Poly Canyon Cogeneration System

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Abstract

This senior project focuses on the simulation of the Cal Poly – Poly Canyon Cogeneration facility using SKM. The purpose of this project is to model the cogeneration system in the SKM software so theoretical calculations and analysis can be executed. This required an ample amount of research of the facility, collecting data about the cogeneration facility, a deep understanding of one-line diagrams, and efficiently learning the SKM software to produce an adequate model of the system. The data was obtained and examined from the Cal Poly facility offices. The cogeneration facility was simulated with a power systems analysis program called SKM, which was provided by a lab room in the electrical engineering building. The analysis performed on the overall system included a load flow study, a fault analysis, and an arc flash evaluation. With the results of the SKM software, the engineers working in the facility department can use this data for future improvements to the system. Improvements that could be made include adding protective devices at areas that are susceptible to faults, figuring out future power flow conditions, and using arc flash data to make the system safer. After project completion, I learned about power system design and protection in the fundamental form. I also learned how to isolate faults using protection devices. Additionally, this project has provided me with real-world knowledge in terms of power system design, and a better understanding of devices such as transformers, motors, and most importantly, generators. This project has also helped me learn the powerful SKM software that is used in the industry today for power system design.

Introduction

Creating a power system to provide energy to the community is very intricate. It is comprised of parts including generation, transmission and distribution. For this project, the focus is on generation and minor transmission, and the design implemented for the generators themselves. When creating a power system, the most important concerns involve safety, reliability, efficiency, and cost. Designing a power system on a computer software program—such as SKM—allows engineers to consider all of these factors. Using the analysis of the load flow data, the engineers can determine the efficiency of the system by identifying how much power is at each load. From there, engineers can determine if anything needs to be added or removed, thus making the system more reliable and cost effective. Using fault analysis addresses the issue again of reliability; the analysis can determine how the system will respond to certain types of faults. Using arc flash evaluation, the concerns of safety are addressed, giving technicians information on how they should go about working on the equipment if a fix is needed. A power system that is designed properly will address the issues of safety, reliability, efficiency, and cost. The importance of having continuous power without failure is vital to everyone.

Background

The Poly Canyon Village cogeneration system was designed in 2006 and completed in 2009. It is a 500 kW system comprised of two 250 kW Stowell synchronous generator power units running at 480 V 3-phase. These generators run using natural gas fired reciprocating engines manufactured by Man. This cogeneration system is expected to produce 1,900,000 kWh of electricity per year, enough to power about 170 average homes. The system also provides space heating, domestic hot water, and heating for a student recreation swimming pool. The Poly Canyon Village itself has housing for up to 2700 students.

Modes of Simulation

When designing a power system, there are three main types of analysis conducted once the system is designed.

Fault analysis is a tool that provides engineers the ability to address reliability issues of the power system. A fault is defined as a short circuit within the system that causes the system to fail. The two main types of faults are symmetrical and asymmetrical. Symmetrical faults are defined when all three phases of the transmission line are short-circuited. Symmetrical faults are uncommon in the environment. The most common are Asymmetrical faults; these consist of line-to-line, single-line to ground, and double-line to ground faults. These faults are shown in the figure below.

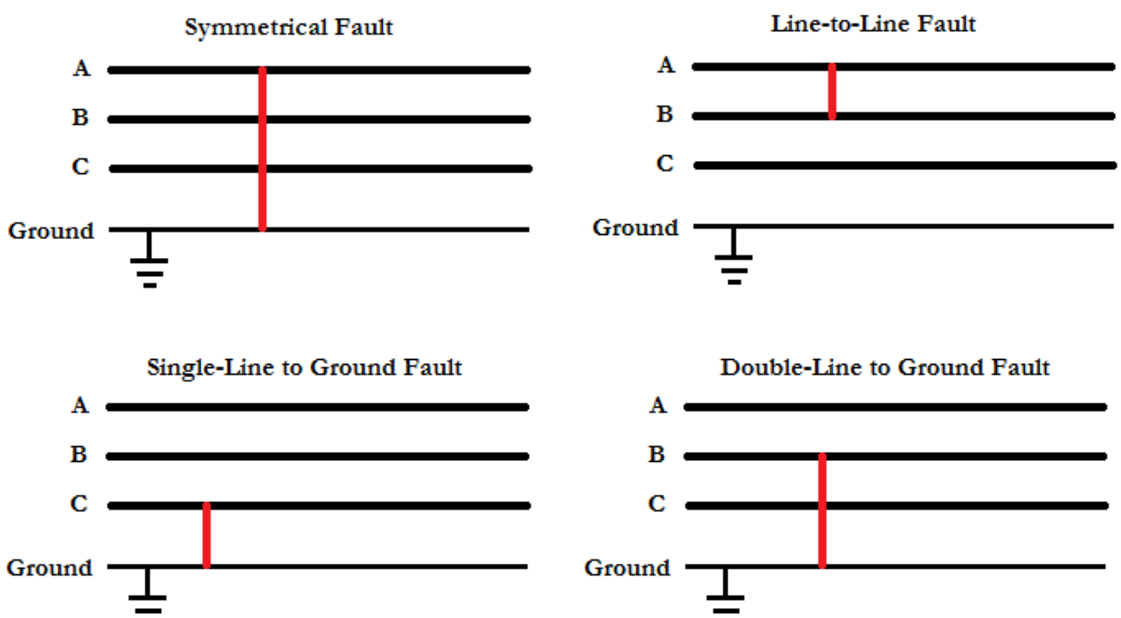

Figure 1: Symmetrical and Asymmetrical Faults

Load flow study shows how power is used and delivered within the power system. Understanding how power is used and delivered gives engineers options on how to prevent

a device from overloading and failing. This study is helpful in overall reliability of the system. For this project, a load 380 kW is used instead of a utility source in order to show the two generators running at nearly full load.

Arc flash is an electrical surge that results from a low impedance connection to ground. Arc flash evaluation is important for the safety of technicians as they may end up working on or near the equipment. A technician can provide a low impedance path to ground and cause and arc flash. This can lead to serious injury or death. The arc flash evaluation gives technicians information on how long it takes to clear an arc flash as well as what clothing should be worn when working near the equipment.

Materials and Requirements

The requirement of this senior project is to accurately model the Poly Canyon Cogeneration System. This is focusing on the electrical side of the generation only, not the heat generation. Not all information was found for each specific device. This is purely a design project; the materials consist of elements that are used in the SKM program. These elements are listed below:

- Synchronous Generators: 2
- Transformers: 1
- Buses: 12
- Synchronous Motors: 5
- Motor Overload: 2
- Loads: 1
- Cables: 9
- Switches: 10
- Fuses: 2
- Utility: 1

Research

The research needed to complete this project required attaining a broad range of data from the facilities department. The facilities department building has data for every building in Cal Poly. This is where the one-line diagrams were obtained for the Poly Canyon cogeneration room. In addition, Cal Poly meters the demand for every building, but unfortunately, these records were unavailable for the Poly Canyon cogeneration room. This was due to a facility department member's unavailability to show these records. Therefore, the load flow analysis of my report cannot be compared to actual data. In addition, devices such as radiator units, battery chargers, glycol solution units, and some switchboard devices were not included. This was due to either insufficient information about performance and part numbers or information not relating to the electrical generation side of this project.

This project's purpose for the load flow analysis was captured by setting the two generators near their full load capability. This was done to see the close-to-maximum power that the generators could output. This output power can then be used by Cal Poly or distributed to the utility (PG&E). Please Refer to Appendix C for the load flow analysis for the cogeneration system.

Impedances and cable data were also obtained through the facilities department. The database provided the type and size of each cable. Although the length of all cables were not attainable, it was safe to assume no cable was longer than ten feet due to the compact room size of the cogeneration system. Cable data that could not be acquired was applied through SKM.

Transformer data was obtained from the one-line diagrams. The kVA ratings, turn's ratio, and the type of connection (Delta, Wye, or Wye-to-ground) were given within the one-line diagrams.

Fuse data was limited to the maximum amperage the fuse could withstand. As for the switches, no useable information was found.

Specifications for the motors were found in the Poly Canyon Cogeneration data books. These included horsepower rating, RPM, minimum efficiency, and leading or lagging power factor.

Generator data was found from the one-line diagrams as well as the data books. This data included power rating, voltage rating, RPM, efficiency, and leading or lagging power factor.

Design

Once the initial data was acquired, the next part of the project was to design and implement the Poly Canyon cogeneration system. Based on my past software experience, my original thought was to choose either PowerWorld or ETAP to design and build my project. However, I was advised to try out the SKM software by my project advisor. The SKM software was also accessible through the Cal Poly system, and was installed in a few lab rooms.

The SKM software initially seemed demanding, but after reading tutorials and watching videos found on the SKM website, http://www.skm.com/af.shtml, the process of designing became simpler. SKM is much like ETAP as far as user interface; both allow the ability to make quick connections and have a large library of devices and part numbers. For someone who has never used a power system program before, SKM offers quick and easy learning of the software.

The layout design for this power system was kept close to the one-line diagrams offered by the facilities department. That way, if any changes did need to be made in the future, the facilities department could easily find a specific part or device they are looking for. The original one-line diagram can be found in Appendix A – Figure 6, this is one of the one-line diagrams that was achieved from the facilities department. The final SKM layout of my design can be found in Appendix A – Figure 7. Again, some devices were not included due to the fact the information about them was unattainable or did not serve purpose in the electrical design.

The design started with the two synchronous generators. This is the most important part of the design because these generators are what create the electrical power. The one-line diagram for the generator from the facilities department shows many components within it.

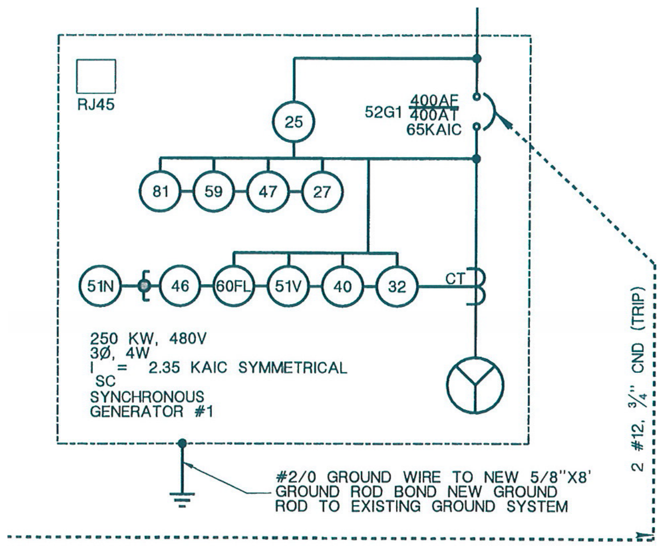

Figure 2: Generator One-Line Diagram

There are many devices other than the synchronous generator. These devices are all labeled in Appendix B. The numbers on these devices signify a certain type of protection device and are following the ANSI device numbers. The name and number of these parts can be found on, http://en.wikipedia.org/wiki/ANSI_Device_Numbers. Implementing all of these devices individually would take much longer to design; therefore, I will discuss what these devices do to protect the generator.

Starting from the synchronous generator, the line first hits a device CT, which stands for current transformer. The current transformer isolates the protection and measuring devices from what can be very high voltage in the monitored circuit. This is then connected to 32, 40, 51V, 60FL, 46, and 51N. 32 is a directional power relay, this protects the generator from motoring. 40 is a field relay, it monitors the magnitude of excitation by measuring the relationship between the voltage and the frequency. 51V is a voltage restrained overcurrent

relay, this protects the system by limiting the voltage if a certain amount of current is exceeded. 60FL is a voltage or current balance relay, it controls the amount of current or voltage flow. 46 is a phase balance current relay, it is used to detect phase loss and unbalance within the system. 51N is a neutral inverse time relay, this allows overload currents that occur during operation, but does not allow loading of lines and equipment.

Above this line of protection, we have 27, 47, 59, and 81. 27 is an undervoltage relay, this keeps machinery from starting automatically when incoming power is restored after a power outage, or when incoming power is too low. 47 is a phase balance voltage relay, it is used to keep phase voltages balanced. 59 is an over voltage relay, this protects the system when an incoming voltage is too high. 81 is a frequency relay, it functions when a predetermined frequency value is met.

Finally, at the top of the protection devices we see a 25 in parallel with a 52G circuit breaker. 25 is a synchronizing check device, this checks to make sure the generator is in phase with whatever it is supplying power to. For example, the generator phase must match the phase of the utility (PG&E). 52G is an AC circuit breaker, this protects the generator if there is an overload or short circuit.

The generators are connected with a cable and protective switch to BUS-0001. The cable's specifications were listed on the one-line diagram, but SKM provides libraries to find typical values of standard cables. The data was consistent with the one-line diagram data. The cable length and wire size varied depending on the design. BUS-0001 is connected to two synchronous motors along with protective devices for each. BUS-0001 is then connected to BUS-0007. BUS-0007 is connected to three motors, each with protective devices. BUS-0007 is then connected to a transformer that leads to BUS-0012. The SKM libraries also helped with transformer design. The impedance values were estimated based on

if the transformer was oil air, forced air, or dry. The one transformer used in the design was a Dry type. Finally, BUS-0012 would normally be connected to the utility (PG&E), but was connected to a 380 kW load for the load flow analysis.

SKM delivers a list of key features helping engineers to efficiently design a power system. One of these features included marking a device with a title of "Incomplete" or "Complete." This is helpful if an engineer needs to come back to this device given he or she does not have the sufficient specifications for the device. When the status of a device is "Incomplete," it turns to a different color, thereby notifying the engineer that this specific device requires more information. Another feature was marking a device either "In Service" or "Out of Service." This helps when needing to turn off specific devices or branches in order to test a part of one's system. Once the layout in SKM was complete, the analysis could be started. *Errors in the design will become apparent during the analysis and will be addressed in the following two sections.*

Analysis

There are three types of analysis that were performed on the Poly Canyon cogeneration system: load flow analysis, short circuit (fault) analysis, and arc flash evaluation. This was done within SKM by selecting “Balanced System Studies” from the menu. Then selecting “Demand Load,” “Load Flow,” and “Short Circuit.” The “Arc Flash Evaluation” had to be selected separately under the menu. SKM then ran all the studies and notified me of errors and warnings. Once my simulation was complete and the warnings and errors corrected, the final study for this project was performed. It must be noted that although the system produced no errors, this does not suggest that the system is constructed correctly. This system shows errors in the form of syntax, but this does not show possible real life errors.

Once the studies were complete, selecting “data block format” gives the ability to show the data for load flow, bus fault currents, and arc flash. The load flow data blocks are shown in Appendix A – Figure 8. These data blocks are helpful for troubleshooting purposes and can provide visual results of the tasks the program is performing. SKM also generates reports that organize the data for each study. This data has been converted into tabular form in Appendices C, D, and E for load flow, short circuit, and arc flash, respectively.

During the analysis for generating load flow, the data blocks on SKM one-line diagram helped me analyze my errors in the design. Once I had completed my design, I noticed that one of my errors was that the power was being fed back into the system due to the infinite bus created by the utility (PG&E). This was obviously incorrect so instead of

creating a utility, I made a 380 kW load where the utility would be. This shows the actual power leaving the cogeneration system when the generators are operating near full load. Having designing the whole power system before testing each segment after it was created, led to many initial errors that could have been avoided. This made for a good learning experience, the next time I use this program I will isolate different sections of the power system and test each one separately. Using the "In Service/Out of Service" feature mentioned in the design section, I isolated different sections of my project and started correcting errors.

Results

Load Flow

The data that is most important for load flow analysis is the voltage drop across each bus. SKM calculates the percentage voltage drop (%VD), this is done by dividing the design voltage by the load flow. The voltage drops within the whole system varied between 0.02% to 12.83%. The highest voltage drop was across the BUS-0012, which is the last bus before the power is outputted to the utility; in my design's case, the power being absorbed by the load. This is a flaw in my design because this does not give an accurate real life measurement of the load flow to the utility because the voltage drops significantly when transferring the power to the load. The lowest voltage drop was on CBL-0009, this is the cable before the transformer before BUS-0012. The voltage drop here is low because the cable is simply transferring the power to a transformer, there is no load bearing on the cable other than the cable itself.

The largest amount of power flow is recorded through CBL-0005 at 408.6 kW. This makes sense because at this point in the system it is power has only been used up by two other motors, and the rest is being sent toward BUS-0007. The smallest voltage drop is 8.4 kW for each of the ½ horsepower motors attached to BUS-0007. This is believable since the motors only require ½ horsepower and is the smallest load in this design. All the data for the load flow analysis can be found in Appendix C.

Short Circuit (Fault) Analysis

The data for the fault analysis shows both symmetrical and asymmetrical fault occurrences. The data that I have provided shows a 3-Phase fault (symmetrical) along with Single-Line to Ground fault (asymmetrical). Faults currents are shown for each of the three primary buses including: BUS-0001, BUS-0007, and BUS-0012.

Starting with the 3-Phase symmetrical fault, the largest initial system RMS fault current was 5417.3 Amps < -87.0^{o} at BUS-0001. Where the smallest RMS fault current was at BUS-0012 at 164.5 Amps < -55.0^{o}, this is due to the much higher bus voltage compared to BUS-0001 and BUS-0007. Since these were 3-Phase faults, the phase angle between each was equally 120^{o}.

The single-line to ground asymmetrical fault is more important than the 3-phase fault because it is more likely to happen. Again the largest initial system RMS fault current was at BUS-0001 with 7292.3 Amps < -86.0^{o}. Although the RMS fault current at BUS-0012 was 0.0 Amps < 30^{o}. This is because the thevenin equivalent impedance becomes infinite therefore no current will be able to pass through. The data also supplies phase currents for each phase, and it is noted that one phase always will have zero current due to the single line to ground fault.

Arc Flash Evaluation

The arc flash evaluation is only evaluated on the three buses of the power system. This makes for a very general study without any particulars. The largest arc flash was found at BUS-0012 to be 36 inches. This makes sense because it has the highest voltage of the three buses. The most important information taken from the SKM program is the recommended personal protective equipment. This is specifications for the technicians on what type of clothing to wear when operating on or near this device. A warning can be printed out of each bus with the suggested precautions. An example of this is shown below for each of the three buses.

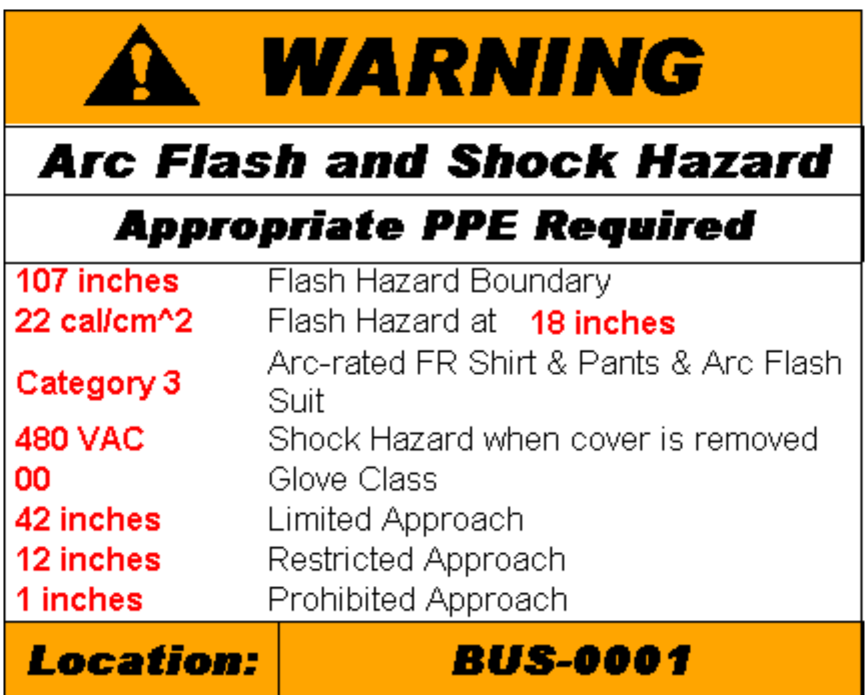

Figure 3: Arc Flash for BUS-0001

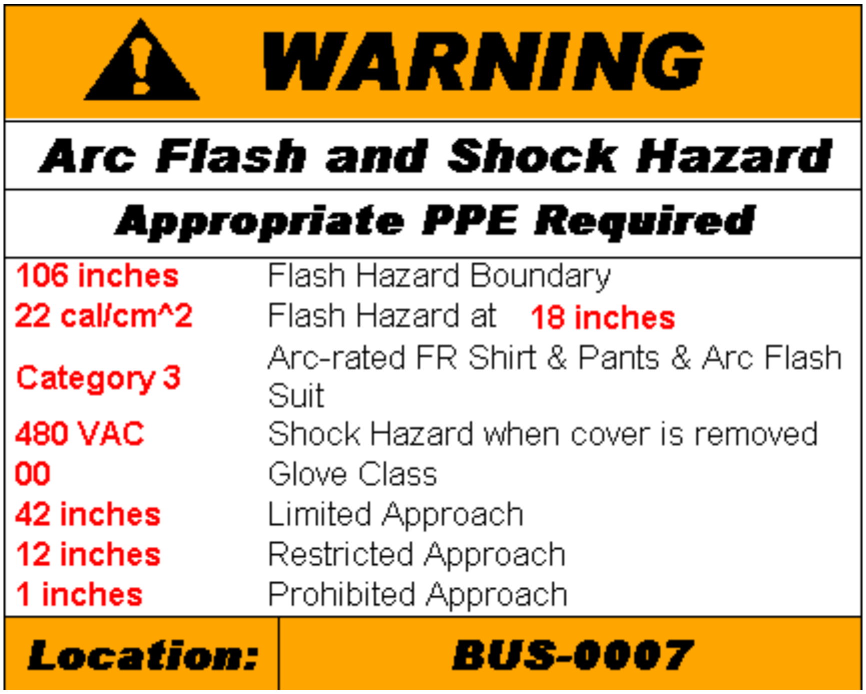

Figure 4: Arc Flash for BUS-0007

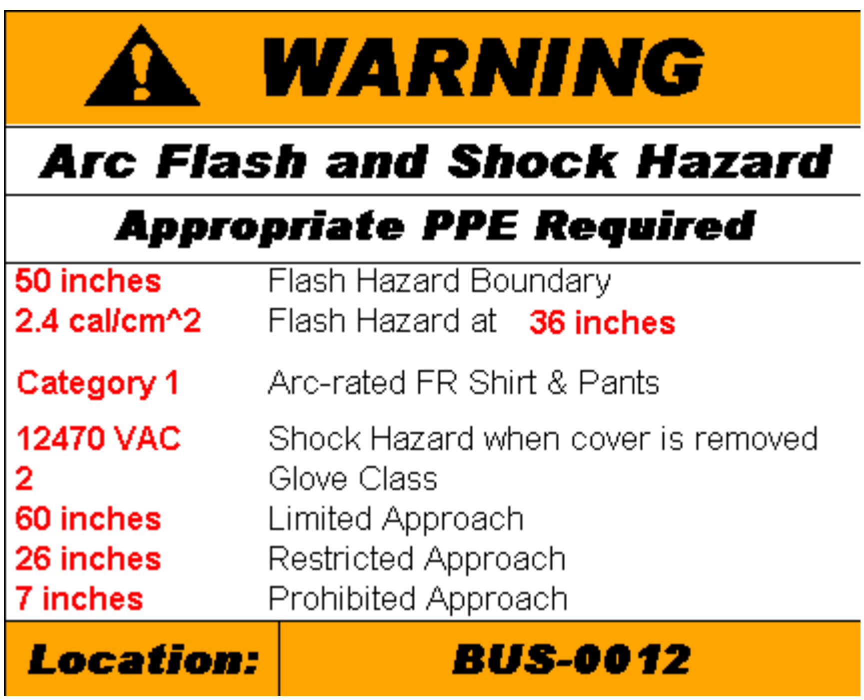

Figure 5: Arc Flash for BUS-0012

Conclusion

For this senior project, the majority of my efforts went into designing the Poly Canyon Cogeneration System accurately and efficiently as I could. To do this, extensive research and understanding of one-line diagrams were necessary; along with the knowledge on how to design with the SKM software equipment. Although there are some errors with the final results, the experience of the project proved to be both educational and beneficial. The load flow results show where the highest voltage drops within the system are, and where the power is being distributed. While some major losses are still present, I believe the design in SKM accurately represents the necessary components in the Poly Canyon Cogeneration System to the best of my ability. There is much room for improvement, especially on the mechanical engineering side; this is further explained in the next section. The most important skill I have learned from the completion of my senior project was how to analyze one-line diagrams effectively and use the SKM software to model a power system. These tools and skills can be applied in the future when working for a utilities or building design company.

Future Work

I believe my work can be used in the future to further expand the entire Cal Poly system. Since all the data and design of my project is complete, a future student can build off the design or further break down the Poly Canyon Cogeneration system. For example, a mechanical engineer could do an analysis of the heat energy created by the cogeneration system. In addition, my project introduces device protection, one can take their project deeper and further examine these protection devices. Additionally, the SKM software can be used as a teaching tool in power related courses. Students can perform hand calculations and then compare with the SKM software.

Citations

"Welcome to SKM Systems Analysis, Inc." *SKM Systems Analysis, Inc. - Power System Software and Arc Flash Hazard Analysis and Design Solutions*. Web. 15 June 2011. <http://www.skm.com/af.shtml>.

"ANSI Device Numbers." *Wikipedia*. 11 July 2011. <http://en.wikipedia.org/wiki/ANSI_Device_Numbers>.

Appendix A – Poly Canyon Cogeneration One Line Diagram

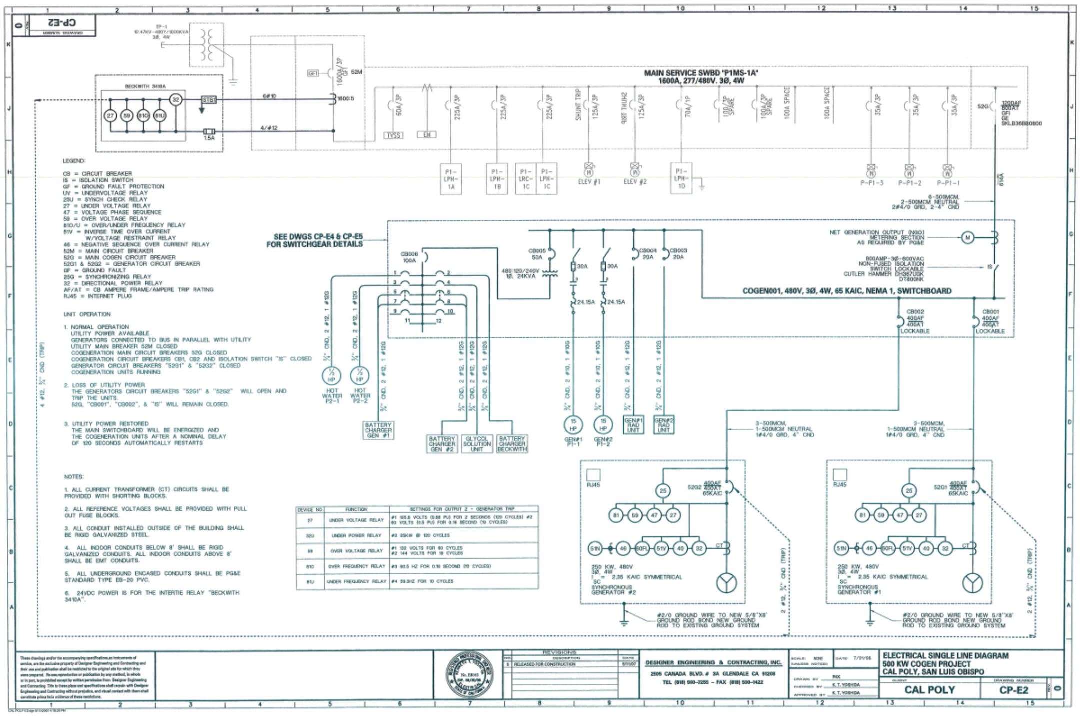

Figure 6: Cal Poly Cogeneration One-Line Diagram (Actual)

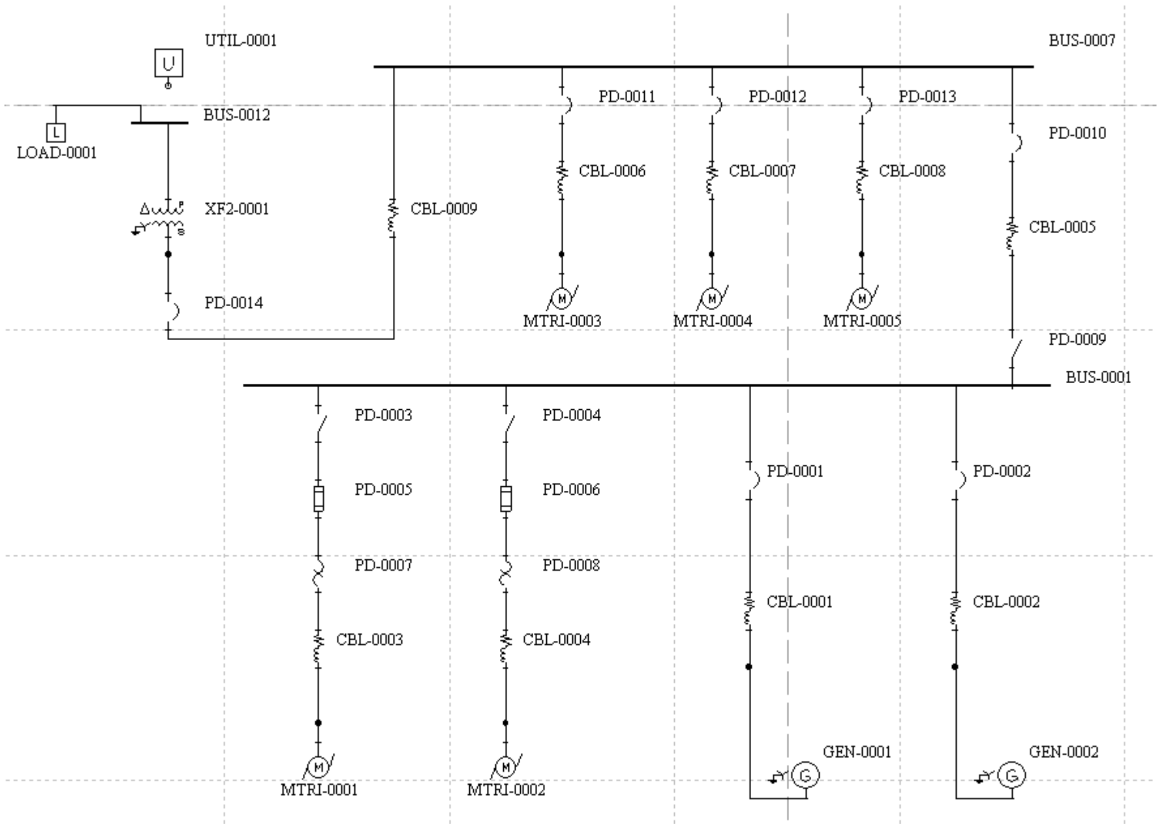

Figure 7: Cal Poly Cogeneration One-Line Diagram (SKM Design)

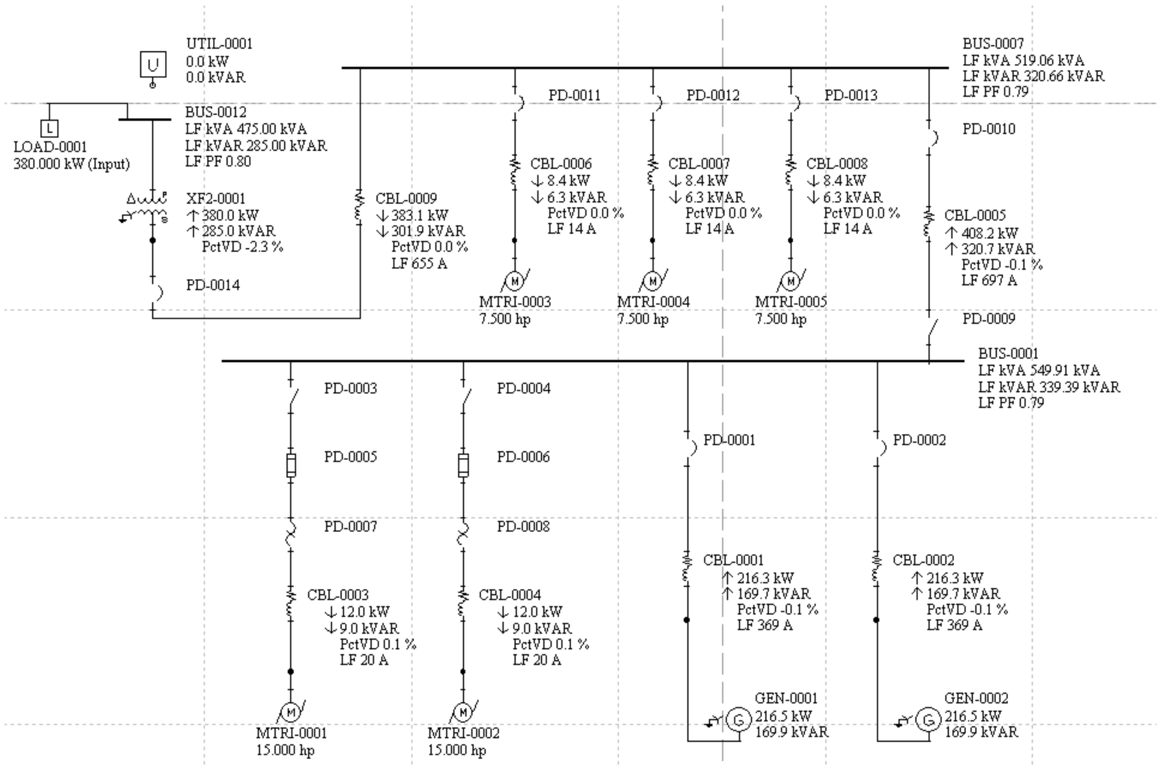

Figure 8: Cal Poly Cogeneration One-Line Diagram (SKM with Datablocks)

Appendix B – Component Legend

Figure 9: Synchronous Generator

Figure 10: Synchronous Motor

Figure 11: Bus

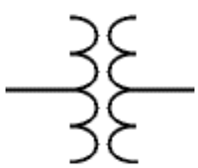

Figure 12: Transformer

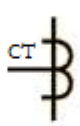

Figure 13: Current Transformer

Figure 14: Circuit Breaker

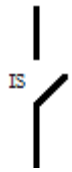

Figure 15: Isolation Switch

Figure 16: Fuse

Figure 17: Motor Overload

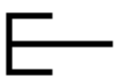

Figure 18: Utility

Figure 19: Starter Motor

Figure 20: Ground

Figure 21: Synchronizing Check Device

Figure 22: Undervoltage Relay

Figure 23: Directional Power Relay

Figure 24: Field (over/under excitation) Relay

Figure 25: Phase-Balance Current Relay

Figure 26: Phase-Balance Voltage Relay

Figure 27: Neutral Inverse Time Relay

Figure 28: Voltage Restrained Overcurrent Relay

Figure 29: Overvoltage Relay

Figure 30: Voltage or Current Balance Relay

Figure 31: Frequency Relay

Figure 32: Over Frequency Relay

Figure 33: Under Frequency Relay

Appendix C – Load Flow Analysis

Note: These values are based on a 380 kW load shown in Figure 7 instead of a utility source to find near maximum load flow.

Table 1: Swing Generators Design

Source	*Voltage (Per Unit)*	*Angle (Degrees)*	*Power (kW)*	*Reactive Power (kVAR)*	*%VD*	*Utility Impedance*
GEN-0001	1.0	0.0	216.46	169.89	10.29	2.4 + j48.0
GEN-0002	1.0	0.0	216.46	169.89	10.29	2.4 + j48.0

Table 2: Main Buses Design

Main Bus	*Design Volts (V)*	*Bus Volts (V)*	*%VD*	*Bus Voltage (Per Unit)*	*Angle (Degrees)*
BUS-0001	480	430	10.36	0.896	-6.4
BUS-0007	480	430	10.49	0.895	-6.4
BUS-0012	12470	10871	12.83	0.872	-7.8

Table 3: Balanced Load Flow (Buses and Cables)

Load	*Feeder Amps*	*%VD*	*Projected Power Flow*				*Losses Through Feeder*		
			kW	kVAR	kVA	PF	kW	kVAR	kVA
BUS-0002 CBL-0001	368.9	0.07	-216.3	-169.7	275.0	0.79 lagging	0.1	0.2	0.2
BUS-0003 CBL-0002	368.9	0.07	-216.3	-169.7	275.0	0.79 lagging	0.1	0.2	0.2
BUS-0006 CBL-0003	20.2	0.07	12.0	9.0	15.1	0.80 lagging	0.0	0.0	0.0
BUS-0005 CBL-0004	20.2	0.07	12.0	9.0	15.1	0.80 lagging	0.0	0.0	0.0
BUS-0007 CBL-0005	697.5	0.13	-408.6	-321.3	519.8	0.79 lagging	0.4	0.7	0.8
BUS-0001 CBL-0005	697.5	0.13	-408.2	-320.7	519.1	0.79 lagging	0.4	0.7	0.8
BUS-0008 CBL-0006	14.0	0.05	8.4	6.3	10.4	0.80 lagging	0.0	0.0	0.0
BUS-0009 CBL-0007	14.0	0.05	8.4	6.3	10.4	0.80 lagging	0.0	0.0	0.0
BUS-0010 CBL-0008	14.0	0.05	8.4	6.3	10.4	0.80 lagging	0.0	0.0	0.0
BUS-0011 CBL-0009	655.4	0.02	383.1	301.9	487.7	0.79 lagging	0.1	0.1	0.1

Table 4: Balanced Load Flow (Bus and Transformer)

Load	*XF Amps*	*VD, %VD*	*Projected Power Flow*				*Losses Through Transfer*			*Branch Diversity Load*	
			kW	kVAR	kVA	PF	kW	kVAR	kVA	kW	kVAR
BUS-0011 XF2-0001	25.2	-288, -2.31	-380.0	-285.0	475.0	0.8 lag	3.0	16.8	17.1	380.0	285.0

Table 5: Balanced Load Flow Bus Data Summary

Bus Name	*Base Voltage (V)*	*Per Unit Voltage*
BUS-0001	480	0.8964
BUS-0002	480	0.8971
BUS-0003	480	0.8971
BUS-0005	480	0.8957
BUS-0006	480	0.8957
BUS-0007	480	0.8951
BUS-0008	480	0.8946
BUS-0009	480	0.8946
BUS-0010	480	0.8946
BUS-0011	480	0.8949
BUS-0012	12470	0.8717

Table 6: Balanced Load Flow Branch Data Summary

Branch Name	*From Bus*	*To Bus*	*Type*	*%VD*	*Amps*	*kVA*	*Rating %*
CBL-0001	BUS-0001	BUS-0002	FDR	-0.07	368.94	274.96	85.80
CBL-0002	BUS-0001	BUS-0003	FDR	-0.07	368.94	274.96	85.80
CBL-0003	BUS-0001	BUS-0006	FDR	0.07	20.20	15.05	67.32
CBL-0004	BUS-0001	BUS-0005	FDR	0.07	20.20	15.05	67.32
CBL-0005	BUS-0007	BUS-0001	FDR	-0.13	697.50	519.06	162.21
CBL-0006	BUS-0007	BUS-0008	FDR	0.05	14.03	10.44	46.78
CBL-0007	BUS-0007	BUS-0009	FDR	0.05	14.03	10.44	46.78
CBL-0008	BUS-0007	BUS-0010	FDR	0.05	14.03	10.44	46.78
CBL-0009	BUS-0007	BUS-0011	FDR	0.02	655.40	487.73	40.96
XF2-0001	BUS-0012	BUS-0011	TX2	-2.31	25.23	475.00	47.38

Total System Losses: 4.0 kW 18.0 kVAR

Appendix D – Short Circuit (Fault) Analysis

Note: All Per Unit Values are expressed on a 100 MVA Base.

Table 7: Swing Generators in Per Unit

Source Name	*Voltage*	*Angle*
GEN-0001	1.0	0.0
GEN-0002	1.0	0.0

Table 8: Pre-Fault Voltage Profile

BUS Name	*Base Volts*	*Per Unit Volts*	*Angle (degree)*
BUS-0001	480.0	1.0	0.0
BUS-0002	480.0	1.0	0.0
BUS-0003	480.0	1.0	0.0
BUS-0005	480.0	1.0	0.0
BUS-0006	480.0	1.0	0.0
BUS-0007	480.0	1.0	0.0
BUS-0008	480.0	1.0	0.0
BUS-0009	480.0	1.0	0.0
BUS-0010	480.0	1.0	0.0
BUS-0011	480.0	1.0	0.0
BUS-0012	12470.0	1.0	30.0

Three Phase Fault at BUS-0001

Table 9: Bus-0001 Pre Report (3P)

Voltage Base LL	480				
Initial System RMS Fault Current (Amps/Deg)	5417.3 < -87.0				
Thevenin Equivalent Impedance (PU)	1.253 + j22.168				
Thevenin Impedance X/R Ratio	17.685				
Asymmetrical RMS Interrupting Amps	.5 cycle	2 cycles	3 cycles	5 cycles	8 cycles
	8395.8	6596.8	6025.8	5570.3	5435.6
Initial System RMS Faulted Bus Voltages (PU/Deg) (at .5 Cycles)	Phase A	Phase B	Phase C		
	0.0 < 0.0	0.0 < 0.0	0.0 < 0.0		
Initial RMS Faulted Current (Amps/Deg) (at .5 Cycles)	Phase A	Phase B	Phase C		
	5417.3 < -86.8	5417.3 < 153.2	5417.3 < 33.2		

Table 10: BUS-0001 Initial System Bus Voltages (at .5 Cycles) (3P)

BUS Name	*Phase A*	*Phase B*	*Phase C*
BUS-0002	0.005 < -29	0.005 < -149	0.005 < 91
BUS-0003	0.005 < -29	0.005 < -149	0.005 < 91
BUS-0005	0.0045 < -81	0.0045 < -159	0.0045 < 39
BUS-0006	0.0045 < -81	0.0045 < -159	0.0045 < 39
BUS-0007	0.0004 < -26	0.0004 < -146	0.0004 < 94

Table 11: BUS-0001 Initial RMS System Branch Flows (at .5 Cycles) (3P)

First Bus	*From Fault*	*Branch Name*	*Vbase L-L*	*Phase A*	*Phase B*	*Phase C*
BUS-0001	BUS-0002	CBL-0001	480	2491.9 < 93	2491.9 < -27	2491.9 < -147
BUS-0001	BUS-0003	CBL-0002	480	2491.9 < 93	2491.9 < -27	2491.9 < -147
BUS-0001	BUS-0005	CBL-0004	480	106.3 < 96	106.3 < -24	106.3 < -144
BUS-0001	BUS-0006	CBL-0003	480	106.3 < 96	106.3 < -24	106.3 < -144
BUS-0007	BUS-0001	CBL-0005	480	221.0 < -84	221.0 < 156	221.0 < 36

Three Phase Fault at BUS-0007

Table 12: BUS-0007 Pre Report (3P)

Voltage Base LL	480				
Initial System RMS Fault Current (Amps/Deg)	5370.9 < -86.0				
Thevenin Equivalent Impedance (PU)	1.371 + j22.353				
Thevenin Impedance X/R Ratio	17.685				
Asymmetrical RMS Interrupting Amps	.5 cycle	2 cycles	3 cycles	5 cycles	8 cycles
	8251.3	6418.0	5878.5	5483.4	5382.1
Initial System RMS Faulted Bus Voltages (PU/Deg)(at .5 Cycles)	Phase A	Phase B	Phase C		
	0.0 < 0.0	0.0 < 0.0	0.0 < 0.0		
Initial RMS Faulted Current (Amps/Deg) (at .5 Cycles)	Phase A	Phase B	Phase C		
	5370.9 < -86.5	5370.9 < 153.5	5370.9 < 33.5		

Table 13: BUS-0007 Initial System Bus Voltages (at .5 Cycles) (3P)

BUS Name	*Phase A*	*Phase B*	*Phase C*
BUS-0001	0.0102 < -29	0.0102 < -149	0.0102 < 91
BUS-0008	0.0031 < -81	0.0031 < 159	0.0031 < 39
BUS-0009	0.0031 < -81	0.0031 < 159	0.0031 < 39
BUS-0010	0.0031 < -81	0.0031 < 159	0.0031 < 39
BUS-0011	0.0 < 0.0	0.0 < 0.0	0.0 < 0.0

Table 14: BUS-0007 Initial RMS System Branch Flows (at .5 Cycles) (3P)

First Bus	*From Fault*	*Branch Name*	*Vbase L-L*	*Phase A*	*Phase B*	*Phase C*
BUS-0007	BUS-0001	CBL-0005	480	5149.7 < 93	5149.7 < -27	5149.7 < -147
BUS-0007	BUS-0008	CBL-0006	480	73.8 < 96	73.8 < -24	73.8 < -144
BUS-0007	BUS-0009	CBL-0007	480	73.8 < 96	73.8 < -24	73.8 < -144
BUS-0007	BUS-0010	CBL-0008	480	73.8 < 96	73.8 < -24	73.8 < -144
BUS-0007	BUS-0011	CBL-0009	480	0.0 < 0.0	0.0 < 0.0	0.0 < 0.0

Three Phase Fault at BUS-0012

Table 15: Bus-0012 Pre Report (3P)

Voltage Base LL	12470.0				
Initial System RMS Fault Current (Amps/Deg)	164.5 < -55.0				
Thevenin Equivalent Impedance (PU)	2.411 + j28.036				
Thevenin Impedance X/R Ratio	11.627				
Asymmetrical RMS Interrupting Amps	.5 cycle	2 cycles	3 cycles	5 cycles	8 cycles
	242.1	182.5	170.8	165.3	164.6
Initial System RMS Faulted Bus Voltages (PU/Deg) (at .5 Cycles)	Phase A		Phase B		Phase C
	0.0 < 0.0		0.0 < 0.0		0.0 < 0.0
Initial RMS Faulted Current (Amps/Deg) (at .5 Cycles)	Phase A		Phase B		Phase C
	164.5 < -55.1		164.5 < -175.1		164.5 < 64.9

Table 16: BUS-0012 Initial System Bus Voltages (at .5 Cycles) (3P)

BUS Name	*Phase A*	*Phase B*	*Phase C*
BUS-00011	0.2043 < -5	0.2043 < -125	0.2043 < 115

Table 17: BUS-0012 Initial RMS System Branch Flows (at .5 Cycles) (3P)

First Bus	*From Fault*	*Branch Name*	*Vbase L-L*	*Phase A*	*Phase B*	*Phase C*
BUS-0012	BUS-0011	XF2-0001	480	4274.4 < 95	4274.4 < -25	4274.4 < -145

Single-Line to Ground at BUS-0001

Table 18: BUS-0001 Pre Report (SLG)

Voltage Base LL	480				
Initial System RMS Fault Current (Amps/Deg)	7292.3 < -86.0				
Thevenin Equivalent Impedance (PU)	3.598 + j49.352				
Thevenin Impedance X/R Ratio	13.718				
Sequence Equivalent Impedance (PU)	Z1		Z2		Z0
	1.253 + j22.17		1.253 + j22.17		1.091 + j5.016
Asymmetrical RMS Interrupting Amps	.5 cycle	2 cycles	3 cycles	5 cycles	8 cycles
	10974.9	8378.7	7745.2	7366.6	7297.1
Initial System RMS Faulted Bus Voltages (PU/Deg)(at .5 Cycles)	Phase A		Phase B		Phase C
	0.0 < 0.0		0.858 < -100.3		0.9012 < 99.8
Initial RMS Faulted Current (Amps/Deg) (at .5 Cycles)	Phase A		Phase B		Phase C
	7292.3 < -85.8		0.0 < 0.0		0.0 < 0.0

Table 19: BUS-0001 Initial System Bus Voltages (at .5 Cycles) (SLG)

BUS Name	*Phase A*	*Phase B*	*Phase C*
BUS-0002	0.0058 < -32	0.8581 < -100	0.9015 < 100
BUS-0003	0.0058 < -32	0.8581 < -100	0.9015 < 100
BUS-0005	0.0041 < -80	0.8561 < -100	0.9032 < 100
BUS-0006	0.0041 < -80	0.8561 < -100	0.9032 < 100
BUS-0007	0.0106 < -32	0.8619 < -100	0.8945 < 99

Table 20: BUS-0001 Initial RMS System Branch Flows (at .5 Cycles) (SLG)

First Bus	*From Fault*	*Branch Name*	*Vbase L-L*	*Phase A*	*Phase B*	*Phase C*
BUS-0001	BUS-0002	CBL-0001	480	2490.5 < 93	865.1 < -83	865.1 < -83
BUS-0001	BUS-0003	CBL-0002	480	2490.5 < 93	865.1 < -83	865.1 < -83
BUS-0001	BUS-0005	CBL-0004	480	95.4 < 97	47.7 < -83	47.7 < -83
BUS-0001	BUS-0006	CBL-0003	480	95.4 < 97	47.7 < -83	47.7 < -83
BUS-0007	BUS-0001	CBL-0005	480	2123.6 < -83	1825.6 < -83	1825.6 < -83

Single-Line to Ground Fault at BUS-0007

Table 21: BUS-0007 Pre Report (SLG)

Voltage Base LL	480				
Initial System RMS Fault Current (Amps/Deg)	7284.7 < -86.0				
Thevenin Equivalent Impedance (PU)	3.619 + j49.402				
Thevenin Impedance X/R Ratio	13.649				
Sequence Equivalent Impedance (PU)	Z1	Z2	Z0		
	1.371 + 22.353	1.371 + 22.353	0.877 + j4.696		
Asymmetrical RMS Interrupting Amps	.5 cycle	2 cycles	3 cycles	5 cycles	8 cycles
	10956.3	8360.7	7731.2	7357.3	7289.3
Initial System RMS Faulted Bus Voltages (PU/Deg)	Phase A	Phase B	Phase C		
	0.0 < 0.0	0.862 < -99.6	0.8937 < 99.3		
Initial RMS Faulted Current (Amps/Deg)	Phase A	Phase B	Phase C		
	7284.7 < -85.8	0.0 < 0.0	0.0 < 0.0		

Table 22: BUS-0007 Initial System Bus Voltages (at .5 Cycles) (SLG)

BUS Name	*Phase A*	*Phase B*	*Phase C*
BUS-0001	0.0117 < -31	0.0102 < -149	0.0102 < 91
BUS-0008	0.0028 < -80	0.8607 < -100	0.8952 < 99
BUS-0009	0.0028 < -80	0.8607 < -100	0.8952 < 99
BUS-0010	0.0028 < -80	0.8607 < -100	0.8952 < 99
BUS-0011	0.0043 < -59	0.8653 < -99	08898 < 99

Table 23: BUS-0007 Initial RMS System Branch Flows (at .5 Cycles) (SLG)

First Bus	*From Fault*	*Branch Name*	*Vbase L-L*	*Phase A*	*Phase B*	*Phase C*
BUS-0007	BUS-0001	CBL-0005	480	5121.4 < 94	1864.3 < -84	1864.3 < -84
BUS-0007	BUS-0008	CBL-0006	480	66.7 < 97	33.4 < -83	33.4 < -83
BUS-0007	BUS-0009	CBL-0007	480	66.7 < 97	33.4 < -83	33.4 < -83
BUS-0007	BUS-0010	CBL-0008	480	66.7 < 97	33.4 < -83	33.4 < -83
BUS-0007	BUS-0011	CBL-0009	480	1964.4 < 96	1964.4 < 96	1964.4 < 96

Single-Line to Ground Fault at BUS-0012

Table 24: Bus-0012 Pre Report (SLG)

Voltage Base LL	12470.0				
Initial System RMS Fault Current (Amps/Deg)	0.0 < 30				
Thevenin Equivalent Impedance (PU)	Infinite				
Thevenin Impedance X/R Ratio	0.0				
Sequence Equivalent Impedance (PU)	Z1	Z2	Z0		
	2.411 + j28.04	2.411 + j28.04	Infinite		
Asymmetrical RMS Interrupting Amps	.5 cycle	2 cycles	3 cycles	5 cycles	8 cycles
	0.0	0.0	0.0	0.0	0.0
Initial System RMS Faulted Bus Voltages (PU/Deg)	Phase A	Phase B	Phase C		
	0.0 < 0.0	1.732 < -120	1.7321 < -180		
Initial RMS Faulted Current (Amps/Deg)	Phase A	Phase B	Phase C		
	0.0 < 0.0	0.0 < 0.0	0.0 < 0.0		

Table 25: BUS-0012 Initial System Bus Voltages (at .5 Cycles) (SLG)

BUS Name	*Phase A*	*Phase B*	*Phase C*
BUS-00011	1.0 < 0.0	1.0 < -120	1.0 < 120

Table 26: BUS-0012 Initial RMS System Branch Flows (at .5 Cycles) (SLG)

First Bus	*From Fault*	*Branch Name*	*Vbase L-L*	*Phase A*	*Phase B*	*Phase C*
BUS-0012	BUS-0011	XF2-0001	480	0.0 < 0.0	0.0 < 0.0	0.0 < 0.0

Table 27: Fault Analysis Summary

Bus Name	*Voltage L-L*	*Available Fault Current*	*3 Phase Fault*	*X/R*	*Line to Ground Fault*
BUS-0001	480	5417.3	17.7	7292.26	13.7
BUS-0007	480	5370.9	16.3	7284.70	13.6
BUS-0012	12470	164.5	11.6	0.0	0.0

Appendix E – Arc Flash Evaluation

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	Required Protective FR Clothing Category	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal
1	BUS-0001	PD-0005	0.480	5.42	3.88	0.11	0.08	0.004	0.000	Yes	PNL	25	3	18	0.05	Category 0 (*N2)				
2	BUS-0001	PD-0006	0.480	5.42	3.88	0.11	0.08	0.004	0.000	Yes	PNL	25	3	18	0.05	Category 0 (*N2)				
3	BUS-0001	IndMtr Decay @5cycles	0.480	5.42	3.88	0.22	0.22	0.083	0.000	Yes	PNL	25	16	18	0.96	Category 0 (*N2)				
4	BUS-0001	MaxTripTime @2.0s	0.480	5.42	3.88	4.98	3.62	2	0.000	Yes	PNL	25	107	18	22	Category 3 (*N2) (*N9)	# 0001			
5																				
6	BUS-0007	PD-0005	0.480	5.37	3.86	0.11	0.08	0.004	0.000	Yes	PNL	25	3	18	0.05	Category 0 (*N2)		10.00		
7	BUS-0007	PD-0006	0.480	5.37	3.86	0.11	0.08	0.004	0.000	Yes	PNL	25	3	18	0.05	Category 0 (*N2)		10.00		
8	BUS-0007	IndMtr Decay @5cycles	0.480	5.37	3.86	0.22	0.22	0.083	0.000	Yes	PNL	25	16	18	0.95	Category 0 (*N2)				
9	BUS-0007	MaxTripTime @2.0s	0.480	5.37	3.86	4.94	3.59	2	0.000	Yes	PNL	25	106	18	22	Category 3 (*N2) (*N9)	# 0002			
10																				
11	BUS-0012	PD-0005	12.47	0.16	0.16	0.00	0.00	0.004	0.000	No	SWG	153	2	36	0.01	Category 0 (*N11) (*N2)		20.00		
12	BUS-0012	PD-0006	12.47	0.16	0.16	0.00	0.00	0.004	0.000	No	SWG	153	2	36	0.01	Category 0 (*N11) (*N2)		20.00		
13	BUS-0012	IndMtr Decay @5cycles	12.47	0.16	0.16	0.00	0.00	0.083	0.000	No	SWG	153	9	36	0.10	Category 0 (*N11) (*N2)				
14	BUS-0012	MaxTripTime @2.0s	12.47	0.16	0.16	0.15	0.15	2	0.000	No	SWG	153	50	36	2.4	Category 1 (*N11) (*N2) (*N9)	# 0003			
15																				

Figure 34: Arc Flash Evaluation

Appendix F – Senior Project Timeline

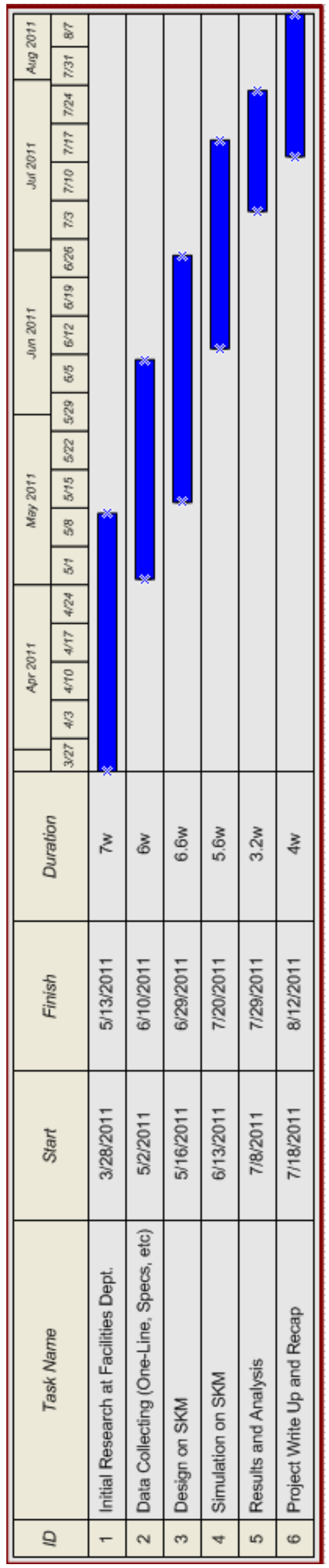

Figure 35: Senior Project Design Gantt Chart