incorporated and rechecked by both the peer reviewer and the original drafter.

3.4 Non-Functional Testing

Non-functional testing is not required in order to complete our project. Though we utilized CDEGS to perform the grounding study and will utilize Microsoft Excel to perform the lightning study, this software was provided to us by our client and performing tests to determine how that software operates is outside the scope of our project.

3.5 Process

3.5.1 Grounding Design

The grounding study and design of the site's grounding grid each had their own unique checks and balances. The main test is to plug the design into the CDEGS program to ensure that the maximum voltage is below the minimum threshold and the impedance of the grounding system is below the industry standards of 2 ohms.

Soil Resistivity Measurements

The soil resistivity measurements were given to us by Burns and McDonnell, so it required no testing on our part. This is a theoretical design and will not actually be built, so they gave us numbers that were similar to past projects they had completed in the midwest. This means that if we were to actually build the substation that we are designing and went and performed the Wenner 4-Point Method in the field, we would obtain similar resistivity values.

Area of the ground grid

The area of the ground grid is determined by the size of the site. Multiple factors go into the sizing of the site and in turn, the area of the substation. Those factors include the number of lines entering/exiting the substation, equipment ratings, voltage levels, and land grading. Our client provided the size of the site would be 400 ft by 400 ft. We used this to design a ground grid that would run underneath the surface of the substation and extend to the parameter of the fence. Our initial grid design would cover a 400 ft. by 400 ft. area, with spacing measurements of 30 ft. by 30 ft. between conductor runs. After multiple iterations of the design process and testing, cost was taken into account and we optimized the grounding system to extend out to the 400 ft. by 400 ft. parameter with spacings of 70 ft. by 70 ft. between conductor runs.

Ground fault currents

The maximum ground fault current is decided based on various possible fault currents. A simulation taking into account the voltage levels entering and exiting the substation, the ratings of the equipment, and the overall system is ran. This simulation outputs multiple possible fault currents. The maximum fault current is decided based on the clients specifications. Because of the expense and complexity of this simulation, Burns & McDonnell provided us with the maximum fault current that would be taken into account in the design of Cyclone Substation.

Ground conductor
When designing a grounding system, conductor sizing and material must be calculated and optimized. Most grounding systems use copper or copper-clad steel. The ground conductor was sized using Equation 9.10. The parameters needed to complete the calculation were in part supplied by Burns & McDonnell and IEEE 80 standard. Upon finishing the ground conductor calculations, we contacted our client who confirmed we had calculated the correct conductor size.

Safety considerations
When performing a grounding study, safety considerations defined by IEEE 80 standard must be met. The standard defines tolerable limits of body currents, shock situations, and touch and step voltages. The ground grid is designed to take on the maximum fault current to ensure those in the vicinity of the substation are in a safe environment. The grounding system is designed to cover the area of the substation, as well as extend 3 ft. outside the parameter of the fence. The ground grid is tied into each piece of equipment above ground to provide a path to the grounding system. These safety conditions were tested during our CDEGS simulation.

Under **Section 2.2.1 Design Analysis** we discussed about the importance of efficiency when designing the substation. One way to efficiently design the ground grid is with the CDEGS software. We found this to be a much more efficient solution instead of computing it all by hand. We will keep this in mind when moving forward with the rest of our design elements. Computer software proves to be much more cost efficient and the ability to redesign one component without having to recalculate everything.

Flow Diagram of the Process

The figure below outlines the process for designing a ground grid. This process was based off the process for designing a ground grid found in IEEE 80-2013. We used a similar process outlined in IEEE 80 to ensure our design met industry standards and was accurate.

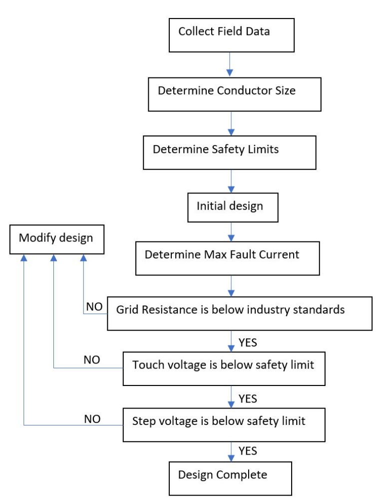


Figure 13: Flow Diagram for Grounding Design

3.5.2 Physical Design

The physical design had several checks and balances. Most of the checks and balances were done through quality review of the designs and how to best optimize the substation yard layout. The checks were done both by a peer and a qualified lead engineer from Burns and McDonnell.

Bus Sizing

The bus sizing was very straight forward as there are industry standards for the differing voltage levels for which conductors to use for the rigid bus. These industry standards were communicated to us from our clients, so we were not required to run any calculations for it. The selected bus from our client makes a lot of sense, as it is rated for our expected currents and will be able to handle the additional current in case of a fault.

Placement of All Major Equipment

This section was the most tasking for the physical design of the substation. The equipment was preliminarily placed in the most logical order with the transformer in the middle of the substation and the low-side breaker placed near the line to Des Moines and the high-side breakers near the line to Cedar Falls. To design this we followed the examples given to us by Burns and McDonnell and constantly communicated with the client regarding our design and how best to modify it. The control house was also placed centrally to optimize the lengths of the cable runs from the equipment in the yard. The main drafter completed the design in AutoCAD and then another member reviewed the design before any questions were brought up to the client. The testing here was actually just reviewing the design, as we are not able to test this design until the design is built and we are just designing it and not building it.

Termination Tower Placement for 138/69 kV Yards

The termination tower placement was a simple thing to complete. The termination towers needed to be placed in close proximity to the fences, next to the breakers, and close to the line directions from Des Moines and Cedar Falls. The termination towers also included the lightning masts, so the protection of the transformer was taken into consideration when placing these. The client verified that the placement of the termination towers was within their standards and sufficiently spaced.

Orientation of the Substation

The orientation of the substation was pretty much incorporated into the placement of the termination towers. The lines to Cedar Fall and Des Moines dictated where termination towers were placed and then to optimize that the breakers needed to be placed close by. This process was reviewed by another group member other than the drafter and finally approved by the client as well.

Future Expansion of the 138 kV Yard

This consideration was a major task, as we needed to incorporate a massive amount of space for a future expansion. The future expansion would increase the reliability and flexibility of the substation. Going from a ring bus to a breaker-and-a-half formation would make it so that each breaker can be separately isolated and the substation will still be fully energized. That means that if maintenance is needed then the substation does not need to go out of service which is very economical for the client. To incorporate this expansion into our design we added another bay of breakers and verified with the client that the design was correct and no errors were included in the final design.

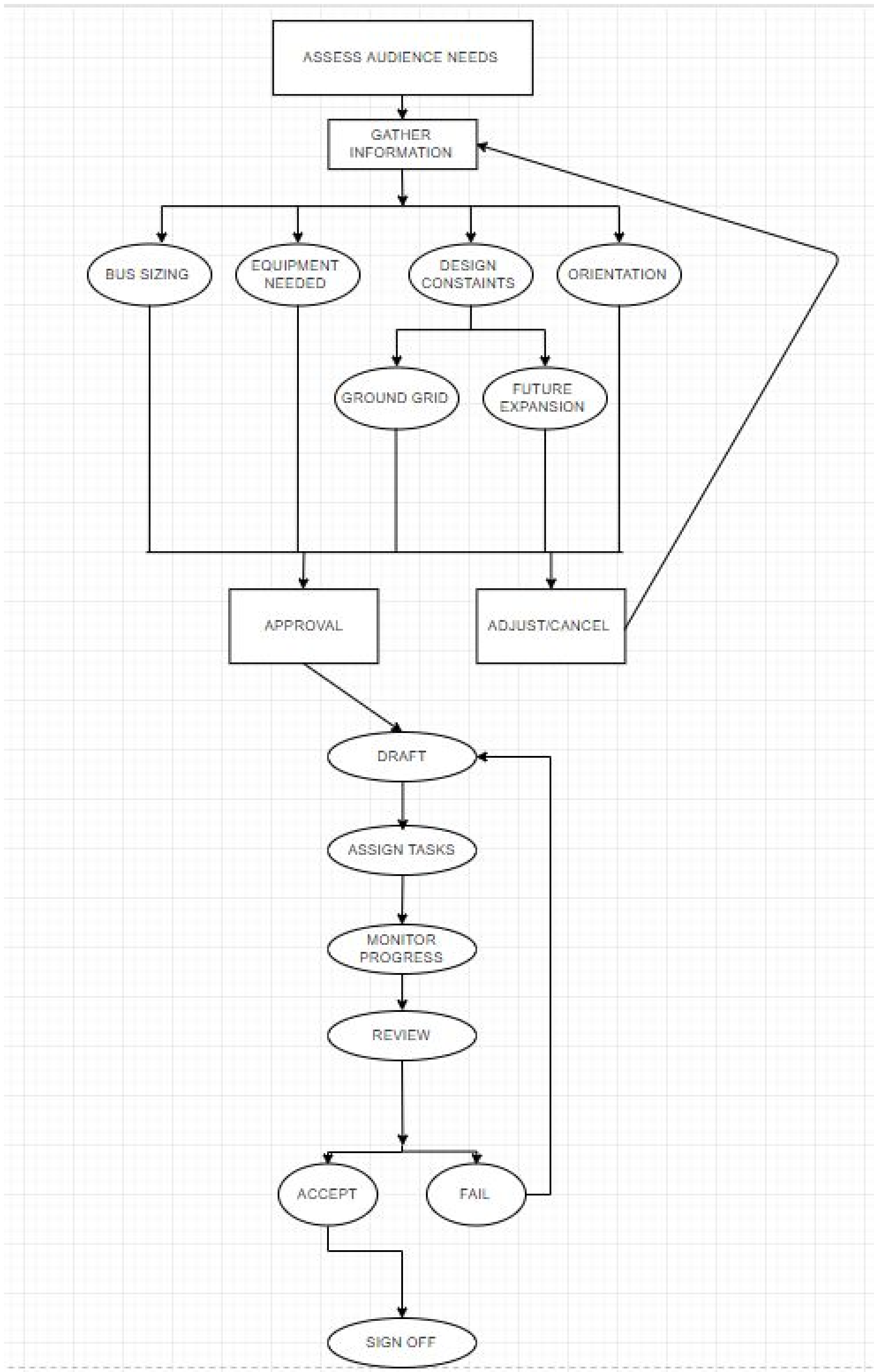


Figure 14: Flow Diagram for Physical Design

3.5.3 Lightning Protection Design

The lightning protection study was performed by a trial and error method. Once heights were chosen for new lightning masts and the radii of the zones of protection were determined, the zones of protection were drafted in AutoCAD. If the zones of protection or the interactions between those zones did not cover all critical substation equipment, the heights of the new lightning masts had to be increased in order to increase the radii of the zones of protection.

3.6 Results

3.6.1 Grounding Design

As mentioned above, an iterative process was performed to optimize the grid spacing for the grounding design. We started with a grid spacing of 30 feet and increased by 10 feet each iteration. Below are the results for 50 feet spacing, 70 feet spacing and 80 feet spacing. Since we performed many iterations and 50 feet spacing was still passing, we chose to only show the results for 50 feet spacing since it is a mid point between the starting point and the optimized design.

Optimization

The figures below show the results for touch and step voltage test with 50 feet spacing. When evaluating results from CDEGS, there must be no colors on the grid to consider it a passing study. The two figures below are all white on the grid and the maximum values in the legend are less than the minimum threshold, therefore they are passing.

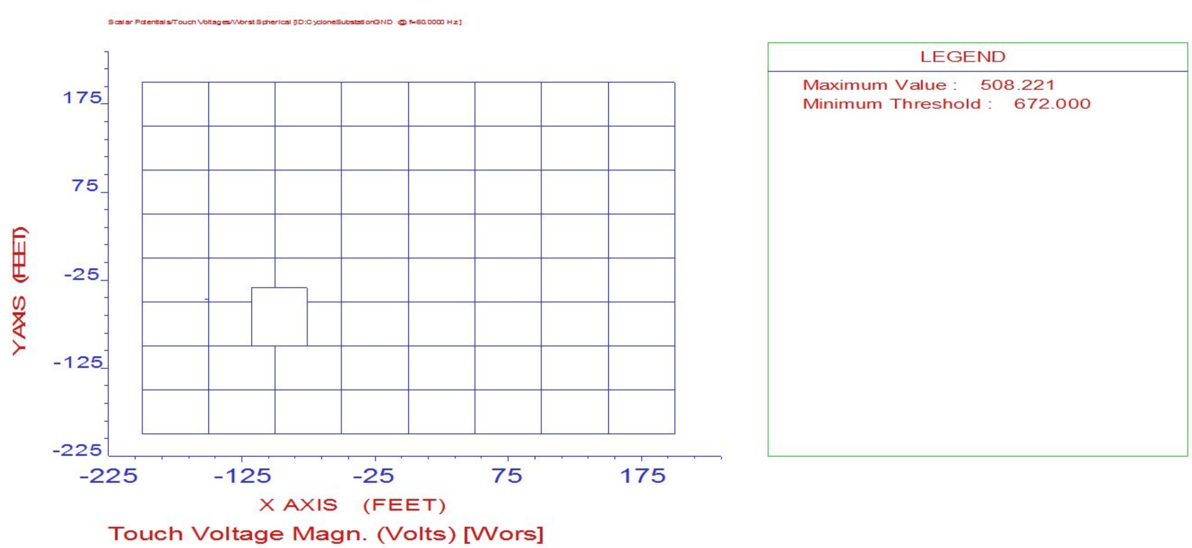


Figure 15: Touch Voltage Results with 50’x50’ spacing

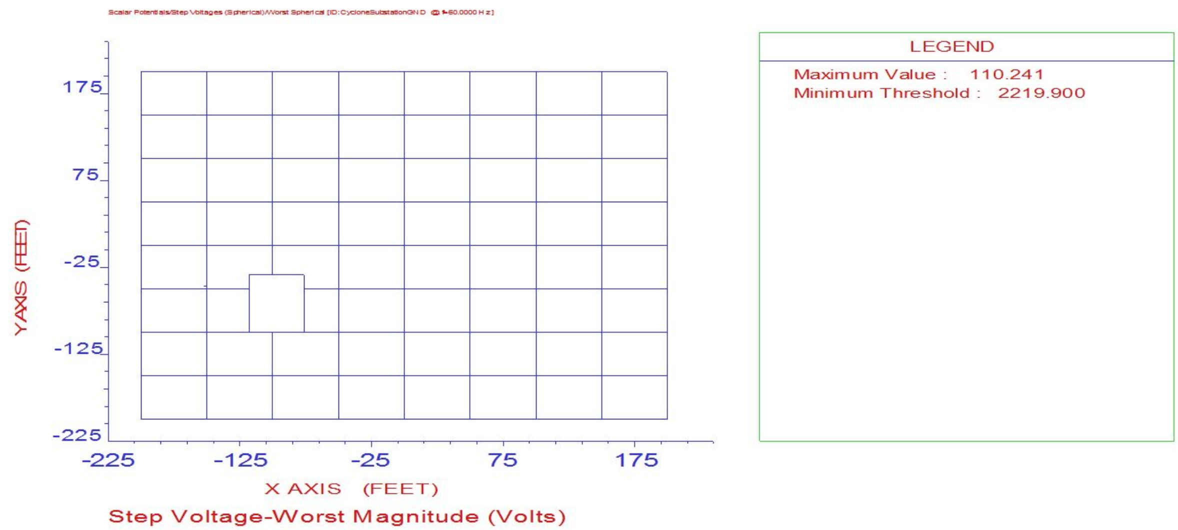


Figure 16: Step Voltage Results with 50’x50’ spacing

Failure

The figures below show the results from studies that were considered failures. When we first began the iteration process, we needed to determine if a surface layer would be necessary. We ran the study with 30 feet spacing, which is fairly conservative, and no surface layer and we had areas on the grid that were above the minimum threshold (colors were seen on the grid). This can be seen in Figure XX This helped us determine that a surface layer would be necessary for the ground grid to pass. When performing the iterative process, we had to increase the spacing by 10 feet each time until the study was no longer passing. Figure XX shows 80 feet spacing with a surface layer, which is not passing. This helped us determine that 70 feet spacing was as large as we could increase the spacing while still obtaining a passing study.

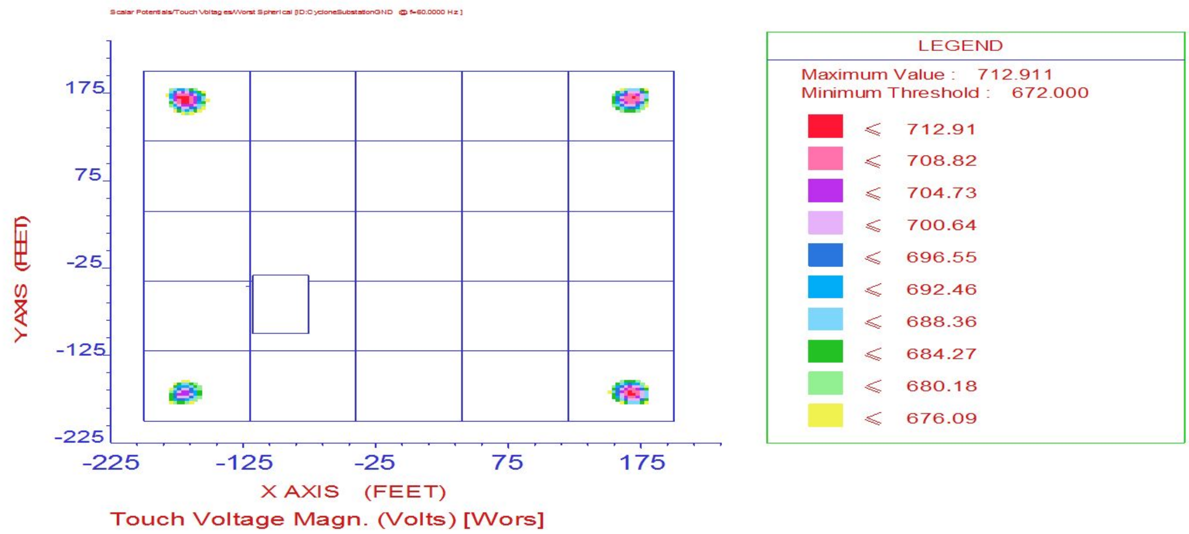


Figure 17: Touch Potential Results with 30’x30’ Spacing Without Crushed Rock Layer

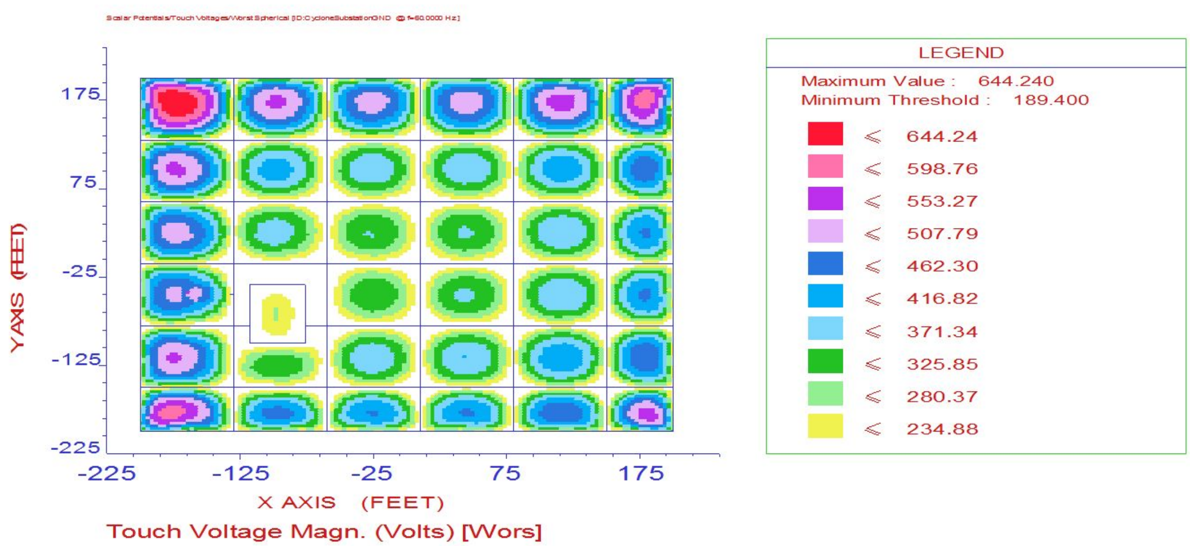


Figure 18: Touch Potential Results with 80’x80’ Spacing

Success

We determined the largest spacing that could still pass was 70 feet. In the figures below, the maximum voltage is below the minimum threshold. For the touch voltage, the maximum voltage is only 28 volts lower than the minimum so therefore we determined we could not increase the spacing any larger. This design is optimized considering costs and materials and is the design that will be submitted to the client.

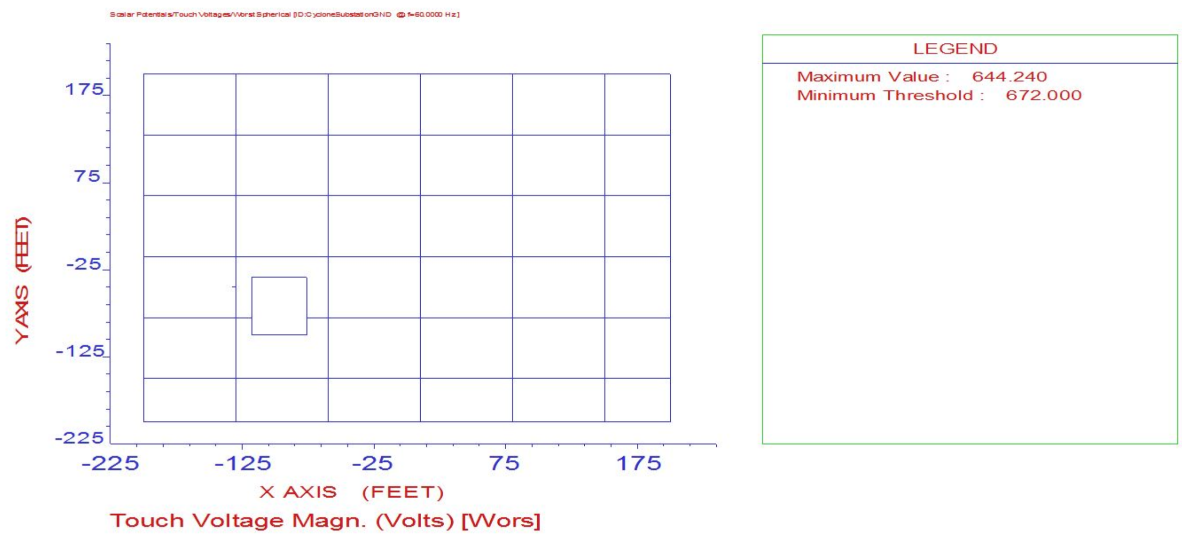


Figure 19: Touch Voltage Results for 70’x70’ Spacing

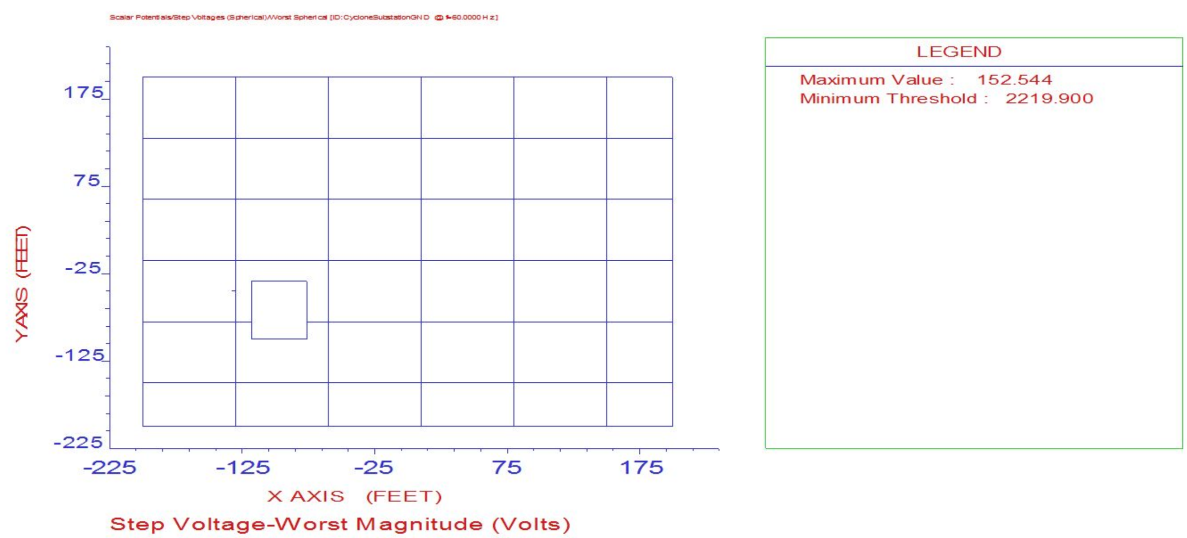


Figure 20: Step Voltage Results for 70’x70’ Spacing

The final check to determine if the design is acceptable is to ensure that the impedance of the grounding system is below the industry standard of 2 ohms. In figure 21 below, it can be seen that the impedance of the grounding system is 0.1921246 ohms. Since this value is much lower than 2 ohms, we can determine the grounding design is acceptable.

```
 STARTING TIME= 20:41:55:56


 ===========< M A L Z        ( SYSTEM INFORMATION SUMMARY ) >===========

 Run ID....................................: CycloneSubstationGND
 System of Units ...........................: British
 Earth Potential/Magnetic Field Calculations : Potentials
 Number of Energization Source Busses .......:     1
  Current Injected in Reference Source Bus....: 21000 Amps
 Energization Scaling Factor (SPLITS/FCDIST/specified)..:   1.0000
 Number of Original Conductors ..............:    78
 Number of Frequency Values to be Analyzed...:     1
 Power Source Frequency......................:   60.000     Hertz
 Impedance Values are Based On...............:   60.000     Hertz
 Total Length of Conductor Network...........:   6357.9     feet
1

 CHARACTERISTICS OF MEDIA SURROUNDING NETWORK
 ============================================
 AIR LAYER :  Resistivity............:  0.100000E+13 ohm-meters
              Relative Permittivity..:   1.00000
              Relative Permeability..:   1.00000

 >>> SOIL TYPE : Multi-Layer Horizontal

 LAYER RESISTIVITY  |------ RELATIVE -------|   THICKNESS
  No.  (ohm-meter)  Permittivity Permeability    (feet)
 ----- ------------ ------------ ------------ ------------
     1   137.028       1.00000      1.00000      0.409472
     2   22.4626       1.00000      1.00000       3.28360
     3   52.8007       1.00000      1.00000      Infinite
1

 Case Number.................................:     1
 Frequency for This Case.....................:   60.000      Hertz
 GPR of Reference Source Bus (#  1)....Magn..:     4034.618     Volts
                                       Angle.:     3.525928     degrees

 Impedance of Grounding System.........Magn..:    0.1921246     Ohms
                                       Angle.:     3.525928     degrees

 End of Report #1
```

Figure 21: Impedance of Grounding System

What we Learned

We learned that not every first simulation is going to yield the passing results we strive for. We need to be patient when receiving a failed simulation report and step back and understand why it failed. Moving forward, we will be more meticulous before running simulations on work we are not confident with. Take time to comb through each component and run various QC checks on our work to ensure that we do not have a costly mistake that would set us back.

Implementation Issues and Challenges

As we begin to progress with each phase of our project, as engineers, we try and do it as efficiently as possible. Implementing a ground grid for a substation of this size should not be too overly conservative. We will continue to struggle with trying to minimize elements such as the ground grid to try and save cost and time spent.

3.6.2 Physical Design

The drafting process for the physical design of our yard began by looking at example drawings from another substation provided to us by our client. Our client also provided us with topical cutouts of each major piece of equipment needed for the design of the plan-view along with the corresponding profile views for the equipment so we could draft the elevation views.

Design of the plan-view

The design of our yard (plan-view) began by gathering the information needed to satisfy all requirements set by our client. The information included: equipment needed, bus sizing for both 138 kV and 69 kV yards, orientation of the yard, ring bus configurations, future expansion considerations, and gathering ground grid information to understand design constraints.

After we had all of the information needed, we began the drafting process of the yard. To start, we created a boundary based off of the ground grid. This provided us with an area where we could begin to place equipment. The equipment list necessary is explained in the table below.

SECTION	EQUIPMENT	DESCRIPTION
TRANSFORMER	138/69 kV transformer	3-phase power transformer
	Strain bus	Needed to connect the transformer to the 69 kV and 138 kV buses
69 KV YARD	69 kV breaker	Used for the transformer low-side
	Disconnect switch	Required for breaker to interrupt or open an electrical circuit for purposes of inspection and maintenance
	CCVTs	Coupling Capacitor Voltage Transformers (one per phase)
	Bus support	Needed to support the stretch of bus between equipment
	H-Frame termination tower	Terminate the transformer and distribute energy to 69 kV line
	Rigid Bus	Used to connect the rigid bus to the termination tower
	Strain Bus	Acts as a path from the transformer, to the breaker, to the termination tower, and to the CCVTs
	138 kV breaker	Used for the transformer high-side
	Disconnect switch	Required for breaker to interrupt or open an electrical circuit for purposes of inspection and maintenance
	CCVTs	Coupling Capacitor Voltage Transformers (one per phase per breaker)
	Transition Structure	Needed to redirect the bus location and to account for the change in height between the high-side and the low-side

138 KV YARD	Rigid Bus	Used in the connection between the circuit breaker and the disconnect switch
	Strain Bus	Acts as a path from the transformer, to the breaker, to the termination tower, and to the CCVTs
	H-Frame termination tower	Terminate the transformer and distribute energy to 138 kV line

Table 3: Equipment List

Now we are able to place the equipment to accommodate the design constraints and requirements from our client.

First draft of plan-view

Failures

The first draft of the plan-view did not pass the requirements set forth by our client, as expected. We did not account for the correct phase spacing between the 69 kV and 138 kV yard. We also added equipment that was not necessary in the 138 kV yard. There were too many bus structures. The distance between equipment also needed to be minimized to reduce costs. We added too many CCVT's on the 138 kV yard and we failed to add any CCVT's on the 69 kV yard. And we failed to orient the layout correctly to accommodate for the destinations of both 138 kV and 69 kV lines. The first draft of our substation plan-view is shown below.

First draft of plan-view

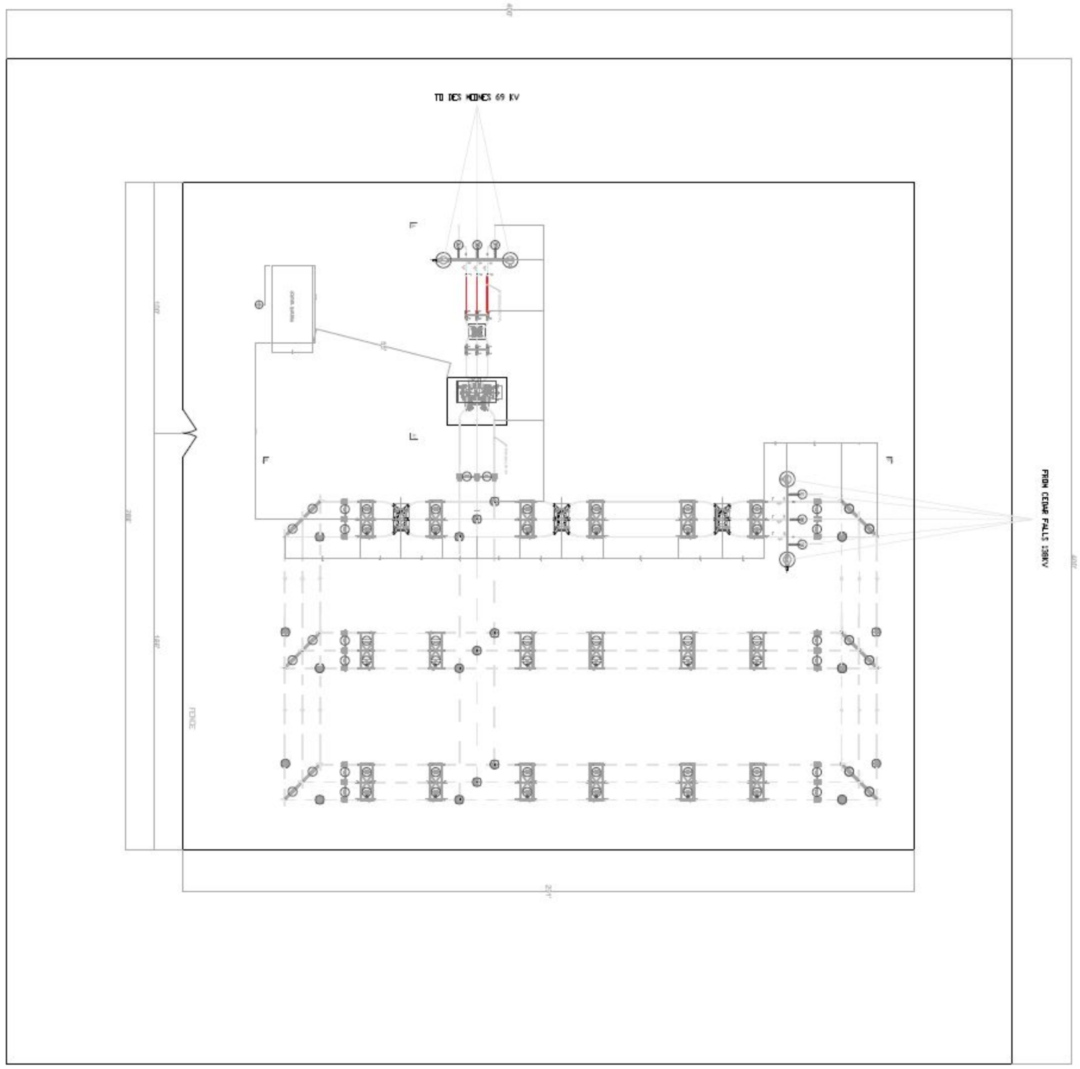


Figure 22: First Draft of Plan-View

Approved design of plan-view

Success

After making the necessary changes to the design, our client approved the design of our substation. Below is a table highlighting the changes made.

FIRST DRAFT	**APPROVED DESIGN**
Incorrect phase spacing of 69 kV yard	Decreased phase spacing to reflect the industry standard of 5” Schedule 40
Incorrect phase spacing of 138 kV yard	Increased phase spacing to reflect industry standard of 8” Schedule 80
Extra equipment on the 138 kV ring bus	Removed extra equipment on 138 kV ring bus configuration to match client demands
Unnecessary bus structures	Removed unnecessary bus structures to reflect client demand of bus structure every 30 feet
Distance between equipment too long	Decreased distances between equipment to conserve space and account for future expansion
Too many CCVT’s on 138 kV yard	Removed unnecessary CCVT’s on 138 kV side
No CCVT’s on 69 kV ard	Added CCVT’s to the 69 kV side
Incorrect orientation of substation	Accounted for the position of termination tower to reflect the incoming and outgoing lines of the substation

Table 4: Changes Made to Plan View

Approved plan-view

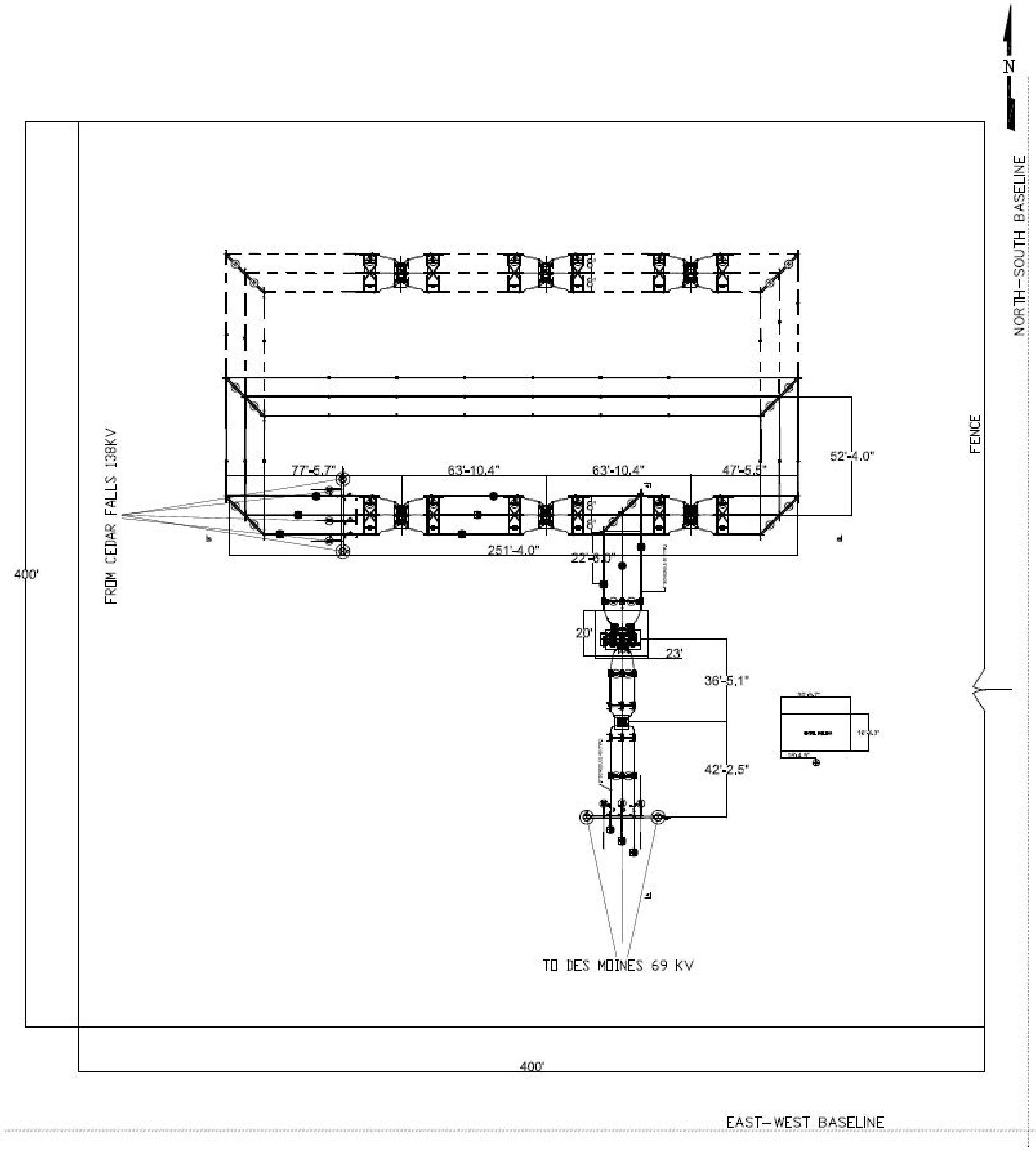


Figure 23: Approved Plan View

Design of elevation views A-A, B-B

The elevation views were drafted in accordance with the plan-view. As previously stated, you needed to coordinate between the plan-view and each elevation because of the location of each piece of equipment along with determining the correct heights of each bus. The information gathering step was not necessary during this step. What each elevation view will include can be visible on the plan-view.

Draft of elevation views A-A & B-B

Failure

As expected, the first draft of our elevation views were not approved by our client. But we only had small issues. The spacing of each piece of equipment was approved, but we did not account for the difference in heights between busses. We needed to add surge arrestors on all line positions to ground faults that may travel over the line. These should be the first piece of equipment that a line hits when it enters the substation.

First Draft of elevation A-A

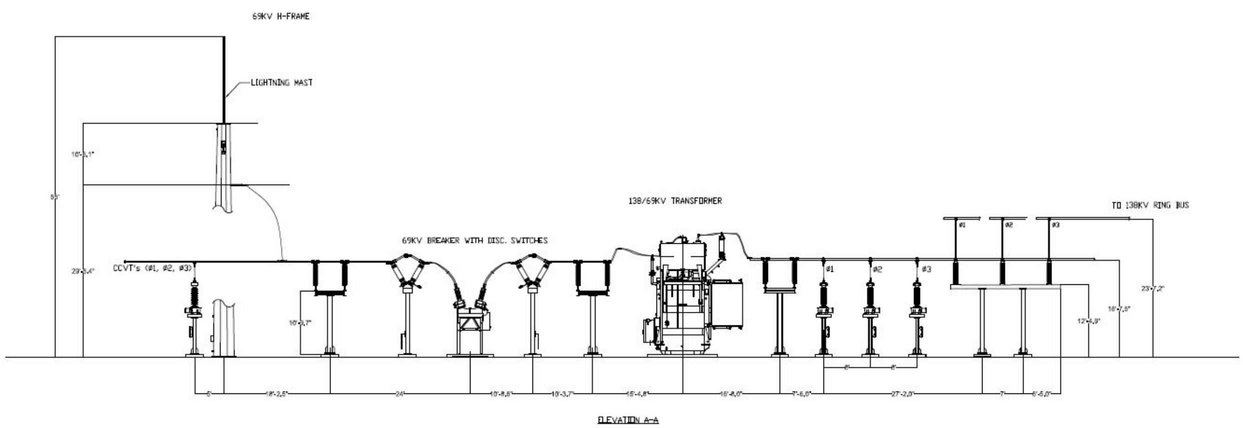


Figure 24: First Draft of Elevation A-A

First draft of elevation B-B

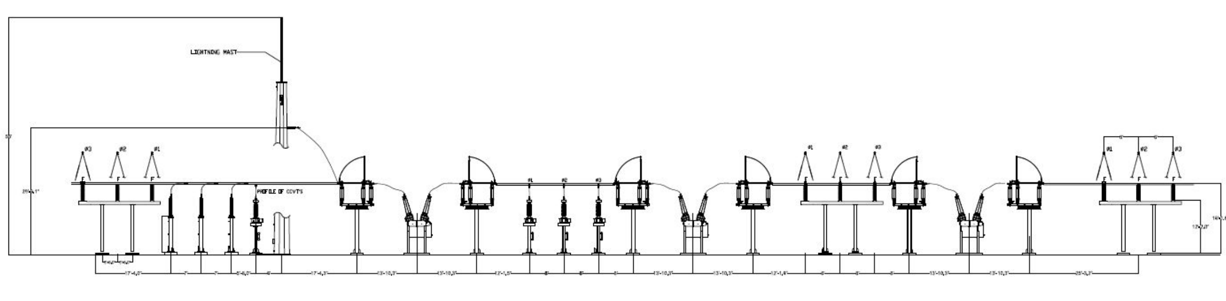


Figure 25: First Draft of Elevation B-B

Approval of elevation views A-A & B-B

Success

After making the necessary changes, both our elevation views were approved by our client. See the table below for a better understanding of what we changed.

Elevation A-A & B-B

FIRST DRAFT	APPROVED ELEVATION A-A
Account for elevation changes between the 69 kV bus and the 138 kV bus	Added a transition structure to account for the transition from the 69 kV bus to the 138 kV bus and to account for the change in height between busses
Add surge arrestors to each line	Added surge arrestors after the H-Frame termination tower

Table 5: Changes Made to Elevation A-A

Approved A-A

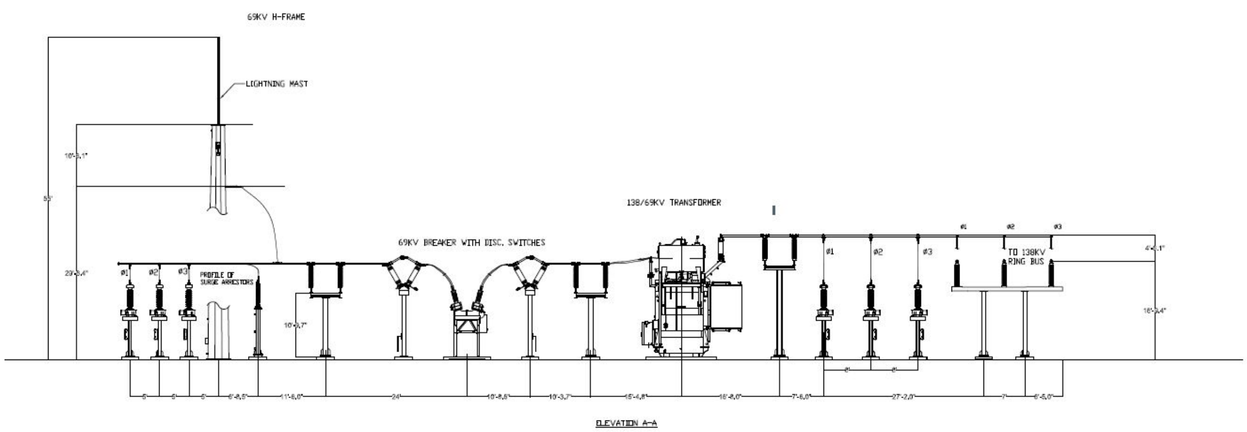


Figure 26: Approved Elevation A-A

Approved B-B

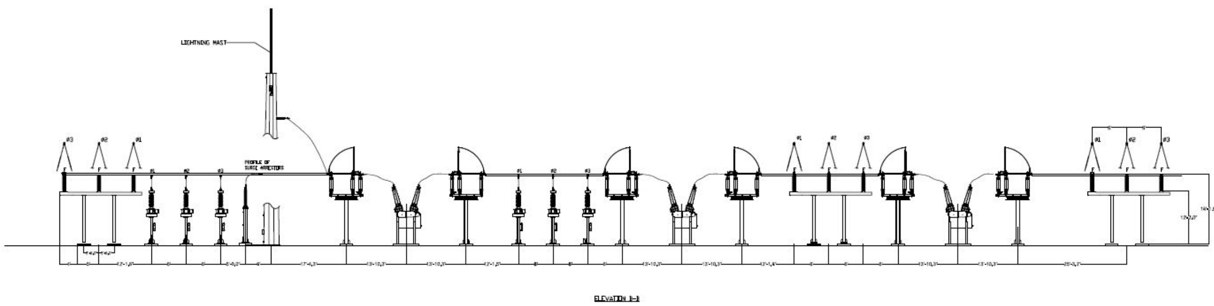


Figure 27: Approved Elevation B-B

Design of lighting protection

To go along with the lighting protection report, we also needed to draft a lighting protection drawing to highlight the zones of protection and to show what equipment would be covered by lighting masts during a lightning strike. There are lightning masts on each H-Frame termination structure which is seen exiting both the 138 kV and the 69 kV yard. The design of the protection is important to understand. The area of protection provided by each lighting mast is highlighted by a circle which features a hatched area. Everything within the hatched area is covered in case of a lighting strike.

First draft of lighting protection

Failure

The first draft of our lighting protection overlay was not approved. Our client wanted to increase each radius of coverage to limit the number of additional masts. He also wanted to show how each lighting mast zone of protection would interact with other zones of protection, as this increases the area that can be protected by the same amount of masts.

First draft

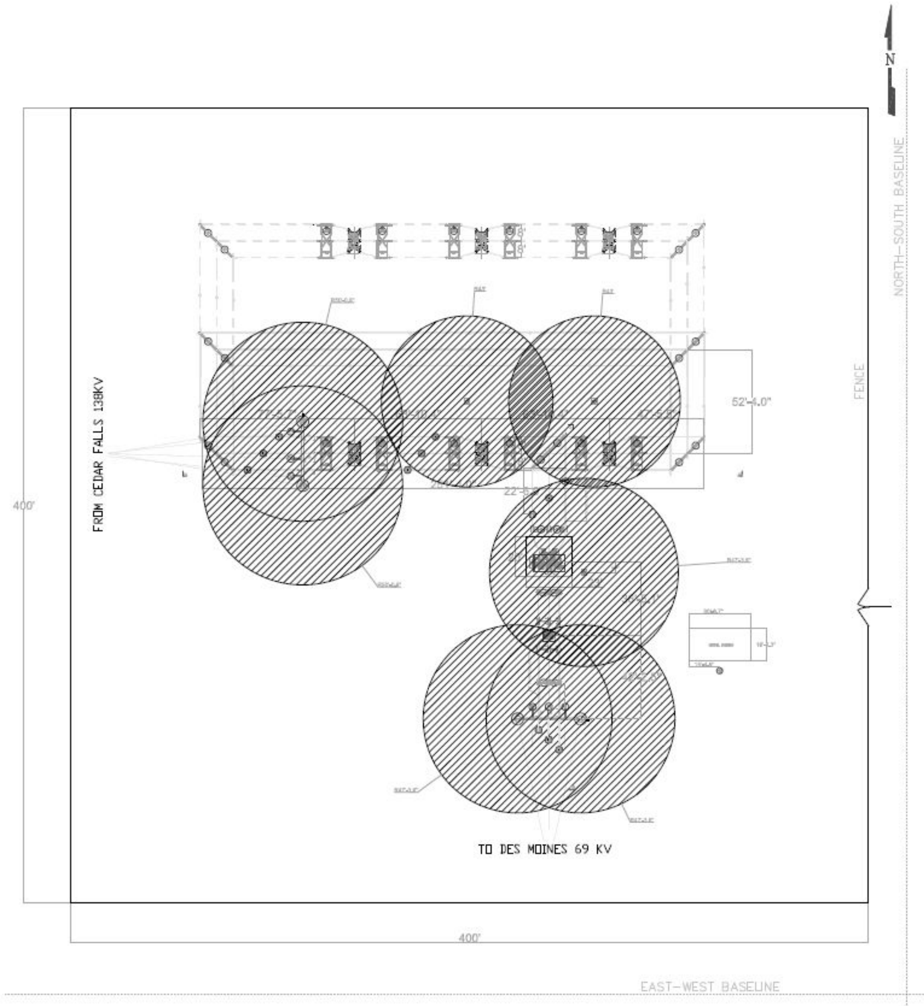


Figure 28: First Draft of Lightning Protection

Approval of lighting protection diagram

After making the changes necessary, our client approved the design of our protection. See the table below to understand the process of how we were able to have an approved drawing.

FIRST DRAFT	APPROVED LIGHTING PROTECTION
Increase the radius of each circle	Per our clients instruction we changed each radius to limit the amount of lighting masts
Show zone of protection	We drafted the interaction between each lightning mast to show how each mast worked with each other.

Table 6: Changes Made to Lightning Protection Diagram

Approved protection diagram

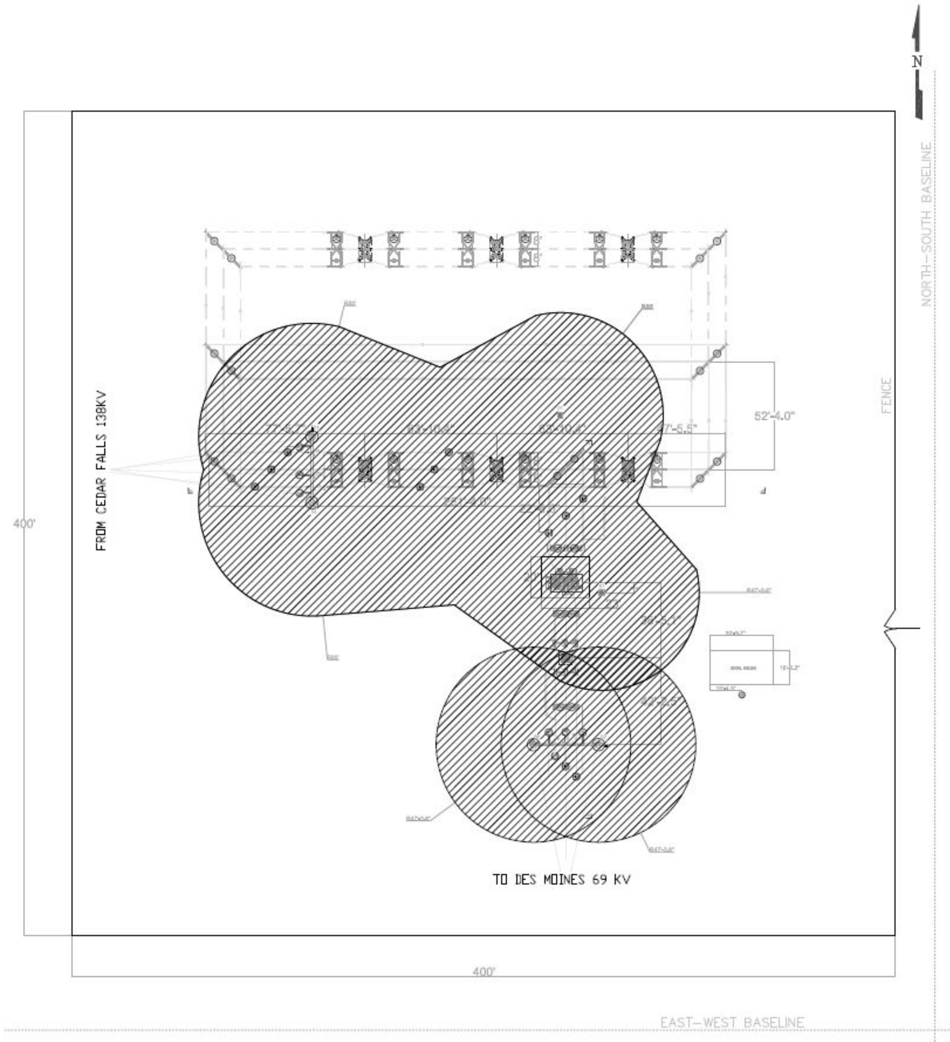


Figure 29: Approved Lightning Protection

4 Closing Material

4.1 Conclusion

For this project, we have done an extensive amount of research on substation design. This research will allow us to move forward with the design of the substation. So far, we have completed the grounding design, physical design, and the lightning protection design. Our grounding design was created using IEEE 80 and was optimized using an iterative process. Our physical design was completed by determining the equipment needed for the substation and using previous examples to create a design that follows standards and is functional. The lightning protection design was created following the completion of the physical design. Calculations were performed for this study to determine the size of the masts that must be added to ensure all equipment is safe in the event of lightning. Throughout the entire substation design, we want to ensure that we keep cost in mind. When completed, our substation will serve as a means of interconnection between a new wind generation plant being constructed outside of Ames, IA and the pre-existing transmission system. This substation will raise or lower the voltage of the electric power flowing into the substation.

4.2 References

Ieeexplore.ieee.org. (2018). *80-2013 - IEEE Guide for Safety in AC Substation Grounding - IEEE Standard*. [online] Available at: https://ieeexplore.ieee.org/document/7109078?reload=true [Accessed 12 Oct. 2018].

Ieeexplore.ieee.org. (2018). *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 02 Dec. 2018].

4.3 Appendices