69/12KV Substation Design

ISU Senior Design Group: May 15-01

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1. PROJECT OVERVIEW

1.1 PROJECT DESCRIPTION:

Electrical substations are an essential part of an electrical generation, transmission and distribution system where voltage is transformed from high to low, or in reverse. It links various power system components such as transmission lines, transformers, generators, and loads. The primary function of a substation includes:

- Transforming voltages to different levels by use of transformers
- Communication with other substations and the regional control center
- Interconnection of various transmission lines across a region
- Monitoring of system health via the control center
- System protection

These functions are vital to the reliability of continued power to the grid and are addressed via comprehensive substation design and maintenance. The focus of this project is to complete the detail protection and control design of a 69kV/12kV distribution substation. The station is a 69kV/12kV sectionalized radial bus substation.

1.2 PROJECT SCOPE

The scope of this project has been predefined by our client, Black & Veatch, in a "Project Description" document. The scope of this project is summarized within this section. Black & Veatch has required a comprehensive design plan that incorporates physical design, protection and control design, and engineering management services. While the technical requirements of this project are highlighted, the ability to provide professional documentation and communication is just as imperative within the scope of this project.

1.2.1 PHYSICAL LAYOUT DESIGN

The team will be responsible for determining the layout of the control house arrangement and panel layouts. The substation will be designed to avoid using excess space, while at the same time providing room for future expansions in case of increase in load requirements.

1.2.2 SCHEMATICS

Proper documentation of the design and schematics will be provided by the senior design team. Schematics will be needed for both within the control house and outside. The inside of the control house will focus on panel wiring. Outside the control house, we will need to properly connect all conductors.

1.2.3 SUBSTATION PROTECTIVE RELAYING & CONTROL SYSTEM DESIGN

The team will be expected to design a protective relaying scheme for the substation. This will include circuit breakers, circuit switches, and other components. All models will be verified for proper operation via their datasheets.

1.3 EXCLUDED FROM PROJECT SCOPE

1.3.1. SITE SURVEY INFORMATION

The design team will not be expected to evaluate and consider different geographical areas for feasibility of potential siting. The client has agreed to provide the design team with elevation cuts at a later date.

1.3.2. SYSTEM SIMULATION AND TESTING

While all due diligence will be paid to make sure the system is built for safe and reliable operation, no simulations will be run on the design. No other type of formal testing will be done. Verification of the team's design documents will be done via design review meetings with the client, Black & Veatch.

1.4 DELIVERABLES

The following list of expected deliverables was set forth by Black & Veatch. The first deliverable is the development of an engineering man-hour budget and schedule for this project in order to plan the overall senior design project. Black & Veatch will work with our team to manage the scope of the project to allow completion during the fall and spring semesters.

1.4.1. FIRST SEMESTER (FALL 2014)

- Development of an engineering man-hour budget and schedule for the project with tracking of hours spent on each task (for comparison to actual budgeted engineering man-hours, presented at each design review)
- Design One-line Diagram
- Design Physical Layouts for Control House
- Design Schematic Document

1.4.2. SECOND SEMESTER (SPRING 2015)

- Complete Schematics
- Design Panel Layouts
- Communication Equipment Assignments
- Materials Required List
- Design Justifications
- Three-line Diagrams

1.5 DESIGN CONSTRAINTS

1.5.1 OPERATING ENVIORNMENT

As this project is about building a hypothetical substation, the environment and weather of the location will serve as constraints for this project. Though these will not directly affect any of our calculations, these constraints need to be taken into account when considering soil type, humidity, temperatures, snow etc. All of these parameters will affect some of our layout design such as foundation planning and grounding.

1.5.2 STANDARDS APPLICABLE

Standards play a significant role in optimizing the design process and serve as rigid design constraints. There are several standards set by international authorities that govern the design of substations. Below are a few of the primary standards that are appropriate in terms of the early phases of the project's development.

Public Safety

Substations should be safe for people who may have occasion to be near them. The primary means of ensuring public safety at substations is by erecting a suitable barrier such as a metal fence. Unless local restrictions are more conservative, the fence needs to meet the minimum requirements set by IEEE St. 1119, 'IEEE guide for Fence Safety Clearances."

Power Transformer Standard

Power transformers need special care in their application, specification and procurement because of their great importance and complexity. Hence they need to follow some industry standards and guides of national organizations such as the American National Standards Institute (ANSI), IEEE, etc., and RUS IP 202-1, 'List of Materials Acceptable for use on Systems of RUS Electrification Borrowers.'

Grounding Standards

The most recommended authoritative guide for grounding safety and standard: IEEE Std. 80, "Guide for Safety in Substation Grounding"

Client Standards

When engineers are working on designs for their clients, they often have to work with client constraints and standards. Client constraints are criteria that engineers must adhere to. Some of the constraints that we have to keep in mind are to explain some of the changes that have been made to our drawings with in revision blocks and to insert old revision blocks next to the current revision block. In addition, the same naming convention needs to be used for the different devices that have been used in our drawings. In a similar manner, the same naming convention needs to be use for all the drawing file names. A drawing list has also been created in Microsoft Access. The drawing list lists the file names of our drawings along with the corresponding name of the drawing from the title block. Within the drawings, standard electrical drawing symbols are used and this convention has been followed for all the modification that were made to the standard drawings.

1.6 RISKS

Designing a substation often involves some risks associated with it. While designing a substation, the designers need to consider various risks such as its location, its weather conditions, protection, control and complying with project deadlines. Proximity of the substations to wetlands is essential in order to avoid flooding and its proximity to animals such as rodents can have adverse effects on the substation functioning. In a similar way, the selection of appropriate protection and control is critical to avoid risk.

1.6.1 RISKS TO THE PROJECT TIMELINE

It is easy to get distracted and wander off from the project timeline. Best possible practices and measures should be taken to work hand-in-hand with the planned project timeline.

2. SYSTEM LEVEL DESIGN

2.1 SYSTEM LEVEL REQUIREMENTS

2.1.1 FUNCTIONAL REQUIREMENTS

Due to the theoretical nature of this project, no physical items are expected as deliverables. The requirements given are all necessary to the proper design of a functional distribution substation. Therefore, the following requirements are considered to be **functional:**

- Development of an engineering man-hour budget and schedule for the project with tracking of hours spent on each task (for comparison to actual budgeted engineering man-hours, presented at each design review)
- Substation layout of the sectionalized radial transmission substation
- Support smart grid communications by selecting equipment which enables and supports Ethernet capabilities
- Configure the protective relay scheme to include primary and backup relays for the transformer, as well as for circuit protection
- Development of protection and control design documents based upon the protective relay scheme identified by B&V

2.1.2 NON-FUNCTIONAL REQUIREMENTS

In addition to the functional requirements of the substation, there are non-functional requirements that need to be taken into consideration during the design process:

- Layout of the control house arrangement minimizes land use
- Make panel layouts user friendly for technicians to be able to effectively and efficiently replace equipment and troubleshoot issues

2.2 SYSTEM DESIGN

2.2.1 CONCEPT BLOCK DIAGRAM

This project has been divided up into five different design phases to organize the design process more effectively and improve the efficiency of our work. The following block diagram outlines the five phases and their intermediate steps.

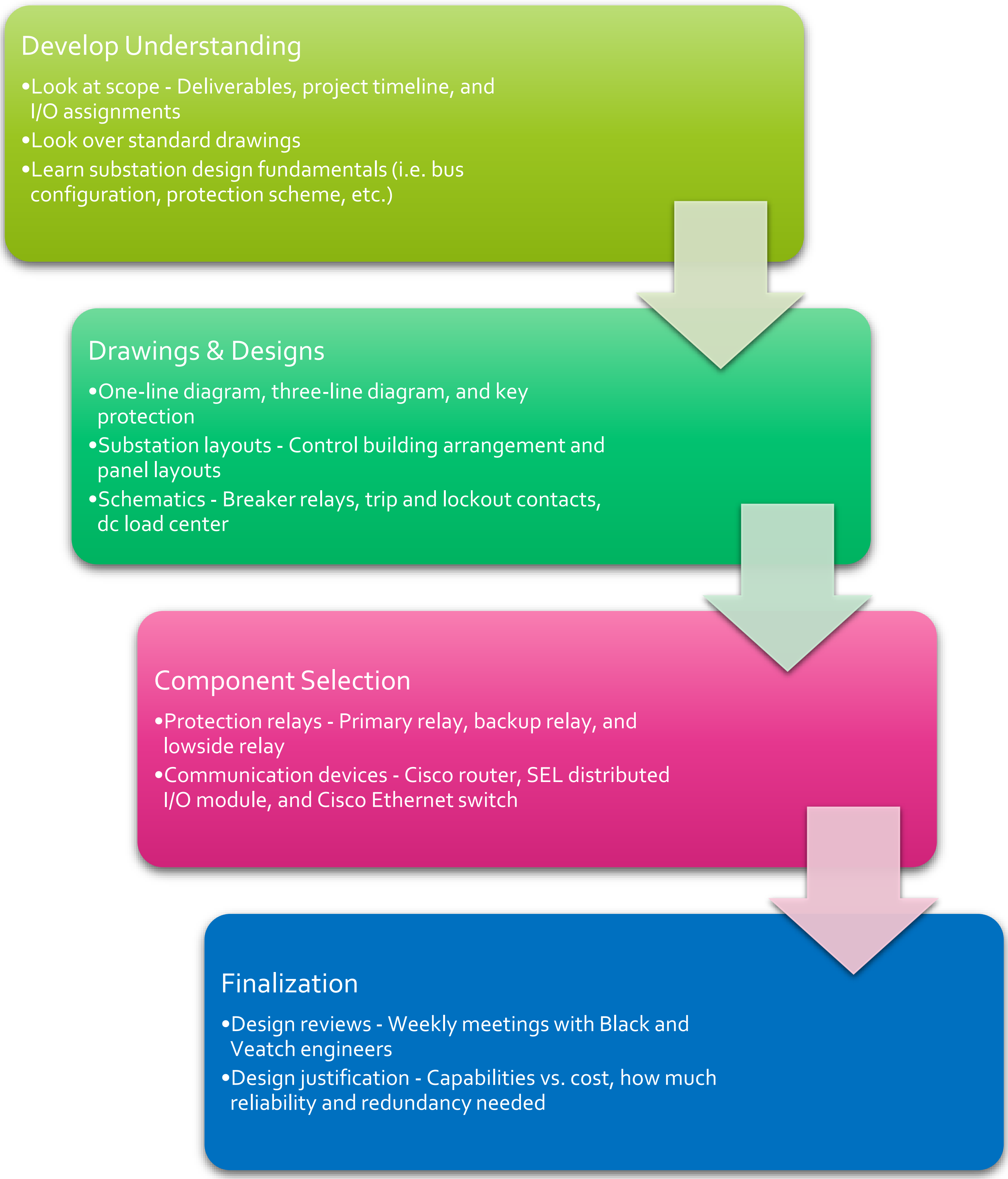


Figure 1: Concept block diagram

3. DESIGN PROCESS AND FUNCTIONAL DECOMPOSITION

3.1 SYSTEM INPUT/OUTPUT ANALYSIS

The substation is a sectionalized radial bus system with two incoming lines and two outgoing lines.

3.1.1 SYSTEM INPUTS

The input to the system is a line carrying power delivered from transmission lines coming from a transmission substation. This is labeled “HS Volts line” on the one-line diagram. This line has communications signals which are sent with one phase of the power line and later filtered off the power line using a wave filter.

3.1.2 SYSTEM OUTPUTS

The system has two outgoing lines, labeled “Cir 1” and “Cir 2”. One of these lines is feeding an industrial load. Each relay within the substation can be considered a subsystem with its own outputs.

3.2 HARDWARE/SOFTWARE SPECIFICATIONS

The project is entirely software based and no physical deliverables are required. We will primarily be working with AutoCAD.

3.2.1 SIMULATIONS AND MODELING

The project will be almost entirely modeled in AutoCAD. The one-line diagram, three line-diagram, physical layout, control house arrangement, panel layouts, and AC/DC auxiliary system schematics will all be developed in AutoCAD.

Simulations will not be required for our project. Only the software models are included in the deliverables.

3.3 PROCEDURES AND SPECIFICATIONS

3.3.1 TESTING

No formal testing is required for the project since we are only providing software models of the substation. We will verify our designs by consulting with professional engineers at Black and Veatch. Professor Dr. Ajjarapu will be looking over our designs as well. Black and Veatch conducts internal reviews of its substation design documents within the company, so this process reflects the industry’s standards. Towards the end of the semester we as a team overlooked each of the drawings to look for errors and correct them on the actual drawings. Any conceptual issues were sent back along with the feedback in the drawings. Almost all our drawings were created in AutoCAD, datasheets and info were created in access files.

3.3.2 IMPLEMENTATION

There are many challenges associated with this project. Each of our project group members had little to no substation knowledge before starting this project so we have all needed to learn an immense amount of information about substations before beginning the design process. Finding a good starting point for the design process was difficult because the research process is quite extensive.

To date, the senior design team has completed numerous iterations of the design-review-revise process on all the drawings. The final design review was completed on April 24^{th}, 2015. The details of each phase of the implementation are below.

Phase One

The first phase of design reviews served as a checkpoint for both Black and Veatch and the Iowa State senior design team. Prior to these design reviews, the Iowa State team had received no formal design direction and the first design attempt was based solely on background research and referencing previous substation design drawings provided by Black and Veatch. The focus of this initial design review was to discuss the functionality of the main substation components with a heavy focus on the one-line diagram.

Phase Two

Following the feedback received during the phase one design review, the team focused on the protective relaying schematics. The primary, backup, and low-side relays were replaced with new relays that have Ethernet capabilities. The I/O assignments were provided by the Black and Veatch team. Upon multiple reviews of the schematics, the team received positive feedback on the relay schematics. The team was advised to research the datasheets of the Schweitzer Engineering Laboratories (SEL) relays for port assignments and functionalities.

Phase Three

Based on the relay schematics, the team continued to work on the other schematics. This included the two feeders, bank 1, bus 1, and main connection schematics. These drawings helped to fill out the rest of the

Phase Four

Following the completion of the schematics, the team worked on the panel layouts within the control substation. In the panels is where the actual relays and communication equipment are housed and wired. After the completion of the panel layouts, it was time to finish the schematics associated with the Ethernet switch, remote terminal unit (RTU), and router. The main feedback from Black and Veatch was the proper port designations for the communication equipment. The Iowa State team could not find the suitable datasheets for the communication equipment, and the Black and Veatch team helped us with this. The Iowa State team has submitted their final drawing revisions to Black and Veatch, and a final design review will occur soon. This final review will be the most critical, with Black and Veatch pointing out all changes that they wished to be made.

4. DESIGN DECISIONS, DISCUSSIONS AND JUSTIFICATIONS

4.1 ONE LINE DIAGRAM

The one line diagram is a simplified graphical representation of three phase power system. Electrical equipment such as circuit breakers, transformers, bus bars and conductors are shown by standardized schematic symbols. Elements on the diagram do not represent the physical size or location of the equipment.

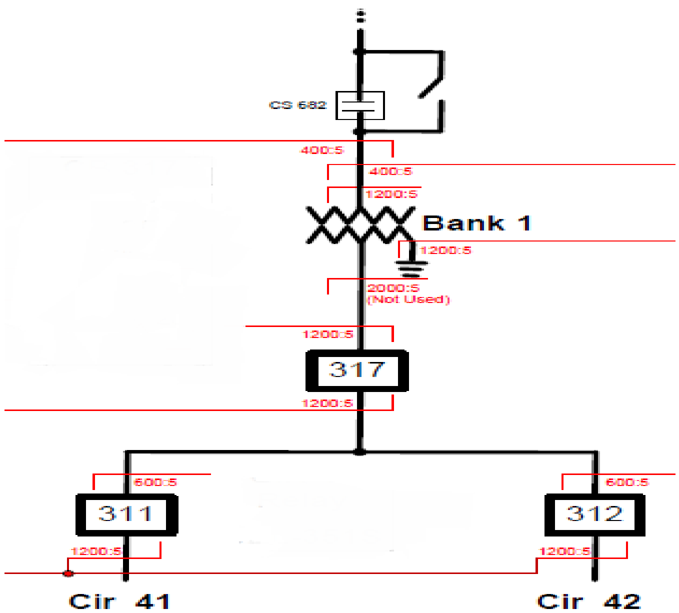


Figure 2: One line

4.1.1 FORMATION

In every substation, a breaker scheme must be selected for the system. In certain systems, the formations are very complex and redundant to increase the reliability and safety of the substation, whereas in other systems simple schemes are used for the sake of cost and lack of necessity for complicated systems.

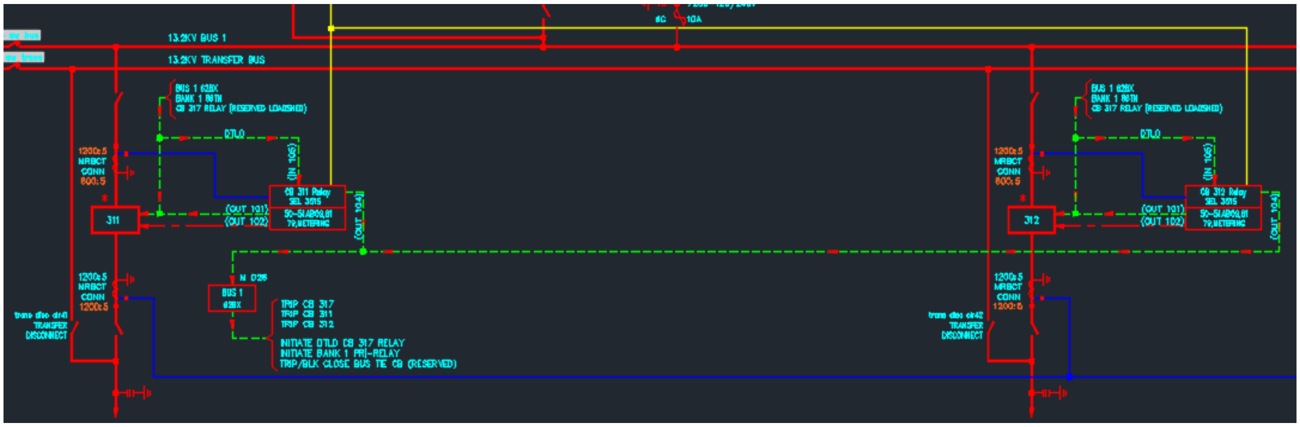


Figure 3: Bus configuration

Our substation scheme is called a sectionalized radial bus formation. A radial bus formation is one of the simplest formations. It is simplified and low in cost, but if a circuit breaker fails to trip, the entire substation is lost. To prevent loss of the entire substation, a transfer bus is added. So, if there is any fault on the main bus, the power flow is transferred to the transfer bus to keep the factory running. The image above shows our bus configuration.

4.2 KEY PROTECTION

The key protection drawing is the biggest and the most important part of our design process. It gives a clear picture of how all the equipment is placed and connected in the substation. This drawing gives detail about, CT ratios, Transformer rating, locations of motorized switches and circuit breakers; and protection relay Input/output assignments. Hence, it gives an overall idea of our protection scheme.

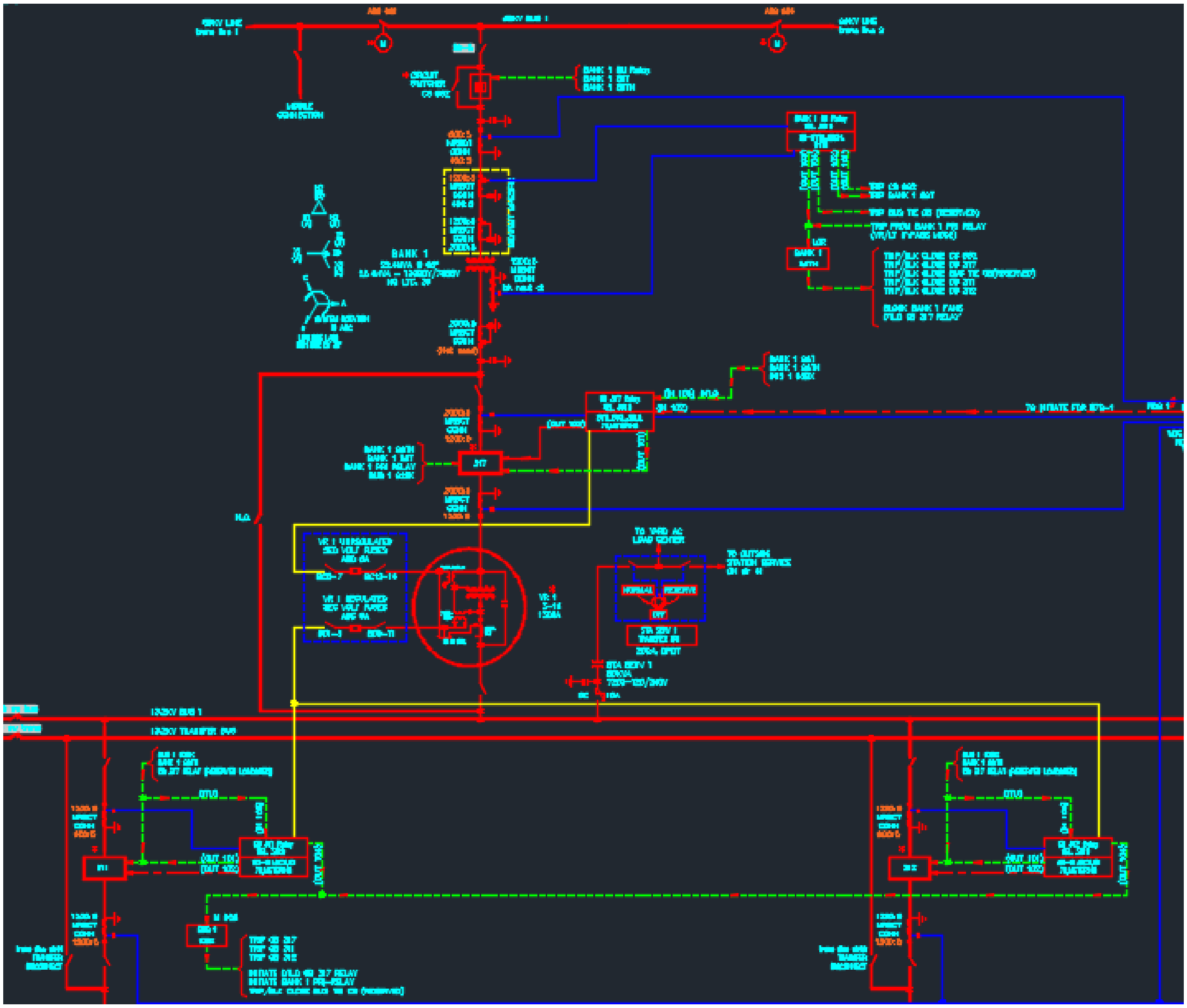


Figure 4: Key protection drawing

4.3 PROTECTION RELAYS

The protection relays control and monitors the entire substation and if a fault is detected, they take necessary actions to isolate the fault by tripping the respective circuit breaker. It also sends data to the master control station of the company that operates the substation. In our substation, we are using a total of 6 protection relays, all manufactured by Schweitzer Engineering Laboratories.

4.3.1 PRIMARY RELAY

The primary relay we used is a SEL – 487E Transformer protection relay. The transformer is the most expensive part of a substation. This relay constantly monitors currents and voltages on either side of the transformer to identify any faults within the substation. If a fault is detected, it isolates the transformer by tripping the circuit breaker or switch on the fault side. This SEL-487E will have CTs from the high side of the transformer and the CTs on the 13kV Bus side of the low side breaker. Check Appendix 5 for primary relay wiring drawing.

Figure 5: Primary relay

4.3.2 BACKUP RELAY

The backup relay functions very similarly to the primary relay. It acts as a backup protection for the transformer. If the primary relay fails, the backup relay will jump in to action to take care of the protection. For this relay, we used a SEL – 351S. Check Appendix 5 for backup relay wiring drawing.

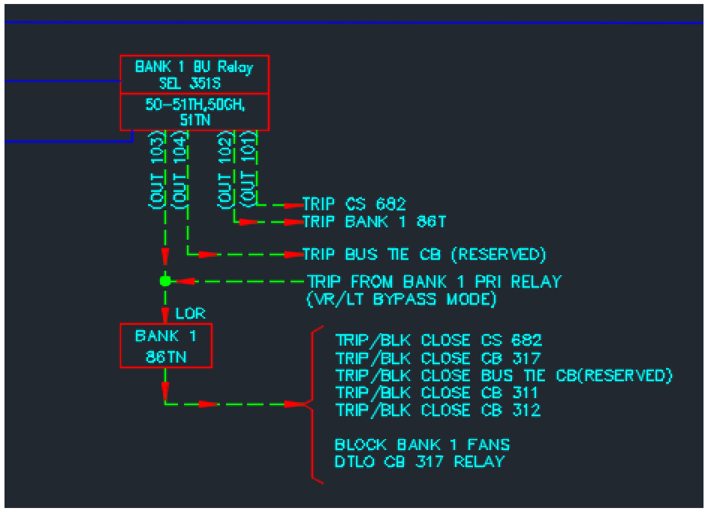


Figure 6: Backup relay

4.3.3 LOW-SIDE BREAKER RELAY

The low-side breaker relay is specifically assigned for the low-sided breaker (CB 317). If any fault is detected on either side of the breaker, it opens the breaker to protect the substation equipment. For this relay, we used a SEL – 351S. Check Appendix 5 for low-side breaker relay wiring drawing.

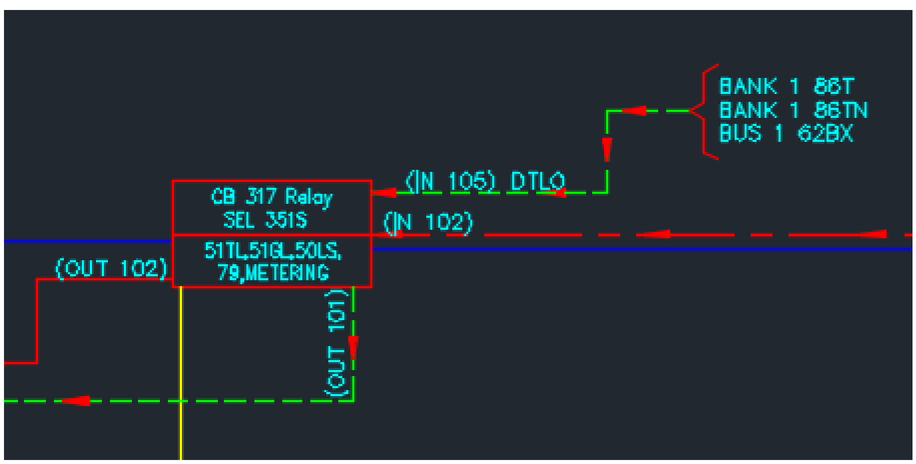


Figure 7: Low-side breaker relay

4.3.4 CIRCUIT RELAYS

The circuit relays are responsible for the breakers which separate the substation from the factory (CB 311 and CB 312). If any fault is detected on either side of the breaker, these relays open the breakers and stop the fault from propagating. For these relays, we used SEL – 351Ss.

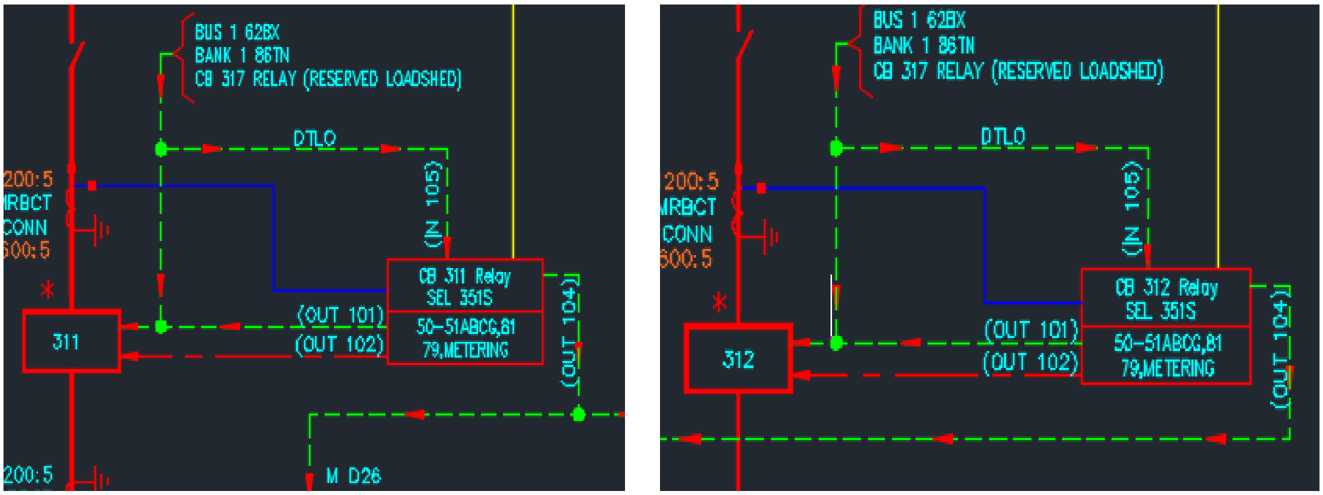


Figure 8: Circuit relays

4.4 CONTROL HOUSE LAYOUT

The control house contains the switchboard panels, batteries, battery chargers, relay, metering, and control equipment. It provides year round weather protection and security for the control equipment. It is arranged to resemble actual equipment and the circuit layout. Cables enter the house via windows, sleeves, or cable pits and are handled with cable trenches, false floors, or conduits.

4.4.1 CONTROL PANEL ARRANGMENT

Black and Veatch sent us a standard panel general arrangement for the control building and the clients control panel arrangement. Changes are to be made to the standard panel general arrangement drawing so that it fits the physical and control design.

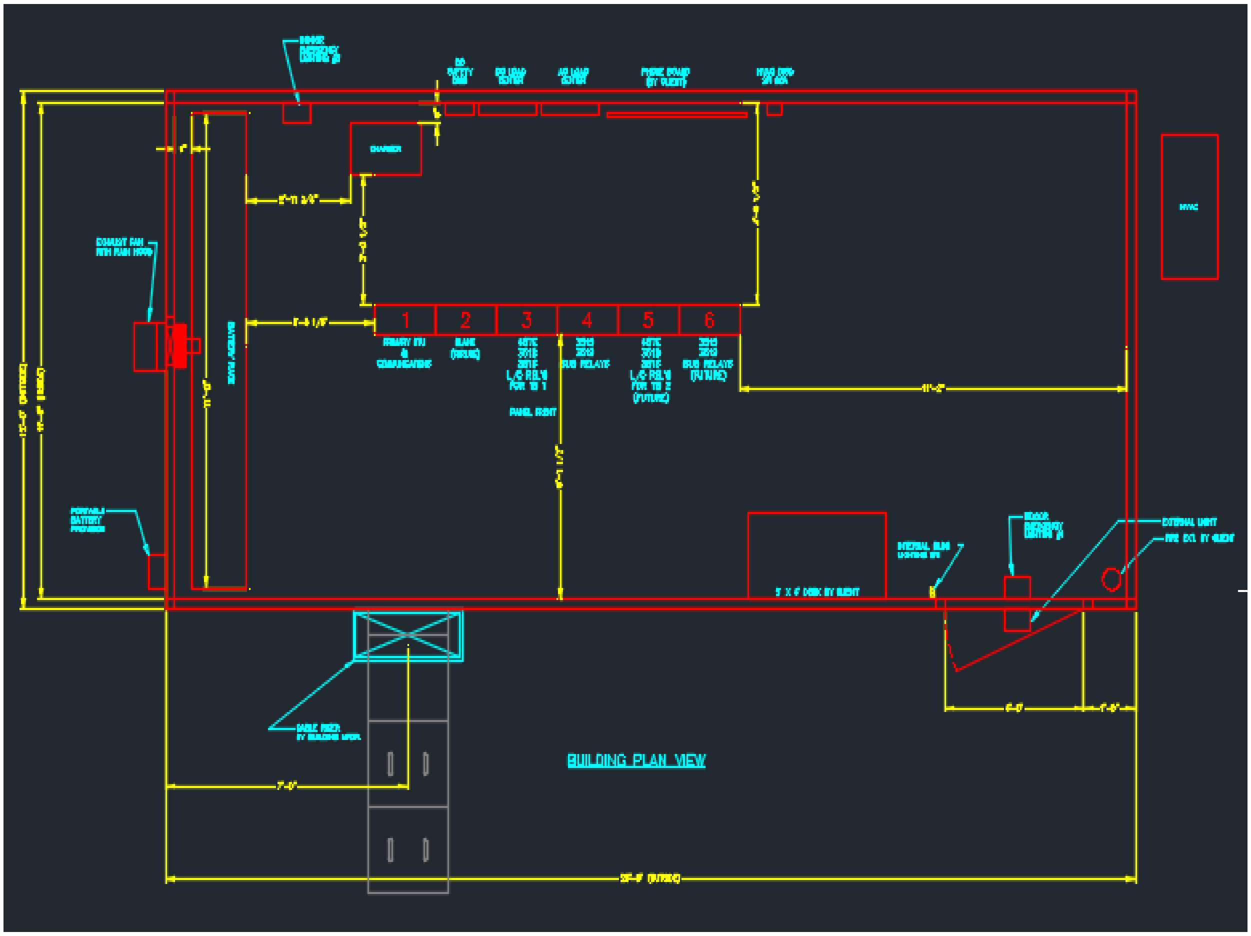


Figure 9: Control house arrangement

The following drawing is the control house with the elevated wire track. We installed an elevated wire track to provide auxillary power to the control panels and the low voltage equipment inside the control house. We had the option of installing an underground raceway or an elevated wiretrack but chose the latter because it was economically feasible and allowed more space in the control house for maneuverbility in case of maintenance work.

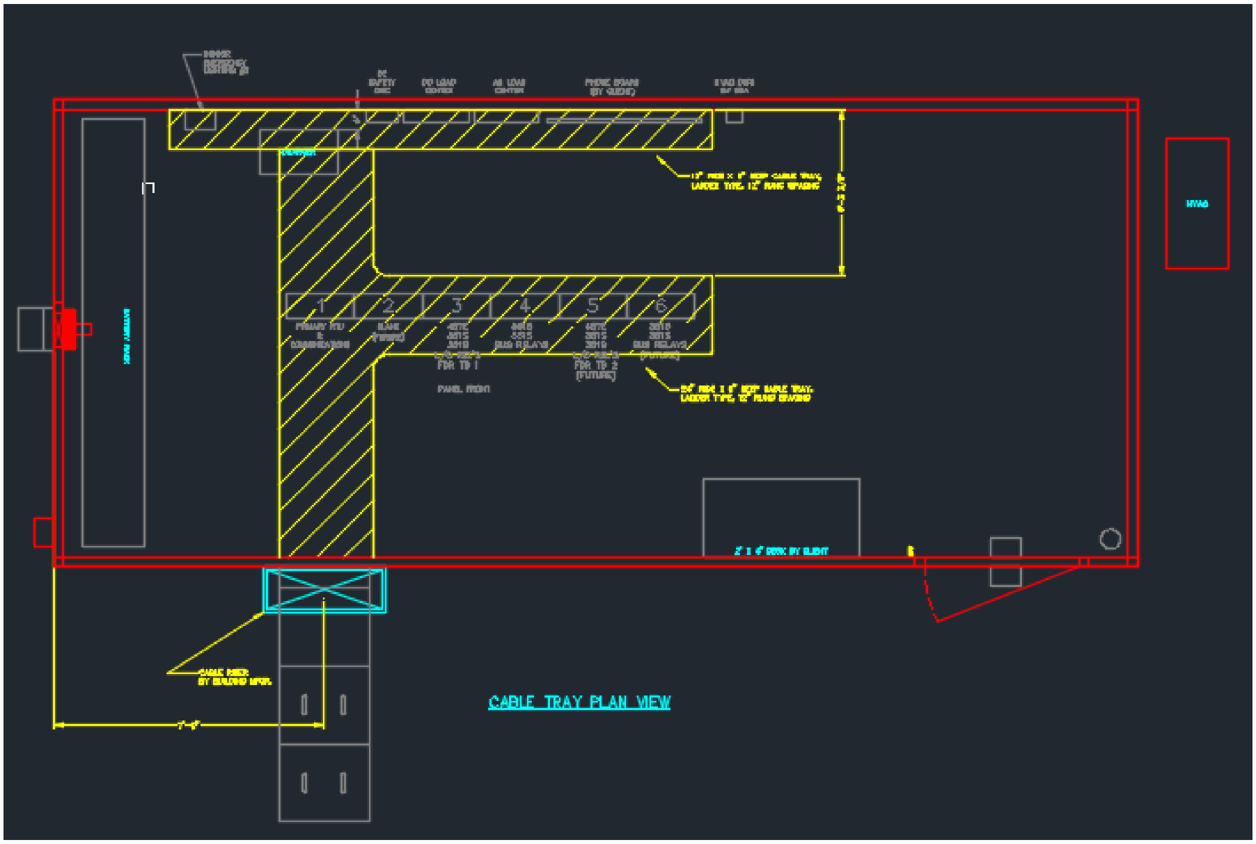


Figure 10: Control house arrangement (with wire track shown)

5. WORK PLAN

5.1 SCHEDULING: AUG 26, 2014 – MAY 10, 2015

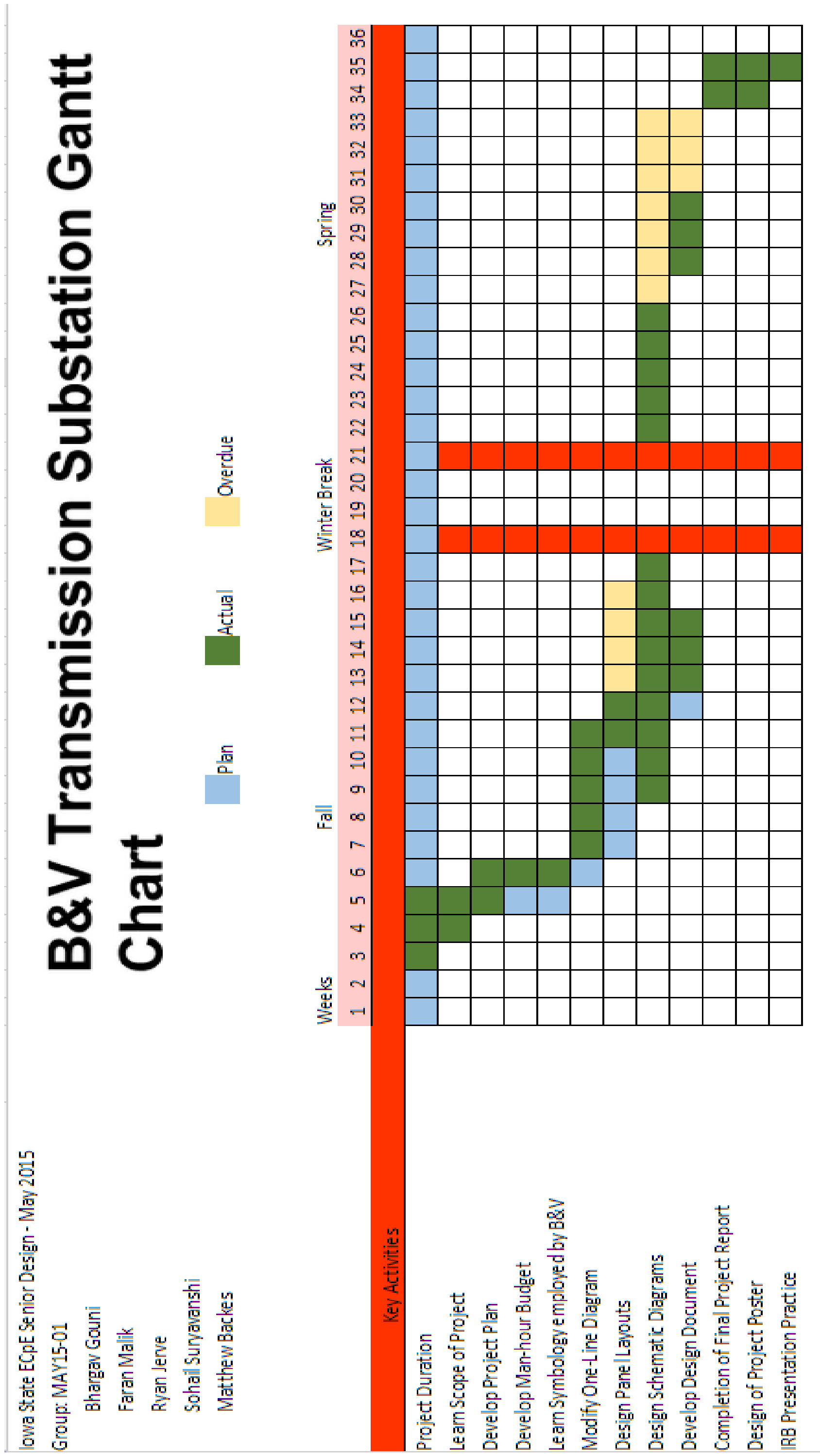


Figure 11: Gantt Chart

5.2 WORK BREAKDOWN STRUCTURE

Review Materials	Responsible Party	Details
Understanding Requirements and Specifications	Entire Team	Substation Design manual Scope Document
Project Documents	Entire Team Entire Team Matt Backes Matt Backes Sohail Suryavanshi	Project plan Design Document Gantt Chart Engineering Man-hour Budget Materials Required List
Layouts	Bhargav Gouni Faran Malik, Ryan Jerve Bhargav Gouni, Matt Backes Sohail Suryavanshi	One Line Diagram Control House layout Panel Layouts AC Yard & Building
Protection & Control Design Schematics	Matt Backes Ryan Jerve, Sohail Suryavanshi Bhargav Gouni, Faran Malik Ryan Jerve, Faran Malik Matt Backes Entire Team	Primary Relay Backup Relay Low-side Breaker Relay Bank 1 & Bus 1 Communication Schematics Design justifications

5.3 RESOURCE ALLOCATION

Software	AutoCAD
Hardware	ECpE Lab Resources
Advisor	Dr. Venkataramana Ajjarapu
Black & Veatch Contacts	Adam Literski Josephine Namatovu Umair Ilyas

Name	**Personal Role**
Matt Backes	Team Leader
Bhargav Gouni	Key Concept Holder
Faran Malik	Communication Leader
Ryan Jerve	Communication Leader
Sohail Suryavanshi	Webmaster

6. CONCLUSION

This senior design project has helped us learn the physical, protection, and control design of a 69kV/12kV distribution substation along with the different components that are used within a substation. As a team, we developed an engineering man-hour budget, one-line diagram, three-line diagram, panel layout design, schematics, bus and insulator design, and selected equipment sizes for various components along with performing various substation level calculations. This project was very helpful in learning about the various components that are used within a distribution substation. We obtained real world experience by working with an off-campus client virtually along with learning to deal with time constraints and working as a team.

APPENDICES

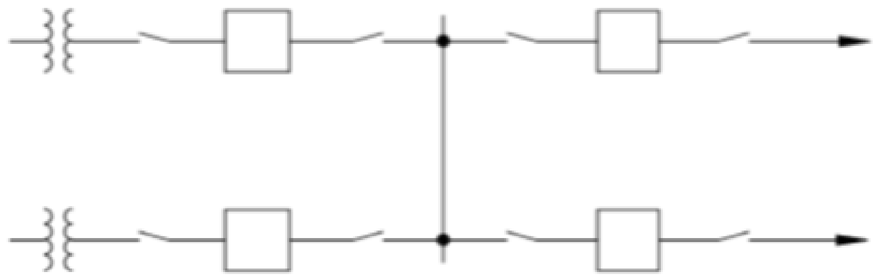
APPENDIX 1: OPERATION MANUAL

Simulations are not required to be run on the designs nor is any formal testing required since we are only providing software models of the substation. Professional Engineers at Black and Veatch will verify our designs as they are completed. A review of our design will be executed to make sure that all the requirements are met. Dr. Ajjarapu will look over our designs as well. Black and Veatch conducts internal reviews of its substation design documents within the company, so this process reflects the industry's standards.

APPENDIX 2: DESIGN ALTERNATIVES

For our substation there were multiple bus schemes we could implement in our system. We chose the sectionalized radial bus configuration due to its superior protection. However, any of the other bus configurations are viable design options and each has its own set of strengths and weaknesses.

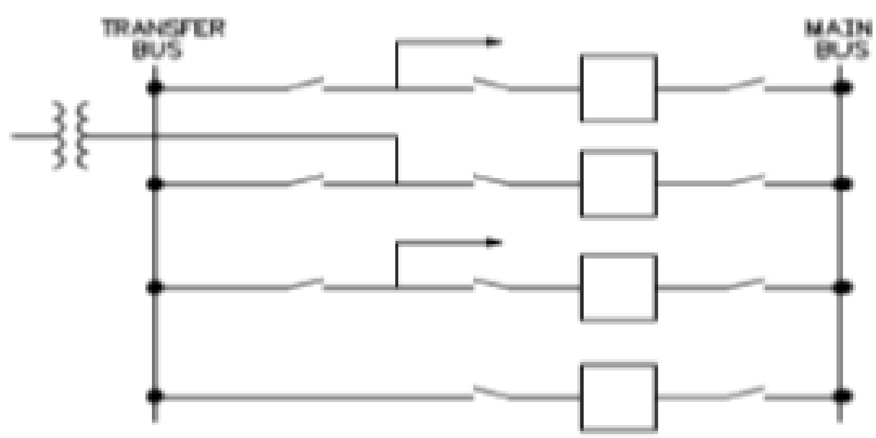
Single Bus



The image shown above is a diagram representation of a single bus arrangement. On this diagram, the square blocks represent circuit breakers, the switch symbols represent disconnect switches, the symbols on the far left represent the transformer, and the line running down the center is the bus. The single bus scheme is the simplest and cheapest of all options. The main advantage of this arrangement is the cost. Because it uses fewer circuit breakers than other configurations, the overall cost will be significantly lower. It also uses less space than other schemes and can easily be expanded. The design's simplicity can be advantageous as well.

However, the single bus arrangement is also the least reliable of all options. In the event of a fault, the transformer will be protected but the entire bus will fail, causing the substation to be inoperable. If maintenance must be performed on a circuit breaker, the entire circuit must be de-energized to do so. This can be overcome by the addition of breaker bypass switches, but that may result in the protection system for the substation being disabled.

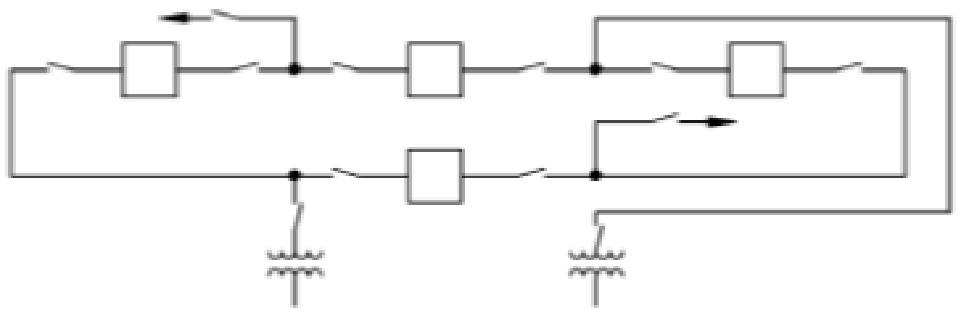
Main and Transfer Bus



The above image is the main and transfer bus configuration. This scheme contains two separate and independent buses: a main bus and transfer bus. In normal operation, all circuits, both incoming and outgoing, are connected to the main bus. However, if a circuit breaker must be repaired for maintenance, the circuits can be fed and protected from the transfer bus while the main bus is de-energized and repaired. Being able to maintain operation during maintenance is a major advantage of the system. The cost of this system is reasonable as well. Though it does require more area than a single bus, it is still fairly small and easily expandable.

The disadvantages of this system is that an additional circuit breaker is needed for a bus tie, which increases the cost. Unlike the single bus, the protection and relaying for this configuration can become complicated. For this scheme a fault will cause the loss of an entire substation, as with the single bus.

Ring Bus



Another configuration used in many substations is the ring bus (shown above). In this system, a sectionalizing circuit breaker has been placed between the two open-ended buses. This creates a closed loop on the bus with each section separated by a circuit breaker. This provides significant protection and reliability. Each circuit is double fed, and since there is no main bus, a fault will not result in the entire loss of the substation. Any circuit breaker can be fixed without de-energizing the entire system as well.

Although the prevention of an entire substation loss by this system is ideal, the circuit may have a non-ideal combination after the sectionalizing circuit breaker trips. Each circuit must have its own potential source for relaying, which increases costs. The ring bus is rather complicated as well.

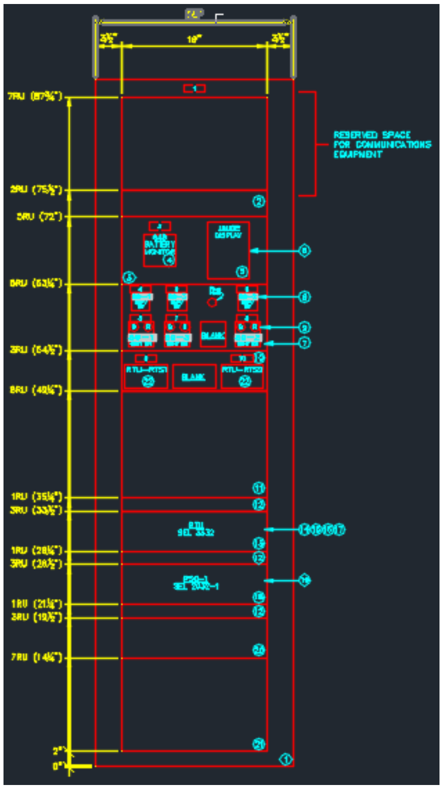
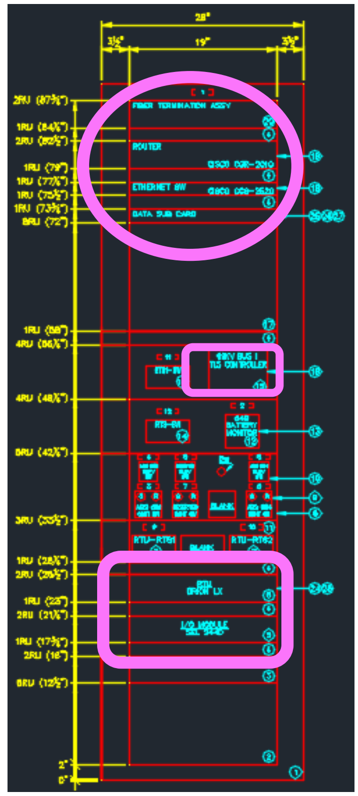
APPENDIX 3: WHAT DID WE LEARN

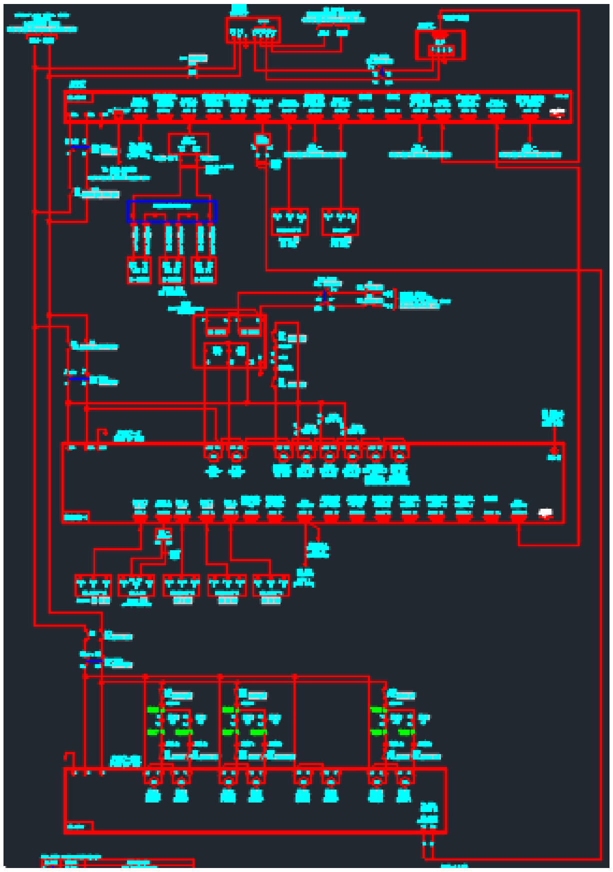
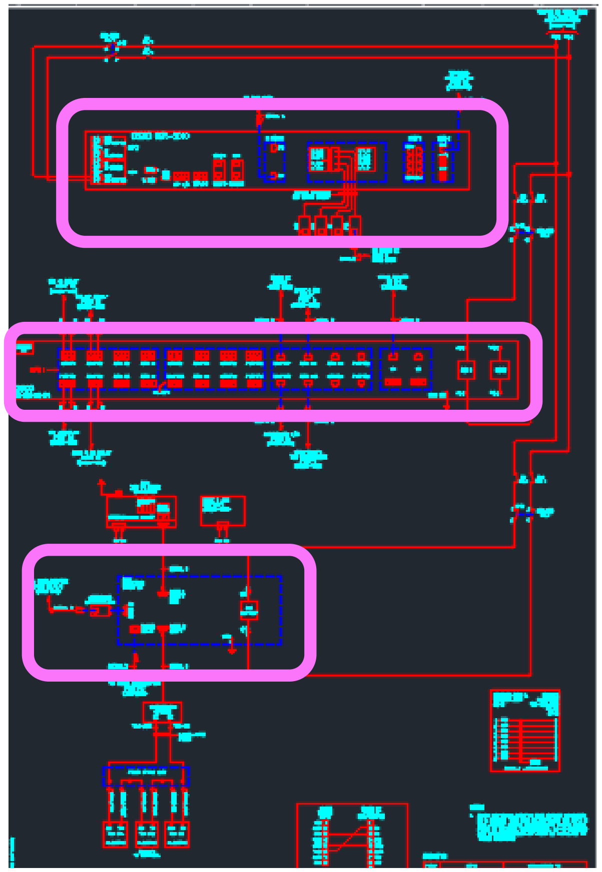
This project required a steep learning curve. We had to master the basics of substation design to understand our project scope. For the most part we had to figure things out ourselves. A project such as this goes far beyond the scope of what is covered in power courses at Iowa State. While we learn the fundamentals of power flow and analysis, the specific details of implementing substation design is not covered. We as a group had several discussions and we always tried explaining things to each other and these interactions enhanced our thinking and learning process. Also, Professor Dr. Ajjarapu provided us with a lot of material on substation design to help us work our way through the project more easily.

Working for a consulting company like Black & Veatch gave us a glimpse of how things work at a consulting firm. We had to understand the industry methods and also the design standards set by Black & Veatch. Almost all of our project had to be dealt with in AutoCAD. So, all of us had to become adept at this software.

Last but not the least, we learned the important skill of working with others. Our group is pretty diverse and this helped us become more effective communicators which is becoming increasingly significant in today's global economy.

APPENDIX 4: BEFORE AND AFTER DRAWINGS

Standard Drawing	Updated Drawing
ds-s-22-4 comm pnl lo	PANEL 1 - SEL2440, ORION RTU, TLS CONTROLLER (01501-W07)
	 [1] Added Cisco communication equipment [2] Added SEL TLS controller [3] New RTU (OrionLX) and Distributed I/O (SEL 2440)

ds-s-22-4 comm rtu.dwg	SCHEMATIC DC-RTU, ROUTER & ETHERNET SWTICH
	 [1] New Cisco Router [2] New Cisco Ethernet Switch [3] New Remote Terminal Unit (RTU) - OrionLX

APPENDIX 5: RELAY WIRING DRAWINGS

PRIMARY RELAY WIRING DRAWING

Wiring diagram of primary relay drawing:

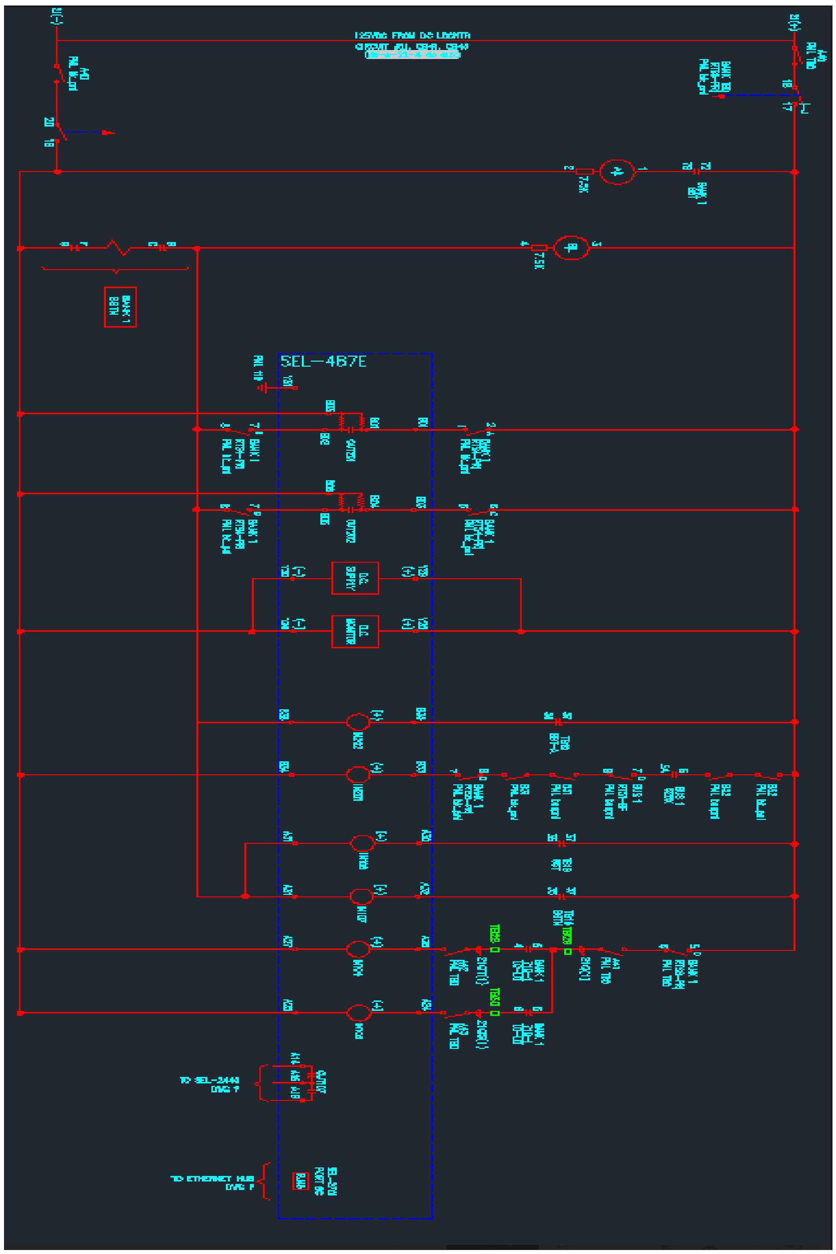


Figure 12: PRIMARY RELAY WIRING

BACKUP RELAY WIRING DRAWING

Wiring drawing of the Backup relay:

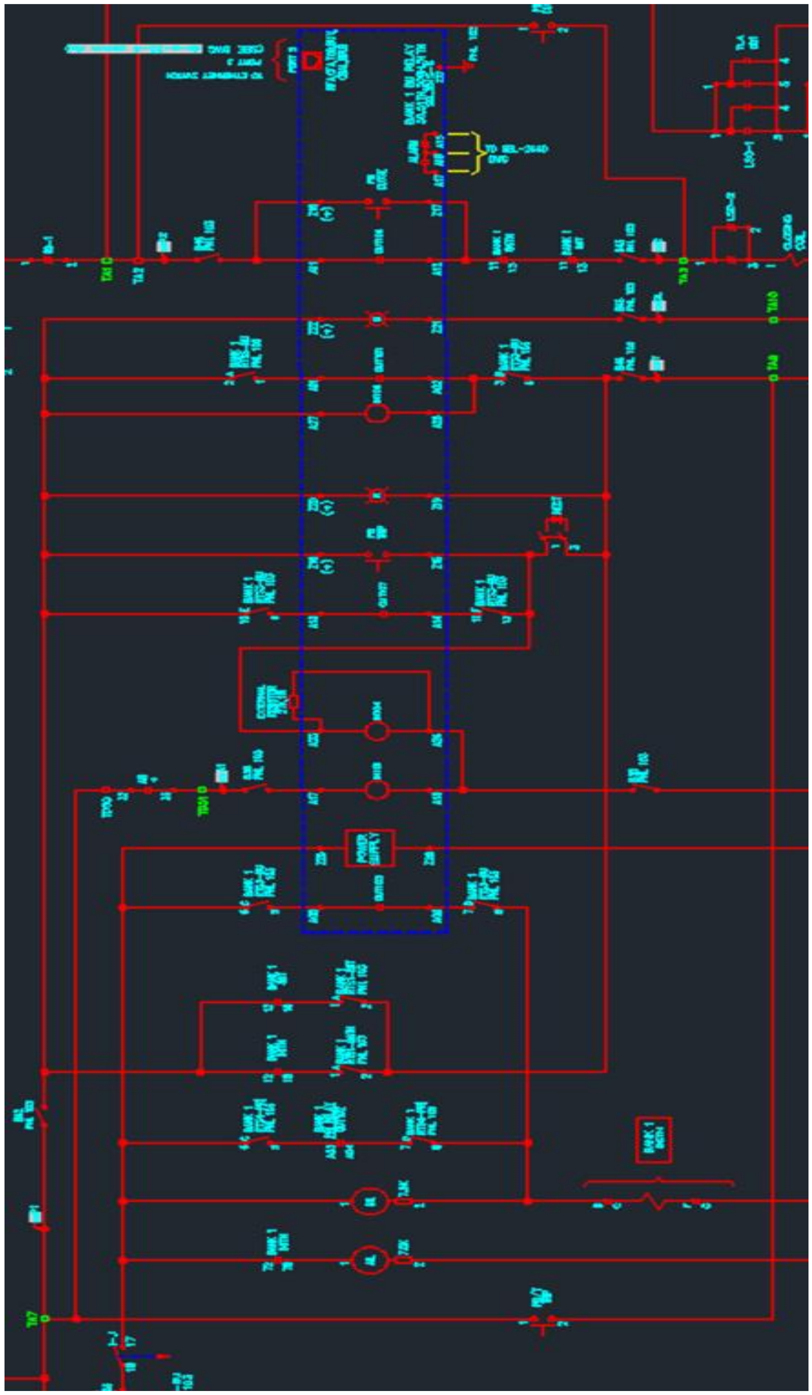


Figure 13: Backup relay wiring

Wiring diagram of the low side breaker relay drawing:

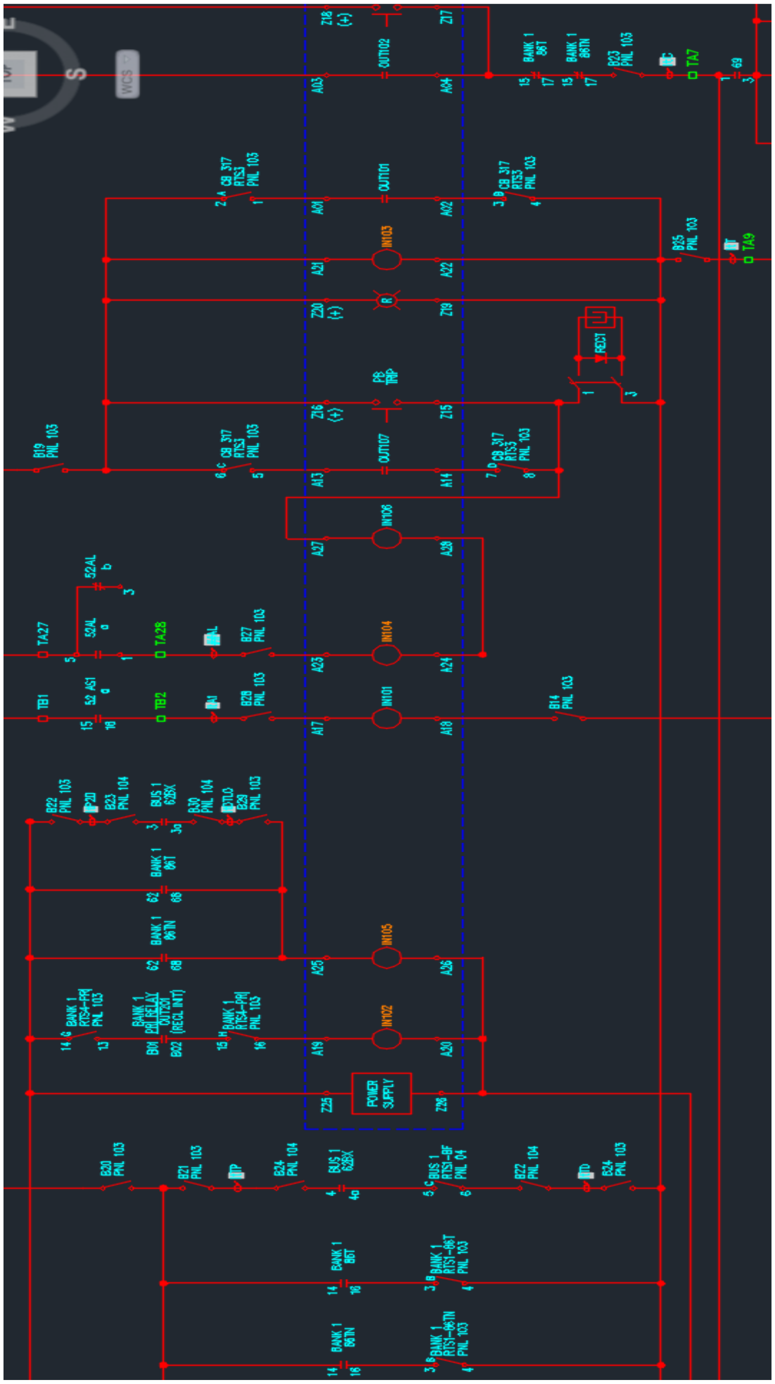


Figure 14: Low side breaker relay wiring

APPENDIX 6: PANEL LAYOUTS

BANK PANEL LAYOUT

The bank panel houses the Primary relay, Backup relay and the Low side breaker relay.

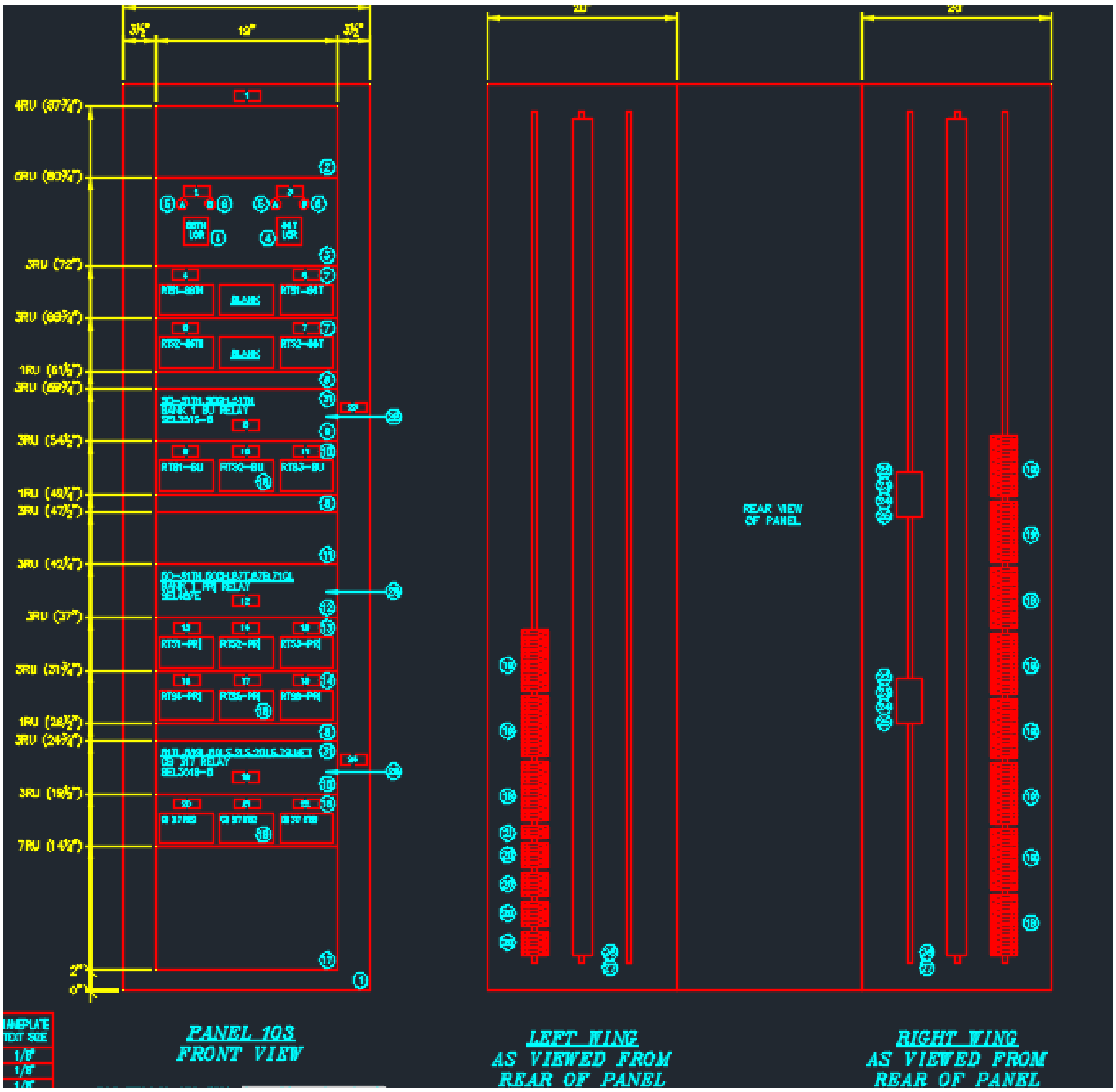


Figure 15: Bank Panel Layout

BUS PANEL LAYOUT

The bus panel houses the two circuit relays.

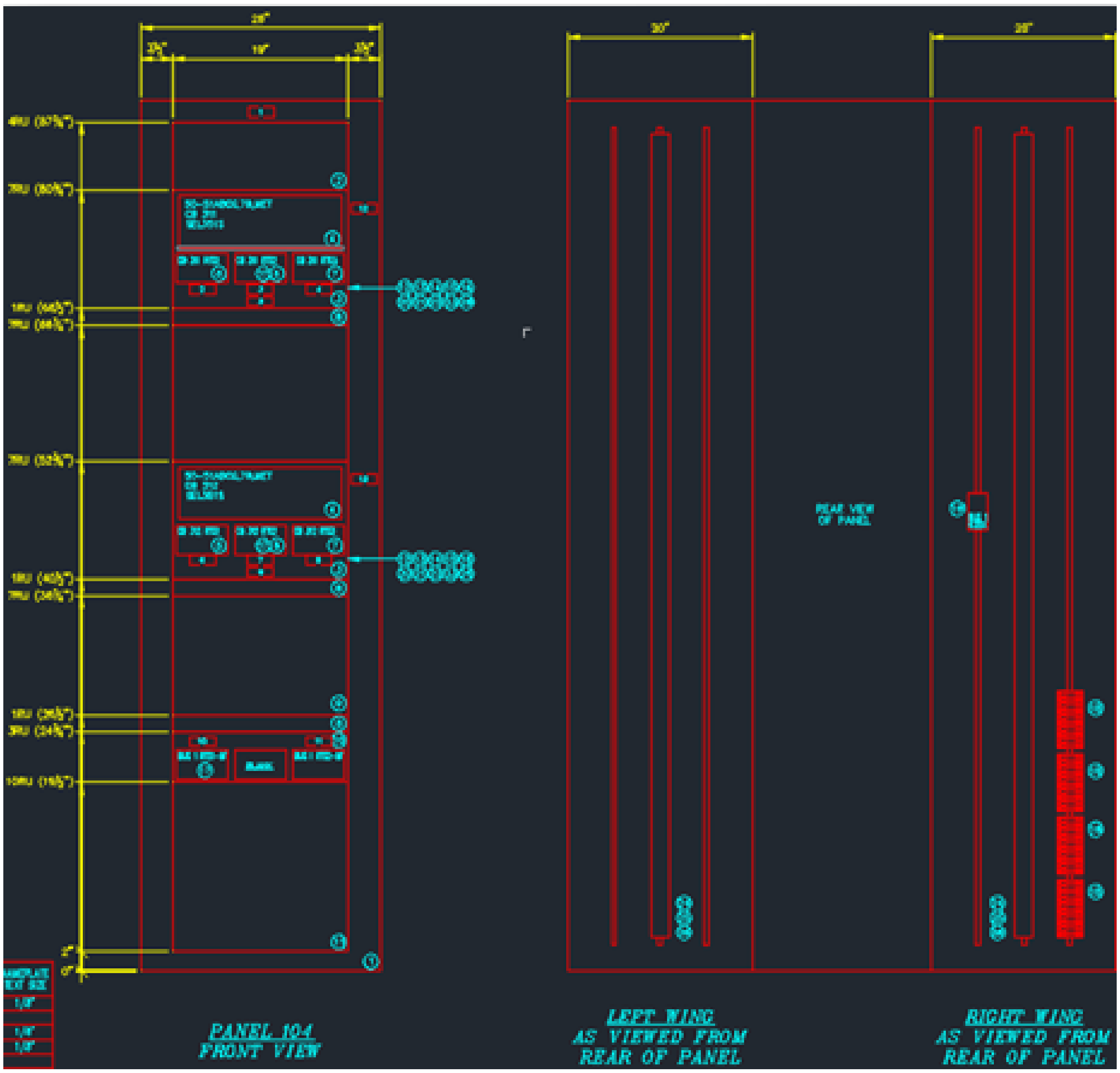


Figure 16: Bus Panel Layout

REFERENCES

Throughout the senior design project, we utilized outside resources to help us attain the proper background information about substation design and the different components that go into them. These resources come from a multitude of sources, but all care was taken to only take information from credible sources. Some resources were referred by Dr. Ajjarapu, while others were found through our own research.

[1] Kezunovic, M. (2010, February 15). The Twenty-First Century Substation Design. *PSERC Webinar Series.* Retrieved April 10, 2015.

[2] Kezunovic, M., Ghavami, M., Guo, C., Guan, Y., Karady, G., & Dam, L. (2010, September 15). The 21st Century Substation: Final Project Report. Retrieved April 7, 2015.

[3] Stockton, B. (2001, June 7). Design Guide For Rural Substations. Retrieved April 14, 2015, from http://www.rd.usda.gov/files/UEP_Bulletin_1724E-300.pdf