Power Protection Analysis for a Ten Bus System

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Abstract

Each power system built in the industry requires a protection plan. Undetected faults in a power system can contribute to hazardous conditions, overheating of power devices, low or high system voltages, unbalanced conditions, and blackouts [4]. This senior project is the design of a protection plan for a power system using the software Electric Transient Analyzer Program (ETAP). With ten buses, five transformers, two generators, two motors, and six transmission lines, there are many possibilities for a fault to occur. The Load flow and fault analysis are studied before the system is protected. All components of the system are protected using methods such as differential and overcurrent protection. Without a proper power protection plan, any disturbance within the network has a chance of rendering the network inoperable. This project illustrates the protection styles and techniques used by professional engineers in the field of power.

Chapter 1: Introduction

Power protection is the art and science of safeguarding the power system components and people during abnormal (fault) conditions. If a fault goes undetected, conditions can become hazardous, power devices can overheat, system voltages can go low or high, conditions can be unbalanced, power flow can be prevented, and the system can become unstable. The objectives of a protection plan are to detect and isolate faults being selective, economical, reliable, and fast. These principles are best explained using the 5 S's of protection; security, selectivity, sensitivity, speed, and simplicity [12]. ETAP is the leading software in power protection and contains the tools needed to protect the network.

The power system I was tasked with protecting is shown in *Figure 1*. In this one line diagram, information about the system is displayed. Those values are used for all of the calculations throughout the entirety of the project, with any other values used being assumed. *Figure 2* shows the transmission line lengths and whether the transformers of the system are Y connected or delta connected. The protection begins with load flow and fault analysis. Next, the transmission lines are protected using distance and overcurrent protection. The generators and transformers are then protected using differential and overcurrent protection. The busbars are protected using busbar protection, while the motors and static loads are protected using locked rotor and overcurrent protection respectively. After the system is completely protected, the software is used to simulate the protection plans with the addition of relays.

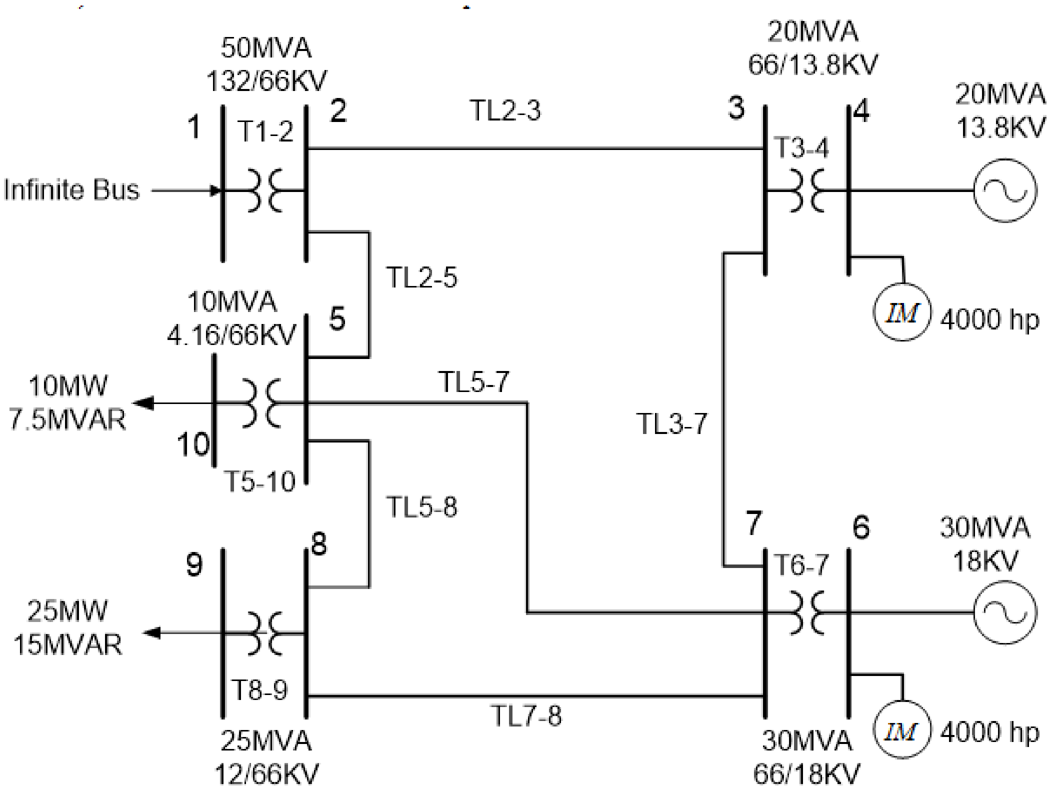
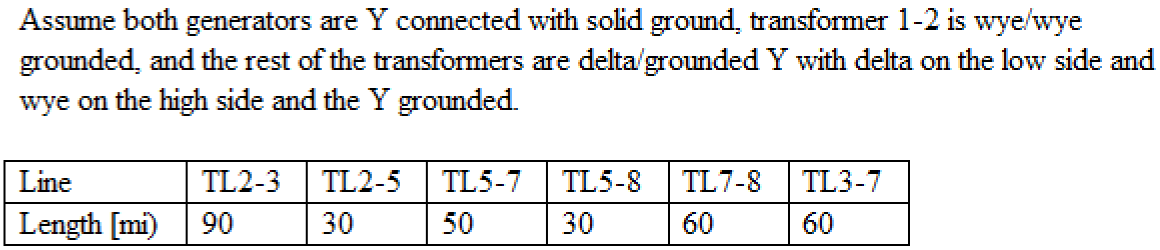


Figure 1: One Line Diagram for the Power System [11]



Assume both generators are Y connected with solid ground, transformer 1-2 is wye/wye grounded, and the rest of the transformers are delta/grounded Y with delta on the low side and wye on the high side and the Y grounded.

Line	TL2-3	TL2-5	TL5-7	TL5-8	TL7-8	TL3-7
Length [mi)	90	30	50	30	60	60

Figure 2: Assumptions and Line Lengths for the Power System

Whether the transformers and generators are grounded Y or delta influences the system greatly. In delta configuration, the phase voltage is equal to the line voltage. In Y configuration, the phase voltage is the line voltage divided by root 3. Consequently, in Y configuration, the phase current and line current are equal. In delta configuration the phase current is line current divided by root 3. If the correct connections aren’t known, all values could be affected by a factor of root 3.

Chapter 2: Customer Needs, Requirements, and Specifications

2.1. Customer Needs Assessment

The customer for this project is my advisor, Dr. Shaban. I was tasked by my employer to protect a ten-bus power system network and design a protection plan for it. The tasks completed are load flow and fault analysis for the system, generator protection, motor protection, transformer protection, bus protection, and line protection.

2.2. Requirements and Specifications

My customer was straightforward with what he wanted and listed out what he wanted in his assignment to me [11]. I was able to develop the requirements and specifications for this project from the list of instructions. I used the ETAP software to analyze the power system. Shown below in *Table 1* are the marketing requirements and specifications.

Marketing Requirements	**Engineering Specifications**	**Justification**
1	All of the network analysis is implemented in ETAP.	The project requires ETAP because it is the software that Cal Poly offers to its electrical engineering students for free use in the student project lab.
2, 3	Load flow and fault analysis are performed for the network, with the voltages and currents at the different buses documented.	The values found during the load flow and fault analysis are needed to design the protection plan.

4, 5	Generator and Motor protection are performed with the component values chosen documented.	Differential protection, overcurrent protection, and impedance protection are the types of protection that can be done for the generators and motors.
6, 7	The transformers and buses are protected and the component values chosen are documented.	The transformers and busses will have differential protection.
8	Line protection is performed and the component values chosen for optimal protection are documented.	Using distance relays is the most convenient way to perform line protection.

Table 1: Requirements and Specifications

1. Completed using ETAP
2. Load Flow Analysis
3. Fault Analysis
4. Generator Protection
5. Motor Protection
6. Transformer Protection
7. Bus Protection
8. Line Protection

Delivery Date	Deliverable Description
April 2015	Design Review
May 2015	EE 461 demo
May 2015	EE 461 report
Nov 2015	EE 462 demo
Dec 2015	ABET Sr. Project Analysis
Dec 2015	Sr. Project Expo Poster
Dec 2015	EE 462 Report

Table 2: Project Deliverables

Chapter 3: Ten-Bus Network

3.1 Network Construction in ETAP

Before any parts of the system could be protected, the system itself needed to be constructed in the software. The network assembled in ETAP is shown in *Figure 3* and its zones of protection shown in *Figure 4*. The different protection zones overlap in the figure to show that no section of the system is unprotected from faults. The chosen configuration of the transmission lines has a height of 70 ft. The phase conductor type was chosen as EPRI_M with the spacing between both A and B and B and C equal to 15 ft. With the spacing from A to C equal to 30 ft. The higher the voltage of the transmission line, the greater the height and conductor spacing should be. The infinite bus also needed to have a short circuit MVA equal to 4200 in order for the system to operate.

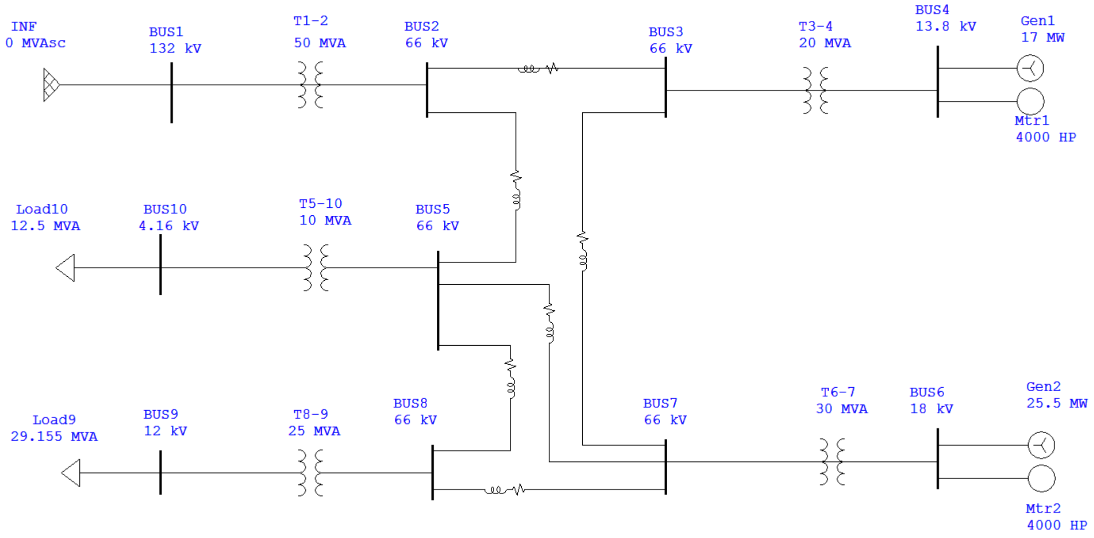


Figure 3: Network Construction in ETAP

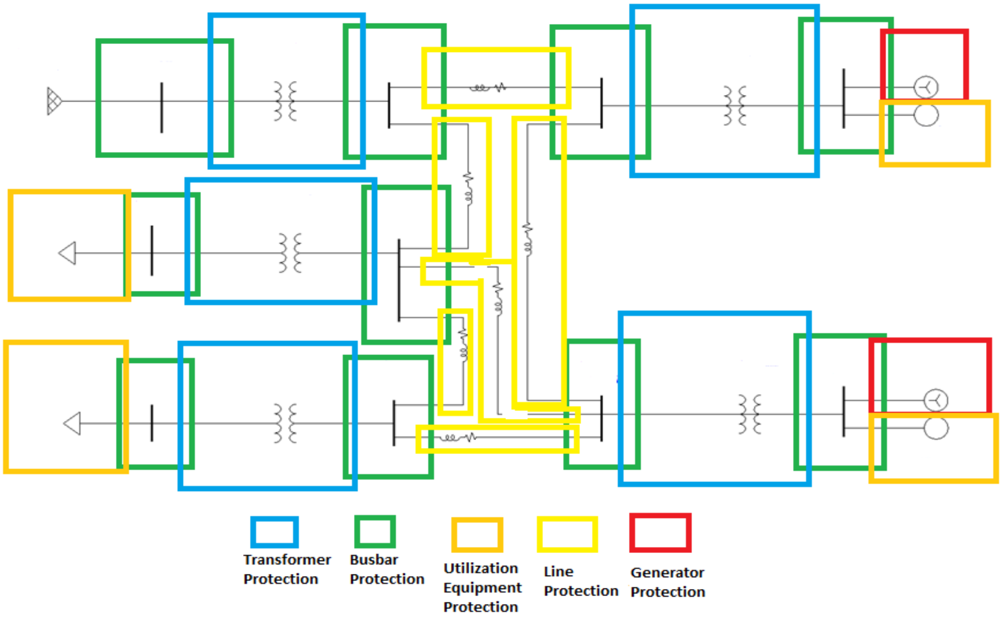


Figure 4: Protection Zones of the Power System

3.2 Load Flow Analysis

In order to plan a full power system protection scheme for the given system, a load flow analysis is required. The analysis spots any problems with the system which must be corrected before any protection plan can commence. The load flow analysis shown in *Figure 5* was completed using ETAP 12.5 and constructed using the given instructions with default equipment settings. The goal of the load flow analysis is to have each bus voltage percentage be between 95% and 105%. After the initial load flow analysis, issues were found at both generators, as well as at buses 5, 8, 9, and 10. The parts of the network with problems are highlighted in red and those close to being a problem are highlighted in pink. The system cannot operate with problems at its generators and buses. The method chosen to fix the problems was to add capacitive banks to the red buses to raise the voltage percentage up and the updated system is shown in *Figure 6*. The way the MVAR values were chosen for the capacitors was by adding a synchronous generator to the bus and observing how much reactive power it was distributing to compensate for the under voltage bus. The added capacitors also helped remove any problems with the generators as well. The updated load flow analysis without any red highlighted components is shown in *Figure 7*.

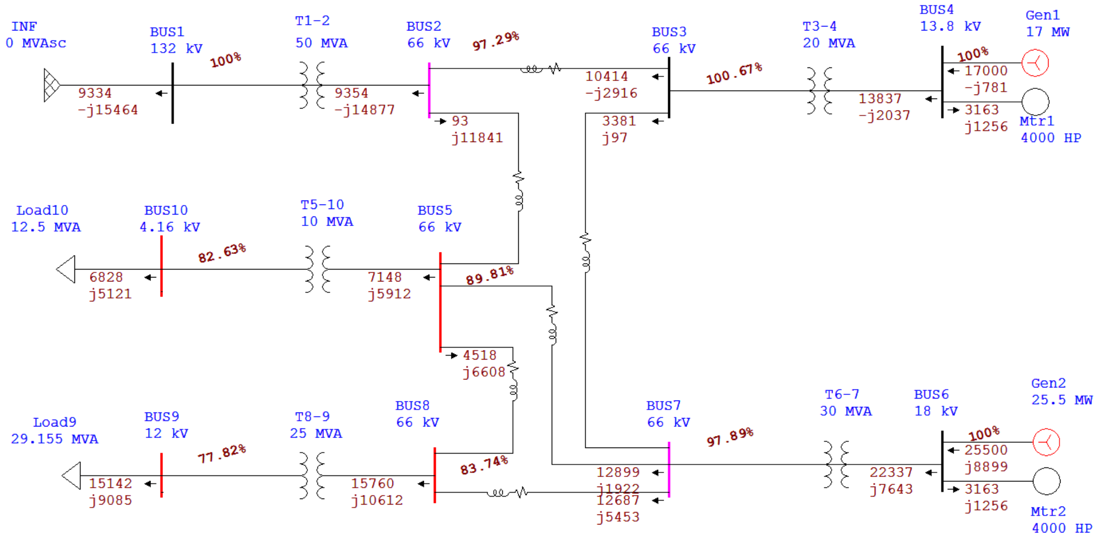


Figure 5: Initial Load Flow Analysis

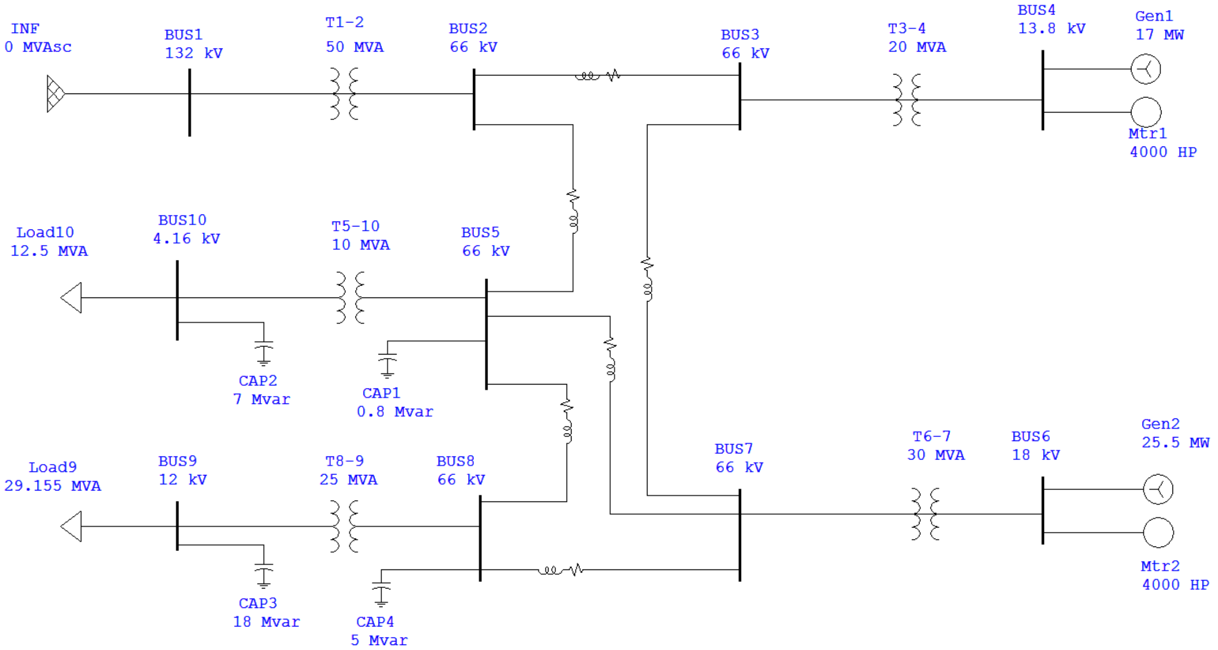


Figure 6: ETAP System with Capacitors Added

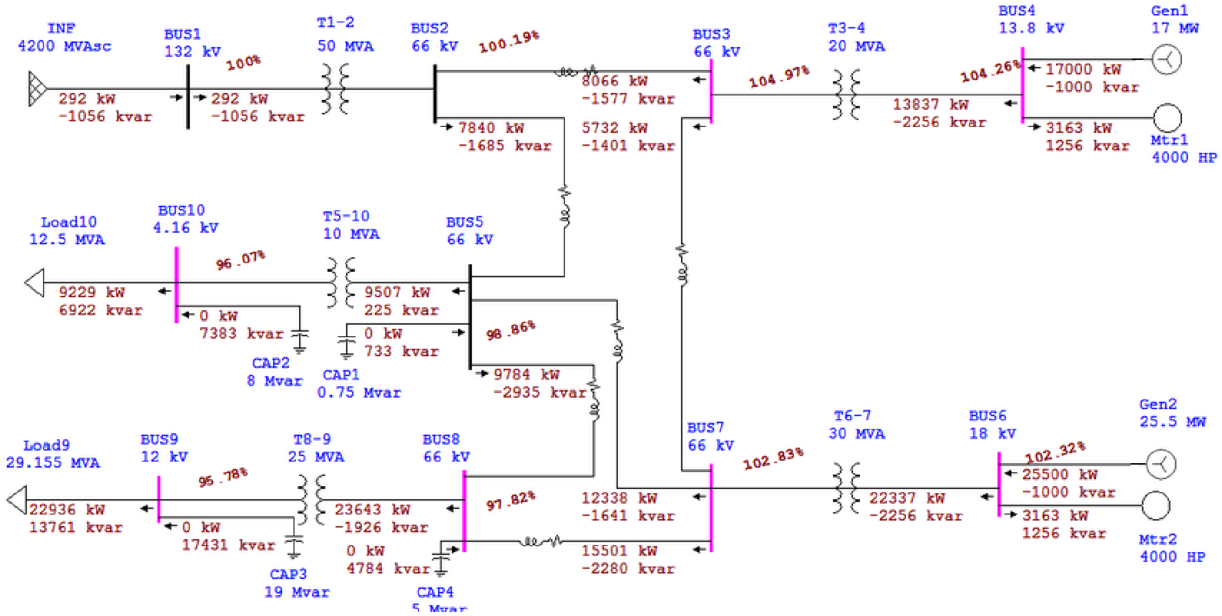
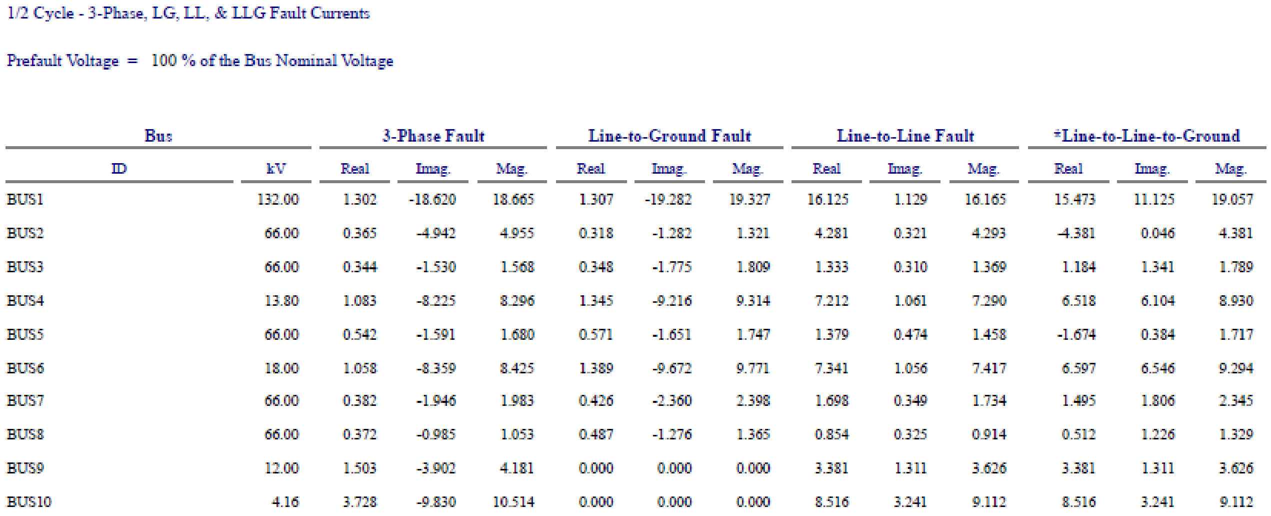


Figure 7: Load Flow Analysis after Capacitors Added

3.3 Fault Analysis

A short circuit analysis should be performed in addition to the load flow analysis which tells the possible fault currents in the system. *Figure 8* shows the three-phase, single line to ground (SLG), line to line (LL) and double line to ground (DLG) fault currents for a fault on each bus respectively. The SLG fault currents are the highest while the LL fault currents are about 85 - 87 % of the three phase fault current. Bus 1 and bus 10 have the highest fault currents, bus 2 and bus 3 have moderate fault currents and busses 5 and 9 have the smallest fault currents. *Figure 9* shows the positive, negative, and zero sequence impedances of each of the buses and was also included in the short circuit report.

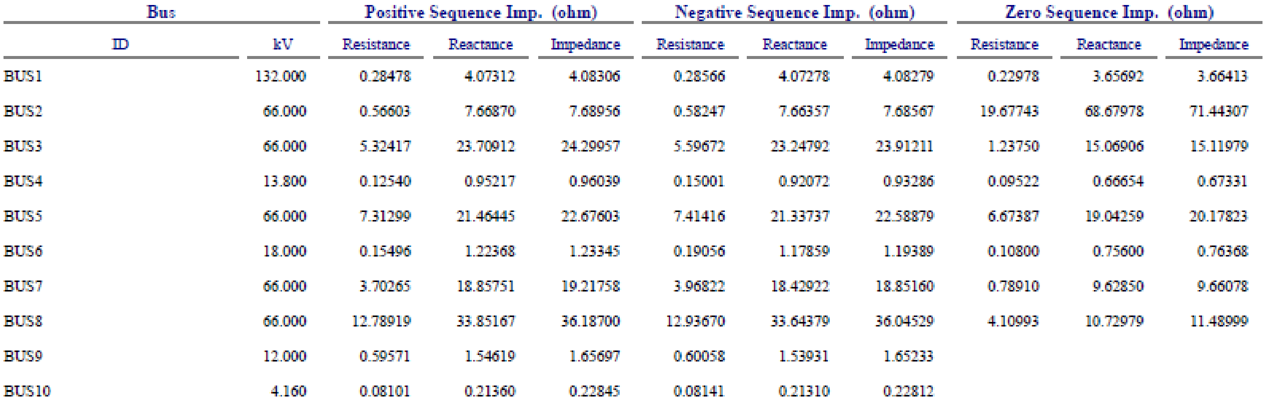


1/2 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			*Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
BUS1	132.00	1.302	-18.620	18.665	1.307	-19.282	19.327	16.125	1.129	16.165	15.473	11.125	19.057
BUS2	66.00	0.365	-4.942	4.955	0.318	-1.282	1.321	4.281	0.321	4.293	-4.381	0.046	4.381
BUS3	66.00	0.344	-1.530	1.568	0.348	-1.775	1.809	1.333	0.310	1.369	1.184	1.341	1.789
BUS4	13.80	1.083	-8.225	8.296	1.345	-9.216	9.314	7.212	1.061	7.290	6.518	6.104	8.930
BUS5	66.00	0.542	-1.591	1.680	0.571	-1.651	1.747	1.379	0.474	1.458	-1.674	0.384	1.717
BUS6	18.00	1.058	-8.359	8.425	1.389	-9.672	9.771	7.341	1.056	7.417	6.597	6.546	9.294
BUS7	66.00	0.382	-1.946	1.983	0.426	-2.360	2.398	1.698	0.349	1.734	1.495	1.806	2.345
BUS8	66.00	0.372	-0.985	1.053	0.487	-1.276	1.365	0.854	0.325	0.914	0.512	1.226	1.329
BUS9	12.00	1.503	-3.902	4.181	0.000	0.000	0.000	3.381	1.311	3.626	3.381	1.311	3.626
BUS10	4.16	3.728	-9.830	10.514	0.000	0.000	0.000	8.516	3.241	9.112	8.516	3.241	9.112

Figure 8: Fault Analysis Report (Currents in KA)



Bus		Positive Sequence Imp. (ohm)			Negative Sequence Imp. (ohm)			Zero Sequence Imp. (ohm)		
ID	kV	Resistance	Reactance	Impedance	Resistance	Reactance	Impedance	Resistance	Reactance	Impedance
BUS1	132.000	0.28478	4.07312	4.08306	0.28566	4.07278	4.08279	0.22978	3.65692	3.66413
BUS2	66.000	0.56603	7.66870	7.68956	0.58247	7.66357	7.68567	19.67743	68.67978	71.44307
BUS3	66.000	5.32417	23.70912	24.29957	5.59672	23.24792	23.91211	1.23750	15.06906	15.11979
BUS4	13.800	0.12540	0.95217	0.96039	0.15001	0.92072	0.93286	0.09522	0.66654	0.67331
BUS5	66.000	7.31299	21.46445	22.67603	7.41416	21.33737	22.58879	6.67387	19.04259	20.17823
BUS6	18.000	0.15496	1.22368	1.23345	0.19056	1.17859	1.19389	0.10800	0.75600	0.76368
BUS7	66.000	3.70265	18.85751	19.21758	3.96822	18.42922	18.85160	0.78910	9.62850	9.66078
BUS8	66.000	12.78919	33.85167	36.18700	12.93670	33.64379	36.04529	4.10993	10.72979	11.48999
BUS9	12.000	0.59571	1.54619	1.65697	0.60058	1.53931	1.65233			
BUS10	4.160	0.08101	0.21360	0.22845	0.08141	0.21310	0.22812			

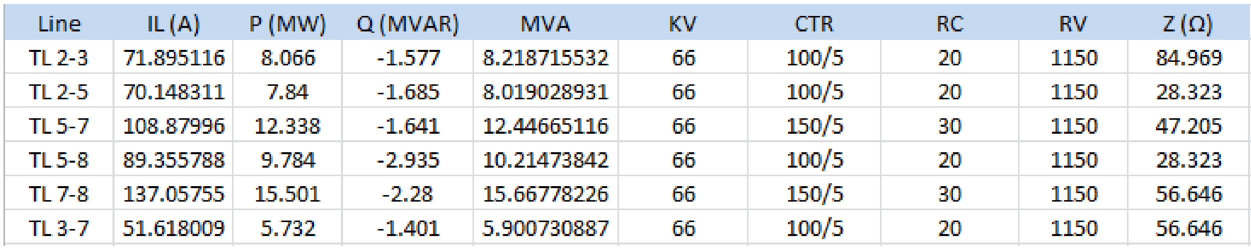
Figure 9: Fault Analysis Report (Impedance)

3.4 Transmission Line Protection

The first piece of the network to protect is the transmission lines. The transmission lines are the link of connections within the power system and are vital to protect and be able to disconnect in case of a fault. Distance directional protection relays are a common way design method together with pilot protection.

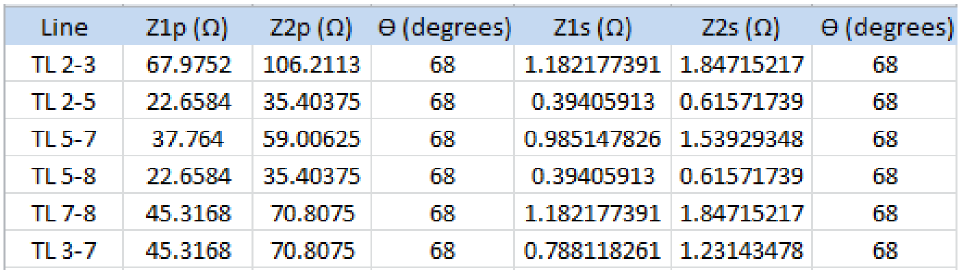
Distance protection senses the impedance of the line and trips if the resulting impedance is too low due to a fault. The impedance is derived from a voltage and current transformer. The distance protection is then connected to a directional relay which determines where the fault is located and whether or not to trip. The directional relay is often designed at 70 or 75° in both the forward or reversed direction. Now, relays designed by SEL can be set at any angle. The distance protection is further divided into different protection zones which acts as back up and overlap protection of adjacent lines. Zone 1 is often set at 80% of the line, Zone 2 at 125% and Zone 3 at 250%. For this project Zone 3 protection is neglected since the transmission lines aren't too long.

The equation used for the rated current throughout the project’s calculations is $Irated = \frac{KVA}{\sqrt{3}KV}$. After finding the rated current; the CTR is chosen by rounding up the rated current value to the nearest hundred. The mho X/R radius can be found from the line impedance and the angle setting of the relay by the equation $2Z_r = \frac{Z_{Line}\langle 75°\rangle}{\cos(68°-75°)}$. The forward directed relay is set from the origin and the reversed directed relay is set from the end of the transmission line. The needed CT and PT ratios are here converted directly from the load currents and bus voltages of the system. The values chosen and calculated from the ETAP design are shown in *Table 3.* With those values it is possible to find the primary and secondary zone impedances which are shown in *Table 4.* In *Figure 10* an example of how the different protection zones overlap is shown. The blue and green circles are the forward protection zones and the red and aqua circles are backward protection zones. They have the same impedance values only one differential relay is set from the origin and the backward relay is set from the end of the transmission line, looking the opposite way.



Line	IL (A)	P (MW)	Q (MVAR)	MVA	KV	CTR	RC	RV	Z (Ω)
TL 2-3	71.895116	8.066	-1.577	8.218715532	66	100/5	20	1150	84.969
TL 2-5	70.148311	7.84	-1.685	8.019028931	66	100/5	20	1150	28.323
TL 5-7	108.87996	12.338	-1.641	12.44665116	66	150/5	30	1150	47.205
TL 5-8	89.355788	9.784	-2.935	10.21473842	66	100/5	20	1150	28.323
TL 7-8	137.05755	15.501	-2.28	15.66778226	66	150/5	30	1150	56.646
TL 3-7	51.618009	5.732	-1.401	5.900730887	66	100/5	20	1150	56.646

Table 3: Line Protection Values Chosen and Calculated



Line	Z1p (Ω)	Z2p (Ω)	ϴ (degrees)	Z1s (Ω)	Z2s (Ω)	ϴ (degrees)
TL 2-3	67.9752	106.2113	68	1.182177391	1.84715217	68
TL 2-5	22.6584	35.40375	68	0.39405913	0.61571739	68
TL 5-7	37.764	59.00625	68	0.985147826	1.53929348	68
TL 5-8	22.6584	35.40375	68	0.39405913	0.61571739	68
TL 7-8	45.3168	70.8075	68	1.182177391	1.84715217	68
TL 3-7	45.3168	70.8075	68	0.788118261	1.23143478	68

Table 4: Zones 1 and 2 Impedance at 68 Degrees

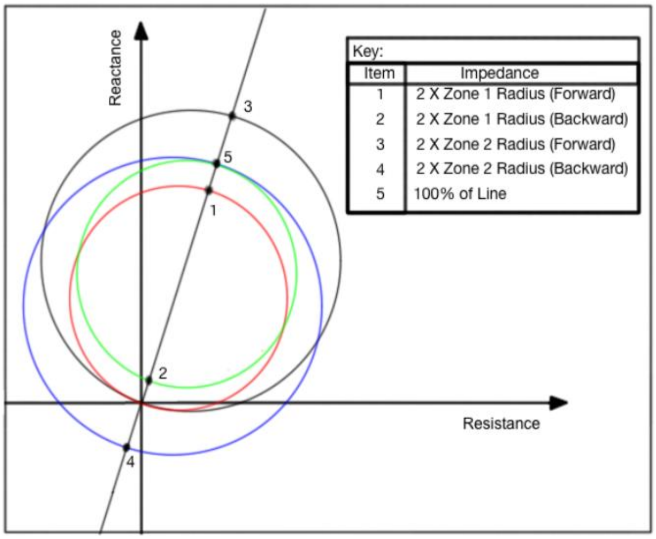


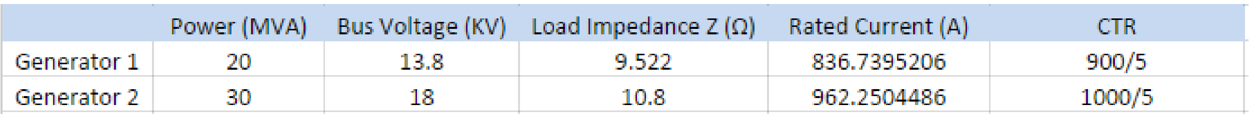
Figure 10: MHO Characteristic for Distance Protection of Transmission Lines

3.5 Generator Protection

The next step is to design a generator protection scheme for both of the generators. The protection schemes used are differential and overcurrent protection. The generators are protected from internal faults with differential protection. The differential protection compares the ingoing and outgoing phase currents of the machine and trips on a small imbalance. This difference is in most cases due to an internal fault which is what we want to protect against. Some small imbalances can occur during transients and mismatch between the current transformers and the pick-up current can account for that. A typical pickup current for generator protection is between 0.14-0.28 A. The pickup current chosen was 0.15 A

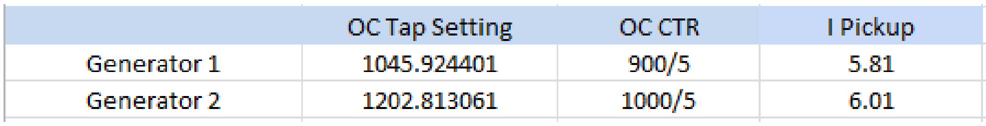
In addition to these protection schemes, overcurrent, overheating and negative sequence protection would be needed as well. The overcurrent protection is placed in phase and protects against large external faults and work as a back-up protection. Each generator is assumed to handle a max load current on 125% of the rated current. It is assumed that the solid state protection relays include both negative sequence and overheating relays which will warn and trip for any large negative sequence currents and overheating conditions.

The generators power, currents, voltage and impedance ratings are shown in *Table 5*. The rated current is derived from the rated MVA and the line bus voltage. The impedance for the relay was found from the ETAP generator characteristics. The CTRs were chosen after finding the rated current of each generator and are 900/5 (Gen 1) and 1000/5 (Gen 2). The CT selections for the overcurrent protection are based on 125% rated current but use the same CTRs. The pickup currents chosen for generators 1 and 2 were found by dividing the OC Tap setting by the OC CTR and then rounding the value up to the closest value. The overcurrent protection values are shown in *Table 6.*



	Power (MVA)	Bus Voltage (KV)	Load Impedance Z (Ω)	Rated Current (A)	CTR
Generator 1	20	13.8	9.522	836.7395206	900/5
Generator 2	30	18	10.8	962.2504486	1000/5

Table 5: Generator Differential Protection



	OC Tap Setting	OC CTR	I Pickup
Generator 1	1045.924401	900/5	5.81
Generator 2	1202.813061	1000/5	6.01

Table 6: Generator Overcurrent Protection

3.6 Transformer Protection

The system has five power transformers that need protection. This is often realized using differential protection. While using differential protection, one must consider high magnetizing inrush currents, different voltage levels and the delta/wye phase shifts. Since the transformers are a vital part of the system, ground and overcurrent protection as backup will also be considered.

The differential protection is completed in two steps. The first step is to cancel out the zero sequence and the 30 degree phase shift created by the delta-wye connection by connecting the CTs in delta on the wye side and in wye on the delta side. Second, adjust the CT ratio and tap selection to reduce the operating mismatch. Likewise, assure a safe margin in the mismatch percentage to account for unknown CT errors. The mismatch percentage is given by the equation: $M = 100 \times \frac{\frac{I_H}{I_L} - \frac{T_H}{T_L}}{Smallest}$

This differential protection may operate due to large inrush or magnetizing currents that energize the transformer, voltage dips and/or sympathetic inrush currents from the nearby energizing transformers. In order to avoid operation during these natural high currents, the differential protection must be set to detect when a large mismatch is due to an internal fault or a temporarily large inrush current. A harmonic detection observer is one solution to that problem while keeping the differential protection operational during all time. [13]

Ground protection is another vital backup protection against external line-to-ground faults and can be designed using differential overcurrent relays and/or autotransformers. It is assumed that CT ratios around 100:5 would be able to detect a ground fault current while CT ratios of 1000:5 and above would have too low of a sensitivity. If that is the case, the CT ratios could be adjusted by an autotransformer.

The main task for all protection schemes is to detect the zero sequence fault current and compare it to a differential relay or to a time overcurrent relay as a backup. The transformers could be either grounded solemnly on the wye side or through a zigzag transformer on the delta side of the transformer (*Figure 11*). The ground protection is guaranteed by a differential relay with an overcurrent relay as a backup protection. [13]

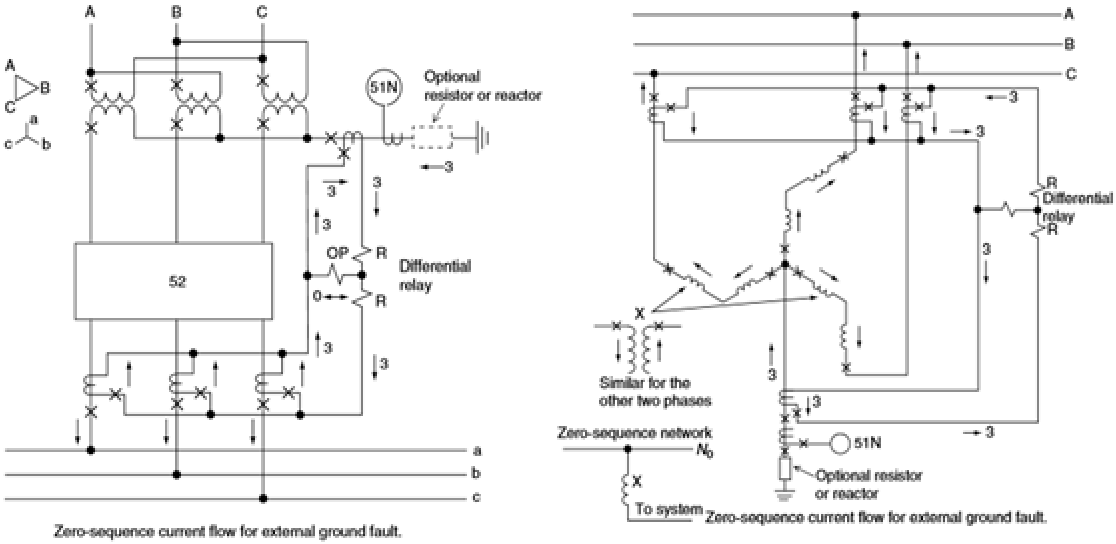


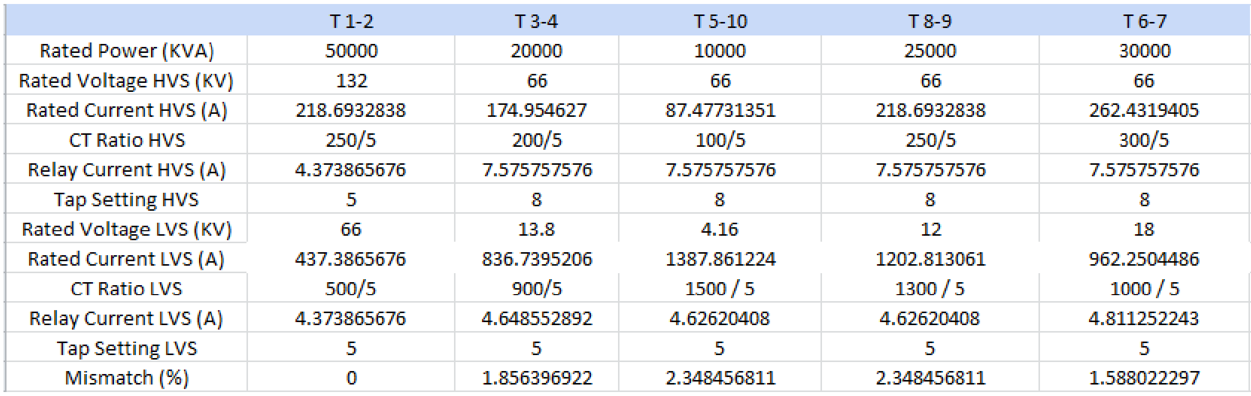
Figure 11: Zigzag Ground Protection (Delta Side) and Ground Protection (Wye Side) for the Transformer on Left and Right Sides Respectively [13]

In addition to differential and ground protection, an overcurrent relay should be added as backup for phase faults. This is especially vital for large loaded transformers which would inflict major damage if the primary differential protection would fail. A typical setting for the CTs of an instantaneous overcurrent relay is 150-200% of the largest three phase fault current [13]. The inrush current is typically between 8-12 times the rated current and for this experiment the current was estimated at 10 times the rated current.

Differential relay protection with harmonic detection is used as primary protection with phase overcurrent protection as a backup for all four transformers. In addition, wye side overcurrent differential grounding is added as a backup for SLG faults since they are the most common type of fault. The transformers are connected in delta on the low voltage side and wye on the high voltage side according to given instructions.

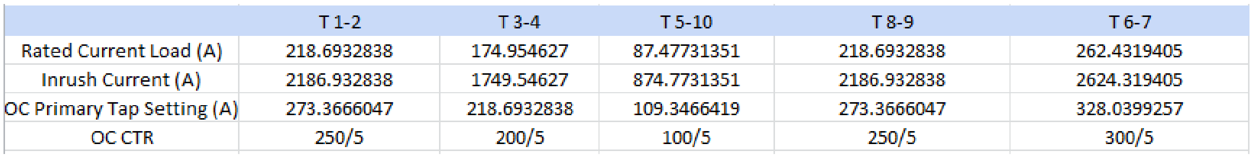
Table 7 shows the rated currents on the primary and secondary side with appropriate CT ratios, tap settings, and resulting mismatch for each transformer. Each CT is assumed to have tap settings between 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. An overall mismatch between 3-5 % is assumed to be a good balance between sensitivity and safe margin. The pickup currents are set to 0.2 A, a little bit higher than in the generator protection case to account for the CT mismatch.

Table 8 shows the overcurrent protection in accordance with the expected inrush currents. Also note that the some CTs are slightly underrated compared to its estimated overcurrent. In this design the over current tap setting is assumed to be 125% of the rated current.



	T 1-2	T 3-4	T 5-10	T 8-9	T 6-7
Rated Power (KVA)	50000	20000	10000	25000	30000
Rated Voltage HVS (KV)	132	66	66	66	66
Rated Current HVS (A)	218.6932838	174.954627	87.47731351	218.6932838	262.4319405
CT Ratio HVS	250/5	200/5	100/5	250/5	300/5
Relay Current HVS (A)	4.373865676	7.575757576	7.575757576	7.575757576	7.575757576
Tap Setting HVS	5	8	8	8	8
Rated Voltage LVS (KV)	66	13.8	4.16	12	18
Rated Current LVS (A)	437.3865676	836.7395206	1387.861224	1202.813061	962.2504486
CT Ratio LVS	500/5	900/5	1500 / 5	1300 / 5	1000 / 5
Relay Current LVS (A)	4.373865676	4.648552892	4.62620408	4.62620408	4.811252243
Tap Setting LVS	5	5	5	5	5
Mismatch (%)	0	1.856396922	2.348456811	2.348456811	1.588022297

Table 7: Transformer Differential Protection



	T 1-2	T 3-4	T 5-10	T 8-9	T 6-7
Rated Current Load (A)	218.6932838	174.954627	87.47731351	218.6932838	262.4319405
Inrush Current (A)	2186.932838	1749.54627	874.7731351	2186.932838	2624.319405
OC Primary Tap Setting (A)	273.3666047	218.6932838	109.3466419	273.3666047	328.0399257
OC CTR	250/5	200/5	100/5	250/5	300/5

Table 8: Transformer Overcurrent Protection

3.7 Busbar Protection

The busbars require circulating current protection and also appropriate selected CTs. In addition, the protection design for the buses depends on the bus arrangement. In this project, it is assumed that a single bus-single breaker should be used if three or fewer feeders are connected to the bus. Otherwise, a single bus with a tie-breaker is used. Both arrangements are shown in *Figure 12.*

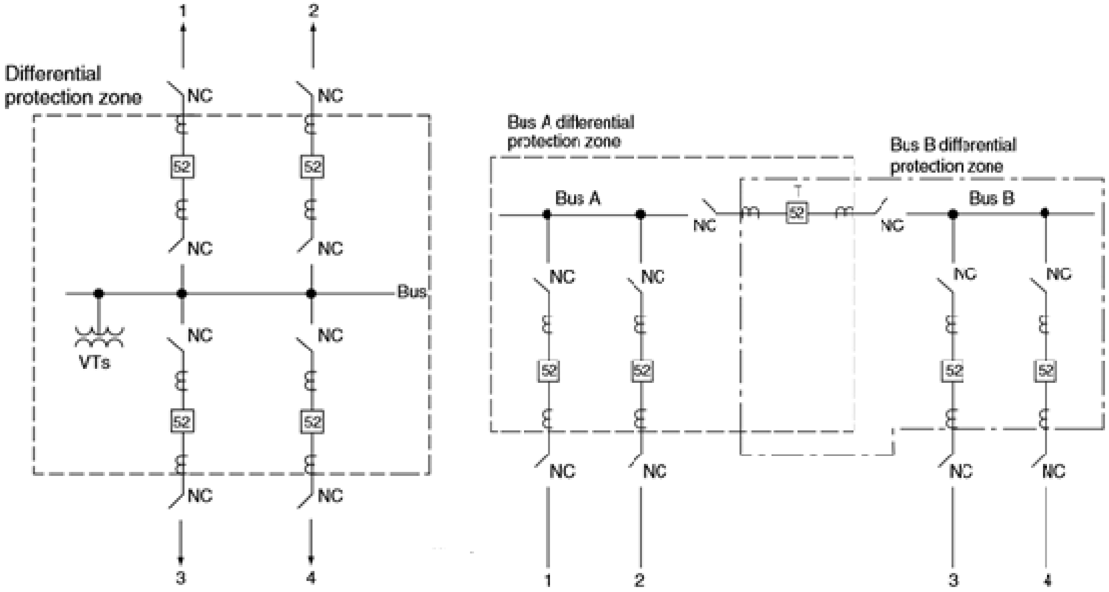


Figure 12: Single Bus-Single Breaker (Left) and Single Bus with a Tie-Breaker (Right) [13]

The system has ten buses with differing amounts of connected feeders. Eight of them have three or fewer feeders connected and are therefore considered to have a single bus to single breaker configuration. The arrangement is simple and economical but lack in flexibility during faults and maintenance.

The other buses have more than three feeders connected and are designed as a single bus with a tie-breaker. The tie-breaker increases flexibility and may keep half of the bus and half of the connectors in operation if a fault occurs. With additional power sources, the load can be transferred through the bus connection.

A simple protection scheme for the buses is using either differential or circulating current relays. The circulating current relay is normally cheaper than the differential relay and would be appropriate for simple bus arrangements as single bus-single breaker and single bus with a tie breaker. The principle is explained in *Figure 13*. For each bus, the current going in is equal to the current going out. For an internal fault, the current going in and the current going out would not add up and the resulting current would flow through the operating relay and trip the breakers. For an external fault, the ingoing and outgoing currents would stay the same and not trip for that fault.

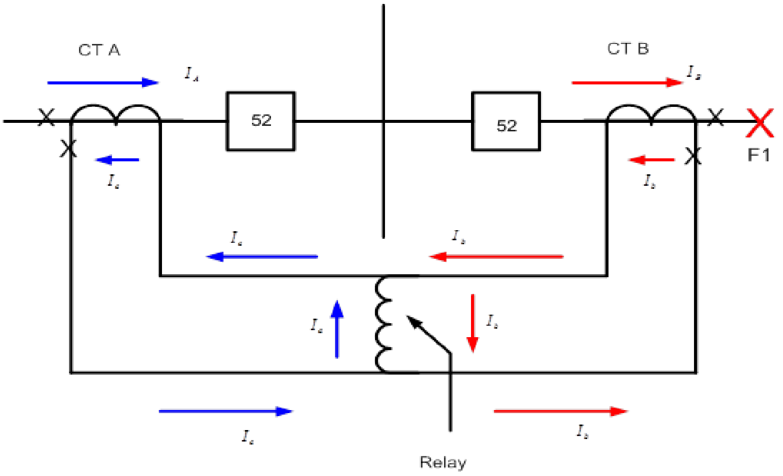
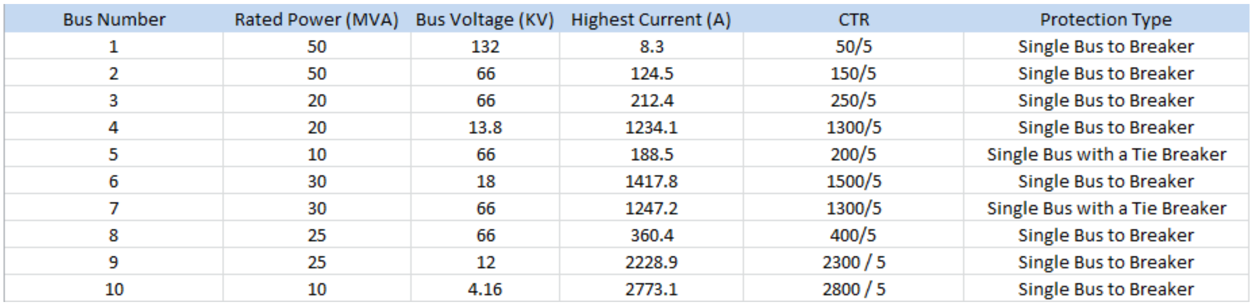


Figure 13: The Principle for Circulating Current Protection [13]

This is true for a single line to ground fault. However, a line to line fault would still keep the amount of current going in and out the same and wouldn’t detect the fault. A solution to that is to have a circulating current relay for each phase. For the single bus with a tie breaker, the bus and feeders will be divided into two sections, separated by the tie breaker. An additional circulating current relay is added covering both sections for monitoring purposes.

The first step is to define which buses should be single bus and which ones would be single bus with a tie breaker. In the single bus and tie-breaker case, the protection scheme must be able to operate with the breaker both open and closed. When choosing CT relays, each relay for all feeders must have the same ratio to guarantee that the relay currents will cancel each other. The CT ratios should also strive to match the max load on the connected feeders to the bus. They should not risk saturation if the current were to rise due to a loss of a neighbouring line/feeder. Let the load currents, extracted from the generators and/or loads connected to each bus, be the general CT ratio for that specific bus. These CTs are also the ones used for the overcurrent backup protection for the transmission lines. The highest currents are found by comparing the currents entering and leaving the bus in the load flow analysis figure and choosing the highest value. *Table 9* shows the results of busbar protection.



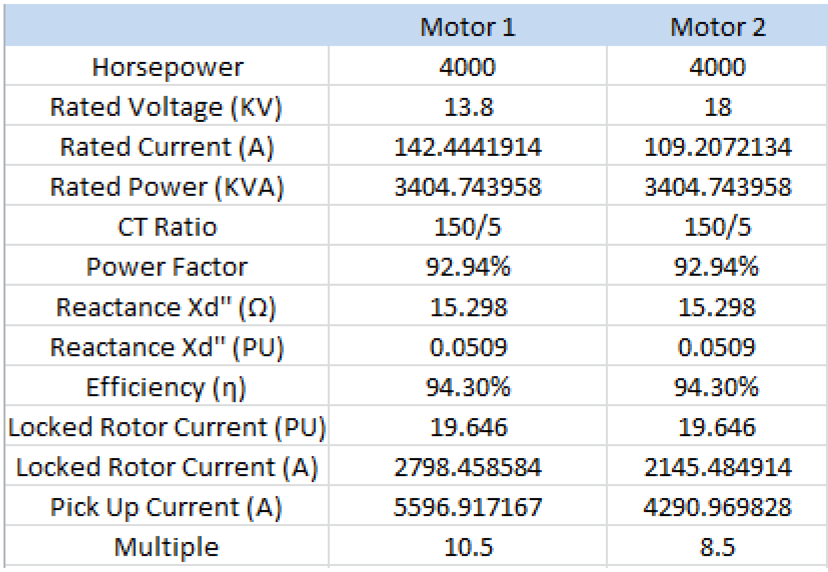
Bus Number	Rated Power (MVA)	Bus Voltage (KV)	Highest Current (A)	CTR	Protection Type
1	50	132	8.3	50/5	Single Bus to Breaker
2	50	66	124.5	150/5	Single Bus to Breaker
3	20	66	212.4	250/5	Single Bus to Breaker
4	20	13.8	1234.1	1300/5	Single Bus to Breaker
5	10	66	188.5	200/5	Single Bus with a Tie Breaker
6	30	18	1417.8	1500/5	Single Bus to Breaker
7	30	66	1247.2	1300/5	Single Bus with a Tie Breaker
8	25	66	360.4	400/5	Single Bus to Breaker
9	25	12	2228.9	2300 / 5	Single Bus to Breaker
10	10	4.16	2773.1	2800 / 5	Single Bus to Breaker

Table 9: Busbar Protection

3.8 Motor and Static Load Protection

The motors and static loads are the last part of the system in need of protection. Both require instantaneous overcurrent protection and the induction motors also need locked rotor protection. Induction motors must be protected against phase/ground faults, thermal damage and locked rotor conditions. This requires overcurrent and locked rotor protection through an impedance relay. The overcurrent relay CTR should be selected according to the motor's rated load current with a pickup current about 1.6-2 times larger than the locked rotor current. This will ensure that the overcurrent won't trip during start-up when the motor is locked. The pick-up current must be at least 2 times smaller than the possible minimum fault current which in this case is the line to line fault current. The contribution from the induction motor to this fault has been neglected for simplicity reasons. Furthermore, adding an impedance relay will ensure that the motor protection will trip for undesirable locked rotor conditions. A mho relay with a time delay will trip the coil if the motor stays to long in the locked rotor condition.

Static load protection can be handled by a simple overcurrent relay with an assumed overcurrent on 125% of the rated load current. This will disconnect the feeders and remove the load from the grid protecting against any possible equipment damage and overheating. The power system includes two induction motors and two static loads. The induction motor parameters are given from the ETAP simulation and the rated KVA from the equation $kVA_{rated} = \frac{Horsepower*0.746}{Pf*efficiency}$. The results of the motor protection in the system are shown in *Table 10*. The power factor, reactance, per unit reactance, and efficiency are obtained from the ETAP program while the rated current, locked rotor current, and pick up current, and multiple are calculated. The equation to find the locked rotor current is $ILR(pu) = \frac{1}{\mathrm{Xd}''}$. To convert from per unit to amps, the value is multiplied by the rated current.



	Motor 1	Motor 2
Horsepower	4000	4000
Rated Voltage (KV)	13.8	18
Rated Current (A)	142.4441914	109.2072134
Rated Power (KVA)	3404.743958	3404.743958
CT Ratio	150/5	150/5
Power Factor	92.94%	92.94%
Reactance Xd" (Ω)	15.298	15.298
Reactance Xd" (PU)	0.0509	0.0509
Efficiency (η)	94.30%	94.30%
Locked Rotor Current (PU)	19.646	19.646
Locked Rotor Current (A)	2798.458584	2145.484914
Pick Up Current (A)	5596.917167	4290.969828
Multiple	10.5	8.5

Table 10: Motor Protection

The locked rotor impedance relay is set at the induction motor's sub-transient reactance Xd" (*Figure 14*). When the detected impedance stays within the circle for too long, a time delay relay will close a contact which sends a trip signal to disconnect the machine. Any inrush currents are assumed to briefly stay within the zone without risk of tripping the time delay setting.

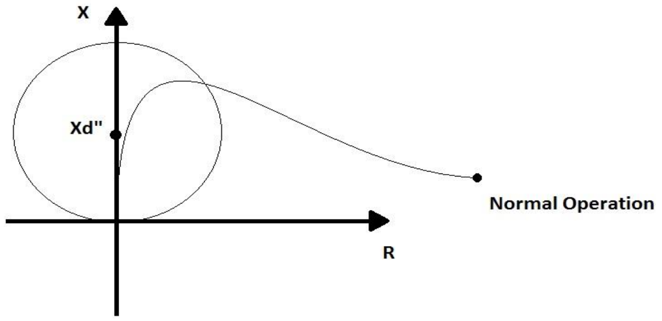
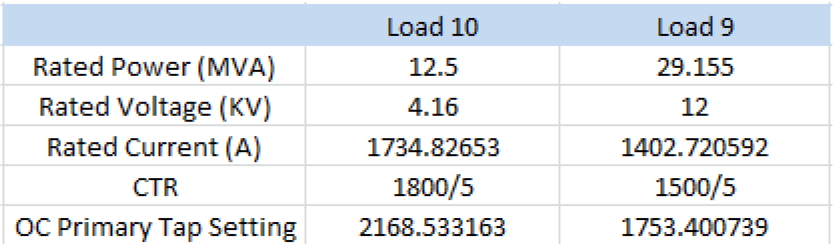


Figure 14: MHO characteristics for Locked Rotor Protection [13]

The static load overcurrent CT ratios were based on the expected overcurrent of 125% of the rated current and the overcurrent protection results are shown in *Table 12*. The rated current was given from each load's power and voltage ratings.



	Load 10	Load 9
Rated Power (MVA)	12.5	29.155
Rated Voltage (KV)	4.16	12
Rated Current (A)	1734.82653	1402.720592
CTR	1800/5	1500/5
OC Primary Tap Setting	2168.533163	1753.400739

Table 11: Overcurrent Protection for Static Loads

3.9 Implementation and Simulation using ETAP

The first part of the system protected is the busbars. In *Figure 15*, bus protection using ETAP is shown. Notice how the CTs surrounding the bus are all tied together to one relay. To simplify the figure, I chose to only show one section of the network with bus protection. *Figure 16* shows the system with relays added to protect the network. Certain connections were left out due to simplicity reasons. I used the ETAP's library to find the particular relay I needed. I chose to use relays manufactured by Schweitzer since they are some of the most commonly used relays in the industry.

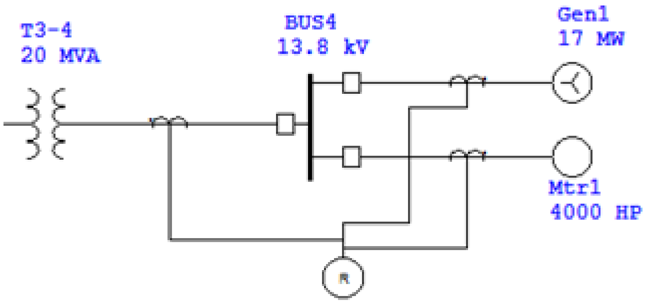


Figure 15: ETAP Simulation with Bus Bar Protection Implemented

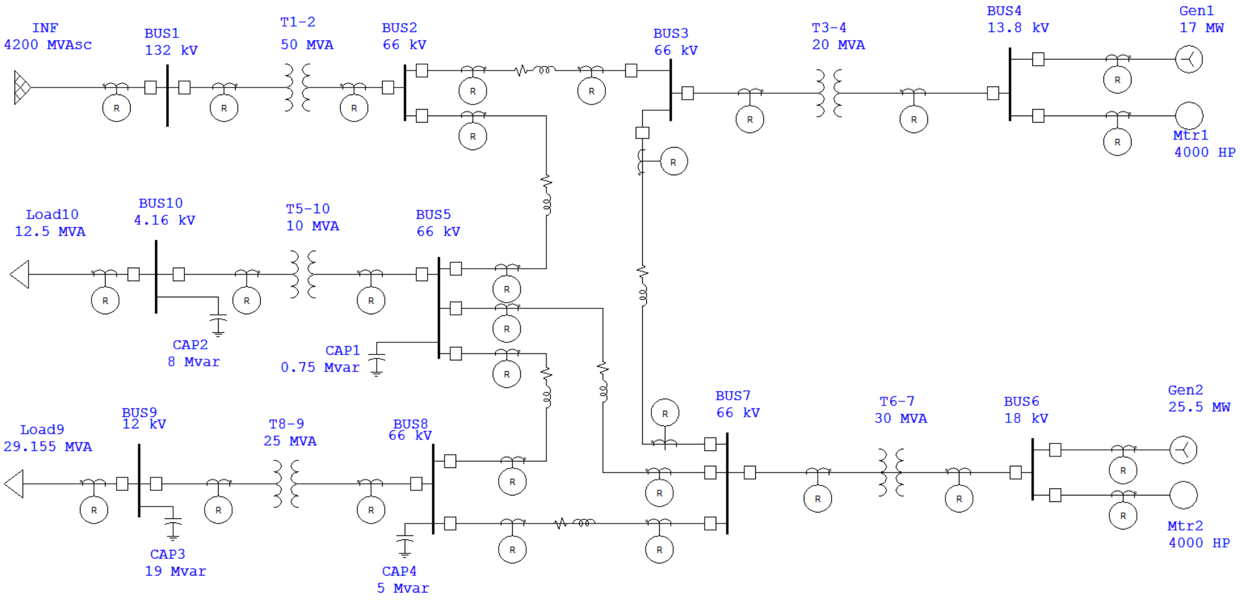


Figure 16: ETAP Simulation with Relays Added

For the motors, two SEL-710 relays are used. These relays provide locked-rotor, overload, unbalance and short circuit protection for the two motors. SEL-300G relays are used to provide primary and secondary protection for the generators in the system. The SEL-267 relays are used to protect the transmission lines with directional overcurrent and distance protection. For the transformers and bus bars, SEL-387 relays are used since they provide differential and overcurrent protection for both. With all of the relays, current transformers, and circuit breakers added, this system now has protection from all types of faults.

Chapter 4: Conclusions

The goal of this project was to find an optimum protection strategy for the system given. The factors considered while working on this project were security, selectivity, sensitivity, speed and simplicity. The instrument transformers were chosen carefully to be able to sense the fault current conditions. Tap settings were set with regards to normal operation currents as well as large inrush currents for the induction motor and different CT requirements for the transformer differential relay. Main and backup protection schemes have also been designed as far as possible (often made up by a distance or differential protection as main and an overcurrent as a backup). Hence, the sensitivity, selectivity and security design goals have been meet. Concerning speed, the relays in the system will act according to the settings when a fault occurs, ensuring the system remains functional. Simplicity is the last requirement which was one of the main factors considered when protecting the network. Using uniform types of relays helps make functions operate as smooth as possible, and makes the system easier to troubleshoot. Having the protection zones for the system overlap also helps keep the protection design as cost effective as possible.

This project concerns a relatively small power system with only five transformers and ten buses. However, it is clear that even for small power systems the protection requirements are important. All pieces of the network need both main and backup protection and the different types of faults, special equipment conditions, and overall abnormalities need to be factored in as well. In this project, only the most basic and standard protection requirements have been considered. It should be noted that additional main systems, backup systems thermal protection and abnormalities such as voltage drops could also be added to the protection design. Moreover, another type of protection that will become more important especially when upgrading to microprocessor based relays is cyber protection. It will be a high priority when the power grid becomes more dependent on signaling and piloting between relays, ensuring that the communication lines are secure. Transmission lines have previously being locally monitored at the substation but with the developing of solid state relays, smart grids and digital signal applications cyberspace security would also be a concern for power engineers.

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Appendix A: Senior Project Analysis

Power Protection Analysis for a Ten Bus System

Sean Hanna

Advisor: Ali Shaban: AS: 02/27/2015

1. Summary of Functional Requirements: This senior project solves the system by performing fault and load flow analysis. Motor, generator, transformer, bus, and transmission line protection are performed as well [11]. The overall design operates without error during a simulated fault.

2. Primary Constraints: Significant challenges were faced in the design process. Getting familiar with the ETAP software took some time and effort. Choosing which protection method to use is also very important since each decision has an effect on the entire system.

3. Economic: Since the project is implemented using the ETAP software installed on the computers in the electrical engineering building, the electricity used power the computers and lights in the building. The poster board purchased for the senior project expo will cost approximately $6.99. The input of the experiment is the power system design in ETAP. The amount of time that this project takes is highlighted in the Gantt chart below. This senior project takes approximately 150 hours to complete over twenty weeks. There could be a profit if the protection strategy is used by a company. If that is the case, assembling the system could cost the company hundreds of thousands of dollars.

4. If manufactured on a commercial basis: Techniques involving the different forms of protection could be used if this network is manufactured on a commercial basis. There are professional engineers that could design a better protection strategy than the one in this report and would have a better chance of getting their product manufactured on a commercial basis.

5. Environmental: The cost of electricity to power the network will affect the surrounding environment. The transformers, generators, and motors all have emissions that can harm the environment. If any pieces of the system were to fail, the damages could affect its ecosystem and the species that live in it. Safety should be a priority for the system's operators and routine maintenance is a necessity.

6. Manufacturability: There wouldn't be any issues with manufacturing this project since it is designed using ETAP software. One would look at the design and then be able to manufacture the components needed and then arrange them correctly.

7. Sustainability: If the users were to use renewable energy to power the system, the network could become marginally sustainable. Resources consumed include the power feeding the system as well as all of the

materials used in constructing the network. Recycling old transformers, generators, motors, busbars, and transmission lines can make the manufacturing process more sustainable as well.

8. Ethical: The system is designed with the goal of cost efficiency and overall safety. It is this utilitarian approach which will benefit the largest amount of people. There might be a professional engineer that could coordinate a better power protection plan than I so they could improve on my design, making it more efficient.

9. Health and Safety: If the system were implemented, all of the precautions taken while working with machinery and high voltages would have to be followed as well or someone could get seriously injured. If a power surge happened while someone was working close to the transformer then it could explode or electrocute the person operating the component.

10. Social and Political: This project impacts anyone who could possibly use my design to power what they needed powered. One could use my design as a small part of their much larger system. The stakeholders in this project are me, my advisor Dr. Shaban, and Cal Poly.

11. Development: The tool used to develop this project is the software ETAP. This software is downloaded onto the computers in the electrical engineering building. The techniques outlined in the ETAP user's manual [1] are applied to complete the project.

Appendix B: Functional Decomposition (Level 0 and Level 1)

The construction of the level zero block diagram shown below in *Figure 17* was relatively simple to design. The input to the diagram is the design shown in *Figure 1* while the outputs are the load flow and fault analysis, as well as protection for the generators, motors, lines, buses, and transformers. The module is the ETAP software which is the medium used to complete the senior project.

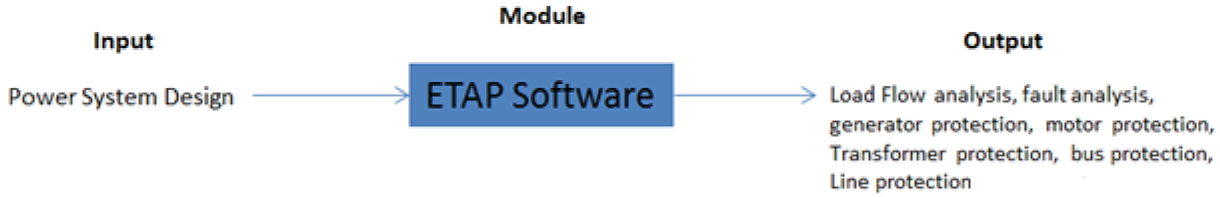

Figure 17: Level 0 Block Diagram

Module: ETAP Software.

Input: Power System Design.

Output: Load Flow Analysis, Fault Analysis, Generator Protection, Motor Protection, Line Protection, Bus Protection, and Transformer Protection.

Functionality: Once the system is designed using the ETAP software, load flow and fault analysis is performed. Generator, motor, line, bus, and transformer protection are performed as well.

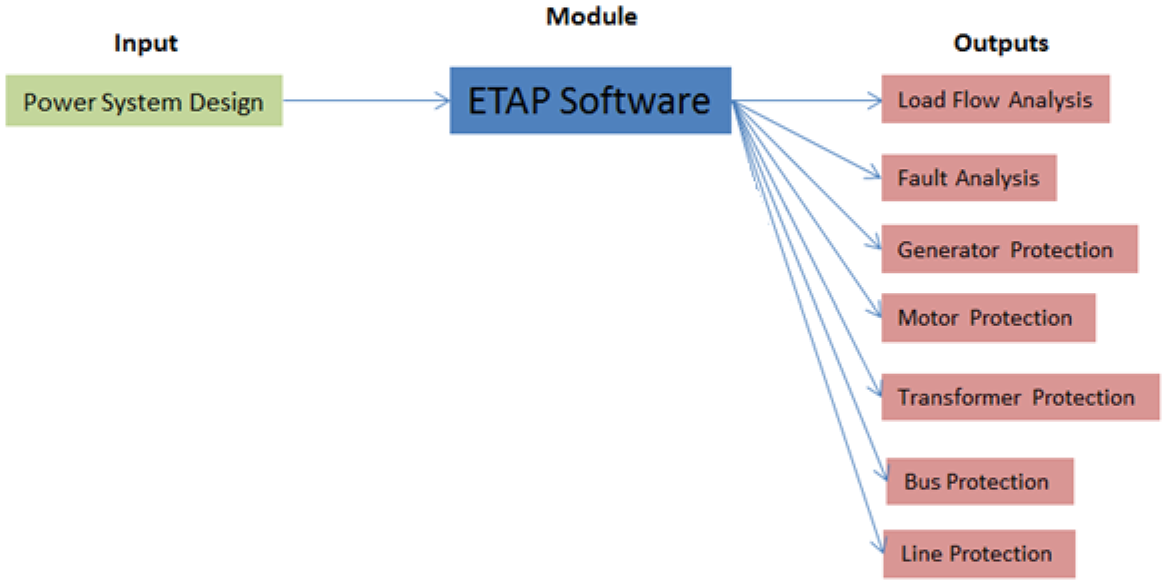

Figure 18: Level 1 Block Diagram

Above is the level one block diagram where the outputs of the system are divided into separate blocks since they are separate processes.

Appendix C: Project Planning (Gantt Chart and Cost Estimates)

Shown below in *Figure 19 is* the Gantt chart for the project. Each analysis and protection plan took about two to three weeks to complete since there are many design build test iterations where steps are repeated. Documentation for the report was also done continuously.

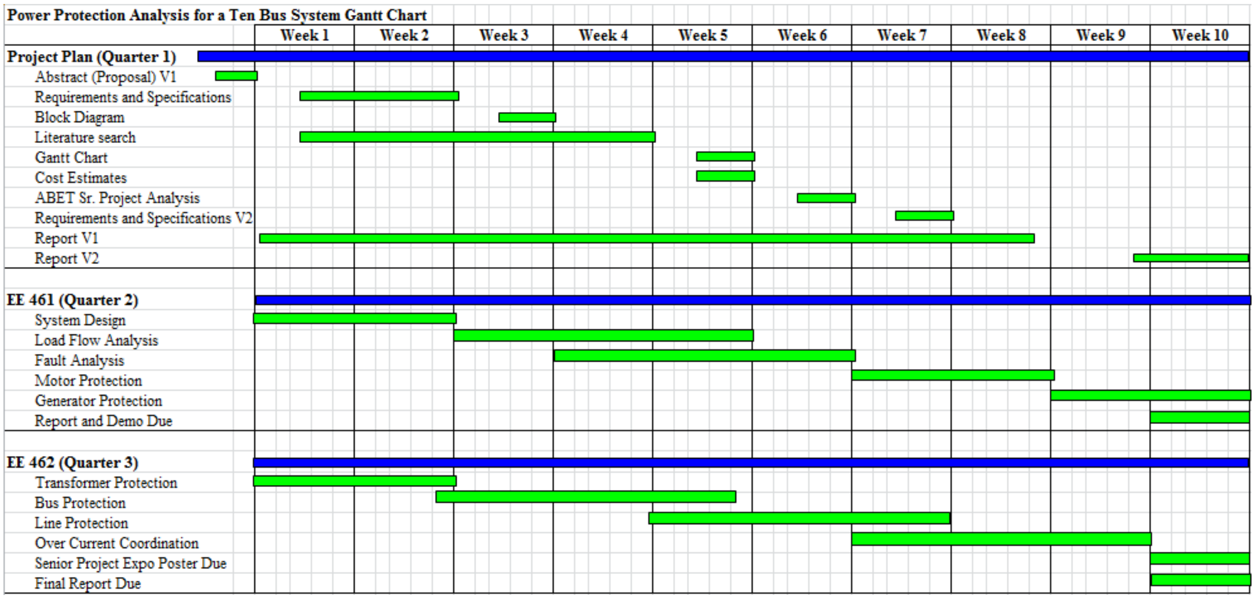

Figure 19: Gantt Chart

The cost estimates for the project are shown below in *Table 3*. Normally costing $500, the ETAP software is available for free on the Cal Poly computers. My individual labor on the project is also free since I am the only person working on it. The only part of the project that will actually cost me money is the poster board needed for the senior project expo.

Task	Cost	Explanation
ETAP Software	$0.00	The software is installed on computers in the EE building.
Poster Board	$6.99	The approximate cost of a senior project expo poster board at office depot.
Labor	$0.00	My labor for this project is free.

Total	$6.99	The poster board is the only thing purchased for the project.

Table 12: Cost Estimates