Introduction:

The term project for the Power System Protection (EE466) course this semester was about designing a protective scheme for a full system. We are asked to design a system containing different components like transformers, induction motors, synchronous motors, circuit breakers and loads. The previously mentioned components were designed and connected according to the following parameters:

Element	**Parameters**
Main Source	3-phase: MVAsc = 2000, X/R = 55.
Generator	Subtransient Model, Round-rotor, Typical Data.
All Induction Motors	Use “Std MF” Option
Lump Loads	70% Mtr Load; LRC = 650%, “High”; X/R = 15; Use “Std MF” Option.
Cables	For all branch/equipment cables: Tmin = 50, Tmax = 75

After that, we are asked to define the required protection type for each component. Then, a relay of the correct type will be connected to the properly chosen current transformer (CT).

The report shows the design of the protective scheme on ETAP and how the components are connected. It also shows the chosen protection type for each component and the type of relay along with the CT ratio. The report also contains some results generated by ETAP like the Load Flow, the Short-Circuit Test and the relay coordination chart. All the results are shown for two different configurations where the circuit breaker connecting the two major parts of the scheme is once closed and opened in the second configuration.

Procedure:

1- Normal Configuration (closed-tie CB):

We started the design by adding all the components to the ETAP edit mode and connected them to form the wanted diagram. We entered the specifications of each component as required by the previously mentioned table. The full scheme is shown in Figure 1.

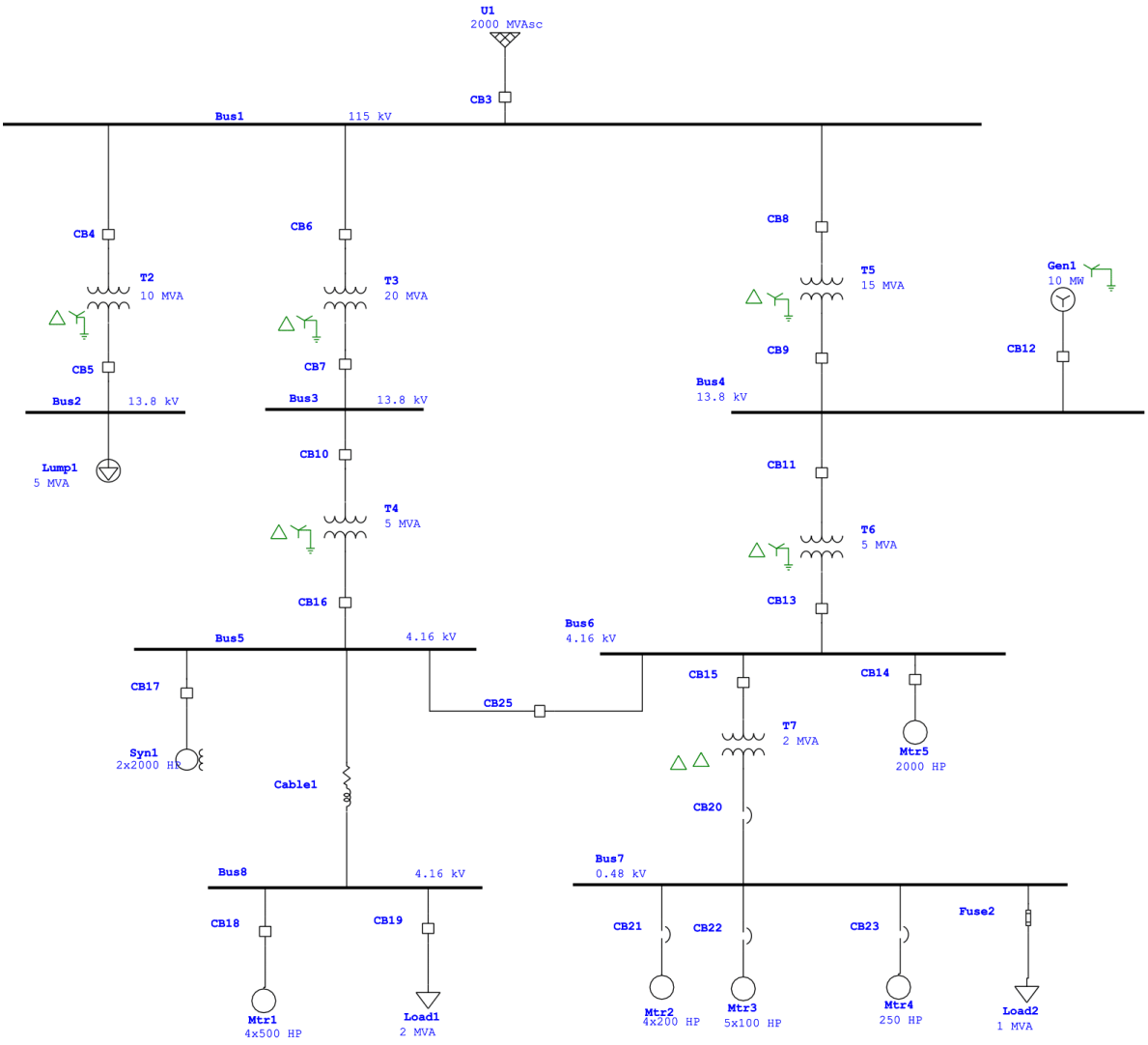

Figure 1. Full Diagram before adding relays.

To determine the correct CT ratios, we need information on the current flowing in each component of the circuit. These current readings will help setting the relays for the correct fault values. To get this information about the current, we did a Load Flow Analysis. It resulted in showing the current and the power of each branch in the diagram. These results are shown in Figure 2.

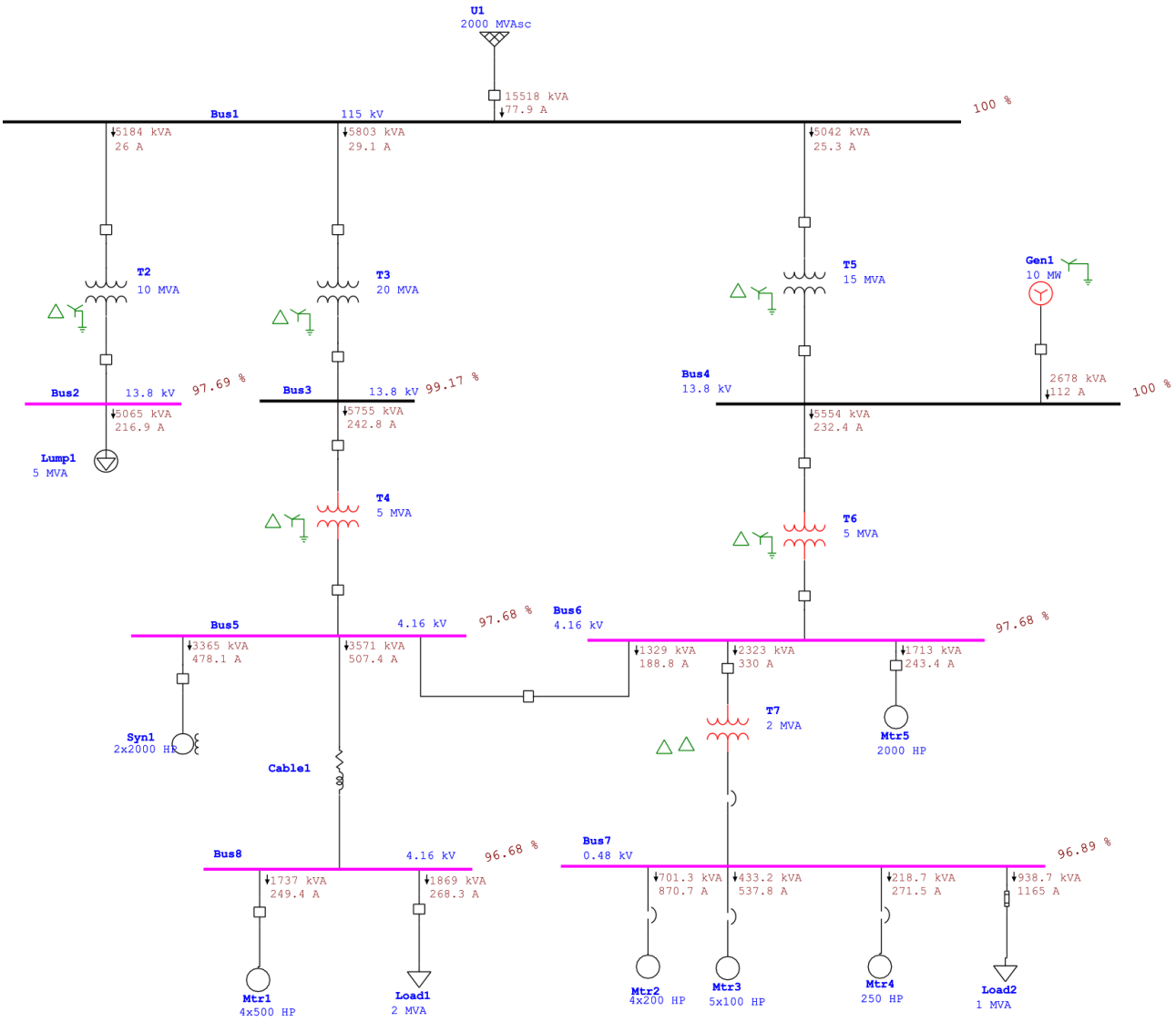

Figure 2. Full Diagram with Load Flow Analysis results.

We also applied the Short-Circuit Test Analysis for faults in all buses in the diagram. This will show us the fault current at each bus. The fault current results can be used to determine the appropriate CT ratios and set the relays properly. Short-Circuit Analysis results are shown in Figure 3.

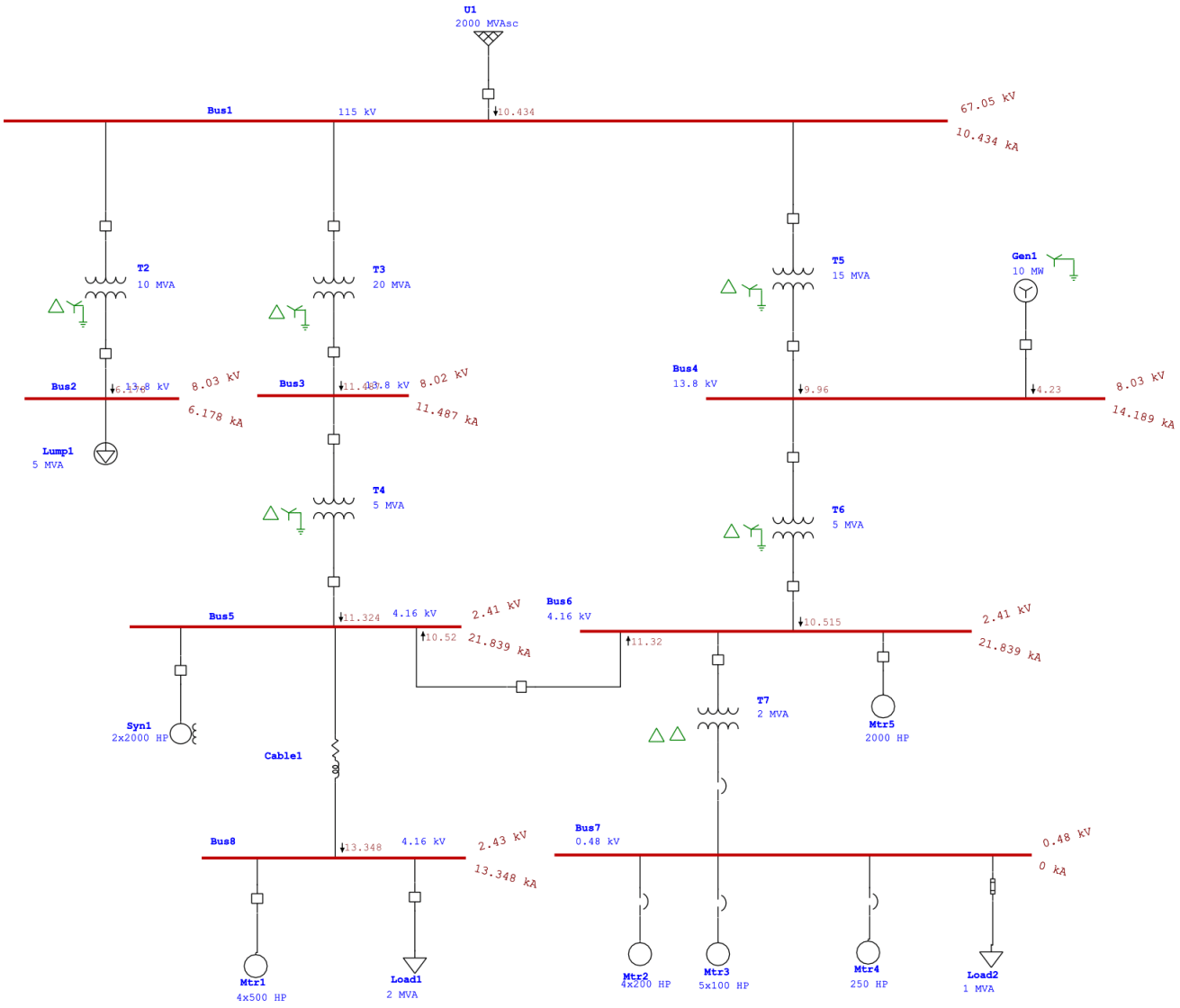

Figure 3. Full Diagram with Short-Circuit Analysis results.

Now we need to choose CT ratios and relays properly to trip the circuit breakers in a correct way. Any chosen CT ratio need to follow standard values to be ready for implementation in reality. Figure 4 shows the standard CT ratio values.

IEEE C57.13 Table 8 - Standard multi-ratio current transformer taps*

Ratio	Tap	Ratio	Tap	Ratio	Tap	Ratio	Tap	Ratio	Tap	Ratio	Tap
600:5 MR		1200:5 MR		2000:5 MR		3000:5 MR		4000:5 MR		5000:5 MR	
50:5	X2-X3	100:5	X2-X3	300:5	X3-X4	300:5	X3-X4	500:5	X1-X2	500:5	X2-X3
100:5	X1-X2	200:5	X1-X2	400:5	X1-X2	500:5	X4-X5	1000:5	X3-X4	1000:5	X4-X5
150:5	X1-X3	300:5	X1-X3	500:5	X4-X5	800:5	X3-X5	1500:5	X2-X3	1500:5	X1-X2
200:5	X4-X5	400:5	X4-X5	800:5	X2-X3	1000:5	X1-X2	2000:5	X1-X3	2000:5	X3-X4
250:5	X3-X4	500:5	X3-X4	1100:5	X2-X4	1200:5	X2-X3	2500:5	X2-X4	2500:5	X2-X4
300:5	X2-X4	600:5	X2-X4	1200:5	X1-X3	1500:5	X2-X4	3000:5	X1-X4	3000:5	X3-X5
400:5	X1-X4	800:5	X1-X4	1500:5	X1-X4	2000:5	X2-X5	3500:5	X2-X5	3500:5	X2-X5
450:5	X3-X5	900:5	X3-X5	1600:5	X2-X5	2200:5	X1-X3	4000:5	X1-X5	4000:5	X1-X4
500:5	X2-X5	1000:5	X2-X5	2000:5	X1-X5	2500:5	X1-X4			5000:5	X1-X5
600:5	X1-X5	1200:5	X1-X5			3000:5	X1-X5				

Figure 4. Standard CT ratios.

The primary side of each CT must have a rating value in the range of:

$$2\times I_{max-Load} < I_{Pickup} < \frac{1}{3}\times I_{max-fault}$$

To **increase the relay's dependability**, we will always choose values that are **closer to the maximum load current**.

Table 1 summarizes all the information about the CT ratios, the protection type, relay types and relays' functions.

Figure 5 shows the diagram after connecting all the CTs and relays.

Table 1. CT Ratios and Relays for Closed-CB configuration.

Element	$I_{max\text{-}load}$	CT Ratio	Protection Type	Relay Model	Relay Function
Main source	77.9A	200:5	TDOC	ABB 51D	Open CB3
T2 (high side)	26A	100:5	TDOC	ABB 51D	Open CB4
T2 (low side)	216.9A	500:5	TDOC	ABB 51D	Open CB5
T2	-	-	Differential	ABB 87HU	Open CB4-CB5
T3 (high side)	29.1A	100:5	TDOC	ABB 51D	Open CB6
T3 (low side)	242.8A	500:5	TDOC	ABB 51D	Open CB7
T3	-	-	Differential	ABB 87HU	Open CB6-CB7
T4 (high side)	242.8A	500:5	TDOC	ABB 51D	Open CB10
T4 (low side)	805.4A	2000:5	TDOC	ABB 51D	Open CB16
T4	-	-	Differential	ABB 87HU	Open CB10-CB16
T5 (high side)	25.3A	100:5	TDOC	ABB 51D	Open CB8
T5 (low side)	210.8A	500:5	TDOC	ABB 51D	Open CB9
T5	-	-	Differential	ABB 87HU	Open CB8-CB9
T6 (high side)	232.4A	500:5	TDOC	ABB 51D	Open CB11
T6 (low side)	770.9A	2000:5	TDOC	ABB 51D	Open CB13
T6	-	-	Differential	ABB 87HU	Open CB11-CB13
T7 (high side)	330A	800:5	TDOC	ABB 51D	Open CB15
T7 (low side)	2860A	5000:5	TDOC	ABB 51D	Open CB20
T7	-	-	Differential	ABB 87HU	Open CB15-CB20
Gen1	112A	250:5	TDOC	GE Multiln 489	Open CB12
Syn1	478.1A	1000:5	TDOC	GE Multiln IAC-66	Open CB17
Mtr1	249.2A	500:5	TDOC	GE Multiln IAC-66	Open CB18
Mtr2	870.7A	2000:5	TDOC	GE Multiln IAC-66	Open CB21
Mtr3	537.8A	1100:5	TDOC	GE Multiln IAC-66	Open CB22
Mtr4	271.5A	600:5	TDOC	GE Multiln IAC-66	Open CB23
Mtr5	243.4A	500:5	TDOC	GE Multiln IAC-66	Open CB14
Load1	268.3A	600:5	TDOC	ABB 51D	Open CB19

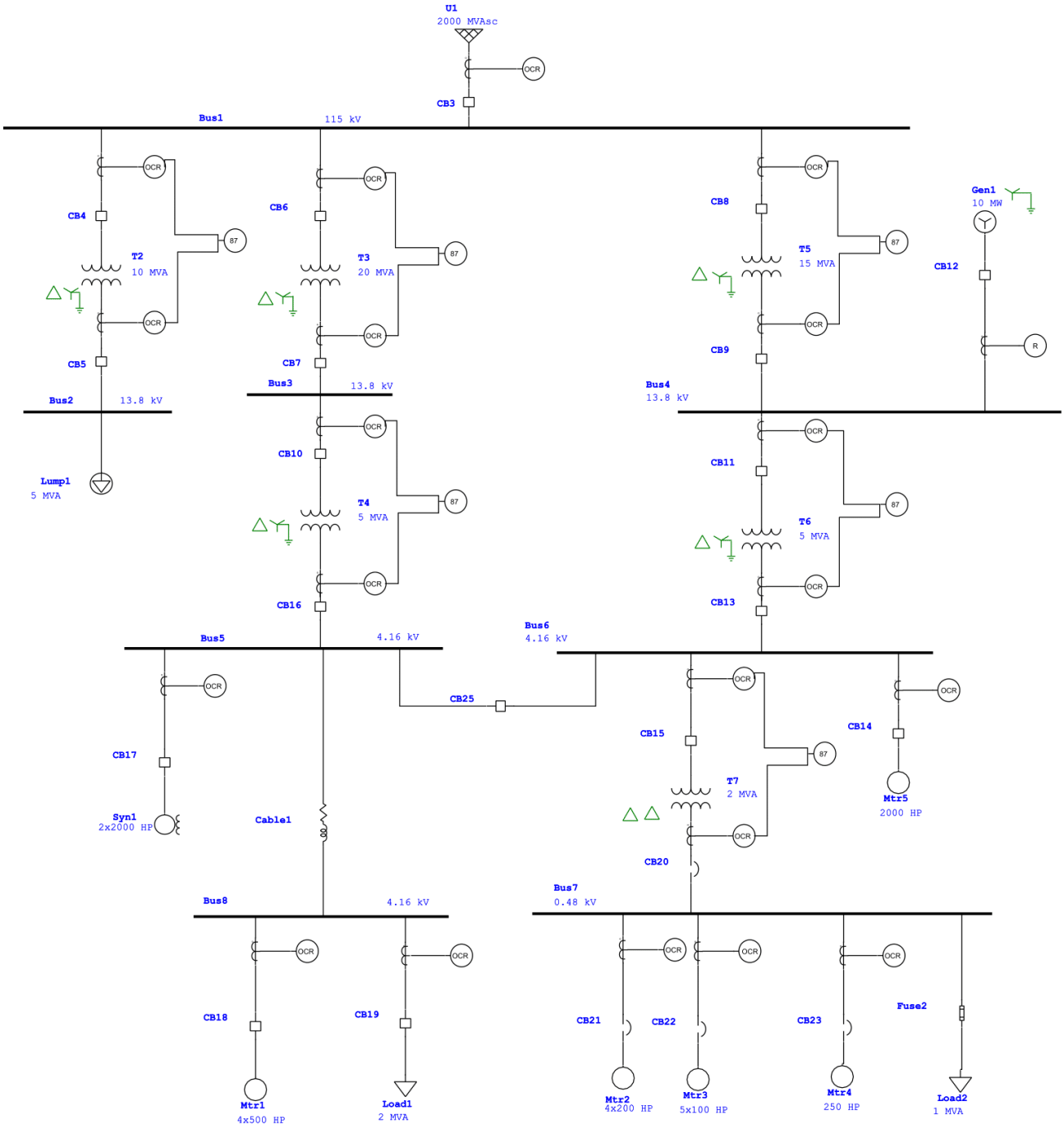

Figure 5. Full Diagram with CTs and Relays

The last step of checking the protective scheme in this configuration is to test the Sequence of Operation of all the relays. We will do that by showing the Sequence of Operation of relays due to a fault in all the buses one by one. Figures 6-13 show the sequence of operation reports for faults at buses 1-8.

Sequence of Operation:

Fault at BUS 1:

3-Phase (Symmetrical) fault on bus: Bus1

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
0.9	Relay25	2.809	0.9		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
84.2	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
141	Relay3	10.041	< 141		Phase - OC1 - 51
161	Relay19	3.042	161		Phase - OC1 - 51
205	Relay21	0.365	205		Phase - OC1 - 51
224	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
245	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
288	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
351	Relay10	0.996	351		Phase - OC1 - 51
351	Relay15	0.996	351		Phase - OC1 - 51
411	Relay5	0.875	411		Phase - OC1 - 51
434	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
434	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
448	Relay13	3.263	448		Phase - OC1 - 51
494	CB5		83.3		Tripped by Relay5 Phase - OC1 - 51
531	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
683	Relay4	0.105	> 683		Phase - OC1 - 51
683	Relay12	0.12	> 683		Phase - OC1 - 51
767	CB4		83.3		Tripped by Relay4 Phase - OC1 - 51
767	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
2769	Relay25	2.809	2769		Overload Phase - Thermal
2853	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal
3672	Relay27	1.031	3672		Phase - OC1 - 51
3755	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
5107	Relay29	0.833	5107		Phase - OC1 - 51
5191	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
5287	Relay28	1.639	5287		Phase - OC1 - 51
5370	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
6588	Relay31	2.303	> 6588		Phase - OC1 - 51
6588	Relay32	1.417	> 6588		Phase - OC1 - 51
6588	Relay33	0.719	> 6588		Phase - OC1 - 51
6638	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51
6638	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
6638	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51

Figure 6. Fault at BUS1 (Closed-CB Configuration).

Fault at BUS 2:

3-Phase (Symmetrical) fault on bus: Bus2

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
145	Relay5	5.245	145		Phase - OC1 - 51
160	Relay4	0.629	160		Phase - OC1 - 51
229	CB5		83.3		Tripped by Relay5 Phase - OC1 - 51
234	Relay3	0.6	234		Phase - OC1 - 51
243	CB4		83.3		Tripped by Relay4 Phase - OC1 - 51
318	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51

Figure 7. Fault at BUS2 (Closed-CB Configuration).

Fault at BUS 3:

3-Phase (Symmetrical) fault on bus: Bus3

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
10.3	Relay25	0.617	10.3		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
93.6	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
142	Relay10	9.822	142		Phase - OC1 - 51
144	Relay12	1.179	144		Phase - OC1 - 51
162	Relay3	1.202	162		Phase - OC1 - 51
205	Relay15	1.82	205		Phase - OC1 - 51
226	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
228	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
236	Relay13	5.96	236		Phase - OC1 - 51
245	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
289	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
319	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
390	Relay18	0.914	390		Phase - OC1 - 51
473	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
515	Relay16	2.995	515		Phase - OC1 - 51
598	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
6377	Relay27	0.759	6377		Phase - OC1 - 51
6460	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
6588	Relay28	1.207	> 6588		Phase - OC1 - 51
6588	Relay29	0.613	> 6588		Phase - OC1 - 51
6672	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
6672	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
152998	Relay25	0.617	152998		Overload Phase - Thermal
153082	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal

Figure 8. Fault at BUS3 (Closed-CB Configuration).

Fault at BUS 4:

3-Phase (Symmetrical) fault on bus: Bus4

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
0.7	Relay25	4.101	0.7		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
84.0	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
142	Relay19	8.58	142		Phase - OC1 - 51
146	Relay21	1.03	146		Phase - OC1 - 51
166	Relay3	1.118	166		Phase - OC1 - 51
214	Relay18	1.72	214		Phase - OC1 - 51
226	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
229	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
249	Relay16	5.634	249		Phase - OC1 - 51
249	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
297	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
333	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
436	Relay10	0.834	436		Phase - OC1 - 51
436	Relay15	0.834	436		Phase - OC1 - 51
519	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
519	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
615	Relay13	2.733	615		Phase - OC1 - 51
683	Relay12	0.1	> 683		Phase - OC1 - 51
698	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
767	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
1388	Relay25	4.101	1388		Overload Phase - Thermal
1471	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal
6588	Relay27	0.743	> 6588		Phase - OC1 - 51
6588	Relay28	1.181	> 6588		Phase - OC1 - 51
6588	Relay29	0.6	> 6588		Phase - OC1 - 51
6672	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
6672	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
6672	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51

Figure 9. Fault at BUS4 (Closed-CB Configuration).

Fault at BUS 5:

3-Phase (Symmetrical) fault on bus: Bus5

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
5.1	Relay25	0.848	5.1		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
88.4	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
176	Relay10	2.397	176		Phase - OC1 - 51
176	Relay15	2.397	176		Phase - OC1 - 51
176	Relay18	2.393	176		Phase - OC1 - 51
195	Relay13	7.851	195		Phase - OC1 - 51
195	Relay16	7.84	195		Phase - OC1 - 51
230	Relay19	1.546	230		Phase - OC1 - 51
244	Relay12	0.288	244		Phase - OC1 - 51
260	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
260	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
260	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
278	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
279	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
299	Relay3	0.468	299		Phase - OC1 - 51
313	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
328	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
382	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
383	Relay21	0.185	383		Phase - OC1 - 51
466	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
556	Relay22	7.195	556		Phase - OC1 - 51
606	CB20		50.0		Tripped by Relay22 Phase - OC1 - 51
683	Relay24	0.851	> 683		Phase - OC1 - 51
767	CB15		83.3		Tripped by Relay24 Phase - OC1 - 51
2253	Relay27	1.671	2253		Phase - OC1 - 51
2336	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
2722	Relay29	1.35	2722		Phase - OC1 - 51
2765	Relay28	2.657	2765		Phase - OC1 - 51
2805	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
2848	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
3613	Relay32	2.297	3613		Phase - OC1 - 51
3663	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
3971	Relay33	1.165	3971		Phase - OC1 - 51
4021	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
4229	Relay31	3.734	4229		Phase - OC1 - 51
4279	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51
44495	Relay25	0.848	44495		Overload Phase - Thermal
44579	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal

Figure 10. Fault at BUS5 (Closed-CB Configuration).

Fault at BUS 6:

3-Phase (Symmetrical) fault on bus: Bus6

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
5.1	Relay25	0.848	5.1		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
88.4	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
176	Relay10	2.397	176		Phase - OC1 - 51
176	Relay15	2.397	176		Phase - OC1 - 51
176	Relay18	2.393	176		Phase - OC1 - 51
195	Relay13	7.851	195		Phase - OC1 - 51
195	Relay16	7.84	195		Phase - OC1 - 51
230	Relay19	1.546	230		Phase - OC1 - 51
244	Relay12	0.288	244		Phase - OC1 - 51
260	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
260	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
260	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
278	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
279	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
299	Relay3	0.468	299		Phase - OC1 - 51
313	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
328	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
382	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
383	Relay21	0.185	383		Phase - OC1 - 51
466	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
556	Relay22	7.195	556		Phase - OC1 - 51
606	CB20		50.0		Tripped by Relay22 Phase - OC1 - 51
683	Relay24	0.851	> 683		Phase - OC1 - 51
767	CB15		83.3		Tripped by Relay24 Phase - OC1 - 51
2253	Relay27	1.671	2253		Phase - OC1 - 51
2336	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
2722	Relay29	1.35	2722		Phase - OC1 - 51
2765	Relay28	2.657	2765		Phase - OC1 - 51
2805	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
2848	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
3613	Relay32	2.297	3613		Phase - OC1 - 51
3663	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
3971	Relay33	1.165	3971		Phase - OC1 - 51
4021	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
4229	Relay31	3.734	4229		Phase - OC1 - 51
4279	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51
44495	Relay25	0.848	44495		Overload Phase - Thermal
44579	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal

Figure 11. Fault at BUS6 (Closed-CB Configuration).

Fault at BUS 7:

3-Phase (Symmetrical) fault on bus: Bus7

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
164	Relay22	28.764	164		Phase - OC1 - 51
187	Relay24	3.404	187		Phase - OC1 - 51
214	CB20		50.0		Tripped by Relay22 Phase - OC1 - 51
270	CB15		83.3		Tripped by Relay24 Phase - OC1 - 51
2870	Relay32	2.813	2870		Phase - OC1 - 51
2920	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
3082	Relay33	1.427	3082		Phase - OC1 - 51
3132	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
3229	Relay31	4.574	3229		Phase - OC1 - 51
3279	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51

Figure 12. Fault at BUS7 (Closed-CB Configuration).

Fault at BUS 8:

3-Phase (Symmetrical) fault on bus: Bus8

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
17.0	Relay25	0.505	17.0		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
100	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
246	Relay10	1.428	246		Phase - OC1 - 51
246	Relay15	1.428	246		Phase - OC1 - 51
246	Relay18	1.425	246		Phase - OC1 - 51
299	Relay13	4.676	299		Phase - OC1 - 51
300	Relay16	4.67	300		Phase - OC1 - 51
329	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
329	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
330	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
383	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
383	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
386	Relay19	0.921	386		Phase - OC1 - 51
422	Relay12	0.171	422		Phase - OC1 - 51
470	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
505	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
591	Relay3	0.279	591		Phase - OC1 - 51
675	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
683	Relay21	0.11	> 683		Phase - OC1 - 51
767	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
2607	Relay29	1.41	2607		Phase - OC1 - 51
2691	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
3833	Relay27	0.995	3833		Phase - OC1 - 51
3917	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
5702	Relay28	1.583	5702		Phase - OC1 - 51
5785	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
6588	Relay31	2.224	> 6588		Phase - OC1 - 51
6588	Relay32	1.368	> 6588		Phase - OC1 - 51
6588	Relay33	0.694	> 6588		Phase - OC1 - 51
6638	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51
6638	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
6638	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
1672753	Relay25	0.505	1672753		Overload Phase - Thermal
1672836	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal

Figure 13. Fault at BUS8 (Closed-CB Configuration).

The following figure (Figure 14) shows the Time Dial plot for each Relay:

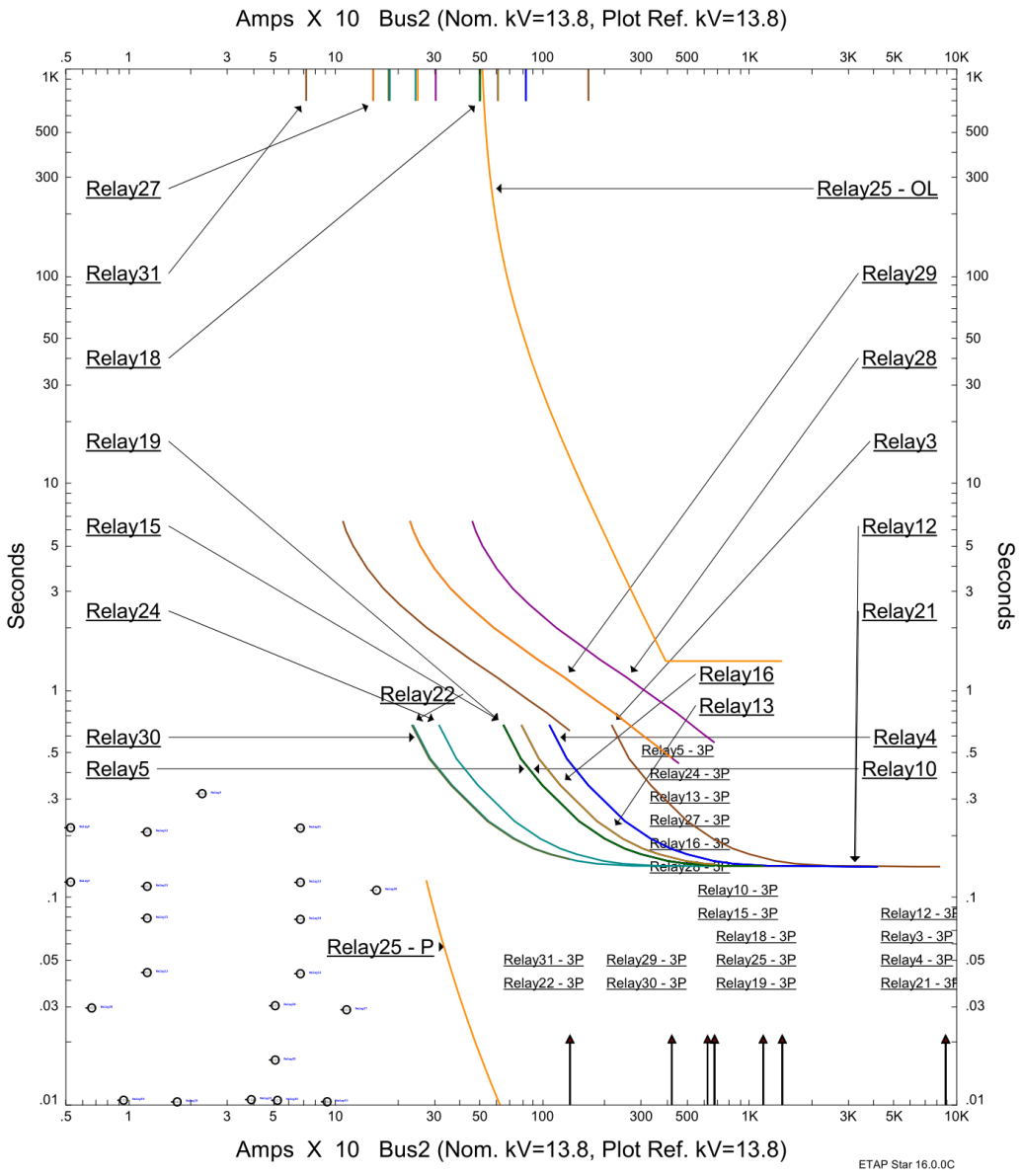

Figure 14. Time Dial plot for Closed-CB configuration.

2- Tie-Open Configuration (Open-tie CB):

Now, we will repeat all the previous work but for a different configuration. This configuration has the same elements but CB25 is opened. The full diagram of the configuration is shown in Figure 15.

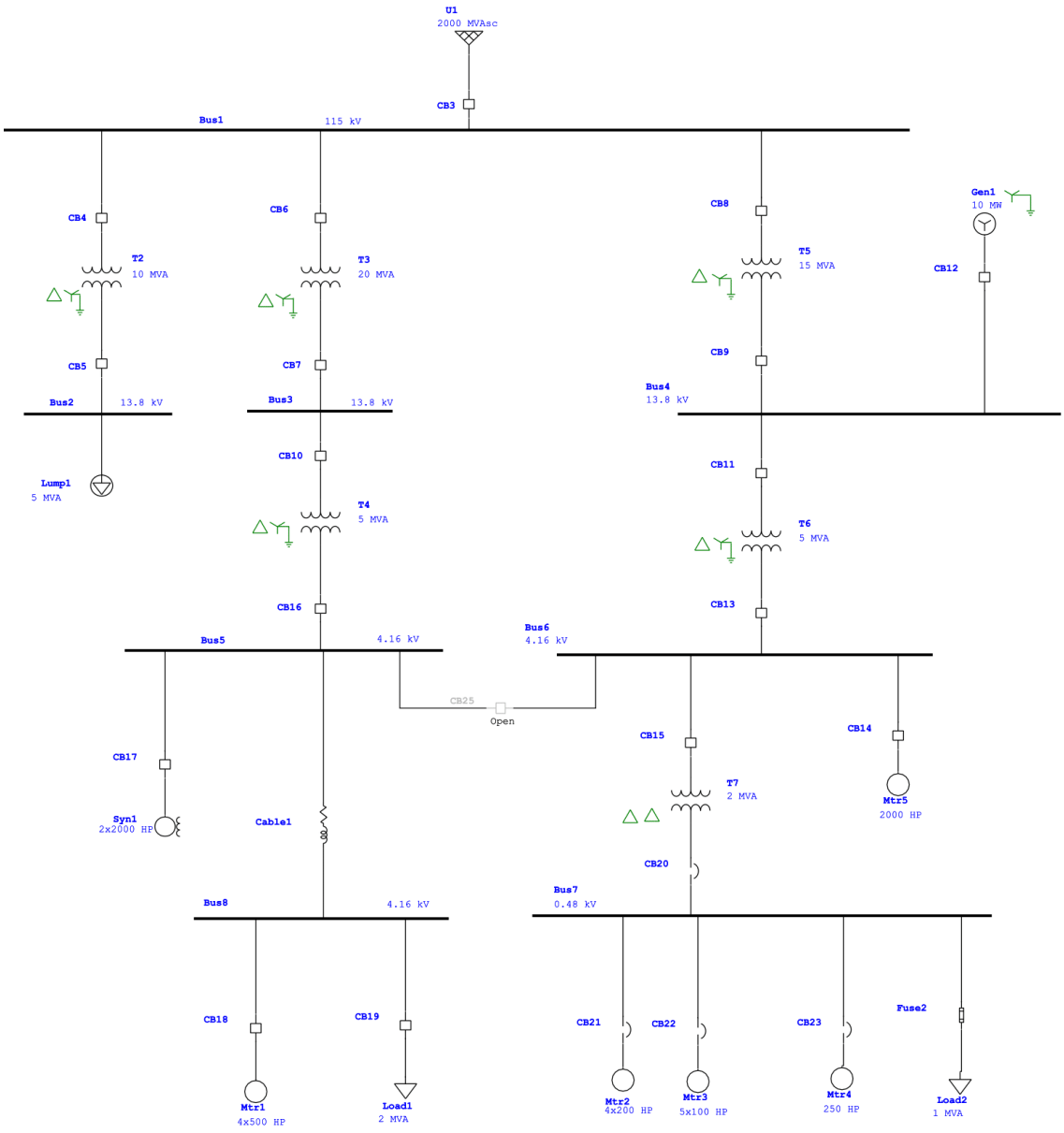

Figure 15. Full Diagram for Open-CB configuration.

In the next two figures (Figure 16, 17), the results of the Load Flow Analysis and the Short-Circuit Analysis for the Open-tie CB configuration are shown.

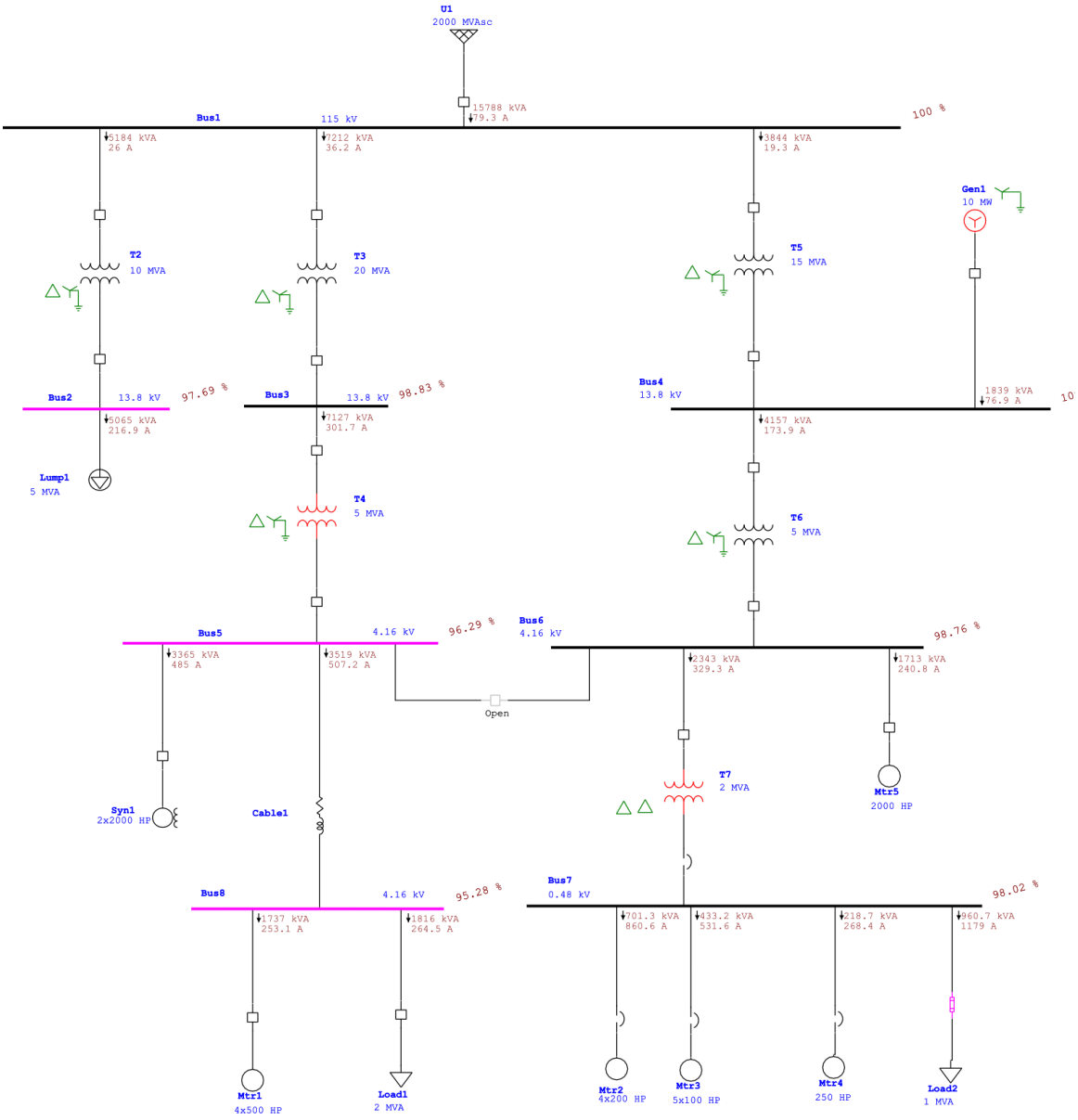

Figure 16. Load Flow Analysis results for Open-CB configuration.

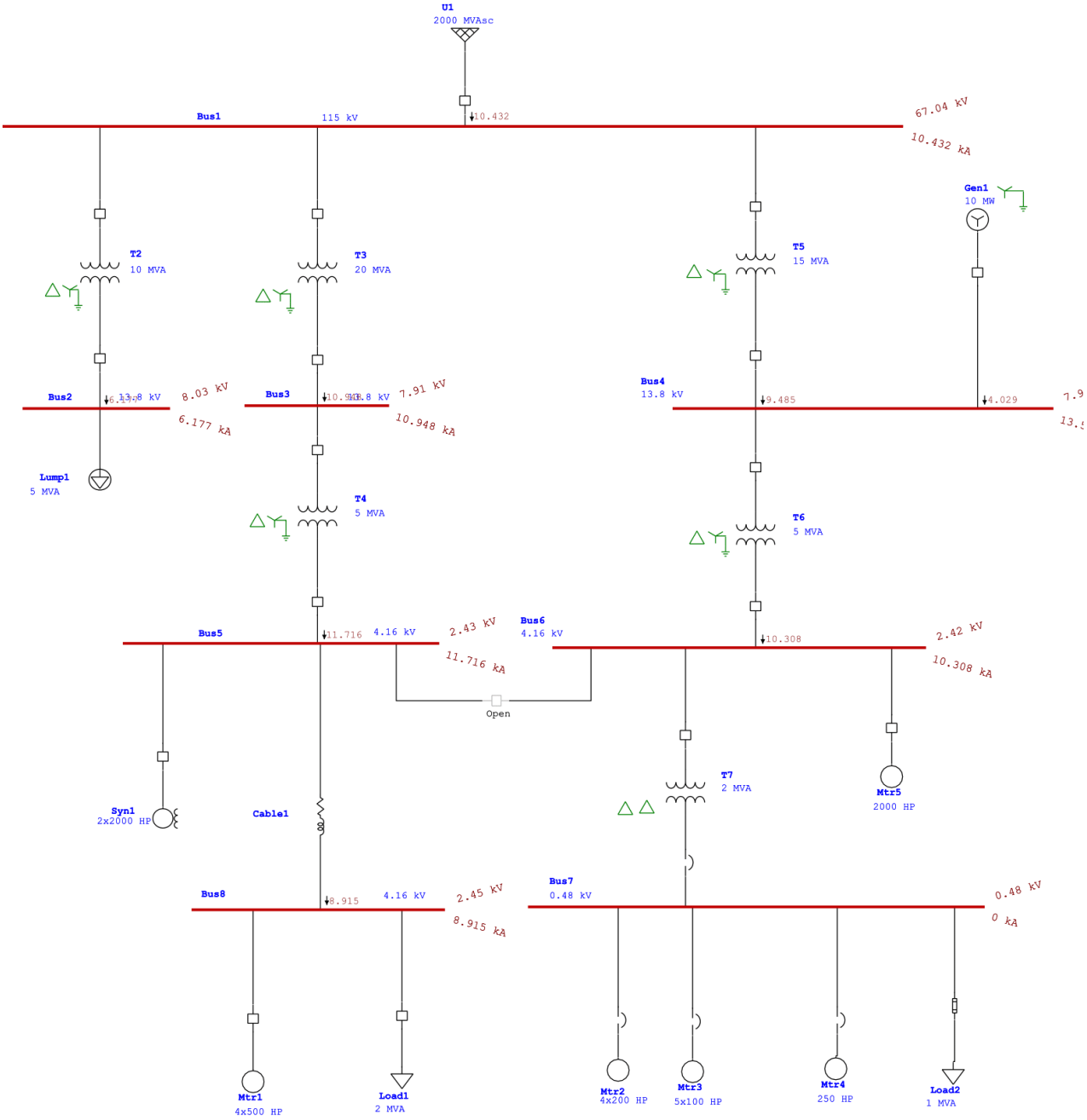

Figure 17. Short-Circuit Analysis results for Open-CB configuration.

After that, the relays and the CTs were added to this new configuration. Table 2 summarizes all the details of the newly added CTs and relays. Figure 18 show the full diagram of the configuration after adding the relays and the CTs.

Table 2. CT and Relays Information for the Open-CB configuration.

Element	$I_{max\text{-}load}$	CT Ratio	Protection Type	Relay Model	Relay Function
Main source	73.9A	150:5	TDOC	ABB 51D	Open CB3
T2 (high side)	26A	100:5	TDOC	ABB 51D	Open CB4
T2 (low side)	216.9A	500:5	TDOC	ABB 51D	Open CB5
T2	-	-	Differential	ABB 87HU	Open CB4-CB5
T3 (high side)	36.2A	100:5	TDOC	ABB 51D	Open CB6
T3 (low side)	301.7A	600:5	TDOC	ABB 51D	Open CB7
T3	-	-	Differential	ABB 87HU	Open CB6-CB7
T4 (high side)	301.7A	600:5	TDOC	ABB 51D	Open CB10
T4 (low side)	1000.8A	2000:5	TDOC	ABB 51D	Open CB16
T4	-	-	Differential	ABB 87HU	Open CB10-CB16
T5 (high side)	19.3A	100:5	TDOC	ABB 51D	Open CB8
T5 (low side)	160.8A	500:5	TDOC	ABB 51D	Open CB9
T5	-	-	Differential	ABB 87HU	Open CB8-CB9
T6 (high side)	173.9A	500:5	TDOC	ABB 51D	Open CB11
T6 (low side)	576.9A	1100:5	TDOC	ABB 51D	Open CB13
T6	-	-	Differential	ABB 87HU	Open CB11-CB13
T7 (high side)	329.3A	800:5	TDOC	ABB 51D	Open CB15
T7 (low side)	2860A	5000:5	TDOC	ABB 51D	Open CB20
T7	-	-	Differential	ABB 87HU	Open CB15-CB20
Gen1	76.9A	150:5	TDOC	GE Multiln 489	Open CB12
Syn1	485 A	1000:5	TDOC	GE Multiln IAC-66	Open CB17
Mtr1	253.1A	500:5	TDOC	GE Multiln IAC-66	Open CB18
Mtr2	860.6A	2000:5	TDOC	GE Multiln IAC-66	Open CB21
Mtr3	531.6A	1100:5	TDOC	GE Multiln IAC-66	Open CB22
Mtr4	268.4A	600:5	TDOC	GE Multiln IAC-66	Open CB23
Mtr5	240.8A	500:5	TDOC	GE Multiln IAC-66	Open CB14
Load1	264.5A	600:5	TDOC	ABB 51D	Open CB19

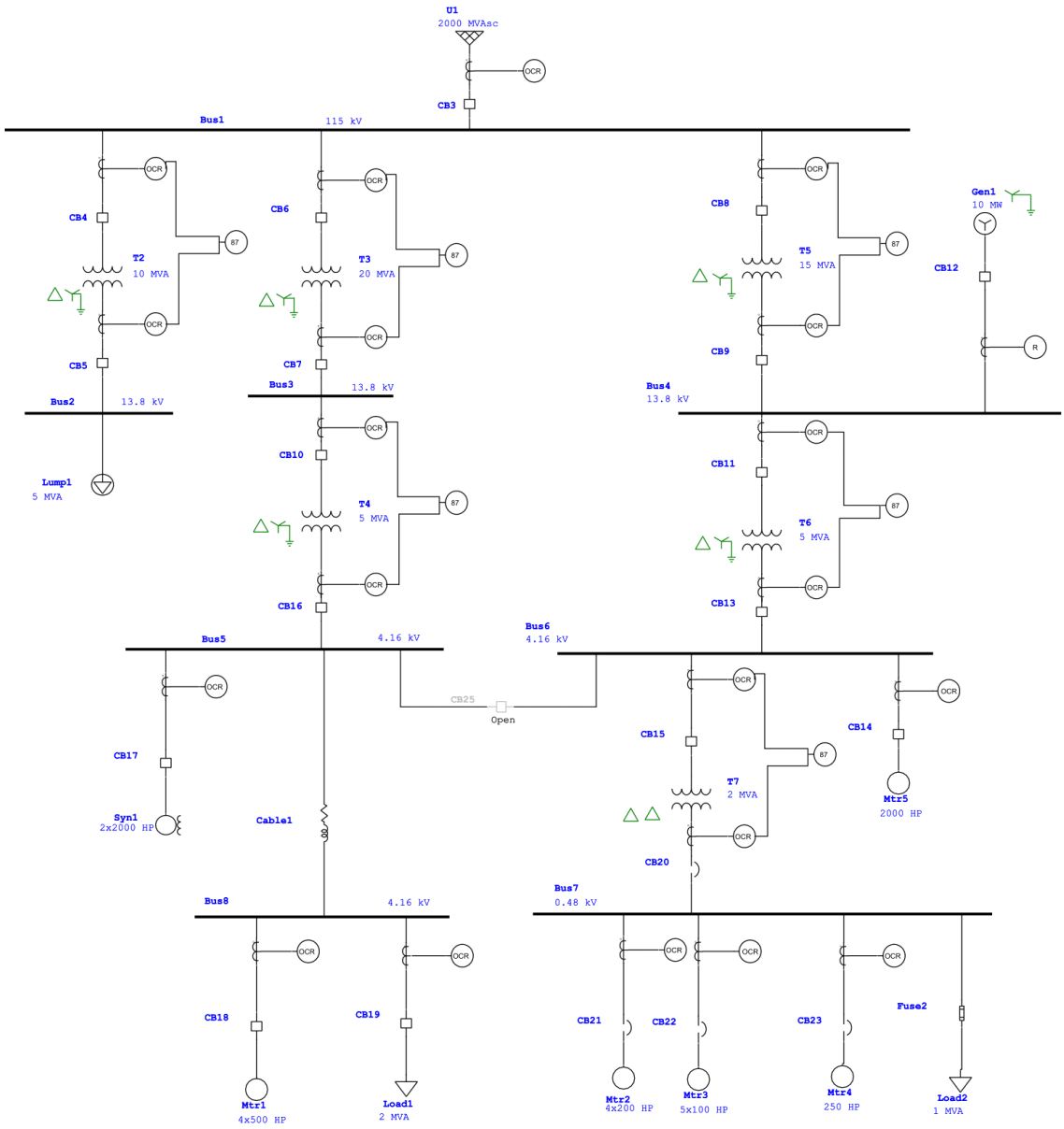

Figure 18. Full diagram with CTs and Relays for Opened-Tie CB configuration.

The last step was to analyze the Sequence of Operation of the relays for a fault at each bus in the system. Figure 19-26 show the Sequence of Operation reports for buses 1-8.

Sequence of Operation:

Fault at BUS 1:

3-Phase (Symmetrical) fault on bus: Bus1

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
0.9	Relay25	2.754	0.9		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
84.2	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
141	Relay3	10.041	< 141		Phase - OC1 - 51
160	Relay19	3.171	160		Phase - OC1 - 51
199	Relay21	0.381	199		Phase - OC1 - 51
224	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
243	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
283	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
411	Relay5	0.875	411		Phase - OC1 - 51
436	Relay10	0.833	436		Phase - OC1 - 51
436	Relay15	0.833	436		Phase - OC1 - 51
494	CB5		83.3		Tripped by Relay5 Phase - OC1 - 51
520	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
520	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
616	Relay13	2.73	616		Phase - OC1 - 51
683	Relay4	0.105	> 683		Phase - OC1 - 51
683	Relay12	0.1	> 683		Phase - OC1 - 51
700	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
767	CB4		83.3		Tripped by Relay4 Phase - OC1 - 51
767	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
2885	Relay25	2.754	2885		Overload Phase - Thermal
2968	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal
4330	Relay29	0.92	4330		Phase - OC1 - 51
4413	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
4435	Relay27	0.906	4435		Phase - OC1 - 51
4441	Relay28	1.811	4441		Phase - OC1 - 51
4518	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
4525	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51
6588	Relay31	2.025	> 6588		Phase - OC1 - 51
6588	Relay32	1.246	> 6588		Phase - OC1 - 51
6588	Relay33	0.632	> 6588		Phase - OC1 - 51
6638	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51
6638	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
6638	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51

Figure 19. Fault at BUS1 (Opened-CB Configuration).

Fault at BUS 2:

3-Phase (Symmetrical) fault on bus: Bus2

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
145	Relay5	5.245	145		Phase - OC1 - 51
160	Relay4	0.629	160		Phase - OC1 - 51
229	CB5		83.3		Tripped by Relay5 Phase - OC1 - 51
234	Relay3	0.601	234		Phase - OC1 - 51
243	CB4		83.3		Tripped by Relay4 Phase - OC1 - 51
318	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51

Figure 20. Fault at BUS2 (Opened-CB Configuration).

Fault at BUS 3:

3-Phase (Symmetrical) fault on bus: Bus3

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
75.6	Relay25	0.311	75.6		Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
142	Relay10	9.898	142		Phase - OC1 - 51
144	Relay12	1.188	144		Phase - OC1 - 51
159	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
165	Relay3	1.133	165		Phase - OC1 - 51
226	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
228	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
249	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
397	Relay15	0.901	397		Phase - OC1 - 51
480	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
530	Relay13	2.95	530		Phase - OC1 - 51
614	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
3839	Relay29	0.994	3839		Phase - OC1 - 51
3922	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
3924	Relay28	1.957	3924		Phase - OC1 - 51
4007	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51

Figure 21. Fault at BUS3 (Opened-CB Configuration).

Fault at BUS 4:

3-Phase (Symmetrical) fault on bus: Bus4

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
0.7	Relay25	4.101	0.7		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
84.0	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
142	Relay19	8.674	142		Phase - OC1 - 51
145	Relay21	1.041	145		Phase - OC1 - 51
172	Relay3	1.02	172		Phase - OC1 - 51
226	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
229	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
255	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
683	Relay16	2.035	> 683		Phase - OC1 - 51
683	Relay18	0.621	> 683		Phase - OC1 - 51
683	Relay22	5.809	> 683		Phase - OC1 - 51
733	CB20		50.0		Tripped by Relay22 Phase - OC1 - 51
767	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
767	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
1388	Relay25	4.101	1388		Overload Phase - Thermal
1471	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal
2724	Relay27	1.349	2724		Phase - OC1 - 51
2807	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
4977	Relay32	1.855	4977		Phase - OC1 - 51
5027	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
5817	Relay33	0.941	5817		Phase - OC1 - 51
5867	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
6519	Relay31	3.015	6519		Phase - OC1 - 51
6569	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51

Figure 22. Fault at BUS4 (Opened-CB Configuration).

Fault at BUS 5:

3-Phase (Symmetrical) fault on bus: Bus5

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
175	Relay10	2.444	175		Phase - OC1 - 51
175	Relay15	2.444	175		Phase - OC1 - 51
193	Relay13	8.007	193		Phase - OC1 - 51
240	Relay12	0.293	240		Phase - OC1 - 51
258	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
258	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
276	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
323	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
588	Relay3	0.28	588		Phase - OC1 - 51
671	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
2722	Relay29	1.35	2722		Phase - OC1 - 51
2765	Relay28	2.657	2765		Phase - OC1 - 51
2805	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
2848	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51

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Figure 23. Fault at BUS5 (Opened-CB Configuration).

Fault at BUS 6:

3-Phase (Symmetrical) fault on bus: Bus6

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
6.0	Relay25	0.784	6.0		Phase - OC1 - 51
20.0	Relay6		20.0		Phase - 87
89.3	CB12		83.3		Tripped by Relay25 Phase - OC1 - 51
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
175	Relay18	2.441	175		Phase - OC1 - 51
193	Relay16	7.996	193		Phase - OC1 - 51
219	Relay19	1.658	219		Phase - OC1 - 51
258	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
276	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
302	CB9		83.3		Tripped by Relay19 Phase - OC1 - 51
351	Relay21	0.199	351		Phase - OC1 - 51
435	CB8		83.3		Tripped by Relay21 Phase - OC1 - 51
556	Relay22	7.195	556		Phase - OC1 - 51
606	CB20		50.0		Tripped by Relay22 Phase - OC1 - 51
683	Relay24	0.851	> 683		Phase - OC1 - 51
767	CB15		83.3		Tripped by Relay24 Phase - OC1 - 51
2253	Relay27	1.671	2253		Phase - OC1 - 51
2336	CB14		83.3		Tripped by Relay27 Phase - OC1 - 51
3613	Relay32	2.297	3613		Phase - OC1 - 51
3663	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
3971	Relay33	1.165	3971		Phase - OC1 - 51
4021	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
4229	Relay31	3.734	4229		Phase - OC1 - 51
4279	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51
57003	Relay25	0.784	57003		Overload Phase - Thermal
57086	CB12		83.3		Tripped by Relay25 Overload Phase - Thermal

Figure 24. Fault at BUS6 (Opened-CB Configuration).

Fault at BUS 7:

3-Phase (Symmetrical) fault on bus: Bus7

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
176	Relay22	24.02	176		Phase - OC1 - 51
209	Relay24	2.843	209		Phase - OC1 - 51
226	CB20		50.0		Tripped by Relay22 Phase - OC1 - 51
292	CB15		83.3		Tripped by Relay24 Phase - OC1 - 51
559	Relay18	0.718	559		Phase - OC1 - 51
642	CB11		83.3		Tripped by Relay18 Phase - OC1 - 51
683	Relay16	2.352	> 683		Phase - OC1 - 51
767	CB13		83.3		Tripped by Relay16 Phase - OC1 - 51
2870	Relay32	2.813	2870		Phase - OC1 - 51
2920	CB22		50.0		Tripped by Relay32 Phase - OC1 - 51
3082	Relay33	1.427	3082		Phase - OC1 - 51
3132	CB23		50.0		Tripped by Relay33 Phase - OC1 - 51
3229	Relay31	4.574	3229		Phase - OC1 - 51
3279	CB21		50.0		Tripped by Relay31 Phase - OC1 - 51

Figure 25. Fault at BUS7 (Opened-CB Configuration).

Fault at BUS 8:

3-Phase (Symmetrical) fault on bus: Bus8

Data Rev.: Base Config: Normal Date: 12-26-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
20.0	Relay6		20.0		Phase - 87
103	CB4		83.3		Tripped by Relay6 Phase - 87
103	CB5		83.3		Tripped by Relay6 Phase - 87
206	Relay10	1.819	206		Phase - OC1 - 51
206	Relay15	1.819	206		Phase - OC1 - 51
236	Relay13	5.958	236		Phase - OC1 - 51
289	CB7		83.3		Tripped by Relay10 Phase - OC1 - 51
289	CB10		83.3		Tripped by Relay15 Phase - OC1 - 51
319	CB16		83.3		Tripped by Relay13 Phase - OC1 - 51
320	Relay12	0.218	320		Phase - OC1 - 51
404	CB6		83.3		Tripped by Relay12 Phase - OC1 - 51
683	Relay3	0.208	> 683		Phase - OC1 - 51
767	CB3		83.3		Tripped by Relay3 Phase - OC1 - 51
2607	Relay29	1.41	2607		Phase - OC1 - 51
2691	CB18		83.3		Tripped by Relay29 Phase - OC1 - 51
3866	Relay28	1.977	3866		Phase - OC1 - 51
3949	CB17		83.3		Tripped by Relay28 Phase - OC1 - 51

Figure 26. Fault at BUS8 (Opened-CB Configuration).

In Figure 27, we can see the Time Dial plots for each relay in the Open-tie CB configuration.

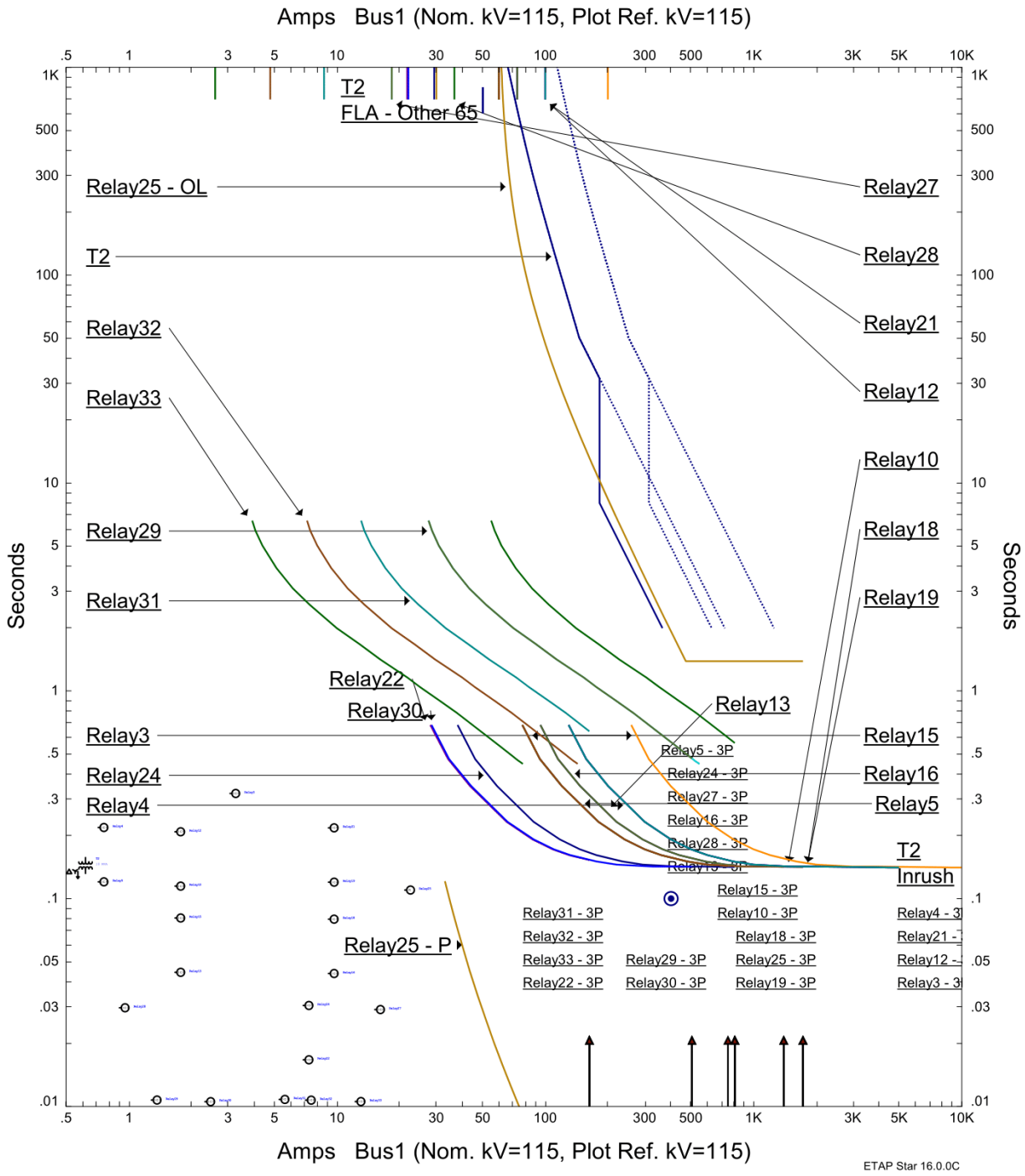

Figure 27. Time Dial plot for all relays in Opened-CB configuration.

Conclusion:

In this report, we showed all the details of our work on the EE466 term project. The project was about designing a protective scheme for a given diagram. We showed in detail the CT ratios for the CTs we added along with the Relays models and function. Next, we showed the results of the Sequence of Operation Analysis to demonstrate the relay coordination for faults on all buses. We used the Load Flow Analysis results to help us choose the correct CT ratios. All these steps were done on two different configurations of the diagram which are the Closed-tie CB and the Opened-tie CB configurations. We can see from the Sequence of Operation results in both configurations that in some faults (like faults in buses 5, 6) are simpler to handle in the Opened-tie configuration. This is due to the isolation of elements between the two parts of the diagram. It was a very interesting project and it enhanced our understanding of the course especially in relay coordination.