Substation Design

Design Document

Team Number
SDMAY19-17

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

1 Introduction

1.1 Acknowledgement

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

1.2 Problem and Project Statement

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

General Purpose

For this reason, substations are necessary throughout power grids. The primary function of a substation is to raise or lower the voltage of the electric power flowing into the substation. The main piece of equipment located at a substation is a power transformer, an electromagnetic apparatus capable of raising or lowering an input voltage, then transmitting electric power—at a raised or lowered output voltage, relative to the input voltage—long distances or distributing it to electricity 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, which allow utilities to isolate electrical equipment—including electrical-current-carrying lines—from the rest of the power circuit/power grid should a fault occur somewhere in the power grid.

General Problem Statement

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

General Solution Approach

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

1. Specifications:

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

2. Substation Layout:

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

3. Bus and Insulator Sizing Design

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

4. Ground grid

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

5. Raceway

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

6. Control Building

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

7. 125V DC Station Battery Design

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

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

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

8. Relaying and Controls

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

9. Lightning Protection

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

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

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

10. Communications

The Iowa State Senior Design team will do the following:

i. Create a communications block diagram and design the substation communications network using a combination of serial and ethernet network equipment.

ii. Design microwave radio system for communications transport. This will include frequency selection, tower sizing and placement.

iii. Provide equipment quotes and engineering cost estimate.

iv. Generate a SCADA points list from a provided template.

v. Configure the RTU and protective relays, as specified by the points list and comm block diagram, to provide SCADA information to a remote master station.

vi. Program a local HMI in the RTU to show an animated one line with real-time values and an alarm annunciator.

vii. Program a remote EMS master using Kepware on Windows

1.3 Operational Environment

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

1.4 Intended Users and Uses

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

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

1.5 Assumptions and Limitations

Assumptions:

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

Limitations:

- The new substation would be built in or near Ames, IA

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

1.6 Expected End Product and Deliverables

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

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

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

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

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

2. Specifications and Analysis

2.1 Proposed Design

So far, our team has spent a considerable amount of time gathering information from our client. Being provided with an in-depth, chronologically ordered list of tasks, we generated a timeline for completion. Our first two client deliverables are the grounding study and lightning protection study reports.

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

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

Soil Resistivity Measurements

Before designing a grounding grid, soil resistivity of a site must be measured. These parameters were supplied to us by Burns & McDonnell. Assuming uniform resistivity at our site, once given parameters the following calculation is performed:

Equation 9.1

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

Where:

ρ_a = Apparent resistivity of the soil in Ω-m

R = Measured resistance in ohms

a = Distance between adjacent electrodes in meters

b = Depth of the electrodes in meters

Area of the ground grid

It is generally advisable to design the area of the ground grid to be as large as possible; however, cost optimizations must be considered. Our site is rectangular in shape and after running different layouts using CDEGS software, we decided to make the copper grounding system 30 ft. x 30 ft. with distances of 3 ft. between inner lines.

Ground fault currents

When a substation bus or transmission line is faulted to ground, the flow of ground current in both magnitude and direction depends on the impedances of the various possible paths of flow. Included below is an illustration of a possible case of ground faults:

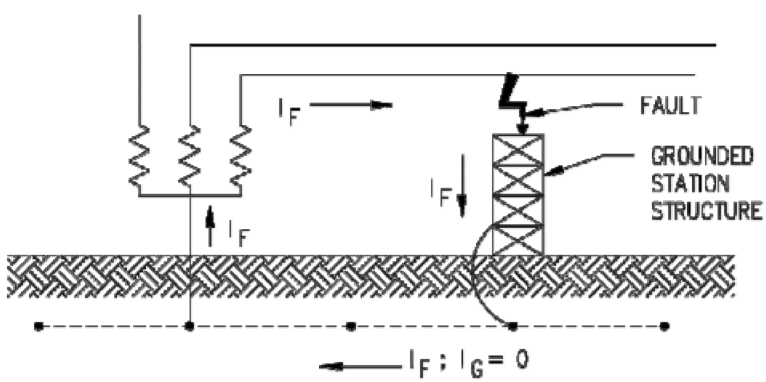

FIGURE 9.2: Fault Within Local Substation, Local Neutral Grounded. Ref. IEEE Std. 80, Draft 13, June 19, 1998, Figure 15-1. Copyright © 1998. IEEE. All rights reserved.

Different cases of ground fault currents had to be considered in our design. These considerations were made when designing our grounding system in CDEGS.

Ground conductor

In designing a grounding system, conductor sizing must be calculated and optimized. It should be noted that copper is commonly used, but copper-clad steel is also used in higher-security situations. Ground conductor was sized using

Equation 9.10

$$A_{kcmil} = I \frac{197.4}{\sqrt{\left(\frac{TCAP}{t_c \alpha_r \rho_r}\right) \cdot \ln\left(\frac{K_o + T_m}{K_o + T_a}\right)}}$$

Where:

I	=	rms fault current in kA
A_{kcmil}	=	Area of conductor in kcmil
T_m	=	Maximum allowable temperature in °C
T_a	=	Ambient temperature in °C
T_r	=	Reference temperature for material constants in °C
α_o	=	Thermal coefficient of resistivity at 0°C in 1/°C
α_r	=	Thermal coefficient of resistivity at reference temperature T_r in 1/°C
ρ_r	=	Resistivity of the ground conductor at reference temperature T_r in μΩ-cm
K_o	=	$1/\alpha_o$ or $(1/\alpha_r) - T_r$ in °C
t_c	=	Fault current duration in seconds
$TCAP$	=	Thermal capacity per unit volume from Table 9.2, in $J/(cm^3 \cdot {}^\circ C)$

Using information supplied but Burns & McDonnell and after consulting IEEE 80, we optimized the conductor sizes for the substation.

Safety considerations

When performing a grounding study, several safety standards must be met. IEEE 80 defines tolerable limits of body currents, shock situations, and touch and step voltages. Among other resources, the figures included in the IEEE 80 manual were useful when creating our design.

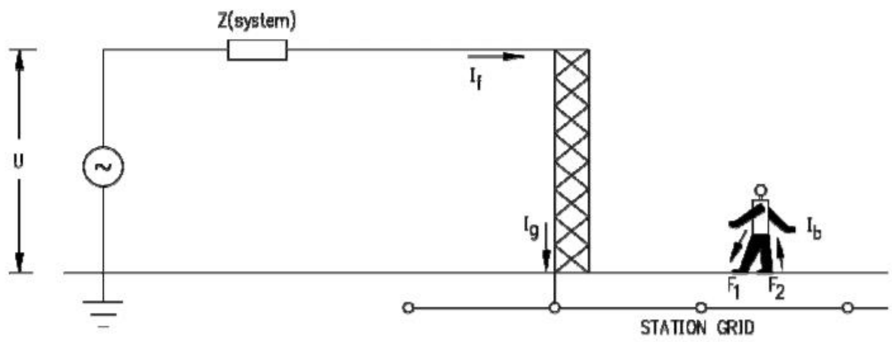

FIGURE 9.33: Exposure to Step Voltage. Ref. IEEE Std. 80, Draft 13, June 19, 1998, Figure 7-4.

Design of substation ground system

Following the collection of all data, the grounding system could be designed. During this process, we used the Substation Design Guide provided to us by Burns & McDonnell, which included 16 steps that were to be followed in order to produce a functional design.

IEEE 80: Guide for Safety in AC Substation Grounding

IEEE 80 was referred to throughout our grounding study. Equations, images, and definitions were used throughout the study and aided us in our system design.

2.2 Design Analysis

A major component that the substation design team has been concerned about is efficiency. We want to ensure that the design is done accurately but also is done in the most cost-effective way. We have tried to incorporate this in the grounding study. This grounding study is done using the CDEGS software. As a starting point, we made the copper conductors 30 feet apart, but after running the simulation, we determined that this ground grid is too conservative and too costly. We then have to redesign the ground grid and determine the maximum distance that can be used for the design to still pass. We will incorporate this trial and error process with all of the software that we use as well as with various other design aspects to ensure that we find the most efficient way to design the substation.

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

3 Testing and Implementation

3.1 Interface Specifications

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

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

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

3.2 Hardware and software

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

Specifically, CDEGS is a software program used in a grounding study. The engineer is responsible for going to the site location selected for the substation to be built upon and collecting soil resistivity values using probes and a multimeter. The Wenner method is used in our approach. This method obtains soil resistivity values across the diagonal of the substation site. These values are then plugged into CDEGS RESAP program to create a soil model. The

RESAP tool creates a model that shows the different layer in the soil. These layers show how much current is absorbed in the earth at the site of the substation.

Another important study that our project requires is a lightning study. Like the grounding study, the lightning study observes the substation layout in regards to ensuring the safety of the substation, but in this case, it is more conscious of the safety of the equipment. The Rolling Sphere method is used as the approach in our study. A software called WINigs is used to examine the pre-designed substation layout. A simple explanation of the programs main task is to ensure that there are enough masts, towers, or dead-end structures in place to ensure that if lightning strikes over the substation, the strike will hit the highest points in the substation, absorbing the shock into the Earth, as opposed to the lightning striking the expensive equipment such as breakers or transformers.

3.3 Functional Testing

A grounding plan is designed prior to the grounding test based off of client templates and uploaded into the CDEGS MALZ program. 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.

3.4 Non-Functional Testing

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

3.5 Process

Section 2 Testing Methods

The grounding study and design of the site's grounding grid each had their own unique checks and balances. The main check for our calculations from the equation's listed in **Section 2.1**, is CDEGS.

Soil Resistivity Measurements
The parameters needed to solve this equation were supplied to us by Burns & McDonnell for another substation site that met all requirements. We have not yet received the parameters for Cyclone substation. Once received, we will measure the percent difference between our Clients parameters and for the Cyclone Substation.

Area of the ground grid
Generally, we would design the largest ground grid possible. Since cost optimizations were considered, we decided to run our tests using a rectangular ground grid that measures 30 ft x 30' with distances between inner lines. These decisions were based off reports from CDEGS after running a combination of possibilities. But, after consulting with our clients, we decided that 30 ft x 30 ft ground grid was too conservative. We ended up with a ground grid of 40 ft x 40 ft.

Ground fault currents
By taking Figure 9.2 into consideration, one can calculate by hand, the ground fault currents. To eliminate human error and time wasted we ran this simulation, given parameters from Burns & McDonnell, on CDEGS.

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

Safety considerations
When performing a grounding study, safety considerations defined by IEEE 80 standard must be met. The standard defines tolerable limits of body currents, shock situations, and touch and step voltages. This was tested during our CDEGS simulation.

Under **Section 2.2 Design Analysis** we discussed about the importance of efficiency when designing the substation. One way to efficiently design the ground grid is with the CDEGS software. We found this to be a much more efficient solution instead of computing it all by hand. We will keep this in mind when moving forward with the rest of our design elements. Computer software proves to be much more cost efficient and the ability to redesign one component without having to recalculate everything.

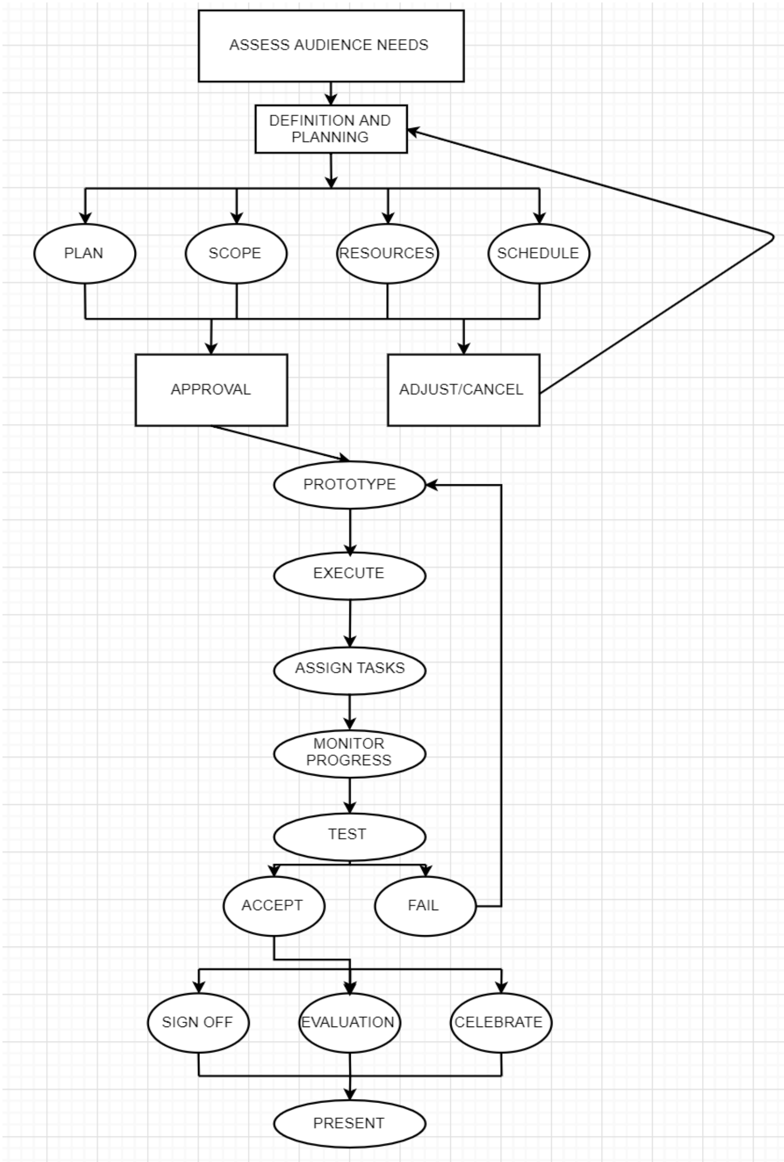

Figure 1: Flow Diagram of the Process

3.6 Results

Failures

As mentioned in **Section 3.5** our only failure was during our first simulation of the ground grid. After running the CDEGS simulation using a 30 ft x 30 ft ground grid, we did not get the results that were industry standard. After consulting with our clients, we came to the conclusion to increase the ground grid size to 40 ft x 40 ft.

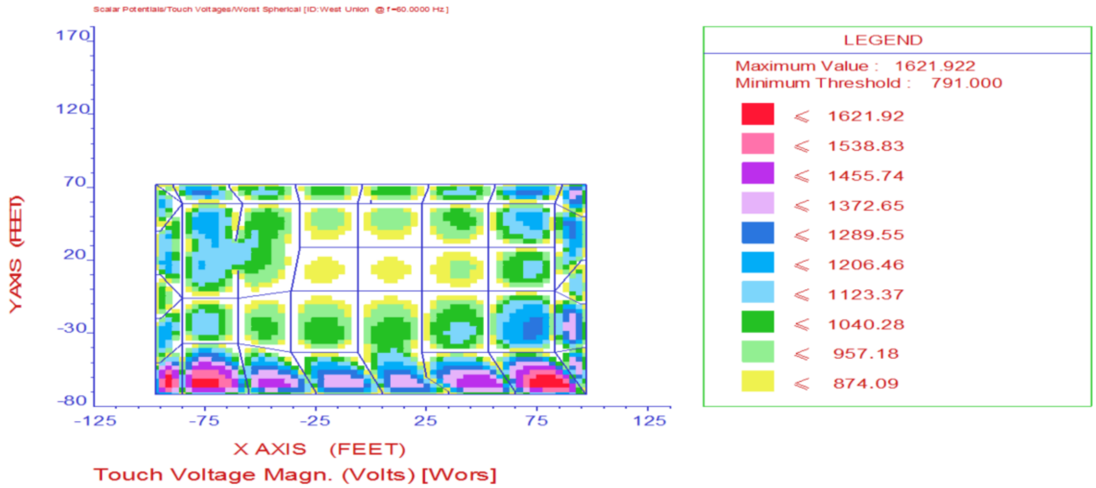

Figure 2: CDEGS Initial Failure Report

Success

After initial failure, our clients suggest we try a larger ground grid. We tried one of 40’ x 40’. Which yielded a PASS.

```
===========< 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 ..............:   106
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...........:   11070.     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..:     3870.253     Volts
                                      Angle.:     2.263500     degrees

Impedance of Grounding System.........Magn..:    0.1842978     Ohms
                                      Angle.:     2.263500     degrees

End of Report #1
```

Figure 3: CDEGS Passing MALZ Report

```
Report #1:

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

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


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


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


End of Report #1
```

Figure 4: CDEGS Passing RESAP Report

What we Learned

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

Implementation Issues and Challenges

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

4 Closing Material

4.1 Conclusion

For this project, we have done an extensive amount of research on substation design. This research will allow us to move forward with the design of the substation. So far, we have begin work on our grounding study. During this study and throughout the entire substation design, we want to ensure that we keep cost in mind. When completed, our substation will serve as a means of interconnection between a new wind generation plant being constructed outside of Ames, IA and the pre-existing transmission system. This substation will raise or lower the voltage of the electric power flowing into the substation.

4.2 References

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

4.3 Appendices