

Substation Design

Final Report

Team Number

SDMAY19-17

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List of Definitions

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 thank Manimaran Govindarasu, the faculty advisor for this project, for serving the team as a technical and professional advisor.

1.2 Problem and Project Statement

Since 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 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. 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.

2. Substation Layout:

The Iowa State Senior Design team will design a substation layout—including substation equipment, the control building, rigid bus, structures and perimeter fence—which allows for future expansion and maximum flexibility.

3. 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.

4. AC Studies (Auxiliary Transformer and Cable Sizing)

The Iowa State Senior Design team will size a station service transformer for all auxiliary AC loads. This is often referred to as an SL&P (Station Light and Power) transformer or an auxiliary transformer. Each auxiliary load will be taken into account and multiplied by a specific demand factor based on the probability that it will be on or running. This is done so we do not oversize the transformer. These loads consist of existing loads such as lights both indoors and outdoors, cooling fans, heaters, receptacles, battery charger, as well as future loads if the substation is added to. From this we can calculate our maximum estimated kVA demand. Once we have this, we will size our auxiliary transformer. Since the auxiliary transformer will have a maximum current associated with it, we can then size the proper cable for it.

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

5. 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

6. Relaying and Controls

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

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 the regional extreme temperatures and regional extreme weather of Ames, IA.

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
- The new substation should have room for expansion to a breaker-and-a-half 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 were documents and drawings that the Substation Design team combined as a final package and sent to the client. Along with the documents and drawings, the Substation Design team also provided studies that were the basis for design package decisions. In addition, the Substation Design team provided a 3D model of the completed substation, with the major equipment being displayed in an easy to view manner.

The first two deliverables to the client were the grounding and lightning studies. These deliverables were sent to the client on November 2nd, 2018. The grounding study utilized software provided by the client to assist in the design and analysis of the grounding grid. The grounding design was reliant on this study and with this study, the Substation Design team was able to appropriately design a ground grid consistent with IEEE 80 standards and ensure the touch and step potential limits and resistance to remote earth were all within acceptable parameters. The lightning protection for the substation was designed in accordance with IEEE Standard 998-2012. The lightning study clearly summarized the orientation and protection results for each grouping of shielding electrodes, summarized the failure rate of the substation and provided a recommended configuration of the shielding electrodes which included the maximum effective heights of the lightning masts and shield wires.

The second deliverable to the client was the physical design of the substation, which was sent to the client on November 30th, 2018. The physical design of the substation included drawings which showed the layout of the whole substation. The physical design was shown on a plan view drawing which included the locations of the following: the substation equipment, control building, rigid bus, structures and the perimeter fence. This deliverable also included section

cuts from the overall plan view, which showed the elevation view of the substation and also included the Bill of Material call-outs for major equipment shown in the drawing. This deliverable was designed keeping client preferences and cost in mind and allowing for future substation expansion. The physical design was based off of the grounding and lightning studies.

The third deliverable to the client was the AC/DC study, which was sent to the client on March 1st, 2019. The AC/DC study specified the battery sizing that was needed to power the station during a station service outage. The study took into account all of the equipment at the substation and followed the standards described in IEEE 485. The study report included a summary of the design requirements, definitions of the calculations used and a summary of the results and the Substation Design team's recommendation for the battery design.

The fourth and final deliverable to the client was the Controls and the Networks, Integration, and Automation (NIA) design package, which was sent to the client on April 12th, 2019. This package included the final design of the substation's controls and communications equipment. The controls package also included several drawings which represent the complete controls for the substation. These drawings included a one-line diagram, a 69kV circuit breaker schematic, three 138kV circuit breaker schematics, line differential schematics and transformer schematics.

2. System Design and Development

2.1 Grounding Design

The first task the Substation Design team completed was the grounding study and the site's grounding grid design. 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

To design the site's grounding grid, the Substation Design team used the software CDEGS 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

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. 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.

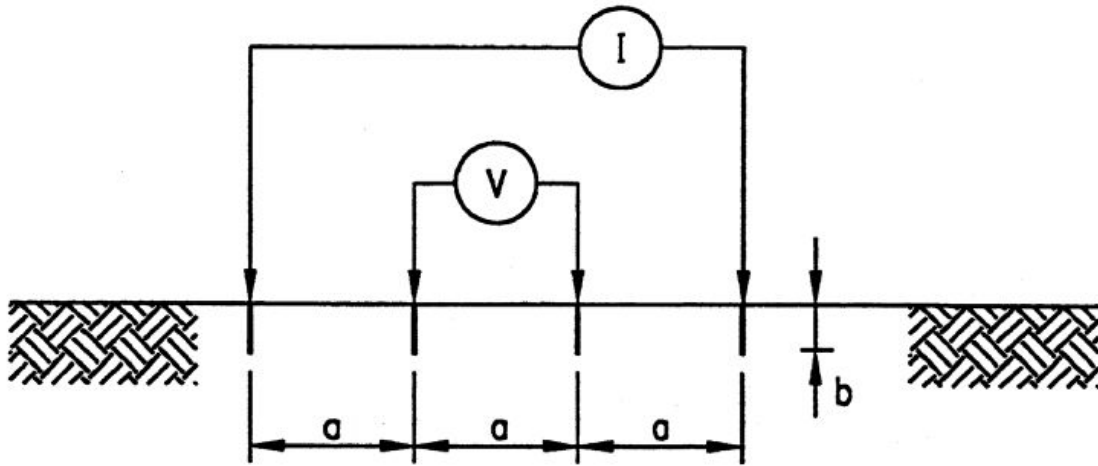


Figure 1: Probe locations for Wenner 4-Point Method

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

where

- ρ_a is the apparent resistivity of the soil in $\Omega\text{-m}$
- 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 (feet)	Resistivity (ohms-m)
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.

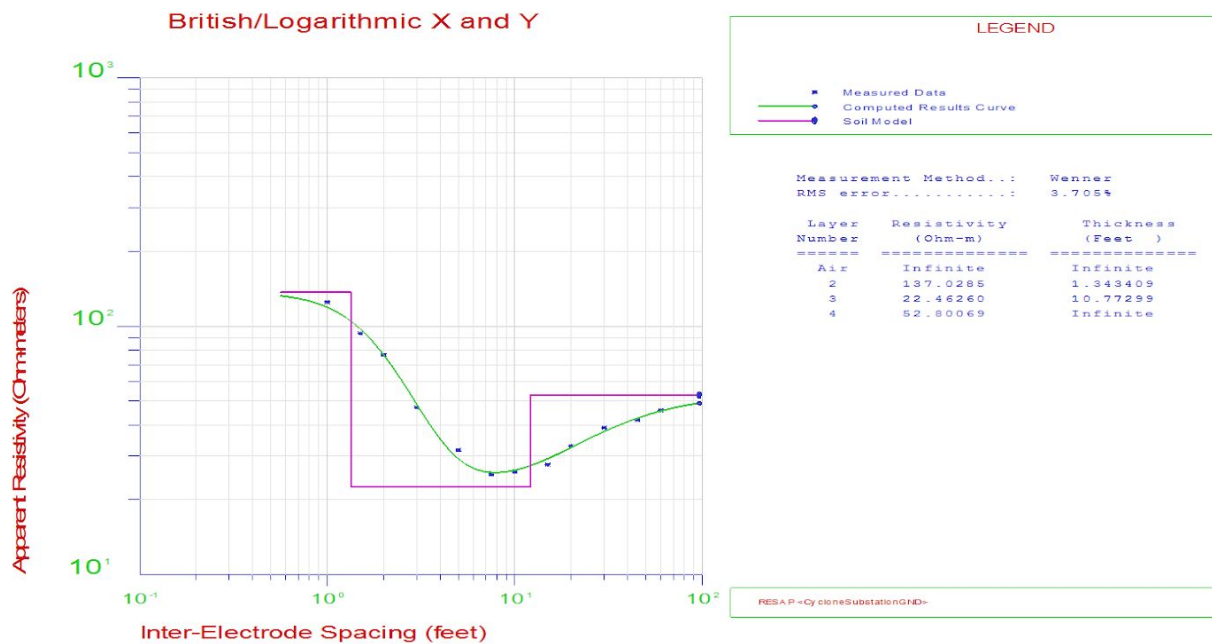


Figure 2: RESAP Model for Cyclone Substation

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 Number	<--- LAYER CHARACTERISTICS ---> Resistivity (ohm-m)	Thickness (Feet)	Reflection Coefficient (p.u.)	Resistivity Contrast 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

Figure 3: Layer Characteristics of Soil Model for Cyclone Substation

In Figure 3 above, one 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 the 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. The Substation Design team used the soil model to decide which layer of soil they wanted to direct the fault current to. In this case, one can see that layer 2 has the smallest resistance. In our design, 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.

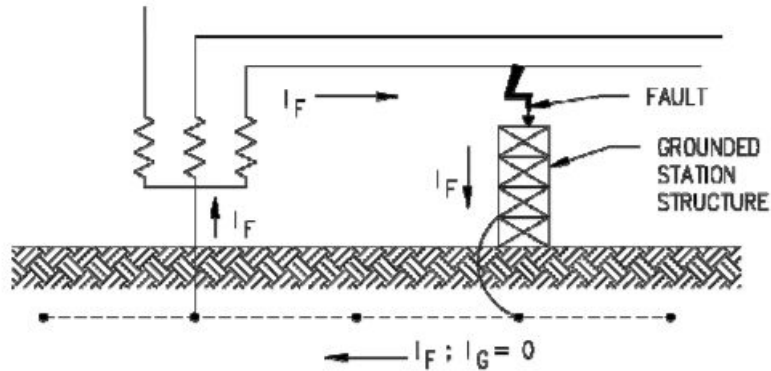


FIGURE 9.2: Fault Within Local Substation, Local Neutral Grounded. Ref. IEEE Std. 80, Draft 13, June 19, 1998, Figure 15-1. Copyright © 1998. IEEE. All rights reserved.

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. 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. To determine the grid spacing, we performed an iterative process where we started with 30 foot spacings, both horizontally and vertically inside the perimeter of the grid, of copper, as recommended by our client to get a baseline for our design. We then 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 (°C)	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. The grounding system is designed to cover the area of the substation, as well as extend 3 ft. outside the parameter of the fence.

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.

The screenshot shows the SAFETY software interface with the following settings:

- Fault Clearing Time (sec):** 0.5
- Body Resistance:** IEEE (selected), IEC, User-Defined
- IEC Percentage:** Percentage: 75% (selected), 100% (hand-to-hand), 50% (2 hands-to-2 feet)
- Fibrillation Current Calculation Method:** 50KG-IEEE
- Resistivity:** Sub-Surface Uniform Soil Layer Resistivity (Ohm-m): 137.03
- Frequency:** 60
- Foot Resistance Calculation Method:** IEEE Std.80-2013
- Extra Resistance (shoe, glove, etc):** [Empty]
- Foot Resistance:** [Empty]
- Reference Soil Surface Covering Resistivity:** 1000
- IEC Options:** IEC Standard Revision: 2005, Body Resistance Curve: 95% of Population Exceeds Curve, Contact Moisture: Dry
- Reference Insulating Surface Layer:** Surface Layer Thickness: 4 Inches, Surface Resistivity (Ohm-m): 3000, No Surface Layer Is Installed (unchecked)
- Decrement Factor:** Default (selected), User-Defined, Computed
- X/R Ratio:** [Empty]
- Decr. 1:** [Empty]
- Decr. 2:** [Empty]
- Decr. 3:** [Empty]
- Safety Limits (Volts):** Safe Touch Voltage: 672.0, Safe Step Voltage: 2219.9
- Save Settings:** for MALZ Only (selected), for MALT, MALZ and HIFREQ
- Buttons:** Generate Safety Threshold Limits and Report, Load Argon Software..., Reset, OK, Cancel

Figure 5: Safety Thresholds for Cyclone Substation

Design of substation ground system

After all the data was collected, the soil model was created, and all the client's specifications were made, the grounding system was 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.

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.

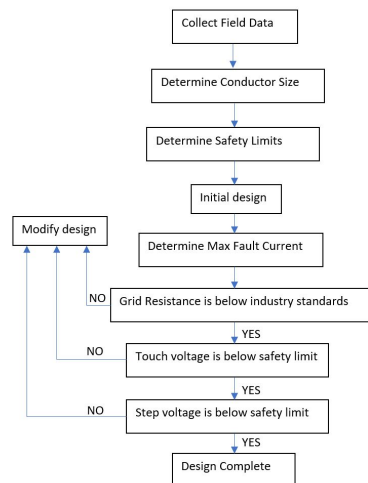


Figure 6: Flow Diagram for Grounding Design

2.2 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 designed this substation for future expansion to a breaker-and-a-half configuration. 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, the phases were required to be 8 feet apart on the high side 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 7: Termination Towers with H-Frames

Orientation of the Substation

Along with the placement of the H-Frames, the orientation of the substation needed to be considered. The substation was oriented so the lines to Des Moines come out of the the low side breaker and the lines to Cedar Falls come 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 configuration, 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 were 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.

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.

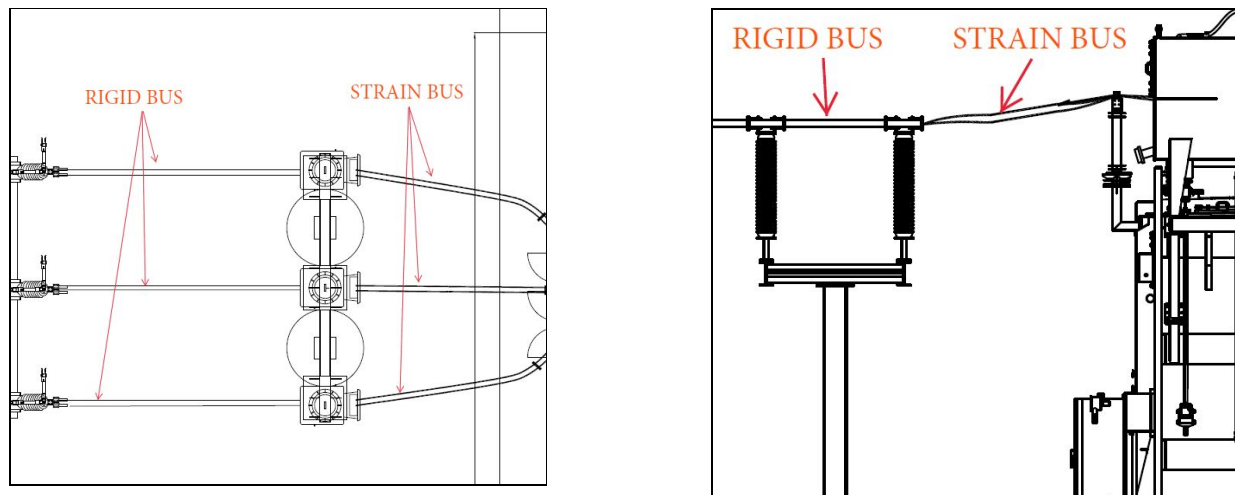


Figure 8 & Figure 9: Plan View and Elevation View of Rigid and Strain Bus

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 came last in our drafting process because we needed 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 lightning 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

2.3 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 the Substation Design 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.

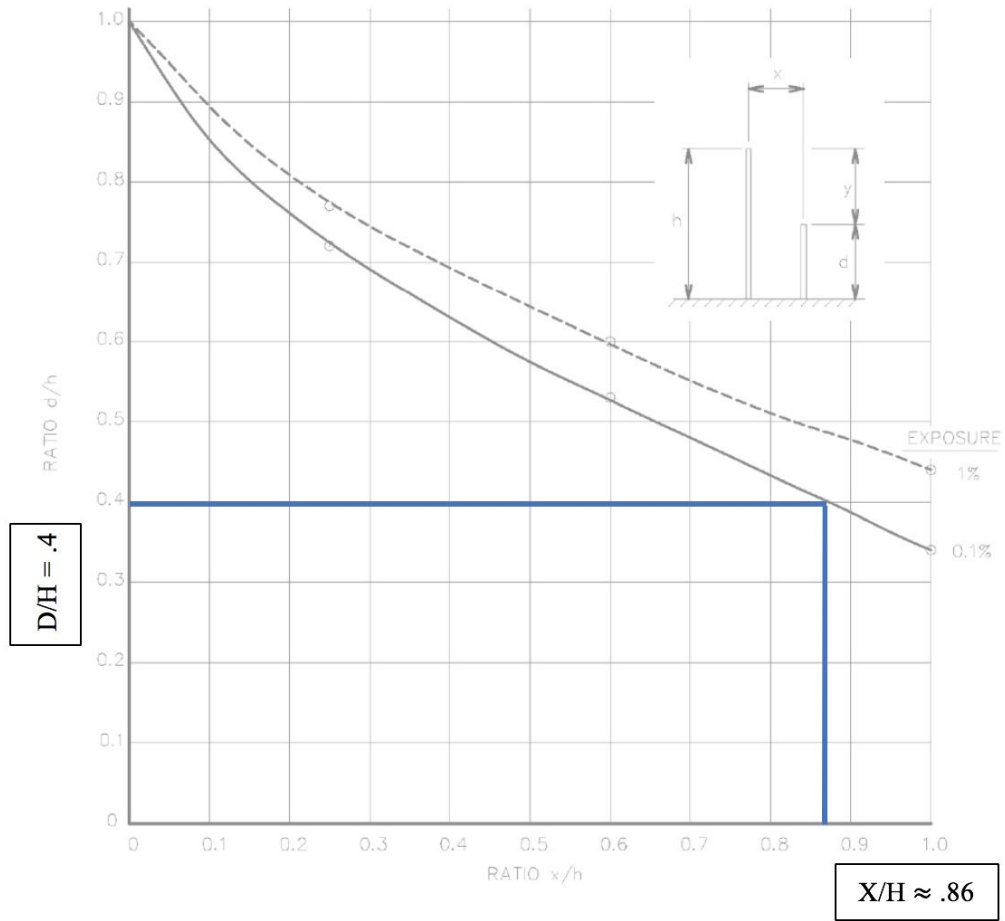


Figure 10: Exposure Curve to Determine X/H

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.

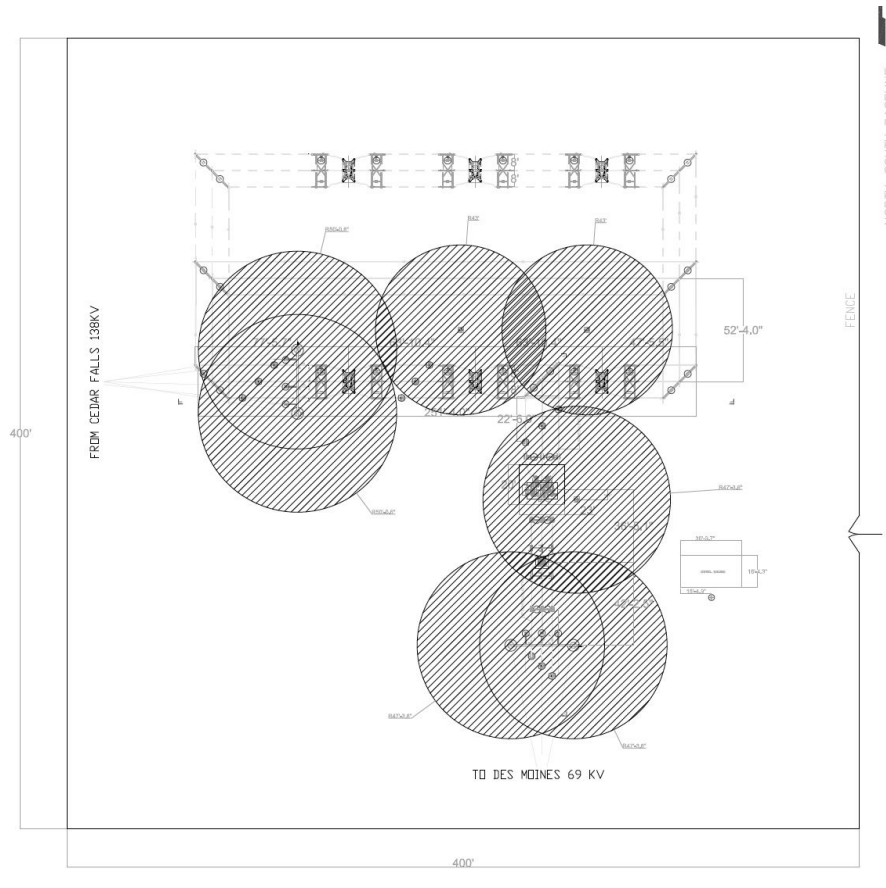


Figure 11: Initial Lightning Protection Design

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.

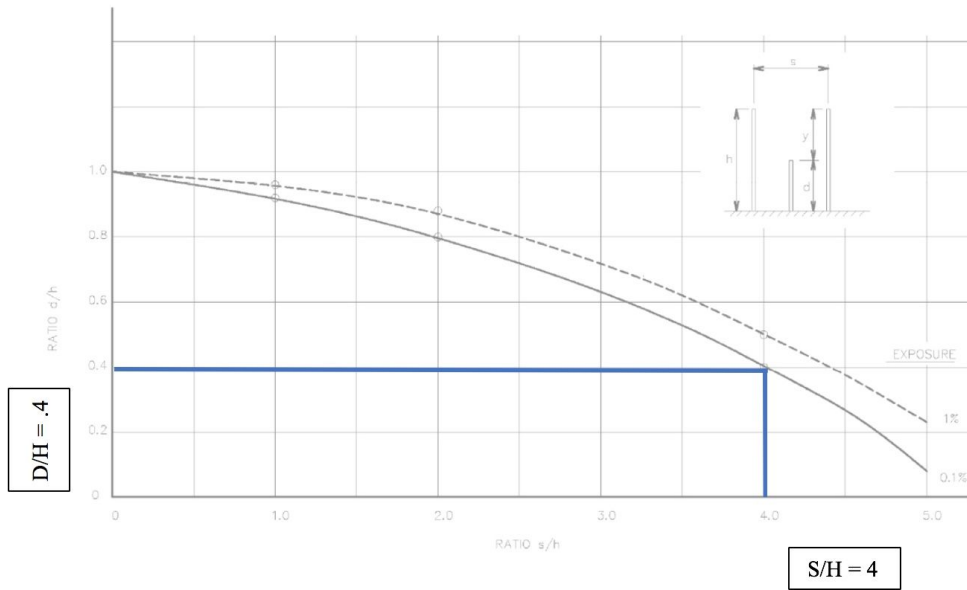


Figure 12: Exposure Curve to Determine S/H

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.

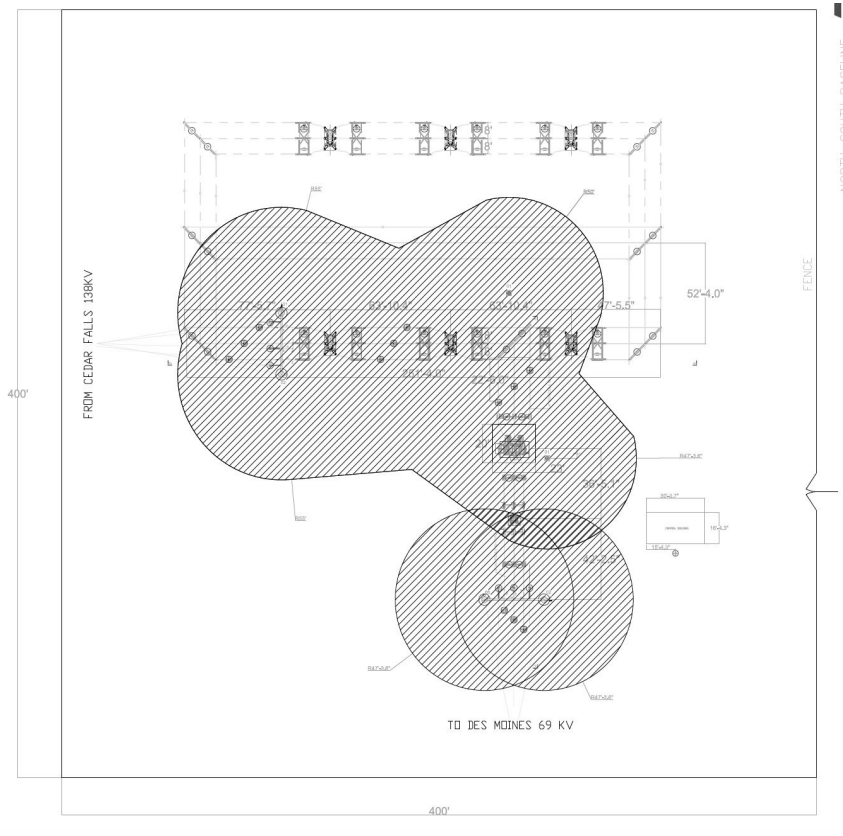


Figure 13: Optimized Lightning Protection Design

2.4 AC Study

To begin the AC Study, all AC loads associated with this substation, including existing and future loads were tabulated. An example of how this was performed is listed below.

Existing Panel		AC-1		200 A Main Bus		200 A Main Breaker						
Volts		240 Y/120V		3 Phase		10kA SYM. A.I.C. Minimum						
Feed via		Cu AWG 2 Directly Buried		4 Wire		NEMA 1 Enclosure						
				Surface Mounted								
Pole No.	Trip Amps	No. Pole	Wire	Load Served	Load - kVA			Pole No.	Trip Amps	No. Pole	Wire	Load Served
					Ø1	Ø2	Ø3					
1	20	1		Control House Indoor Lights (4) and Receptacles (4) (120v)	0.82			2	20	2		Flood Lights (4) 240v
3	20	2		Control House Outdoor Security Lights (2) (240v)	0.50	0.30		4				
5						0.50		6	50	2		Control House HVAC Unit (240v)
7	30	1		Transformer Heaters, Outlet, and Lamps (120v)	1.39			8				
9	30	2		Transformer Fan Motors (240v)	4.00			10	20	1		Transformer Pump (120v)
11						1.15		12	30	1		Future Transformer Heaters, Outlet, and Lamps (120v)
13	30	2		Future Transformer Fan Motors (240v)	1.88			14	20	1		Future Transformer Pump (120v)
15						1.15		16	20	1		#1 69kV Breaker Lights/Receptacles (120v)
17	30	2		#1 69kV Breaker Heaters (240v)	0.25			18	20	1		#2 69kV Breaker Lights/Receptacles (120v)
19					0.25			20	30	2		#2 69kV Breaker Heaters (240v)
21	20	1		Future 69kV Breaker Lights/Receptacles (120v)	0.25			22				
23	30	2		Future 69kV Breaker Heaters (240v)	0.25			24	20	1		#1 138kV Breaker Lights and Receptacles (120v)
25					0.25			26	30	2		#1 138kV Breaker Heaters (240v)
27	20	1		#2 138kV Breaker Lights and Receptacles (120v)	1.50			28				
29	30	2		#2 138kV Breaker Heaters (240v)	0.25			30	20	1		#3 138kV Breaker Lights and Receptacles (120v)
31					1.50			32		2		#3 138kV Breaker Heaters (240v)
33	20	1		#4 138kV Breaker Lights and Receptacles (120v)	1.50			34				
35	30	2		#4 138kV Breaker Heaters (240v)	0.25			36	20	1		Future #1 138kV Breaker Lights and Receptacles (120v)
37					1.50			38	30	2		Future #1 138kV Breaker Heaters (240v)
39	20	1		Future #2 138kV Breaker Lights and Receptacles (120v)	1.50			40				
41	20	1		Future #3 138kV Breaker Lights and Receptacles (120v)	0.25			42	20	1		Future #4 138kV Breaker Lights and Receptacles (120v)
Total Per Phase Load (Including Existing)					17.59	10.78	11.84	Total Demand Factor <u>72.5%</u>				
Unbalance load					31.3%	19.8%	11.7%					
Total Connected Load								Total Est. Demand Load				
40.20 kVA 96.71 A								29.14 kVA 70.11 A				

Table 3: AC Loads

Once all AC loads were tabulated, a specific demand factor was incorporated to calculate the maximum estimated kVA demand, at the worst case scenario. The worst case scenario turned

out to be winter at night, as all security lights and equipment heaters are assumed to be on. An example of how this was performed is displayed below.

Demand Factor Calculation									
EQUIPMENT:	AC-1								
	240								
LOAD TYPE	Ø1			Ø2			Ø3		
	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)
Control House Indoor Lights (4) and Receptacles (4) (120v)	0.62	0.30	0.19						
Flood Lights (4) 240v	0.50	1.00	0.50						
Control House Outdoor Security Lights (2) (240v)				0.30	1.00	0.30			
				0.50	1.00	0.50			
Control House HVAC Unit (240v)							0.30	1.00	0.30
							4.00	0.50	2.00
Transformer Heaters, Outlet, and Lamps (120v)	1.39	0.90	1.25						
	4.00	0.50	2.00						
Transformer Fan Motors (240v)				1.15	1.00	1.15			
Transformer Pump (120v)				1.68	0.50	0.84			
Future Transformer Heaters, Outlet, and Lamps (120v)							1.39	0.90	1.25
Future Transformer Fan Motors (240v)	1.15	0.10	0.12						
Future Transformer Pump (120v)	1.68	0.50	0.84						
#1 69kV Breaker Lights/Receptacles (120v)				1.15	0.10	0.12			
#1 69kV Breaker Heaters (240v)				0.25	0.42	0.11			
#2 69kV Breaker Lights/Receptacles (120v)							0.25	1.00	0.25
#2 69kV Breaker Heaters (240v)	0.25	1.00	0.25				0.25	0.42	0.11
Future 69kV Breaker Lights/Receptacles (120v)									
Future 69kV Breaker Heaters (240v)				0.25	0.42	0.10			
#1 138kV Breaker Lights and Receptacles (120v)				0.25	1.00	0.25			
#1 138kV Breaker Heaters (240v)	1.50	1.00	1.50						
#2 138kV Breaker Lights and Receptacles (120v)				0.25	0.42	0.11			
#2 138kV Breaker Heaters (240v)				1.50	1.00	1.50			
#3 138kV Breaker Lights and Receptacles (120v)							1.50	1.00	1.50
#3 138kV Breaker Heaters (240v)	1.50	1.00	1.50				0.25	0.42	0.11
#4 138kV Breaker Lights and Receptacles (120v)				0.25	0.42	0.11			
#4 138kV Breaker Heaters (240v)				1.50	1.00	1.50			
Future #1 138kV Breaker Lights and Receptacles (120v)							1.50	1.00	1.50
Future #1 138kV Breaker Heaters (240v)	1.50	1.00	1.50				0.25	0.42	0.11
Future #2 138kV Breaker Lights and Receptacles (120v)				0.25	0.42	0.11			
Future #2 138kV Breaker Heaters (240v)				1.50	1.00	1.50			
Future #3 138kV Breaker Lights and Receptacles (120v)							0.25	0.42	0.11
Future #3 138kV Breaker Heaters (240v)							1.50	1.00	1.50
Future #4 138kV Breaker Lights and Receptacles (120v)							0.25	0.42	0.11
Future #4 138kV Breaker Heaters (240v)							1.50	1.00	1.50
TOTAL:	14.59	69.51%	10.14	9.03	72.83%	6.57	11.34	76.04%	8.62

Table 4: Demand Factors Table

In doing these calculations, the total estimated demand load kVA that the station service will have to supply was found to be 39.94kVA. Therefore, the client shall select a station service transformer that can accommodate this expected kVA demand. The standard size transformer that meets this demand is rated at 50 kVA, which should adequately provide for station service. If a 50kVA is not readily available, it is common to select a 75kVA transformer.

Conductor Design

The conductor should be sized based upon the maximum current the SL&P transformer can supply. That will guarantee the cable to be large enough if more AC loads are added. This current can be calculated from:

$$P = V * I * \sqrt{3}$$

Where, $P = 50\text{kVA}$, $V = 240\text{v}$. Solving for I gets 120.28 A .

Utilizing table 310.15(B)(16) from the National Electric Code tells us that our wire should be of size AWG 2 to satisfy ampacity.

BMcD requires a maximum voltage drop along the conductor of 4.5%. We will utilize the following equation to verify that AWG 2 Cu is large enough to prevent a voltage drop greater than 4.5%.

$$A = \rho \cdot I^2 L / V$$

A = area in cmils

ρ = Resistivity of Copper in $\Omega \cdot \text{cmil}/\text{ft}$

L = length of conductor in feet

V = Allowable Voltage Drop

This equation is based upon $R = \rho \cdot L / A$, where resistance of a conductor may be calculated.

$$\rho = 10.37 \Omega \cdot \text{cmil}/\text{ft}$$

$$I = 120.28\text{ A}$$

$$V = 120\text{ V}$$

$L = 100\text{ft}$ (Length from SL&P transformer to AC panels.

This gives us an area of $46,088.88\text{ cmils}$. This is in between AWG 3 and 4.

To satisfy voltage drop, our wire would have to be AWG 3. However, our ampacity has dictated AWG 2, so AWG 2 should be selected.

2.5 DC Study

The DC system is a key component of an electrical substation. The DC system provides auxiliary control power for communication and control equipment, relays and supervisory control and data acquisition (SCADA) equipment. It also provides the power required to trip and reclose circuit breakers, circuit switchers and motor-operated disconnect switches. The DC system is comprised of a battery set, a battery charger, DC panelboards, DC wiring and a battery disconnect.

DC loads are totaled and classified in order to size the batteries, chargers and panels used in the DC system. The control building will be sized to accommodate the 125V DC battery and charger. The design must follow the guidelines of IEEE 485-2010. The minimum cell voltage has been specified as 1.75V/cell and the EnerSys PowerSafe CC-M battery shall be used in the design. This battery features calcium plates, demonstrating maximized performance and reduced watering requirements in long discharge use. This type of battery has a capacity range of 50-200Ah. The Amp-hour requirements are to be calculated in accordance with the equations presented in IEEE 485-2010 and the battery selection to be made based on the cell sizing worksheet, completed using the outcomes of the duty cycle analysis.

The typically worst case scenario included a bus fault, assuming all bus breaker trip coils operate for 1 minute. The worst case scenario looked at in this study includes a breaker failure connected to the high side of the transformer. In this situation, the backup breakers would be

the other two breakers on the high side and the one on the low side. This breaker failure, followed by a transformer lockout, would take out the two high side breaker and low side breaker used as backup for the first breaker failure.

The worst case scenario being analyzed for this study takes into account the possibility of multiple problems occurring within a short period of time. Typically, the worst case scenario includes a bus fault. The worst case scenario looked at in this study includes a breaker failure connected to the high side of the transformer. The backup for this worst case scenario would be the other two breakers on the high side and the one on the low side, followed by a transformer lockout. This would in turn take out the two high side breakers and low side breaker used as backup for the first breaker failure.

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

Period	Loads	Total Amperes	Duration	Amp-Hours
A1	L1+L2	52.56	1	0.876
A2	L2	4.56	480	36.48
A3	L2+L3	6.096	475	48.26
A4	L2+L3+L4	13.696	1	0.23
A5	L2+L3+L5	180.096	1	3.0016
A6	L2+L3+L6	6.296	4	0.42
A7	L2+L3+L7	N/A	7	

Total=89.27
Ah

Table 5: Loads, Amperes, Duration, and Amp-Hours for Duty Cycle

From the previous Table 5, a duty cycle can be shown as the following figure.

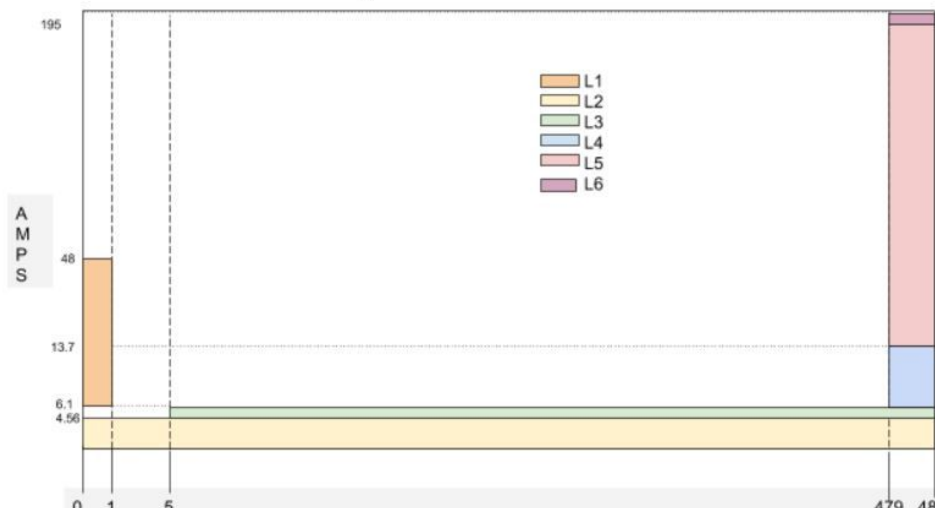


Figure 14: Duty Cycle

The DC system designed for the Cyclone substation has been sized to include all necessary DC loads in the yard and control house. The duty cycle diagram was created in order to analyze the 8-hour period over which various DC loads would be necessary. The worst case tripping scenario analyzed for this study was a bus fault, assuming that the bus breaker tip coils would all operate for one minute. It was decided that the emergency lighting in the control house would turn on after a five minute delay period to ensure that a momentary outage is not taking place. The DC system was designed with the worst case tripping scenario in mind and a margin was put in place to ensure the system would outlast future issues involving temperature change and the age of the batteries, as well as a general design margin of 10%. Throughout the design process, IEEE standards were referenced and industry standards put into use.

The DC system has been designed in order to support all DC loads inside the control house, as well as in the yard, over an 8 hour duty cycle. The Enersys 3CC-5M batteries are utilized in order to support this load such that no AC power is available to supply the batteries with a constant charge. The battery charger size was calculated to ensure the recharging period of the batteries would stay under 24 hours. The Hindle AT10 Battery Charger was selected in order to recharge the DC batteries to their full capacity in under 15 hours.

2.6 One-line

The creation of the One-Line is the primary overview of the whole protection and controls design. To create this, the protection document and the physical design of the substation were needed. The protection document contained the information on how all of the relays are connected and how they connect to all of the equipment in the yard. The primary draft was created in Visio and sent to the client for notes and revisions. The preliminary draft can be seen below in Figure 15.

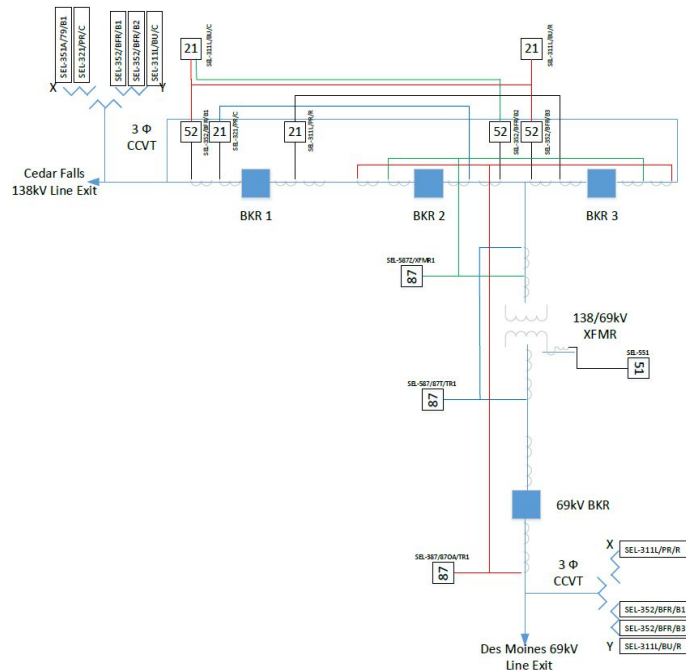


Figure 15: Preliminary One-Line Draft Sent to the Client

After I sent this draft to the client, there were several emails and phone calls back and forth regarding the design. We added directional relaying on the low side of the breaker instead of the original monitoring of the bus 138kV. I also added the Station Service Transformer on the tertiary winding of the transformer, and revised some of the ANSI device number. The final preliminary One-Line in Visio can be seen below.

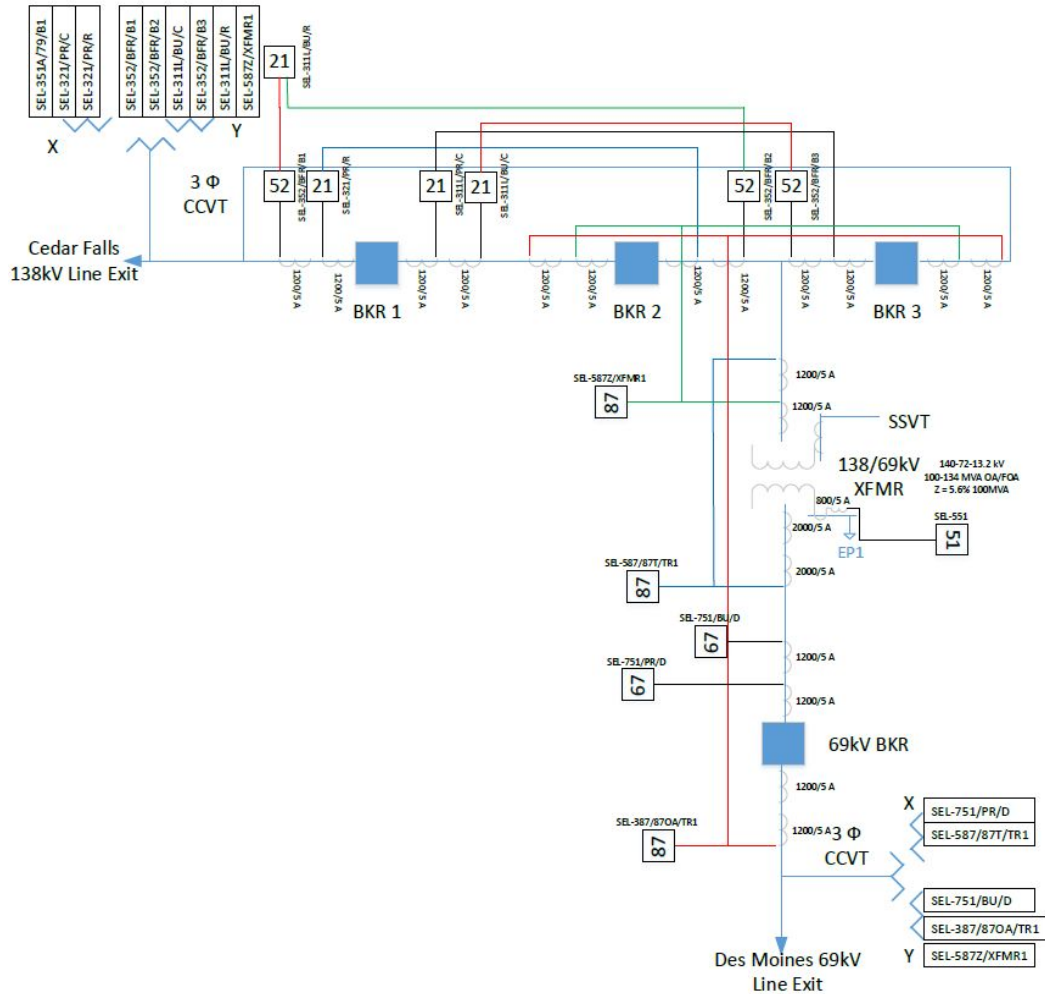


Figure 16: Final Preliminary Draft of the Protection and Controls One-Line

Once the preliminary draft of the One-Line was completed, then the one-line was drafted in AutoCAD to make the drawing consistent with the style and formatting provided by Burns and McDonnell. The Preliminary draft was the basis for the AutoCAD drawing. The first draft of the One-Line can be seen below.

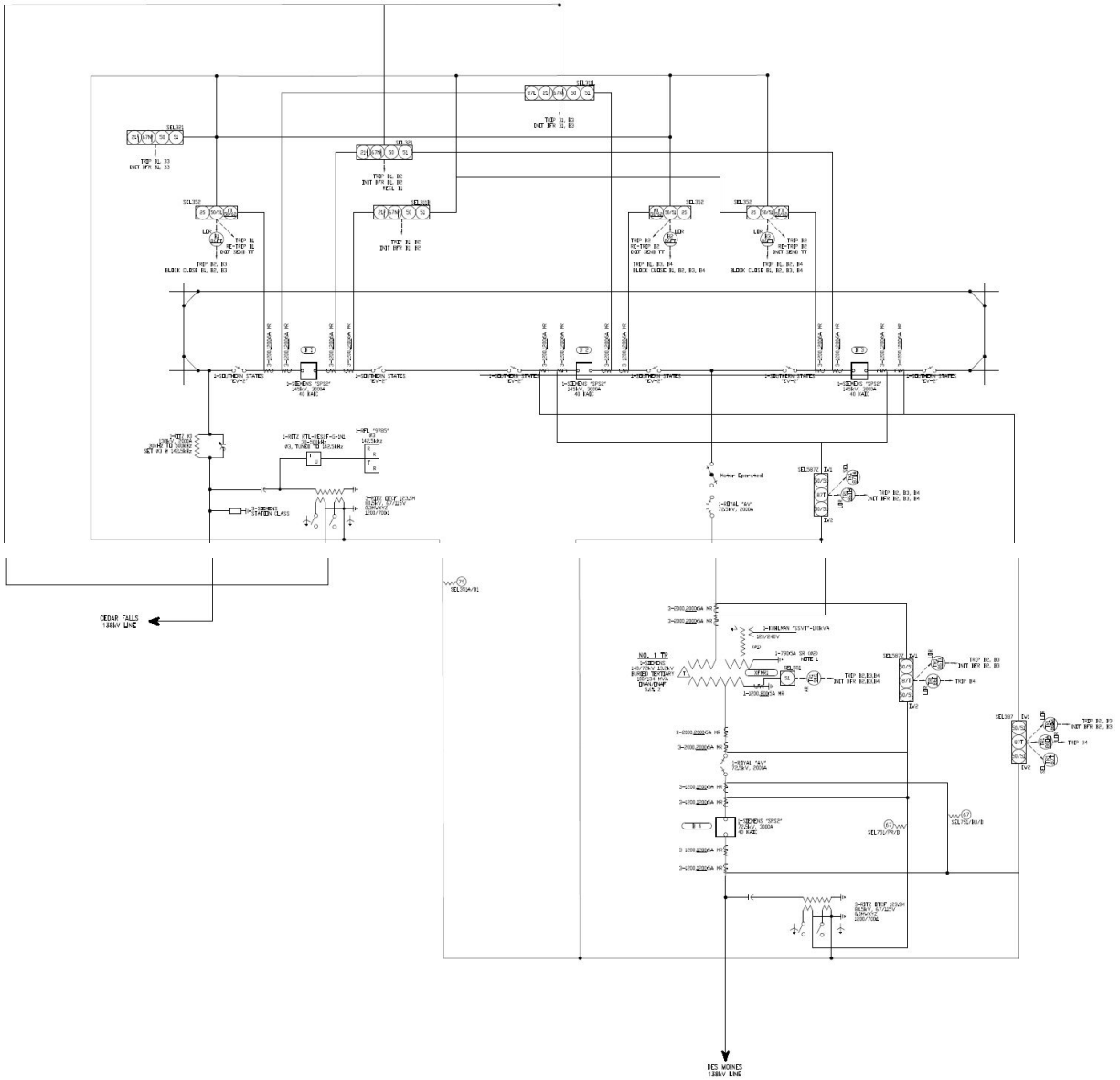


Figure 17: First Draft of the One-Line Diagram in AutoCAD

The first draft was revised several times after the CCVT was added on the high side of the transformer. The connections to the PTs were also changed to show the correct potential circuit diagrams. A border was also added to be consistent with the other drawings. The final draft can be seen below in figure 18.

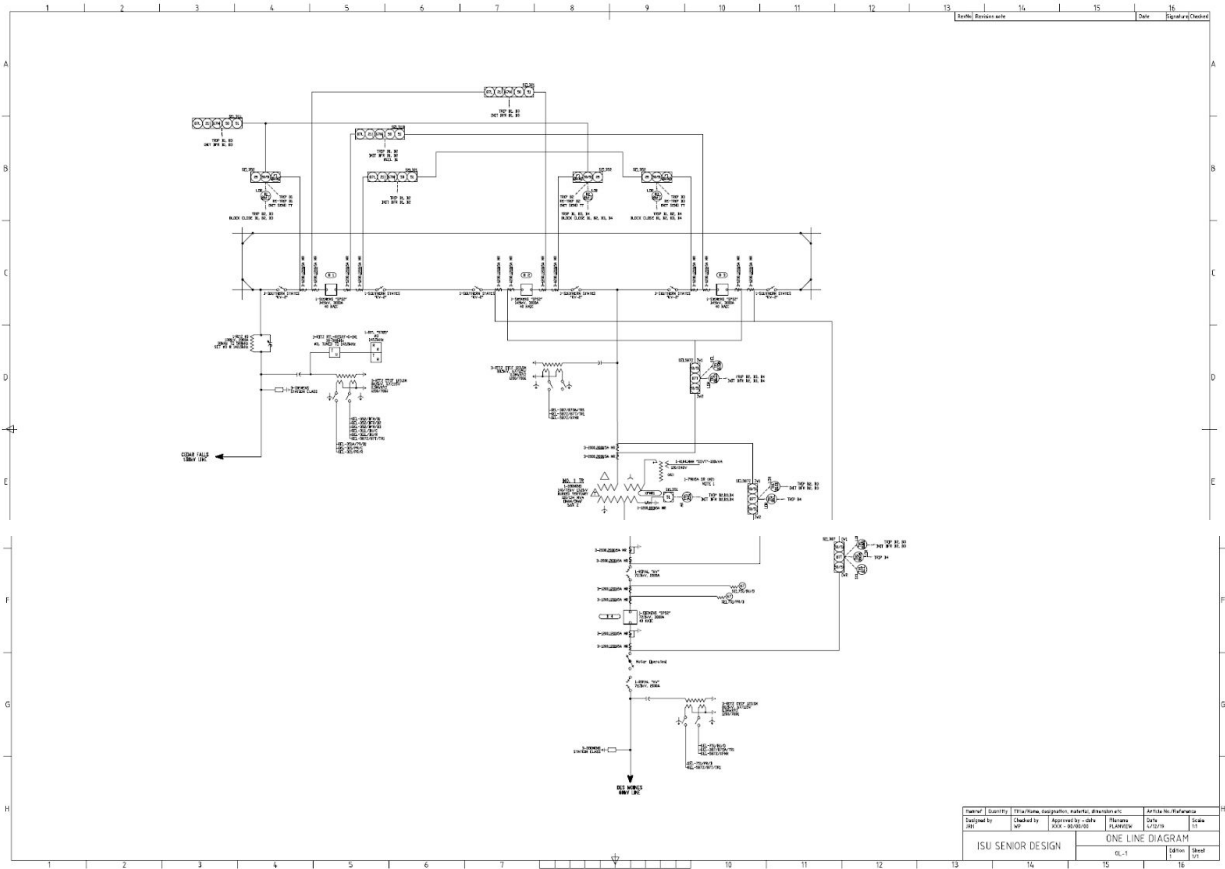


Figure 18: Final Draft of the One-Line Diagram

2.7 Transformer Schematics

The seventh task our team completed was the design of the AC and DC schematics for transformer and all interactions between each component. The sections we completed are as follows.

- I. Transformer Differential Relaying DC Schematic
- II. Transformer Lead Differential Relaying DC Schematic
- III. Overall Differential Relaying DC Schematic
- IV. Ground Overcurrent Protection
- V. All Subsequent AC Schematics

Development of All DC Schematics

There were two factors that played into the design of the DC transformer schematics. They are as follows:

- I. Equipment needed
- II. Interactions between equipment

Equipment Needed

To begin the drafting process, we needed to gather all equipment specifications needed to satisfy the protection requirements. For the transformer DC schematics, there are two major components for each drawing. The table below highlights all the major pieces of equipment:

DC Schematic	Equipment
138/69 kV Transformer Differential Relaying	SEL-0587103X5X1
	Electroswitch "LOR", (86T/TR1)
	Electroswitch "LOR", (86TX/TR1)
138/69 kV Transformer Lead Differential Relaying	SEL-0587Z0X325H12XX
	Electroswitch "LOR", (86TH/TR1)
138/69 kV Transformer Overall Differential Relaying	SEL-038750-4X5HXX4XX
	Electroswitch "LOR", (86OA/TR1)
	Electroswitch "LOR", (86OAX/TR1)
138/69 kV Transformer Ground Overcurrent Protection	SEL-055100-3X5X1X
	ABB "AR" Aux tripping relay

Table 6: Equipment in Transformer Schematics

After determining all the major pieces of equipment needed to complete each schematic, we were able to begin drafting. First, we placed the equipment in each draft, then we looked to the interactions between the SEL devices and each breaker and transformer.

Interactions between equipment

After the first step in the draft process, we turn to the interactions between contact points of each device. There are two separate ways to determine all of the contact assignments. The first is by looking at the one-line diagram. The one-line diagram shows how each relay interacts with all breakers, transformer and other relays. For example, the figure below shows the outputs for this specific SEL device.

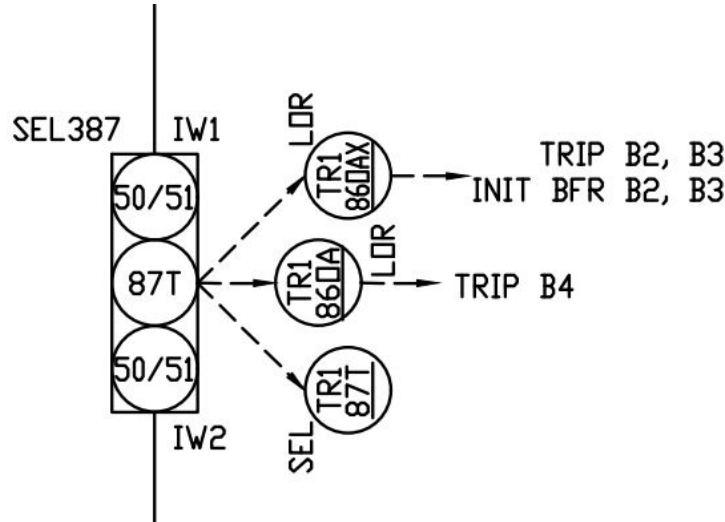


Figure 19: One-line Depiction of SEL-387 Contact Assignments

Each of the contacts shown to the right of the device have to be reflected on our DC schematic diagram. As you can see above, the SEL-387 device has interactions with two lockout relays and one SEL relay device. This can also be found by looking at the protection requirement document that our client provided us with. This can be seen in the figure below:

138/69kV Transformer (XFMR1) Overall Differential Relaying

1- Schweitzer “SEL-038750-4X5HXX4XX” (87OA/TR1) current differential relay. New, to be used for XFMR1 overall differential protection.

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

CT – 69kV Bkr B4, line-side, top CT, 1200/5 (240/1) [Input to I_W1]
 CT – 138 kV Bkr B2, line-side, top CT, 1200/5 (240/1) [Input to I_W2]
 CT – 138 kV Bkr B3, line-side, top CT, 1200/5 (240/1) [Input to I_W3]

Output Contact Assignments:

OUT101 – Trip 86OA/TR1 & 86OAX/TR1 Lockout Relays
 OUT102 – SEL587 (87T/TR1), IN2
 OUT103 – spare
 OUT104 – spare
 OUT105 – spare
 OUT106 – spare
 Alarm – SCADA Relay Failure

Input Contact Assignments:

IN101 – 138kV Bkr B2 (52a)
 IN102 – 138kV Bkr B3 (52a)
 IN103 – 69kV Bkr B4 (52a)
 IN104 – SEL587 (87T/TR1). OUT 2
 IN105 – spare
 IN106 – spare

Figure 20: Protection Requirement for SEL-387

As you can see, the output contact assignments reflect what was drafted on the one-line diagram. This double-verification method allows the team to move through these drafts without confusion and remain confident in what they are doing. The final product is seen below in Figure 21. We then repeated these steps to create similar drawings which can be found in section 3.5.7.

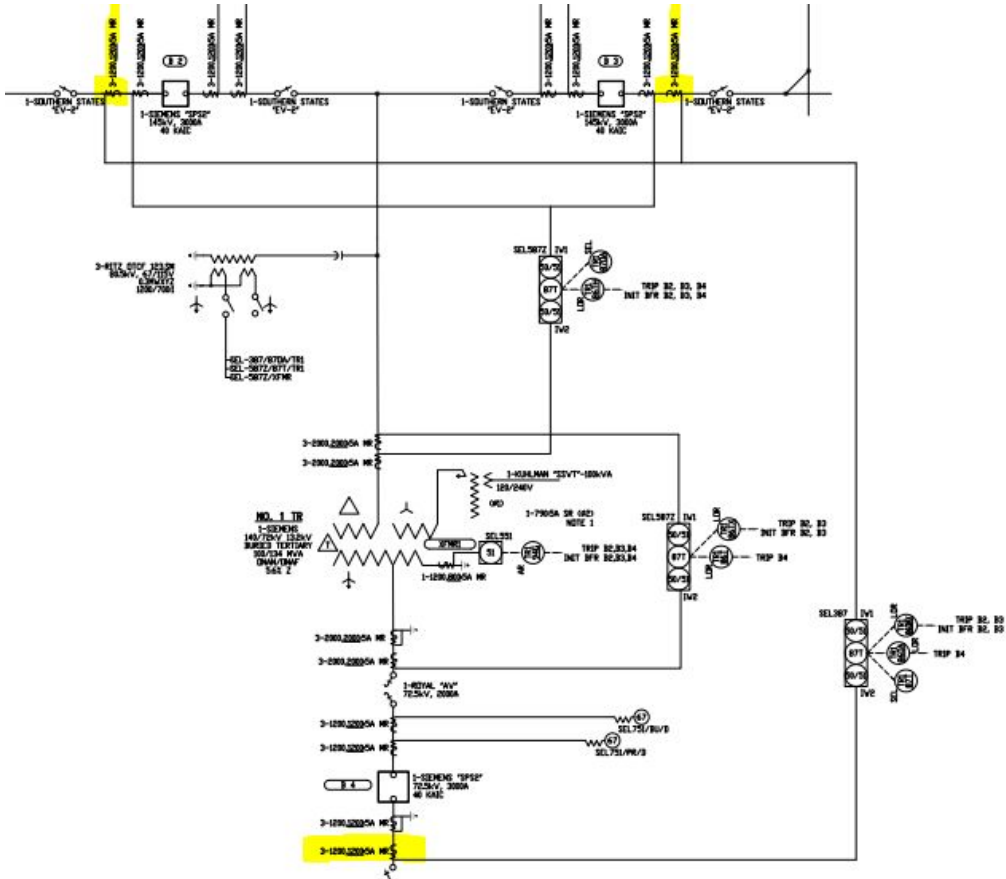


Figure 22: SEL-387 AC CT Contacts

After we determined the CT contacts for the device, we were able to draft the AC portion of that relay. It was quite simple, but required coordination with the breaker schematics. This coordination meant that what we had drafted had to show the same on the breaker AC schematics. Below in Figure 23, you will find the completed AC schematic for the SEL-387 relay. This process was continued for all SEL devices and can be found in section 3.5.7.

SEL-387
870A/TR1

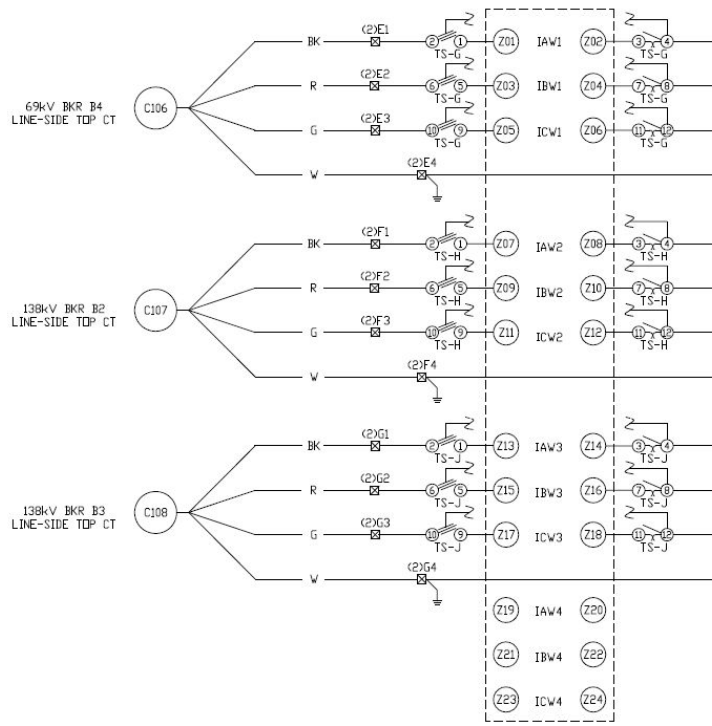


Figure 23: SEL-387 AC Schematic

2.8 Breaker Schematics

The breaker schematics were created for all four breakers at this substation. There are three 138kV breakers and one 69kV breaker. The breaker schematics were based off of the one-line diagram and the protection requirements document.

First, when designing the breaker schematics, there was a phone call with the client regarding the formatting and style for the schemes. Also, on the phone call, the process of adding the appropriate contact inputs and outputs was discussed to give a solid starting point for the schematics. The first step after that was to add test switches and the outputs for the breaker relays. The outputs and the inputs for the relays were in the protection requirements document and the desired outputs can be seen below in figure 24.

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

Output Contact Assignments:

OUT101 – Trip 138kV Bkr B1 86BFT aux relay

OUT102 – Re-trip Bkr B1

OUT103 – Enable Bkr B1 Close (Sync Check)

OUT104 – Init Send TT (Des Moines Line)

OUT105 – Init Send TT (Cedar Falls Line)

OUT106 – spare

OUT107 – spare

Input Contact Assignments:

IN101 – Bkr B1 Breaker Failure Initiate

IN102 – Bkr B1 Status – 52/a contact

IN103 – spare

IN104 – spare

IN105 – spare

IN106 – spare

Electroswitch series 24 switch to be used as a Failure to Trip cutoff switch (FT/CO). This switch shall be utilized to disable the Failure to Trip relaying for testing and maintenance. Escutcheon to read “ON” and “OFF” with the “ON” position to be in the twelve o’clock position.

Electroswitch series 24 Lock-Out Relay (86BF/B1)

Contacts to be utilized as follows:

- Trip Bkr B2 and Block Close
- Trip Bkr B3 and Block Close
- Block Close Bkr B1
- Send DTT to Des Moines via primary SEL311L
- Send DTT to Des Moines via backup SEL311L
- Stop Carrier on Cedar Falls Line
- SCADA Indication (closed in “OFF” position)

Figure 24: Breaker B1 Output and Input Tables

The Outputs would then be added to the appropriate places in the schematics, so for example the trip B1, would be added to the first tripping circuit for breaker B1. To complete this, coordination within the group was needed, especially for the status contact points and the Init Send contacts.

The inputs for the relays were a little bit more tricky, as the breaker failure initiate came from many different sources. In the case of breaker B1, the primary and backup line differential relaying were input contacts for IN101, so the Des Moines primary and backup and the Cedar Falls primary and backup output contacts on the line differential relays were all input contacts for the breaker failure initiate. These inputs required a thorough understanding of the schematics and what should prevent or allow the breaker failure relaying to be initiated.

The next part on the breaker schematics was the lock-out relays, shown at the bottom of figure 24. These lock-out relays needed to have their contacts inserted on multiple other drawings, so

that the functions were fulfilled. These lock-out relays were slightly tricky to deal with and there was a lot of coordination needed to completely implement them into the drawings.

Next, the tripping and block close circuits needed to be completed. The tripping circuits had contacts from many different sources, including the breaker failure relay, the line differential relay, the lock-out relays, and the auxiliary transformer relays. The tripping circuits has normally open contacts all in parallel, so that when any contact is closed, the tripping coil in the breaker is energized and the breaker is opened. For the block close circuit, there are normally closed contacts all in series.

Lastly, once all of the DC components were completed, the AC schematics were created. The AC schematics were based off of the One-Line and showed the connections from the three phases of the bus to the Current Transformers to the current inputs on the relays. Below the submittal for breaker B1 can be seen in figure 25. The other completed drawings can be found in section 3.5.8.

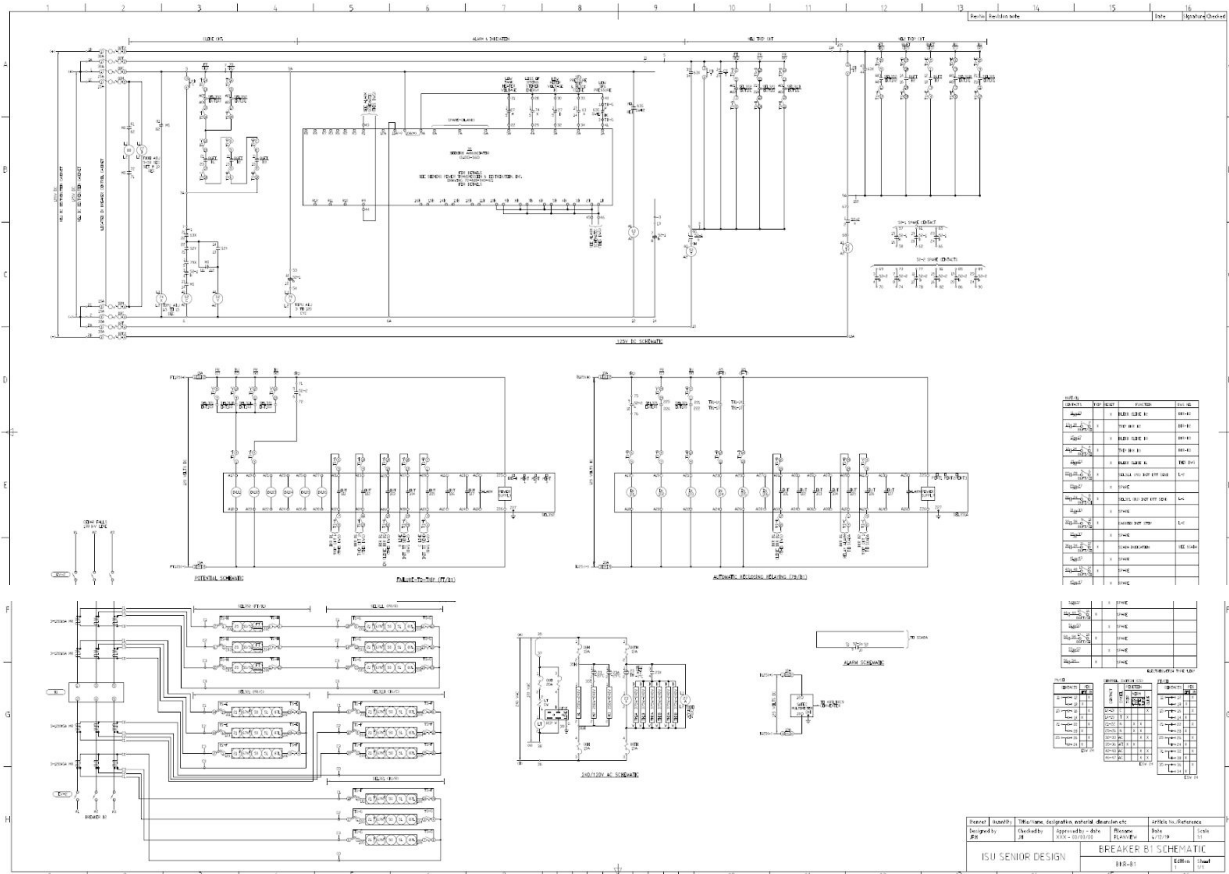


Figure 25: Breaker B1 Submittal

2.9 Line Differential Schematics

The process followed for line differential schematics is the same process outlined in section 2.7. The completed drawings for the line differential schematics can be found below in section 3.5.9.

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 were used to calculate critical values to remain in agreement with IEEE standards. For our project, we performed multiple studies. These studies required handwritten calculations to be made, and design criteria were then based off of these calculated values. After the handwritten calculations are done, the values were entered into software that determined specifications of equipment and regulates if the proposed design aligns with the written standards. All drawings were creating using the software AutoCAD.

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 if 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 create 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

The empirical curves method was employed to determine the lightning protection design for our substation. We were provided with an intra-company-developed Microsoft Excel program (that is used by employees of Burns and McDonnell) to confirm results found through by-hand calculations based on the empirical curves method. Additionally, the lightning protection design was done using AutoCAD.

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.

3.3.3 Protection and Controls

For the testing of all the drawings for protection and controls, a QC process was utilized to ensure accuracy and cost efficiency. We asked Burns and McDonnell for the QC process that

they use, and modified it to better suit our project. The quality review process contains 6 steps and is outlined below:

- Q1 Review: Independent evaluation of completing initial planning and preparation activities, setting study objectives, and/or conceptual design activities. Performed by a peer reviewer or review team
- Q2 Review: Independent evaluation of completing preliminary project activities. Includes written design basis for design projects and study/analysis data for report projects. Performed by a peer reviewer or review team.
- Q3 Review: Final checking of design documents. Performed by designer.
- Q4 Review: Peer review of reports and design documents. Performed by peer reviewer or review team.
- Q5 Review: Review of complete design, procurement, and/or construction packages. Performed by review team.
- Q6 Review: Review of complete design, procurement, and/or construction packages. Performed by Burns and McDonnell engineer.

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 utilized 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 Results

3.5.1 Grounding Design

As mentioned above, an iterative process was performed to optimize the grid spacing for the grounding design. We wanted to ensure that our design was created with the highest level of accuracy as well as optimize our design to keep the cost down for our client. We started with a grid spacing of 30 feet and increased by 10 feet each iteration. 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

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.

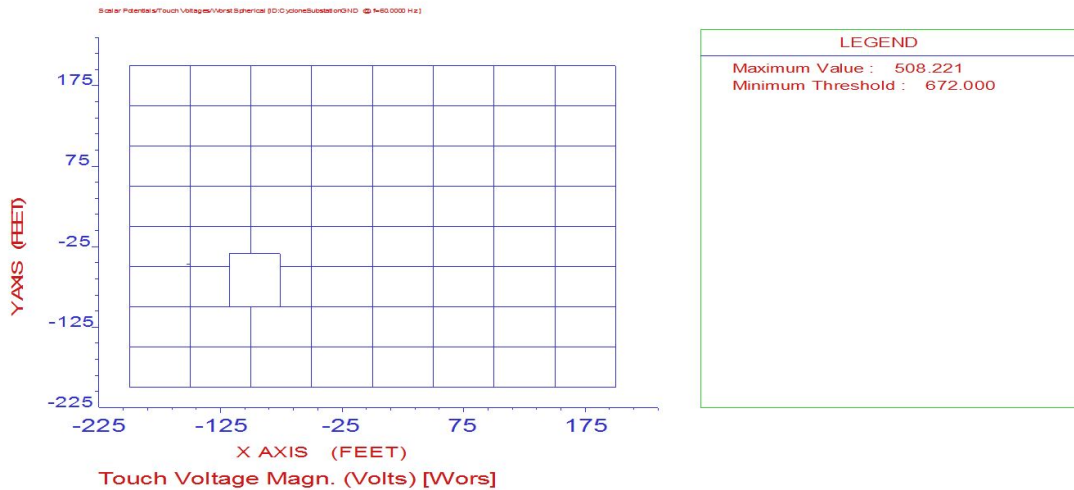


Figure 26: Touch Voltage Results with 50'x50' spacing

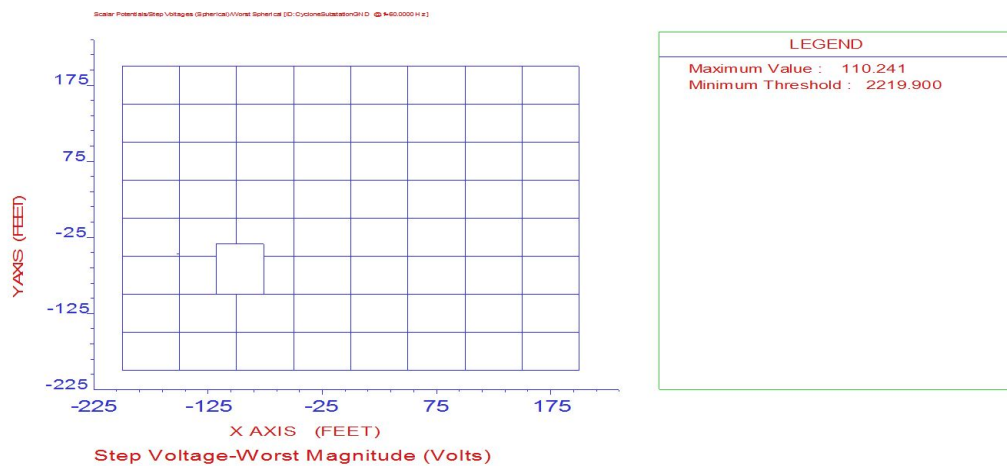


Figure 27: Step Voltage Results with 50'x50' spacing

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 28. 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 29 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

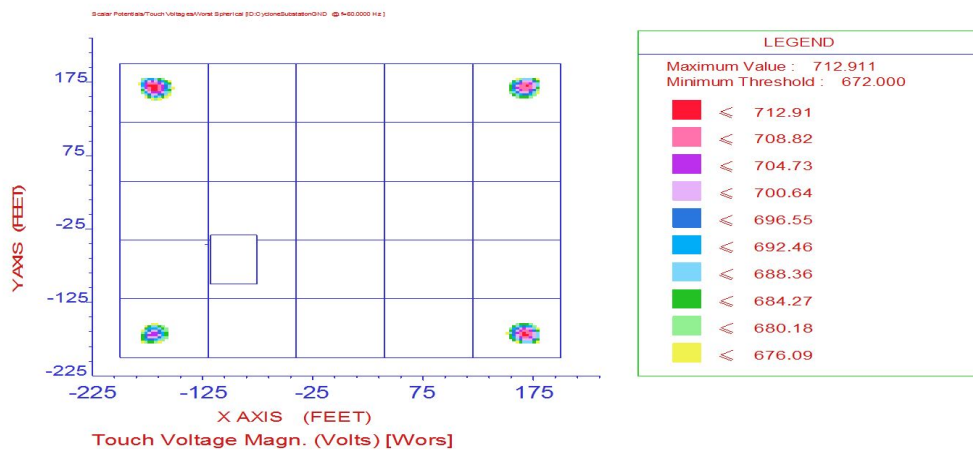


Figure 28: Touch Potential Results with 30'x30' Spacing Without Crushed Rock Layer

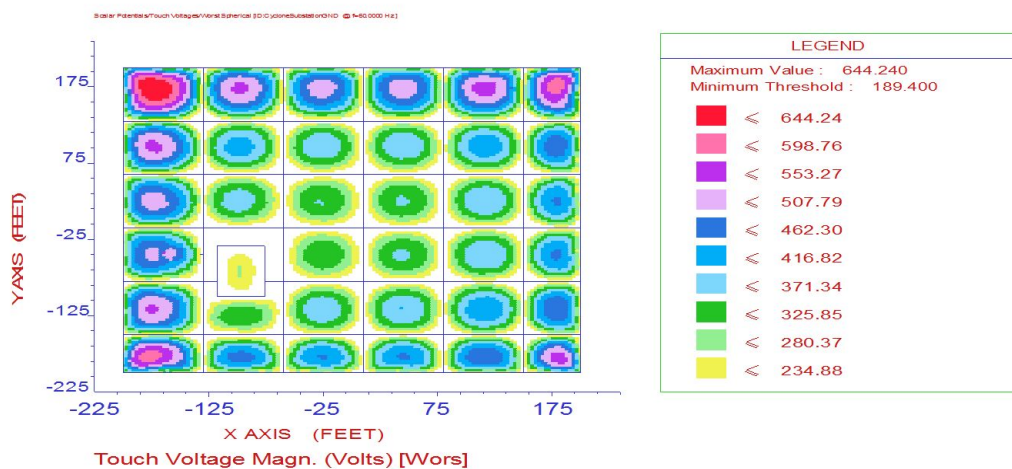


Figure 29: Touch Potential Results with 80'x80' Spacing

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.

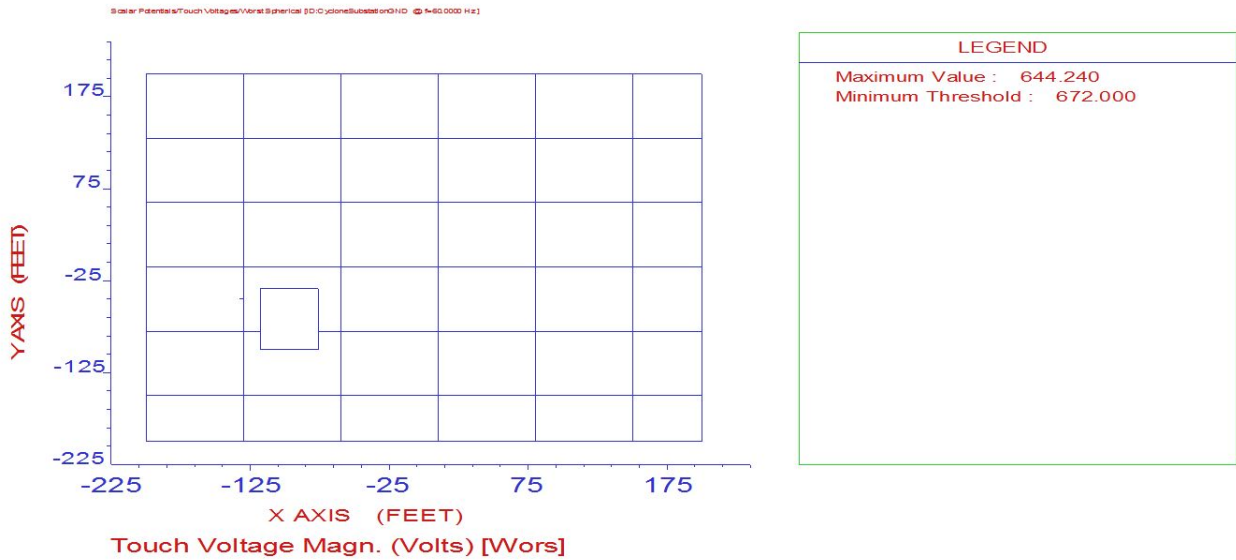


Figure 30: Touch Voltage Results for 70'x70' Spacing

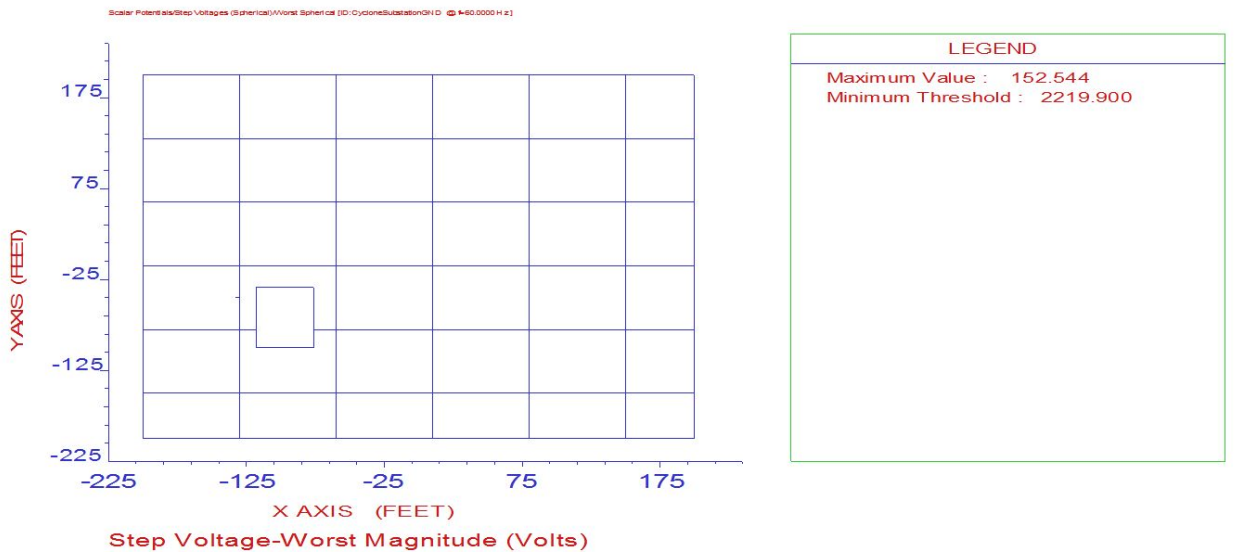


Figure 31: Step Voltage Results for 70'x70' Spacing

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 32 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 32: Impedance of Grounding System

3.5.2 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 YARD	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
	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 7: 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

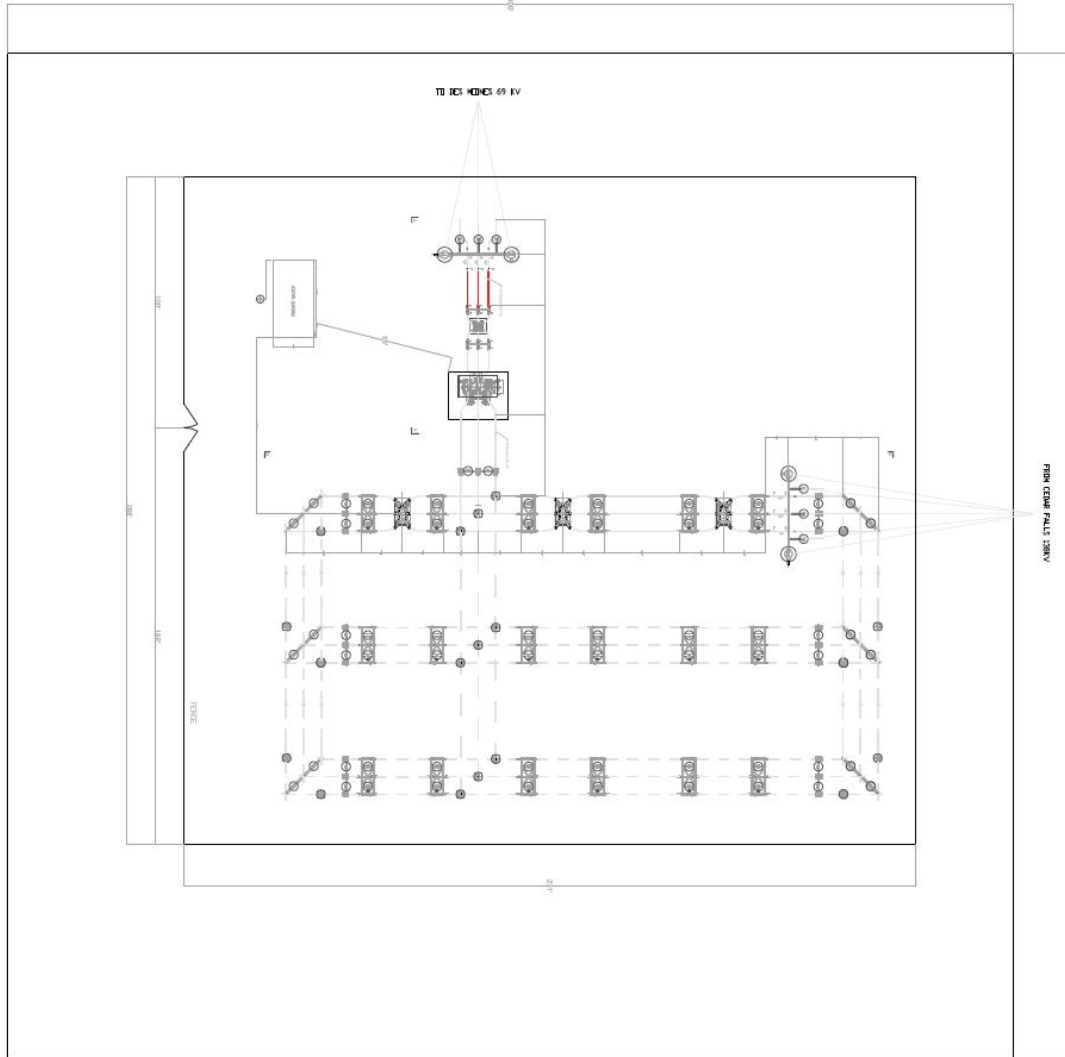


Figure 33: First Draft of Plan-View

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 8: Changes Made to Plan View

Approved plan-view

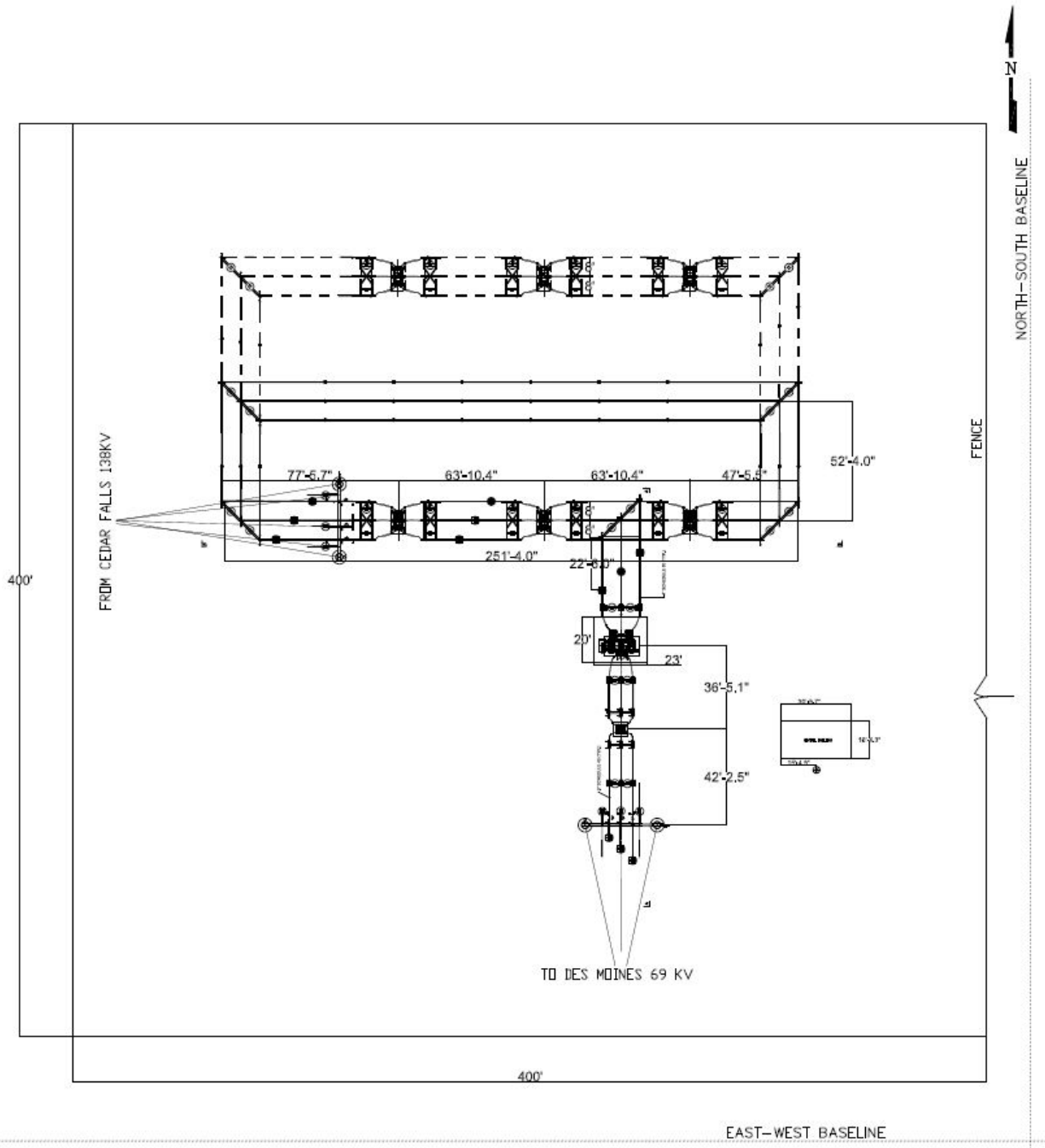


Figure 34: Approved Plan View

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

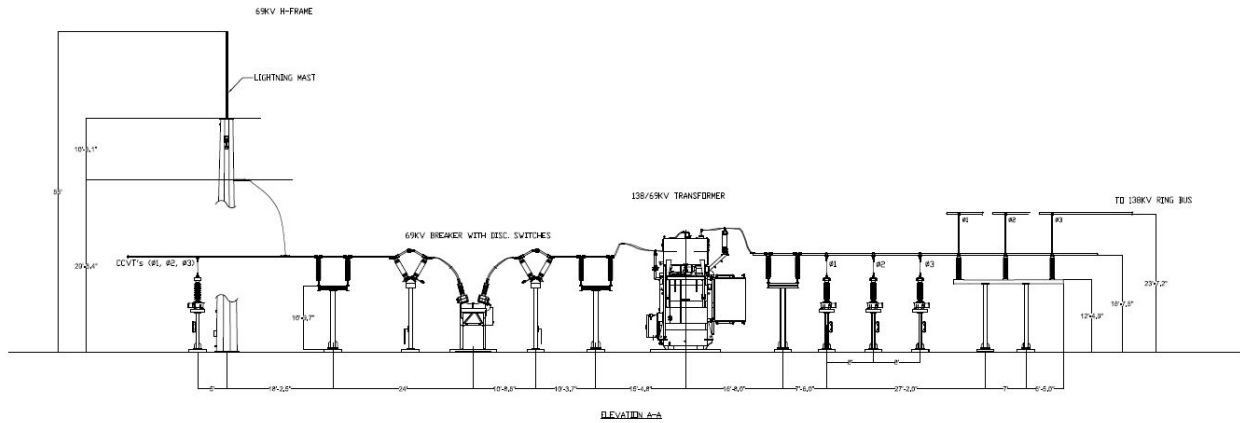


Figure 35: First Draft of Elevation A-A

First draft of elevation B-B

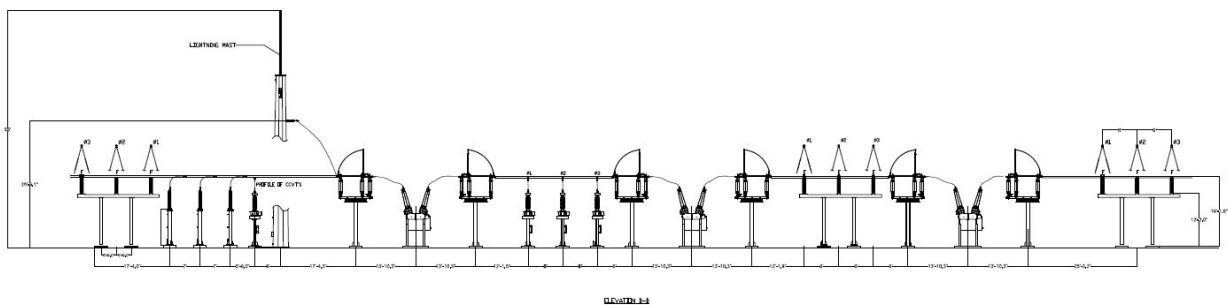


Figure 36: First Draft of Elevation B-B

3.5.3 Lightning Protection Design

Design of lightning protection

To go along with the lightning protection report, we also needed to draft a lightning protection drawing. A simple explanation of the purpose of lightning protection was to ensure that there were enough masts and/or shielding wires in place to ensure that if lightning struck the substation, the lightning strike would hit the highest point/s within the substation, absorbing the shock and dissipating it into the earth, as opposed to striking the expensive equipment. There are lightning masts on each H-Frame termination structure; there is one such structure in the 138 kV yard and one in the 69 kV yard. The design of the protection is important to understand. The area of protection provided by each lightning mast is highlighted by a circle which features a hatched area. Everything within the hatched area is protected in case of a lightning strike.

The lightning protection design was determined 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.

First draft of lightning protection

Failure

The first draft of our lightning 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 lightning mast zone of protection would interact with other zones of protection, as this increases the total area that can be protected by the same amount of masts.

First draft

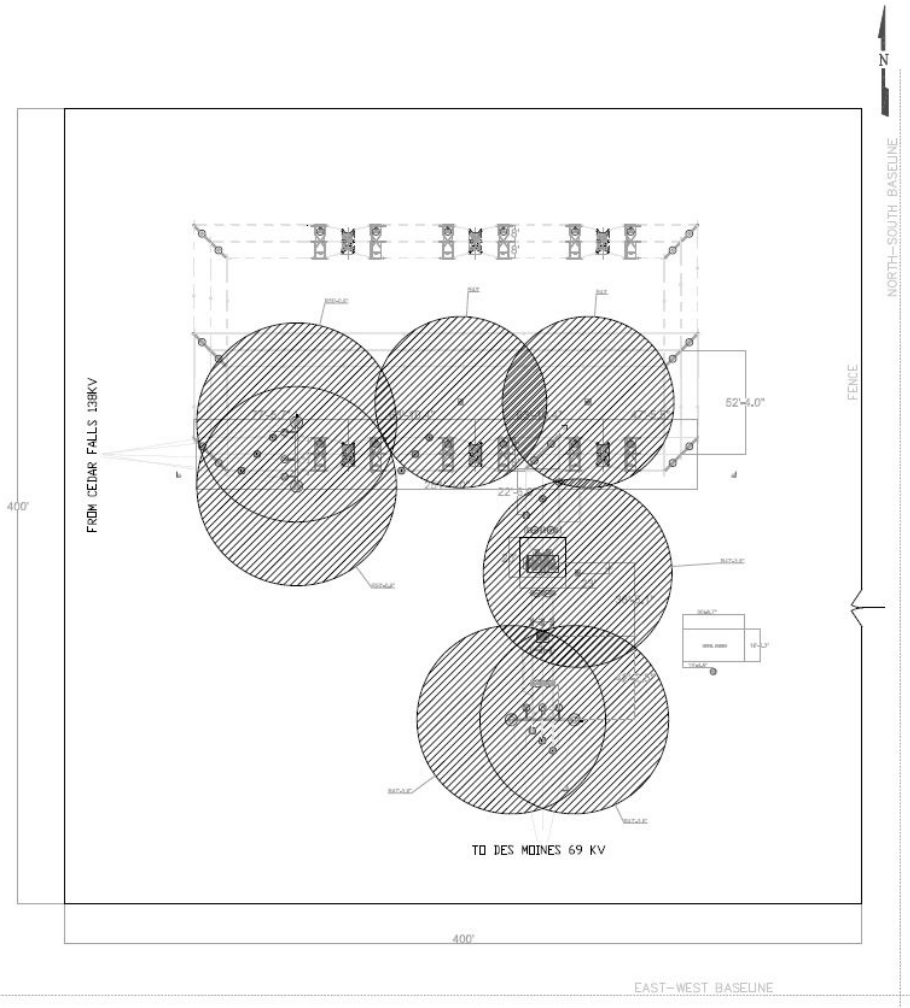


Figure 39: First Draft of Lightning Protection

Approval of lightning protection diagram

After making the necessary changes, 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 10: Changes Made to Lightning Protection Diagram

Approved protection diagram

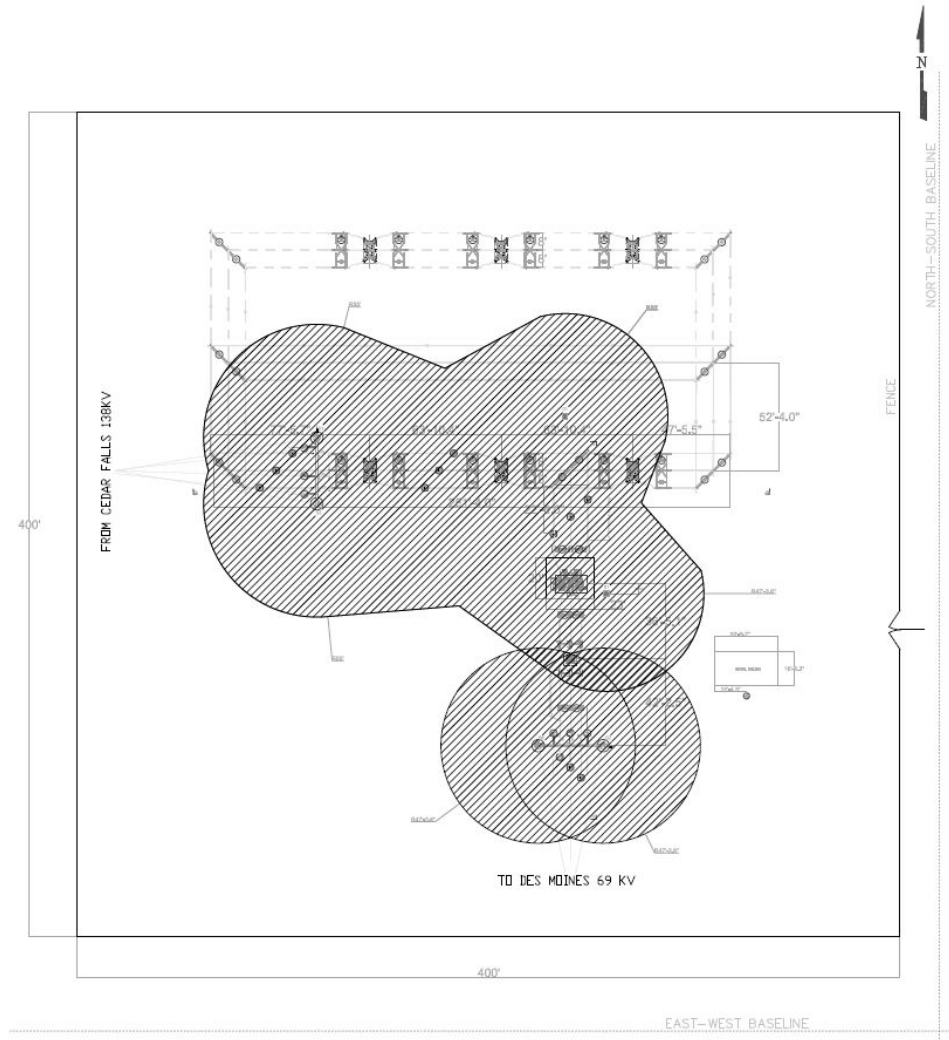


Figure 40: Approved Lightning Protection

3.5.4 AC Study

Auxiliary Transformer Sizing: 50kVA

Cable Sizing: To satisfy voltage drop, our wire would have to be AWG 3 Cu. However, our ampacity has dictated AWG 2 Cu, so AWG 2 Cu should be selected. The cable will be directly buried and the client will choose insulation type.

3.5.5 DC Study

IEEE Standard 485 goes into detail on how to calculate the number of positive plates required for the battery. To do this, the load profile shown in Figure 14 was used in conjunction with the current per positive plate required to bring the batteries' voltage to 1.75 per cell in a specified amount of time. The latter is provided by the battery manufacturer. The following Figure 41 illustrates how the largest positive plate size can be found. By using the multiplying factors from the manufacturer's data sheet, the

calculated number of positive plates equals 1.69, which can be rounded up to 2. The total number of plates for the battery can be calculated using the following equation.

$$\text{total number of plates} = 1 + (2 * \text{number of positive plates})$$

The total number of plates equals 5. The Enersys battery CC-5M will be able to supply the substation considering that the rated capacity of the battery is 100Ah, and the required amount should not exceed 89.4 Ah

1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+ M6=	481	6.3	8.342857143	
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+ M6=	480	6.3		-7.619047619
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+ M6=	475	6.3	0.2438095238	
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4+M5+M6	1	75	0.1013333333	
5	A5=	180.096	A5-A4=	166.4	M5=	0	T=M5+M6	0			
6	A6=	6.296	A6-A5=	-173.8	M6=	0	T=M6	0			
									Sec Sub Total	8.688	-7.619047619
									6 Total	1.068952381	***
Section 7: First Seven Periods Only - If A6 is greater than A7, go to section 8.											
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+ M7=	481	6.3	8.342857143	
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+ M7=	480	6.3		-7.619047619
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+ M7=	475	6.3	0.2438095238	
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4+ M7=	1	75	0.1013333333	
5	A5=	180.096	A5-A4=	166.4	M5=	0	T=M5+M6+M7	0			
6	A6=	6.296	A6-A5=	-173.8	M6=	0	T=M6+M7	0			
7	A7=		A7-A6=	-6.296	M7=	0	T=M7	0			
									Sec Sub Total	8.688	-7.619047619
									7 Total	1.068952381	***
Maximum Section Size (8) 1.068952381 PLUS (+) Random Section Size (9) EQUALS (=) Uncorrected Size - (US) (10) 1.068952381											
US (11)		X Temp Corr (12)	1.15	X Design Margin (13)		1.1	X Age Fact (14)		1.25	EQUALS (=) (15)	1.690280952
When the cell size (15) is greater than a standard cell size, the next larger cell is required											
Required cell size (16)		(A) - Positive Plates		2			Total # Plates =			5	
		(B)- Ampere Hours				Therefore cell (17)	Rated for		is required		
									Amp-hrs		
Project: Senior Design Date: 02/19/19 Page:											
Lowest Expected Electrolyte Temp (F):		55 Degrees F	Min. Cell Voltage:		1.75 V/cell	Cell Mfg:		Enersys			
1	2	3	4	5	6	7					
	Load	Change In Load	Duration of period	Time to end of section	Capacity at T min Rate	Required Section Size					
Period	Amperes	Amperes	minutes	minutes	(BA) Amps / Pos (RT) or (6B) K factor (KT)	(3)*(BA)=Positive Plates or (3)*(6B)= Rate Amp Hours	POS Values	NEG Values			
Section 1: First Period Only - If A2 is greater than A1, go to section 2											
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1=	1	75	0.7008	***
									Sec 1 Total		***
Section 2: First two periods only - If A3 is greater than A2, go to section 3.											
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2	6	63	0.8342857143	
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2	5	63		-0.7619047619
									Sec Sub Total	0.8342857143	-0.7619047619
									2 Total	0.07238095238	***
Section 3: First three periods only - If A4 is greater than A3, go to section 4.											
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2+M3	480	6.3	8.342857143	
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3	479	6.3		-7.619047619
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3	474	6.3	0.2438095238	
									Sec Sub Total	8.586666667	-7.619047619
									3 Total	0.9676190476	***
Section 4: First Four Periods only - If A5 is greater than A4, go to section 5.											
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+ M4=	481	6.3	8.342857143	
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3+M4	480	6.3		-7.619047619
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+M4	475	6.3	0.2438095238	
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4	1	75	0.1013333333	
									Sec Sub Total	8.688	-7.619047619
									4 Total	1.068952381	***
Section 5: First Five Periods Only - If A6 is greater than A5, go to section 6.											
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+ M5=	481	6.3	8.342857143	
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+ M5=	480	6.3		-7.619047619
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+M4+M5	475	6.3	0.2438095238	
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4+M5	1	75	0.1013333333	
5	A5=	180.096	A5-A4=	166.4	M5=	0	T=M5	0			
									Sec Sub Total	8.688	-7.619047619
									5 Total	1.068952381	***
Section 6: First Six Periods Only - If A7 is greater than A6, go to section 7.											

Figure 41: Battery Sizing Spreadsheet

When sizing the battery charger, the capacity (A) in amps can be found by the following equation where L is the continuous load being 4.56 Amps, C is the ampere hours emergency discharge which is the 100 Ah battery rating of the EnerSys 3CC-5M. H is the number of hours recharge time assumed to be 24 hours, and the 1.1 constant is a factor accounting for the efficiency of lead acid cells.

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

The charger capacity is calculated to be 9.14Amps, and therefore, the next larger size, provided by Hindlepower, capable of handling 12 Amps, will be sufficient for the substation.

The DC system has been designed in order to support all DC loads inside the control house, as well as in the yard, over an 8 hour duty cycle. The EnerSys 3CC-5M batteries are utilized in order to support this load such that no AC power is available to supply the batteries with a constant charge. The battery charger size was calculated to ensure the recharging period of the batteries would stay under 24 hours. The Hindle AT10 Battery Charger was selected in order to recharge the DC batteries to their full capacity in under 15 hours.

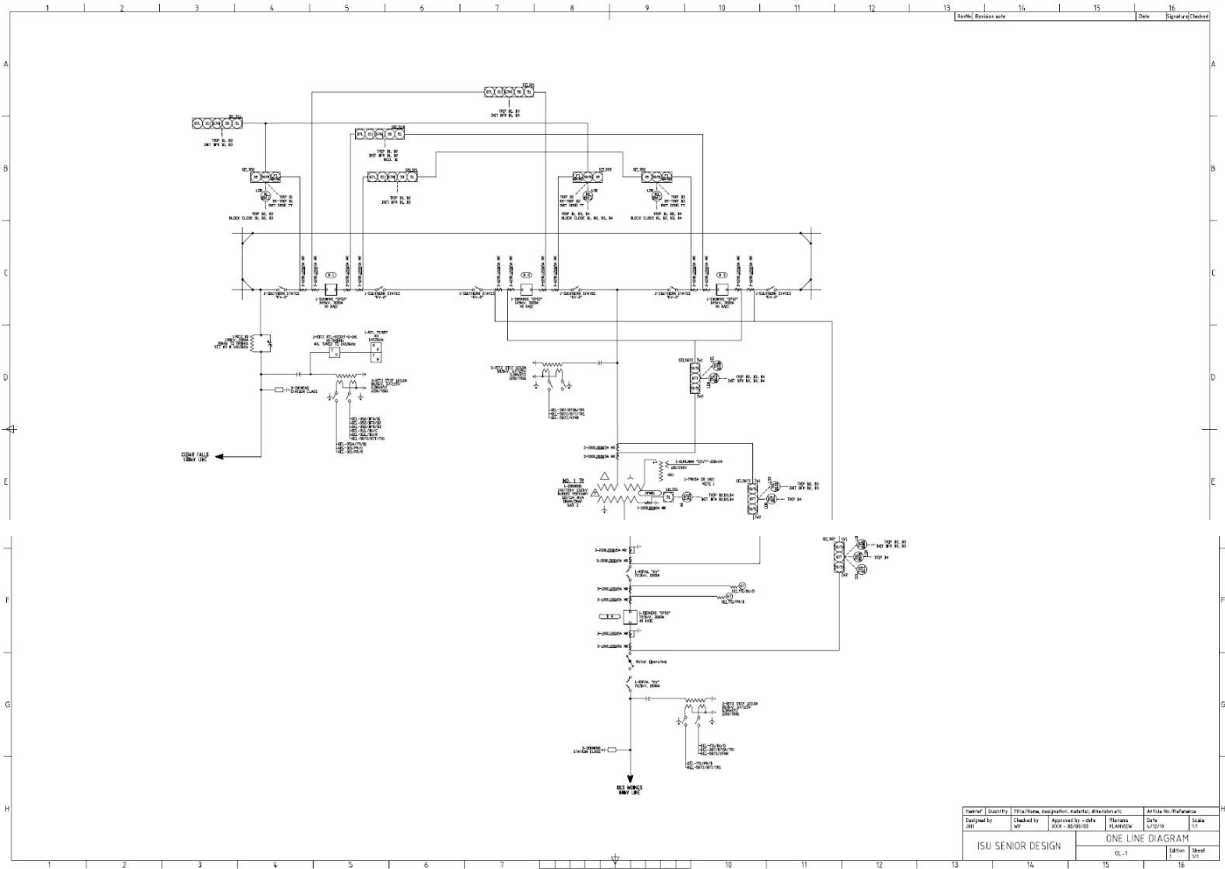


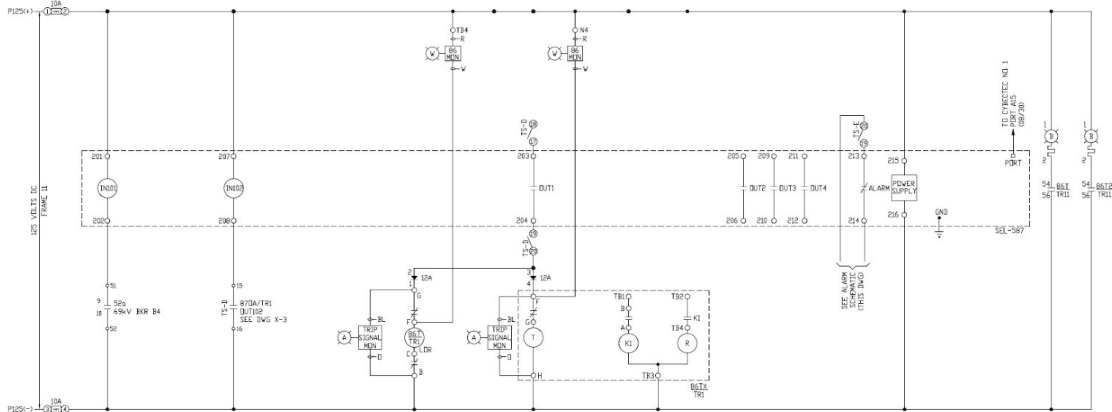
Figure 43: Final Draft AutoCAD One-Line Diagram

3.5.7 Transformer Schematics

Based on our one-line, there were four different SEL devices that protected the one-line, therefore, we completed four different schematics for each SEL device. We also created AC schematics for the CTs for each of these SEL devices. The drawings for all four DC schematics and the two AC schematics can be found below.

DC Transformer Schematics

NO 1 TR DIFFERENTIAL RELAYING (87T/TR1)



CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11 ₁ 11 ₂	X			
12 ₁ 12 ₂	X		TRIP 138kV BKR B2	BKR-B2
13 ₁ 13 ₂	X			
14 ₁ 14 ₂	X		TRIP 138kV BKR B3	BKR-B3
21 ₁ 21 ₂	X			
22 ₁ 22 ₂	X		INITIATE BKR FAILURE ON B2	BKR-B2
23 ₁ 23 ₂	X			
24 ₁ 24 ₂	X		INITIATE BKR FAILURE ON B3	BKR-B3
31 ₁ 31 ₂	X		SPARE	
32 ₁ 32 ₂	X		SPARE	
33 ₁ 33 ₂	X		SPARE	
34 ₁ 34 ₂	X		SPARE	
41 ₁ 41 ₂	X		SPARE	
42 ₁ 42 ₂	X		SPARE	
43 ₁ 43 ₂	X		SPARE	
44 ₁ 44 ₂	X		SPARE	
51 ₁ 51 ₂	X		SPARE	
52 ₁ 52 ₂	X		SPARE	
53 ₁ 53 ₂	X		SPARE	
54 ₁ 54 ₂	X		SCADA INDICATION	THIS DWG

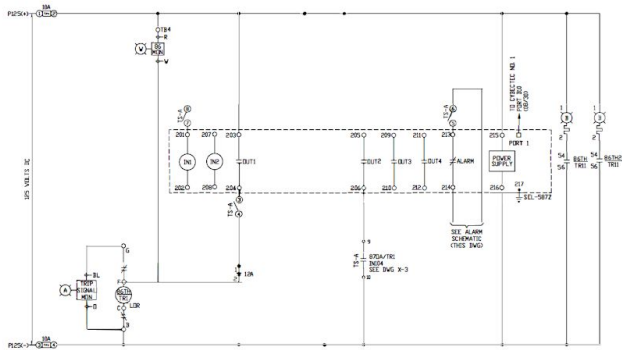
ELECTROSMITH TYPE 1,08K*

CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11 ₁ 11 ₂	X			
12 ₁ 12 ₂	X		TRIP 69kV BKR B4	BKR-B4
13 ₁ 13 ₂	X			
14 ₁ 14 ₂	X		XTRM DIFF RELAY ALARM	SEE SCADA
21 ₁ 21 ₂	X			
22 ₁ 22 ₂	X		DE-ENERGIZE XTRM FANS	SEE SCADA
23 ₁ 23 ₂	X		SPARE	
24 ₁ 24 ₂	X		SPARE	
31 ₁ 31 ₂	X		SPARE	
32 ₁ 32 ₂	X		SPARE	
33 ₁ 33 ₂	X		SPARE	
34 ₁ 34 ₂	X		SPARE	
41 ₁ 41 ₂	X		SPARE	
42 ₁ 42 ₂	X		SPARE	
43 ₁ 43 ₂	X		SPARE	
44 ₁ 44 ₂	X		SPARE	
51 ₁ 51 ₂	X		SPARE	
52 ₁ 52 ₂	X		SPARE	
53 ₁ 53 ₂	X		SPARE	
54 ₁ 54 ₂	X		SCADA INDICATION	THIS DWG

ELECTROSMITH TYPE 1,08K*

Figure 44: DC Transformer Differential Relaying Schematic (X-1)

NO. 1 TR 138kV BUS/LEAD DIFF RELAYING (87TH/TR1)



CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11 ₁ 11 ₂	X			
12 ₁ 12 ₂	X		TRIP 138kV BKR B2	BKR-B2
13 ₁ 13 ₂	X			
14 ₁ 14 ₂	X		TRIP 138kV BKR B3	BKR-B3
21 ₁ 21 ₂	X			
22 ₁ 22 ₂	X		TRIP 69kV BKR B4	BKR-B4
23 ₁ 23 ₂	X			
24 ₁ 24 ₂	X		INITIATE BKR FAILURE ON B2	BKR-B2
25 ₁ 25 ₂	X			
26 ₁ 26 ₂	X		INITIATE BKR FAILURE ON B3	BKR-B3
27 ₁ 27 ₂	X			
28 ₁ 28 ₂	X		INITIATE BKR FAILURE ON B4	BKR-B4
31 ₁ 31 ₂	X			
32 ₁ 32 ₂	X		SHORT 138kV RELAY PHASE A CT	
33 ₁ 33 ₂	X			
34 ₁ 34 ₂	X		SHORT 138kV RELAY PHASE B CT	
35 ₁ 35 ₂	X			
36 ₁ 36 ₂	X		SHORT 138kV RELAY PHASE C CT	
37 ₁ 37 ₂	X			
38 ₁ 38 ₂	X		SCADA INDICATION	THIS DWG

ELECTROSMITH TYPE 1,08K*

Figure 45: DC Transformer Differential Relaying Schematic (X-2)

AC Transformer Schematics

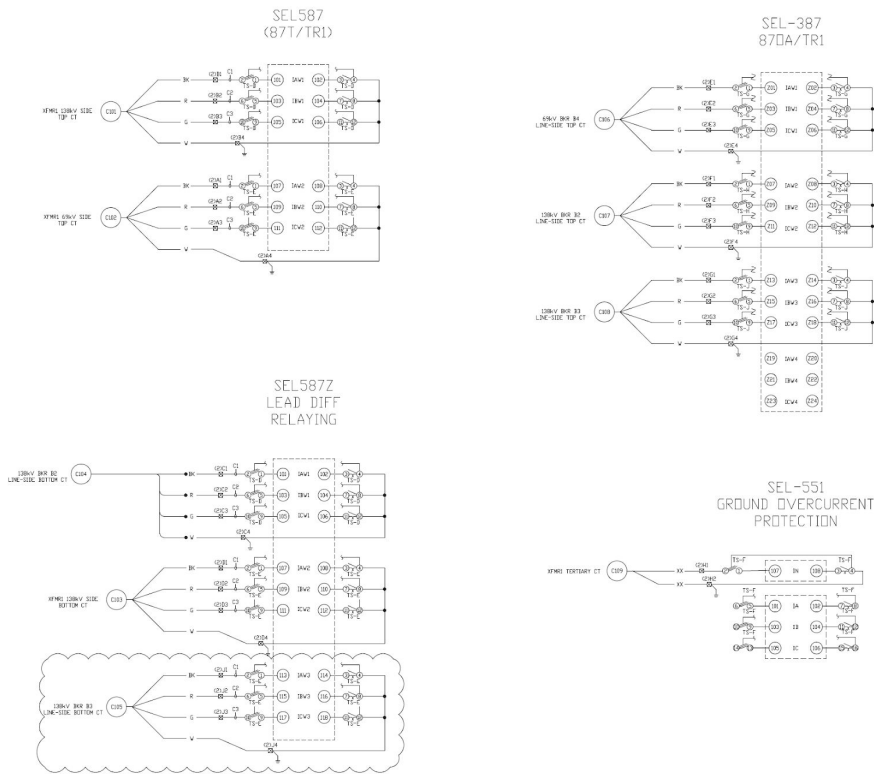


Figure 48: AC Transformer Differential Relaying Schematic (X-1-AC)

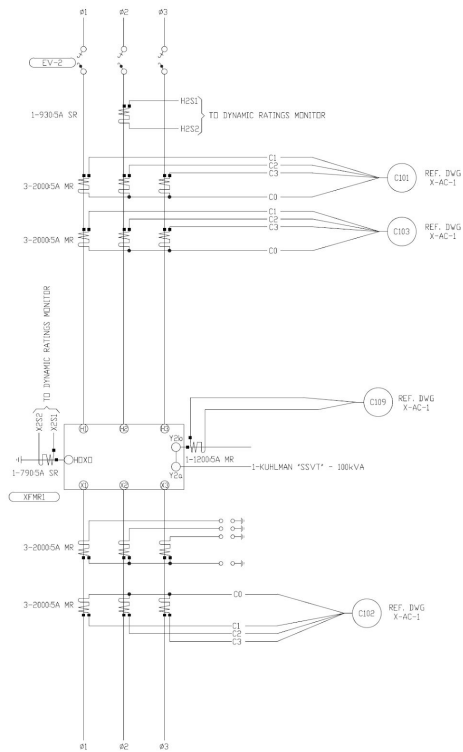


Figure 49: AC Transformer Differential Relaying Schematic (X-2-AC)

3.5.8 Breaker Schematics

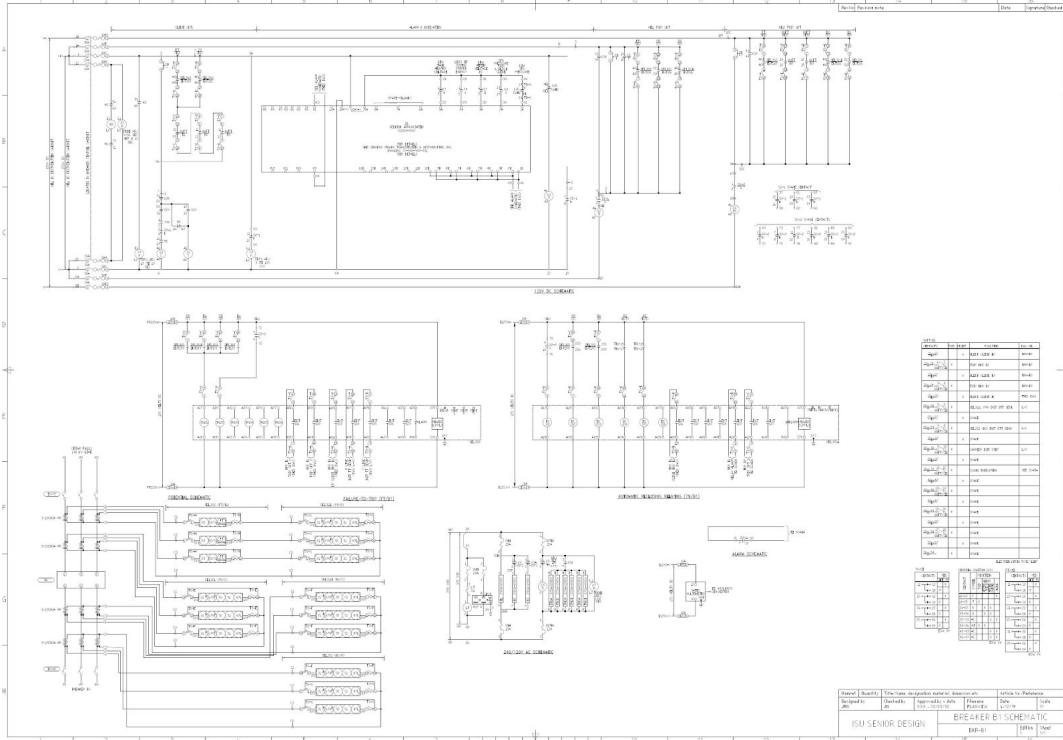


Figure 50: Breaker B1 Submittal

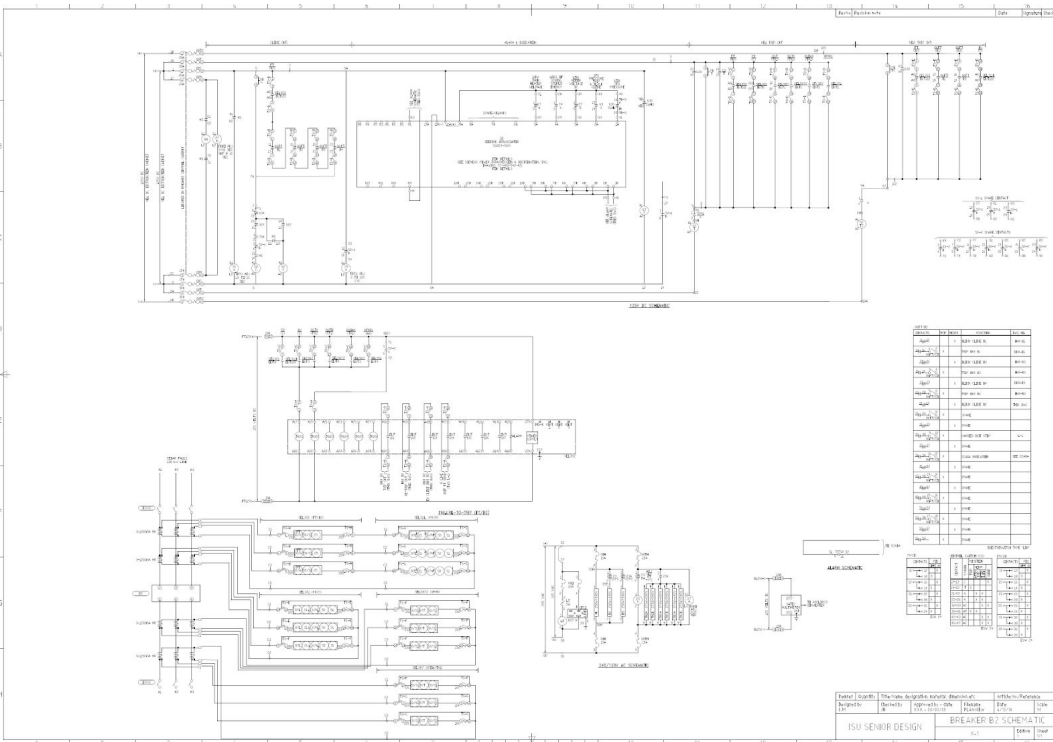


Figure 51: Breaker B2 Submittal

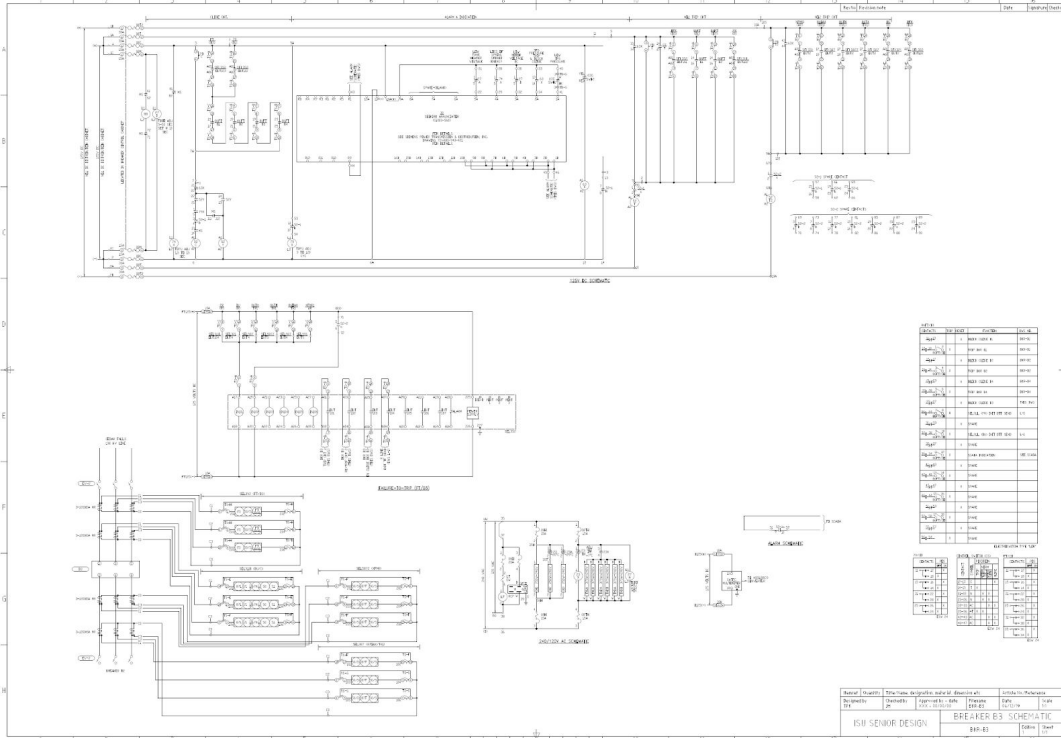


Figure 52: Breaker B3 Submittal

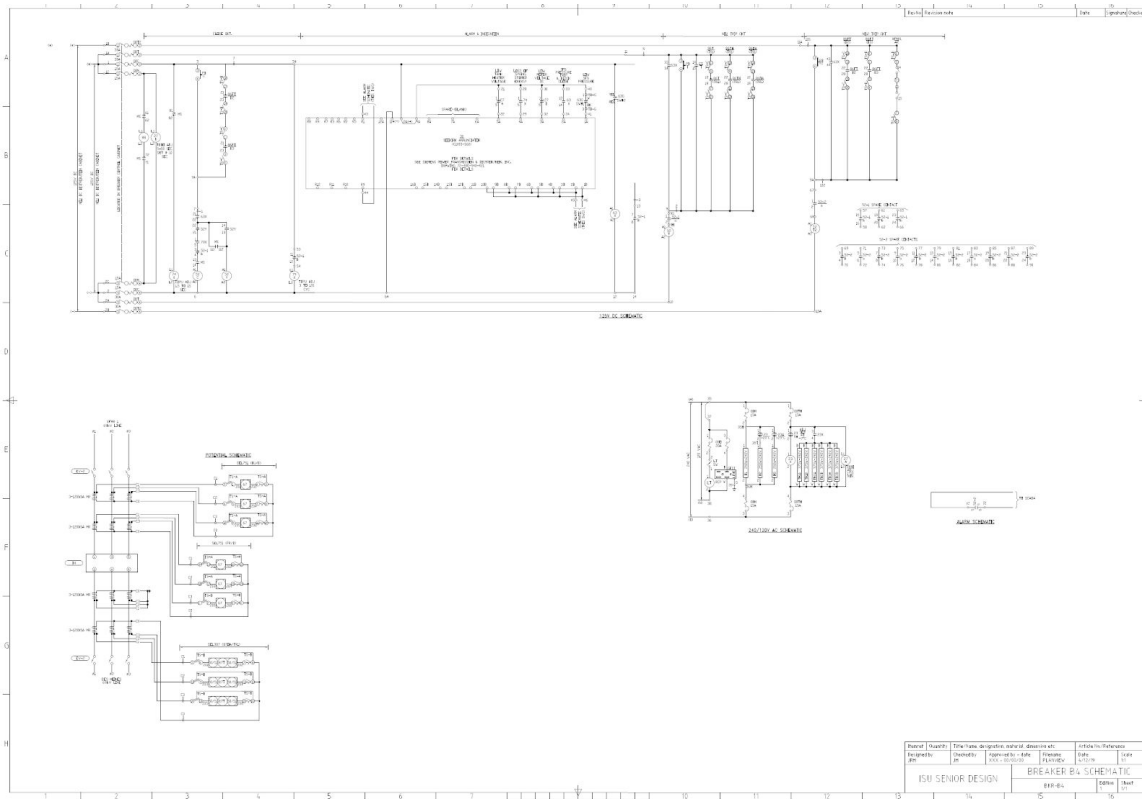


Figure 53: Breaker B4 Submittal

AC Line Differential Schematics

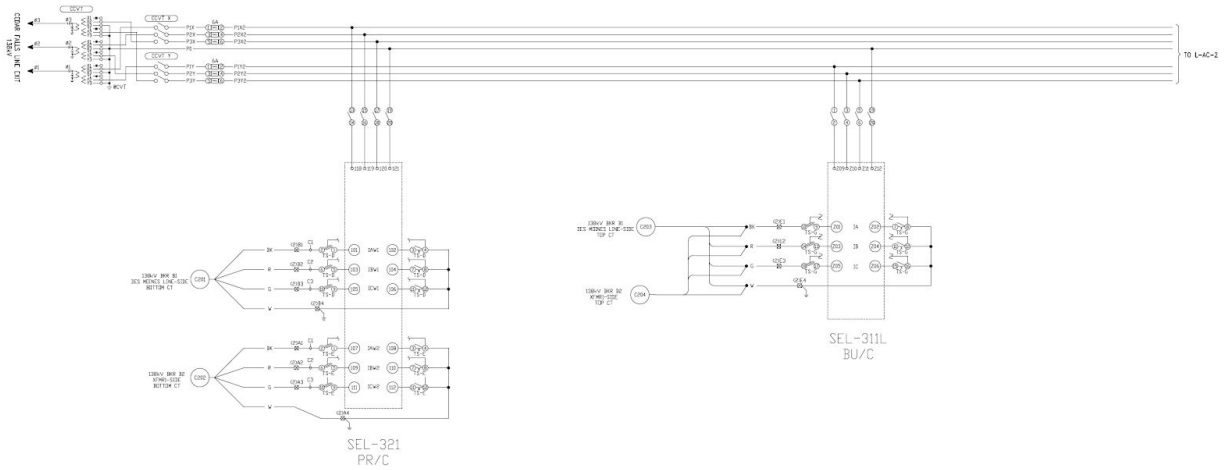


Figure 56: AC Line Differential Relay (L-1-AC)

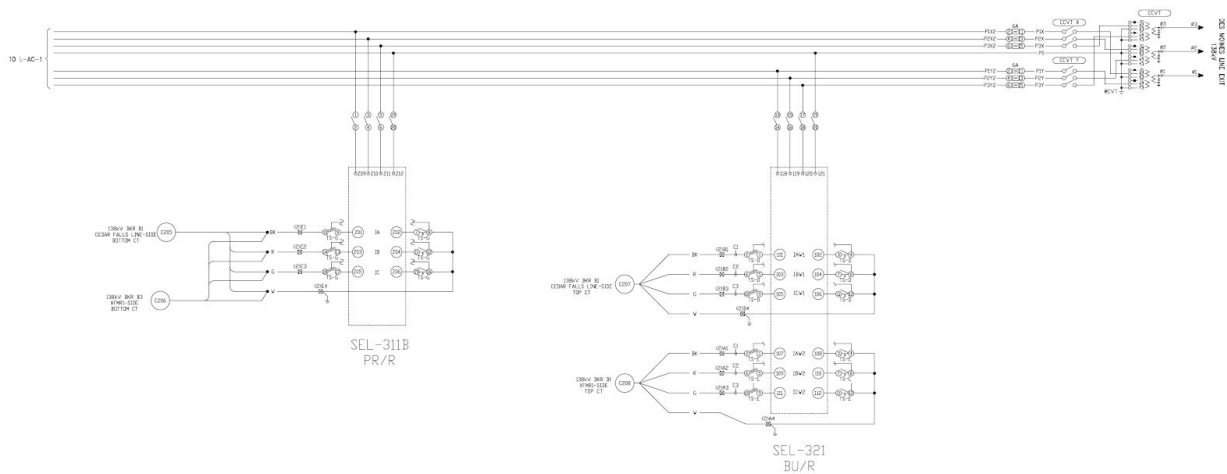


Figure 57: AC Line Differential Relay (L-2-AC)

4 Project and Risk Management

4.1 Task Decomposition and Roles and Responsibilities

We decided to split up the project by looking at the amount of work and assigning the number of people accordingly. For both semesters, we each had at least one task assigned to us to be completed. The breakdown of the roles and responsibilities for the project and who performed each can be found below in table 11.

1st Semester	
Grounding Study and Grounding Report	Rebecca Franzen & Riley O'Donnell
Lightning Protection Study	Tom Kelly & Connor Mislivec
Physical Design	Wilson Pietruszewski & Jake Heiller
2nd Semester	
AC Study and Report	Nicolaus Cory
DC Study and Report	Rebecca Franzen
One-Line	Jake Heiller
Breaker Schematics	Jake Heiller, Tom Kelly, & Connor Mislivec
Transformer Schematics	Riley O'Donnell & Wilson Pietruszewski
Line Differential Schematics	Riley O'Donnell & Wilson Pietruszewski

Table 11: Project Task Breakdown

4.2 Project Schedule

For the most part, we managed to stay on schedule during the 1st semester; however, we did not account for the revisions we would have to make with the grounding study and the lightning study after sending them to the client, so they took longer than expected. This can be seen below by looking at figure 57 and figure 58. After our first deliverable, we made sure to get the physical design in early to receive comments before the due date to ensure we had a full complete deliverable by the set date.

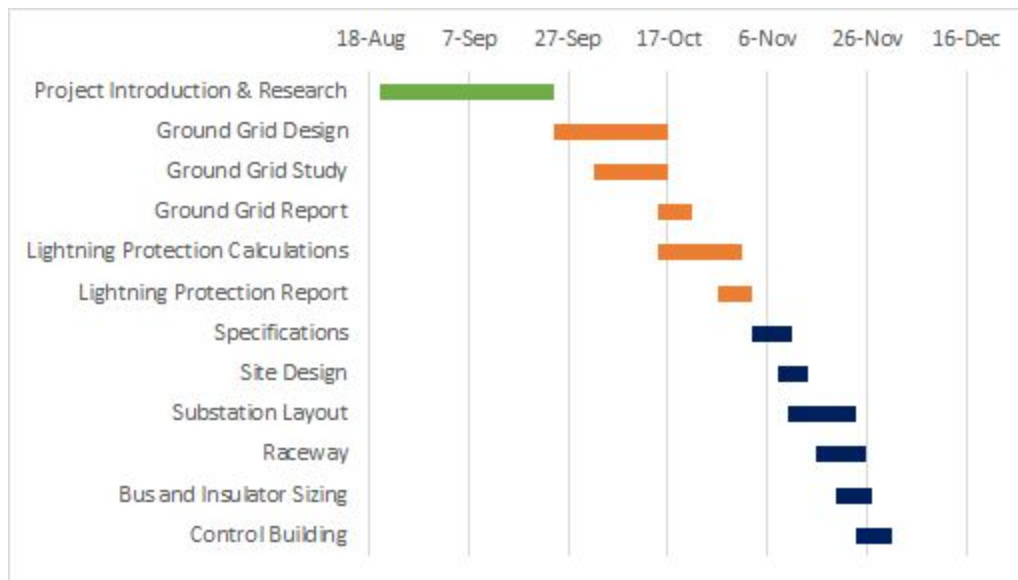


Figure 58: 1st Semester Proposed Schedule

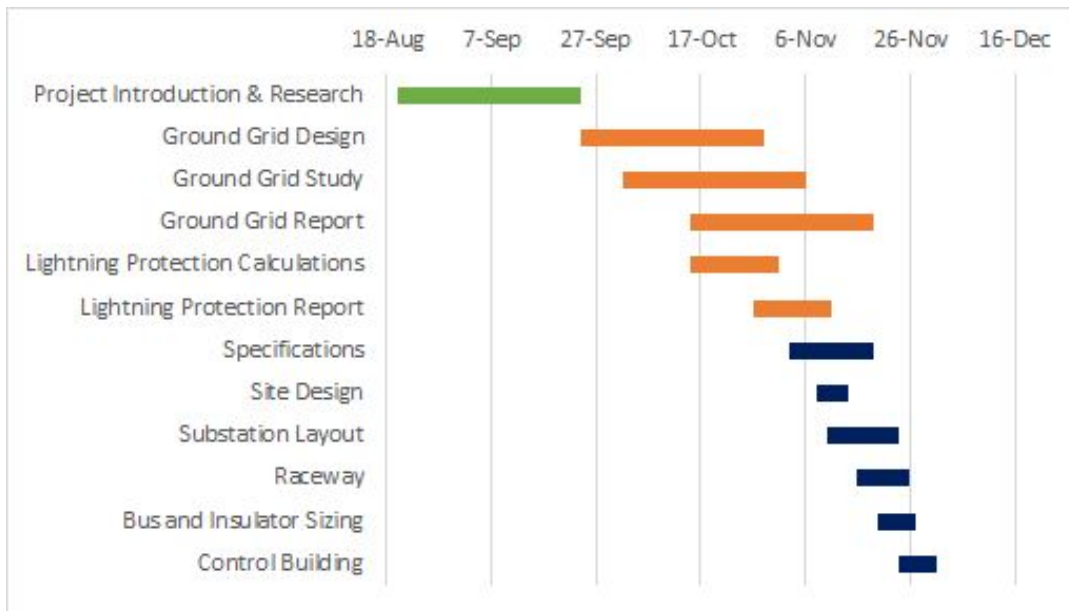


Figure 59: 1st Semester Actual Schedule

For second semester, we again reached all of our deadlines; however, the client changed some of the work that was to be done throughout the semester. We determined that the communication block diagram and network design were too simple and would be mostly incorporated into our one-line. Instead of doing these tasks, we added another study, the AC study. This can be seen by looking at the two figures below.

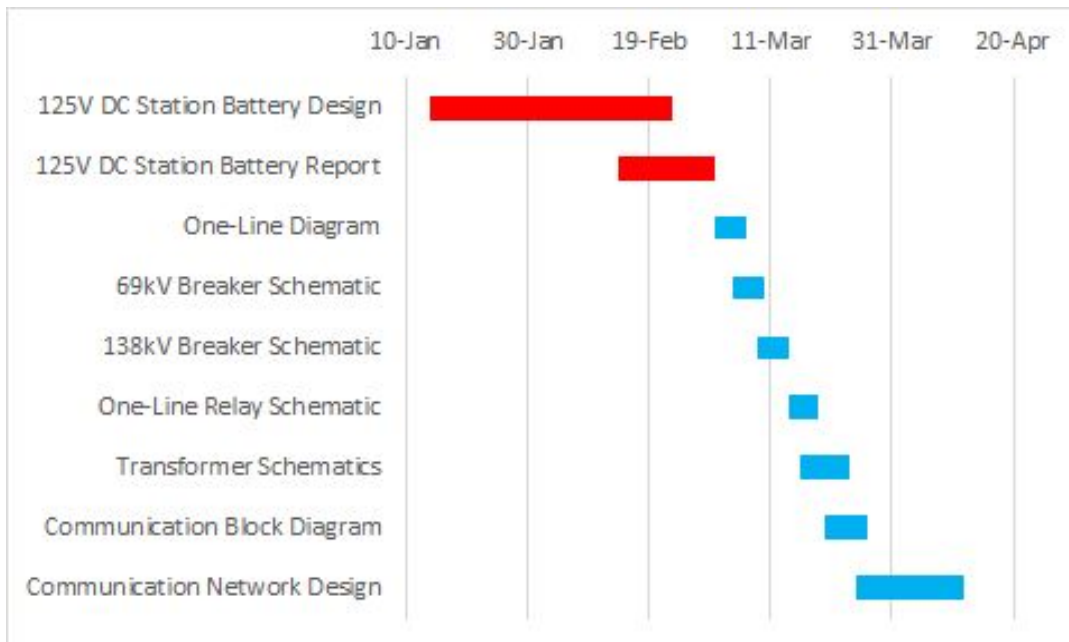


Figure 60: 2nd Semester Proposed Schedule

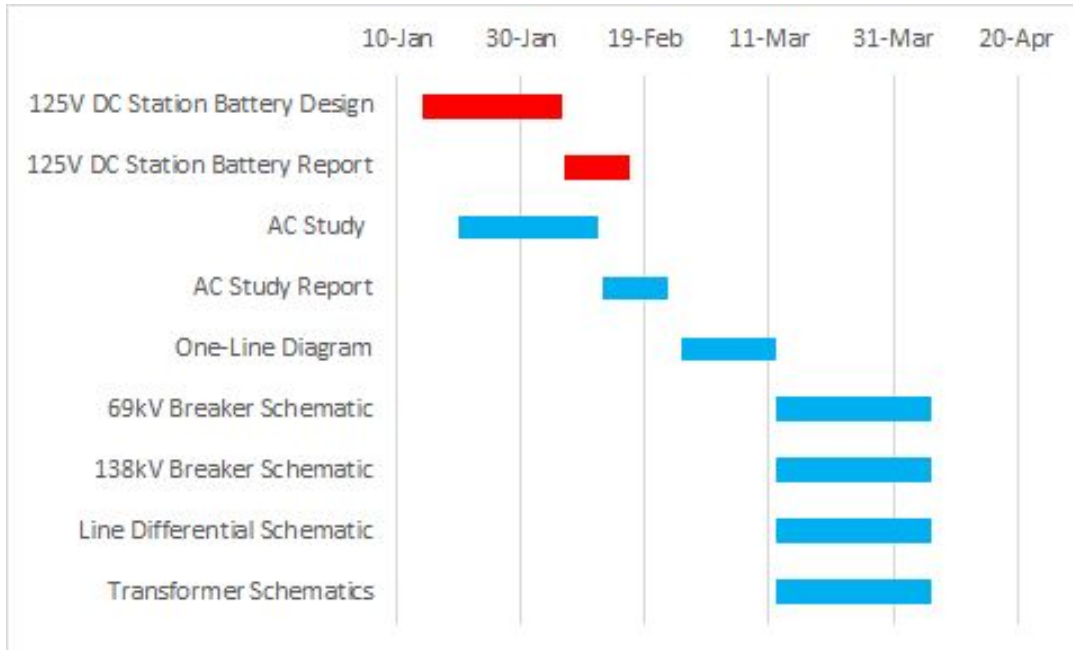


Figure 61: 2nd Semester Actual Schedule

4.3 Lessons Learned

Throughout the project there were many lessons that we learned about project management and the real work place. Some of these lessons include:

- Do not procrastinate
- Ask questions when appropriate
- Celebrate good, hard work
- Always have someone look over completed work
- Understanding design scope to avoid unnecessary work
- Understanding why certain tasks are performed

5 Closing Material

5.1 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.

5.2 References

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Generic 138kV-69kV Transformer Drawing. (Per Client Spec)

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5.3 Appendices

This appendix contains all the deliverables throughout the two semesters that were submitted to Burns and McDonnell. It contains reports for grounding study, lightning protection study, AC study, and DC study. It contains drawings, which are labeled, for physical layout, one-line, transformer schematics, breaker schematics, and line differential schematics.

Report on the

Cyclone Substation Grounding

BMcD

Project No. C2019

February 2019

Cyclone Substation Grounding

Prepared for

**BMcD
Kansas City, MO**

October 2018

Project No. C2019

Prepared by

Iowa State University Senior Design

INDEX AND CERTIFICATION

**BMcD
Cyclone Substation Grounding
Project No. C2019**

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LIST OF ABBREVIATIONS

<u>Abbreviation</u>	<u>Term/Phrase/Name</u>
IEEE	Institute of Electrical and Electronic Engineers
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis
GPR	Ground Potential Rise

1.0 EXECUTIVE SUMMARY

The purpose of this study is to analyze the grounding system to ensure that the step and touch voltages are below the minimum threshold per IEEE (Institute of Electrical and Electronic Engineers) Standard 80 requirements for the Cyclone Substation. Cyclone Substation is a 138 kV substation to be interconnected with a new wind generation plant. This substation has three 138kV breakers, one 69kV breaker, and one 69/138kV transformer. An original grounding design has been tested and grounding provisions will be added as necessary to ensure safe touch and step potentials which meet/exceed the requirements outlined in IEEE Standard 80. CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) was used for the analysis of the substation grid. The methodology, assumptions, and results of the study are discussed in this report.

This grounding study was performed assuming maximum fault conditions. The worst fault current value was provided by the client to be 21kA. The X/R ratio was assumed to be 20, the default value given in CDEGS and IEEE Standard 80. The maximum fault clearing time and ground resistivity was given by the client. This grounding study also evaluates the Ground Potential Rise (GPR) as well as the resistance to earth. This study indicates that the ground grid design meets industry standards and is consistent with IEEE 80.

2.0 DESIGN METHODOLOGY

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.

2.1 Soil Model

In a grounding system, the Earth is represented by a pure resistance. The multiple layers in the soil represent resistors in series with a certain level of resistivity. 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. 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. The soil resistivity test measurements for this grounding study can be found in Table 2.1.

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 2-1 in section 2.1 of this document. 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 2-1 : RESAP Soil Model

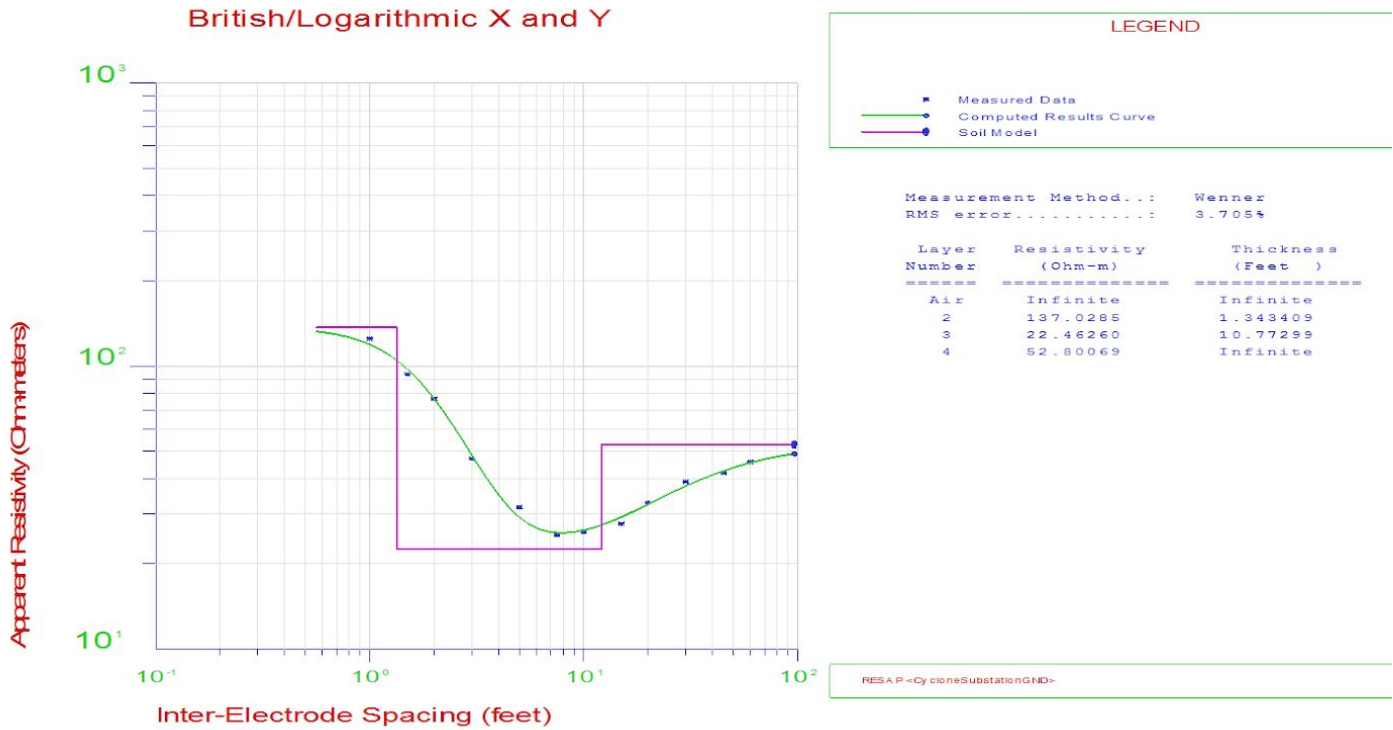


Figure 2-2 : Resistivity Model

```

Report #1:

===== < R E S I S T I V I T Y   ( S Y S T E M   I N F O R M A T I O N   S U M M A R Y ) > =====

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      <--- LAYER CHARACTERISTICS --->      Reflection      Resistivity
Number     Resistivity      Thickness      Coefficient      Contrast
          (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.

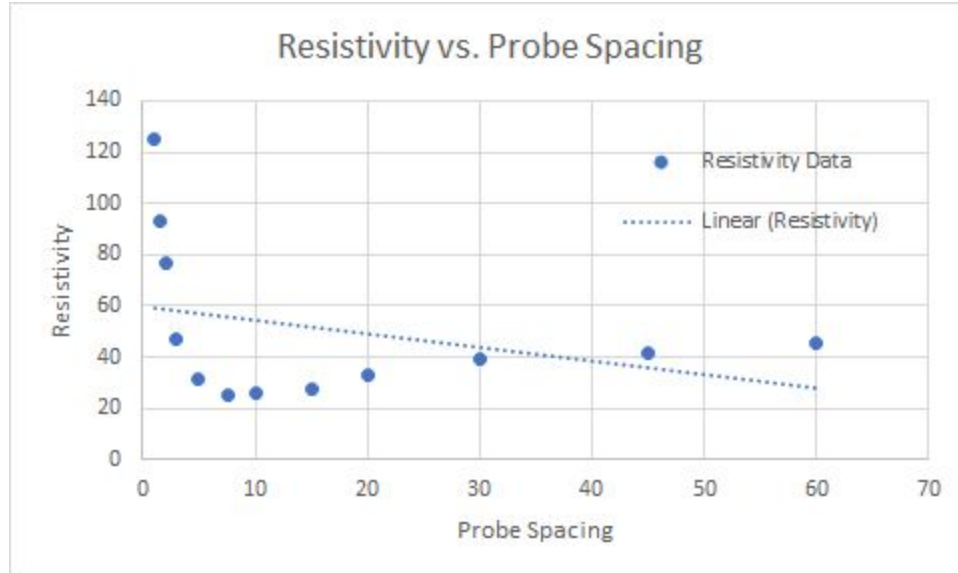
End of Report #1
  
```


Table 2-1: Resistivity Measurements

Probe Spacing (feet)	Resistivity (ohms-m) 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

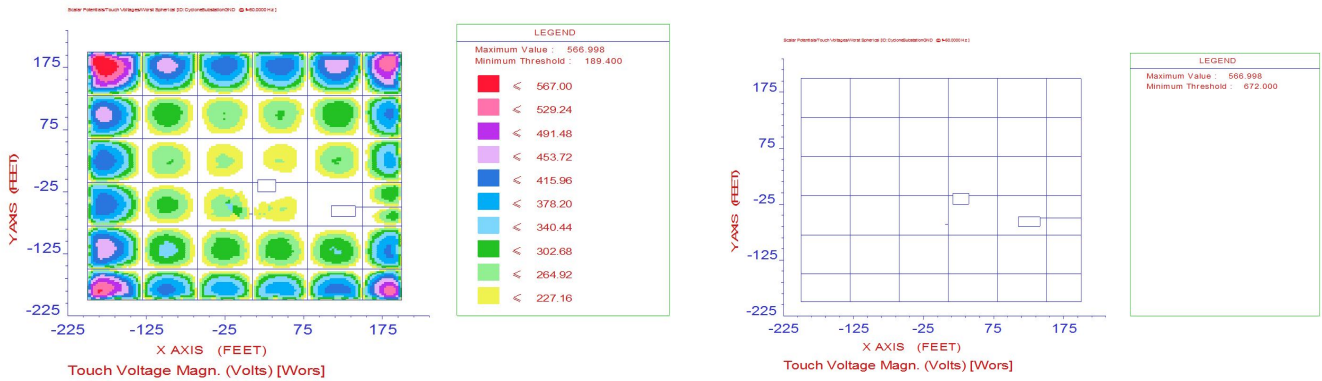
The resistivity data taken is presented again in Figure 2-3 plotted in Microsoft Excel with a best fit curve.

Figure 2-3: Site Resistivity Measurements



A layer of crushed rock is added to the substation as an additional layer of resistance to the earth. In this study, a 4 inch layer of 3000 Ohm-meter crushed rock was taken into account in the step and touch potential voltages. The contrast between the step and touch potential voltages with and without the presence of crushed rock can be seen in Figure 2-4 of section 2.1 in this document.

Figure 2-4: Touch Potential Voltage Test With Crushed Rock Layer vs. Native Soil



2.2 Determination of Resistance and GPR:

In Figure 2-5 the Cyclone Substation 138/69kV ground grid resistance is shown as 0.177 ohms.

Figure 2-5: Grid System Resistance Results

```

===== < 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 .....: 87
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.....: 6441.5      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      1.34341
2  22.4626     1.00000      1.00000      10.7730
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..: 3777.484      Volts
                                         Angle..: 3.263913      degrees

Impedance of Grounding System.....Magn..: 0.1798802      Ohms
                                         Angle..: 3.263913      degrees
End of Report #1

```

When fault conditions are present, a portion of the fault current flows through the ground grid. This flow of current will cause the ground grid potential to rise with respect to remote earth. The other portion of the fault current will flow through the neutrals and shield wires which leave the station and are properly grounded. Neutrals and shield wires will provide a low-resistance current path to remote earth. This low-resistance path “splits” the available fault current. This current split is known as a “Split Factor.” While performing this grounding study, we assumed worst fault current and did not utilize a split factor.

Ground potential rise, or GPR, occurs when large amounts of electricity enter the earth. This usually happens when there is a fault in high voltage equipment or because of a lightning strike. When these events occur, the electric potential in both the ground grid as well as the surrounding soil will rise. When the electric potential of the surrounding soil rises, the area can become hazardous for both personnel and equipment. In Figure 2-5, the value for GPR is shown to be 3718.154V using the CDEGS software.

Figure 2-6: Grid System GPR Results

```

===== < 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 .....: 87
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.....: 6441.5 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      1.34341
2  22.4626     1.00000      1.00000     10.7730
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..: 3777.484 Volts
                                         Angle..: 3.263913 degrees
Impedance of Grounding System.....Magn..: 0.1798802 Ohms
                                         Angle..: 3.263913 degrees

End of Report #1

```

To calculate GPR the following equation Equation 2-1 is used:

Equation 2-1: Ground Potential Rise

- $GPR = I_g \times R_g$

Where:

GPR is the ground potential rise in volts (V)

I_g is the grid current in amperes (A)

R_g is the ground resistance in ohms (Ω)

$$GPR = 21,000 < 0 \times 0.1770549 < 2.837536 = 3718.154 < 2.837536$$

2.3 Grid Conductor Sizing:

The standard grid conductor size according to the BMCD Ground Reference Document is 4/0 soft drawn bare copper, and the standard ground rod is a 10 ft. rod with a 5/8" diameter. Equation 2-2 is used to verify the standard conductor will withstand a fault of 21 kA.

Equation 2-2: Minimum Conductor Sizing

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

A_{kcmil} = Area of conductor in kcmil

I = Fault Current in kA

K_f = Constant from Table 2 in IEEE 80-2013 for the material at various values of fusing temperature and using the ambient temperature of 40°C

t_c = Duration of Fault current in seconds

$$I = 21kA \quad K_f = 234 \quad t_c = 0.5 \text{ seconds}$$
$$A_{MCM} = 21 \times 7 \times \sqrt{0.5} = 103.945$$

2.4 Safety Criteria

The grounding system of a substation is designed to ensure the safety of a person working or walking in the vicinity of the substation. It provides path by which electric current will dissipate into the earth under normal conditions, as well as fault conditions, without exceeding equipment limits. A ground grid is designed to provide a safe environment under normal conditions, fault conditions, and surges.

IEEE Standard 80 lays out all the necessary measurements and tests to ensure safe working conditions at a substation. In the CDEGS program, the IEEE safety standards are taken into account and a safety table is provided based on various characteristics. The standard weight used when performing grounding analysis is 50 kg. This mass was used, as well as a fault duration of 0.5 seconds, to determine tolerable step and touch voltages for this grounding study, per IEEE Standard 80.

IEEE Standard 80 states that “the magnitude and duration of a current conducted through a human body at a frequency of 60 Hz should be less than the magnitude that can cause ventricular fibrillation of the heart.” A formula provided by that standard shows that the allowable body current for a human weighing 50 kg and a fault duration of 0.5 seconds is 164 mA.

Table 2-2 in section 2.4 of this report outlines the the maximum step and touch voltages that are considered safe in the Cyclone Substation. These values are pulled from figure 2-8 in section 2.4 of this report and are also listed in figure 2-7 in section 2.4 of this report.

Table 2-2: IEEE 80-2000 50kG Safe Touch Voltages

Safety Criterion	Value (V)
Permissible step voltage over insulating surface material	2219.9
Permissible touch voltage over insulating surface material	672.0

Figure 2-7: Permissible Step and Touch Results—3000 Ohms-Meter Layer Resistivity

The screenshot shows the SAFETY software interface with the following settings:

- Fault Clearing Time (sec):** 0.5
- Body Resistance:** IEEE (selected)
- IEC Percentage:** 75% (selected)
- Fibrillation Current Calculation Method:** 50KG-IEEE
- Resistivity:** Sub-Surface Uniform Soil Layer Resistivity (Ohm-m): 137.03
- Frequency:** 60
- Foot Resistance Calculation Method:** IEEE Std.80-2013
- Decrement Factor:** Default (selected)
- IEC Options:** IEC Standard Revision: 2005; Body Resistance Curve: 95% of Population Exceeds Curve; Contact Moisture: Dry
- Reference Insulating Surface Layer:** Surface Layer Thickness: 4 Inches; Surface Resistivity (Ohm-m): 3000
- Safety Limits (Volts):** Safe Touch Voltage: 672.0; Safe Step Voltage: 2219.9

Figure 2-8: Safety Calculations Table

3.0 RESULTS

The grounding system at Cyclone Substation has been designed to ensure a safe environment for a person working or walking in the vicinity of the equipment or the substation fence. A ground grid design was created using 4/0 soft drawn copper runs over a 400'x400' site and 70'x70' spacings. Ground rods are to be installed at each of the four corners of the site, and every 30 feet around the parameter of the site. These ground rods will be 10' long with 5/8" diameter. The transformer foundation pad will be grounded with 500 KCMil Copper, as modeled in the CDEGS SESCad model. After running multiple iterations of the grounding study, the following results were obtained from the listed input values:

Table 2-3 Study Results

<p><u>STUDY INFORMATION</u></p> <p>Fault Clearing Time..... 0.5 seconds</p> <p>Fault Current..... 21 kA</p> <p>Split Factor..... N/A</p> <p>Body Weight..... 50kg</p> <p>Substation Insulating Surface Layer Depth..... 4"</p> <p>Substation Insulating Surface Layer Resistivity..... 3000 Ohm-m</p> <p>Soil Resistivity Method..... Wenner 4-Point</p> <p>Grid Conductor Size..... 4/0 AWG</p> <p>Grid Conductor Type..... Copper, Annealed soft-drawn</p> <p>Transformer Grounding Conductor Type..... 500 kCmil</p> <p>Conductor Burial Depth..... 18'</p> <p>Ground Rod Length..... 10'</p> <p>Ground Rod Diameter..... 5/8"</p> <p>Ground Rod Burial Depth..... 18"</p>	
<p><u>RESULTS</u></p> <p>Soil-Top Layer 1 Resistivity..... 137.028 Ohm-m</p> <p>Soil-Top Layer 1 Thickness..... 1.34341 Feet</p> <p>Soil-Layer 2 Resistivity..... 22.4626 Ohm-m</p> <p>Soil-Layer 2 Thickness..... 10.7730 Feet</p> <p>Soil-Layer 3 Resistivity..... 52.8007 Ohm-m</p> <p>Grid Impedance..... 0.177 Ohm</p>	
<p><u>SUBSTATION RESULTS</u></p> <p>Allowable Step Voltage over Insulated Soil..... 2219.9 V</p> <p>Calculated Step Voltage..... 186.056 V</p> <p>Allowable Touch Voltage over Insulated Soil..... 672.0 V</p> <p>Calculated Touch Voltage..... 566.998 V</p>	

3.1 Ground Grid Model

Figure 3-1 shows the ground grid model created using the SESCAD tool in the CDEGS program when analyzing the grounding system. The model shows a 400'x400' site with 70'x70' spacings of #4/0 soft drawn copper (shown in blue). The transformer foundation pad is grounded using 500 KCmil copper (shown in red) and four 10' 5/8" diameter ground rods buried at the corners (shown in green). Ground rods are also shown to be placed around the parameter of the site, as well as near large equipment in the substation such as circuit breakers and dead end structures. This grounding system

model will help to ensure a safe environment at the substation, and is the most economic choice, as multiple iterations were performed.

Figure 3-1 CDEGS SESCAD Ground Grid Model

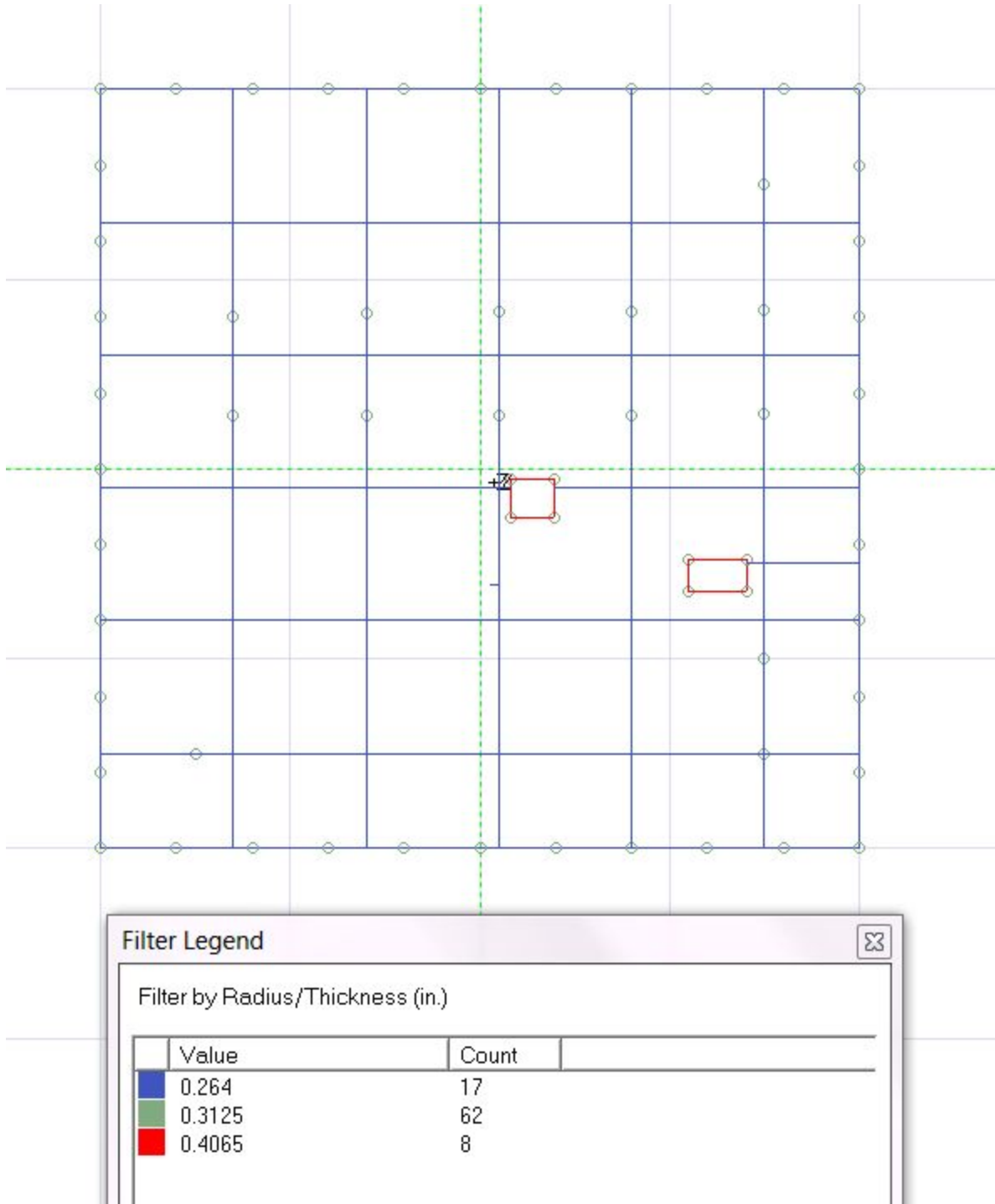


Table 3-1: Ground Grid Physical Parameters:

Physical Parameter	Description
Crushed rock layer	4" thick layer of limestone rock having a wet resistivity of at least 3000 ohm-meter
Conductor type	4/0 MCM soft drawn bare Copper
	500kCmil Copper
Conductor burial depth	18 inches below top of soil
Grounding conductor connection method	Exothermic weld
Copper-Clad Ground rods	10 feet long with a diameter of 5/8 inch (0.3125-inch radius)
Number of ground rods	62
Copper grid dimensions	Approximately 400 feet x 400 feet
Total Copper/4/0 Conductor length	6442 feet
Total Copper/500KCmil Conductor length	95 feet
Total 5/8" Copper Clad Rod Length	620 feet
Average Grid Spacing	70'x70'

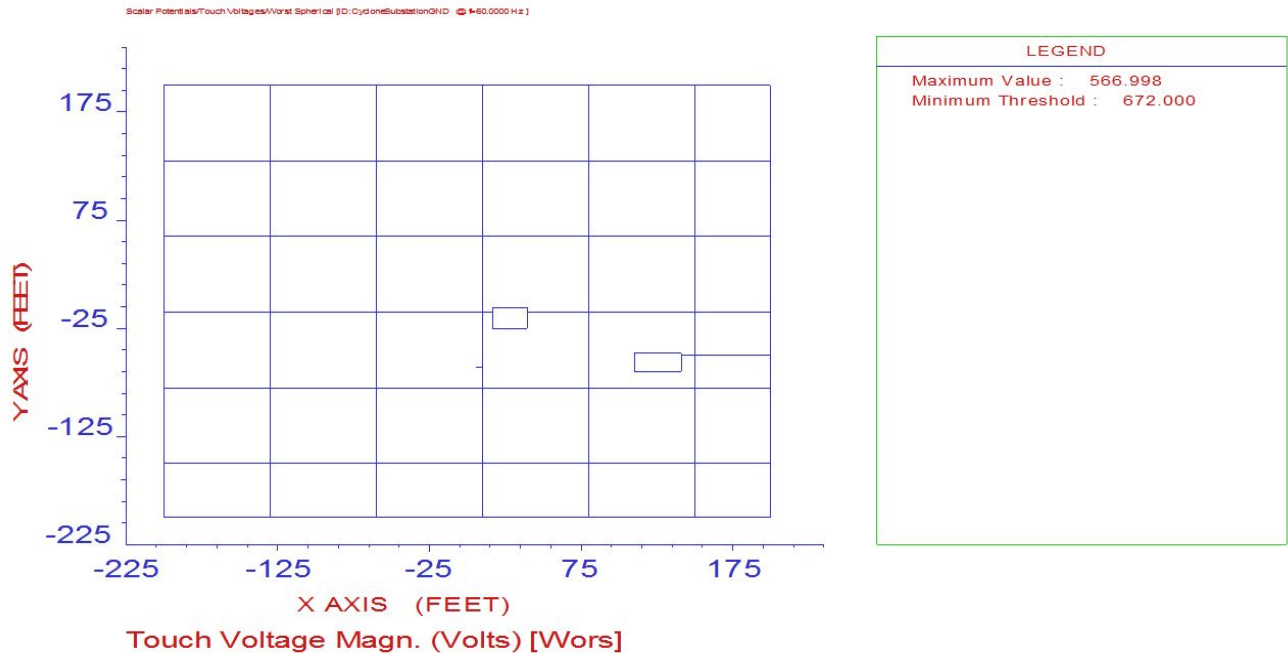
3.2 70'x70' Grid Spacing

After analyzing different grounding studies it was determined 70'x70' would provide a sufficient ground grid. Since anything less than a 70'70' grid would also pass, the larger grid is preferable since making the grid smaller provides minimal added benefits for this fault current. Our initial ground grid used 30'x30' spacings, the next iteration was run using 50'x50' spacings, and 80'x80' spacings following. Once we found that 80'x80' spacings did not provide a safe environment, we implemented the 70'x70' spacings. The results are presented below.

3.2.1 Touch Voltages

Using the fault current requirement of 21kA from BMCD the touch voltages for Cyclone Substation are shown in Figure 3-2. The graph below depicts the touch voltages with no split factor applied on a 70'x70' ground grid.

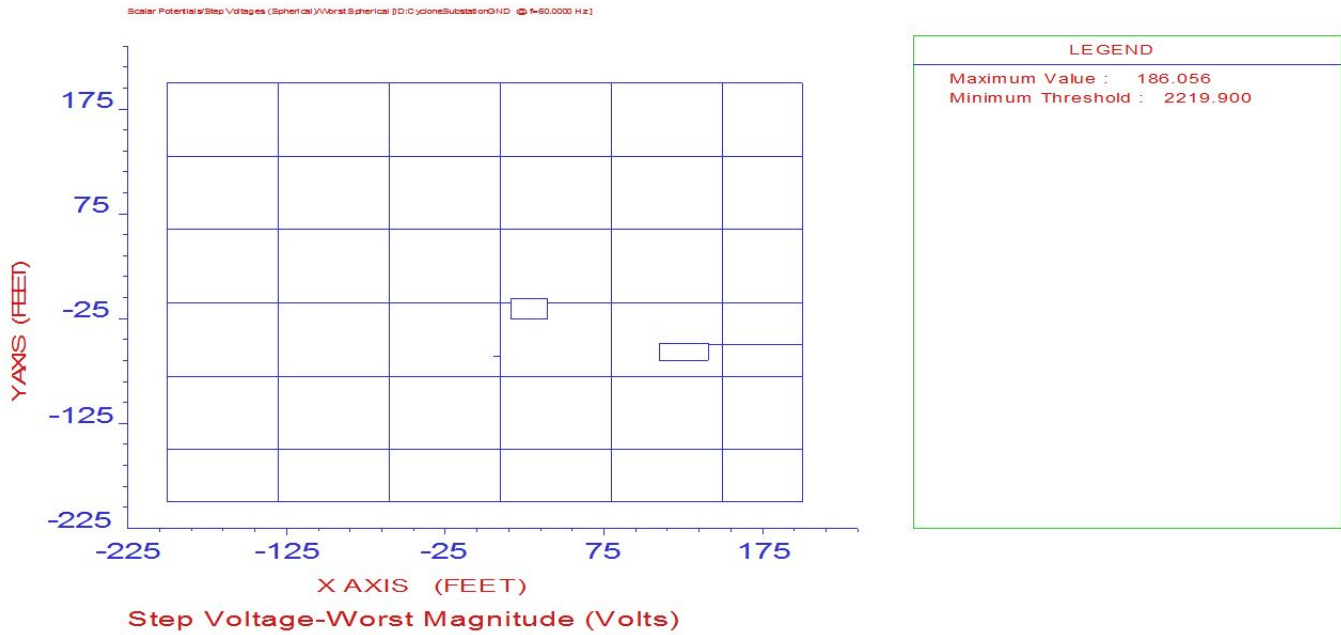
Figure 3-2: Touch Voltage Plot Over Surface Layer (21kA Fault Current)



3.2.2 Step Voltages

Figure 3-3 gives the step voltage of the new ground grid at Cyclone Substation for a 21kA fault current. As shown below, the grid has a maximum step potential value less than the value provided by IEEE 80-2000. This means the step potentials pass for this grid layout.

Figure 3-3: Step Voltage Plot Over Surface Layer (21kA Fault Current)



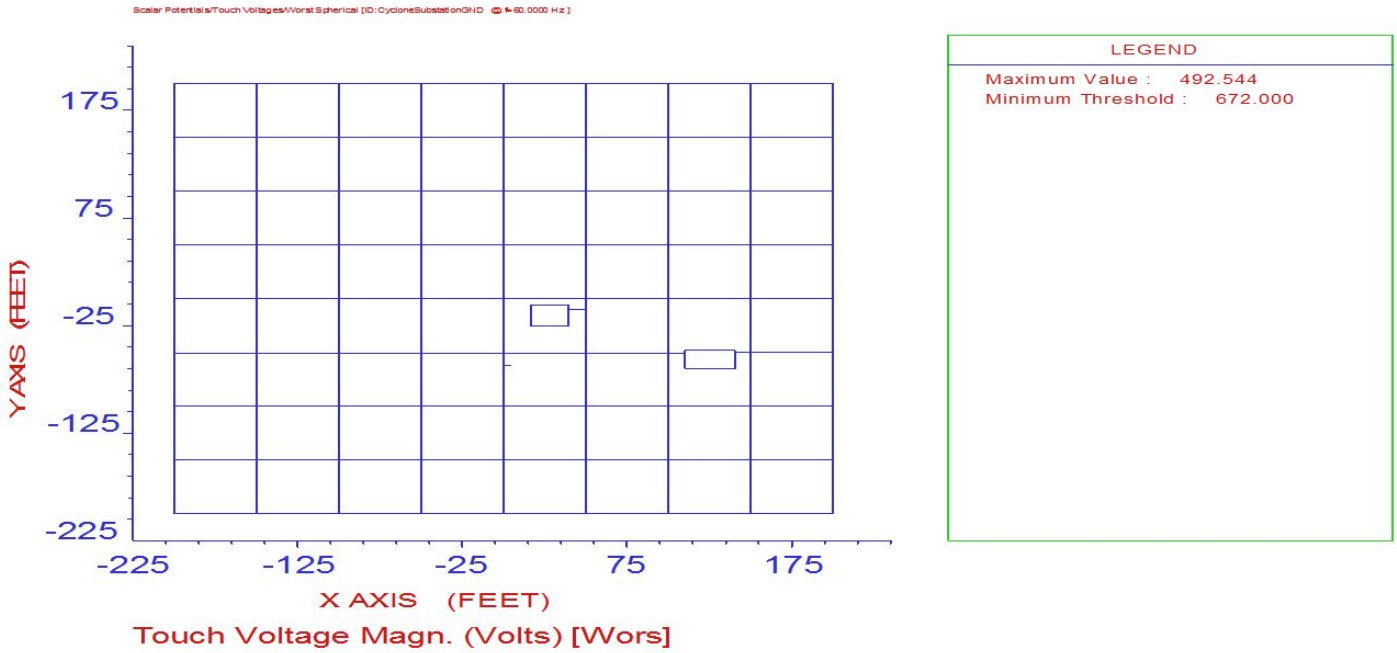
3.3 50'x50' Grid Spacing

After analyzing different grounding studies it was determined that 50'x50' would provide a sufficient ground grid, but would not be necessary since 70'x70' also passes.

3.3.1 Touch Voltages

Using the fault current requirement of 21kA from BMCD the touch voltages for Cyclone Substation are shown in Figure 3-4. The graph below depicts the touch voltages applied on a 50'x50' ground grid.

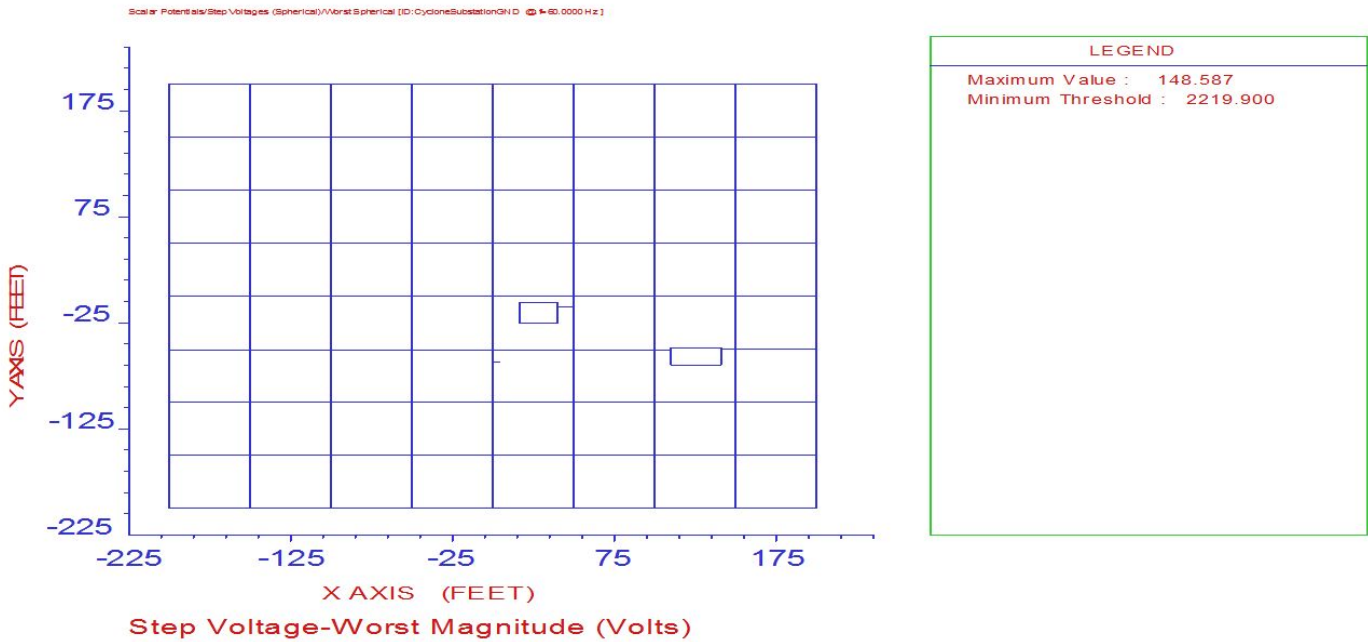
Figure 3-4: Touch Voltage Plot Over Surface Layer (21kA Fault Current)



3.3.2 Step Voltages

Figure 3-5 gives the step voltage of the new ground grid at Cyclone Substation for a 21kA fault current. As shown below, the grid has a maximum step potential value less than the value provided by IEEE 80-2000. This means the step potentials pass for this grid layout.

Figure 3-5: Step Voltage Plot Over Surface Layer (21kA Fault Current)



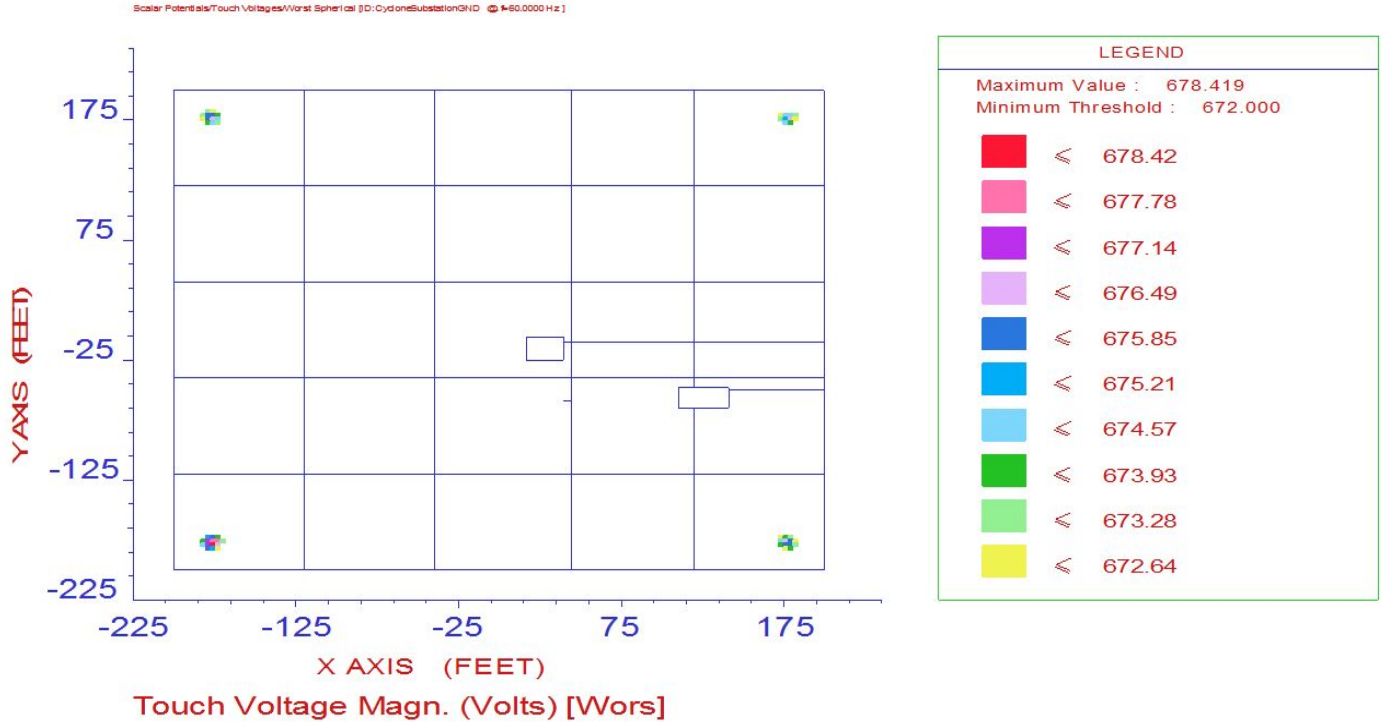
3.4 80'x80' Grid Spacing(Failure Case)

When grid was expanded to 80'x80' it was determined to be unsafe due to dangerous touch potentials near the four corners of the substation area.

3.4.1 Touch Voltages

Using the fault current requirement of 21kA from BMCD, the touch voltages for Cyclone Substation are shown in Figure 3-6. There is a portion of the grid which has a touch voltage greater than the allowable values. This means that this grid will not provide the adequate protection required for this substation. With this case, it shows the 70'x70' grid should be used to eliminate dangerous touch potentials that occur during a fault condition with the aforementioned conditions.

Figure 3-6: Touch Voltage Plot Over Surface Layer (21kA Fault Current)



4.0 CONCLUSIONS

Based on the results presented in this report, it can be concluded that the grounding grid design maintains acceptable touch and voltage limits during the maximum fault conditions. After an iterative process, it can be concluded that the 70'x70' spacing is the most cost-efficient design that also maintains acceptable touch and voltage limits. By using maximum fault conditions, we are not considering a split factor and therefore our results are rather conservative. The ground grid design follows IEEE Standard 80.

5.0 REFERENCES

IEEE Guide for Safety in AC Substation Grounding, IEEE Std. 80, 2013.

CDEGS 101 Training Course, *Substation Grounding Analysis*, Odle & Schuldt, 2013.

Cyclone Substation – Lightning Study

Burns and McDonnell

Cyclone Substation Project

Project No. C2019

Revision 1

February 2019

Cyclone Substation – Lightning Study

prepared for

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**Revision 1
February 2019**

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INDEX
Burns and McDonnell
Cyclone Substation – Lightning Study
Project No. C2019

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LIST OF ABBREVIATIONS

<u>Abbreviation</u>	<u>Term/Phrase/Name</u>
IEEE	Institute of Electrical and Electronic Engineers

1.0 SUMMARY

The following lightning protection report, as well as the associated figures included in the Appendix, details the mathematical method—the empirical curves method—that was employed in order to determine the suggested lightning protection design for Cyclone Substation. Also included in this report is a drawing of that suggested lightning protection design.

Calculations were performed based on an equipment exposure rate of 0.1% to ensure maximum protection of that equipment against lightning strokes. Formulae were derived from the IEEE Standard 998-2012, “IEEE Guide for Direct Lightning Stroke Shielding of Substations”.

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—those located on top of the H-frame termination towers and the masts that should be installed to protect the equipment outside of the zones of protection associated with the H-frame 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.

2.0 DEFINITIONS

<u>Abbreviation</u>	<u>Term/Phrase/Name</u>
D and h(e)	Height of associated equipment (max. equipment height) in feet
H and h(m)	Height of lightning mast in feet
X	Distance between lightning mast and protected equipment in feet
Y	Difference between height of lightning mast and protected equipment in feet ($Y = H - D$)
S	Maximum distance between shielding electrodes in feet
Td	Keraunic level for Iowa
Nk	Ground flash density
Ns	Number of flashes within substation
A	Substation area of protection in square meters

3.0 CALCULATIONS FOR PROTECTION

Expected Shielding Performance

$$N_k = .12 \times T_d = .12 \times 40 = 4.8 \text{ lightning strokes/km}^2/\text{year}$$

$$N_s = N_k \times A / (1000^2) = 4.8 \times 22128.48 / (1000^2) = 0.106217$$

$$SP = N_s \times (\text{Exposure Rate} = 0.1\%) = .000106 \text{ strokes/year}$$

Calculations

- Transformer, 69kV Circuit Breaker, and Low Bus Protection (See Table 1 and Figures 1, 2, 3 & 4)
 - First lightning mast – H-frame lightning mast 01 located on the low side H-frame
Second lightning mast – H-frame lightning mast 02 located on the low side H-frame
 - $h(e) = 16.5'$, $h(m) = 55'$, $D/H = 16.5'/55' = .3$
 - Protection results:
 $X/H \approx 1$, $X = 55'$
Third lightning mast – Lightning mast 01 located near transformer T1
Protecting 3" Schedule 40 bus
 - $h(e) = 22'$, $h(m) = 55'$, $D/H = 22'/55' = .4$
 - Protection results:
 $X/H \approx .87$, $X = 47.85'$
 - Interaction between Lightning mast 01 and “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” H-frame lightning mast 02:
 $S/H \approx 4$, $S = 220'$
 - Interaction between Lightning mast 01 and “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” Lightning mast 01:
 $S/H \approx 4$, $S = 220'$
- 138kV Circuit Breakers and High Bus (including Expansion Bus) Protection (See Table 2 and Figures 5 & 6)
 - First lightning mast – H-frame lightning mast 01 located on the high side H-frame
Second lightning mast – H-frame lightning mast 02 located on the high side H-frame
Protecting 4" Schedule 80 bus
 - $h(e) = 22'$, $h(m) = 55'$, $D/H = 22'/55' = .4$
 - Protection results:
 $X/H \approx .87$, $X = 47.85'$
 - Interaction between H-frame lightning mast 01 and “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” Lightning mast 01:
 $S/H \approx 4$, $S = 220'$

- 138kV Circuit Breakers and High Bus (including Expansion Bus) Protection (See Table 2 and Figure 7)
 - First lightning mast – Lightning mast 01 located between 138kV circuit breakers and expansion bus
Protecting 4” Schedule 80 bus
 - $h(e) = 22'$, $h(m) = 55'$, $D/H = 22'/55' = .4$
 - Protection results:
 $X/H \approx .87$, $X = 47.85'$

Table 1: Calculations for Protection of Transformer, 69kV Circuit Breaker and Low Bus

Lighting Protection	D (feet)	H (feet)	Y (H-D) (feet)	D/H Ratio	X/H Ratio	X (feet)
H-frame lightning mast 01	16.5	55	38.5	.3	1	55
H-frame lightning mast 02	16.5	55	38.5	.3	1	55
Lightning mast 01	22	55	33	.4	.87	47.85

Table 2: Calculations for Protection of 138kV Circuit Breakers and High Bus (including Expansion Bus)

Lighting Protection	D (feet)	H (feet)	Y (H-D) (feet)	D/H Ratio	X/H Ratio	X (feet)
H-frame lightning mast 01	22	55	33	.4	.87	47.85
H-frame lightning mast 02	22	55	33	.4	.87	47.85
Lightning mast 01	22	55	33	.4	.87	47.85

4.0 RECOMMENDATION

The following recommendation is based on the results of the lightning protection study. Interactions between zones of protection of new lightning masts and zones of protection of existing lightning masts were considered when the study was performed. It has been determined that one 55' lightning mast should be installed to protect the transformer, parts of the low bus and parts of the high bus, and that one 55' mast should be installed to protect the 138kV circuit breakers and the high bus.

5.0 REFERENCES

IEEE Standard 998-2012 “IEEE Guide for Direct Lightning Stroke Shielding of Substation”

APPENDIX

Figure 1: Protection of 69kV Circuit Breaker and Low Bus—H-frame lightning masts

IEEE Standard 998-2012
IEEE Guide for Direct Lightning Stroke Shielding of Substations
(IEEE Figure A.1—Protection of an exposed object by a single lightning mast)

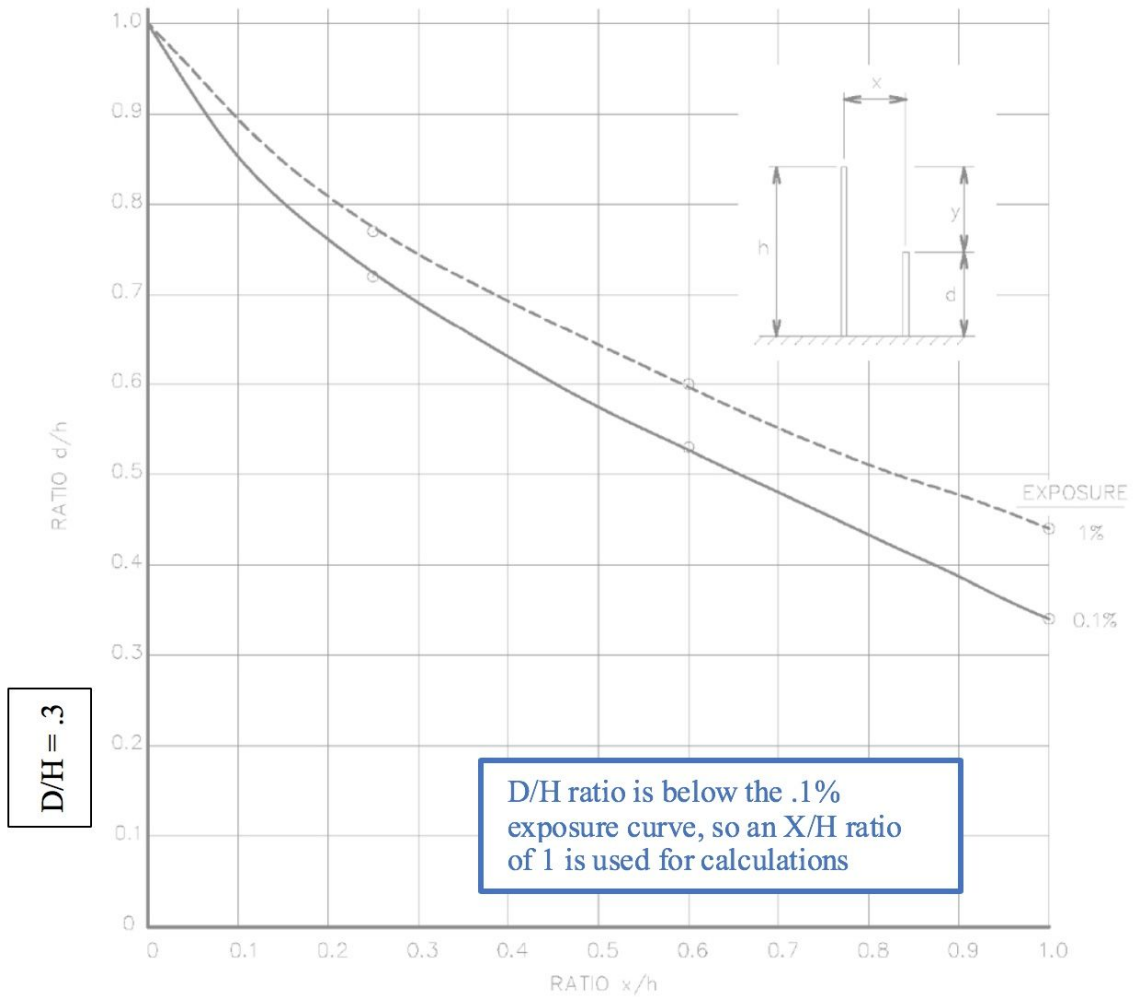


Figure 2: Protection of Transformer—Lightning mast 01

IEEE Standard 998-2012

IEEE Guide for Direct Lightning Stroke Shielding of Substations
(IEEE Figure A.1—Protection of an exposed object by a single lightning mast)

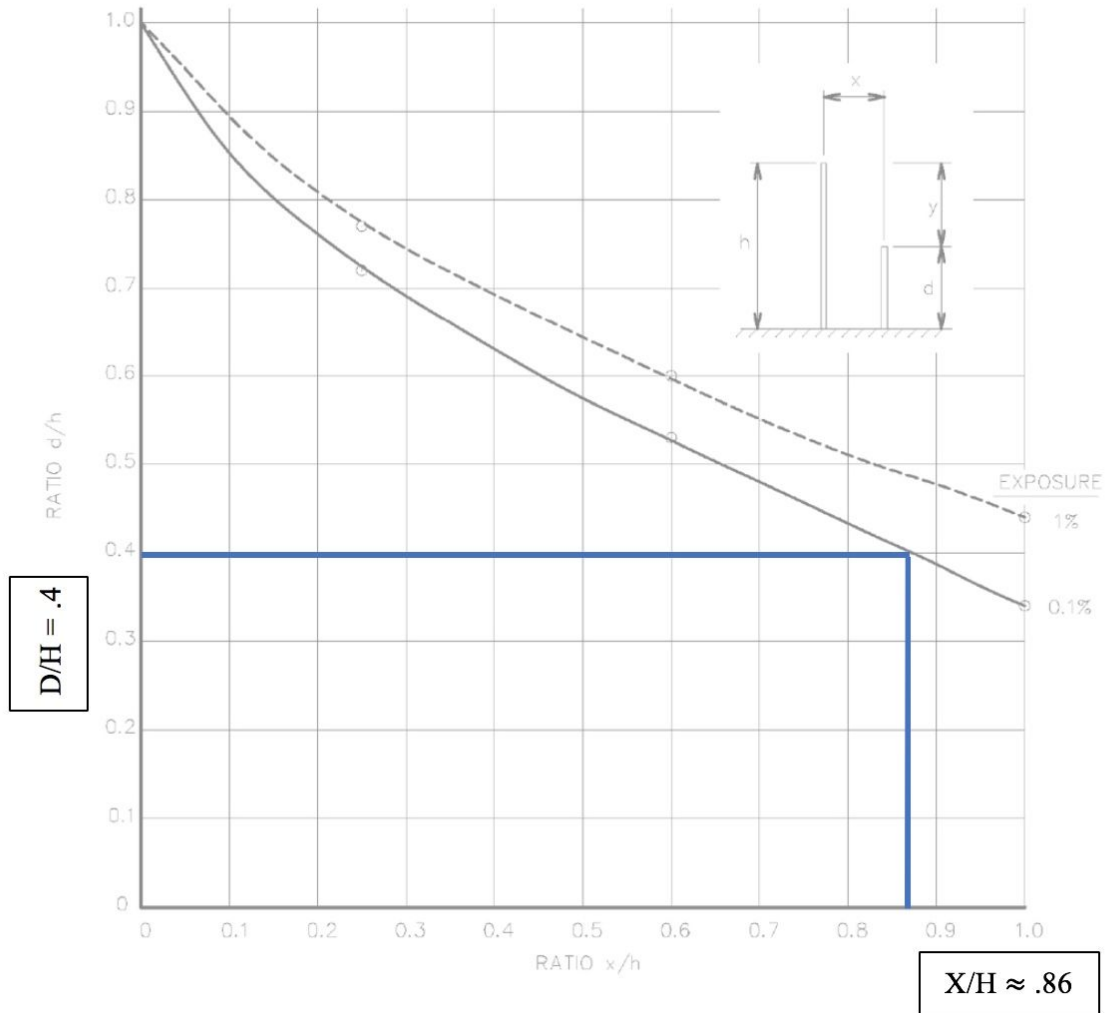


Figure 3: Calculation of interaction between “Transformer, 69kV Circuit Breaker, and Low Bus Protection” Lightning mast 01 and “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” H-frame lightning mast 02

IEEE Standard 998-2012
 IEEE Guide for Direct Lightning Stroke Shielding of Substations
 (IEEE Figure A.3—Protection of an exposed object by two lightning masts)

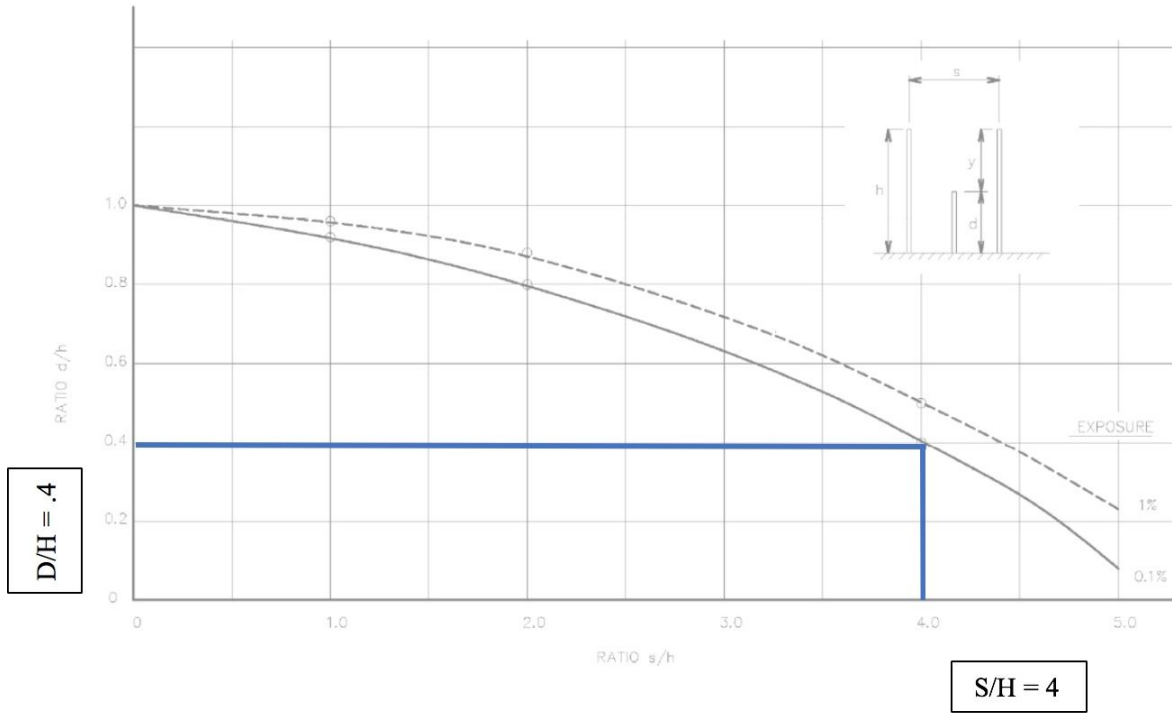


Figure 4: Calculation of interaction between “Transformer, 69kV Circuit Breaker, and Low Bus Protection” Lightning mast 01 and “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” Lightning mast 01

IEEE Standard 998-2012
 IEEE Guide for Direct Lightning Stroke Shielding of Substations
 (IEEE Figure A.3—Protection of an exposed object by two lightning masts)

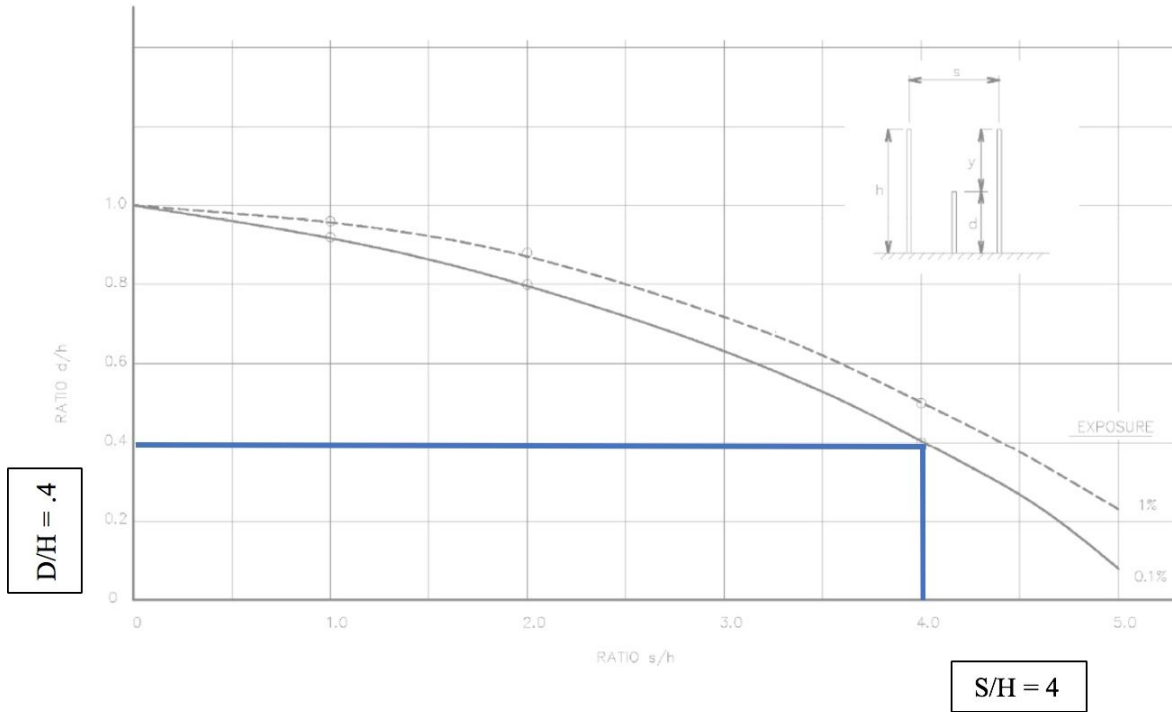


Figure 5: Protection of 138kV Circuit Breakers and High Bus (including Expansion Bus)—H-frame lightning masts

IEEE Standard 998-2012
 IEEE Guide for Direct Lightning Stroke Shielding of Substations
 (IEEE Figure A.1—Protection of an exposed object by a single lightning mast)

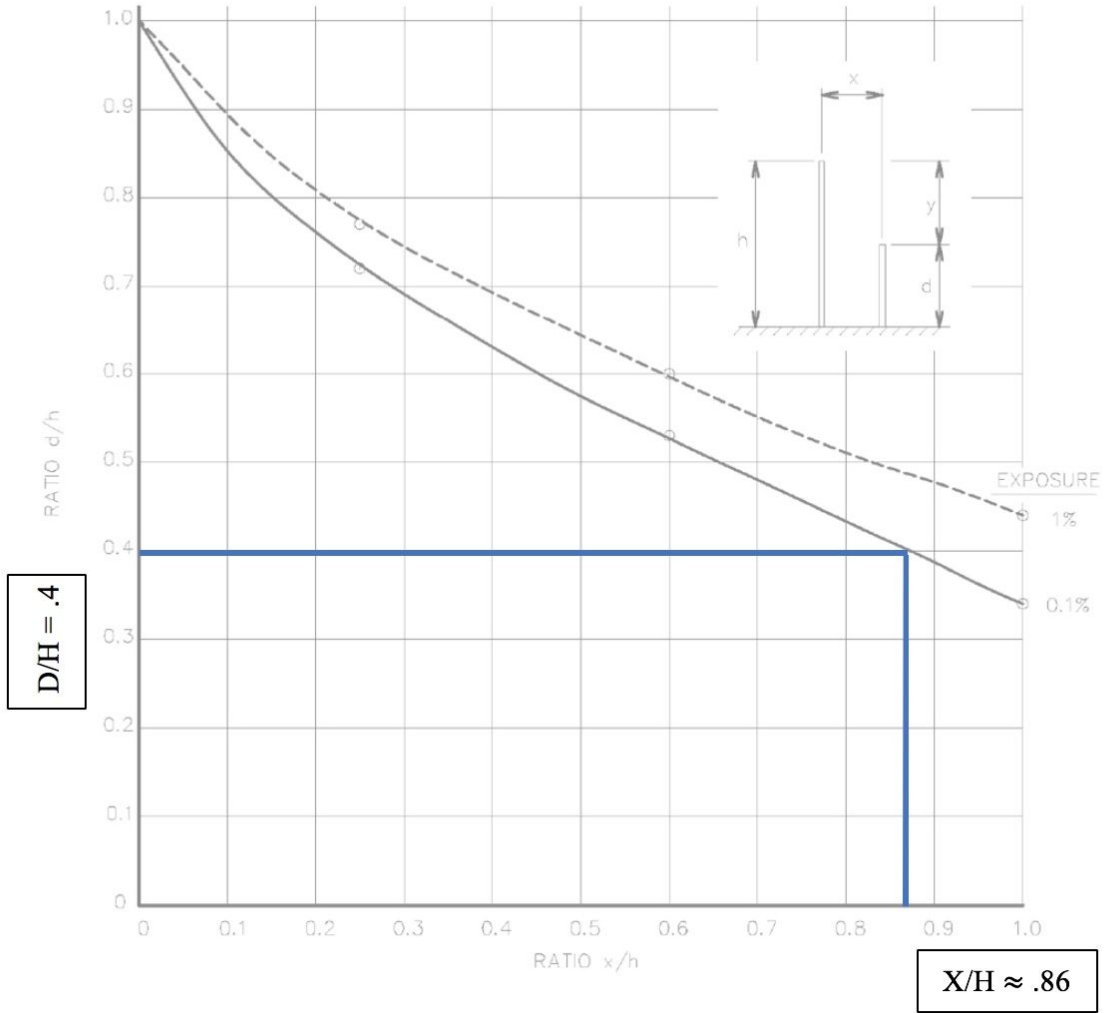


Figure 6: Calculation of interaction between “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” H-frame lightning mast 01 and “138kV Circuit Breakers and High Bus (including Expansion Bus) Protection” Lightning mast 01

IEEE Standard 998-2012
 IEEE Guide for Direct Lightning Stroke Shielding of Substations
 (IEEE Figure A.3—Protection of an exposed object by two lightning masts)

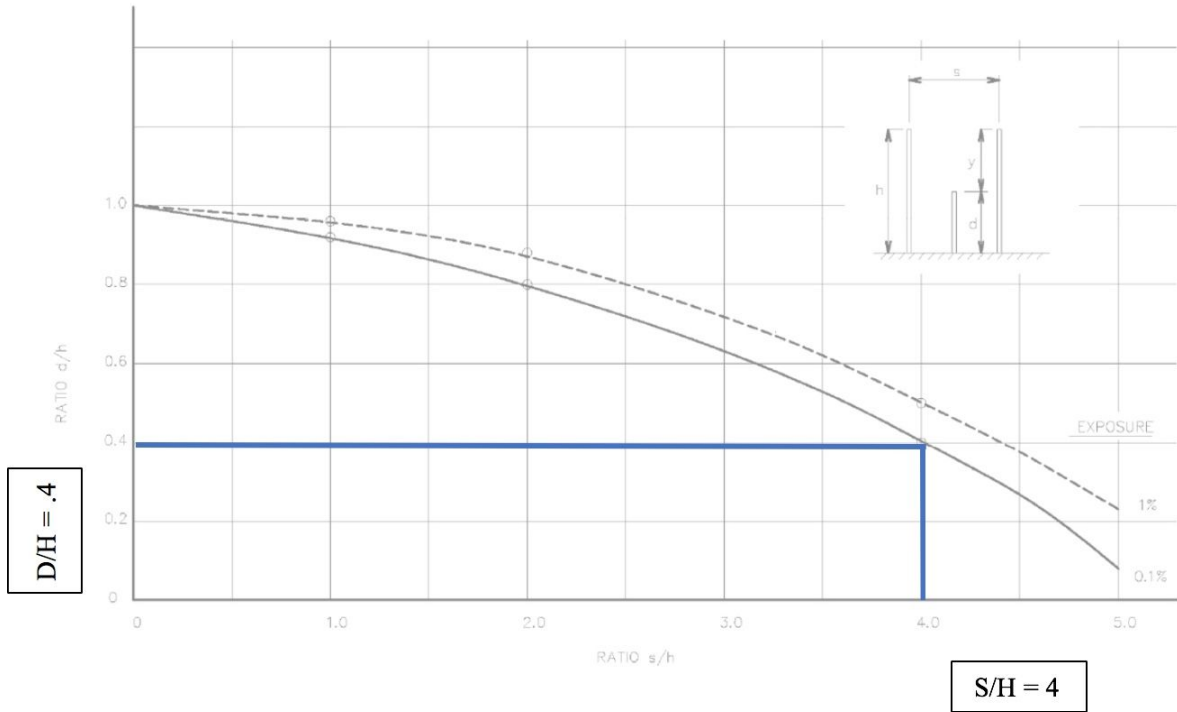


Figure 7: Protection of 138kV Circuit Breakers and High Bus (including Expansion Bus)—Lightning mast 01

IEEE Standard 998-2012
 IEEE Guide for Direct Lightning Stroke Shielding of Substations
 (IEEE Figure A.1—Protection of an exposed object by a single lightning mast)

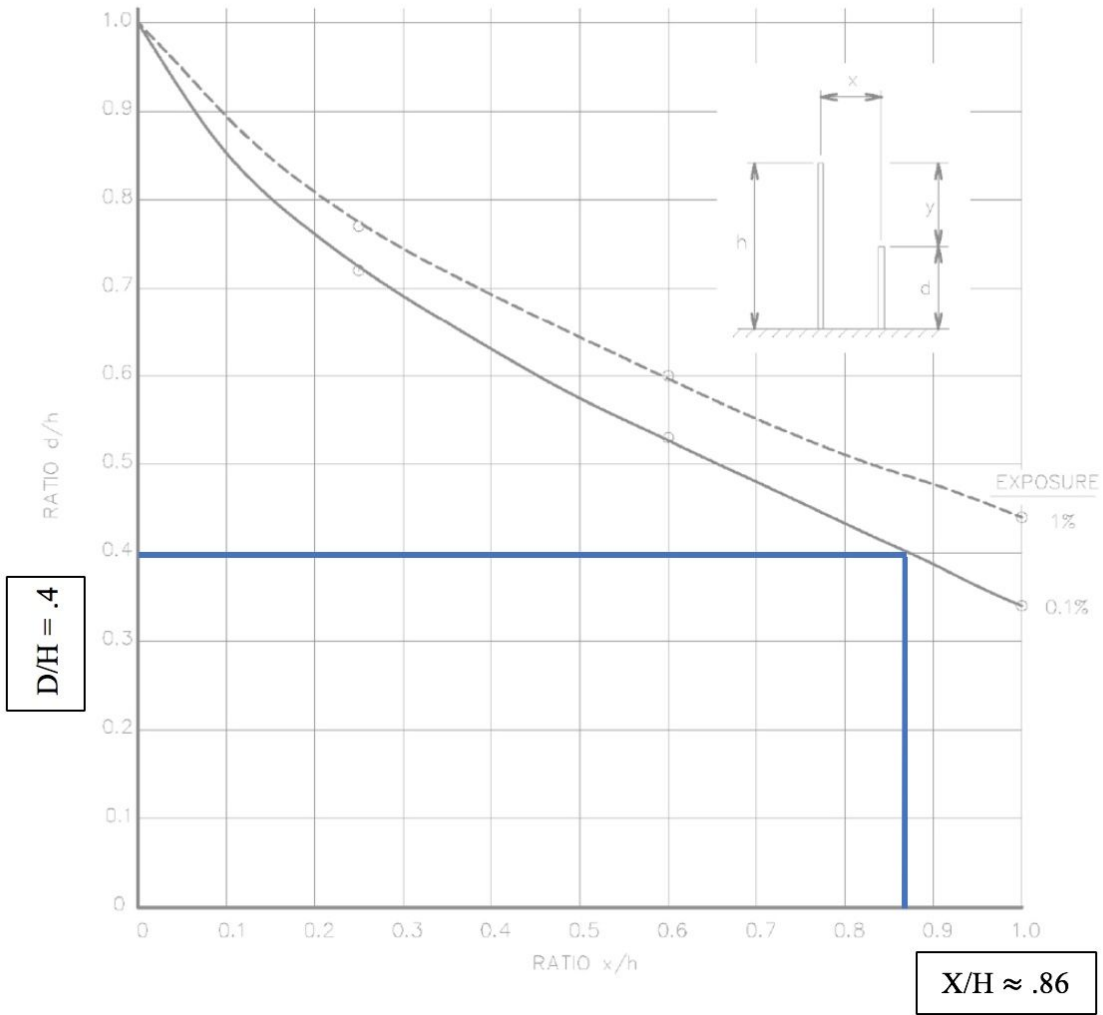
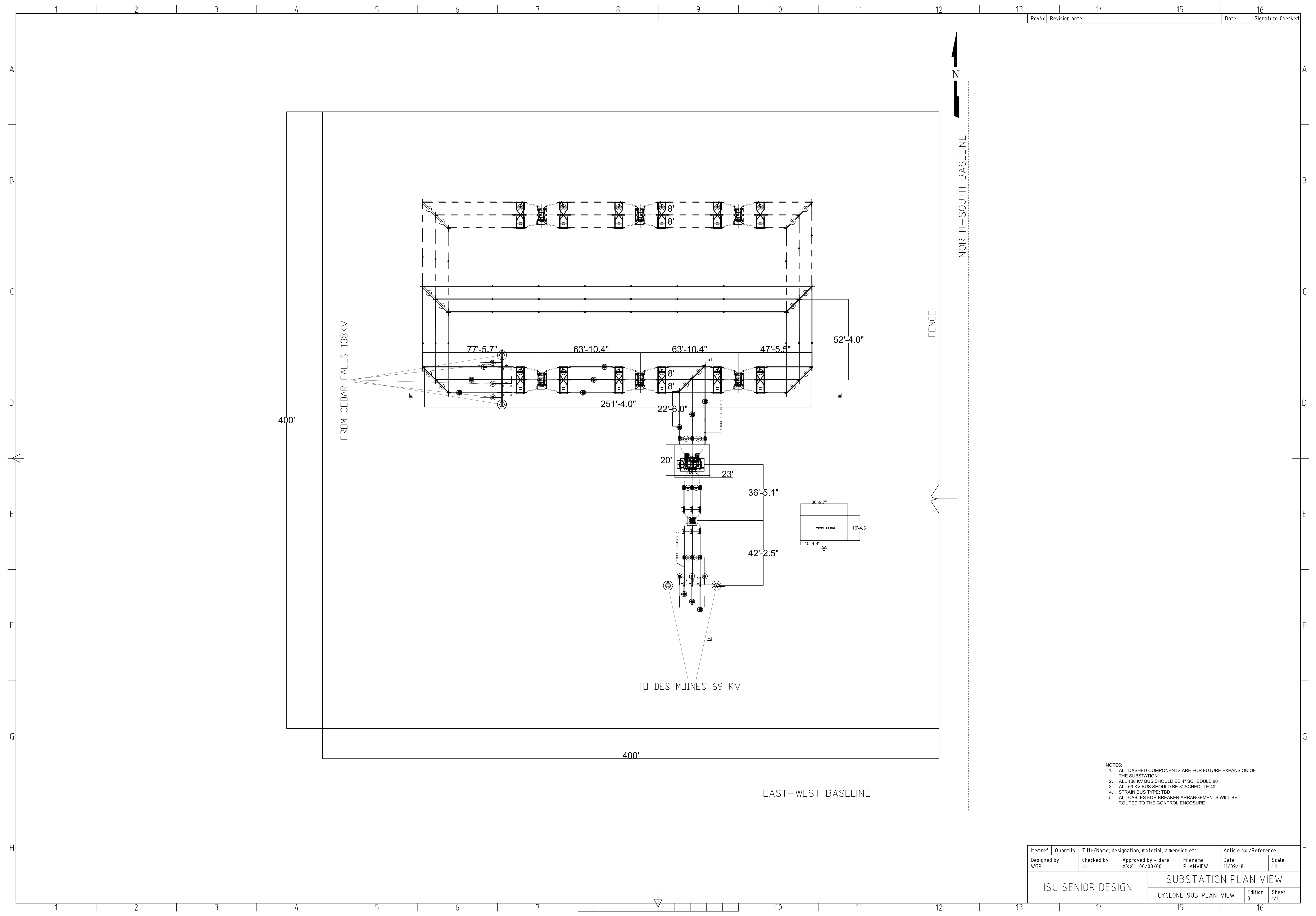
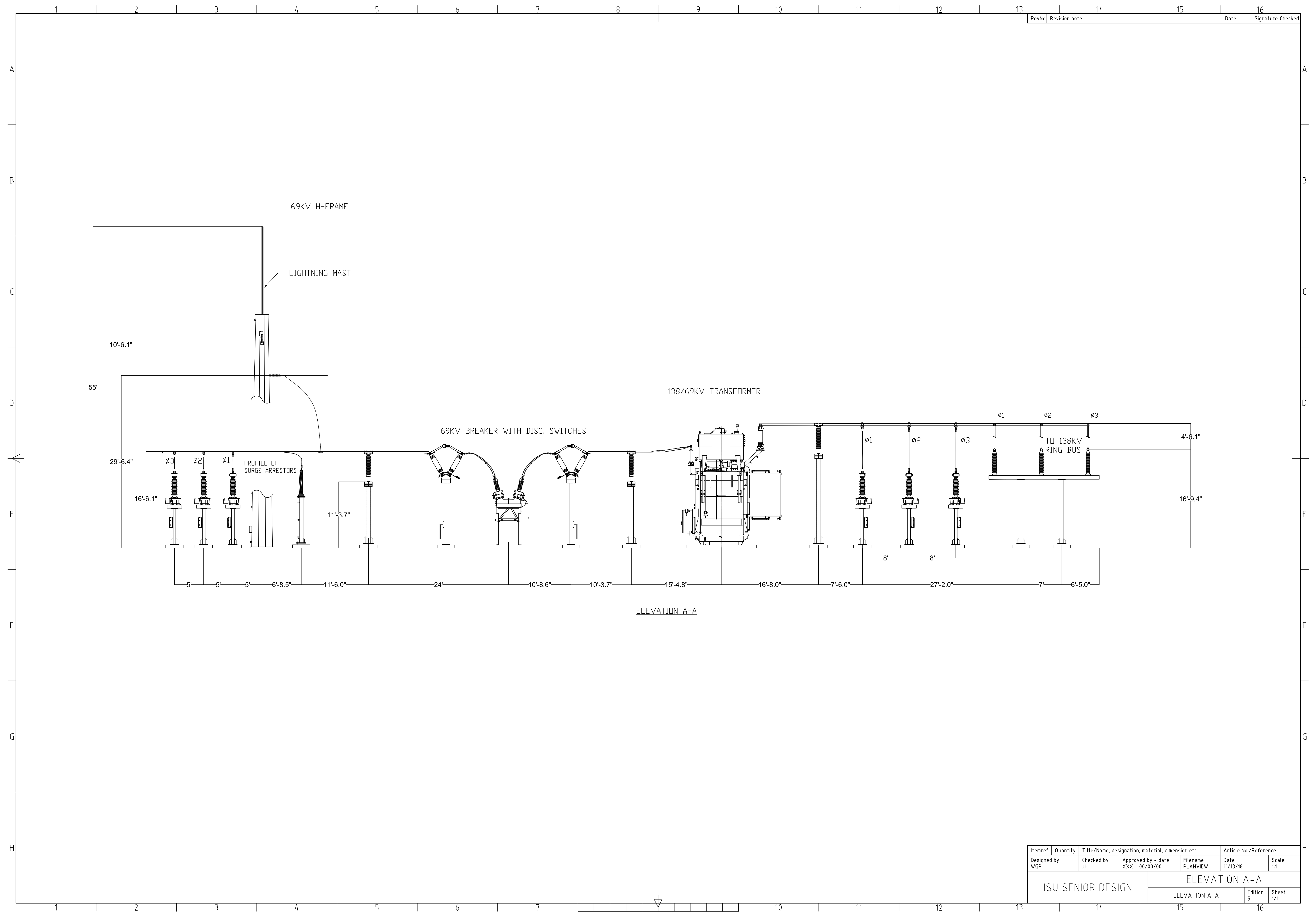


Figure 8: Final lightning protection design

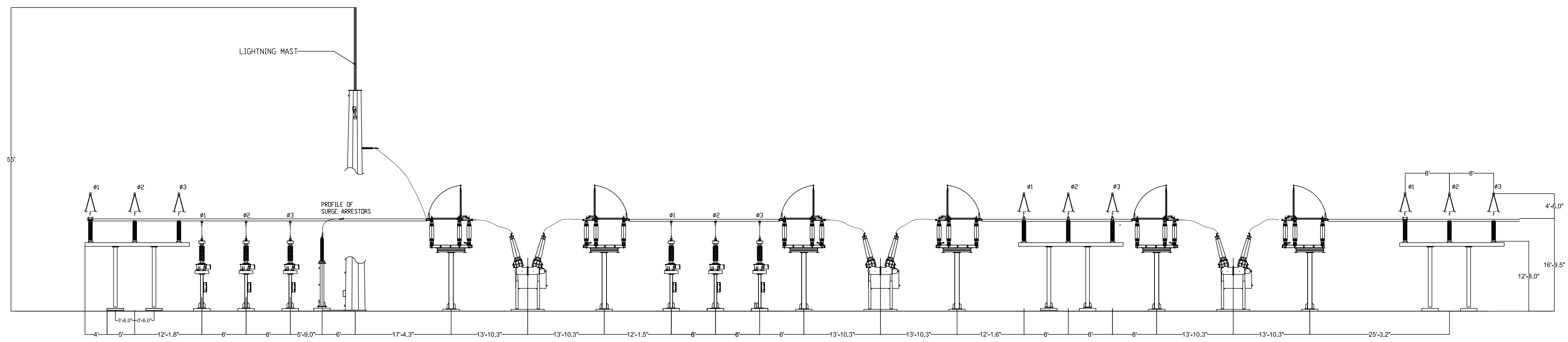


- NOTES:
1. ALL DASHED COMPONENTS ARE FOR FUTURE EXPANSION OF THE SUBSTATION.
 2. ALL 138 KV BUS SHOULD BE 4" SCHEDULE 80
 3. ALL 69 KV BUS SHOULD BE 3" SCHEDULE 40
 4. STRAIN BUS TYPE: TBD
 5. ALL CABLES FOR BREAKER ARRANGEMENTS WILL BE ROUTED TO THE CONTROL ENCLOSURE

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		SUBSTATION PLAN VIEW	
		CYCLONE-SUB-PLAN-VIEW	Edition 3
			Sheet 1/1

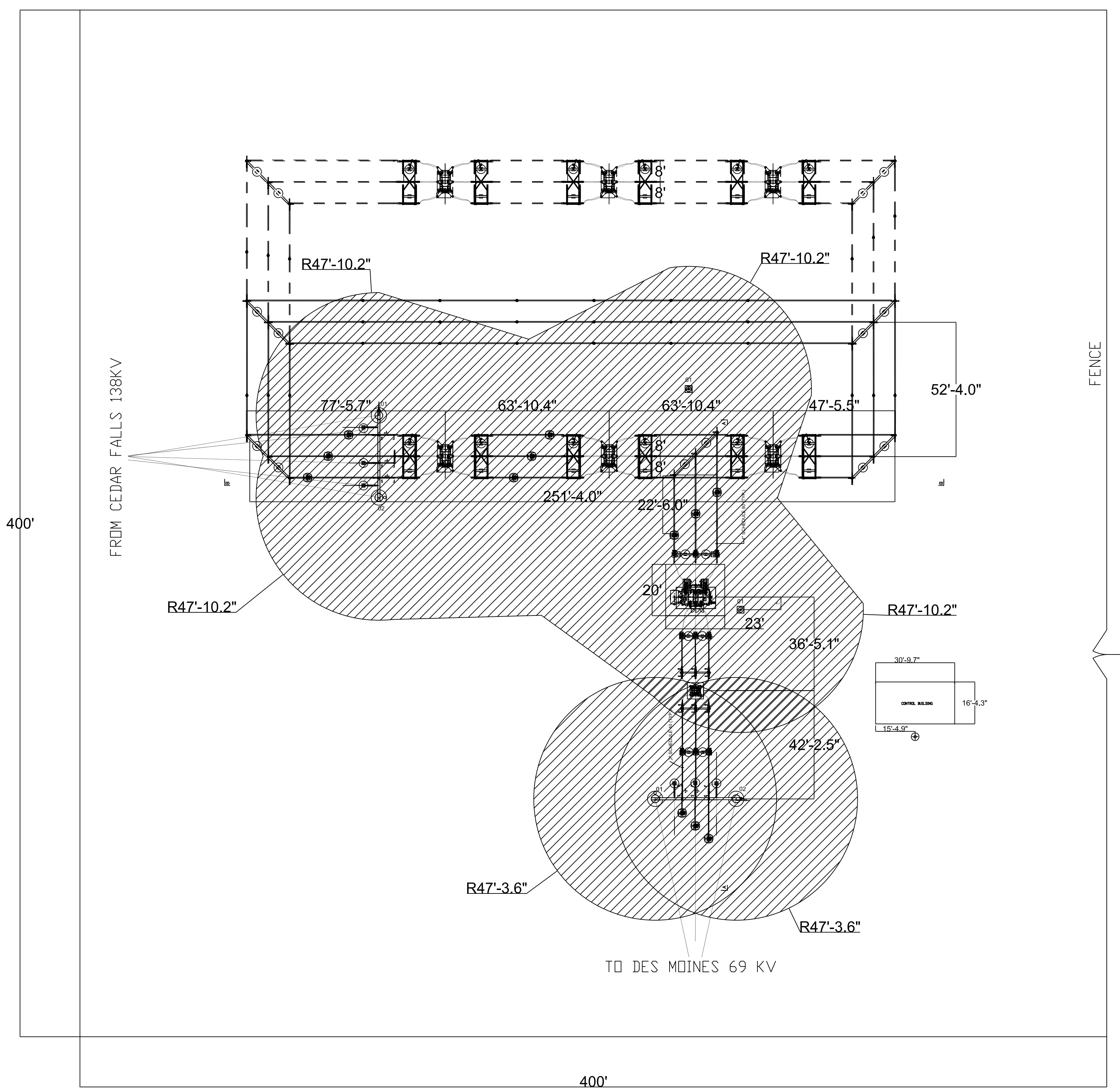


Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		ELEVATION A-A	
ELEVATION A-A		Edition 5	Sheet 1/1



ELEVATION B-B

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		ELEVATION B-B	
ELEVATION B-B		Edition 3	Sheet 1/1



NORTH-SOUTH BASELINE

EAST-WEST BASELINE

- NOTES:
1. ALL DASHED COMPONENTS ARE FOR FUTURE EXPANSION OF THE SUBSTATION.
 2. LIGHTNING MASTS ON H-FRAME IN 69KV YARD ARE 55' ABOVE GROUND.
 3. LIGHTNING MAST FOR T1 IS 55' ABOVE GROUND.
 4. LIGHTNING MASTS IN 138KV YARD ARE 55' ABOVE GROUND.
 5. LIGHTNING MASTS ON H-FRAME IN 138KV YARD ARE 55' ABOVE GROUND.

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by TK	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		LIGHTNING PROTECTION	
		CYCLONE-SUB-PLAN-VIEW-LTG	Edition 3
			Sheet 1/1

Cyclone Substation 125 VDC Battery System Sizing Revision 0

prepared for

Burns & McDonnell

03/01/2019

prepared by

ISU EE sdmay19-17

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1.0 INTRODUCTION

The DC system is a key component of an electrical substation. The DC system provides auxiliary control power for communication and control equipment, relays and supervisory control and data acquisition (SCADA) equipment. It also provides the power required to trip and reclose circuit breakers, circuit switchers and motor-operated disconnect switches. The DC system is comprised of a battery set, a battery charger, DC panelboards, DC wiring and a battery disconnect.

DC loads are totaled and classified in order to size the batteries, chargers and panels used in the DC system. The control building will be sized to accommodate the 125V DC battery and charger. The design must follow the guidelines of IEEE 485-2010. The minimum cell voltage has been specified as 1.75V/cell and the Enersys PowerSafe CC-M battery shall be used in the design. This battery features calcium plates, demonstrating maximized performance and reduced watering requirements in long discharge use. This type of battery has a capacity range of 50-200Ah. The Amp-hour requirements are to be calculated in accordance with the equations presented in IEEE 485-2010 and the battery selection to be made based on the cell sizing worksheet, completed using the outcomes of the duty cycle analysis.

The typically worst case scenario included a bus fault, assuming all bus breaker trip coils operate for 1 minute. The worst case scenario looked at in this study includes a breaker failure connected to the high side of the transformer. In this situation, the backup breakers would be the other two breakers on the high side and the one on the low side. This breaker failure, followed by a transformer lockout, would take out the two high side breaker and low side breaker used as backup for the first breaker failure.

2.0 SYSTEM DESIGN CRITERIA

2.1 BATTERY CELLS

The number of cells (n_{cells}) for the battery can be calculated by the following equation where V_{max} is the maximum system voltage specified to be 125VDC, and V_{charge} is the maximum charge voltage per cell of 2.08VDC.

$$n_{cells} = \frac{V_{max}}{V_{charge}}$$

The number of cells equates to be 60; with this value, the minimum cell voltage (V_{cell}) is 1.75V/cell which is calculated by the following equation where V_{min} is the minimum battery voltage specified to be 105V.

$$V_{cell} = \frac{V_{min}}{n_{cells}} \text{ (V/cell)}$$

2.2 ASSUMED DERATING FACTORS

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

Table 2-1 Battery Correction Factors

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

3.0 LOAD CLASSIFICATIONS

The worst case scenario being analyzed for this study takes into account the possibility of multiple problems occurring within a short period of time. Typically, the worst case scenario includes a bus fault. The worst case scenario looked at in this study includes a breaker failure connected to the high side of the transformer. The backup for this worst case scenario would be the other two breakers on the high side and the one on the low side, followed by a transformer lockout. This would in turn take out the two high side breakers and low side breaker used as backup for the first breaker failure.

The assumption was made that the breakers are set to try one reclose attempt after a fault: Trip, Close, Trip., all occur within the first or last minute of the fault.

Table 3-1 First Minute Loads (Load L1, Time = 1 minute)

Quantity	Device	DC Load Current (A)	Total (A)
1	69KV Breaker Trip	12	12
3	138KV Breaker Trip	12	36
Total =			48

The continuous load is primarily made up of relay loads and devices to be continuously energized throughout the eight hour interval. The table below shows the continuous current and each of the comprising items including future equipment are shown in Appendix A.

Table 3-2 Continuous Loads (Load L2, Time = 480 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
1	Relay & Meter Load	4.56	4.56
Total =			4.56

Emergency lighting loads shown in following table are only required to operate for the last half of the eight hour period(240 minutes), but for our design, we decided to have them operate after the first 5 minutes.

Table 3-3 Momentary Loads (Load L3, Time = 475 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
6	Emergency Lighting	0.256	1.536
Total =			1.536A

The following four tables assume that the transformer fault and failed breaker issues have been resolved and the affected part of the substation can be re-energized. Following the re-energization, it's assumed the station AC service issue is resolved and the eight hour period concluded.

Table 3-4 Momentary Loads (Load L4, Time = 1 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
4	Breaker Reclose	1.9	7.6
Total =			7.6

Table 3-5 Momentary Loads (Load L5, Time = 1 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
4	Breaker Motor Start	43.5	174
Total =			174

Table 3-6 Momentary Loads (Load L6, Time = 1 minutes)

Quantity	Device	DC Load Current (A)	Total (A)
1	Transformer Relay	0.2	0.2
Total =			0.2

Table 3-7 Momentary Loads (Load L7, Time = 7 minutes)

Quantity	Device	DC Load Current (A)	Total (A)

Total =

4.0 BATTERY SIZING

4.1 BATTERY CAPACITY & DUTY CYCLE:

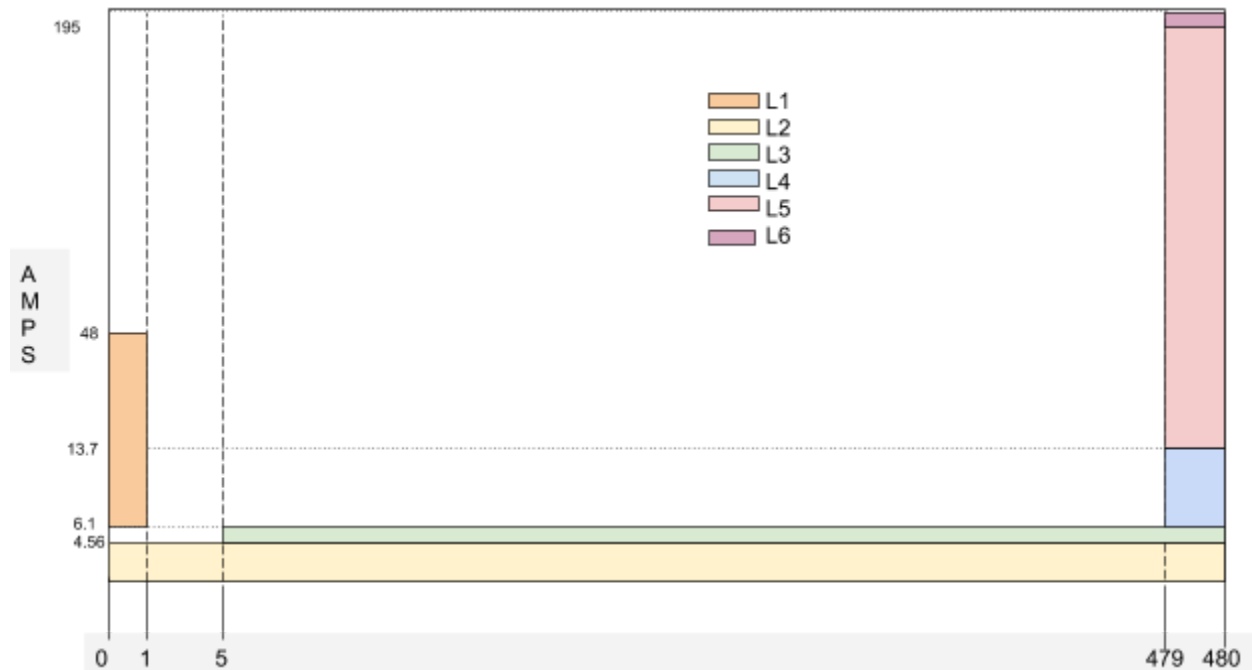
To calculate the total number of amp-hours required of the battery, the 480 minute time frame can be divided into periods where each one can be expressed as a function equal to the total amperes consumed in that time frame. The integral of these piecewise functions over the entire time frame yields the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

Table 4-1 Total Amp Hours

Period	Loads	Total Amperes	Duration	Amp-Hours
A1	L1+L2	52.56	1	0.876
A2	L2	4.56	480	36.48
A3	L2+L3	6.096	475	48.26
A4	L2+L3+L4	13.696	1	0.23
A5	L2+L3+L5	180.096	1	3.0016
A6	L2+L3+L6	6.296	4	0.42
A7	L2+L3+L7	N/A	7	

Total=89.27
Ah

From the previous Table 4-1, a duty cycle can be shown as the following figure.

Figure 4-1 Load Profile

4.2 BATTERY POSITIVE PLATES

IEEE Standard 485 goes into detail on how to calculate the number of positive plates required for the battery. To do this, the load profile shown in Figure 4-1 was used in conjunction with the current per positive plate required to bring the batteries' voltage to 1.75 per cell in a specified amount of time. The latter is provided by the battery manufacturer and can be referenced in Appendix B. The following Figure 4-2 illustrates how the largest positive plate size can be found. By using the multiplying factors from Table 2-1, the calculated number of positive plates equals 1.69, which can be rounded up to 2. The total number of plates for the battery can be calculated using the following equation.

$$\text{total number of plates} = 1 + (2 * \text{number of positive plates})$$

The total number of plates equals 5. The Enersys battery CC-5M will be able to supply the substation considering that the rated capacity of the battery is 100Ah, and the required amount should not exceed 89.4 Ah

Figure 4-2 Battery Sizing Spreadsheet:

Project:	Senior Design			Date:	02/19/19		Page:																									
Lowest Expected Electrolyte Temp (F)	55 Degrees F			Min. Cell Voltage:	1.75 V/cell		Cell Mfg:	Enersys																								
1	2	3	4	5	6	7																										
	Load	Change In Load	Duration of period	Time to end of section	Capacity at T min Rate	Required Section Size																										
Period	Amperes	Amperes	minutes	minutes	(6A) Amps / Pos (Rt) or (6B) K factor (KT)	(3)+(6A)=Positive PLates or (3)x(6b)= Rate Amp Hours	POS Values	NEG Values																								
Section 1: First Period Only - If A2 is greater than A1, go to section 2																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1=	1	75	0.7008	***																					
Section 2: First two periods only - If A3 is greater than A2, go to section 3.																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2	6	63	0.8342857143																						
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2	5	63		-0.7619047619																					
Section 3: First three periods only - If A4 is greater than A3, go to section 4.																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2+M3	480	6.3	8.342857143																						
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3	479	6.3		-7.619047619																					
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3	474	6.3	0.2438095238																						
Section 4: First Four Periods only - If A5 is great than A4, go to section 5.																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2+M3+M4	481	6.3	8.342857143																						
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3+M4	480	6.3		-7.619047619																					
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+M4	475	6.3	0.2438095238																						
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4	1	75	0.1013333333																						
Section 5: First Five Periods Only - If A6 is great than A5, go to section 6.																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2+M3+M4+M5	481	6.3	8.342857143																						
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3+M4+M5	480	6.3		-7.619047619																					
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+M4+M5	475	6.3	0.2438095238																						
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4+M5	1	75	0.1013333333																						
5	A5=	180.096	A5-A4=	166.4	M5=	0	T=M5	0																								
Section 6: First Six Periods Only - If A7 is great than A6, go to section 7.																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2+M3+M4+M5+M6	481	6.3	8.342857143																						
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3+M4+M5+M6	480	6.3		-7.619047619																					
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+M4+M5+M6	475	6.3	0.2438095238																						
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4+M5+M6	1	75	0.1013333333																						
5	A5=	180.096	A5-A4=	166.4	M5=	0	T=M5+M6	0																								
6	A6=	6.296	A6-A5=	-173.8	M6=	0	T=M6	0																								
Section 7: First Seven Periods Only - If A8 is great than A7, go to section 8.																																
1	A1=	52.56	A1-0=	52.56	M1=	1	T=M1+M2+M3+M4+M5+M6+M7	481	6.3	8.342857143																						
2	A2=	4.56	A2-A1=	-48	M2=	5	T=M2+M3+M4+M5+M6+M7	480	6.3		-7.619047619																					
3	A3=	6.096	A3-A2=	1.536	M3=	474	T=M3+M4+M5+M6+M7	475	6.3	0.2438095238																						
4	A4=	13.696	A4-A3=	7.6	M4=	1	T=M4+M5+M6+M7	1	75	0.1013333333																						
5	A5=	180.096	A5-A4=	166.4	M5=	0	T=M5+M6+M7	0																								
6	A6=	6.296	A6-A5=	-173.8	M6=	0	T=M6+M7	0																								
7	A7=		A7-A6=	-6.296	M7=	0	T=M7	0																								
<table border="0" style="width:100%"> <tr> <td>Maximum Section Size (8)</td> <td>1.068952381</td> <td>PLUS (+)</td> <td>Random Section Size (9)</td> <td>EQUALS (=)</td> <td>Uncorrected Size - (US) (10)</td> <td>1.068952381</td> <td colspan="4"></td> </tr> <tr> <td>US (11)</td> <td>X Temp Corr (12)</td> <td>1.15</td> <td>X Design Margin(13)</td> <td>1.1</td> <td>X Age Fact (14)</td> <td>1.25</td> <td>EQUALS (=) (15)</td> <td colspan="4">1.690280952</td> </tr> </table>										Maximum Section Size (8)	1.068952381	PLUS (+)	Random Section Size (9)	EQUALS (=)	Uncorrected Size - (US) (10)	1.068952381					US (11)	X Temp Corr (12)	1.15	X Design Margin(13)	1.1	X Age Fact (14)	1.25	EQUALS (=) (15)	1.690280952			
Maximum Section Size (8)	1.068952381	PLUS (+)	Random Section Size (9)	EQUALS (=)	Uncorrected Size - (US) (10)	1.068952381																										
US (11)	X Temp Corr (12)	1.15	X Design Margin(13)	1.1	X Age Fact (14)	1.25	EQUALS (=) (15)	1.690280952																								
When the cell size (15) is greater than a standard cell size, the next larger cell is required																																
(A) - Positive Plates																																
Total # Plates = 5																																
Required cell size (16)																																
(B)- Ampere Hours																																
Therefore cell (17)																																
Rated for																																
is required.																																
Amp-hrs																																

5.0 BATTERY CHARGER SIZING

When sizing the battery charger, the capacity (A) in amps can be found by the following equation where L is the continuous load being 4.56 Amps, C is the ampere hours emergency discharge which is the 100 Ah battery rating of the Enersys 3CC-5M. H is the number of hours recharge time assumed to be 24 hours, and the 1.1 constant is a factor accounting for the efficiency of lead acid cells.

$$A = L + \frac{(1.1 * C)}{H}$$

The charger capacity is calculated to be 9.14Amps, and therefore, the next larger size, provided by Hindlepower, capable of handling 12 Amps, will be sufficient for the substation.

6.0 CONCLUSION

The DC system designed for the Cyclone substation has been sized to include all necessary DC loads in the yard and control house. The duty cycle diagram was created in order to analyze the 8-hour period over which various DC loads would be necessary. The worst case tripping scenario analyzed for this study was a bus fault, assuming that the bus breaker trip coils would all operate for one minute. It was decided that the emergency lighting in the control house would turn on after a five minute delay period to ensure that a momentary outage is not taking place. The DC system was designed with the worst case tripping scenario in mind and a margin was put in place to ensure the system would outlast future issues involving temperature change and the age of the batteries, as well as a general design margin of 10%. Throughout the design process, IEEE standards were referenced and industry standards put into use.

The DC system has been designed in order to support all DC loads inside the control house, as well as in the yard, over an 8 hour duty cycle. The Enersys 3CC-5M batteries are utilized in order to support this load such that no AC power is available to supply the batteries with a constant charge. The battery charger size was calculated to ensure the recharging period of the batteries would stay under 24 hours. The Hindle AT10 Battery Charger was selected in order to recharge the DC batteries to their full capacity in under 15 hours.

7.0 REFERENCES

- 1) IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications, IEEE Standard 485-2010
- 2) Siemens SPS2 SF6 Breaker Nameplate
- 3) EnerSys Type EC-M Battery Datasheet
- 4) ITC Holdings Corp. ((2018) *Design Guide: Substation DC System*
- 5) Schweitzer Website, www.selinc.com
- 6) J. Thompson, Michael & Wilson, David. (2007). Auxiliary DC Control Power System Design for Substations. 522 - 533. 10.1109/CPRE.2007.359922.
- 7) Varga, Lesley P.E. (2015) *Stationary Battery Sizing*. Retrieved from : http://ewh.ieee.org/r3/atlanta/ias/2014-2015_Presentations/2015-04-20_EEE%20IAS%20Stationary%20Battery%20Sizing.pdf

APPENDIX A – CONTINUOUS LOAD PROFILE**138kV**

Quantity	Relay Description	Power	Current	Total Current
1	SEL-352/BFR/B1		0.2	0.6 Amps
1	SEL-352/BFR/B2		0.2	
1	SEL-352/BFR/B3		0.2	

69kV

Quantity	Relay Description	Power	Current	Total Current
1	SEL-387/87OA/TR1		0.2	0.2

Transformer

Quantity	Relay Description	Power	Current	Total Current
1	SEL-587/87T/TR1		0.2	0.6
1	SEL-587Z/XFMR1		0.2	
1	SEL-551		0.2	

Communication & Metering

Quantity	Relay Description	Power	Current	Total Current
1	SEL-321/PR/C		0.2	1.2
1	SEL-311L/PR/R		0.2	
1	SEL-311L/BU/R		0.2	
1	SEL-311L/BU/C		0.2	
1	SEL-751L/PR/D		0.2	
1	SEL-751L/BU/D		0.2	

Total Continuous Load:

APPENDIX B - ENERSYS EC-M BATTERY DISCHARGE CURRENT

Constant Current

1.215 Specific Gravity

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

Cell Type	Nominal Ah Capacity ¹	Minutes			Hours								
		1	15	30	1	1.5	2	3	4	5	8	12	24
3CC-3M	50	75.0	48.0	37.8	27.0	21.0	17.3	12.9	10.4	8.8	6.3	4.4	2.5
3CC-5M	100	148.0	96.0	75.6	54.0	42.0	34.6	25.7	20.7	17.6	12.5	9.1	5.0
3CC-7M	150	222.0	144.0	113.0	81.0	63.0	51.9	38.6	31.0	26.4	18.8	13.6	7.5
3CC-9M	200	296.0	192.0	151.0	108.0	84.0	69.2	51.4	41.4	35.2	25.0	18.1	10.0

Cyclone Substation AC Station Service Sizing Revision 0

prepared for

BMcD

prepared by

ISU EE sdmay19-17

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1.0 INTRODUCTION

One aspect of substation design is determining the power rating of the station service transformer. Station service transformers provide power to all the auxiliary AC loads throughout the substation. As per BMcD, we will plan for future loads if the substation were to be expanded upon. Examples of AC loads seen in substations would be the control house HVAC units, breaker heaters, transformer heaters, and various lighting used throughout. Simply summing every connected AC load would yield a larger than necessary power rating for the station service transformer. This is because not all loads will be on at once. Thus, the AC loads will be multiplied by a demand factor between 0 and 1. As the demand factor approaches 0, the chance the load will be running decreases. The opposite can be said as the demand factor approaches 1. With that idea in mind, we will predict the worst case scenario. The worst case scenario for this region (Iowa/Midwest) will be the winter at night case. In this case we will assume a transformer is overloaded so the fans are running, all breakers heaters/transformer heaters are running, and the control house heater will be running. Lights atop the control house and flood lights across the yard will also be on. The objective of this study is to properly size the station service transformer for the Cyclone Substation. Once we have a particular SL&P transformer, we will size appropriate conductor that will be run from the SL&P transformer to the AC panels.

2.0 SYSTEM DESIGN

Energized Substation AC Loads

The following tables display connected loads of auxiliary equipment with their respective kVA ratings.

Existing Panel		AC-1		200 A		Main Bus		200 A		Main Breaker		
Volts		240 Y/120V		3		Phase		10kA		SYM. A.I.C. Minimum		
Feed via		Cu AWG 2 Directly Buried		4		Wire		NEMA 1		Enclosure		
				Surface		Mounted						
Pole No.	Trip Amps	No. Pole	Wire	Load Served	Load - kVA			Pole No.	Trip Amps	No. Pole	Wire	Load Served
					Ø1	Ø2	Ø3					
1	20	1		Control House Indoor Lights (4) and Receptacles (4) (120v)	0.62 0.50			2	20	2		Flood Lights (4) 240v
3	20	2		Control House Outdoor Security Lights (2) (240v)		0.30 0.50		4				
5							0.30 4.00	6	50	2		Control House HVAC Unit (240v)
7	30	1		Transformer Heaters, Outlet, and Lamps (120v)	1.39 4.00			8				
9	30	2		Transformer Fan Motors (240v)		1.15 1.68		10	20	1		Transformer Pump (120v)
11							1.15 1.39	12	30	1		Future Transformer Heaters, Outlet, and Lamps (120v)
13	30	2		Future Transformer Fan Motors (240v)	1.15 1.68			14	20	1		Future Transformer Pump (120v)
15						1.15 0.25		16	20	1		#1 69kV Breaker Lights/Receptacles (120v)
17	30	2		#1 69kV Breaker Heaters (240v)			0.25 0.25	18	20	1		#2 69kV Breaker Lights/Receptacles (120v)
19					0.25 0.25			20	30	2		#2 69kV Breaker Heaters (240v)
21	20	1		Future 69kV Breaker Lights/Receptacles (120v)		0.25 0.25		22				
23	30	2		Future 69kV Breaker Heaters (240v)			0.25 0.25	24	20	1		#1 138kV Breaker Lights and Receptacles (120v)
25					0.25 1.50			26	30	2		#1 138kV Breaker Heaters (240v)
27	20	1		#2 138kV Breaker Lights and Receptacles (120v)		0.25 1.50		28				
29	30	2		#2 138kV Breaker Heaters (240v)			1.50 0.25	30	20	1		#3 138kV Breaker Lights and Receptacles (120v)
31					1.50 1.50			32		2		#3 138kV Breaker Heaters (240v)
33	20	1		#4 138kV Breaker Lights and Receptacles (120v)		0.25 1.50		34				
35	30	2		#4 138kV Breaker Heaters (240v)			1.50 0.25	36	20	1		Future #1 138kV Breaker Lights and Receptacles (120v)
37					1.50 1.50			38	30	2		Future #1 138kV Breaker Heaters (240v)
39	20	1		Future #2 138kV Breaker Lights and Receptacles (120v)		0.25 1.50		40				
41	20	1		Future #3 138kV Breaker Lights and Receptacles (120v)			0.25 0.25	42	20	1		Future #4 138kV Breaker Lights and Receptacles (120v)
Total Per Phase Load (Including Existing)					17.59	10.78	11.84	Total Demand Factor <u>72.5%</u>				
Unbalance load					31.3%	19.6%	11.7%					
Total Connected Load					31.3%			Total Est. Demand Load				
40.20 kVA		96.71 A					29.14 kVA		70.11 A			

TABLE AC-1

Existing Panel		AC-2		200 A Main Bus		150 A Main Breaker						
Volts		240 Y/120V		3 Phase		10kA SYM. A.I.C. Minimum						
Feed via		4-#2/0N Cu Cable		4 Wire		NEMA 1 Enclosure						
				Surface Mounted								
Pole No.	Trip Amps	No. Pole	Wire	Load Served	Load - kVA			Pole No.	Trip Amps	No. Pole	Wire	Load Served
					Ø1	Ø2	Ø3					
1	30	2		Future #2 138kV Breaker Hosters (240v)	1.50			2	30	2		Future #3 138kV Breaker Hosters (240v)
					1.50							
3						1.50		4				
						1.50						
5								6	30	2		Future #4 138kV Breaker Hosters (240v)
							1.50					
7	20	1		Battery Charger (125v)	1.80			8				
					1.50							
9								10				
11								12				
13								14				
15								16				
17								18				
19								20				
21								22				
23								24				
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27								28				
29								30				
31								32				
33								34				
35								36				
37								38				
39								40				
41								42				
Total Per Phase Load (including Existing)					6.30	3.00	1.50	Total Demand Factor <u>100.0%</u>				
Unbalance load					75.0%	16.7%	58.3%					
Total Connected Load					75.0%			Total Est. Demand Load				
10.80 kVA		45.00 A					10.80 kVA		45.00 A			

TABLE AC-2

Demand Factor Calculation									
EQUIPMENT:	AC-1								
	240								
LOAD TYPE	Ø1			Ø2			Ø3		
	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)
Control House Indoor Lights (4) and Receptacles (4) (120v)	0.62	0.30	0.19						
Flood Lights (4) 240v	0.50	1.00	0.50						
Control House Outdoor Security Lights (2) (240v)				0.30	1.00	0.30			
				0.50	1.00	0.50			
Control House HVAC Unit (240v)							0.30	1.00	0.30
Transformer Heaters, Outlet, and Lamps (120v)	1.39	0.90	1.25				4.00	0.50	2.00
Transformer Fan Motors (240v)	4.00	0.50	2.00						
Transformer Pump (120v)				1.15	1.00	1.15			
				1.68	0.50	0.84			
Future Transformer Heaters, Outlet, and Lamps (120v)							1.15	1.00	1.15
Future Transformer Fan Motors (240v)	1.15	0.10	0.12				1.39	0.90	1.25
Future Transformer Pump (120v)	1.68	0.50	0.84						
#1 69kV Breaker Lights/Receptacles (120v)				1.15	0.10	0.12			
#1 69kV Breaker Heaters (240v)				0.25	0.42	0.11			
#2 69kV Breaker Lights/Receptacles (120v)							0.25	1.00	0.25
#2 69kV Breaker Heaters (240v)	0.25	1.00	0.25				0.25	0.42	0.11
Future 69kV Breaker Lights/Receptacles (120v)				0.25	0.42	0.10			
Future 69kV Breaker Heaters (240v)				0.25	1.00	0.25			
#1 138kV Breaker Lights and Receptacles (120v)							0.25	1.00	0.25
#1 138kV Breaker Heaters (240v)	0.25	1.00	0.25				0.25	0.42	0.10
#2 138kV Breaker Lights and Receptacles (120v)	1.50	1.00	1.50						
#2 138kV Breaker Heaters (240v)				0.25	0.42	0.11			
#3 138kV Breaker Lights and Receptacles (120v)				1.50	1.00	1.50			
#3 138kV Breaker Heaters (240v)	1.50	1.00	1.50				1.50	1.00	1.50
#4 138kV Breaker Lights and Receptacles (120v)				0.25	0.42	0.11			
#4 138kV Breaker Heaters (240v)				1.50	1.00	1.50			
Future #1 138kV Breaker Lights and Receptacles (120v)							1.50	1.00	1.50
Future #1 138kV Breaker Heaters (240v)	1.50	1.00	1.50				0.25	0.42	0.11
Future #2 138kV Breaker Lights and Receptacles (120v)				0.25	0.42	0.11			
Future #2 138kV Breaker Heaters (240v)				1.50	1.00	1.50			
Future #3 138kV Breaker Lights and Receptacles (120v)							0.25	0.42	0.11
Future #4 138kV Breaker Lights and Receptacles (120v)							0.25	0.42	0.11
TOTAL:	14.59	69.51%	10.14	9.03	72.83%	6.57	11.34	76.04%	8.62

TABLE AC-1 Demand Factor

Demand Factor Calculation									
EQUIPMENT:	AC-2								
LOAD TYPE	①			②			③		
	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)	CONNECTED LOAD (kVA)	DEMAND FACTOR	ESTIMATED DEMAND (kVA)
Future #2 138kV Breaker Heaters (240v)	1.50	1.00	1.50						
Future #3 138kV Breaker Heaters (240v)	1.50	1.00	1.50						
				1.50	1.00	1.50			0.00
				1.50	1.00	1.50			1.50
Future #4 138kV Breaker Heaters (240v)							1.50	1.00	1.50
Battery Charger (125v)	1.80	1.00	1.80						
	1.50	1.00	1.50						
					0.00	0.00			
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Conductor Design

The conductor should be sized based upon the maximum current the SL&P transformer can supply. That will guarantee the cable to be large enough if more AC loads are added. This current can be calculated from:

$$P = V \cdot I \cdot \sqrt{3}$$

Where, $P = 50\text{kVA}$, $V = 240\text{v}$. Solving for I gets 120.28 A .

Utilizing table 310.15(B)(16) from the National Electric Code tells us that our wire should be of size AWG 2 to satisfy ampacity.

BMcD requires a maximum voltage drop along the conductor of 4.5%. We will utilize the following equation to verify that AWG 2 Cu is large enough to prevent a voltage drop greater than 4.5%.

$$A = \rho \cdot I^2 \cdot L / V$$

A = area in cmils

ρ = Resistivity of Copper in $\Omega \cdot \text{cmil}/\text{ft}$

L = length of conductor in feet

V = Allowable Voltage Drop

This equation is based upon $R = \rho \cdot L / A$, where resistance of a conductor may be calculated.

$$\rho = 10.37 \Omega \cdot \text{cmil}/\text{ft}$$

$$I = 120.28\text{ A}$$

$$V = 120\text{ V}$$

$L = 100\text{ft}$ (Length from SL&P transformer to AC panels).

This gives us an area of $46,088.88\text{ cmils}$. This is in between AWG 3 and 4.

To satisfy voltage drop, our wire would have to be AWG 3. However, our ampacity has dictated AWG 2, so AWG 2 should be selected.

Assumptions and Notes

- [1] Existing equipment for original construction includes one 138kV-69kV transformer, one 69kV breakers, and three 138kV breakers.
- [2] Future equipment that may be added in the future consists of an additional 138kV-69kV transformer, an additional 69kV breaker, and three additional 138kV breakers. The station service transformer was sized to accommodate future expansion.
- [3] In normal practice, wire sizes would be sized appropriately and specified in Tables AC-1 and AC-2 for each load. This has been deemed beyond the scope of the project by BMcD personnel as we are working in a limited time frame.
- [4] Loads are assumed to be purely resistive with a power factor of 1 to simplify calculations. In practice power factor would have to be taken into account for lights and any other equipment that has a power factor less than 1.
- [5] Breaker and Transformer kVA totals were found using nameplate values found on their respective drawings.
- [6] Battery Charger kVA was calculated with nameplate ratings gathered from the Hindle Power brochure and includes a safety factor of 1.2 as per BMcD.
- [7] Transformer Pump kVA was calculated with nameplate information from the Stancor Brochure.
- [8] Breaker cabinet lights, transformer lights, and indoor control room lights are assumed to be 65W as requested by BMcD.
- [9] Receptacles are assumed to be 90W per outlet as per NEC 220.
- [10] Flood lights are assumed to be 250W and security lights are assumed to be 300W.
- [11] Demand factors were input assuming a winter at night scenario as well as using basic engineering judgement.
- [12] Breaker lights and receptacles were given demand factors of 1 and .2 respectively. This gives these circuits a demand factor of .42.
- [13] Transformer heaters, transformer convenience outlet, and transformer lamps were given demand factors of 1, .2, and 1 respectively. This gives these circuits a demand factor of .9.

[14] The ampacity of the conductor will be based upon the maximum current the SL&P transformer may supply.

$$50\text{kVA}/(240\text{v}*\text{sqrt}(3)) = 120.28\text{A}.$$

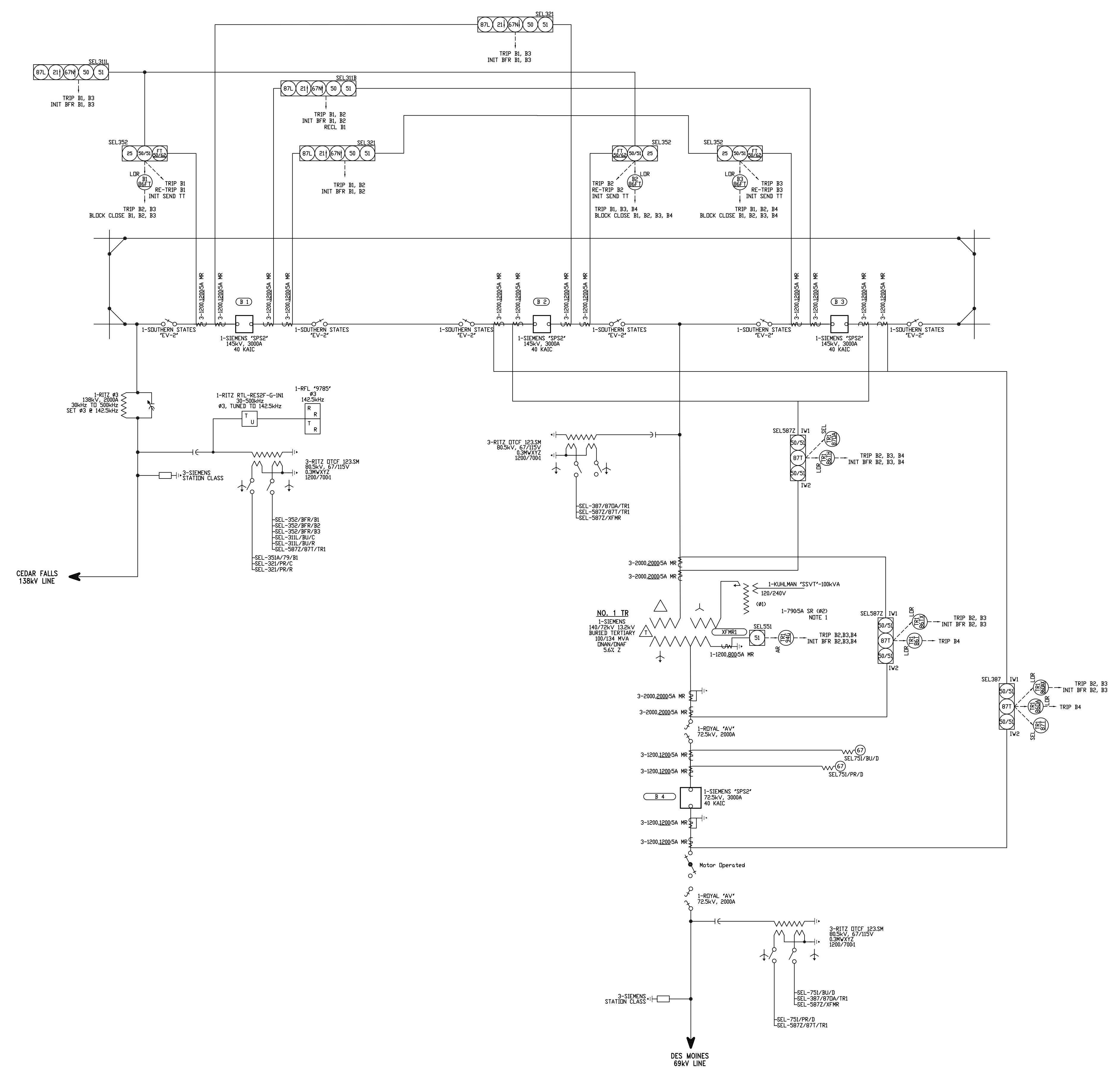
[15] Conductor assumptions: Copper cable, directly buried, one way length of conductor is 100 feet, maximum acceptable voltage drop per BMcD is 4.5%, temperature rating of 90 degrees Celsius. Insulation type is client preference.

3.0 CONCLUSION

In Table AC-1 and Table AC-2, all AC auxiliary loads are tabulated along with their load profiles listed in kVA. The total connected load at substation is 51kVA. In the two Demand Factor Tables , the worst case scenario (winter at night) kVA totals are calculated using BMcD standards and NEC standards. The total estimated demand load kVA that the station service will have to supply is 39.94kVA. Therefore, the client shall select a station service transformer that can accomodate this expected kVA demand. The standard size transformer that meets this demand is rated at 50 kVA, which should adequately provide for station service. If a 50kVA is not readily available, it is common to select a 75kVA transformer.

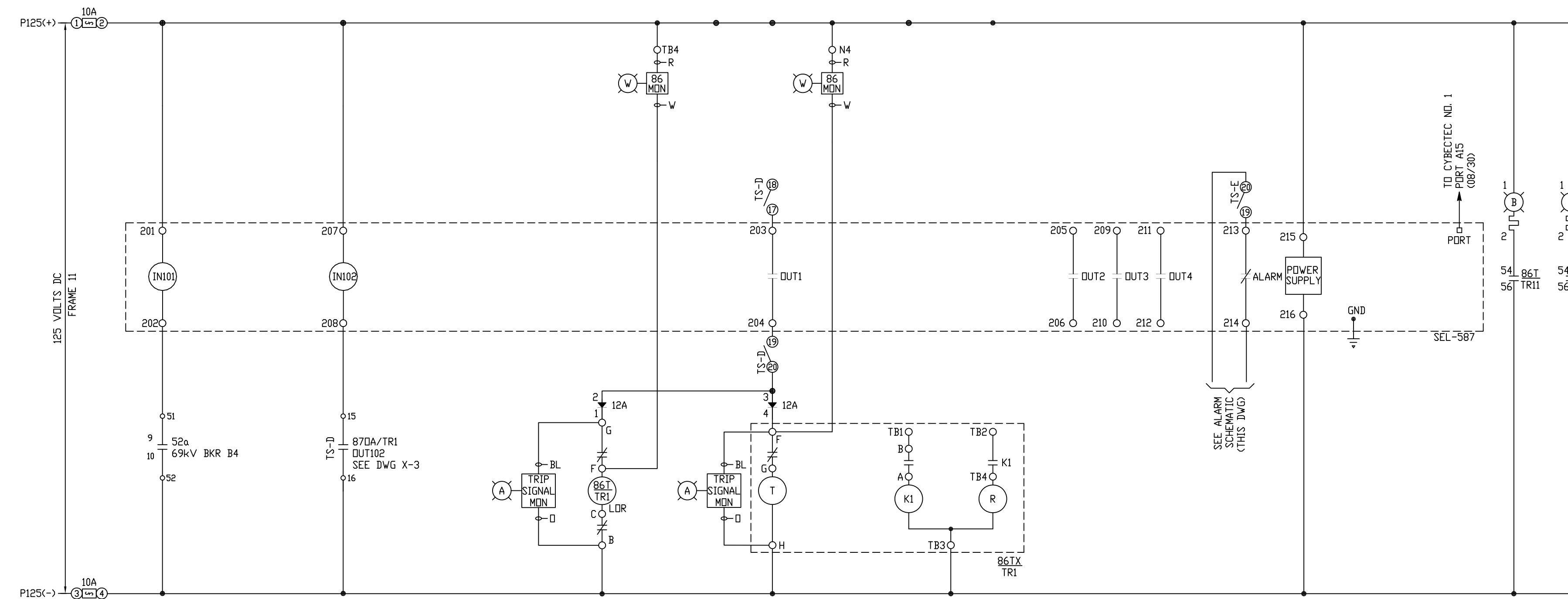
4.0 REFERENCES

- [1] BMcD Engineering Standards, Section 1, AC Systems. 2 Feb 2019
- [2] Siemens Energy Inc. 69 kV breaker elementary drawings. SPS2 72.5-31.5 2 Feb 2019
- [3] Siemens Energy Inc. 138 kV breaker elementary drawings. SPS2 145-31.5 2 Feb. 2019
- [4] Generic 138kV-69kV Transformer Drawing. (Per Client Spec)
- [5] HindlePower Battery Charger Product Data Sheet. 2 Feb. 2019
- [6] Stancor Duplex Oil-Minder® System Submittal SE-100 115 Volt Single Phase Product Data Sheet. 27 Feb. 2019
- [7] NEC NFPA 70. Table 310.15 (B)(16) 27 Feb. 2019



Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by JRH	Checked by WP	Approved by - date XXX - 00/00/00	Filename PLANVIEW
Date 4/12/19		Scale 1:1	
ISU SENIOR DESIGN			ONE LINE DIAGRAM
OL-1			Edition 1
Sheet 1/1			

NO 1 TR DIFFERENTIAL RELAYING (87T/TR1)



CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11, 13	X			
12, 18, 19, 20	X		TRIP 138kV BKR B2	BKR-B2
15, 17		X		
14, 16, 3, 4	X		TRIP 138kV BKR B3	BKR-B3
21, 23		X		
22, 28, 5, 6	X		INITIATE BKR FAILURE DN B2	BKR-B2
25, 27		X		
24, 26, 7, 8	X		INITIATE BKR FAILURE DN B3	BKR-B3
31, 33		X	SPARE	
32, 38, 9, 10	X		SPARE	
35, 37		X	SPARE	
34, 36, 11, 12	X		SPARE	
41, 43		X	SPARE	
42, 48, 13, 14	X		SPARE	
45, 47		X	SPARE	
44, 46, 15, 16	X		SPARE	
51, 53		X	SPARE	
52, 58, 17, 18	X		SPARE	
55, 57, 19, 20	X			
54, 56	X		SCADA INDICATION	THIS DWG

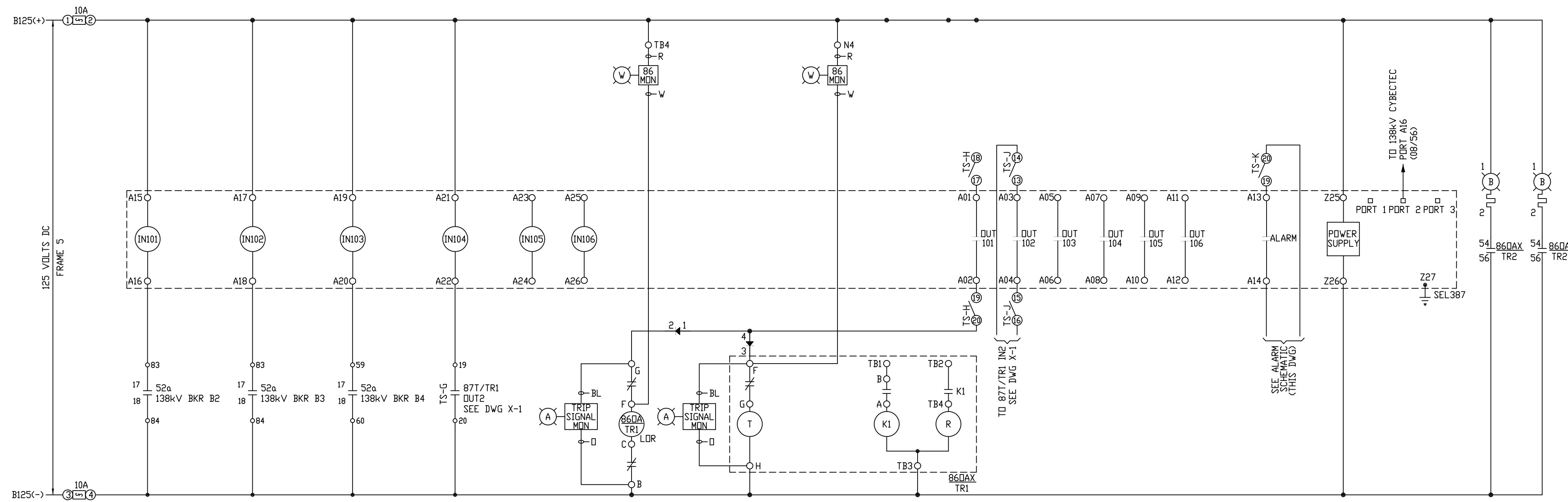
ELECTROSWITCH TYPE "LOR-ER"

CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11, 13	X			
12, 18, 19, 20	X		TRIP 69kV BKR B4	BKR-B4
15, 17		X		
14, 16, 3, 4	X		XFMR1 DIFF RELAY ALARM	SEE SCADA
21, 23		X		
22, 28, 5, 6	X		DE-ENERGIZE XFMR1 FANS	SEE SCADA
25, 27		X	SPARE	
24, 26, 7, 8	X		SPARE	
31, 33		X	SPARE	
32, 38, 9, 10	X		SPARE	
35, 37		X	SPARE	
34, 36, 11, 12	X		SPARE	
41, 43		X	SPARE	
42, 48, 13, 14	X		SPARE	
45, 47		X	SPARE	
44, 46, 15, 16	X		SPARE	
51, 53		X	SPARE	
52, 58, 17, 18	X		SPARE	
55, 57, 19, 20	X			
54, 56	X		SCADA INDICATION	THIS DWG

ELECTROSWITCH TYPE "LOR"

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		XFMR1 DIFF RELAYING DC	
X-1		Edition 1	Sheet 1/1

NO 2 TR OVERALL DIFFERENTIAL RELAYING (870A/TR1)



CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11-13		X		
12-18	X		TRIP 69kV BKR B4	BKR-B4
15-17		X		
14-16	X		XFMR DIFF RELAY ALARM	SEE SCADA
21-23		X	SPARE	
22-28	X		SPARE	
23-27		X	SPARE	
24-28	X		SPARE	
31-33		X	SPARE	
32-38	X		SPARE	
35-37		X	SPARE	
34-36	X		SPARE	
41-43		X	SPARE	
42-48	X		SPARE	
45-47		X	SPARE	
44-46	X		SPARE	
51-53		X	SPARE	
52-58	X		SPARE	
55-57		X	SPARE	
54-56	X		SCADA INDICATION	THIS DWG

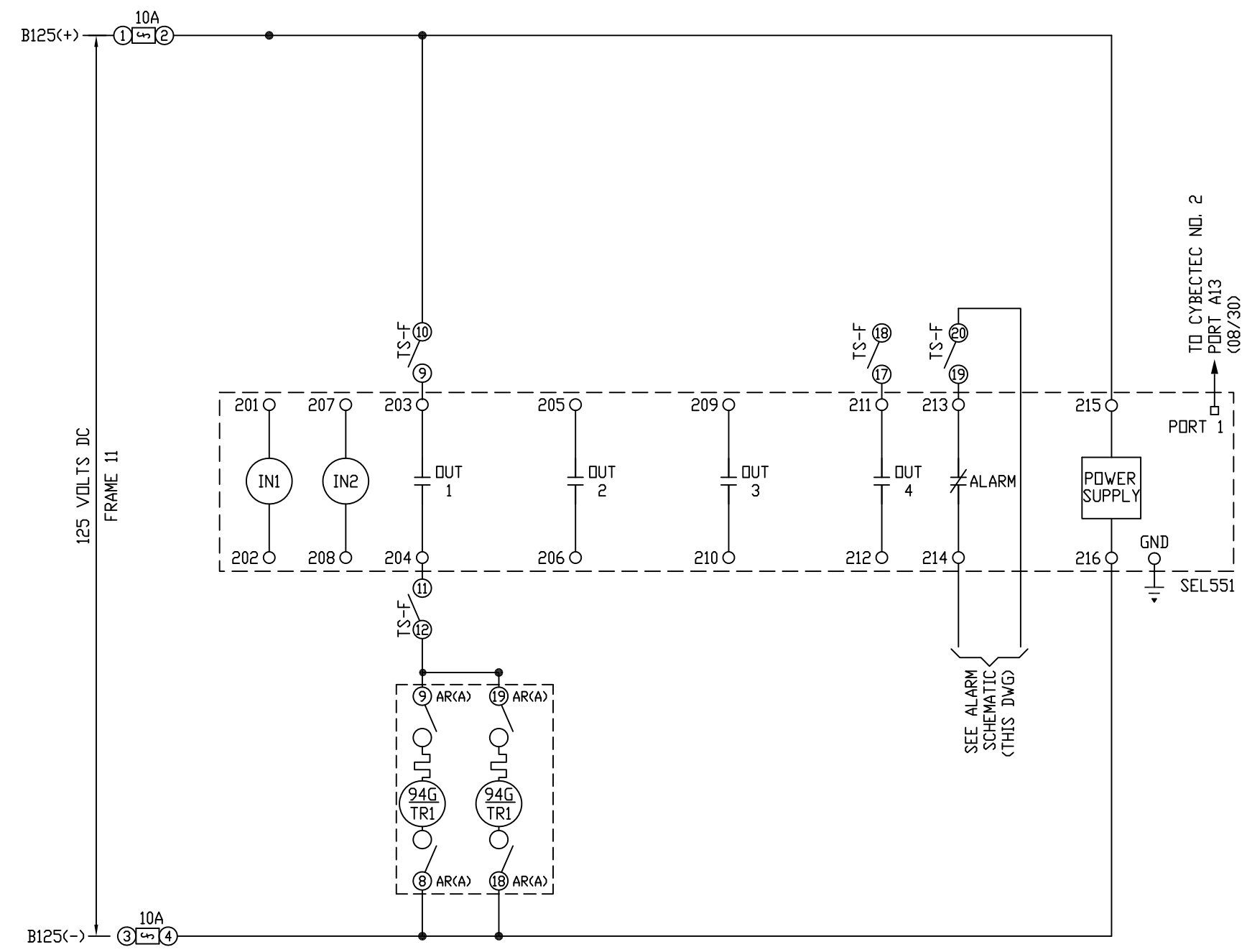
ELECTROSWITCH TYPE 'LOR'

CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11-13		X		
12-18	X		TRIP 138kV BKR B2	BKR-B2
15-17		X		
14-16	X		TRIP 138 BKR B3	BKR-B3
21-23		X		
22-28	X		INITIATE BKR FAILURE DN B2	BKR-B2
25-27		X		
24-26	X		INITIATE BKR FAILURE DN B3	BKR-B3
31-33		X	SPARE	
32-38	X		SPARE	
35-37		X	SPARE	
34-36	X		SPARE	
41-43		X	SPARE	
42-48	X		SPARE	
45-47		X	SPARE	
44-46	X		SPARE	
51-53		X	SPARE	
52-58	X		SPARE	
55-57		X	SPARE	
54-56	X		SCADA INDICATION	THIS DWG

ELECTROSWITCH TYPE 'LOR-ER'

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		XFMR1 OVERALL DIFF RELAY	
X-3		Edition 1	Sheet 1/1

NO. 1 TR OVERCURRENT BACKUP RELAYING (51G/TR1)

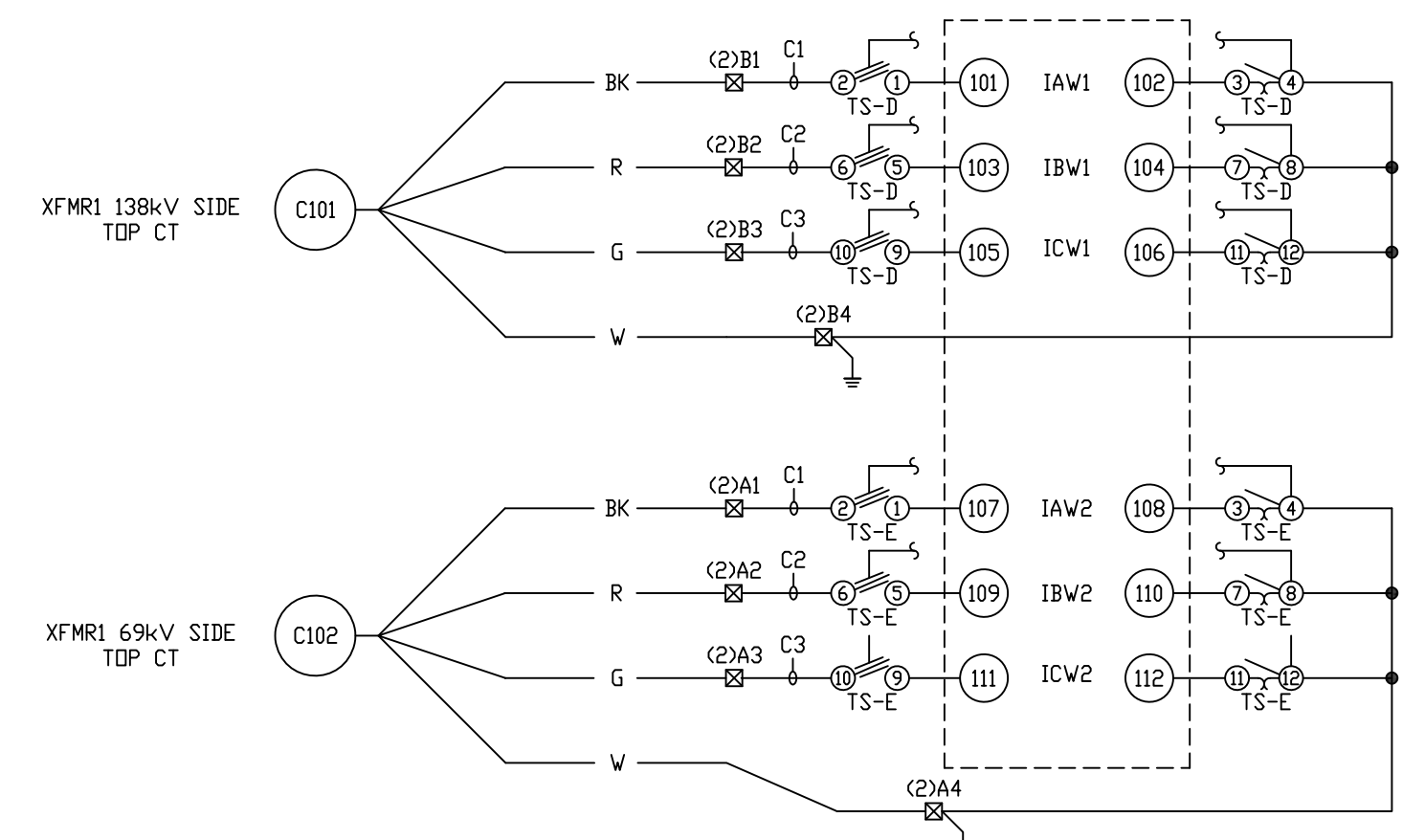


94G/TR1 (AR-A)		
CONTACTS	FUNCTION	DWG. NO.
11-12-13-14-15-16	TRIP 138kV BKR B2	BKR-B2
12-13-14-15-16	TRIP 138kV BKR B3	BKR-B3
14-15-16	TRIP 69kV BKR B4	BKR-B4
16-17	INITIATE BKR FAILURE DN B2	BKR-B2
1-10	INITIATE BKR FAILURE DN B3	BKR-B3
8-9	INITIATE BKR FAILURE DN B4	BKR-B4
4-5	SPARE	
6-7	SCADA INDICATION	THIS DWG

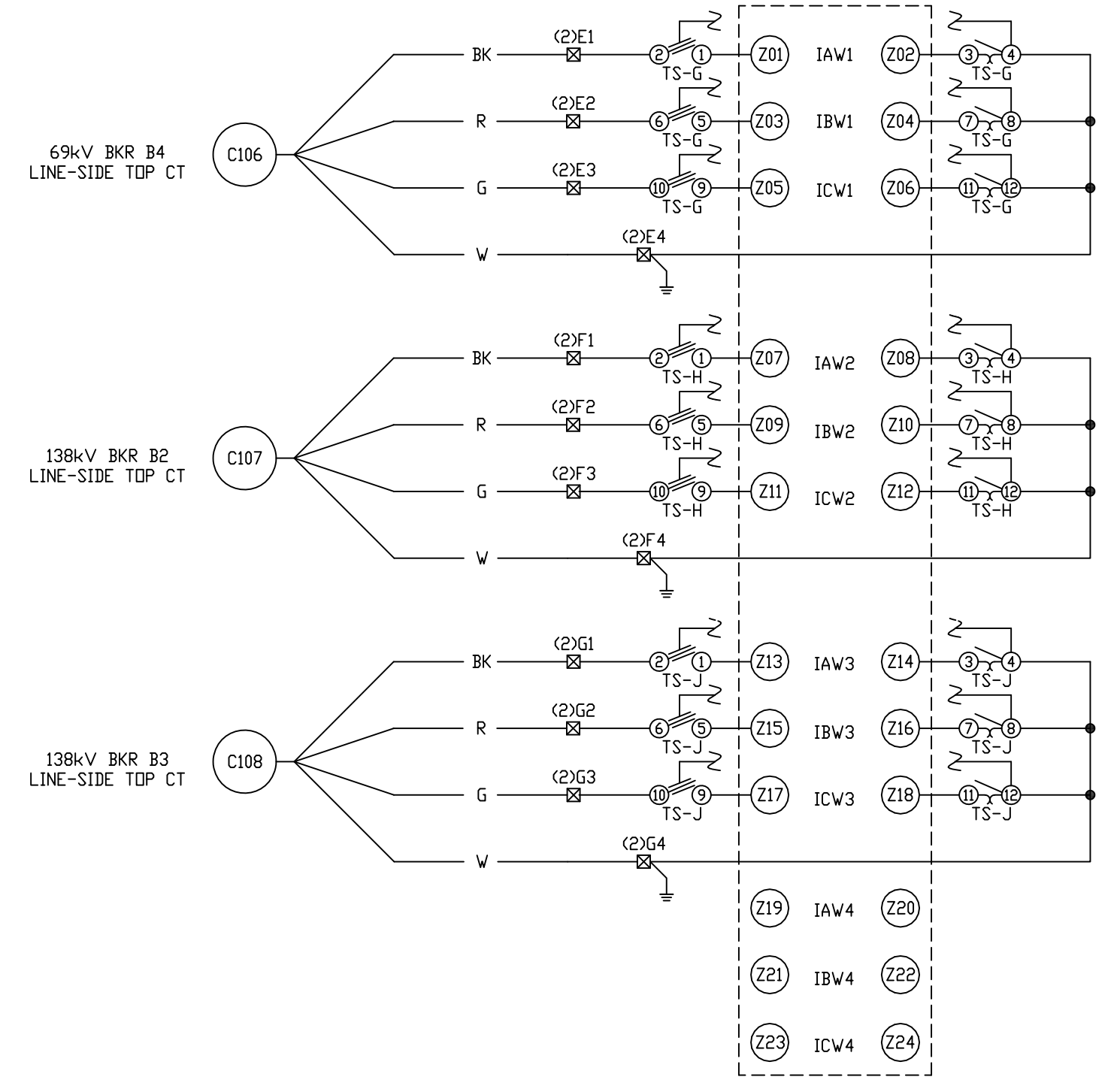
TYPE 'AR'

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		XFMR1 OVERCURRENT	
X-4		Edition 1	Sheet 1/1

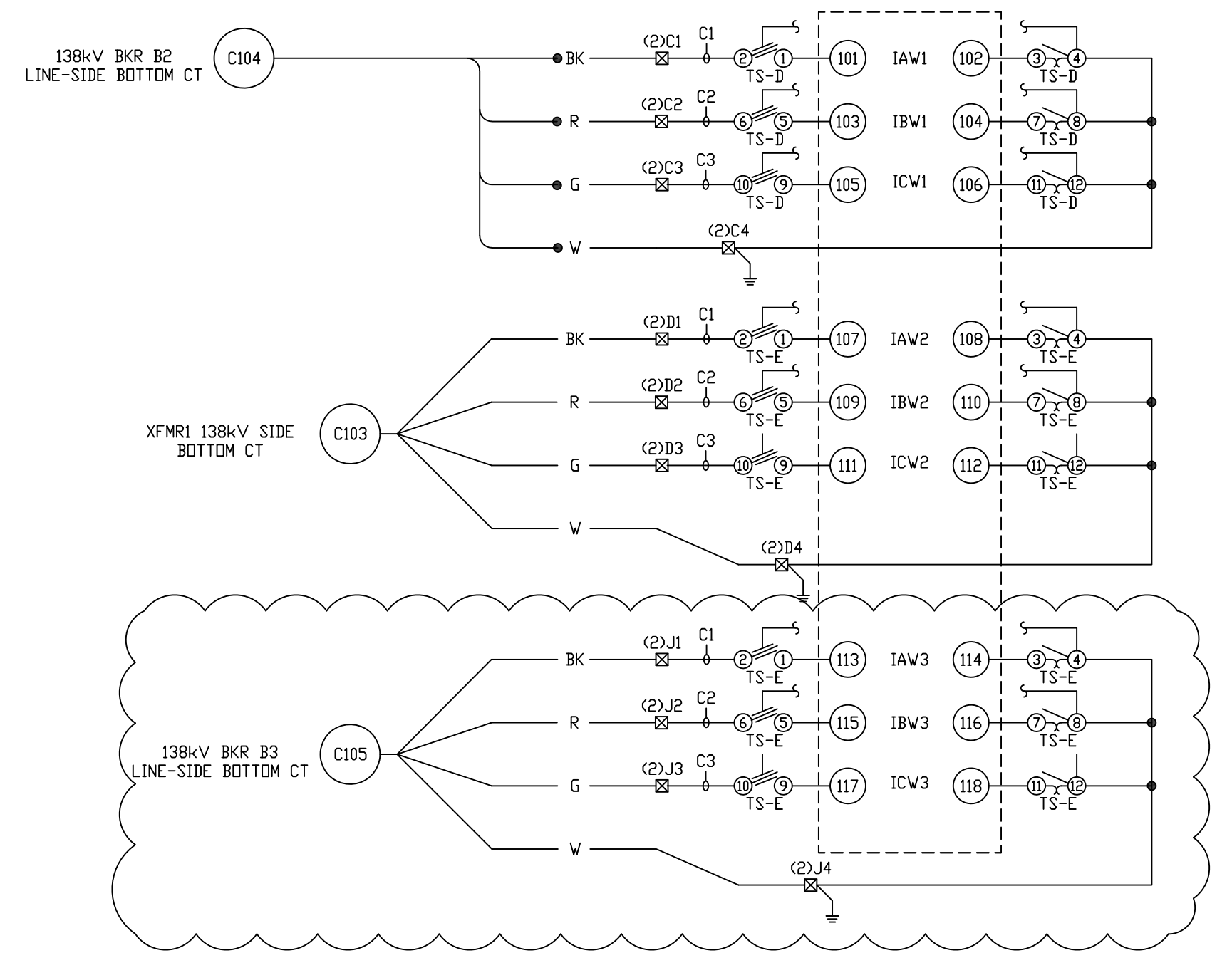
SEL587
(87T/TR1)



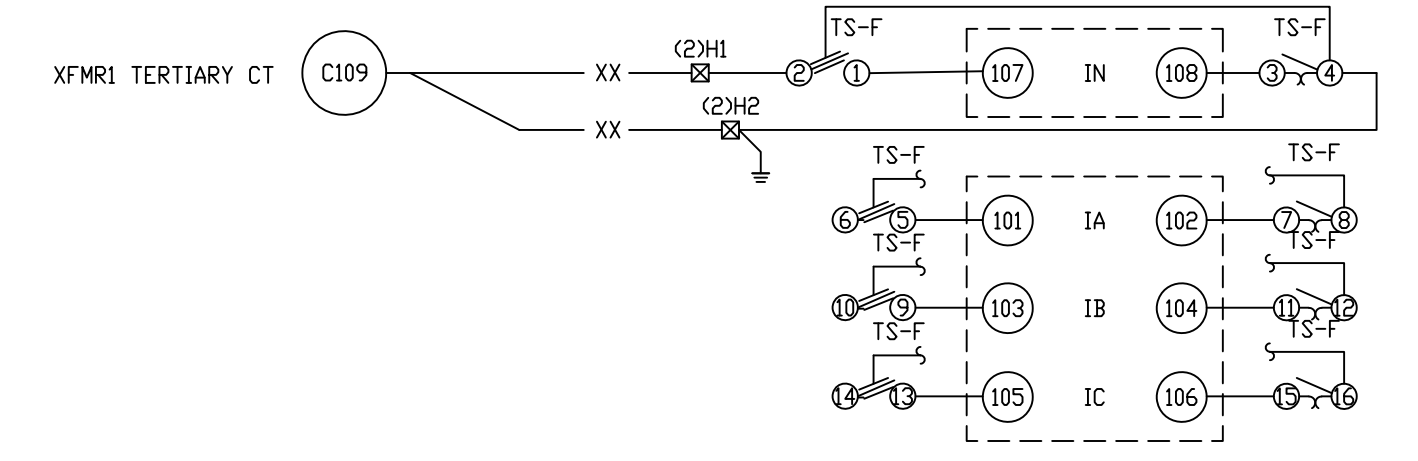
SEL-387
870A/TR1



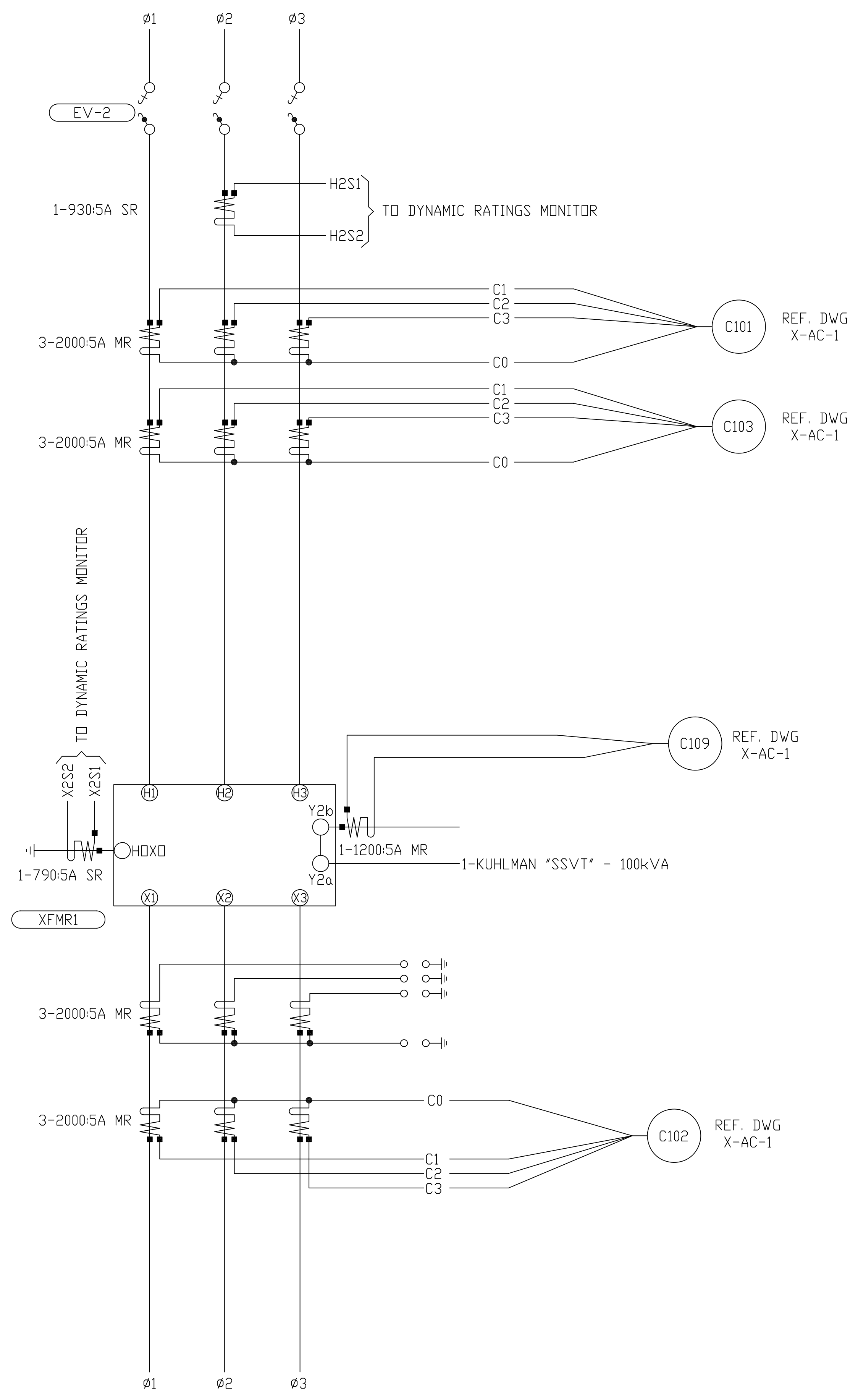
SEL587Z
LEAD DIFF
RELAYING



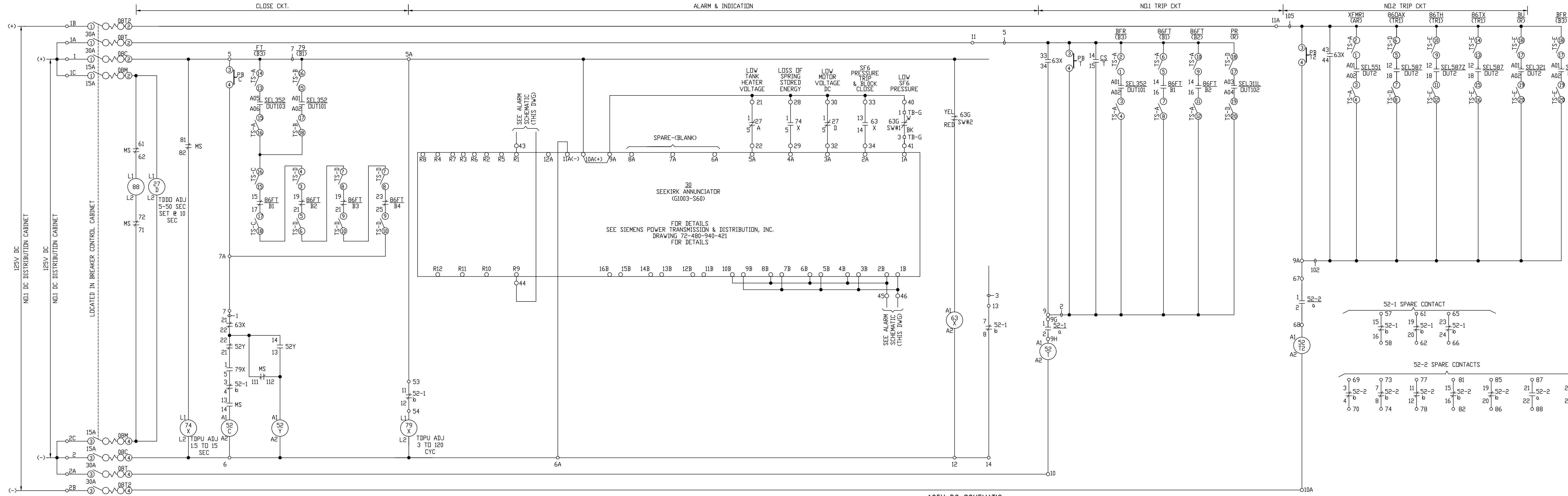
SEL-551
GROUND OVERCURRENT
PROTECTION



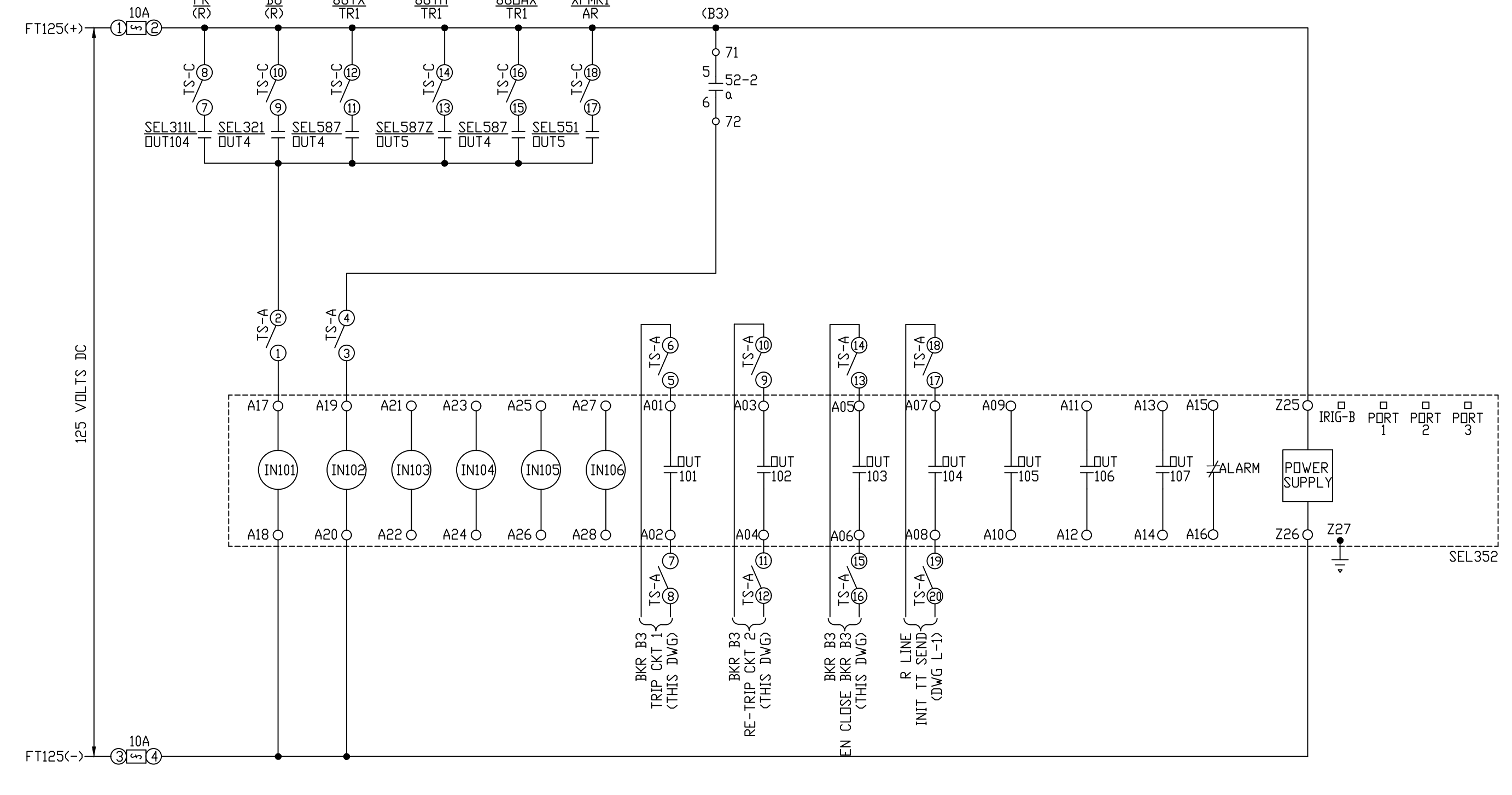
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Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
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Edition 1		Scale 1/1	
Sheet 1/1		Date 11/13/18	



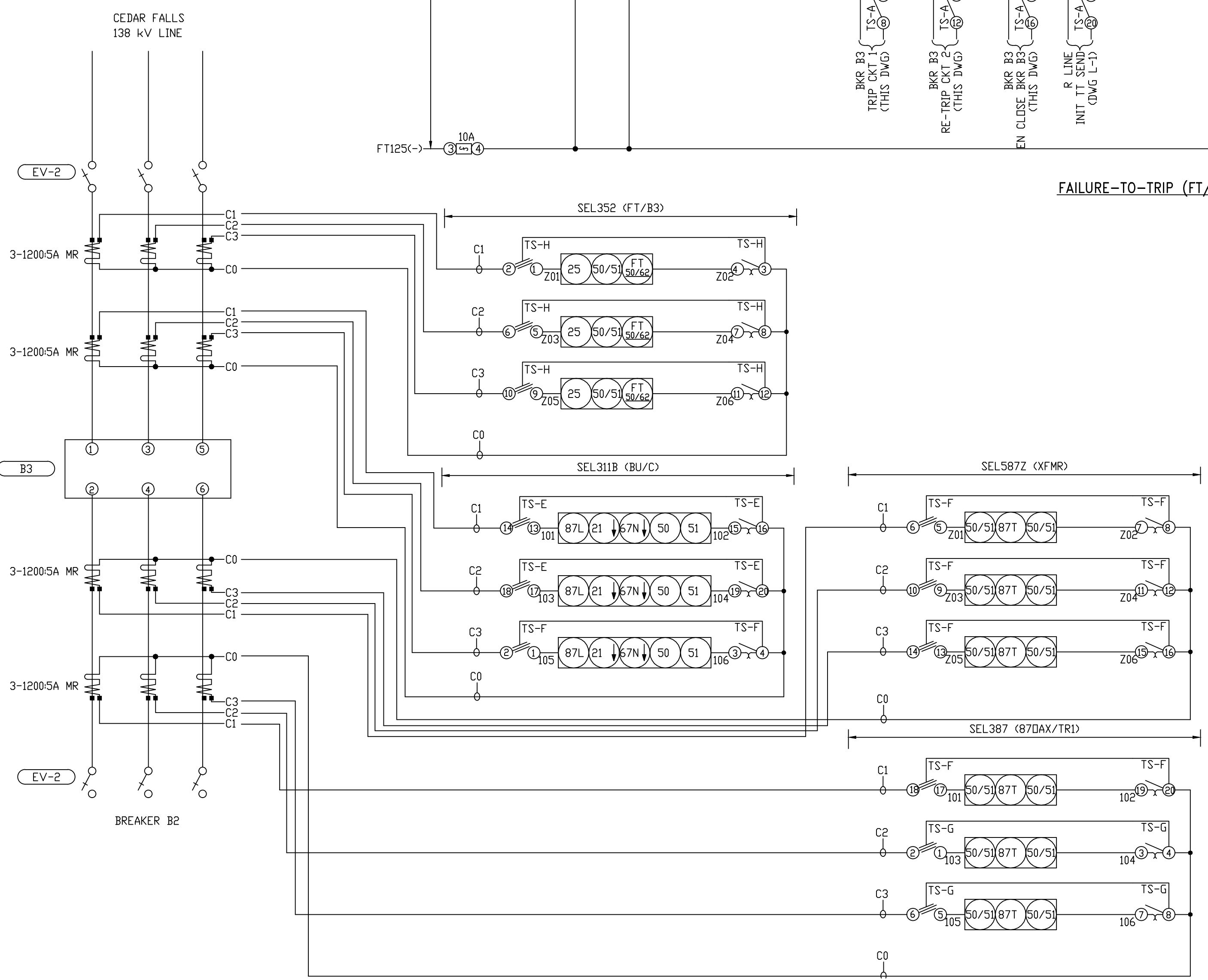
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Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		XFMR1 AC SCHEMATIC	
X-AC-2		Edition 1	Sheet 1/1



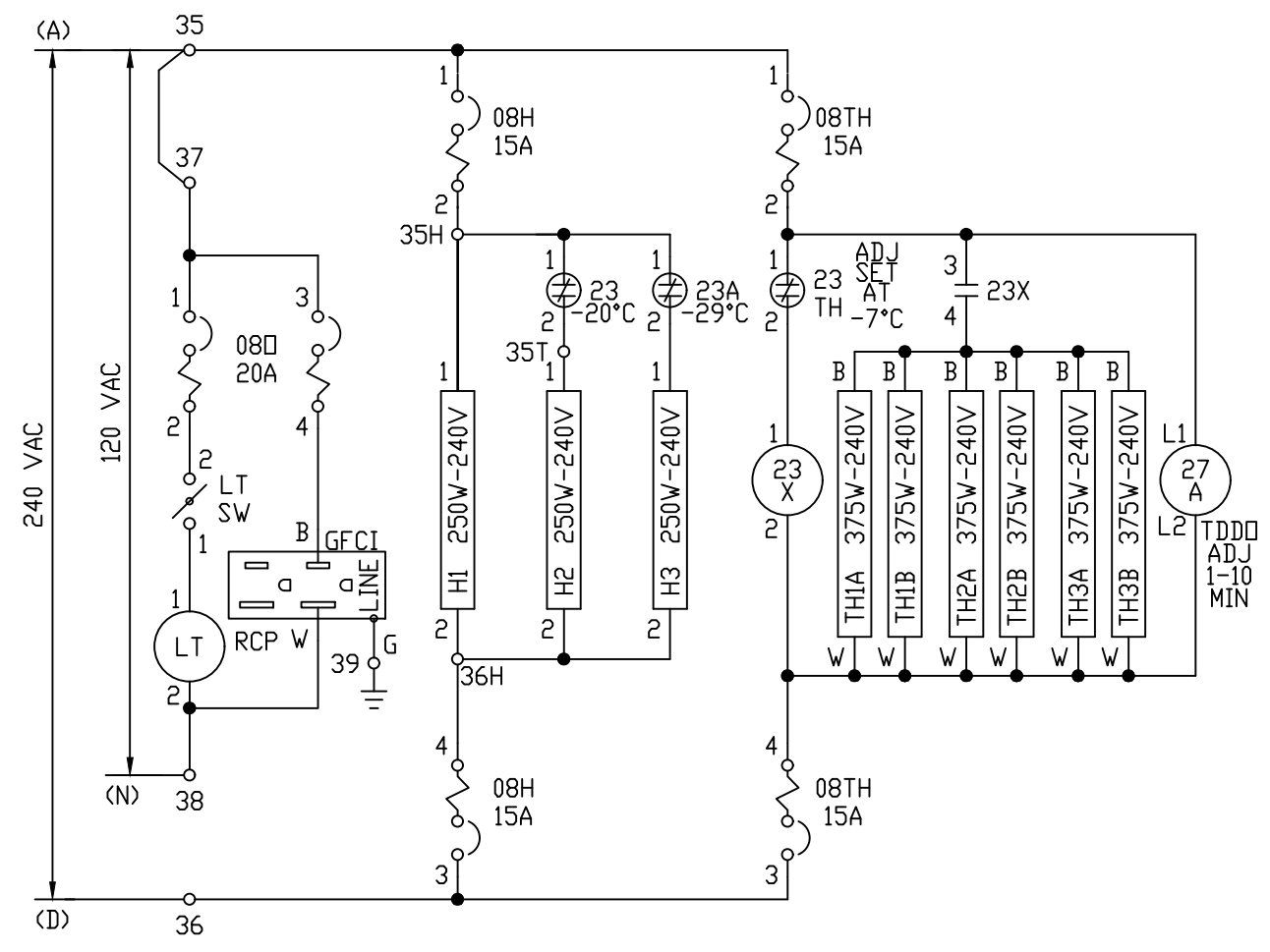
125V DC SCHEMATIC



FAILURE-TO-TRIP (FT/B3)



240/120V AC SCHEMATIC

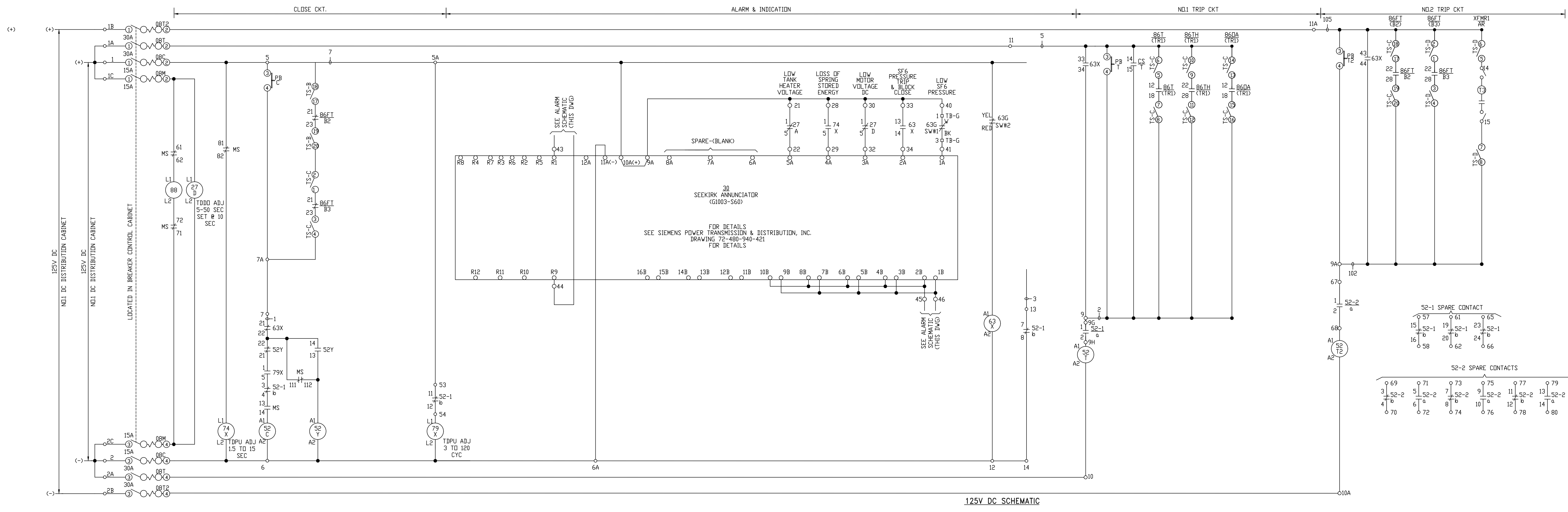


ALARM SCHEMATIC

CONTACTS	TRIP	RESET	FUNCTION	DWG NO.
11#13	X		BLOCK CLOSE B1	BKR-B1
14#18	X		TRIP BKR B1	BKR-B1
15#17	X		BLOCK CLOSE B2	BKR-B2
16#14	X		TRIP BKR B2	BKR-B2
21#23	X		BLOCK CLOSE B4	BKR-B4
24#28	X		TRIP BKR B4	BKR-B4
25#27	X		BLOCK CLOSE B3	THIS DWG
26#24	X		SEL311 OPN INIT DTT SEND	L-1
31#33	X		SPARE	
32#38	X		SEL311 CRP INIT DTT SEND	L-1
35#37	X		SPARE	
36#34	X		SCADA INDICATION	SEE SCADA
41#43	X		SPARE	
42#48	X		SPARE	
45#47	X		SPARE	
46#44	X		SPARE	
51#53	X		SPARE	
52#58	X		SPARE	
55#57	X		SPARE	
56#31	X		SPARE	

79/C0		ELECTROSWITCH TYPE "LDR"			
CONTACTS	POS	CONTACT	POSITION	CONTACTS	POS
11	12	X		11	12
15	16	X		15	16
21	22	X		21	22
25	26	X		25	26
31	32	X		31	32
35	36	X		35	36

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by TPK	Checked by JH	Approved by - date XXX - 00/00/00	Filename BKR-B3
ISU SENIOR DESIGN		BREAKER B3 SCHEMATIC	
BKR-B3		Edition 1	Sheet 1/1

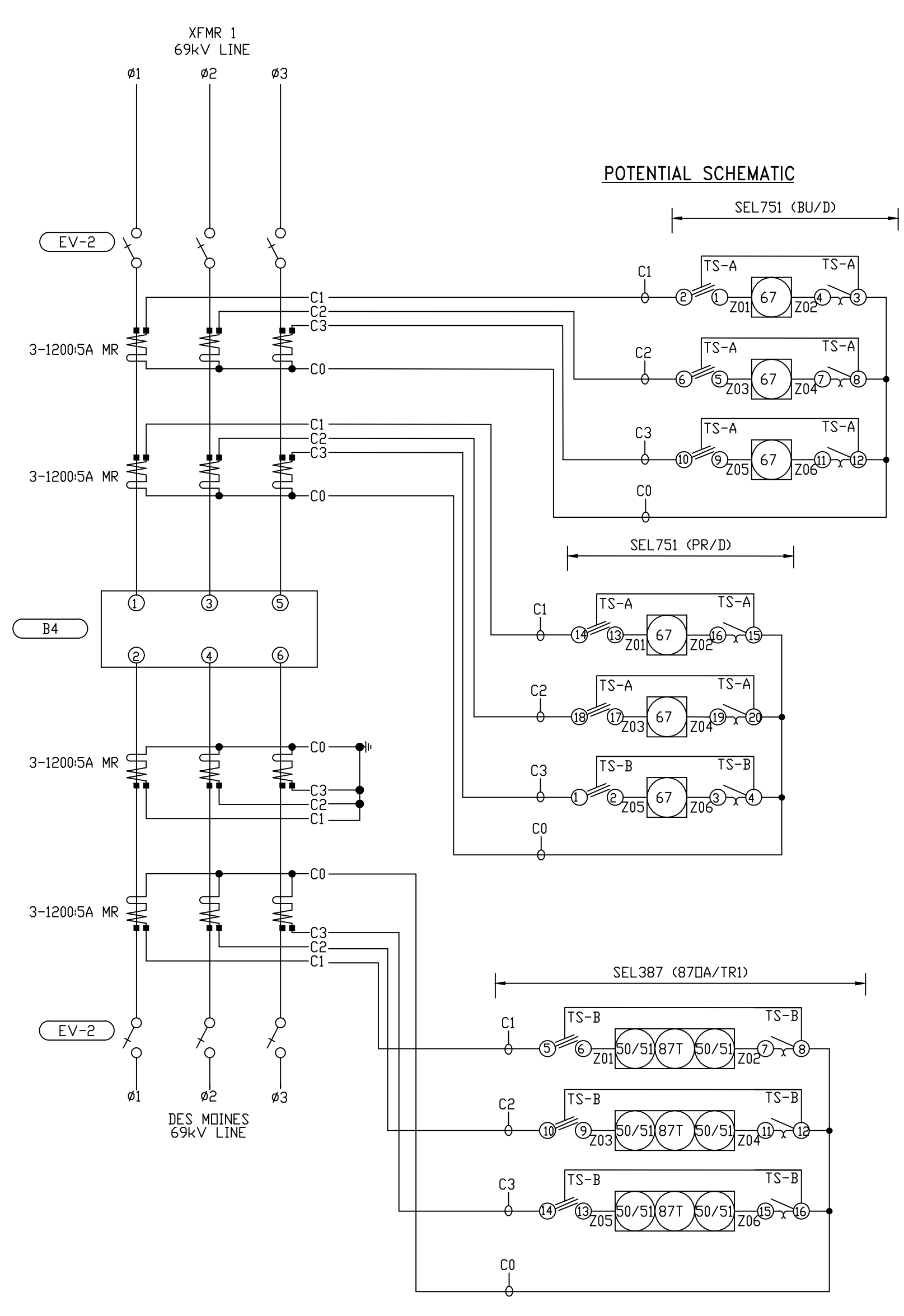


125V DC SCHEMATIC

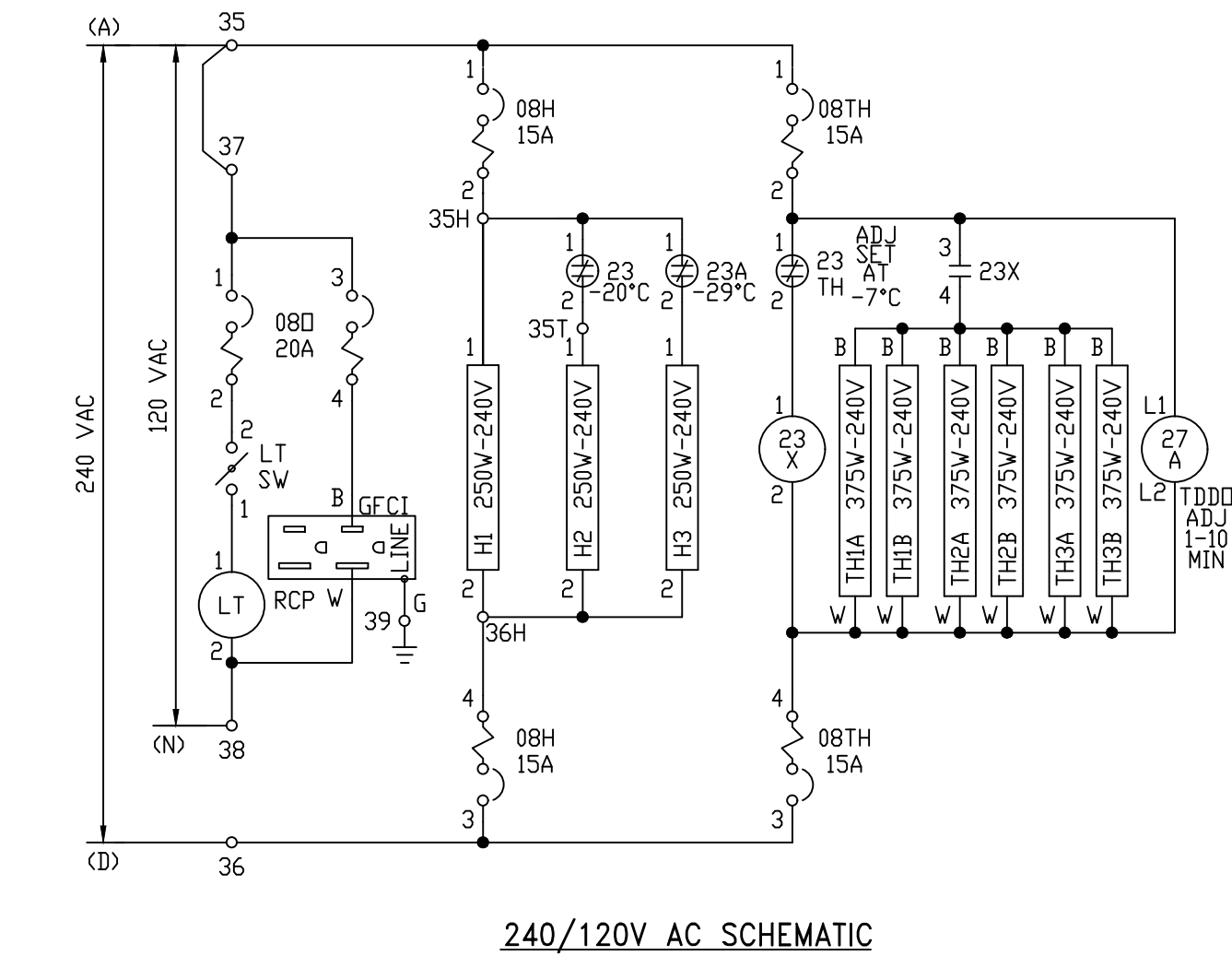
52-1 SPARE CONTACT

9 69	9 71	9 73	9 75	9 77	9 79	9 81	9 83	9 85	9 87	9 89
3 52-2	5 52-2	7 52-2	9 52-2	11 52-2	13 52-2	15 52-2	17 52-2	19 52-2	21 52-2	23 52-2
4 67	6 69	8 71	10 73	12 75	14 77	16 79	18 81	20 83	22 85	24 87
5 70	7 72	9 74	11 76	13 78	15 80	17 82	19 84	21 86	23 88	25 90

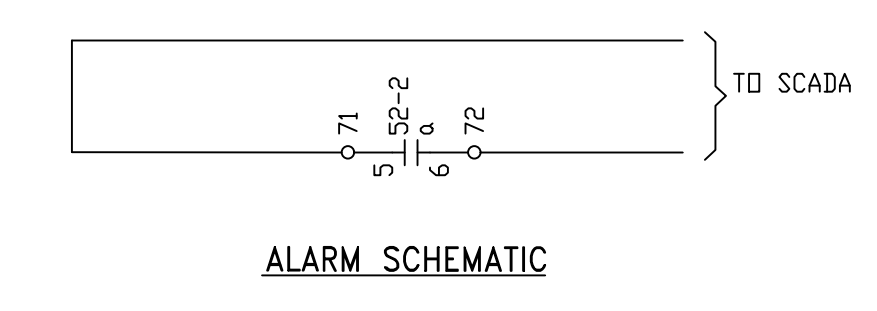
52-2 SPARE CONTACTS



POTENTIAL SCHEMATIC

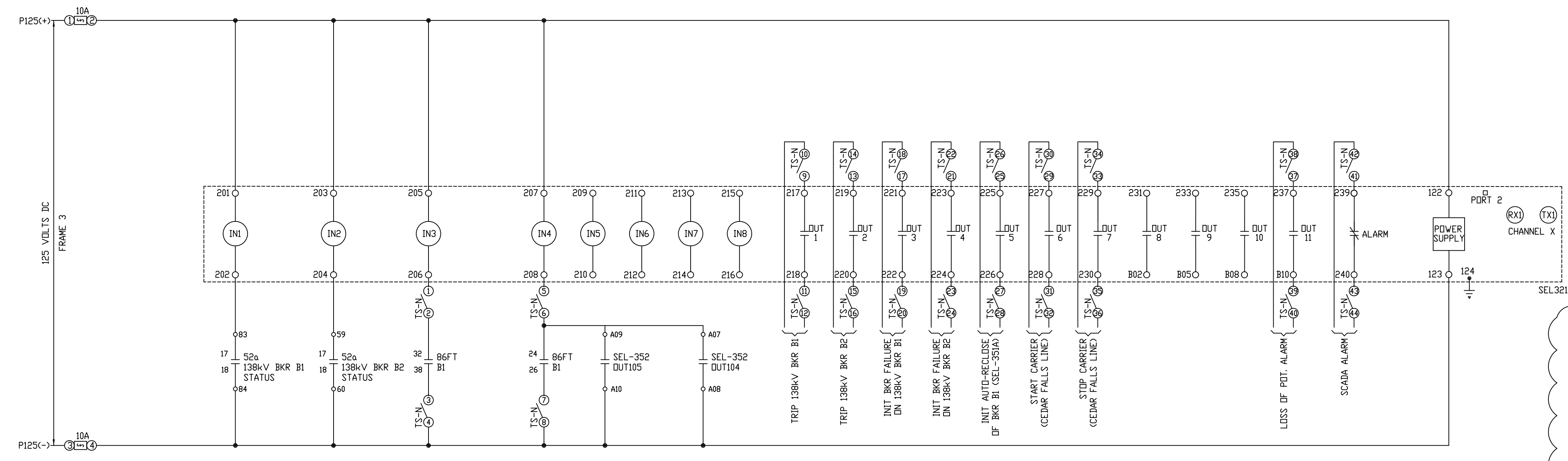


240/120V AC SCHEMATIC

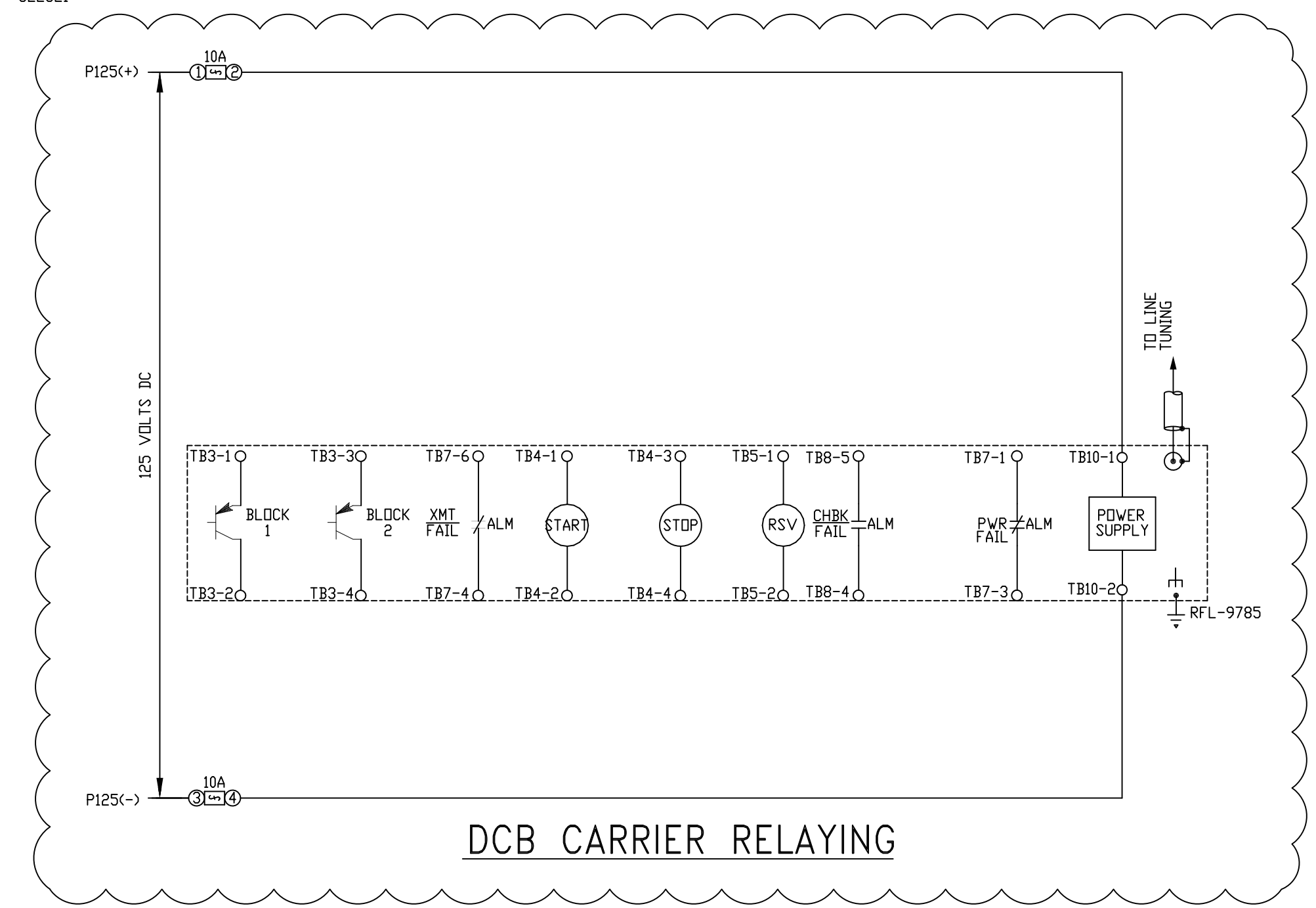


ALARM SCHEMATIC

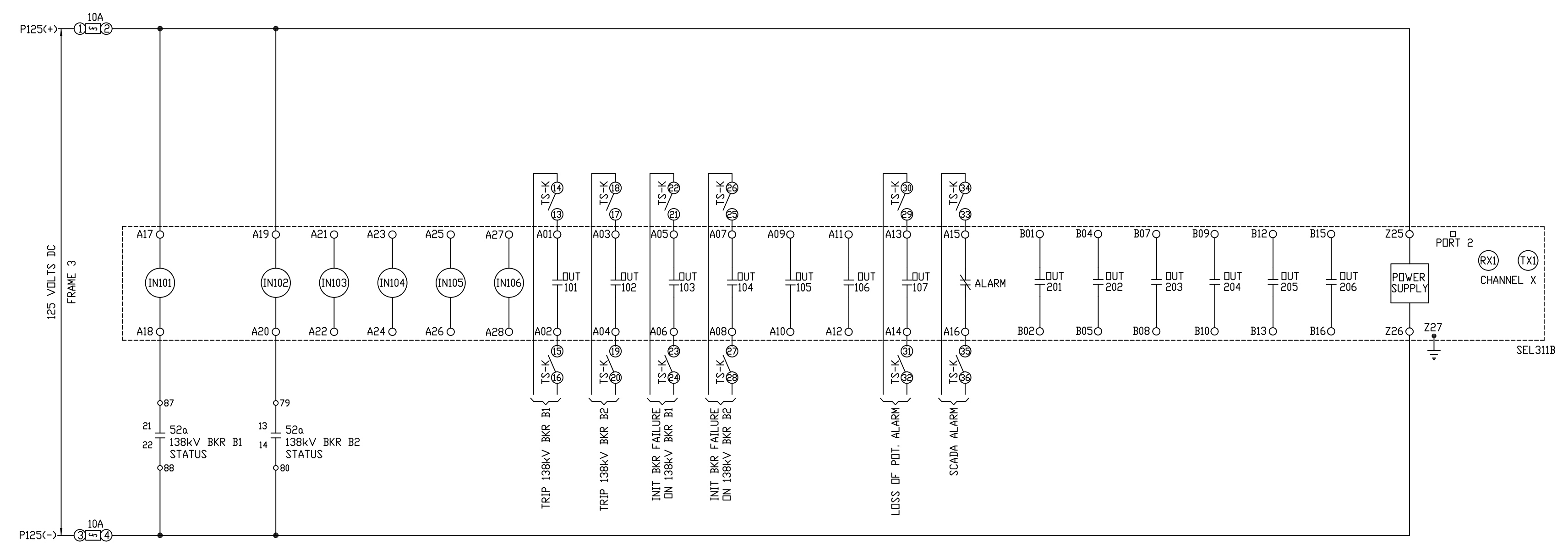
Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by JRH	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		BREAKER B4 SCHEMATIC	
BKR-B4		Edition 1	Sheet 1/1



PRIMARY LINE RELAYING

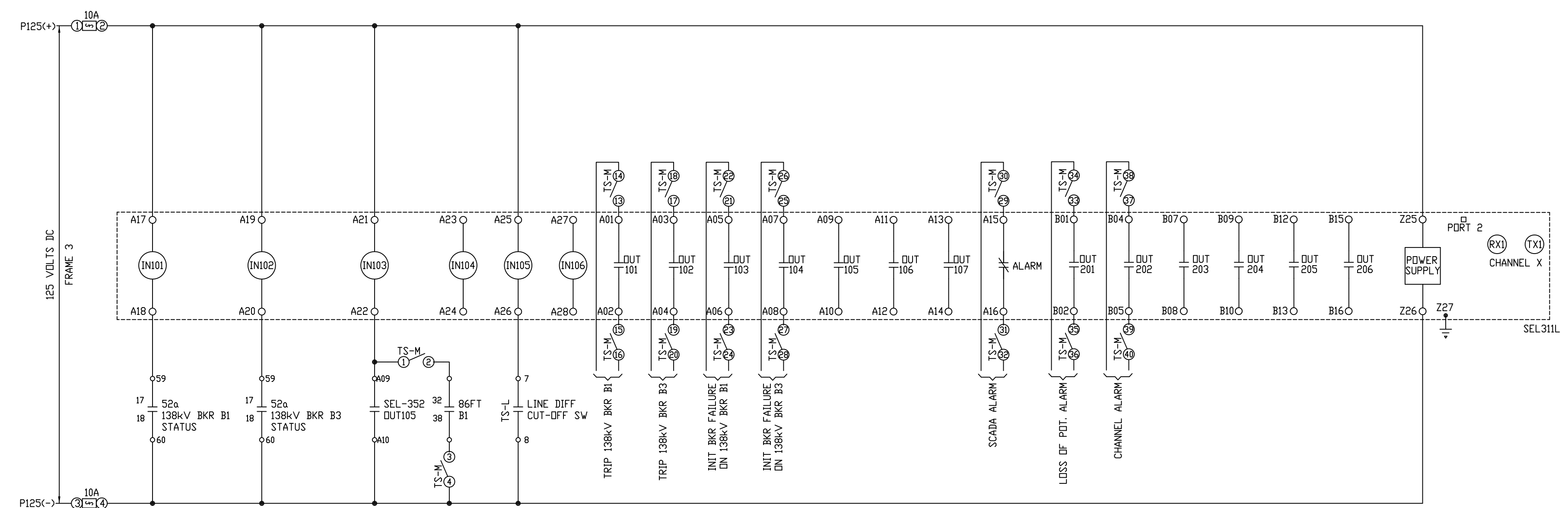


DCB CARRIER RELAYING

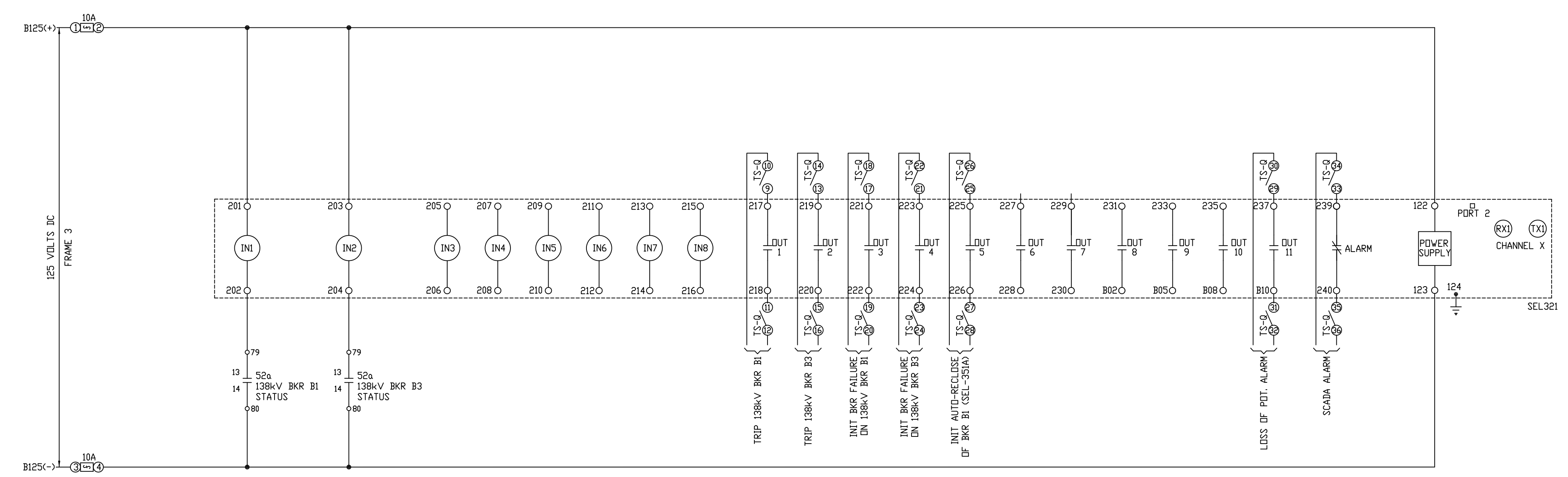


BACKUP LINE RELAYING

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		138kV CF LINE DIFF RELAY	
L-1		Edition 1	Sheet 1/1

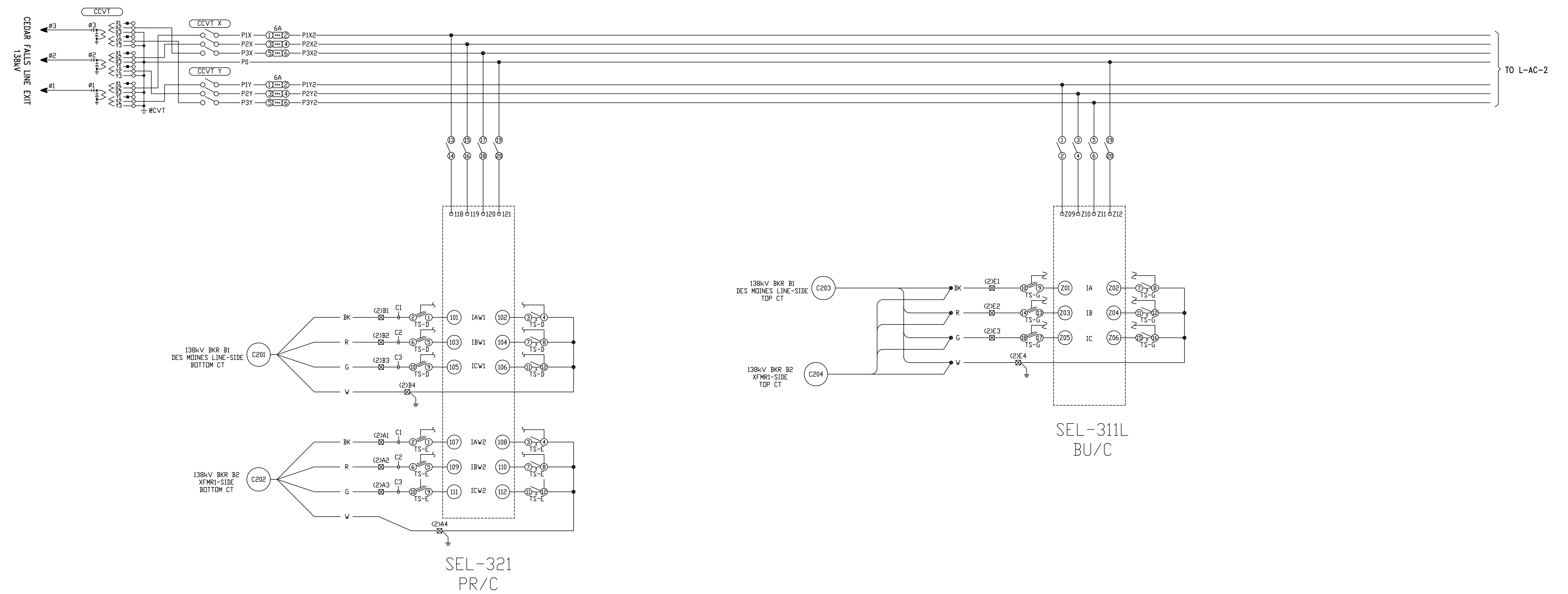


PRIMARY LINE RELAYING

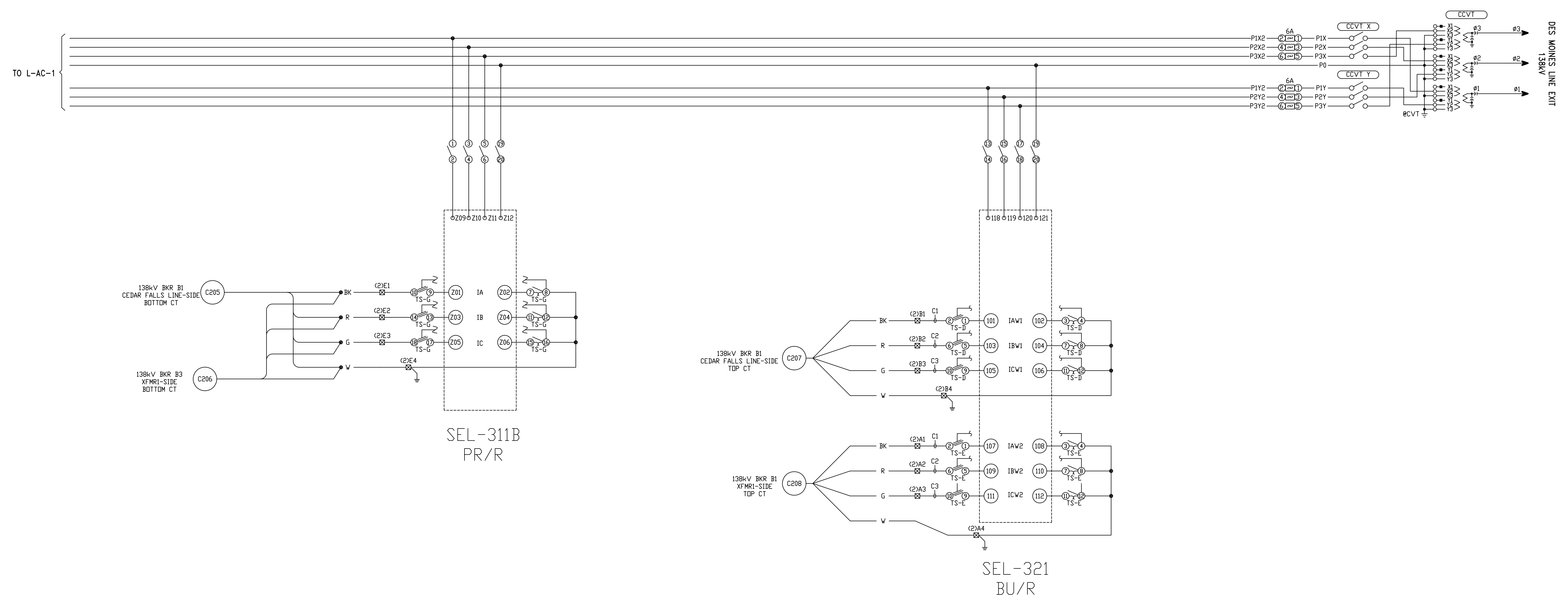


SECONDARY LINE RELAYING

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		138kV DSM LINE DIFF RELAY	Date 11/13/18
L-2		Edition 1	Scale 1:1
Sheet 1/1			



Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		CEDAR FALLS AC LINE DIFF	
L-AC-1		Edition 1	Sheet 1/1



Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
Designed by WGP	Checked by JH	Approved by - date XXX - 00/00/00	Filename PLANVIEW
ISU SENIOR DESIGN		DES MOINES AC LINE DIFF	
L-AC-2		Edition 1	Sheet 1/1